MAX PLANCK INSTITUTE
FOR INTELLIGENT SYSTEMS

SCIENTIFIC REPORT

2016 - 2021

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Max Planck Institute for Intelligent Systems

SCIENTIFIC REPORT 2016 – 2021

December 2021

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PREFACE

This report presents research done at the Max Planck Institute for Intelligent Systems from January 2016 to November 2021. It is our fourth report since the founding of the institute in 2011. Due to the fact that the upcoming evaluation is an extended one, the report covers a longer reporting period.

This scientific report is organized as follows: we begin with an overview of the institute, including an outline of its structure, an introduction of our latest research departments, and a presentation of our main collaborative initiatives and activities (Chapter 1). The central part of the scientific report consists of chapters on the research conducted by the institute's departments (Chapters 2 to 6) and its independent research groups (Chapters 7 to 24), as well as the work of the institute's central scientific facilities (Chapter 25). For entities founded after January 2016, the respective report sections cover work done from the date of the establishment of the department, group, or facility. These chapters are followed by a summary of selected outreach activities and scientific events hosted by the institute (Chapter 26). The scientific publications of the featured departments and research groups published during the 6-year review period complete this scientific report.

Bernhard Schölkopf, Managing Director, November 2021

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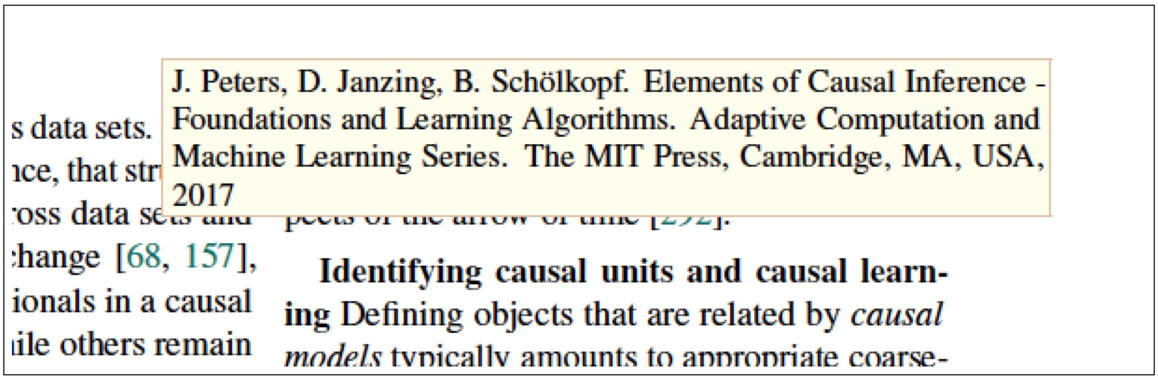

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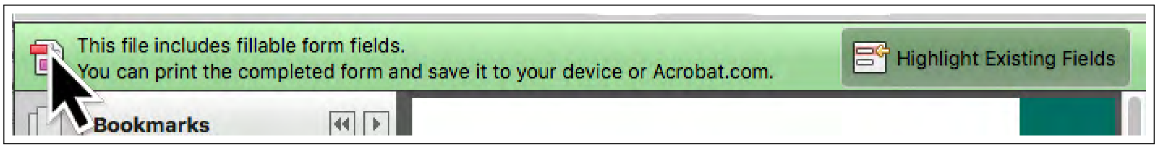

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1 OVERVIEW

1.1 Introduction

1.1.1 Scientific Concept of the Institute

The Max Planck Institute for Intelligent Systems (MPI-IS) strives to understand the principles of perception, action, and learning in autonomous systems that successfully interact with complex environments. In addition to gaining scientific understanding about natural intelligent systems, the institute's researchers further aim to use such insights to design future artificially intelligent systems that can benefit humanity. The institute has two campuses, building on the local strengths of each site. The two institute sites in Stuttgart and in Tübingen are located on the Max Planck Campuses and spatially connected to four neighboring Max Planck institutions. Together, Stuttgart and Tübingen form one of the biggest clusters of institutes within the Max Planck Society. The close proximity to several institutes and universities covering various disciplines supports many opportunities for scientific collaboration and creates organisational synergies that our institute profits from. We combine theory, software, and hardware expertise in a single interdisciplinary center to enable the pursuit of creative and impactful research on a wide range of connected topics within the thriving research field of intelligent systems.

Our Tübingen site focuses more on computational aspects of intelligence, with departments in the broad fields of computer vision and machine learning, plus independent research groups that bring in perspectives from theory, algorithms, and robotics. The institute's Stuttgart site concentrates on physical realizations of intelligent systems with departments in the broad fields of mobile micro-robots and haptics, with independent research groups that emphasize smaller scales, biological inspiration, and control. Of course, many intelligent systems that we study involve both computational and physical aspects, providing ample opportunities for cross-site inspiration and collaboration.

The concept of the institute is inspired by the observation that biological systems have developed sophisticated abilities through interaction, evolution, and learning that enable them to act successfully in complex environments, and that a similar approach – although poorly understood at present – can be taken to synthesize effective autonomous systems. Regardless of their origin, form, or scale, we refer to such systems as intelligent systems. Understanding the computational and physical intelligence that underlies nature's systems is a major challenge: we work both to adequately describe such behavior and to use its key characteristics to invent synthetic, bio-hybrid, and human-assistive systems.

The field of artificial intelligence (AI) has long sought to create intelligent synthetic systems with capabilities similar to those of biological systems; the approach has traditionally involved explicit rules encoded in a computer program. This approach has succeeded for some well-defined tasks such as playing chess, but it has thus far dramatically failed for many tasks that are easily solved by biological systems (e.g., vision or movement control). These challenging tasks are often characterized by high-dimensional inputs and/or state spaces and complex stochastic nonlinear environments, in which case explicit models and simple behavioral rules are hard to design – humans have learned them over many years, and there is no reason for evolution and learning to produce solutions that are easy to comprehend post hoc.

A paradigm shift has taken place over the last few decades in major subfields of artificial intelligence, such as information retrieval and computer vision. Rule-based systems have been all but superseded by approaches that use machine learning. Consequently, machine learning methods have found their way into most fields of research and development and are now widely used in many areas that are highly relevant to human society.

However, researchers in fields that involve hardware systems (such as robots) still commonly try to handcraft solutions to challenging problems. In other words, these areas are in a state comparable to computer vision some time ago. Hand-engineered solutions are typically brittle and often work only in highly structured environments (e.g., factory assembly lines); they usually cannot generalize to novel situations and unstructured environments. We believe that machine learning has the potential to enable a performance jump in hardware-related intelligent systems similar to the jump that it facilitated in visual object detection and recognition.

Importantly, learning-based approaches are not limited to traditional engineering domains where systems have been designed to allow for classical control techniques: in principle, a learning-based approach can also be pursued in domains that are not amenable to standard engineering methods (e.g., bio-hybrid systems), as long as the basic mechanisms of perception, action, and adaptivity can be incorporated into such systems. Creating these new intelligent systems will likely also spur the invention of learning methods that can transcend the assumptions of problems in a single domain. A major organizing principle for the institute is the concept of a perception-action-learning loop. Biological systems function by perceiving relevant aspects of the world and their own state, processing these aspects, and continuously deciding what actions to take based upon the results. While the computations involved in the processing of perceptual data and the generation of actions – and in particular the closed-loop properties of perception-action-learning systems – are far from understood in biological systems, they appear to involve aspects of learning and adaptation, as well as processes of inference, in the face of uncertain and even hidden information. Synthetic autonomous systems interacting with the world fundamentally face the same challenges: based on noisy measurements taken in a complex world, they need to perform actions that let them carry out critical tasks, such as maintaining their structural integrity, navigating a dynamic environment, manipulating an object, or harvesting energy.

As in biology, researchers at the MPI for Intelligent Systems investigate systems at length scales as small as nanometers. Small-scale mobile robots represent some of the most basic synthetic or bio-hybrid perception-action-learning systems one can hope to build in the next decade or two. By inventing such systems, we hope to gain insight into the intelligence that the small-scale biological world exhibits, including how the physical environment influences the perception-action cycle. Our scientists also study and learn from the animal world, including insects, fish, birds, and mammals. Inherent limitations in on-board sensing, perception, computation, power, and actuation capabilities necessitate advanced physical design, materials, interactions, computing, and controls. In contrast to microsystems, human-like systems exploit significantly more memory and processing power in their perception-action loops, leading to potentially different mechanisms of perception, action, and learning (and also providing opportunities for technology to augment human capabilities). However, we believe that the methods of learning and control in perception-action loops share essential aspects across platforms and scales. Our institute uniquely brings together expertise in theory, software, and hardware to address the fascinating and important research field of intelligent systems. The potential of this approach for basic science rests in the hope that even systems that are too complex to be analyzed in their entirety may be reducible to organizing principles that can be studied, comprehended, and applied in new contexts.

1.1.2 Impact

While our institute started as an endeavour of basic research, we have since come to embrace the opportunities and challenges afforded by closely interacting with real-world problems. The Stuttgart-Tübingen region forms the center of the State of Baden-Württemberg, one of the leading economic regions not only in Germany but also Europe's powerhouse and, by some measures, most innovative area. The greater Stuttgart metropolitan region is home to some of the largest companies in the automotive and technology sector and to thousands of successful small and medium-sized enterprises, known for its innovative drive and inventive spirit, with a high level of productivity and low unemployment.

The academic and industrial environment in the region Stuttgart and Tübingen provided the ideal ground to establish a world-leading ecosystem in Intelligent Systems. Our institute joined forces with key players from industry, science and politics to establish a regional cluster in the field of Artificial Intelligence – Cyber Valley. Through this initiative, the Max Planck Society, the State of Baden-Württemberg, the Universities of Stuttgart and Tübingen, and several industry partners promote a start-up culture and heavily strengthen the local research activities in the field of Intelligent Systems. With the International Max Planck Research School for Intelligent Systems (IMPRS-IS) we have formed a highly visible and unique graduate school of internationally recognized faculty, that attracts outstanding Ph.D. students from around the world. Together with the University of Tübingen we have established the Tübingen AI Center, which is one of the flagship centers of competence within Germany's national AI strategy.

While this has strongly boosted our local impact, we maintain a distinctively international perspective. Researchers at the Max Planck Institute for Intelligent Systems collaborate with the best labs all over the world, and the Institute has strong partnerships with leading research institutions, e.g., Ph.D. programs with Cambridge University and Carnegie Mellon University. In order to boost the research capacities and to pool scientific know-how in the emerging field of Learning Systems in Europe, we joined forces with ETH Zurich to form the Max Planck ETH Center for Learning Systems (CLS). This first joint research center of the Max Planck Society and ETH Zurich brings together leading researchers in the field of learning systems and provides unique training opportunities for Ph.D. students. The goals of CLS are to achieve a fundamental understanding of perception, learning and adaptation in complex systems, by providing a platform for exchange in research and education.

Building upon our successful programs with Cambridge University and ETH Zurich, we co-initiated the European Laboratory for Learning and Intelligent Systems (ELLIS), which was created in 2018 to build a network of excellence to compete with the major AI hotspots in the US and China. Machine learning has triggered the current revolution in AI with impact on all surrounding disciplines such as computer vision and sensory processing in general, data science, symbolic and rule-based reasoning, robotics, and human-computer interaction. In this revolution, the distinction between academic and industrial research is vanishing, with rapid and broad commercialization of results. This has led to a need to strengthen European research excellence to remain competitive. ELLIS has set out to retain and attract the best talent, and just like Cyber Valley, it is testimony to the leadership role that our institute has already assumed in driving progress in AI both regionally and internationally.

1.2 Organization

Departments The institute currently has six departments dedicated to intelligent systems research. Each department is headed by a director of the institute:

Empirical Inference Department (Tübingen), Prof. Dr. Bernhard Schölkopf

Haptic Intelligence Department (Stuttgart), Katherine J. Kuchenbecker, Ph.D.

Perceiving Systems Department (Tübingen), Dr. Michael J. Black

Physical Intelligence Department (Stuttgart), Prof. Dr. Metin Sitti

Robotic Materials Department (Stuttgart), Dr. Christoph Keplinger

Social Foundations of Computation Department (Tübingen), Dr. Moritz Hardt

Chapters 2 through 6 outline the research of the first five of these departments during the reporting period. Dr. Moritz Hardt joined the institute on a part-time basis on July 1, 2021. He will be located full-time at the institute starting January 1, 2022. The research plans of this new department are outlined briefly in Section 1.5.2.

Dr. Stefan Schaal, the former director of the **Autonomous Motion Department** in Tübingen, left the Max Planck Society on April 30, 2018. Bernhard Schölkopf is currently acting director of this department. Given their scientific relevance to intelligent systems, the scientific publications of this department are listed at the end of this report.

The Stuttgart site presently has two additional departments that were part of the former Max Planck Institute for Metals Research:

Modern Magnetic Systems Department (Stuttgart), Prof. Dr. Gisela Schütz

Theory of Inhomogeneous Condensed Matter Dept. (Stuttgart), Prof. Dr. Siegfried Dietrich

Given their distinct research foci, these two departments are not covered in this report.

In its final state, we anticipate that the Max Planck Institute for Intelligent Systems will have four departments in each site, for a total of eight, plus a large number of independent research groups and central scientific facilities.

Research Groups In addition to the departments, the institute has been hosting 16 independent research groups in the intelligent systems research direction during the reporting period: one permanent Max Planck Research Group (P-MPRG), six fixed-term Max Planck Research Groups (MPRG), five fixed-term Cyber Valley Max Planck Research Groups (CV-MPRG), one fixed-term ERC starting grant group (ERC-StG), one fixed-term Emmy Noether research group (funded by Deutsche Forschungsgemeinschaft; DFG-ENP), and two fixed-term Independent Research Groups (IRG) with other funding sources. Like departments, each group has a home campus but interacts with researchers at both sites. Each of these research groups is led independently by a scientist.

Current independent research groups:

Autonomous Learning (MPRG) (Tübingen), Dr. Georg Martius

Dynamic Locomotion (MPRG) (Stuttgart), Dr. Alexander Badri-Spröwitz

Embodied Vision (CV-MPRG) (Tübingen), Dr. Jörg Stückler

Human Aspects of Machine Learning (IRG) (Tübingen), Dr. Samira Samadi

Intelligent Control Systems (CV-MPRG) (Stuttgart), Prof. Dr. Sebastian Trimpe

Learning and Dynamical Systems (DFG-ENP) (Tübingen), Dr. Michael Mühlebach

Locomotion in Biorobotic & Somatic Systems (CV-MPRG) (Stuttgart), Dr. Ardian Jusufi

Micro, Nano, and Molecular Systems (P-MPRG) (Stuttgart), Prof. Dr. Peer Fischer

Movement Generation and Control (ERC-Stg) (Tübingen), Prof. Dr. Ludovic Righetti

Neural Capture and Synthesis (MPRG) (Tübingen), Dr. Justus Thies

Organizational Leadership & Diversity (IRG) (Stuttgart), Dr. Ksenia Keplinger

Physics for Inference and Optimization (CV-MPRG) (Tübingen), Dr. Caterina De Bacco

Rationality Enhancement (CV-MPRG) (Tübingen), Dr. Falk Lieder

Former independent research groups hosted at the institute during the reporting period:

Autonomous Vision (MPRG) (Tübingen), Prof. Dr. Andreas Geiger (until May 2021)

Probalistic Learning (MPRG) (Tübingen), Prof. Dr. Isabel Valera (until March 2020)

Probabilistic Numerics (MPRG) (Tübingen), Prof. Dr. Philipp Hennig (until October 2018)

The research of all 16 of these groups is covered by this report in Chapters 7 through 22.

Max Planck Fellows The Max Planck Fellow program of the Max Planck Society aims to promote cooperation between outstanding university professors and Max Planck researchers. By strengthening ties with universities, the program fosters cutting-edge research on both sides. During their initial five-year term, which can be extended, Max Planck Fellows typically set up a small group at the host institute, jointly funded by the hosting institute and the Max Planck Society. The institute has been hosting two Max Planck Fellow groups during the reporting period:

Physical Reasoning & Manipulation (Stuttgart), Prof. Dr. Marc Toussaint (until June 2021)

Statistical Learning Theory (Tübingen), Prof. Dr. Ulrike von Luxburg

The research of these two Max Planck Fellow Groups is covered by this report in Chapters 23 and 24.

Since October 2021 the institute also hosts four ETH professors as Max Planck Fellows. The professors were recently appointed by the Max Planck Society under the umbrella of the successful research partnership within the Max Planck ETH Center for Learning Systems to intensify the cooperation and further strengthen the joint research efforts with ETH Zurich in Switzerland. They each will lead a small group at the institute:

Coordinative Intelligence (Tübingen), Prof. Dr. Thomas Hofmann (since October 2021)

Human-centric Vision & Learning (Tübingen), Prof. Dr. Ottmar Hilliges (since July 2021)

Interactive Learning (Tübingen), Prof. Dr. Andreas Krause (since September 2021)

Magnetic Resonance Imaging (Stuttgart), Prof. Dr. Klaas Prüssmann (since September 2021)

Central Scientific Facilities The MPI for Intelligent Systems also operates several central scientific facilities (CSFs, called ZWEs in German). Led by one or more scientists holding a Ph.D. and staffed with engineers and technicians, each CSF provides a particular type of scientific and technical support to our departments and groups. Such centralized support is a hallmark of the Max Planck Society and greatly expands the scope and quality of the research our scientists can pursue. The Materials CSF in Stuttgart was created by merging CSFs of the former MPI for Metals Research, while the rest of the Stuttgart CSFs and all of those in Tübingen were custom designed for our institute:

Materials CSF (Stuttgart)

Medical Systems CSF (Stuttgart)

Optics and Sensing Laboratory (Tübingen)

Robotics CSF (Stuttgart)

Scientific Computing CSF (Tübingen)

Software Workshop (Tübingen)

Chapter 25 describes the work of our current CSFs.

In addition to the CSFs, the institute includes several scientific-technical service units such as several specialized workshops, as well as a library in Stuttgart.

Management The eight directors of the institute constitute the Board of Directors of the Max Planck Institute for Intelligent Systems. The Board of Directors is headed by the institute's overall Managing Director, with support from the deputy Managing Director; these two directors hail from our two campuses and each lead their sub-institute's Board of Directors, which handle decisions relevant to the respective local institute site. Currently, the Boards are headed by:

Managing Director: Prof. Dr. Bernhard Schölkopf (until December 31, 2021)

Deputy Managing Director: Prof. Dr. Metin Sitti (Managing Director from January 1, 2022)

The institute's administration and the Scientific Coordination Office (SCO) support the directors in all administrative and scientific matters. To better reflect the needs of our growing institute, we established our own administration in September 2019. The new administration jointly serves both institute sites. The central administration was previously shared with the MPI for Solid State Research in Stuttgart. The SCO was newly established in 2018 to bridge and coordinate the scientific and externally facing activities for the entire institute and both sub-institutes. SCO's responsibilities include public relations, website, event management, reporting and documentation, grants, and policy. The Cyber Valley initiative, the ELLIS initiative, the International Max Planck Research School for Intelligent Systems (IMPRS-IS), and the Max Planck ETH Center for Learning Systems (CLS) are all closely associated with the Scientific Coordination Office.

1.3 Scientific Advisory Board

To ensure superior scientific quality, each Max Planck Institute is regularly evaluated by a Scientific Advisory Board (SAB). The President of the Max Planck Society appoints experts from leading international research institutions and universities to serve on the SAB. The Scientific Advisory Board of the MPI for Intelligent Systems currently consists of the following nine members:

- Prof. Dr. Costantino Creton (CNRS, ESPCI, PSL, Paris, France)
- Prof. Dr. Rita Cucchiara (Università degli Studi di Modena e Reggio Emilia, Modena, Italy)
- Prof. Dr. Dario Floreano (EPFL, Lausanne, Switzerland)
- Prof. Dr. William T. Freeman (Massachusetts Institute of Technology, Cambridge, MA, USA)
- Prof. Dr. Zoubin Ghahramani (University of Cambridge, UK), **Chair**
- Prof. Dr. Maja J. Matarić (University of Southern California, Los Angeles, CA, USA)
- Prof. Dr. Barbara Mazzolai (Istituto Italiano di Tecnologia – IIT, Pontedera, Italy)
- Prof. Dr. Helge Ritter (Bielefeld University, Germany)
- Prof. Dr. Fabian J. Theis (Helmholtz Munich, Germany)

The Scientific Advisory Board meets at the institute every three years to perform the main part of their evaluation. An extended evaluation takes place every six years, including additional rapporteurs who participate in several Scientific Advisory Board evaluations across the Max Planck Society. Since the institute's founding in 2011, the Scientific Advisory Board of the Max Planck Institute for Intelligent Systems has had four evaluation meetings, as follows:

- February 16 – 18, 2022 (extended evaluation)
- April 1 – 3, 2019
- April 18 – 20, 2016 (extended evaluation)
- January 12 – 14, 2013

The following individuals previously served on our Scientific Advisory Board for the indicated time spans:

- Prof. Dr. Andrew Blake (University of Cambridge, UK), 2012 – 2018
- Prof. Dr. Josef A. Käs (University of Leipzig, Germany), 2012 – 2016
- Prof. Dr. Danica Kragic (KTH, Stockholm, Sweden), 2012 – 2020
- Prof. Dr. Vijay Kumar (University of Pennsylvania, Philadelphia, PA, USA), 2016 – 2018
- Prof. Dr. Massimiliano Pontil (IIT, Genova, Italy), 2012 – 2020
- Prof. Dr. Yair Weiss (Hebrew University of Jerusalem, Israel), 2012 – 2021
- Prof. Dr. Itamar Willner (Hebrew University of Jerusalem, Israel), 2008 – 2012

1.4 Board of Trustees

The Board of Trustees is an assembly of influential representatives from politics, administration, industry, science, and media. Its objective is to connect the institute to the public, particularly in the local region around Stuttgart and Tübingen. The Board of Trustees of the MPI for Intelligent Systems currently includes the following members:

- Prof. Dr.-Ing. Thomas Bauernhansl (Director, Fraunhofer IPA, Stuttgart)
- Dr. Michael Bolle (Entrepreneur & Advisor, Stuttgart)
- Gerhard Borho (Member of the Management Board Finance, Festo SE, Esslingen)
- Dr. Anna Christmann, MdB (Member of the German Bundestag, Stuttgart)
- Christoph Dahl (Managing Director, Baden-Württemberg Stiftung gGmbH, Stuttgart)
- Prof. Dr. Bernd Engler (President, University of Tübingen)
- Christian O. Erbe (Managing Director, Erbe Elektromedizin GmbH, Tübingen)
- Dr. Ralf Herbrich (Senior Vice President, Zalando SE, Berlin), **Deputy Chair**
- Dr. Stefan Kaufmann (Former Member of the German Bundestag, Stuttgart)
- Dr. Frank Nopper (Lord Mayor of the City of Stuttgart)
- Boris Palmer (Lord Mayor of the City of Tübingen)
- Prof. Dr. Bernd Pichler (Dean, Faculty of Medicine, University of Tübingen)
- Prof. Dr.-Ing. Wolfram Ressel (Rector, University of Stuttgart)
- Dr. Jeanne Rubner (Head of Editorial Department, Bayerischer Rundfunk, Munich), **Chair**
- Dr. Simone Schwanitz (Head of Department, Ministry for Science, Research and Arts Baden-Württemberg, Stuttgart; membership will end on December 31, 2021)
- Dr. Florian Stegmann (State Secretary, State Ministry Baden-Württemberg, Stuttgart)
- Dr.-Ing. Michael Steiner (Member of the Executive Board Research and Development, Dr. Ing. h.c. F. Porsche AG, Stuttgart)

1.5 New Departments

Since the last meeting of the Scientific Advisory Board in 2019, two new departments were established at the Max Planck Institute for Intelligent Systems:

Robotic Materials Department (Stuttgart), Dr. Christoph Keplinger, since August 2020

Social Foundations of Computation Dept. (Tübingen), Dr. Moritz Hardt, since July 2021

1.5.1 Robotic Materials Department

On July 28, 2020, Christoph Keplinger signed his contract to join the Max Planck Society as a Scientific Member of the Max Planck Institute for Intelligent Systems (MPI-IS) and as Director at the Institute. Only a few days later, on August 1, he started full time employment and founded the Robotic Materials (RM) Department in Stuttgart. This condensed timeline was the result of appointment negotiations that had to be postponed several times due to severe travel restriction during early phases of the Corona pandemic, and the wish to align the move with the beginning of the schoolyear for Christoph's older daughter. Considering the many challenges of an intercontinental move during a pandemic, with delays on all fronts, the relocation of the family with their two young daughters still went as well as can be expected; this was only possible thanks to the great support of the MPI IS community and in particular to the help of director colleagues, underlining the mutual commitment to a positive, collegial and successful collaboration for many years to come. Before joining the Max Planck Society, Christoph was an Assistant Professor of Mechanical Engineering and a Fellow of the Materials Science and Engineering Program at the University of Colorado Boulder, where he also held an endowed appointment serving as Mollenkopf Faculty Fellow. To this date, he still holds an appointment at the University of Colorado Boulder, where he is now an Eminent Visiting Professor of Soft Robotics, a position that will allow him to finish remaining research projects as principal investigator and continue advising graduate students who remained in Boulder after the move.

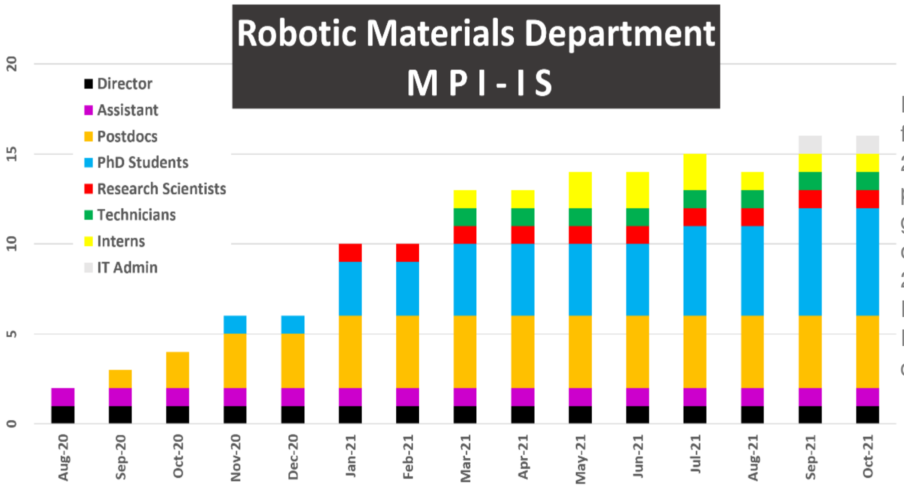


Figure 1.1: Since its founding in August 2020, the RM Department has already grown to a team size of currently 16. In 2022, several new PhD students and Postdocs will join the department.

A major focus of the first year was to recruit outstanding postdocs, PhD students, and other team members to dynamically kick off the ambitious scientific agenda of the new RM Department. It was particularly noteworthy that a major fraction of the postdocs and PhD students from Christoph's lab in Boulder decided to continue their academic careers at MPI IS and to move with him to Stuttgart, thereby easing the transition and accelerating the restart of research activities in the new lab. Additional growth of the team was planned with careful consideration of space constraints due to the upcoming renovation of lab and office spaces. New PhD students were recruited both through the IMPRS-IS and the Max Planck ETH CLS programs. The monthly composition of the RM

Department since its inception is shown in Figure 1.1, where the current 16 team members come from multiple different research fields (including physics, chemistry, and multiple engineering disciplines), from 12 nations, 5 continents and about one third are women – highlighting that Christoph carefully considers interdisciplinarity, international representation and diversity when hiring new group members, as he is convinced that these are key ingredients for scientific excellence and for a highly creative environment.

Another major focus of Christoph's first year at MPI IS was to select and purchase initial scientific equipment; this turned out to be an unexpectedly tedious undertaking due to the current global chip shortage and other supply chain problems that caused long shipping delays for many central pieces of equipment. Despite these obstacles, and as a result of strong determination and diligence of the entire RM team, the lab now has access to a wide range of characterization, fabrication and computation tools, as detailed in section 6.4 Equipment of this report. In addition to acquiring equipment, detailed plans for the renovation of the entire assigned lab and office space were completed in summer 2021; these plans are now already approved and renovations are scheduled to start in March 2022. The new lab space will include 3 large, open, general purpose labs that stimulate collaboration within the department, two chemistry labs that will allow synthesis and fabrication of functional polymers, a laminar flow-based cleanroom space for dust-sensitive experiments, a lab for specialized mechanical and electrical materials characterization tools, as well as a lab that will house a custom-designed and highly adaptable, modular system for roll-to-roll or sheet-to-sheet fabrication of multilayer polymer composite structures. Additionally, the renovation will provide the department with a "show room" to demonstrate experimental results to collaborators and visitors, as well as a "creativity room" that will provide researchers with a stimulating environment for brainstorming sessions and scientific discussions.

As detailed in section 6.1 Research Overview, the RM Department aims to establish new interdisciplinary bridges between the robotics and materials science communities; specifically, current major thrusts of research include soft robotics, functional polymers and energy capture, three interrelated areas that are critical to the field of robotic materials – a new class of material systems that tightly integrate actuation, sensing and even computation to provide physical building blocks for intelligent systems of the future. Harnessing both the unique long-term perspective on research that is possible within the Max Planck Society, as well as local research synergies within the Cyber Valley ecosystem, the RM Department devises new classes of robotic materials by simultaneously addressing fundamental questions in the underlying materials science using tools from physics or chemistry (supported by multiple already ongoing collaborations with other groups both from IS as well as FKF on the Stuttgart Max Planck campus), as well as working on entirely new designs of robots that are based on intelligent materials systems, and that can tap into the rapidly growing toolkit from the areas of learning and perception, emerging from the Tübingen campus (initial fruitful collaborations are already ongoing). Thus, the department is able to proceed from inventing new materials to testing these in complex robotics systems that make use of the latest discoveries in machine learning in an extremely short period of time, thereby creating a cutting-edge local research ecosystem that will rapidly advance the state of the art. As of October 2021, the RM department is additionally collaborating with groups from both local universities, local Fraunhofer institutes and industry, as well as internationally with leading academic labs from the USA, Switzerland, Sweden, Austria and China. All members of the RM department are visibly passionate about the research program, working hard, and seeing first success stories with papers being accepted in high-quality journals, as well as multiple papers in advanced preparation for submission. Christoph is regularly invited to give talks about latest research results at prestigious speaking opportunities (see section 6.4 Director profile), and has recently authored two comment/perspective-type articles together with collaborators on the future of the field of soft robotics, that are now both accepted in Nature Materials and Nature respectively. Overall, the RM Department is off to a great start, and the team is highly motivated to continuously push boundaries and explore new frontiers.

1.5.2 Social Foundations of Computation Department

Figure 1.2: The Max Planck Society has appointed the professor from the University of California, Berkeley as a director at the Tübingen site of the Max Planck Institute for Intelligent Systems. He founds the Social Foundations of Computation department, which extends the institute's deep expertise in machine learning, artificial intelligence, robotics and physical systems towards a social perspective on computer science.

Computer scientist Moritz Hardt, Ph.D., has accepted a call to the Max Planck Institute for Intelligent Systems. He joined the institute part-time in July 2021, and will start working full-time in Tübingen as of January 2022. His newly established department "Social Foundations of Computation" aims to build foundations of computation that thrive on social context. The research is intended to contribute to a paradigm shift within computer science that treats computer science from the ground up as a social science that takes into account the role of society as a whole, as well as the actions and dynamic behavior of individuals – especially when algorithms influence people's life chances.

"Our research will examine the interplay between algorithms and society," says Moritz Hardt. "Not only looking at isolated consequences of the technology, our research aims to develop computational methods that are built on social foundations from the outset. The goal is to develop a social perspective on computer science that extends the discipline itself to a social science."

In a world increasingly permeated by algorithms, only recently, a research community in computer science has been growing, questioning how often sensitive data leads to decisions, and foregrounding people who produce and consume data. The topic of fairness, for example, became a central focus of research within the machine learning community only about five years ago. An active field of research emerged that is receiving ever more attention. With Hardt's appointment, the Max Planck Society is strengthening basic research within computer science that considers the role of society as well as norms and values as an integral part of computation. Every statistical model, prediction or calculation should be based on a social foundation; especially when a computer, rather than a human, makes decisions, Hardt claims.

"Moritz Hardt has made fundamental mathematical and algorithmic contributions to the interaction between machine learning methods and their social embedding. We are very pleased that he will continue his research at the MPI-IS, working together to develop an artificial intelligence that brings to the fore its responsibility for shaping our future," says Bernhard Schölkopf, Managing Director at the MPI-IS.

Hardt, who received his doctorate from the University of Princeton in 2011, became intrigued with the topic of privacy and fairness in sensitive data analysis early on in his doctoral work, when the topic had little to no support within the community. "I got into social issues through my work on differential privacy. I realized it wasn't just about privacy, but many other questions that computer scientists had previously ignored over the decades. Computer science had neglected society. Even today, social problems are often categorized as a consequence of the technology rather than a central object of research," says Hardt.

Social Foundations of Computation has four focus research areas: Applying machine learning in social and economic contexts, formulating social and dynamic actions as mathematical models, as well as examining the validity and reliability of statistical methods and the construction of datasets within scientific communities. Another focus is the pursuit of normative goals and, in particular, how to formulate values and norms mathematically. "My goal as a director at the institute is to make it easier for other researchers to work on forward-looking questions that are currently underappreciated," Hardt says.

Celestine Mendler-Dünner, a group leader who is helping to build up the new department, has already started her work at the Tübingen site of MPI-IS. Her research focuses on modeling social dynamics and how to incorporate them into the design of machine learning algorithms. She has previously worked with Moritz Hardt in Berkeley and contributed to shaping the department's research direction. Additional appointments will follow in a timely manner. The department is expected to grow to a total of about two dozen scientists.

Prior to his appointment as director at MPI-IS, Moritz Hardt was an Assistant Professor in the Department of Electrical Engineering and Computer Sciences at the University of California, Berkeley. He received his Ph.D. from the Department of Computer Science at Princeton University with a dissertation on privacy and fairness in the classification of sensitive data. He subsequently worked at IBM Research and Google. Hardt is co-founder of the conference "Fairness, Accountability, and Transparency in Machine Learning." He is co-author of "Fairness and Machine Learning: Limitations and Opportunities" (MIT Press, 2022) and "Patterns, Predictions, and Actions: A Story About Machine Learning" (Princeton University Press, 2022).

Cyber Valley

1.6 Cyber Valley

1.6.1 Overview

In 2016, the Max Planck Institute for Intelligent Systems joined forces with key players from industry, science, and politics to establish the Cyber Valley research consortium, a regional cluster in the field of artificial intelligence. With this initiative, the Max Planck Society, the state of Baden-Württemberg, the Universities of Stuttgart and Tübingen, and companies from the IT and automotive sectors are collaborating to make southwestern Germany a regional hub for research and innovation in the field of intelligent systems. The following private sector partners are members of the consortium: Amazon, BMW, Bosch, IAV, Daimler, Porsche AG, and ZF Friedrichshafen. Moreover, Fraunhofer-Gesellschaft also joined Cyber Valley in November 2019. Cyber Valley also receives support from the Christian Bürkert Foundation, the Gips Schüle Foundation, the Vector Foundation, and the Carl-Zeiss Foundation. Together, these partners have strengthened the region by further enhancing research activities, creating an ecosystem for start-ups and technology transfer, and increasing the visibility of Baden-Württemberg as a global hotspot for AI research and innovation.

Since it was founded five years ago, Cyber Valley has consistently gained momentum, becoming Europe's largest regional consortium for research and innovation in the field of artificial intelligence. Not only has Cyber Valley strengthened research, education, and innovation in the fields of machine learning, computer vision, and robotics, it has also given rise to stronger connections between these scientific disciplines. Numerous large-scale initiatives in AI have taken shape in the region, among them several clusters of excellence at the universities and a new federally funded competence center on machine learning and AI, the Tübingen AI Center. With the establishment of two new buildings in Stuttgart and in Tübingen as well as with its further organizational development and growth, Cyber Valley will continue to grow in the years to come, and the region is poised to firmly establish itself as a European hub in the field of AI.

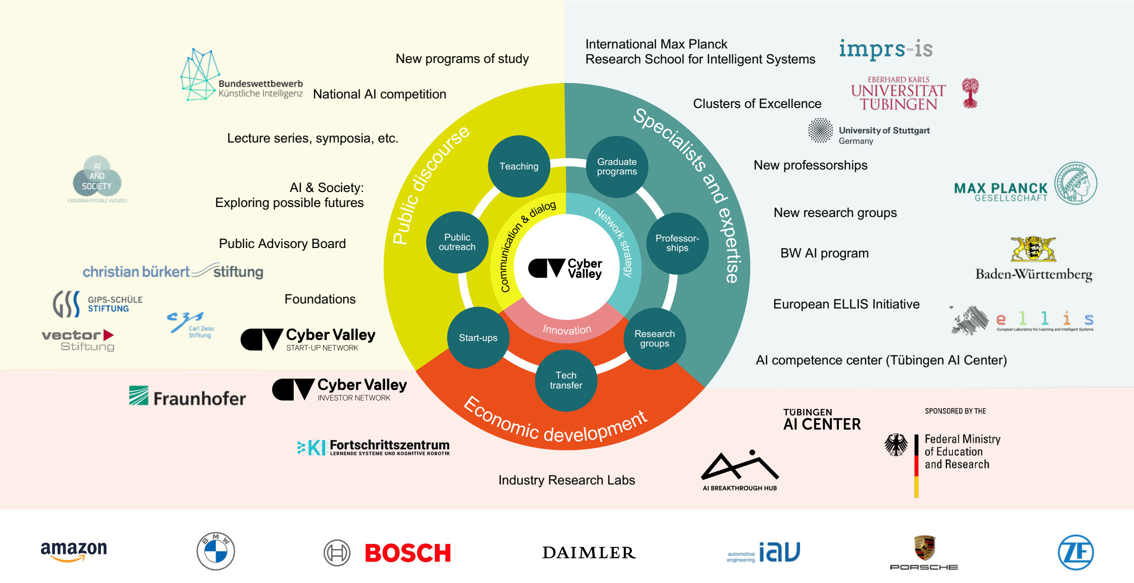


Figure 1.3: The Cyber Valley ecosystem at a glance.

1.6.2 The Cyber Valley Ecosystem

Since the Cyber Valley research consortium was founded at the end of 2016, the partnership between academic institutions and private sector companies has promoted the development of a thriving ecosystem in southwestern Germany. Each year, new and multidisciplinary initiatives have been added to the mix, and the Stuttgart-Tübingen region keeps gaining momentum as a European hotspot for research and innovation in the fields of machine learning, robotics, and computer vision. Today, Cyber Valley is home to numerous institutions and initiatives comprising close to 100 faculty members and more than 1000 researchers in the field of AI.

- New Cyber Valley research groups and new University chairs
- The IMPRS-IS doctoral program (see Section 1.9)
- The Cyber Valley Start-up Network
- The Cyber Valley Investor Network
- The Cyber Valley Public Engagement Program “AI and society: Exploring possible futures”
- The Cyber Valley Health Initiative
- The Tübingen AI Center (see Section 1.8)
- The Fraunhofer Gesellschaft’s AI innovation center Learning Systems in Stuttgart
- The “Machine Learning: New Perspectives for Science” Cluster of Excellence at the University of Tübingen
- Two new Clusters of Excellence at the University of Stuttgart: “Integrative Computational Design and Construction for Architecture” (IntCDC) and “Data-Integrated Simulation Science” (SimTech)
- The European Laboratory for Learning and Intelligent Systems, ELLIS (see Section 1.7)
- The AI Breakthrough Hub
- Germany’s first master’s degree program in machine learning at the University of Tübingen
- The Max Planck Institute for Intelligent Systems in Stuttgart and Tübingen
- The Max Planck Institute for Biological Cybernetics in Tübingen
- New Bosch and Amazon research centers in Tübingen
- Two Bosch “Industry on Campus” professorships at the University of Tübingen
- The Tübingen Center for Rhetorical Science Communication Research on Artificial Intelligence (RHET AI)
- The Interchange Forum for Reflecting on Intelligent Systems (IRIS) in Stuttgart
- The Artificial Intelligence Software Academy (AISA) in Stuttgart
- The Bernstein Center for Computational Neuroscience in Tübingen

as well as further institutions, initiatives, and activities. While some of the above major activities are presented in dedicated sections of this report, in the following we will describe the Cyber Valley core activities and their development.

1.6.3 Five-year Success Story

Together with the other project participants, Winfried Kretschmann (Minister-President of Baden-Württemberg), Theresia Bauer (Minister of Science in Baden-Württemberg), and Martin Stratmann (President of the Max Planck Society) launched the Cyber Valley initiative on Thursday, December 15, 2016, at Stuttgart's Neues Schloss. In the five years since the initial letter of intent was signed, Cyber Valley has reached several important milestones.

In 2017 and 2018, the focus was on hiring and onboarding research group leaders and university chairs, as described in the following, as well as on expanding and consolidating academic partnerships and programs. In particular, the International Max Planck Research School for Intelligent Systems (IMPRS-IS) was launched in 2017 as one of Cyber Valley's key elements to train new generations of young scientists (Section 1.9).

In 2018 and 2019 several large scale academic initiatives were launched within the scope of the most competitive national research programs, building upon the regional network that was established through the Cyber Valley initiative, and involving several researchers who already could be attracted through the new Cyber Valley positions. Specifically, the Tübingen AI Center was selected as one of five national competence centers as the flagship program within the German national AI strategy (Section 1.8). The European Laboratory for Learning and Intelligent Systems, ELLIS, was co-initiated by several scientists based at Cyber Valley's academic partner institutions (Section 1.7). Three new Clusters of Excellence within the framework of the national Excellence Strategy were kicked off in 2019 at the Universities of Stuttgart and Tübingen that are directly linked to Cyber Valley. Moreover, the Max Planck Society and the University of Tübingen joined forces to recruit Peter Dayan and Li Zhaoping, pioneers in the fields of AI and computational neuroscience, to shape the future of our neighbouring Max Planck Institute for Biological Cybernetics, further strengthening academic excellence within Cyber Valley.

Since 2019, several activities focusing on transfer and economic impact were launched. The Fraunhofer Gesellschaft joined Cyber Valley through its IPA and IAO institutes in Stuttgart and established the new AI innovation center Learning Systems dedicated to the transfer of knowledge to mid-sized and small enterprises within the Baden-Württemberg region. Moreover, Amazon's new research center in Tübingen took up operations, with an expected long-term size of up to 200 researchers and engineers, and Bosch announced the establishment of a company's new AI research center in Tübingen for 700 of their employees. All of these activities are in direct vicinity of the Max Planck Campuses in Stuttgart and Tübingen, respectively, and will connect MPI-IS researchers with leading industry research.

Moreover, in 2019, the Cyber Valley Start-up Network was launched with the aim of creating a networking platform for AI start-ups in the Stuttgart-Tübingen region. At the end of the reporting period, this network counted 30 members. To complement the Start-up Network, the Cyber Valley Investor Network was established in September 2020. Local, national and international venture capital firms help young scientists within the Cyber Valley ecosystem acquire the skills they need to succeed as entrepreneurs. In so doing, the Investor Network takes the vision of Cyber Valley as a leading breeding ground for successful AI startups a critical step further.

In addition, as a result of the growing public interest in AI and its development, communications and public engagement activities have become an important part of Cyber Valley. We have therefore created Germany's first dedicated staff positions for public engagement managers, and launched a multi-faceted strategy connecting with the general public and to initiate a process of critical reflection on the ethical and social implications of AI research. In 2019, Cyber Valley established a Public Advisory Board as an independent committee that evaluates the ethical and social implications of research projects. In 2021, Cyber Valley's public engagement program was launched, and two new centers dedicated to researching the impact of AI on Society were established at the Universities of Stuttgart and Tübingen, IRIS and RHET-AI.

In December of 2021, Cyber Valley celebrates its fifth anniversary by showcasing successes of this dynamically growing, yet young, ecosystem through a series of highlight events.

1.6.4 Organization

Organization and management

While institutions and initiatives within the Cyber Valley ecosystem have their own independent decision making and funding processes, the Cyber Valley core research cooperation is governed by a cooperation contract, which specifies several boards that are in charge of decisions:

Cyber Valley Executive Board

The Cyber Valley spokesperson and two deputies form the Executive Board. The three members are representatives of the consortium's three main parties. Currently, the members of the Executive Board are:

- Dr. Michael J, Black, Spokesperson, Director of the Perceiving Systems Department at the Max Planck Institute for Intelligent Systems
- Prof. Dr. Philipp Hennig, Deputy Spokesperson, Chair for the Methods of Machine Learning at the University of Tübingen
- Prof. Dr. Thomas Kropf, Deputy Spokesperson, President of the Corporate Sector Research and Advanced Engineering, Robert Bosch GmbH

Cyber Valley Plenary Assembly

All core partners are represented in the Plenary Assembly, in which each of the three main groups of the Cyber Valley research consortium – the Max Planck Society, the state of Baden-Württemberg and its universities, and the industry partners – cast one third of the votes.The Cyber Valley Plenary Assembly takes decisions concerning the basic and superordinate matters and strategic interests of the Cyber Valley, and elects the Executive Board.

Cyber Valley Research Fund Board

Decisions about the distribution of funds from the Cyber Valley Research Fund are made by the Research Fund Board (RFB), which comprises an equal number of members from academia and industry. In the event of a tie, the academic side decides. The RFB is chaired by the Managing Director of the Max Planck Institute for Intelligent Systems.

Cyber Valley Public Advisory Board

The role of the independent Public Advisory Board (PAB) is to review project proposals from Cyber Valley Research Groups prior to their approval by the Cyber Valley Research Fund Board. The members of the PAB have access to all funding applications and can thus see how the funds are spent. Moreover, the PAB advises the RFB and can request further information, express concerns, and engage in debate. Its members were appointed by Baden-Württemberg's science minister Theresia Bauer. They represent a broad spectrum of relevant disciplines and backgrounds. The Spokesperson of the PAB is Prof. Dr. Regina Ammicht Quinn, Professor of Ethics at the International Centre for Ethics in the Sciences and Humanities (IZEW), University of Tübingen.

Cyber Valley Management Office

The Cyber Valley Management Office is formed by a cross-institutional team led by General Manager Dr. Matthias Tröndle. The Management Unit supports the above boards in the execution and daily management, and provides services for all academic partners in terms of science and education, economic development, digitization, and international relations, Currently, the Cyber Valley Managing Office consists of ten team members. Cyber Valley is increasingly important for the development of the state of Baden-Württemberg. The Cyber Valley management unit will thus continue to focus its efforts on meeting these demands.

Public relations

The heightened interest in AI-related topics has led to a major increase in the number of media requests. Cyber Valley has been featured in all major German print media, both in the science and politics/economics sections. Furthermore, regional radio and television broadcasters have reported on Cyber Valley and its progress many times. Cyber Valley has thus become one of the most visible AI research consortiums in Germany.

Beyond this heightened media attention, events and visits have been important in conveying the goals and research of Cyber Valley to the general public and informing policymakers of the importance of investments in this field. Cyber Valley has held visits for public organizations; for representatives of political parties at the local, regional, and state levels; as well as at the national and international levels. Two prominent examples include the 2020 visit of European Commission Executive Vice-President Margrethe Vestager (see Figure 1.4), as well as two virtual events with German Federal Chancellor Angela Merkel in 2020 (see Figure 1.5).

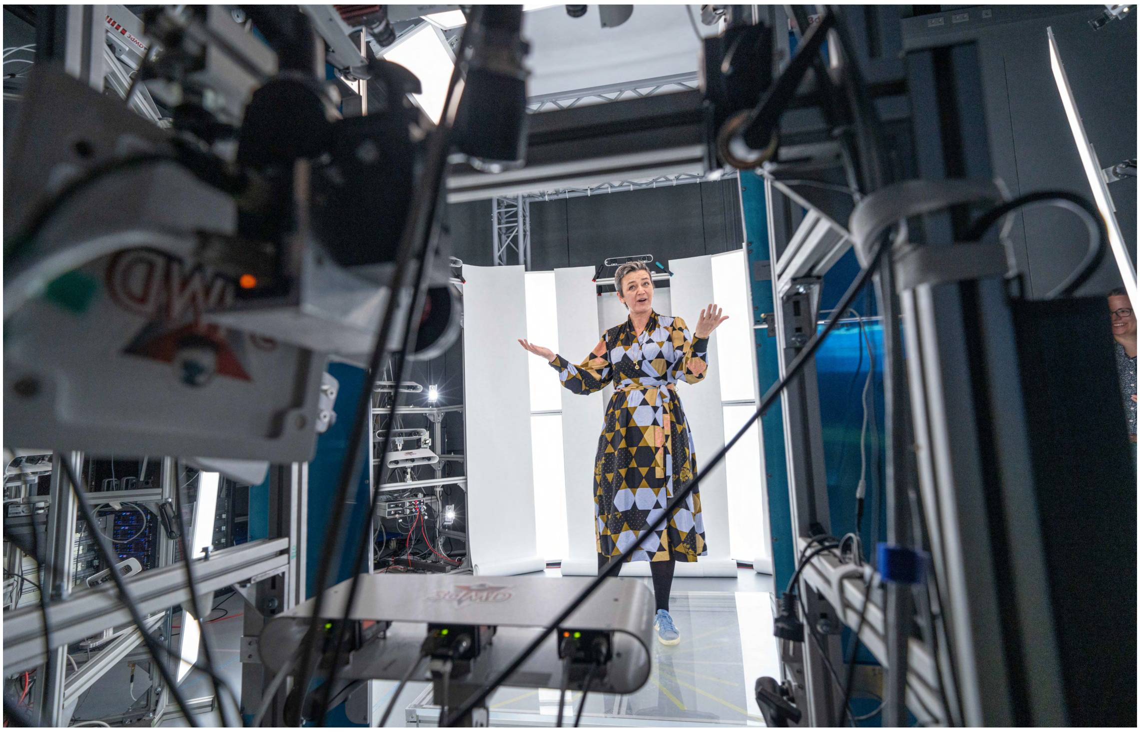


Figure 1.4: Visit from Margrethe Vestager at our institute in 2020

1.6.5 Core Activities

Cyber Valley Research Groups

As core elements of Cyber Valley, new research groups have been established at MPI-IS and the universities of Stuttgart and Tübingen. For an initial period of five years, Cyber Valley partners and supporting foundations have been funding these groups. By the end of the reporting period, discussions about the details of the second funding round were underway.

In September 2017, all Cyber Valley partners took part in a joint hiring symposium at MPI-IS to recruit the first generation of Cyber Valley research group leaders. The institute's initial hiring effort was very successful, with all five selected candidates accepting their offers. All of these outstanding early-career scientists took up their new positions in 2018. Another four were hired at the universities, bringing the total to nine Cyber Valley research groups. While four group leaders have since moved on to tenured positions at leading universities in Europe and North America, there are currently four Cyber Valley group leaders at the MPI-IS, and two at the University of Stuttgart.

Cyber Valley Professorships

Since 2017, several professorships have been established at the universities as additional core elements of Cyber Valley. Some of these new professorships have been be financed by endowments of the industry partners. At the end of the reporting period, Cyber Valley partner institutions counted close to 100 faculty members.

Funding for a total of ten new professorships was initially earmarked for Cyber Valley professorships, in addition to a general expansion of activities in computer science, machine learning, and robotics at both universities. Three professors have since been appointed at the University of Stuttgart, and another three at the University of Tübingen. Further appointment procedures are currently underway at both universities.

Supporting start-ups & promoting entrepreneurship

With its new model of cooperation between science and industry, Cyber Valley has created a stimulating ecosystem for knowledge and technology transfer in the field of artificial intelligence. Cyber Valley aims to promote this by, for instance, encouraging scientists at the consortium's partner institutions to start their own companies. To this end, the Cyber Valley management team was expanded with the hiring of two innovation managers to provide support for young start-ups and up-and-coming entrepreneurs.

In 2020, the Cyber Valley Entrepreneurship Series was launched, an event series that aims to provide interested parties with information on important topics such as getting seed funding and further investment orattracting customers. Thereby, an active platform was established for networking and exchange for the Cyber Valley Start-up Network, launched in late 2019. Network members are required to have a connection to Cyber Valley and their activities must be related to the field of intelligent systems. Meanwhile, 30 start-ups in the fields of Computer Vision & Arts, Production & Services, Health & Life Science, and Robotics are members of this network.

Our Investor Network makes a significant contribution to making Cyber Valley a breeding ground for successful AI start-ups. The initial five network members are well-known venture capital (VC) firms: Atlantic Labs (Berlin), IT-Farm (Tokyo/Palo Alto), BMW i Ventures (Mountain View/Munich), Grazia Equity (Stuttgart), and Gründermotor (Stuttgart).They are committed to providing mentorship to scientists within the Cyber Valley ecosystem by helping them turn research and business ideas into thriving companies. The VC firms' guidance will serve as a springboard for future entrepreneurs, creating the AI jobs of the future.

In summer of 2021, together with partners Square Enix and IT-Farm, Cyber Valley launched "AI GameDev", a competition for start-ups and scientists focusing on ideas for developing AI technologies for the entertainment and gaming industry. An international jury and the audience selected the three winning teams among seven finalists of the competition in December of 2021.

We will continue to further develop and grow these formats as well as introduce several new formats, such as a dedicated incubation program addressing young scientists in cooperation with IMPRS-IS that will be launched in spring of 2022.

Promoting a broad dialog on the societal impact of AI

Since the beginning, Cyber Valley has been committed to promoting an open and transparent dialog on ethical concerns related to AI applications and the potential societal impact of AI. Cyber Valley is pioneering this field by creating two staff positions for Germany's first public engagement managers at academic institutions. We launched our public engagement program in March of 2021 with several dialog formats, among them monthly AI Office Hours and an AI & Society podcast. In addition, a journalist-in-residence program was successfully initiated. For three months, a prominent German journalist took a sabbatical from her duties as a full-time editor and engaged in conversations with scientists to analyze how science communication could be improved to make AI-related topics more accessible to the general public.

Cyber Valley was centrally involved in the establishment of the new Center for Rhetorical Science Communication Research on Artificial Intelligence (RHET AI) in 2021 at the University of Tübingen, that is supported financially by the Volkswagen Foundation, enabling the continuation of Cyber Valley's journalist-in-residence program. In December of 2021, Cyber Valley's public engagement team, together with the Tübingen AI Center, launched KI-Makerspace, a learning space for children and young people to gain their first experience with programming and AI in courses and supervised experimentation, as well as realize their own projects with software and hardware, supported financially by the Vector Foundation.

1.6.6 Future Development

Building infrastructure

The state of Baden-Württemberg, the Max Planck Society, and the universities of Stuttgart and Tübingen will create additional infrastructure by erecting two new buildings; one will be located in Tübingen, built by the State of Baden-Wúrttemberg, and the other will be located in Stuttgart, built by the Max Planck Society. Not only will these buildings be home to research groups and the management unit, they will also have new central scientific facilities dedicated to supporting research, start-ups, and exchanges in the Cyber Valley ecosystem.

Developing an AI ecosystem

Since Cyber Valley was founded, the research consortium has gained significant momentum as numerous large-scale initiatives in AI have taken shape in the region, such as the Tübingen AI Center or several Clusters of Excellence, as described in other sections of this report. In addition, in 2020, Cyber Valley hosted the AI Breakthrough Hub kick-off event with federal Chancellor Angela Merkel at which significant funding was announced to establish an ELLIS institute in Tübingen, as described in the following Section.

Clearly, the Cyber Valley ecosystem will only continue to grow in the years to come. To further expand this dynamic ecosystem as an international accelerator of scientific and economic development, the State of Baden-Württemberg and the Max Planck Society are founding the Cyber Valley GmbH. The purpose of the organization is to strengthen the research, development, application, and acceptance of methods and technologies in the field of intelligent systems. The Cyber Valley GmbH with approximately 20 employees will receive funding from the State of Baden-Württemberg, and is expected to become operational in early 2022.

Figure 1.5: Bernhard Schölkopf during the virtual kick-off of the AI Breakthrough Hub with Chancellor Angela Merkel

ellis
European Laboratory for Learning and Intelligent Systems

1.7 European Laboratory for Learning and Intelligent Systems (ELLIS)

1.7.1 Motivation and Overview

ELLIS - the European Laboratory for Learning and Intelligent Systems is a European grassroots initiative in AI with a focus on scientific excellence, innovation and societal impact. It aims to create a European AI Laboratory inspired by models such as EMBL (European Molecular Biology Laboratory) and the Vector Institute (Toronto). ELLIS builds upon machine learning as driving modern AI — inspired by a model of human intelligence which is not ‘programmed,’ but evolved by interactions and learned from data. Virtually all of the dramatic recent progress and impact of AI in today’s world is fueled by data-driven machine learning.

Machine intelligence will make further progress as modern forms of machine learning and causal inference gain traction, enabled by a new generation of the most talented young students attracted by modern AI. However, Europe is facing major barriers when it comes to retaining top talent in European institutions: lack of competitive salaries, high teaching obligations in universities, rigid environments that do not support a fluid relationship with industry and the creation of startups, and the lack of critical mass due to a fragmented situation with separate islands of excellence.

ELLIS aims to benefit Europe in two ways: (1) ELLIS wants the best basic research to be performed in Europe, to enable Europe to shape how machine learning and modern AI change the world. (2) ELLIS wants to have economic impact and create jobs in Europe, and believes this is achieved by outstanding and free basic research.

Proposed in 2018, ELLIS tackles these goals by pursuing a three-pillar strategy to foster European excellence in this highly competitive field: research programs and fellows, a competitive pan-European PhD program and a network of ELLIS units and ELLIS institutes.

Figure 1.6: The European Laboratory for Learning and Intelligent Systems (ELLIS), first described in an open letter earlier in 2018, is formally announcing the formation of its professional association that will undertake the organization and building of the intellectual and physical structures of ELLIS - Montreal, December 6, 2018

The Max-Planck-Institute for Intelligent Systems, together and in close collaboration with research institutions and leading researchers throughout Europe, plays a key role in establishing the ELLIS initiative and supports the network in every aspect. Together with the University of Tübingen, our institute founded the ELLIS Unit Tübingen, bringing together the scientific excellence in AI research of both institutions.

1.7.2 Organization

Parallel to the start of ELLIS as an European grassroots initiative, the ELLIS Society e.V. was founded as an association under German law to serve as a legal entity for the community, its activities and partnerships. The ELLIS Society e.V. is represented by its Board of Directors, which at the moment are its founding members:

- Prof. Dr. Barbara Caputo, (Politecnico di Torino & Italian Institute of Technology)
- Prof. Dr. Nuria Oliver, (DataPop Alliance, Vodafone Institute & Spanish Royal Academy of Engineering)
- Prof. Dr. Bernhard Schölkopf, (Max Planck Institute for Intelligent Systems)
- Prof. Dr. Max Welling, (University of Amsterdam)
- Prof. Dr. Matthias Bethge, (University of Tübingen)
- Prof. Dr. Andreas Geiger, (University of Tübingen & Max Planck Institute for Intelligent Systems)
- Prof. Dr. Sepp Hochreiter, (Johannes Kepler University Linz)
- Prof. Dr. Josef Sivic, (Czech Technical University, École Normale Supérieure & INRIA)

All activities in the ELLIS pillars are organized and coordinated by committees, which are formed by ELLIS Fellows. These committees organize the evaluation process of new ELLIS Fellows and members, the PhD applications in the PhD & Postdoc Program, the proposals of new ELLIS Units and ELLIS Programs.

The board and the committees are supported by the ELLIS Coordination Office, led by Dr. Daniela Diaconu at the Max-Planck-Institute for Intelligent Systems in Tübingen.

With the implementation of *ELISE*, a Research and Innovation Action funded by the European Commission's Horizon 2020 research and innovation programme with almost 12 Mio Euros, a first set of network activities based on the principles and ideas formulated by ELLIS was started in September 2019.

1.7.3 The Three Pillars of ELLIS

Research Programs & ELLIS Fellows and Scholars

ELLIS has established a European network of top researchers ("Fellows" and "Scholars") working at locations throughout Europe, organized into ELLIS Programs. These Programs are modelled after the Canadian CIFAR Programs, and indeed the first set of ELLIS Programs was reviewed by CIFAR under the leadership of Yoshua Bengio. Each program focuses on a high-impact problem area that has the potential to move the needle in modern AI either in methodology or in an application area. Currently, there are 14 ELLIS Programs, spanning a wide range of topics:

- ELLIS Health
- ELLIS Robot Learning: Closing the Reality Gap!
- Geometric Deep Learning
- Human-centric Machine Learning
- Interactive Learning and Interventional Representations
- Machine Learning and Computer Vision
- Machine Learning for Earth and Climate Sciences
- Multimodal Learning Systems
- Natural Intelligence
- Natural Language Processing
- Quantum and Physics Based Machine Learning
- Robust Machine Learning
- Semantic, Symbolic and Interpretable Machine Learning
- Theory, Algorithms and Computations of Modern Learning Systems

The programs hold regular workshops and lecture series. Due to the Covid-19 pandemic, most of the scheduled program meetings and workshops were currently held as online events. In particular, early on in the pandemic, ELLIS organized a series of Covid-19 workshops, initiating new cooperations and bringing together the efforts and the scientific expertise of the AI and ML community to support the global initiative to fight the pandemic. The first workshop in the Covid-19 series in April 2020 drew more than 1000 participants online, demonstrating the ability of ELLIS to activate the community.

While ELLIS was initiated by our institute, by now six different Max Planck Institutes are involved, and ELLIS has thus helped create a network of AI initiatives inside the Max Planck Society. Max Planck scientists are involved in most of the ELLIS Programs, specifically:

- MPI for Biogeochemistry (Machine Learning for Earth and Climate Science)
- MPI for Biological Cybernetics (Natural Intelligence)
- MPI for Informatics (Human-centric Machine Learning, Machine Learning and Computer Vision)
- MPI for Intelligent Systems (ELLIS Robot Learning, Interactive Learning and Interventional Representations, Machine Learning and Computer Vision, Robust Machine Learning, Theory, Algorithms and Computations of Modern Learning Systems)
- MPI for the Science of Light (Quantum and Physics Based Machine Learning)
- MPI for Software Systems (Human-centric Machine Learning)

The selection of new programs and Fellows is highly competitive, with international peer review performed by existing ELLIS Fellows.

ELLIS Fellows advance science and act as ambassadors of ELLIS. They provide strategic advice and leadership not just scientifically, but also in terms of how to develop the network. ELLIS Scholars are outstanding junior scientists, often assistant professors, who do not yet have the seniority of a Fellow but are on a clear trajectory to reach this level.

Every proposed Fellow goes through an evaluation process by the ELLIS Fellow committee. The selection is based solely on scientific excellence. Proposals are checked against a set of criteria such as publications at top tier conferences, high impact, international awards and prizes.

As of November 2021, ELLIS has over 380 Fellows and Scholars, who represent European excellence in Artificial Intelligence and Machine Learning (Fellows, median: 16927 Citations, h-index 54; Scholars, median: 3216 Citations, h-index 24). More than 120 of ELLIS Fellows and Scholars successfully applied for ERC Grants.

The ELLIS Fellowship Programs bring together academics at regular meetings throughout Europe to promote free exchange of ideas and help create a European community of top AI researchers to retain and attract talent. Together, they stand up for European interests and generate high international visibility.

PhD and PostDoc Program

The ELLIS PhD & Postdoc Program supports excellent young researchers across Europe by connecting them to leading researchers and offering a variety of networking and training activities, including boot camps, summer schools and workshops of the ELLIS Programs.

Facilitating collaboration among top talent is part of ELLIS's DNA: ELLIS PhD students and postdocs are supervised by two ELLIS members from different institutions. They conduct cutting-edge, curiosity-driven research in machine learning or related fields and conduct their research at both partner institutions during their appointment.

ELLIS seeks to attract the world's brightest minds and helps them become the future leaders in AI. ELLIS PhD students or postdocs enjoy the benefits of:

- an international network of over 200 leading machine learning researchers (who participate in student recruitment), in both academia and industry
- joint supervision by leading researchers
- collaboration with top research groups
- funding (through advisors' resources) to conduct curiosity-driven fundamental research and to attend conferences
- access to high-end infrastructure
- contributing to society by working on high-impact challenges and developing ethical and trustworthy AI, the trademark for AI "made in Europe"

The ELLIS PhD & Postdoc Program offers two career paths: an academic track and an industry track. These tracks have separate requirements for admission and criteria for activity during the appointment, but otherwise offer the same benefits, network and resources to the applicant.

The academic track is based on a collaboration between 2 top European academic institutions from different countries, with one advisor from each institution supervising the research.

The industry track is based on a collaboration between 1 top European academic institution and 1 European industry player (e.g., a university and a company).

Since the start in 2020, 120 PhD students and PostDocs have already been accepted, 58 by nomination and 62 by central recruiting. In the first round of central recruiting in 2020 over 1300 applications from more than 70 countries were received, with more than 100 ELLIS fellows and scholars providing joint supervision. In 2021 the interest in the ELLIS PhD & Postdoc Program grew again and in the central recruiting over 1700 applications were received.

ELLIS Units

Highly innovative ecosystems emerge at outstanding academic institutions that serve as international talent magnets and incubators of innovation. Thus, rather than just building a virtual network amongst institutions, ELLIS is creating new working environments for outstanding researchers to enable them to combine cutting-edge research with the creation of start-ups and industrial impact.

As a waypoint towards the creation of ELLIS Institutes, we launched a program to establish *ELLIS Units* at existing institutions. They bring together the best AI researchers at their locations and fulfil a set of criteria to ensure excellence and thus be competitive at the international level.

The official launch of the first 30 ELLIS Units took place on September 15th 2020. Since the first 17 units were announced in December 2019 during the NeurIPS conference in Vancouver, the ELLIS initiative has gained significant momentum, adding another 13 units at top research institutions across Europe in 2020 and 4 more in 2021. All of these underwent a thorough and competitive review process.

Among the current ELLIS units, Tübingen, Saarbrücken, Jena, Stuttgart have been founded with strong involvement of the local Max Planck Institutes; in addition, several ELLIS units are located at other Max Planck sites (Berlin, Heidelberg, Freiburg, Munich).

Alicante
Berlin
Copenhagen
Delft
Freiburg
Haifa (Technion)
Helsinki
Lausanne (EPFL)
Linz
London (UCL)
Milan
Munich
Oxford
Prague
Stuttgart
Turin
Vienna (IST Austria)

Amsterdam
Cambridge
Darmstadt
Edinburgh
Genoa
Heidelberg
Jena
Leuven
Lisbon
Manchester
Modena (Unimore)
Nijmegen
Paris
Saarbrücken
Tel Aviv
Tübingen
Zürich (ETH)

1.7.4 Outlook

From the beginning, the interest of the European AI and ML community in ELLIS has been very high, as is the interest in being able to participate in the initiative. The ELLIS network now has over 700 members, including over 300 Fellows, and continues to grow.

ELLIS participates in a number of European activities and applications, always dedicated to promote scientific excellence in the field of Artificial Intelligence and Machine Learning and to open internationally competitive career opportunities for outstanding young scientists in this field in Europe. On September 30, 2021, ELLIS was awarded the “Deutscher KI-Preis 2021” of the newspaper DIE WELT, honouring outstanding achievements in the field of artificial intelligence.

1.7.5 Founding an ELLIS Institute

Based on discussions with Max Planck President Martin Stratmann, the goal of ELLIS has been, from the start, to establish a European network of outstanding institutes dedicated to modern AI. Inspired by both the EMBL Institutes and the Pan-Canadian AI Initiative that led to the foundation of Vector, MILA and AMII, we are arguing at the national and European level that such a network needs to create opportunities that provide truly attractive opportunities to allow us to counter the two types of brain drain hurting Europe in modern AI: brain drain towards the US, and brain drain towards outstanding industry labs such as DeepMind, Google Brain, and FAIR.

In December of 2020, at an event with the Federal Chancellor Angela Merkel, Baden-Württemberg's Minister-President Kretschmann, EU Commission Executive Vice President Vestager, and others, the private Hector Foundation -(established by Hans-Werner Hector, one of the founders of SAP - announced to provide 100 Mio EUR to establish the first such institute in Tuebingen. While this money is reserved exclusively for science and will be spent for the recruitment of *Hector Endowed ELLIS Fellows*, the State of Baden-Württemberg has agreed to provide resources for facilities and administrative services of the ELLIS Institutes. Together with the Tübingen AI Center, the new institute will form a growing AI campus, the AI Breakthrough Hub, which also includes Cyber Valley and which is expected to significantly increase Germany's appeal to international talent in the field of artificial intelligence. It has been agreed that Bernhard Schölkopf will temporarily be allowed to act as founding director for the ELLIS Institute, during which time he will reduce his MPI appointment.

The plans for the Institute have been worked out throughout the year of 2021 between the State of Baden-Württemberg, the University of Tübingen and the Max Planck Society. In order to create highly attractive positions, we will – in a model similar to the Vector Institute – employ joint recruitments between the ELLIS Institute and the University or MPI-IS, respectively. In the case of the University of Tübingen, the main instrument will be recruitments on full professorship level, and it is planned that candidates will receive offers that combine a permanent professorship with a fixed-term Hector Endowed ELLIS Fellowship. In the case of MPI-IS, we will combine the ELLIS Fellowships with fixed-term positions t on the level of Max Planck Research Group Leaders. These joint recruitments will be connected to and supported by the Tübingen AI Center which brings together the Max Planck Institute for Intelligent Systems and the University of Tübingen to form a permanent center of competence within Germany's national AI strategy (see the following section.) We are convinced that these opportunities for joint recruitment will be a win-win situation for all local partners and will add a highly needed and internationally unique instrument to our "recruiting toolbox" as a globally leading AI campus, which will allow us to remain attractive in the international competition for the leading researchers in the field of AI, and to further increase the number of positions that we can offer. For the candidates, this will create an attractive and unique combination of early career options combined with a steady stream of full professorship target positions, thus creating informal tenure track opportunities, a model that has already proven highly successful in the past on our campus. We are excited about the opportunities afforded by this potential for attracting outstanding talent and thus further expanding our site which is central to both Cyber Valley and the overall ELLIS network. However, we also anticipate some growing pains, including the need for additional office and lab space.

1.8 Tübingen AI Center

Figure 1.7: Core faculty members of the Tübingen AI Center

1.8.1 History and further development

In October 2018, the Max Planck Institute for Intelligent Systems and the University of Tübingen jointly established a competence center for artificial intelligence and machine learning, the Tübingen AI Center. This center is one of five competence centers in Germany, which are funded by the Ministry of Education and Research and are the flagship of Germany's national AI strategy. The Tübingen AI center is embedded in the Cyber Valley ecosystem, and will form close ties with the future ELLIS Institute in Tübingen. Together, these activities form the foundation for an *AI Breakthrough Hub* to significantly increase Germany's appeal to international talent in the field of artificial intelligence.

Initially, the German Federal Ministry of Education and Research sponsored the center for a runtime of four years (2018-2022). In 2020, the funding of the Tübingen AI Center was further increased to support the preparation for a planned steadying of the center in the context of the joint strategy of the German Federal government and the State governments. In December of 2020, federal Chancellor Angela Merkel and Baden-Württemberg's Minister-President Winfried Kretschmann gave the go-ahead for the AI Breakthrough Hub project to significantly increase their governments' support for Tübingen as a location for excellence in AI research and innovation. In the years to come, several hundred million euros will be invested in research and development in the field of artificial intelligence (AI) – including significant funds from the private Hector foundation, to support fellowships within a new ELLIS Institute that will closely connect with the Tübingen AI Center.

In June 2021, the University of Tübingen and the Max Planck Institute for Intelligent Systems submitted a proposal for permanent continuation of the Tübingen AI Center with the vision that the Center will become the centerpiece of a Europe-leading research and innovation landscape focusing on making the technology of machine learning more widely usable, robust, and beneficial to society. Subject to the final decision of the evaluation committee and the governments, it is expected that the Tübingen AI Center will be transferred to an institutionally and continuously funded structure in the beginning of July 2022. The Tübingen AI Center will be institutionalized as a joint Center between the University of Tübingen and the Max Planck Institute for Intelligent Systems.

1.8.2 Objectives

Since its inception in 2018, the Tübingen AI Center has established itself as a key part of a thriving and internationally recognized machine learning community at the University of Tübingen and the Max Planck Institute for Intelligent Systems. Through the prospective of permanent funding, the Tübingen AI Center aims to become a joint home for leading ML research. It will boost its academic research in the most impactful directions, actively support technology transfer and create a unique teaching environment with a strong focus on machine learning and AI.

The core goals of the Tübingen AI Center are to

(i) attract a critical mass of top machine learning talent,
(ii) provide an ideal environment for impactful high-risk–high-gain research,
(iii) educate the next generation of machine learning experts,
(iv) accelerate technology transfer, and
(v) contribute to a nationally leading education and outreach program in machine learning.

Thereby, the Tübingen AI Center is uniquely poised to become one of the leading places for top international talent in AI. It will also play a key role in aligning the national AI strategy with local and European initiatives as embodied by the AI Breakthrough Hub.

The Tübingen AI Center was an early mover on the topic of “Robust Machine Learning” which now has gained broad attention in the field due to the limitations of today’s machine intelligence. Faculty of the Tübingen AI Center made pioneering contributions to the topic, that has laid the groundwork for the center’s research mission to address the full range of challenges that are necessary to overcome the narrow statistical nature of today’s machine learning models and to infuse them with a stronger common sense of “understanding of the world”. The research in the Tübingen AI Center covers the full stack of ML and causal inference from the foundations to methods, systems, and societal impact.

The Tübingen AI Center will also have a significant budget for accelerating the most promising research and technology transfer activities through independent postdocs and agile high risk–high gain funding for PhD students and applied projects. It will actively support faculty in engaging in startups, or activities that help society engage with AI research. Together with the other German competence centers for AI, it will build a national AI platform with impact across societal sectors. The strong international outlook of the Center will be maintained and strengthened by the close involvement of the faculty with the ELLIS network, comprising many of the world’s top ML researchers.

1.8.3 Organization

Involved Institutes and Departments

On the Max Planck Side, the Tübingen AI Center is currently affiliated with both sites of the Max Planck Institute für Intelligent Systems, as well as with the Max Planck Institute for Biological Cybernetics in Tübingen. During the center’s ramp-up phase one new, fully independent research group on the topic of fairness in AI led by Samira Samadi was established at MPI-IS. With the start of 2022, four more junior research groups newly formed within the MPI-IS will be funded, including a female early career research group. In addition, several junior research groups within institute departments were supported through the center, as well as several research projects led by Principal Investigators at both sites of MPI-IS.

On the University side, several researchers within the Science department and the department of Faculty of Economics and Social Sciences are involved in the Tübingen AI Center, connecting it to various institutes across the university and the Cluster of Excellence “Machine Learning: New Perspectives for Science”. Through the prospective permanent funding, the Tübingen AI Center will be institutionalized as an independent center at the University with its own academic rights.

In total, currently, the Tübingen AI Center consists of 26 research groups with more than 150 scientists, for more details see https://tuebingen.ai/team.

The Tübingen AI Center is closely connected and aligned with ELLIS, through the Board of the ELLIS Society, the ELLIS Unit Tübingen, the planned ELLIS Institute, the ELLIS PhD Program and ELLS research programs. The Tübingen AI Center is also involved in the International Max Planck Research School for Intelligent Systems (IMPRS-IS), and doctoral candidates within the Tübingen AI Center are enrolled in IMPRS-IS.

Management
The Tübingen AI Center is currently lead by its team of directors:

- Prof. Dr. Matthias Bethge, University of Tübingen (director)
- Prof. Dr. Bernhard Schölkopf, Max Planck Institute for Intelligent Systems (co-director)

The leading team is supported by an executive office and a coordination team.

Principal Investigators
Projects within the Tübingen AI Center are led by Principal Investigators at MPI-IS and the University of Tübingen, respectively.

- Dr. Samira Samadi: Leader of the independent Tübingen AI Center research group “Human Aspects of Machine Learning”
- Dr. Michael J. Black, „Robust 3D hand-object interaction” and “Learning to see people in complex scenes”
- Katherine J. Kuchenbecker, Ph.D., „Robust tactile object exploration”
- Dr. Falk Lieder, „Robustes Lernen von Entscheidungsstrategien“
- Dr. Georg Martius, „Erlernen robuster Robotersteuerung“ and „Robustheit und Stabilität gelernter Modelle dynamischer Systeme“
- Prof. Dr. Bernhard Schölkopf, “Learning and comparison of invertible generative models” and “Understanding Deep Probabilistic Models for Robust Learning”
- Dr. Jörg Stückler, „Robustheit von Verfahren zur 3D Rekonstruktion dynamischer Szenen durch Vorhersagemodelle“
- Prof. Dr. Isabel Valera, „Fair decision making: From learning to predict to learning to decide“

1.8.4 Research

The research at the Tübingen AI Center can be grouped into five main areas.

Area A: Robust Machine Learning Principles and Algorithms
This area examines the theoretical foundations of learning. The ability to generalize in a robust manner is closely related to the discovery of causal relationships and the ability to place them in a broader context. Learning systems should not only be able to infer whether a particular variable (e.g. whether a person smokes or not) is statistically associated with a disease, but whether it is the cause of the disease. The focus here is both on the development of the theoretical foundations for developing comprehensive causal models from empirical data and on the empirical question of which definition of causality is most useful in practice. An important goal of this work is to derive guarantees for the behavior of machine learning algorithms in new situations. Other important aspects are the choice of representations, how to deal with uncertainty and the computational efficiency of learning algorithms. On the one hand, the generalization properties depend strongly on the choice of representation; on the other hand, a lot of uncertain information has to be combined to solve inference problems, which means that the estimation of uncertainty can contribute significantly to robustness.

Area B: Robust Perception Learning

The central question in this area is how intelligent systems can learn robust perceptual inference. Our focus is primarily on visual perception and inferring a holistic understanding of the 3D scene from image data. One way to test scene comprehension is to ask whether a system can handle many different tasks ("multi-task learning") or completely novel tasks ("transfer learning") without requiring extensive re-training. Another possibility is to search for new, particularly unusual or unfavorable situations in order to test the robustness of perception. In order to learn robust representations, scientists at the Tübingen AI Center pursue a number of approaches, such as generative image models, compositional ("parts-based") representations or causal inference on image data. These approaches share the common goal of uncovering as many properties of the environment as possible, such as the three-dimensional structure, material properties, movement patterns, known and unknown objects as well as their interactions and causal relationships. A further goal is to develop novel learning approaches that can extract significantly more information with the help of unsupervised training than current computer vision algorithms that require massive amounts of supervised training.

Area C: Robust Action Learning

This area examines robust learning in the context of autonomous agents interacting with their environment (either the real world or in a simulated environment). Nowhere is the need to develop robust learning methods as obvious as here: Even small changes, such as leaning a robot against a wall, can lead to massive state changes that would require a change in the control model with current methods. The central question for achieving autonomous behaviour is therefore whether it is possible to learn large holistic models that function reliably for the entire space of actions – even in new environments. Another exciting aspect concerns the question to what extent active learning behavior can be used to achieve the required robustness particularly effectively. The hypothesis that active learning is crucial is supported by the fact that intervention and testing play an important role in identifying causal relationships. This results in exciting parallels to the search for learning algorithms that are robust against adversarial examples.

Area D: Machine Learning in Medicine

Our cooperation with the Institute for Biomedical Informatics (IBMI) and the DIFUTURE consortium, which is funded within the framework of the BMBF's Medical Informatics Initiative, offers great opportunities to use machine learning for medical applications. Since medical datasets are often very heterogeneous, incomplete and limited in scope, methods of robust learning are particularly valuable in this area. Thus, the development of causal learning methods that specifically address cause and effect and of semi-monitored learning methods with sparse, multimodal data will be an important focus in this area.

Area E: Data Privacy, Fairness, Impact

Machine learning increasingly influences our everyday life, which raises important questions about privacy, fairness and transparency. To strengthen Tübingen's expertise in this area, we focus research in these topics in a fifth core research area. Research in this area – particularly in the field of deep learning – is still largely in its infancy. For example, methods are being developed to apply machine learning methods to sensitive data without allowing conclusions to be drawn about individuals ("differential privacy"). With the increasing use of machine learning for automatic decision making, fairness and transparency are also gaining importance. To prevent the learned decision processes from disproportionately harming certain groups of people (e.g. age, gender) or providing them with advantages, methods are being developed to ensure that algorithms make optimal decisions within a subset of the data (fairness) or to make it comprehensible to the user on which characteristics of the input data the decision is based on (transparency).

1.8.5 Outreach

The Tübingen AI Center identifies with the mission to produce cutting-edge research deeply relevant to society. This cannot be solely achieved by recruiting new, international professors but also by breeding new talent and by investing in the education of people at every single stage of their career. The Tübingen AI Center has set up or is centrally involved in several initiatives that specifically address children and adolescents. These initiatives first aim to ignite the curiosity of young girls and boys in computers and programming. Then they provide the necessary platform for interested young minds to learn more about AI and pursue actual projects in machine learning. Eventually, these initiatives will motivate more and more young people to study this subject and consider a career in science.

National AI School competition "Bundeswettbewerb Künstliche Intelligenz" (BWKI) The federal competition for artificial intelligence motivates pupils to create their own AI application. Pupils get the opportunity to play an active role in impacting our future by proposing AI approaches that tackle ecological, medical, technical, or societal challenges. In 2021, this competition already completed its third annual round. More than 150 students handed in their project ideas in the 2021 competition. In the final, ten selected teams presented their projects to the jury and the audience. So far, more than 4,000 students, teachers and interested parties have already taken advantage of the BWKI's offerings. The BWKI will be held again in 2022. The main sponsor of the competition is the Carl Zeiss Foundation. The competition was also supported by Bosch, Festo, paperspace, Google, Verlagshaus Droemer and Knaur, and was held in cooperation with Cyber Valley, the Media University and the German Alliance for Marine Research.
https://www.bw-ki.de

Online AI Course The online AI course (KI-Kurs) offers the opportunity to learn how to program an AI project. The course comprises programming tutorials and tasks in Python, as well as training that focuses on ethical considerations in the field of AI and machine learning. The course material is developed for individual application, as well as for use in the classroom.
https://ki-kurs.org

KI-Makerspace, in cooperation with Cyber Valley The KI-Makerspace is an extracurricular learning space where children and young people can gain their first experience with programming and artificial intelligence (AI) in courses and supervised experimentation, as well as realize their own projects with software and hardware. The Makerspace also offers a platform for socio-political discussions on the topic of AI. The KI-Makerspace is a joint project of the University of Tübingen with Cyber Valley Public Engagement, the Youth Community Council Tübingen and the Bundeswettbewerb Künstliche Intelligenz (BWKI) of the Tübingen AI Center. It is funded by the Vector Foundation Stuttgart for an initial period of three years.

KI macht Schule Together with KI macht Schule (AI at school), the Tübingen AI Center supports educational outreach about AI through interactive workshops for students in German schools. The workshops cover both technical aspects and ethical implications of AI and allow students to form an opinion about the application of AI in society.
https://ki-macht-schule.de

IT4Kids The IT4Kids initiative teaches primary school pupils basic knowledge in programming. In cooperation with the IT4Kids Team in Aachen, we have created a series of fun programming tasks with Scratch that offer an introduction to the field of programming. We are currently teaching pupils in a basic and advanced course, both onsite and online.
https://it-for-kids.org

1.9 International Max Planck Research School for Intelligent Systems

The International Max Planck Research School for Intelligent Systems (IMPRS-IS) is our institute's main doctoral program and a key element of the Cyber Valley initiative. IMPRS-IS was founded in early 2017 to bring a new generation of young scientists and engineers into our highly multidisciplinary research environment, enabling them to learn to tackle the fundamental challenges of intelligent systems while simultaneously earning a Ph.D. under the mentorship of our directors, group leaders, and top faculty in aligned research areas at our neighboring universities.

IMPRS-IS brings together the MPI for Intelligent Systems, the University of Tübingen, and the University of Stuttgart to form a highly visible and unique graduate school of internationally renowned faculty working at the leading edges of our field. The program aims to advance human knowledge about intelligent systems and directly support our institute's research mission by recruiting, educating, and supporting outstanding doctoral students. The participating faculty, students, and staff are committed to making this doctoral training program among the best worldwide.

Figure 1.8: Photo gallery of the IMPRS-IS community

1.9.1 The Motivation Behind IMPRS-IS

Society has been strongly impacted by the immense progress made in the research fields of artificial intelligence and robotics. These new technologies have changed the way we live, work, learn, and travel. Research in this field is progressing rapidly and has gained momentum on all levels, from ethical concerns and political interests to social, economic, and industrial relevance. Whatever the future may hold, it is important that we in Europe confidently apply our academic and social values and traditions to play a leading role in the development of the intelligent systems of the future. We must not leave such research solely to scientists in North America or China.

The founding of our Max Planck Institute for Intelligent Systems ten years ago and the creation of the Cyber Valley initiative five years ago represent a major strategic investment in basic research designed to enable Germany to play a leading role in the field of intelligent systems. Tomorrow's learning methods will be invented today, most likely by curious, creative, hard-working young people; this is where the IMPRS-IS doctoral school comes in. An interdisciplinary education is required to understand and do research on intelligent systems. Such an educational opportunity has been made possible for the first time in Germany through the structured IMPRS-IS program.

Unsurprisingly, intelligent systems research is being pursued with vigor worldwide; there is thus fierce competition for the best minds in the scientific community at all levels, including doctoral students. Consequently, one of the main missions of the IMPRS-IS is to help our faculty and associated faculty members attract a diverse and excellent set of doctoral scholars from around the world. In particular, we look to recruit candidates with a strong academic background and a master's degree in engineering, computer science, cognitive science, mathematics, control theory, neuroscience, materials science, physics, or related fields. Scholars who join this doctoral program benefit from near-perfect research conditions: they can conduct basic research freely, within a uniquely strong scientific community that is supported by the European values.

1.9.2 Overview

International Max Planck Research Schools have been an integral part of the Max Planck Society's approach to doctoral research since the year 2000, granting talented students from both Germany and abroad the opportunity to earn a doctorate under excellent conditions. Common characteristics of these graduate programs are the close cooperation between an MPI and one or more local universities, a curriculum of research seminars and soft-skill workshops, and a strong academic community that brings together students, faculty, and other researchers.

Our IMPRS-IS is one of 68 such schools. Its creation was enabled by a central grant from the Max Planck Society to MPI-IS with an initial duration of six years, as well as significant funding from the state of Baden-Württemberg for doctoral education at both the University of Tübingen and the University of Stuttgart. The successful grant proposal was led by Dr. Michael J. Black in summer of 2016 with support from Dr. Katherine J. Kuchenbecker and our scientific coordinator, Dr. Matthias Tröndle. Dr. Kuchenbecker has been serving as the IMPRS-IS spokesperson since the school's initiation in January 2017.

The school's Coordinator, Dr. Leila Masri, joined the institute at the start of the establishment of IMRPS-IS in April 2017, followed by the addition of our Program Administrator, Ms. Sara Sorce, in September 2019. The school is additionally supported by our liaison at the University of Tübingen, Ms. Heike Größl, who joined the IMPRS-IS coordination team in July 2020.

1.9.3 School Growth

The International Max Planck Research School for Intelligent Systems enrolled its first class of 28 scholars in fall of 2017 with scholars coming from 11 different countries. These new doctoral students had backgrounds ranging from mathematics, computer science, and machine learning to physics, engineering, and robotics. Since the school's initial launch, application numbers and overall interest have grown immensely. In 2021, the school held its fifth application round and received a record number of applications: 968 total applications were received with applicants representing 55 countries from around the world. 29% of these applicants were female. Importantly, application to IMPRS-IS is free.

In order to properly review these high numbers of applicants, the school has established a very careful selection procedure. IMPRS-IS transparently reviews applicants using a customized online application portal that was developed by the school and is tailored to our needs. Using this online system, a team of over 100 faculty and other Ph.D.-holding scientists thoroughly review all complete applications. All reviewers are trained on good practices for evaluating applications, including an introduction to the topic of unconscious bias in decision making. The coordination office takes special care to assign applications to suitable reviewers with consideration for research interests, educational background, and the geographic distribution of the applicants.

Top candidates are then invited to a final interview symposium. Here, each applicant gives a 15-minute-long scientific talk open to members of our community and conducts interviews with multiple IMPRS-IS faculty and associated faculty members. In the latest recruitment round, 131 applicants participated in this final interview symposium. After this rigorous interview process, 59 scholars accepted offers to begin their Ph.D. research with IMPRS-IS in 2021.

IMPRS-IS is very proud of its scholars; each one is highly talented and motivated and is working to contribute to cutting-edge research that spans the interconnected fields of computational cognitive science, computer graphics, computer vision, control systems, human-computer interaction, machine learning, micro- and nano-robotics, perceptual inference, and robotics. Currently, IMPRS-IS has 219 full scholars that are pursuing their doctorates within the doctoral program, far exceeding its initial vision of recruiting 100 Ph.D. scholars over the course of its initial six-year grant. This makes IMPRS-IS one of the largest of the Max Planck Society's IMPRS doctoral schools. IMPRS-IS scholars hail from over 40 different countries, and 28% of the school's scholars are female.

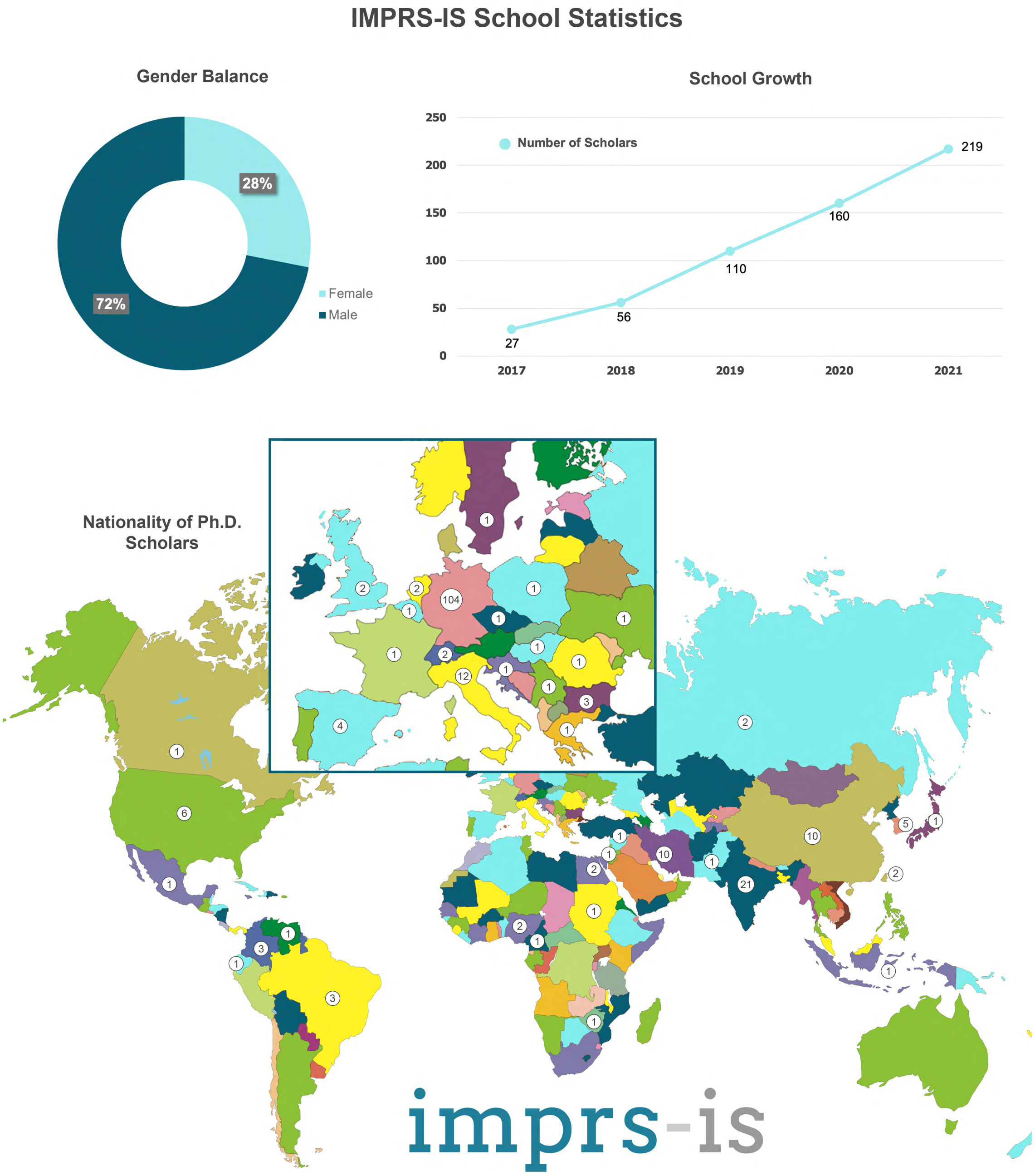


Figure 1.9: Diversity and growth of IMPRS-IS

1.9.4 Contracts and Funding

The standard MPI-IS employment offer is a three-year contract with the equivalent of a 65% E13 position in the TVöD scheme for public employment in Germany; this pay level is matched to the new standard minimum salary for doctoral students within MPG. Importantly, the source from which a particular doctoral student is funded has no bearing on his or her ability to become an IMPRS-IS scholar. About one third of all our scholars are co-funded by the school, with these funding allocations decided by the executive board on the basis of criteria that are aligned with our school's values and communicated clearly to all faculty.

To help contribute to the management of the school, the entire population of scholars elects a set of four student representatives on an annual basis, with one representative for each site of our institute as well as one per university. One of these representatives is then internally selected to represent all of the scholars at meetings of the IMPRS-IS executive board.

IMPRS-IS doctoral researchers have the opportunity to help shape the school in a variety of ways. One prominent example is through the organization of the IMPRS-IS soft skills seminar series (S4) workshops. As part of this organizing team, doctoral researchers collaborate with the IMPRS-IS coordination office as well as the entire student body to offer a series of professional development workshops. Through participation in S4, scholars gain valuable insight on how to organize events as they work to find qualified trainers, advertise to the community, communicate with participants, solicit feedback, and more.

Post-masters and doctoral students who are doing research with an IMPRS-IS faculty member or associated faculty member but who are not IMPRS-IS scholars can become associated students of the school. Application requires only a current curriculum vitae and the endorsement of the supervisor. Associated students take part in the school's activities when space is available.

1.9.5 Objectives

IMPRS-IS offers an interdisciplinary doctoral research program with opportunities to study all key areas of intelligent systems, ranging from computer science to control theory, from mechanical engineering to neuroscience, and from mathematics to materials science.

In addition to ongoing support from their primary advisor(s), each scholar benefits from regular interactions with their Thesis Advisory Committee (TAC). This cross-institutional panel is formed near the start of the Ph.D. and includes two or more IMPRS-IS faculty members (including the scholar's main advisor) and at least one additional member of the IMPRS-IS faculty or associated faculty. These three TAC members must be from at least two different institutions; additional external members are also allowed. To facilitate university admission and eventual graduation, at least one TAC member must be part of the faculty at the university where the student wants to earn their doctorate. The student drives the process of proposing and securing consent from the scientists they believe would add the most to their research. The TAC meets all together on an approximately annual basis for the scholar to present their research; the TAC reviews and provides suggestions on the Ph.D. project, monitors the progress of the scholar, and advises them on further studies and research. The TAC also approves a thesis as ready for submission. When it can be foreseen that a Ph.D. project will not be successfully finished, the TAC can recommend to discontinue the project; this decision must be confirmed by the IMPRS-IS executive board.

The scholar meets with their TAC at least once per year and documents these meetings by written minutes with an executive summary confidentially communicated to the IMPRS-IS coordination office. These meetings preferentially take place in months 6-9, 15-18, and 30-33 after the beginning of a Ph.D. project. On request of the student or one of the TAC members, the TAC can also meet more frequently than once per year.

Beyond the scholar’s own research, the IMPRS-IS program includes the following courses, events, resources:

Figure 1.10: Events, workshops, and courses offered by IMPRS-IS

Cross-institutional exchanges Before the pandemic, every department and research group within the broader IMPRS-IS community participated in cross-site bridging events where interested members of our community could visit each other and learn from lab tours. In addition to the scientific stimulation of such experiences, these occasions helped scholars build their professional networks and fostered a strong community feeling in an informal environment. It is our goal to continue these cross-institutional exchanges when COVID-19 safety regulations allow it.

Annual meetings A member of the school’s coordination office (Dr. Leila Masri or Sara Sorce) meets for 30 to 45 minutes with each IMPRS-IS scholar on an annual basis to hear how their research is going and help them strategize about any challenges they may be facing. Providing such coaching helps our school both support individual scholars as well as hear about and handle any larger issues that may affect our community. Dr. Masri also meets personally with each new faculty member to explain the details of the school and checks in regularly with all faculty, particularly during recruiting season. Dr. Kuchenbecker meets with IMPRS-IS scholars, faculty, and associated faculty who need guidance from an experienced faculty member.

Zentralized Electronic Buddy for Research and Administration (ZEBRA) IMPRS-IS has created a custom online interface specifically designed to provide scholars with a secure and simple way to store pertinent program information and documents. The online platform also keeps the school’s coordination office informed of each scholar’s progress through the program. All IMPRS-IS Ph.D. scholars use ZEBRA to track personal accomplishments and indicate when they have achieved program milestones. Scholars record participation in thesis advisory committee meetings and upload the associated executive summaries. ZEBRA is also specially designed to help track the progress of a scholar’s university enrollment, participation in events and courses, and publications and awards; these centralized data streams can then easily be used to generate reports about IMPRS-IS.

Workshops IMPRS-IS offers an array of professional development workshops open to scholars and faculty. Examples of workshops held in 2021 include training on scientific English writing, marketing for scientists, intercultural communication, working effectively in diverse groups, conflict management, project management, stress management, standards and good practices in software development, structuring and delivering a scientific talk, and poster presentation and design. Additionally, the school offers periodic high-quality workshops on responsible conduct in research because honesty and the observance of the principles of good scientific practice are essential in all scientific work that seeks to expand our knowledge and which is intended to earn respect from the public

Boot camps The entire IMPRS-IS community participates in an annual intensive boot camp. Both faculty and scholars present their latest findings through talks and poster sessions. Additionally, panel discussions, interdisciplinary tutorials, design competitions, and social activities are organized to widen the perspective of the scholars and increase their efficiency and effectiveness as Ph.D. students. In 2021, the IMPRS-IS boot camp was held online to uphold safety regulations in place due to the COVID-19 pandemic. Although all aspects of the event were held virtually, scholars still participated in scientific talks, student talks, a virtual poster session, panel discussions, and social activities. Fig. 4 shows a screenshot taken after the event's keynote by Dr. Bernhard Schölkopf. According to an anonymous online survey after this virtual boot camp, participants were highly satisfied with the experience and offered helpful suggestions for future IMPRS-IS events.

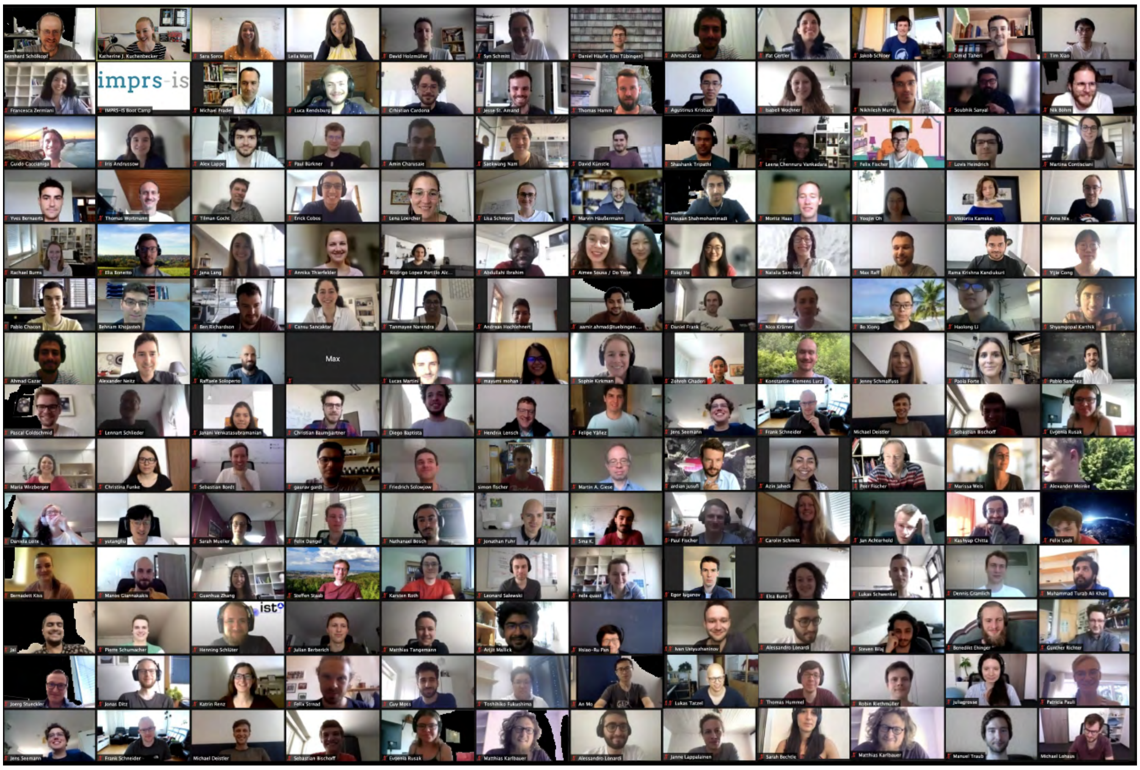


Figure 1.11: IMPRS-IS community photo taken during the virtual 2021 boot camp

Orientation days IMPRS-IS holds orientation days twice per year. This event is designed to provide new Ph.D. students with valuable information pertaining to the doctoral program. Participants receive clear information about IMPRS-IS program requirements with key topics including the thesis advisory committee (TAC), registering at one of the partner universities, and how to take advantage of the many opportunities and resources the school has to offer. Orientation days also aim to help acclimate international students to the Stuttgart and Tübingen area and get them better acquainted with life in Germany. Finally, these events allow for interpersonal exchange so that new doctoral researchers can meet and make friends.

Community events The school offers its doctoral researchers a gateway to a plethora of scientific events either directly organized directly by IMPRS-IS or indirectly offered by one of our partner institutions or collaborators. One prominent example is the Cyber Valley

Entrepreneurship Series, which features education on topics such as artificial intelligence in social innovation, production, logistics, and mobility. This series also offers workshops on grant writing and early funding opportunities, as well as talks and panel discussion on topics such as female leadership, AI in the medical field, and much more.

Networking and social activities The IMPRS-IS organizing team and the school's elected student representatives cultivate a friendly environment by organizing frequent social activities to help students advance academically and personally, all the while driving artificial intelligence and robotics to the forefront of excellent research and setting the groundwork for future research leaders in this field.

Graduation ceremony IMPRS-IS participates in an annual ceremony honoring all Ph.D. graduates affiliated with the Max Planck Institute for Intelligent Systems. The IMPRS-IS community as well as the colleagues and families of graduates are invited to attend this event, which typically takes place in July and celebrates those who successfully defended their doctoral thesis during the previous year.

Culture Club This social group is designed to help acclimate international colleagues to the Stuttgart and Tübingen area. Its monthly meetings offer IMPRS-IS researchers a way to meet new people, discuss intercultural topics, learn helpful tips about navigating life in Germany, and make the most of their time in the region. Co-organized by IMPRS-IS Program Administrator Sara Sorce, Culture Club offer an inclusive space where international colleagues, significant others, and German allies can receive info about getting acclimated in a new cultural environment.

Support programs for women in science IMPRS-IS seeks to increase the number of women in areas where they are underrepresented, so we explicitly encourage women to apply. IMPRS-IS has also established a program that fully funds internships for female master's students doing research with one of our MPI-IS faculty for a duration of up to six months. In addition, IMPRS-IS is a key founder and cooperator of the Athena Group, a bottom-up organization that provides a mentoring program for our young female scientists and supports them in their career development; all female IMPRS-IS scholars are strongly encouraged to join this mentoring program. In collaboration with the Athena Group, the school has also hosted several talks wherein female scientists present a lecture on their research at one of our institute sites and then also talk about their personal career experiences with a small group of individuals in a more intimate setting.

Connecting parents A typical Ph.D. path overlaps with the age of becoming a parent. Within our current student population, more than ten scholars have had their first child since joining the school. Given the privacy of this topic, we work to connect the parents with one another through informal get-togethers that create a network of support. Participation is optional, and invitations to join are given through personal contact between scholars and the coordination office.

1.9.6 Organization

The current faculty of IMPRS-IS includes world-renowned researchers drawn from the MPI for Intelligent Systems, the University of Tübingen, and the University of Stuttgart. All are established leaders in intelligent systems and have the right to advise scholars within the IMPRS-IS.

The following seven faculty currently form the Executive Board of the IMPRS-IS:

Prof. Dr. Frank Allgöwer Professor at the University of Stuttgart and Deputy Spokesperson

Dr. Caterina De Bacco Cyber Valley Research Group Leader at MPI-IS and Equal Opportunity Officer of the Executive Board

Dr. Michael J. Black Director at MPI-IS

Dr. Katherine J. Kuchenbecker Director at MPI-IS and IMPRS-IS Spokesperson

Dr. Christoph Keplinger Director at MPI-IS

Prof. Dr. Hendrik Lensch Professor at the University of Tübingen and Deputy Spokesperson

Dr. Alexander Spröwitz Max Planck Research Group Leader at MPI-IS

1.9.7 Faculty

Any director, professor, or independent research group leader associated with the MPI for Intelligent Systems, the University of Stuttgart, or the University of Tübingen may apply to become a member of the faculty or the associated faculty of the IMPRS for Intelligent Systems. After securing the support of their institution's spokesperson or deputy spokesperson, the prospective faculty member submits a curriculum vitae and a motivational letter. The school's executive board decides on each nomination in a meeting based on the employment status, research track record, relevance of the research direction, and training record of the nominee.

IMPRS-IS presently has 54 faculty and 21 associated faculty members, who may advise scholars, be members of thesis advisory committees, contribute at the boot camp, and give courses. These individuals are Ph.D.-holding scientists in the three participating institutions including leaders of central scientific facilities, non-independent group leaders, and university faculty working at the fringes of intelligent systems. For full lists of our faculty and associated faculty, please see https://imprs.is.mpg.de/people.

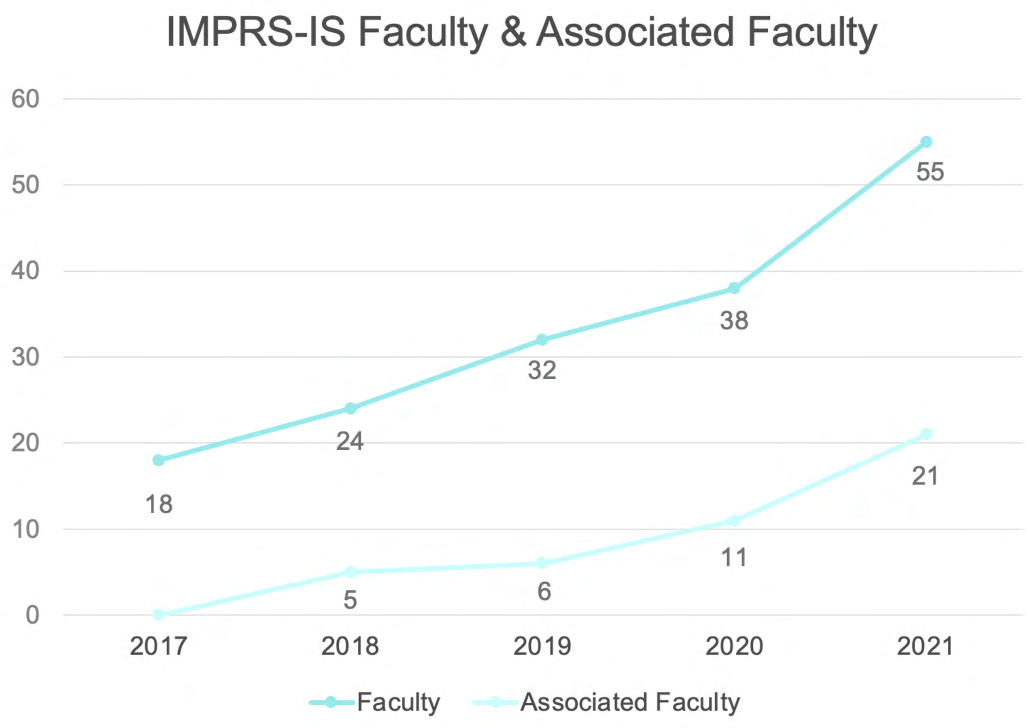


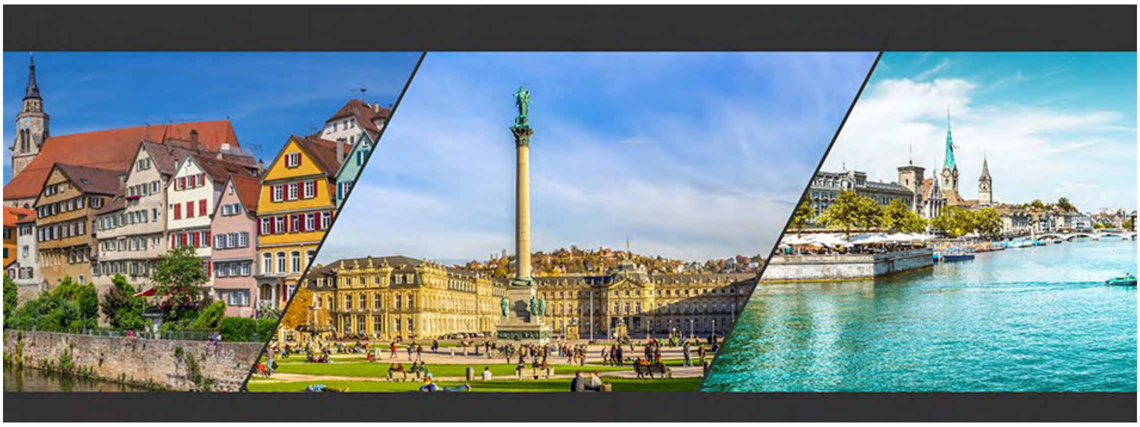
Figure 1.12: IMPRS-IS faculty and associated faculty growth chart

1.9.8 Future Plans

The future of IMPRS-IS looks highly promising; we intend to keep operating it for the lifetime of our institute. The vast increase in applications over our five recruitment rounds underlines the timeliness and importance of interdisciplinary research in intelligent systems. Simultaneously, the high quality and diversity of the students enrolling in this doctoral program show that we are already competitive with top university programs worldwide. Both the MPI for Intelligent Systems and our two partner universities are committed to finding ways to continue growing our school to meet this demand without compromising quality, focus, or personal interactions with our scholars and faculty. Currently, we are working on submitting our first application proposal for an extension of the IMPRS-IS for an additional six years, which would provide central funding for the school until the end of 2030 if granted.

The school's founding in 2017 constituted a key element of the Cyber Valley initiative, confirming that the Stuttgart/Tübingen region is a major AI and robotics research hub in Europe and the world. Every day, the International Max Planck Research School for Intelligent Systems further strengthens this ecosystem in southern Germany, bringing together faculty and students at our three institutions to foster research collaborations, interdisciplinary scientific insights, and friendships that will last a lifetime.

1.10 Max Planck ETH Center for Learning Systems



The Max Planck ETH Center for Learning Systems (CLS) is a joint academic program between the Max Planck Society, primarily the Max Planck Institute for Intelligent Systems (MPI-IS) in Germany and ETH Zurich in Switzerland. The goal of CLS is to advance artificial intelligence by achieving a fundamental understanding of perception, learning and adaption in complex systems through providing a platform for exchange in research and education. While CLS seeks to intensify cooperation between researchers at all career levels, the core element is its cross-institutional co-advised doctoral fellowship program.

Since the foundation of CLS in 2015, both partners have contributed to strong local ecosystems for AI: CyberValley on the German side, and the ETH AI Center, launched in October 2020 as ETH Zurich's central hub for artificial intelligence, on the Swiss side. CLS is thus positioned as the connecting bridge between two of the leading European pillars of AI research.

1.10.1 Brief History

Our Center for Learning Systems is one of around 20 international Max Planck Centers of the Max Planck Society. These Max Planck Centers form platforms within scientific cooperation programs, where the participating Max Planck Institutes and their international partners can bundle their knowledge, experience and expertise and combine complementary methods and know-how to create added scientific value.

The Max Planck ETH Center for Learning Systems was established in November 2015 with an initial run time of five years, becoming the first joint center between the Max Planck Society and the world-famous Swiss research institution. The activities of the center are regulated by an official cooperation agreement signed off by both partners.

In April 2020, following the completion of a successful evaluation, the two partners further strengthened their cooperation with an agreement to extend the joint research venture for another five-year period. Both sides place a high value on this cooperation, believing that strong academic exchange in Europe is vital in order to actively shape developments in modern AI and leads to a higher impact than if every research institution were to forge its own path.

Financially, the center is supported equally by ETH Zurich (50%) and by the Max Planck Society and MPI-IS (50%). The initial budget of 5 million EUR for 2015-2020 has been duplicated by the respective partners for the extension period, giving a total of 10 million EUR for center activities until April 2025.

1.10.2 Objectives

The main objective of CLS is to foster cross-institutional exchange, driving excellent research and laying the groundwork for our future research leaders in the field of AI. CLS addresses crossdisciplinary research questions in the design and analysis of natural and man-made learning systems, with a particular focus on the development of a unified view of learning systems found in natural sciences and engineering disciplines. The center hosts activities in research fields that build our understanding of complex systems via the pursuit of the following six central goals:

- G1 Machine Learning and Empirical Inference of Complex Systems
- G2 Perception-Action-Cycle for Autonomous Systems
- G3 Robust Model-Based Control for Intelligent Behavior
- G4 Robust Perception in Complex Environments
- G5 Design, Fabrication, and Control of Synthetic, Bio-Inspired, and Bio-Hybrid Micro/Nanoscale Robotic Systems
- G6 Neurotechnology and Emergent Intelligence in Nervous Systems.

1.10.3 Organization

Involved Institutes and Departments
On the Max Planck side, the center is affiliated with both sites of the Max Planck Institute for Intelligent Systems, with all current departments and independent research groups participating.

On the ETH Zurich side, the center is jointly operated by the engineering departments of Computer Science (D-INFK), Mechanical and Process Engineering (D-MAVT) and Information Technology and Electrical Engineering (D-ITET). Furthermore, professors of Health Sciences and Technology (D-HEST), Mathematics (D-MATH), Physics (D-PHYS), Biosystems Science and Engineering (D-BSSE) and Civil, Environmental and Geomatic Engineering (D-BAUG) are involved in center activities. For ETH administration purposes, the center is officially connected to the Department of Computer Science.

Since 2019, CLS has involved further outstanding European researchers as CLS Senior Fellows, who can join meetings of the center and provide scientific advice, as well as offering Ph.D .supervision. This expands the CLS network to include Peter Dayan at the Max Planck Institute for Biological Cybernetics in Tübingen, and Bernt Schiele at the Max Planck Institute for Informatics in Saarbrücken.

Participation
Researchers participate in CLS via one of the categories below. For participant numbers, see Table 1.1.

- **Full Ph.D. Fellows:** recruited to the cross-institutional CLS doctoral fellowship program via the annual selection.
- **Associate Ph.D. Fellows:** joined CLS having already started the Ph.D. This category supplied an essential critical mass during the early stages of CLS, but was discontinued in 2020.
- **Associate Postdoctoral Fellows:** join CLS meetings, help shape center activities through the organization of workshops and events, and initiate collaborations. Associate postdoctoral fellows have the chance to arrange short research stays at the partner institute, with costs covered by the program. Postdoctoral researchers working with CLS faculty may apply.
- **Full Faculty Members:** form the senior core faculty of CLS. These are full professors or directors at ETH and MPI-IS, respectively.
- **Associate Faculty Members:** associated/assistant professors at ETH and independent group leaders at MPI. Full professors in related areas can also join CLS as associated members.

	MPI	ETH	Alumni
Full Ph.D. Fellows	18	14	4
Associate Postdoctoral Fellows	6	16	14
Full Faculty Members	8	21	19
Associate Faculty Members	9	24	
CLS Senior Fellows	2	0	0

Table 1.1: Number of CLS participants

- **CLS Senior Fellows:** see section above.

Mutual Affiliations

In 2017, the CLS partner institutions completed arrangements allowing members of the center to be co-affiliated with both institutions. MPI-IS Directors may become ETH Professors, with two cases implemented so far: Bernhard Schölkopf was appointed Affiliated Professor of Empirical Inference in the Department of Computer Science in January 2019, and Metin Sitti as Affiliated Professor of Physical Intelligence in the Department of Information Technology and Electrical Engineering in June 2020.

The reciprocal arrangements allow for up to ten ETH full professors to become Max Planck Fellows at MPI-IS. In 2021, the first applications were approved: in July 2021 Otmar Hilliges founded the Max Planck Fellow group on Human-centric Vision & Learning at MPI-IS. Three further Fellowships are due to start later in 2021: Andreas Krause, Thomas Hofmann and Klaas Prüssmann will lead Max Planck Fellow groups on Interactive Learning, Coordinative Intelligence and Magnetic Resonance Imaging, respectively.

Management

The CLS steering board directs the strategic development of the Center for Learning Systems, and is composed of two co-directors, one from each site (the leading team), plus two deputy co-directors and two additional members. The current board members are:

- Prof. Dr. Bernhard Schölkopf, Director, Empirical Inference Department, MPI-IS (co-director)
- Prof. Dr. Thomas Hofmann, Professor for Data Analytics, Department of Computer Science, ETH Zurich (co-director)
- Prof. Dr. Metin Sitti, Director, Physical Intelligence Department, MPI-IS (deputy co-director)
- Prof. Dr. Bradley Nelson, Professor of Robotics and Intelligent Systems, ETH Zurich (deputy co-director)
- Dr. Georg Martius, Max Planck Research Group Leader, Autonomous Learning Group, MPI-IS
- Prof. Dr. Fanny Yang, Assistant Professor of Computer Science, Statistical Machine Learning (SML) Group, Department of Computer Science, ETH Zurich.

Former steering board members include Philipp Hennig and Andreas Geiger (formerly independent research group leaders at MPI-IS; both now Professorship holders at the University of Tübingen) and Prof. Dr. Luc van Gool, Professor for Computer Vision, ETH Zurich (stepped down pending retirement).

The co-directors and the steering board are supported by the executive office, headed by the CLS coordinator. Initially based at ETH Zurich, since 2017 the position of CLS coordinator has been based at MPI-IS. The current coordinator, Dr. Sarah Danes, took on the role in November 2019 and works closely with colleagues from the IMPRS-IS program as part of the Graduate Education Team of the MPI-IS Scientific Coordination Office. The CLS coordinator is also part of the wider CyberValley coordination network. In addition, ETH Zurich provides an administrative assistant position split between the ETH AI Center (75%) and CLS (25%). Ms. Natalia Marciniak was appointed to this post in January 2021. Thus, the coordination team is ideally placed to optimize synergies between CLS and the ecosystems of both partners.

1.10.4 Doctoral Program

The core element of CLS is an elite cross-institutional co-advised doctoral fellowship program, enrolling between five and ten new students per year. Each fellow has one supervisor from both ETH and MPI; they are primarily based at the location of their main advisor (chosen based on interests and match), with a 12-month exchange period spent at the other location with their co-advisor. The Ph.D. research topics are agreed by these supervisory teams. Successful participants obtain their degree "Doctor of Sciences (Dr. sc. ETH Zurich)" from ETH Zurich. CLS covers 50% of the doctoral salary.

With this program, CLS seeks to drive innovative and impactful research. Doctoral fellows are expected to take advantage of the opportunities offered by both organizations and to actively seek cross-group collaborations. In addition, by enabling young academics to engage in outstanding collaborations and exchanges early in their careers, CLS provides a strong basis for their future professional development.

Recruitment

CLS publishes an annual call for applications in August; applicants apply via an in-house, bespoke online portal with a closing date around November 1st. Short-listed candidates participate in a 2-day CLS Selection Symposium held in January. Participating faculty form the selection committee, which decides which candidates meet the standard for a CLS offer, and discusses possible advisor/co-advisor matches. Successful candidates receive an offer stating the intended primary location, main advisor and co-advisor (with alternative options if applicable).

The selection of CLS Ph.D. fellows is highly competitive, with an acceptance rate of about 2.2%. In the interval since CLS was founded, alternative programs such as IMPRS-IS, ETH AI Center and ELLIS have entered the field. Nevertheless, the interest in the call for CLS applications continues to grow, with many highly-qualified applicants missing the shortlist. The statistics for the 2016 – 2021 selection rounds can be found in Table 1.2.

The CLS doctoral selection provides an important platform for exchange amongst faculty members and is a key driver of new and intensified collaboration. The structured joint recruitment of CLS has helped junior faculty in particular get access to strong students, whilst the high quality of applicants in turn helps build attractiveness when recruiting top group leaders and faculty.

Description	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Number of Applicants	209 (100%)	228 (100%)	252 (100%)	386 (100%)	267 (100%)	362 (100%)*
Invited to panel interview	15(7.2%)	20(8.8%)	20(7.9%)	22(5.9%)	18(6.7%)	30 (8.3%)
Offer after panel interview	6(2.9%)	6(2.6%)	10(4.0%)	12(3.1%)	11(4.1%)	17 (4.7%)
Accepted offer	4(1.9%)	5(2.2%)	8(3.2%)	7(1.8%)	6(2.2%)	8 (2.2%)

Table 1.2: Summary statistics of all CLS Ph.D. application calls and procedures.
*For the 2021 selection, 917 individuals registered an application; only complete applications were considered.

Program development
Since 2016, a total of 38 young researchers have joined the CLS doctoral fellowship program via the annual selection, with the first of these obtaining their doctoral degree in 2020. The program can be considered to have entered a steady state, with a student body of around 30 (Figure 1.13.). The average time to defense is 4 years, 6 months; in most cases this time period includes at least one external internship in addition to the CLS exchange year. The proportion of female CLS doctoral fellows to date is 32%.

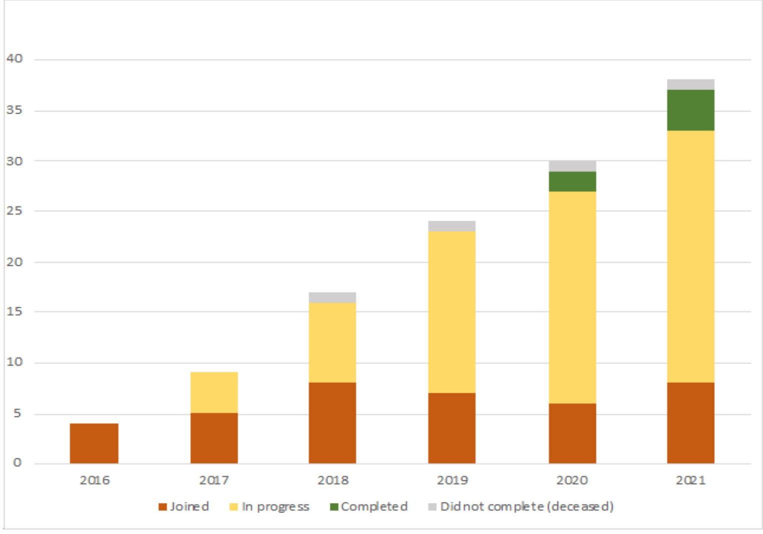


Figure 1.13: Growth of the CLS doctoral fellowship program. Number of fellows, not including associates.

Program activities
Beyond the joint ETH-MPI advisor with 12-month exchange model, the program aims are promoted through (1) specialized workshops; (2) networking through science retreats; (3) short-term research visits. Fellows are also enabled to carry out industry internships.

Since January 2016, CLS has hosted numerous workshops, retreats and other events, all of which are listed here: https://learning-systems.org/events.
Since 2020, a large number of professional skills workshops offered in conjunction with the IMPRS-IS program has enhanced the CLS program. Looking ahead, a new series of topic-specific workshops are in preparation, as well as training on responsible conduct in research. An in-person retreat in Zurich is planned for November 2021.

Since 2018, a grass-roots development from the student body has been the annual election of student representatives who channel feedback on the program to the CLS management and help organise program events. The student representatives meet each other and the coordinator regularly. This constellation directly led to the organization of a successful virtual retreat hosted by the CLS doctoral fellows in July 2021.

Logo for the CLS2021 Summer Fellows Retreat.

The new 2021 doctoral fellows take part in a virtual welcome meeting.

1.10.5 Impact

194 papers have been published since January 2016 through the direct support of the CLS program. In particular, more than 30 joint papers co-authored by MPI-IS and ETH researchers were published in areas not covered by either institution independently. Many more papers have been published that were indirectly supported through CLS. Program fellows state their CLS affiliation in publications and at conferences, and acknowledge CLS as a funding body. In addition, over 40 Ph.D. theses have been published by full and associate CLS doctoral fellows to date.

CLS researchers are recognized by a wide variety of awards, including prizes and grants. Award recipients include not only established researchers; also CLS Ph.D. and Postdoctoral Fellows have been honoured for their work. Below, we list a selection of prizes and accolades received by CLS doctoral researchers.

- Gary Bécigneul: Dieter Rampacher Prize of the Max Planck Society for the youngest Ph.D. graduate (2021).
- Alexis Block: widespread media attention for HuggieBot including radio appearances and news articles by IEEE Spectrum, The Times, NBC News, The New York Times (2018- 21).
- Amir Karimi: Google Ph.D. fellowship in Machine Learning (2021)
- Chantal Göttler: Research highlight in Budrikis, Z. Hydraulic spider legs. Nat Rev Phys 3, 389 (2021).
- Alexis Block: named a 2020 Rising Star in Mechanical Engineering (2020).
- Julian Nubert: Willi Studer Prize and ETH medal of ETH Zurich (2020).
- Francesco Locatello: Google Ph.D. fellowship in Machine Learning (2019).
- Francesco Locatello: ICML best paper award (2019).
- Cathrin Elich: DAGM Best Master thesis award (2019).
- Francesco Locatello: ISBA@NIPS award at Advances in Approximate Bayesian Inference Workshop NIPS (2017).

1.10.6 Further Development

An important ongoing goal is local networking with partners such as the Cyber Valley Initiative on the Tübingen-Stuttgart side and the ETH AI Center on the ETH side. In this context, CLS plans to introduce a mobility grant scheme, so as to extend visiting opportunities to a wider range of researchers. In turn, CLS aims to consciously promote industry partnerships and work on development of an entrepreneur program.

Further program goals include enhanced support for female researchers, for example by earmarking a certain fraction of positions and fellowships for female candidates. Finally, CLS intends to support the efforts of the European Lab for Learning & Intelligent Systems (ELLIS) by supporting ELLIS visitors to the research groups of CLS members.

1.11 Collaborations

1.11.1 External cooperation

In addition to the major initiatives and collaborations described in the previous sections, the institute has established several additional major collaborations worldwide, of which we present some selected structured programs in this section.

Clusters of Excellence at the Universities of Stuttgart and Tübingen The German national Excellence Strategy funds a large number of Clusters of Excellence. The 57 winners were chosen from 88 full proposals and 195 original applications. The Max Planck Institute for Intelligent Systems was involved in four applications, all of which were selected for funding as Clusters of Excellence. In Stuttgart, MPI-IS scientists were directly involved in both of the successful proposals at the University of Stuttgart. In Tübingen, MPI-IS is involved in two of the University of Tübingen's three approved clusters. This quadruple success demonstrates the strength of the Stuttgart/Tübingen region in artificial intelligence and robotics, as well as the synergy between the MPI for Intelligent Systems and its two neighboring universities. Somewhat based on the Max Planck Society's strategic investment in this topic in this region, this success will further strengthen the institute's cooperation with the University of Stuttgart and the University of Tübingen.

The Stuttgart Cluster of Excellence, **"Integrative Computational Design and Construction for Architecture" (IntCDC)** highlights strong research areas at the University of Stuttgart that are complementary to the expertise of MPI-IS researchers and have the potential to benefit humanity. Importantly, the University of Stuttgart recently realigned its research profile under the vision 'Intelligent Systems for a Sustainable Society', thereby creating intensive synergies with research at both sites of the Max Planck Institute for Intelligent Systems. Institute scientists are contributing deep expertise in robotics to the IntCDC cluster, focusing on multi-robot systems and haptic human-robot interaction. There are also close links between MPI-IS and the second successful cluster at the University of Stuttgart, **"Data-integrated Simulation Sciences" (SimTech).**

The Tübingen Cluster of Excellence **"Machine Learning in Science"** is particularly closely linked to the MPI-IS. The cluster's spokesperson, Professor Ulrike von Luxburg, is a Professor of Computer Science at the University of Tübingen and a Max Planck Fellow at the Tübingen site of the MPI for Intelligent Systems. Von Luxburg was the first doctoral student in the Department of Empirical Inference, with which Bernhard Schölkopf established the research field of machine learning in Tübingen in 2001. The cluster's second spokesperson, Professor Philipp Berens, is also an alumnus of Schölkopf's department and has close ties to the MPI-IS. The institute's participation in the other Tübingen cluster **"Image-Guided and Functionally Instructed Tumor Therapies"**, is based on a long-term cooperation in the application of machine learning methods in medical imaging.

Up until 2018, the Max Planck Institute for Intelligent Systems was already involved in the previous version of the SimTech Cluster of Excellence at the University of Stuttgart, as well as the now-closed Cluster of Excellence on integrative neuroscience at the University of Tübingen.

Cambridge Tübingen Ph.D. program in Machine Learning The Empirical Inference Department and the Machine Learning Group of the University of Cambridge are among the world-leading centers of research in machine learning. Launched in 2014, the Cambridge Tübingen Ph.D. fellowship in Machine Learning is a collaborative program in which scientists at both institutions jointly supervise a small group of elite doctoral students. Each year, about two to three Ph.D. fellows are jointly selected via a symposium, and ten Ph.D. students are currently enrolled in the program. Students spend at least one year at each institution, and they benefit from the excellent research environment that both institutions provide. Successful graduates will receive their doctoral degrees from the University of Cambridge.

Carnegie Mellon University / MPI-IS Collaborative Ph.D. program In 2018, the Max Planck Institute for Intelligent Systems and Carnegie Mellon University (CMU) in Pittsburgh, USA, have initiated a joint Ph.D. program, aiming to strengthen the ties between these two leading research institutions in the field of intelligent systems. The CMU/MPI-IS collaborative Ph.D. program was initiated by Metin Sitti, director of the Physical Intelligence Department. Students accepted to participate in this joint Ph.D. program receive top education and training in robotics at CMU, which is one of the world's leading universities in this field. Students begin their research with a professor at CMU for 1.5 to 2 years and continue their research under the supervision of a director or group leader at the MPI-IS for at least another 2 years. Successful graduates will eventually receive their Ph.D. degree from CMU.

Max Planck Centers Max Planck Centers are a central element of the Max Planck Society's internationalisation strategy. In addition to the Max Planck ETH Center for Learning Systems (Section 1.10), the institute has been participating in the Max Planck EPFL Center for Molecular Nanoscience and Technology together with the MPI for Solid State Research (Center director: Klaus Kern). The institute will be involved in two new Max Planck Centers that will follow in 2022. One will be founded together with the University of Toronto and the (MPI for Microstructure Physics in Halle (Saale) (Center director: Joyce Poon), and one will be founded together with the Queens University, Australia, and with the MPI of Colloids and Interfaces in Potsdam (Center director: Peter Fratzl). For MPI-IS, the Physical Intelligence Department is involved in both new Max Planck Centers.

Max Planck Fraunhofer cooperation Within the framework of the national Pact for Research and Innovation, the Max Planck Society and the Fraunhofer Society intend to continue and intensify their cooperation across research areas and disciplines. With Fraunhofer's focus on application, this collaboration is of particular interest to the Max Planck Society. The aim of such a venture is to bring to application the knowledge resulting from collaborative efforts, thereby making a direct contribution to the development and impact of new technologies. The institute is currently participating in the project **Acoustic holograms**, which is a cooperation between the Micro, Nano, and Molecular Systems group, the Empirical Inference Department, and the Fraunhofer Institute for Biomedical Engineering in St. Ingbert and Sulzbach.

Tübingen Research Campus The University of Tübingen and the other research institutes in Tübingen have joined forces to create the Tübingen Research Campus (TRC). Together, these partners work on common research focus areas, keeping science made in Tübingen at the forefront of academic endeavor. They cooperate on specific research projects, through shared facilities, in nurturing emerging academics, and in welcoming scientists from all over the world to Tübingen.

1.11.2 University Professorships

The close collaboration between researchers at the Max Planck Institute for Intelligent Systems and universities world-wide is also reflected in professorships held by the current directors and independent research group leaders of the institute.

Michael J. Black is an Honorary Professor at the University of Tübingen in the department of Computer Science. He was also an Adjunct Professor (Research) at Brown University (Providence, USA) in the department of Computer Science until December 2020.

Siegfried Dietrich is Full Professor in the Faculty of Mathematics and Physics at the University of Stuttgart.

Peer Fischer is a Professor in the Faculty of Chemistry at the University of Stuttgart.

Katherine J. Kuchenbecker is an Adjunct Professor at the University of Pennsylvania (Philadelphia, USA) in the department of Mechanical Engineering and Applied Mechanics. In 2021, she was nominated as Honorary Professor at the University Stuttgart.

Ludovic Righetti is an Associate Professor in the Electrical and Computer Engineering Department and in the Mechanical and Aerospace Engineering Department at the Tandon School of Engineering of New York University (New York, USA).

Bernhard Schölkopf is an Honorary Professor at the Technical University Berlin in the department of Computer Science. He is also an Honorary Professor at the University of Tübingen in the department of Mathematics and Physics. Since January 1, 2019, he is an Affiliated Professor at ETH Zürich in the Computer Science department.

Gisela Schütz is Honorary Professor in the Faculty of Mathematics and Physics at the University of Stuttgart.

Metin Sitti has been an Honorary Professor within SimTech at the University of Stuttgart since 2017. He is an Adjunct Professor at Carnegie Mellon University (Pittsburgh, USA) in the department of Mechanical Engineering. Since October 2018, he has also been a Professor in both the Medical School and the Engineering School at Koç University (Istanbul, Turkey) In 2020 he was appointed as Affiliated Professor in the Institute for Biomedical Engineering at ETH Zurich (Switzerland).

Sebastian Trimpe is Full Professor in the faculty of Mechanical Engineering at RWTH Aachen University.

Max Planck Fellows The Max Planck Fellow program of the Max Planck Society aims to promote cooperation between outstanding university professors and Max Planck researchers. By strengthening ties with universities, the program fosters cutting-edge research on both sides. During their initial five-year term, which can be extended, Max Planck Fellows typically set up a small group at the host institute, funded by an annual budget of 100,000 euros that is provided jointly by the hosting institute and the Max Planck Society. Since July 2021, the institute hosts one Max Planck Fellow group in Tübingen, headed by Professor Ulrike von Luxburg (University of Tübingen). The runtime of the Max Planck Fellow group in Stuttgart, which was headed by Professor Marc Toussaint ended on June 30, 2021. Four new Max Planck Fellowships at the institute held by Professors of ETH Zurich were established in 2021 within the framework of the Max Planck ETH Center for Learning Systems.

1.11.3 Industry Partnerships

Several companies are partnering with and supporting research at the MPI for Intelligent Systems, including:

Cyber Valley The consortium's industry core partners Amazon, BMW, Bosch, Daimler, IAV, Porsche, and ZF Friedrichshafen are supporting the Cyber Valley cooperation with several million euros in the period from 2018 to 2022. The majority of this funding is made available to basic research projects at the MPI for Intelligent Systems and at the partner universities via a competitive procedure within the framework of the Cyber Valley Research Fund. These research funds are used to finance research by doctoral and postdoctoral students.

Amazon Since 2017 Amazon supports basic research at the institute through their Amazon Research Awards program. Two directors from the Max Planck Institute for Intelligent Systems, Bernhard Schölkopf and Michael J. Black, have been appointed Amazon Distinguished Scholars. In December of 2021, the Max Planck Society and Amazon have closed a collaboration framework agreement that will support research projects and PhD fellowships in areas related to machine learning, causal inference, robotics, and computer vision.

Bionaut Labs US-based start-up company Bionaut Labs has been supporting research projects at MPI-IS in the area of medical microrobots.

Google The Max Planck Society and Google closed a framework agreement in 2017 under which two research projects at the MPI for Intelligent Systems in the field of machine learning were funded since then. Moreover, in the reporting period, two MPI-IS PhD students were awarded a Google PhD fellowship via a competitive process.

IAV Cyber Valley partner company IAV supported a joint research project in the field of intelligent control systems.

Intel In 2017, Intel founded the "Network on Intelligent Systems (NIS)" in 2017 with several MPI-IS members as network partners. NIS supports leading academic research and collaboration in robotics, computer vision, motor control, and machine learning, and provided support for basic research projects at the institute.

Microsoft During the reporting period, Microsoft Research has supported four PhD research studentships in the field of computer vision at the institute.

NVIDIA Since 2017, NVIDIA supports research in the field of Computer Vision at the MPI for Intelligent Systems with financial contributions and state-of-the-art GPU hardware through an NVIDIA AI Lab (NVAIL) grant.

Machine Learning Summer Schools Several industry partners have sponsored the 2017 and 2020 editions of the established Machine Learning Summer School program organized buy our institute. 2017: ZF Friedrichshafen, Daimler, Bosch, Kaspersky, Google, and Yandex; 2020: Bloomberg, Google, Amazon, and Bosch.)

In addition, researchers at MPI- IS collaborate with researchers from other international companies such as DeepMind, Facebook, and others. In all cases, cooperation with an industrial partner is subject to clear rules to protect research freedom and intellectual property rights.

1.11.4 Collaboration within the Max Planck Society

The Max Planck Institute for Intelligent Systems has close collaborations, both structural and scientific, with several other Max Planck Institutes, including the following highlights. In addition, institute directors and members participate on all levels in Max Planck wide networks, strategy commissions or hiring committees.

MPI for Biological Cybernetics In addition to collaboration on campus matters, our institute has traditionally also shared close scientific links with the MPI for Biological Cybernetics, where Bernhard Schölkopf began his career as a Max Planck director. With its scientific reorientation in 2018, close research connections between the MPI for Biological Cybernetics and our institute have been emerging. Peter Dayan (director), Li Zhaoping (Max Planck Fellow), and Eric Schulz (group leader) are involved in several of our local and international cooperation activities. Moreover, both institutes have recently launched a joint international internship program that aims to boost the careers of talented students who experience significant (often financial) difficulties in their pursuit of higher education.

MPI for Developmental Biology **(as of January 2022: MPI for Biology Tübingen)** In addition to collaboration on campus matters, scientific collaborations exist in the field of genomics and bioinformatics, in particular with the departments of Ruth Ley and Detlef Weigel.

MPI for Solid State Research In addition to a joint building, we share a large set of scientific-technical services with the MPI for Solid State Research, including workshops, laboratories, and a library. Scientific collaborations in the intelligent systems research direction, exists, for instance with the department of Bettina Lotsch on the topic of biocompatible microswimmers.

Computer Science at Max Planck Several Max Planck Institutes working in the broad area of computer science joined forces in 2018 by founding the Max Planck Graduate Center for Computer and Information Science as a multisite doctoral program; its faculty come from the participating Max Planck Institutes and partnering universities. The other three participating Max Planck Institutes are the **MPI for Software Systems**, the **MPI for Informatics**, and the **MPI for Security and Privacy**. In addition, we are collaborating closely scientifically with these institutes, in particular with the groups of Manuel Gomez Rodriguez (MPI-SWS) and Bernt Schiele (MPI-INF), who is also Senior Fellow of the Max Planck ETH Center for Learning Systems.

Max Planck Centers As described above, the institute collaborates with the **MPI for Microstructure Physics** and **MPI of Colloids and Interfaces** through two new Max Planck Centers.

ELLIS Currently six Max Planck Institutes are involved in the European Laboratory for Learning and Intelligent Systems, thereby forming a network of AI institutes inside the Max Planck Society (MPI for Biogeochemistry, MPI for Biological Cybernetics, MPI for Informatics, MPI for Intelligent Systems, MPI for the Science of Light, MPI for Software Systems.)

BiGmax This initiative of the Max Planck Society and MaxNet centers on Big-Data-Driven Materials Science. Eleven institutes of the Max Planck Society, among them the MPI for Intelligent Systems, combine their know- how in data-driven material science. The aim is a better use of the possibilities associated with analyzing large amounts of data.

Max Planck Quantum Alliance Several Max Planck Institutes have joined a network, the "Max Planck Quantum Alliance", to coordinate their efforts in the domain of Quantum Science and Technology. MPI-IS is represented within this network through the Empirical Inference Department.

2 EMPIRICAL INFERENCE

2.1 Research Overview

The problems studied in the department can be subsumed under the heading of *empirical inference*, i.e., inference performed on the basis of empirical data. Empirical inference includes statistical learning and the inference of causal structures from data, leading to models that provide insight into the underlying mechanisms and make predictions about the effect of interventions. Likewise, the type of empirical data can vary, ranging from biological measurements (e.g., in neuroscience) to astronomical observations. We are conducting theoretical, algorithmic, and experimental studies in empirical inference.

The department was started around statistical learning theory and kernel methods. It has since broadened its set of inference tools to include probabilistic methods and a strong focus on issues of causality. In terms of the inference tasks being studied, we have moved towards tasks that go beyond the well-studied problem of supervised learning, such as semi-supervised learning or transfer learning. We analyze challenging datasets from biology, astronomy, and other domains. No matter whether applications are done in the department or in collaboration with external partners, considering a whole range of applications helps us study principles and methods of inference, rather than inference applied to one specific problem domain.

The most competitive publication venues in empirical inference are NeurIPS (Neural Information Processing Systems), ICML (International Conference on Machine Learning), ICLR (International Conference on Learning Representations), UAI (Uncertainty in Artificial Intelligence), and for theoretical work, COLT (Conference on Learning Theory). Our work has earned us a number of awards, including best paper prizes at most major conferences in the field (NeurIPS, ICML, UAI, COLT, ALT, CVPR, ECCV, ISMB, IROS, KDD). Recent awards include IEEE SMC 2016, ECML-PKDD 2016, an honorable mention at ICML 2017, the test-of-time award for Olivier Bousquet at NeurIPS 2018, received for work he started while he was a member of our department, the best paper award at ICML 2019, and a best student paper award at R:SS 2021.

Theoretical studies, algorithms, and applications often go hand in hand. A specific application may lead to a customized algorithm that turns out to be of independent theoretical interest.

Such serendipity is a desired side effect caused by interaction across groups and research areas, for instance, during our departmental talks (one long talk and two short talks per week). It concerns cross-fertilization of methodology (e.g., kernel independence measures used in causal inference), the transfer of algorithmic developments or theoretical insights to application domains (e.g., causal inference in neuroscience or astronomy), or the combination of different application areas (e.g., using methods of computational photography for magnetic resonance imaging). The linear organization cannot represent all these connections. Below, we have opted for a structure that devotes individual sections to some main application areas and comprises methodological sections on kernel methods, causal inference, probabilistic inference, and statistical learning theory. In addition, one-page descriptions of a selection of projects are provided below.

Statistical Learning Theory

The goal of statistical learning theory is to assess to what extent algorithms learning from data can be successful in principle. The approach is to assume that the training data have been generated by an unknown random source and to develop mathematical tools to analyze the performance of a learning algorithm in statistical terms: for example, by bounding prediction errors ("generalization bounds") or by analyzing large sample behavior and convergence of algorithms on random input ("consistency").

The department has made various contributions to this area, especially in areas of machine learning, where statistical learning theory is less well developed. These include settings like active [545] and transfer learning, privacy preserving machine learning, as well as unsupervised generative modeling.

In recent years, significant progress has been made in the field of unsupervised (deep) generative modeling with generative adversarial networks (GANs), variational autoencoders (VAEs), and other deep neural network based architectures, significantly improving the state of the art in the quality of samples, especially in the domain of natural images. Traditionally the training objectives in VAEs and GANs have been based on f-divergences. Starting from Kantorovich's primal formulation of the optimal transport problem, we showed that it can be equivalently written in terms of probabilistic encoders, which are constrained to match the latent posterior and prior distributions [606]. This leads to a new training procedure of latent variable models called Wasserstain auto-encoders (WAEs) [481]. Another theoretical study of generative modeling led us to propose the AdaGAN, a boosting approach to greedily build mixtures of generative models (e.g., GANs or VAEs) by solving, at each step, an optimization problem that results in the best additional model to reduce the discrepancy between the current mixture model and the target [521].

Pioneered by our lab, kernel mean embedding (KME) of distributions plays an important role in many tasks of machine learning and statistics, including independence testing, density estimation, and more [208]. Inspired by the James-Stein estimator, we introduced a type of KME shrinkage estimator and showed that it can converge faster than the standard KME estimator [244]. We have studied the optimality of KME estimators in the minimax sense in [211] and shown that the convergence rate for the KME, and other methods published in the literature, is optimal and cannot be improved. In [539] we study the minimax optimal estimation of the maximum mean discrepancy (MMD) and its properties which have been linked to three fundamental concepts: universal, characteristic, and strictly positive definite kernels. Building on the analyses in [193], [601], we propose a three-sample test for comparing the relative fit of two models, based solely on their samples [461], and further extend our results to derive a nonparametric goodness-of-fit test for conditional density models, one of the few tests of its kind [394].

Kernel Methods

Learning algorithms based on kernel methods have enjoyed considerable success in a wide range of supervised learning tasks such as regression and classification. One reason for the popularity of these approaches is that they solve difficult nonparametric problems by mapping data points into high dimensional spaces of features, specifically reproducing kernel Hilbert spaces (RKHS), in which

linear algorithms can be brought to bear, leading to solutions taking the form of kernel expansions [208].

Building on this, we develop kernel methods that allow differentially private learning, as well as determining the goodness of fit of a model. We also address the problem of measuring the relative goodness of fit of two models, with runtime complexity linear in the sample size [461]. Inspired by the selective inference framework, we propose an approach for kernel-based hypothesis testing that enables learning the hyperparameters and testing on the full sample without data splitting [356].

Privacy-preserving machine learning algorithms aim to come up with database release mechanisms that allow third parties to construct consistent estimators of population statistics while ensuring that the privacy of each individual contributing to the database is protected. In [488], we develop privacy-preserving algorithms based on kernel mean embeddings, allowing us to release a database while guaranteeing the privacy of the database records.

The expressiveness of the KME makes it suitable as a tool to evaluate the non-trivial effects of a policy intervention or a counterfactual change in certain background conditions. We introduce a Hilbert space representation of counterfactual distributions called a counterfactual mean embedding (CME) that can capture higher-order treatment effects beyond the mean [116]. We extend this idea to conditional treatment effects and propose the conditional distributional treatment effect (CoDiTE), which is designed to encode a treatment's distributional aspects, and heterogeneity [306]. Kernel methods are also applicable in econometrics, with estimation and inference methods based on a continuum of moment restrictions, as we demonstrated in [393], with applications in instrumental variable (IV) regression [353] and proximal causal learning [289].

Optimization lies at the heart of most machine learning algorithms, and we have studied the convergence property of coordinate descent as well as Frank-Wolfe optimization algorithms [515],[499]. A connection between matching pursuit and Frank-Wolfe optimization is explored in [476]. Going beyond first-order methods, in [329], we prove the *exact equivalence* (strong duality) between the distributionally robust optimization (DRO) formulation of learning objectives and dual programs that can be elegantly solved by kernel-based learning algorithms. Relevant to our previous work in statistical learning theory, the resulting *Kernel DRO* algorithm can certify a large set of distribution shifts characterized using MMD.

In the emerging field of quantum machine learning, kernel methods play a central role. Our contributions to this field include the analysis of quantum mean embeddings of probability distributions [156], and a sober look at where quantum kernels might be beneficial [265].

Causal Inference

Statistical dependences underlie machine learning, and their detection in large-scale IID settings has led to impressive results in a range of domains. However, in many situations, we would prefer a causal model to a purely predictive one; e.g., a model that might tell us that a specific variable – say, whether or not a person smokes – is not just statistically associated with a disease, but causal for it.

Pearl's graphical approach to causal modeling generalizes Reichenbach's common cause principle and specifies observable statistical independences a causal structure should entail.

This "graphical models" approach to causal inference has certain weaknesses that we try to address in our work: it only can infer causal graphs up to Markov equivalence, it does not address the hardness of conditional independence testing, it does not worry about the complexity of the underlying functional regularities that generate statistical dependencies in the first place, and it ignores the problem of how to infer causal variables from raw data. Our work in this field is characterized by pursuing four aspects:

1. We often work in terms of structural causal models (SCMs), i.e., we do not take statistical dependences as primary, but rather study mechanistic models which give rise to such dependences.

SCMs do not only allow us to model observational distributions; one can also use them to model what happens under interventions (e.g., gene knockouts or randomized studies).

Under suitable model assumptions like additive independent noise, SCMs admit novel techniques of noise removal via so-called half-sibling regression [246], [235], [90], reveal the arrow of time [544],[233], and permit the design of methods for causal recourse [331],[368].

2. The crucial assumption of the graphical approach to causality is the statistical independence of all SCM noise terms. Intuitively, as the noises propagate through a graph, they pick up dependences due to the graph structure; hence the assumption of initial independence of the noise terms allows us to tease out properties of that structure. We believe, however, that much can be gained by considering a more general *independent mechanism assumption* related to notions of invariance and autonomy of causal mechanisms. Here, the idea is that causal mechanisms are autonomous entities of the world that (in the generic case) do not depend on or influence each other, and changing (or intervening on) one of them often leaves the remaining ones invariant [325],[309],[107].

3. This leads to the third characteristic aspect of our work on causality. Wherever possible, we attempt to establish connections to machine learning, and indeed we believe that some of the hardest problems of machine learning (such as those of domain adaptation and transfer learning) are best addressed using causal modeling. To this end, one may assume, for instance, that structural equations remain constant across data sets and only the noise distributions change [82], that some of the causal conditionals in a causal Bayesian network change, while others remain constant [185], or that they change independently [508], which results in new approaches to domain adaptation [548].

In the context of pattern recognition, learning causal models comprising independent mechanisms helps in transferring information across substantially different data sets [471]. Theoretical work shows that the independence of causal mechanisms can be formalized via group symmetry [484].

Our lab has firmly placed causal inference on the agenda of the machine learning community, contributing a recent award-winning textbook [82], various implications for machine learning, e.g., in deep learning [471], reinforcement learning [462],[305],[271], semi-supervised learning [375], and societal aspects of AI, including fairness [500] and interpretability/accountability/recourse [331],[368].

Causality is also beginning to contribute to a range of applications, e.g., in neuroscience [242], psychophysics [411],[136], epidemiology [354], climate science [161], or natural language processing [270]. A particular highlight was astronomy, where our half-sibling regression confounder removal technique [235],[246] led to the discovery of 21 new exoplanets. For one of them, K2-18b, astronomers in 2019 found traces of water in the atmosphere — the first such discovery for an exoplanet in the habitable zone, i.e., allowing for liquid water (see http://people.tuebingen.mpg.de/bs/K2-18b.html).

4. Traditional causal discovery assumes that the symbols or observables (modeled as random variables) are given a priori (much like in classical AI), and connected by a causal directed acyclic graph. In contrast, real-world observations (e.g., objects in images) are not necessarily structured into those symbols to begin with. The task of identifying latent variables that admit causal models is challenging, but it aligns with the general goal of modern machine learning to learn meaningful representations for data, where 'meaningful' can, for instance, mean interpretable, robust, or transferable [119]. We have argued for the development of *causal representation learning* and are pursuing a number of approaches to help build this field. We have formulated key assumptions, including (1) independent mechanisms and (2) sparse mechanism shift in a position paper in the Proceedings of the IEEE [107], and are assaying ideas to exploit these assumptions for the purpose of learning causal representations. This includes a causal analysis of self-supervised learning methods for automatically separating style and content [260], a novel approach for nonlinear ICA using independent mechanisms [259], as well as a range of other approaches [303],[370],[602],[320],[302],[322],[319].

We have proposed a notion of causal disentanglement [107], generalizing statistical notions [365],[383]. The latter inherit certain shortcomings from the non-identifiability of nonlinear ICA, as pointed out in our paper winning the best paper prize at ICML 2019 [423], cf. also [418].

Causality touches statistics, econometrics, and philosophy, and it constitutes one of the most exciting fields for conceptual basic research in machine learning today. Going forward, we expect that it will be instrumental in taking representation learning to the next level, moving beyond the mere representation of statistical dependences towards models that support intervention and planning, and thus Konrad Lorenz' notion of *thinking* as *acting in an imagined space*.

Probabilistic Inference

The probabilistic formulation of inference is one of the main research streams within machine learning. One of our main themes in this field has been nonparametric inference on function spaces using Gaussian process models [536],[458], [537]. Our methods allow finding the best kernel bandwidth hyperparameter efficiently and are especially well-suited for online learning. Bayesian approaches are also increasingly studied in deep learning [256].

A crucial bottleneck in Bayesian models is the marginalization of latent variables. This can be computationally demanding, so approximate inference routines reducing computational complexity are crucial. In [483],[459], we study the convergence properties of this approach, establishing connections to the classic Frank-Wolfe algorithm. The analyses yield novel theoretical insights regarding the sufficient conditions for convergence, explicit rates, and algorithmic simplifications. While probabilistic inference can indeed be computationally demanding, perhaps surprisingly, probabilistic considerations in *numerical* algorithms can also help speed up computations – including those of high-level probabilistic inference itself [304].

A theoretical study pertaining to probabilistic programming considers the problem of representing the distribution of f(X) for a random variable X [540]. We use kernel mean embedding methods to construct consistent estimators of the mean embedding of f(X). The method is applicable to arbitrary data types on which suitable kernels can be defined. It thus allows us to generalize (to the probabilistic case) functions in computer programming, which are originally only defined on deterministic data types.

We have also studied techniques for representation learning based on differential geometry. We developed fundamental methods relying mainly on stochastic generative models to learn and utilize the underlying geometric structure of the data manifold [431], [366], [313], [304], [295].

Moreover, we have developed probabilistic methods to solve inverse problems in science. In one such study [84] we accurately infer black-hole parameters (such as masses, spins and sky position) from gravitational wave measurements more than 1000 times faster than standard methods, enabling real-time analyses which is crucial for timely electromagnetic follow-up observations.

Computational Imaging

Our work in computational imaging has gradually shifted focus from pure algorithmic approaches towards combinations with physical setups. In both cases, we aim to computationally enable or enhance imaging by data-driven computation.

To recover a high-resolution image from a single low-resolution input, we proposed a novel method for automated texture synthesis in combination with a perceptual loss focusing on creating realistic textures rather than optimizing for a pixel-accurate reproduction of ground truth images during training [523]. By using feed-forward fully convolutional neural networks in an adversarial training setting, we achieve a significant boost in image quality even at high magnification ratios. We also developed an approach to estimate modulation transfer functions of optical lenses [478].

Together with the department for High-Field Magnetic Resonance at the Max-Planck Institute for Biological Cybernetics, we enhanced the quality of MR images [502],[190]. Additionally, we have worked on automatic MRI sequence generation [105], hardware optimization [139], and acceleration of acquisition processes [146].

We have also started to collaborate in the fields of acoustic holography and optical computation with Peer Fischer's lab at our Stuttgart site (cf. page 296). By solving suitable inverse problems using optimization methods, we design devices to generate custom acoustic wave intensity patterns applicable in medicine and one-shot manufacturing. In optical computation, we carry out certain computations using light, with the ultimate goal of designing faster and more energy-efficient machine learning systems. The challenge here lies in the implementation of suitable nonlinearities and in the design of architectures that lend themselves well to what can be implemented using optical devices.

Robot Learning

Robots need to possess a variety of physical abilities and skills to function in complex environments. Programming such skills is a labor- and time-intensive task that often lead to brittle solutions and requiring considerable expert knowledge. We study learning-based approaches instead and use robot table tennis as a testbed. Tracking dynamic movements with inaccurate models is essential for such a task. To achieve accurate tracking, we have proposed a series of adaptive Iterative Learning Control (ILC) algorithms [165]. In real robot experiments on a Barrett WAM, we have studied trajectory generation for table tennis strikes [189], and how to learn such primitives from demonstrations [62].

Moreover, we have built a musculoskeletal robot system, which presents interesting challenges making it suitable for learning. Muscular systems are hard to control using classical methods but allow safe exploration of highly-accelerated motions directly on the real robot, making them suitable candidates to try and learn human-like performance on complex tasks [71]. We have leveraged this to learn precision-demanding table tennis with imprecise muscular robots [2].

Dexterous object manipulation remains an open problem in robotics due to the large variety of possible changes and outcomes in this task. We address this problem by designing benchmarks and datasets as well as a low-cost robotic platform, called TriFinger [22]. The open-source TriFinger platform enables researchers around the world to either easily rebuild real robot benchmarks in their own labs or to remotely submit code that is executed automatically on eight platforms hosted at MPI-IS [600] (allowing robotics research to continue during pandemic lockdown periods). We organized a robotics challenge (https://real-robot-challenge.com/) and conducted research using these platforms, especially on transfer learning [26].

Machine Learning in Neuroscience

The neurosciences present some of the steepest challenges to machine learning. Almost always, there is a high-dimensional input structure – particularly relative to the number of examples, since data points are often gathered at a high cost. Regularities are often subtle, the rest being made up of noise that may be of much larger magnitude (often composed largely of the manifestations of other neurophysiological processes, besides the ones of interest). In finding generalizable solutions, one usually has to contend with a high degree of variability, both between individuals and across time, leading to problems of covariate shift and non-stationarity.

We have designed machine learning techniques to assist with the interpretation of experimental brain data. Supervised and unsupervised learning tools were used to automatically identify activity patterns among large populations of recorded neurons [182],[112]. Causal relationships between neural processes is also of particular interest to neuroscientists, and the tools we develop for observational data have been used to uncover the interactions between brain regions during sleep [133]. Machine learning provided theoretical insight into biological learning by identifying key neural circuits underlying the reliable replay of memorized events [184].

A neuroscientific application area in which we have a long-standing interest is that of brain-computer interfacing (BCI). BCIs hold promise in restoring communication for locked-in patients in late stages of amyotrophic lateral sclerosis (ALS), however, the transfer of findings has been limited due to unclear cognitive abilities in late-stage ALS, inaccessible BCI control strategies, and a focus on laboratory experiments. We characterized how ALS affects neural and cognitive abilities in studies on self-referential processing [209] and changes in brain rhythms [178].

Based on these insights, we developed more accessible BCI control strategies for late-stage ALS patients [549],[231]. To translate this system from the laboratory into home use, we have pioneered a transfer learning approach for BCIs [239] and developed a novel brain-decoding feature for low-channel setups [210]. To evaluate the unsupervised use of this system across multiple days, we developed an open-source framework that couples an easy-to-use application with consumer-grade recording hardware [369]. These advances enable us to build high-performance, cognitive BCIs with off-the-shelf hardware for large-scale applications.

2.2 Selected Research Projects

Statistical Learning Theory

The goal of learning theory is to analyze statistical and computational properties of learning algorithms and to provide guarantees on their performance. The department has made various contributions in this area by providing analyses of algorithms in three important areas: 1) sample-efficient learning, 2) non-parametric distribution comparison, 3) generative modeling.

On **sample-efficient learning**, we provide a formal analysis of compressing a data sample so as to encode a set of functions consistent with the data [545]. In [543] we provide a novel analysis for a life-long learning setup. Unlike previous studies, our work more explicitly identifies conditions of task relatedness that enable sample-efficient learning. In [542] we show that active learning can provide label savings in non-parametric learning settings, in contrast to most previous works that address parametric learning.

Non-parametric distribution comparison Our focus in this area is on estimating the kernel mean embedding (KME) of distributions and its applications. Inspired by the classic James-Stein estimator, we introduced a kernel mean shrinkage estimator (KMSE) and proved that it can converge faster than the plug-in KME estimator [244]. Related to this, in [211], we study the optimality of KME estimators in the minimax sense, and show that the rate $O(n^{-1/2})$ can be achieved by the plug-in estimator of KME, KMSE, and other known estimators. We also study the minimax optimal estimation of the maximum mean discrepancy (MMD), defined as the RKHS distance between KMEs: $\mathrm{MMD}(P, Q) := \|\mu_P - \mu_Q\|$ [539].

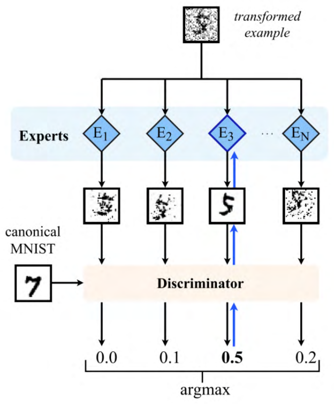
The properties of MMD are known to depend on the underlying kernel and have been linked to three fundamental concepts: universal, characteristic, and strictly positive definite kernels. In [193] we show that these concepts are essentially equivalent and give the first complete characterization of those kernels whose associated MMD metrizes the weak convergence of probability measures. We further derive necessary and sufficient conditions for MMD to metrize tight convergence to a fixed target distribution [601].

Building on these analyses, we propose a three-sample test for comparing relative fit of two models [461]. This generalizes standard non-parametric two-sample testing. In [394], we further extended our results to derive a nonparametric goodness-of-fit test for conditional density models, one of few tests of its kind.

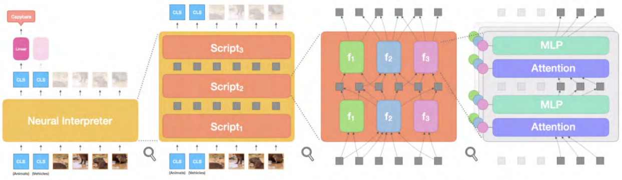
Generative modeling We have proposed a number of theoretically-grounded generative models based on generative adversarial networks (GANs) and variational autoencoders (VAEs). In [521] we study the training of mixtures of generative models from a theoretical perspective. We find a globally optimal closed form solution for performing greedy updates while approximating an unknown distribution with mixtures in any given f-divergence. While training objectives in VAEs and GANs are based on f-divergences, it has been argued that other divergences, in particular, optimal transport distances, may be better suited to the needs of generative modeling. In [606], starting from Kantorovich's primal formulation of the optimal transport problem, we show that it can be equivalently written in terms of probabilistic encoders, which are constrained to match the latent posterior and prior distributions. We then apply this result to train latent variable generative models [481]. When relaxed, the constrained optimization problem leads to a new regularized autoencoder algorithm which we call Wasserstein auto-encoders (WAEs). In [452] and [451] we focus on properties of the latent representations learned by WAEs and show that there are fundamental problems when training WAEs with deterministic encoders when the intrinsic dimensionality of the data is different from the latent space dimensionality. In [429], we propose a new generative procedure based on kernel mean matching to generate images, given a seed image set. This allows us to turn an unconditional GAN into a conditional generative procedure without the need to retrain.

More information: https://ei.is.mpg.de/project/statistical-learning-theory

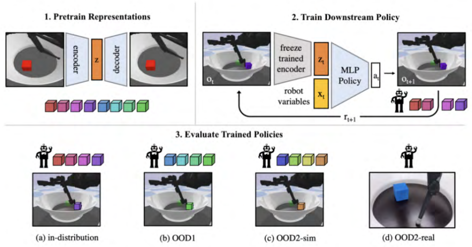
Neural Nets



One of our early models exploring connections between independent mechanisms and gradient based learning.



A recent attention-based model we proposed used independent mechanisms as a guiding principle.



We have conducted a number of advanced empirical studies to quantify the usefulness of disentangled representations.

Figure 2.1: Left: [471]. Right, top: [254]. Right, bottom: [267].

Over the past decade, the paradigm of deep learning has been successful not only in machine learning, but also in the broader scientific community. Substantial effort has gone into the development of deep neural networks, and we have contributed several notable advancements.

Generative modeling In [481],[396], we improve over variational autoencoders by designing more refined regularization mechanisms, thereby making significant progress towards addressing some of the problems constraining VAEs, e.g., poor sample quality and instable training. Besides VAEs, we have also contributed to the field of generative adversarial networks (GANs). In [521], we propose and study a boosting style meta-algorithm which builds upon various modern generative models (including GANs) to improve their quality. Further, in [429], we devise a way to constrain and control the kind of samples produced by a GAN generator. Beyond generative modelling, we have contributed to developing a better understanding of how neural networks work, for instance by exploring similarities and differences between deep neural networks and the human visual system [204],[448].

Causal Learning Our research has also pioneered synergies between causality and deep learning. Foundational to these advancements is the principle of independent causal mechanisms (ICM). These mechanisms may interact in interesting and non-trivial ways, but their inner workings are otherwise independent of each other. In [471], we marry the fundamental notion of ICM with the empirically successful framework of gradient-based learning of neural networks.

In one line of work [309],[319],[319]b,[301], we show how attention mechanisms may serve as a vehicle for incorporating the principle of independent mechanisms into neural networks in a scalable manner. This has lead to impactful architectures that are robust out-of-distribution and can adapt more sample-efficiently to new data. In another line of work [423],[303],[267] we probe disentangled representations using large scale empirical studies that shed light onto the components required to make them work in practice.

Finally, we have hosted various challenges and curated datasets [26],[24] valuable to the deep learning community, and we have pioneered deep learning methods for hard real-world problems such as gravitational wave parameter inference [84].

More information: https://ei.is.mpg.de/project/neural-nets

Kernel Methods

Kernel methods offer a mathematically elegant toolkit to tackle machine learning problems ranging from probabilistic inference to deep learning. Recently, a subfield of kernel methods known as *Hilbert space embedding of distributions* has grown in popularity [208], thanks to foundational work done in our department during the last 10+ years. For a probability distribution $\mathbb{P}$ over a measurable space $\mathcal{X}$, the kernel mean embedding of $\mathbb{P}$ is defined as the mapping $\mu : \mathbb{P} \mapsto \int k(x, \cdot) \, \mathrm{d}\mathbb{P}(x)$ where $k : \mathcal{X} \times \mathcal{X} \to \mathbb{R}$ is a positive definite kernel function. Its applications include, but are not limited to, comparing real-world distributions, independence testing, differentially private learning, and determining the goodness-of-fit of a model. We have a history of contributions to the state-of-the-art in this area. We summarize some recent contributions below.

Based on kernel mean embedding, we developed privacy-preserving algorithms that allow to release a dataset in a differentially private manner [488]. In applications such as probabilistic programming, transforming a base random variable X with a function f forms a basic building block to manipulate a probabilistic model. It then becomes necessary to characterize the distribution of $f(X)$. In [540], we show that for any continuous function f, consistent estimators of the mean embedding of X lead to consistent estimators of the mean embedding of $f(X)$. For Matèrn kernels and sufficiently smooth functions, we provide rates of convergence.

In [192], we generalized the two-variable Hilbert-Schmidt independence criterion (HSIC) to a d-variable counterpart (dHSIC) that allows for testing joint independence of d multivariate random variables. In [461], we addressed the problem of measuring the relative goodness-of-fit of two models using kernel mean embeddings. Given two candidate models, and a set of target observations, it produces a set of interpretable examples that indicate the regions in the data domain where one model fits better than the other. The proposed test has runtime complexity that is linear in the sample size. Inspired by the selective inference framework, we also proposed kernel-based two-sample tests that enable hyperparameter learning and testing on the full sample without data splitting [356].

In [352], we overcame long-standing theoretical limitations of the operator-based conditional mean embedding (CME) by viewing it as a Bochner conditional expectation. As by-products, we present the maximum conditional mean discrepancy (MCMD) and Hilbert-Schmidt conditional independence criterion (HSCIC) as natural extensions of the MMD and the HSIC to conditional distributions. In treatment effect analysis we were thus able to account for distributional aspects of treatment effects while taking into account heterogeneity across the population [306]. In [382], we introduced a conditional density estimator based on the CME to capture multivariate, multimodal output densities with competitive performance compared to recent neural conditional density models and Gaussian processes. We applied CME to model the Perron-Frobenius or Koopman operator, essential in the global analysis of complex dynamical systems [157]. Lastly, we ventured into econometrics by providing a novel representation of conditional moment restriction called maximum moment restriction (MMR), enabling a new family of kernel-based specification tests [393].

In recent years, connections between quantum computing and machine learning have attracted attention [168]. Building upon our tools, we defined quantum mean embeddings as a natural extension of kernel mean embeddings to the quantum setting with appealing theoretical properties [156]. Moreover, we investigated the limitations of learning with quantum kernels and showed that kernels defined on lower-dimensional subspaces may require exponentially many measurements to evaluate [265], reminiscent of the Barren plateau phenomenon in quantum neural networks (QNN). For QNNs, we showed how to adaptively allocate measurements in order to improve the efficiency of gradient-based optimization [137].

More information: https://ei.is.mpg.de/project/kernel-methods

Treatment Effects

Predictive models enabled by modern machine learning methods can help address substantive questions in education, public policy, and social programs, but making reliable predictions in these domains requires accurate modeling of complex outcome distributions as well as accounting for unobserved confounders.

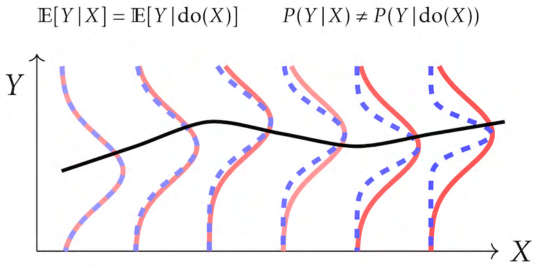


Figure 2.2: A comparison between the observational distribution $P(Y \mid X)$ (red solid line) and interventional distribution $P(Y \mid \mathrm{do}(X))$ (blue dotted line) with the same conditional means, but different higher-order moments (conditional variances).

Distributional treatment effect To model complex outcome distributions, we proposed a *counterfactual mean embedding* (CME) [116] as a Hilbert space representation of the counterfactual distribution $P_{Y\langle 1|0\rangle}(y) := \int P_{Y_1|X_1}(y \mid x)\, dP_{X_0}(x)$. The counterfactual $P_{Y\langle 1|0\rangle}$ represents the outcome of hypothetical change which by definition is not observable, e.g., the birth weight of a baby had the mothers abstained from smoking. Without parametric assumptions, we proposed consistent estimators $\hat{\mu}_{Y\langle 1|0\rangle}$ for the embedding $\mu_{Y\langle 1|0\rangle}$ based on samples from the observable distributions P_{X_0} and $P_{Y_1 X_1}$. We established consistency and convergence rate of $\hat{\mu}_{Y\langle 1|0\rangle}$ which requires weaker assumptions than the previous work. Thanks to our estimators, the CME can be estimated consistently from observable quantities. One of the important applications of our work is offline policy evaluation, which is relevant to program evaluation in economics. In [306], we extended this idea and proposed the *conditional distributional treatment effect* (CoDiTE), which, in contrast to the more common CATE, is designed to encode a treatment's distributional aspects and heterogeneity beyond the mean. We then proposed estimating the CoDiTEs based on the maximum mean discrepancy (MMD) and U-statistics using kernel conditional mean embeddings and kernel ridge U-statistic regression, respectively.

Instrumental variables To account for unobserved confounders, we have developed ML-based methods for instrumental variable (IV) regression. Suppose that X and Y denote treatment and outcome variables, e.g., education and level of income, whose functional relationship can be described by $Y = f(X) + \varepsilon$, $\mathbb{E}[\varepsilon] = 0$. The presence of unobserved confounders, e.g., socio-economic status, prevents us from learning f with the standard nonparametric regression because $\mathbb{E}[\varepsilon \mid X] \neq 0$, i.e., $\mathbb{E}[Y \mid \mathrm{do}(X)] \neq \mathbb{E}[Y \mid X]$. The idea of an instrumental variable (IV) regression is to leverage an instrument Z that (i) induces a variation in X (*relevance*), (ii) affects Y only through X (*exclusion restriction*), and (iii) is independent of the error term ϵ (*exchangeability*). In this case, f satisfies the Fredholm integral equation of the first kind: $\mathbb{E}[Y \mid Z] = \int f(X)\, dP(X|Z)$. Solving for f is an ill-posed inverse problem. In [353], we showed that this problem can be reformulated as a two-player game with a convex-concave utility function. When $\mathcal{F}$ and $\mathcal{U}$ are both RKHSes, the global equilibrium can be obtained in closed form. This reformulation also elucidates the kind of problems for which a game-theoretic perspective as a search for a Nash equilibrium can lead to simpler algorithms than the standard ones that solve the Fredholm integral equation directly. The work also sheds light on the duality between the two-stage and generalized method of moment-based approaches, as later pointed out in our work [289] that applies the methods we develop to the setting of proximal causal learning.

More information: https://ei.is.mpg.de/project/treatment-effects-instrumental-variables

Privacy

Much modern data is collected from devices enabling human-machine interactions. For instance, robot vacuum cleaners may have a built-in camera to navigate where to clean, but the camera can also capture scenes of people in the room. Similarly, user-facing artificial intelligence agents such as virtual assistants collect, store, and transmit potentially privacy-sensitive data. These data might be used to fit machine learning models to solve certain statistical tasks. Many recent papers indicate that fitted machine learning models can expose sensitive information from the dataset they were trained on.

For developing privacy-preserving machine learning methods, the first question we need to answer is how to define privacy and how to measure it. While there are various privacy notions developed in the field, *differential privacy* is currently the gold standard for privacy, due to its rigorous privacy guarantees. Intuitively, the definition states that the probability of any event does not change much when a single individual's data is modified, thereby limiting the amount of information that the algorithm reveals about any one individual.

Equipped with such a notion of privacy, the development of differentially private data analysis methods requires first to decide which quantity we want to guard. Depending on whether we want to share data, statistics, or model parameters, each will require developing different techniques. Below, we look into different modes of sharing.

Model sharing is probably the most popular way to achieve privacy in the current differential privacy literature. Model sharing often focuses on guarding model parameters by adding noise to them before releasing them. Generally, there are two ways of achieving private models. First, one could add noise to the objective function ("objective perturbation") such that the resulting estimates guarantee some level of privacy. Second, one could add noise to the output of an optimization routine ("output perturbation"). Often, objective perturbation techniques end up adding less noise than output perturbation techniques. However, to be able to analyze the relationship between the amount of noise that needs to be added to an objective function and the guaranteed privacy level of a corresponding estimate after optimizing the perturbed objective, it is unavoidable to make significant assumptions (e.g., strong convexity). Many learning problems in machine learning have non-convex objective functions, which limits the usefulness of the existing objective perturbation techniques. We worked on addressing the problem with non-convex objective functions in the context of deep learning [446], and published two articles on privatizing approximate posterior distributions via variational inference [134],[373].

Data sharing requires adding noise to the dataset itself before releasing it. Most of the existing data sharing frameworks are designed for particular data types (e.g., count data, low-dimensional data) or particular purposes (e.g., decision tree algorithms) only. We thus need algorithms to add noise in a way that is truthful to the statistical properties of the raw data while being independent of downstream tasks, for a better utility in various statistical analyses. We published a differentially private kernel method for this task, relying upon kernel mean embedding of datasets in reproducing kernel Hilbert spaces, which (for suitable kernels) retains all information about a distribution [488]. In further works we developed a privacy-preserving data generation framework using random Fourier features [316], and a recent framework for medical image data sharing by generating synthetic images [108].

Statistic sharing requires privatizing statistics computed on privacy-sensitive data. We established a statistic sharing framework in the context of kernel two-sample test [443].

We also worked on a project that intercepts between differential privacy and interoperability of a classifier [372], where we confirmed our hypothesis that model interpretability compromises privacy.

More information: https://ei.is.mpg.de/project/privacy

Probabilistic Inference

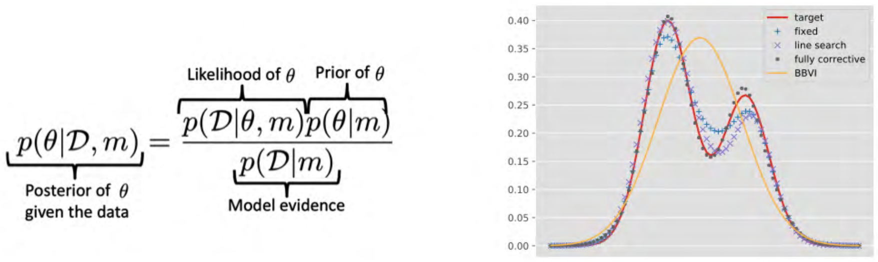


Figure 2.3: Left: Illustration of probabilistic inference. Right: Comparison between black box variational inference (BBVI) and three variants of our boosting BBVI method on a mixture of Gaussians [459].

The probabilistic formulation of inference conditions probability measures encoding prior assumptions by multiplying with a likelihood of the data given the generative process. It remains one of the main research streams within machine learning.

Nonparametric inference on function spaces Gaussian Process models allow for nonparametric inference in function spaces. They have a strong inductive bias specified by the kernel function between observations, which allows for data-efficient learning. One of our main themes in this field has been nonparametric inference on function spaces using Gaussian process models, with its main practical challenge for inference being the cubic complexity in terms of the number of training points.

We provided an analysis of two classes of approximations [536], and explored kernels that can account for invariances between data points [458]. To this end, we construct a kernel that explicitly takes these invariances into account by integrating over the orbits of general symmetry transformations. We provide a tractable inference scheme that generalises recent advances in Convolutional Gaussian Processes.

In work on the Mondrian kernel [537], we provide a new algorithm for approximating the Laplace kernel in any kernel method application (including in Gaussian processes) using random features. Attractive properties of the algorithm include that it allows finding the best kernel bandwidth hyperparameter efficiently and it is well-suited for online learning.

Variational Inference We studied the convergence properties of Boosting Variational inference from a modern optimization viewpoint [483]. We subsequently generalized this approach [459] by showing that boosting variational inference satisfies a relaxed smoothness assumption, leading to richer posterior approximations (see Fig. 2).

Inference on discrete graphical models An open challenge is to perform efficient inference in discrete graphical models. We showed that the popular Gumbel trick is just one method out of an entire family and that other methods can work better [503] (Best Paper Honourable Mention at ICML 2017). We developed a sampling-based Bayesian inference algorithm [173] for the infinite factorial finite state machine model.

Probabilistic programming languages aim to enable data scientists to express probabilistic models without needing to worry about the inference step. We presented an architectural design and a performant implementation of a probabilistic programming library [464]. We showed how to conceptualise inference as manipulating representations of probabilistic programs [465], and studied how to represent distributions of functions of random variables [540] with kernel mean embeddings.

More information: https://ei.is.mpg.de/project/probabilistic-inference

Probabilistic Algorithms

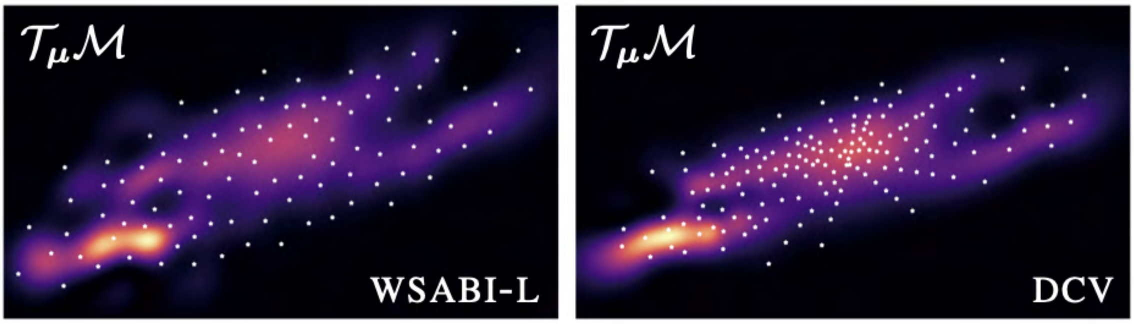


Figure 2.4: From [304]. Adaptive Bayesian quadrature can find highly informative evaluation nodes for integrands (left) that exhibit more structure than random (Monte Carlo) evaluations. In contrast to Monte Carlo, it can be adapted to application-specific computational considerations (such as the fact that additional evaluations are "free" along radii, right), to achieve additional gains.

Probabilistic inference is often thought of as elaborate and intricate - or to put it less charitably: cumbersome and expensive. Work performed in the reporting period shows that probabilistic concepts can, instead, be a *driver* of computational efficiency: Used to quantify sources of error in composite computations, they can guide the automated design of algorithms, yielding robust outputs and predictions.

Controlling computations and their precision When computations are expensive, it pays off to make them as informative as possible. Riemannian Statistics is an example for the chained computations increasingly common in machine learning: Tasks that are simple in Euclidean space, like Gaussian integrals, become challenging on manifolds, where every evaluation of the integrand involves a complicated simulation to compute geodesics. An ICML paper [304] showed that, by finding informative evaluations, adaptive Bayesian quadrature, which casts integration as inference from observations of the integrand, can offer significant gain in wallclock time over traditional Monte Carlo workhorses.

Fast post-hoc uncertainty in deep learning Another recent work addresses *the* most popular application of uncertainty quantification: Deep nets. Constructing approximate posteriors for deep learning is a long-standing problem. Most contemporary Bayesian deep learning methods aim for carefully crafted, high-quality output. As a result, they tend to be expensive and difficult to use. The classic Laplace approximation offers a more sober approach. It is essentially a second-order Taylor expansion of the empirical risk at the network's point estimate. While this puts some limits on fidelity, it has practical advantages: It leaves the point estimate in place, which practitioners spend considerable time tuning; and it can be constructed post-hoc, even for networks pre-trained by others. In a collaboration with partners in Tübingen, at the ETH, in Cambridge and at Deepmind, we developed the *Laplace* Library as a practical tool allowing practitioners easy and computationally cheap access to uncertainty on a comprehensive class of deep neural architectures [256]. The library has already found numerous users, showing the pressing need for uncertainty quantification in deep learning.

Finally, we have explored applications of Bayesian inference algorithms for scientific applications, e.g., to provide fast amortized inference of the parameters of gravitational wave models [84] and in biomedical applications [104].

More information: https://ei.is.mpg.de/project/probabilistic-algorithms

Astronomy

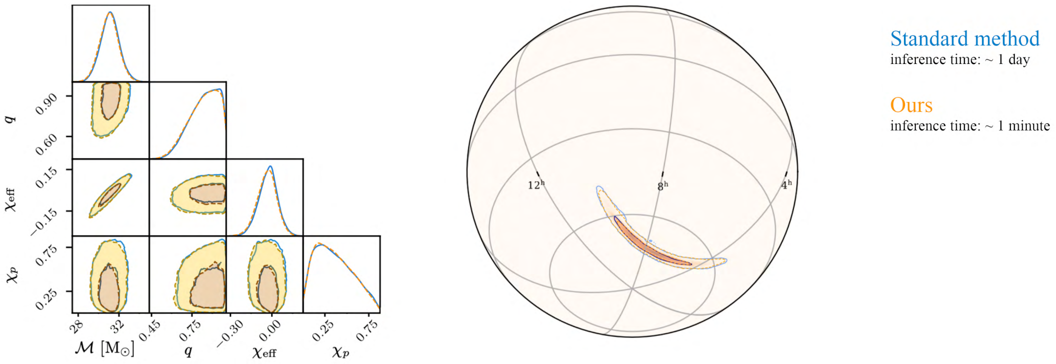


Figure 2.5: Posterior distribution over astrophysical binary black hole parameters for GW150914. Our method (orange) shows excellent agreement with LALInference (blue), while reducing inference times from days to a minute per event. Left panel: black-hole mass and spin parameters. Right panel: sky position of the gravitational wave. Contours represent 50% and 90% credible regions.

Exoplanet search is a thriving subfield of modern astrophysics, not least since the 2019 Nobel Prize in Physics recognized the first discovery of an extrasolar planet. Most of the 4500+ detections so far have used a method called transit photometry, where one observes the brightness of a star over time and searches for periodic "dips" in the light curves that occur when a planet passes in front of its host star and partly occludes it. These light curves are corrupted by systematic noise; however, since different stars are causally independent of each other (being light years apart) as well as of the instrument noise, we can denoise the signal of a single star by removing all information that the measurements of the other stars can explain. Our method, called half-sibling regression (HSR) [246],[235], has led to our discovery of 21 planets[1], including the celebrated K2-18b, the first exoplanet in the habitable zone where water vapor was detected in the atmosphere.

More recently, we have extended the HSR framework to direct imaging, an observation technique different from transit photometry, allowing studying the properties of a planet (e.g., atmospheric composition) in greater detail. Our method [345] is the first post-processing algorithm for high-contrast imaging data that can also incorporate the observing conditions of an observation into the denoising process, once again demonstrating the flexibility of the HSR method.

Gravitational wave science The Nobel Prize-winning detection of gravitational waves (GW) from a binary black hole merger in 2015 was a milestone in physics. However, despite the unprecedented sensitivity of the LIGO detectors, GW detection and analysis remain challenging. Working with the MPI in Potsdam, we have developed an efficient dilated convolutional neural net to identify GW signals from black hole mergers in measurements from the LIGO detectors [159]. Many recent applications of ML to GW detection build upon this work.

GWs encode properties of their astrophysical generators. We have developed an approach to infer such information in real time by training normalizing flows to represent the Bayesian posterior over black hole parameters [84]. Our method reduces inference times from days to a minute per event without sacrificing accuracy. It is further more flexible than conventional methods, and could thereby enable model free treatment of detector noise and routine use of more physically realistic waveform models. We thus expect it to become a leading approach to gravitational-wave parameter inference.

Other Our work on predictive control for periodic error correction [247] has been incorporated into PHD2 Guiding, a widely used autoguiding software in the astrophotography community.

More information: https://ei.is.mpg.de/project/astronomy

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[1] D. Foreman-Mackey, B. Montet, D. Hogg, T. Morton, D. Wang, et al. A systematic search for transiting planets in the K2 data. *The Astrophysical Journal* **806** (2), 2015.

Differential Geometry for Representation Learning

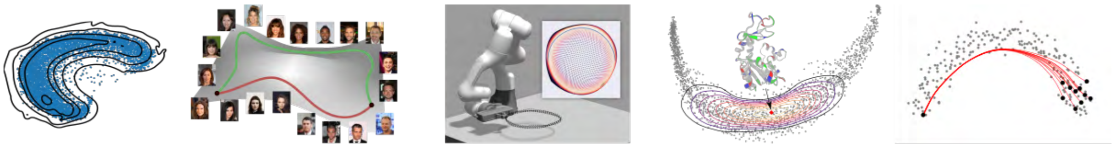


Figure 2.6: Left to right: We use differential geometry to provide a better prior for VAEs, to encode domain knowledge in generative models for improving interpretability and for robot motion skills. In addition, we develop computationally efficient methods for fitting statistical models and computing shortest paths on Riemannian data manifolds.

A common hypothesis in machine learning is that the data lie near a low dimensional manifold which is embedded in a high dimensional ambient space. This implies that shortest paths between points should respect the underlying geometric structure. In practice, we can capture the geometry of a data manifold through a Riemannian metric in the latent space of a stochastic generative model, relying on meaningful uncertainty estimation for the generative process. This enables us to compute identifiable distances, since the length of the shortest path remains invariant under re-parametrizations of the latent space. Consequently, we are able to study the learned latent representations beyond the classic Euclidean perspective. Our work is based on differential geometry and we develop computational methods accordingly.

Geometric priors in latent space Since the latent space can be characterized as non-Euclidean, we replace the standard Gaussian prior in Variational Auto-Encoders (VAEs) with a Riemannian Brownian motion prior, relying on an efficient inference scheme. In particular, our prior is the heat kernel of a Brownian motion process, where the normalization constant is trivial, and also we can easily generate samples and back-propagate gradients using the reparametrization trick [366].

Enriching the latent geometry The ambient space of a generative model is typically assumed to be Euclidean. Instead, we propose to consider it as a Riemannian manifold, which enables us to encode high-level domain knowledge through the associated metric. In this way, we are able to control the shortest paths and improve the interpretability of the learned representation. For instance, on the data manifold of human faces, we may influence the shortest path to prefer the smiling class while moving optimally on the manifold, by using an appropriate Riemannian metric in the ambient space [313].

Probabilistic numerics on manifolds In general, operations on Riemannian manifolds are computationally demanding, so we are interested in efficient approximate solutions. We use adaptive Bayesian quadrature to numerically compute integrals over normal laws on Riemannian manifolds. The basic idea is to combine prior knowledge with an active exploration scheme to reduce the number of required costly evaluations. In addition, we develop a fast and robust fixed-point iteration scheme for solving the system of ordinary differential equations (ODE), which gives the shortest path between two points. The advantage of our approach is that compared to standard solvers, we avoid the Jacobians of the ODE, which is ill-behaved for Riemannian manifolds learned from data [304],[431].

Robot motion skills In robotic applications, the model learns motion skills such that to function in unstructured enviroments, it should be able to generalize under dynamic changes of the environment. For example, if an obstacle is introduced during the action, the robot should avoid it, while performing the task that it is supposed to do. We assume that human demonstrations span a data manifold on which shortest paths constitute natural motion skills. A robot then is able to plan movements through the associated shortest paths in the latent space of a VAE. Additionally, we can simply replace the Euclidean metric of the ambient space with a suitable Riemannian metric to account for dynamic obstacle avoidance tasks *(R:SS '21 best student paper award)* [295].

More information: https://ei.is.mpg.de/project/differential-geometry-for-representation-learning

Causal Inference

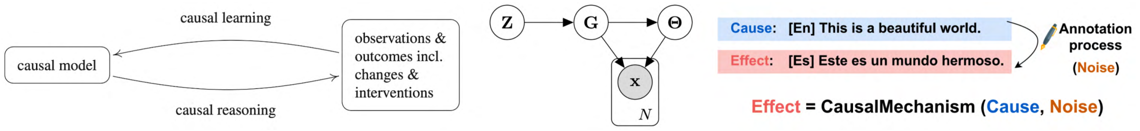


Figure 2.7: (left) In the terminology of our recent book [82], causal inference comprises both causal reasoning and causal learning/discovery: the former employs causal models for inference about expected observations (often, about their statistical properties), whereas the latter is concerned with inferring causal models from empirical data. Some recent work includes: (center) a fully-differentiable Bayesian causal discovery method [258] (NeurIPS'21 spotlight), and (right) an application of causal reasoning to NLP [270] (EMNLP'21 oral).

Both causal reasoning and learning crucially rely on assumptions on the statistical properties entailed by causal structures. During the past decade, various assumptions have been proposed and assayed that go beyond traditional ones like the causal Markov condition and faithfulness. This has implications for both scenarios: it improves identifiability of causal structure and also entails additional statistical predictions if the causal structure is known.

Causal reasoning Under suitable model assumptions (here: additive independent noise), causal knowledge admits novel techniques of noise removal such as the method of half-sibling regression published in PNAS [246], applied to astronomic data from NASA's Kepler space telescope [235].

Apart from entailing statistical properties for a *fixed* distribution, causal models also suggest how distributions *change* across data sets. One may assume, for instance, that structural equations remain constant and only the noise distributions change [238],[82], that some of the causal conditionals in a causal Bayesian network change, while others remain constant [185], or that they change *independently* [508], which results in new approaches to domain adaptation [548],[430],[596].

Based on the idea of no shared information between causal mechanisms [82], we developed a new type of conditional semi-supervised learning [375]. More recently, we showed that causal structure can explain a number of published NLP findings [270], and explored its use in reinforcement learning [305],[271].

Causal learning/discovery We have further explored the basic problem of telling cause from effect in bivariate distributions [485], which we had earlier shown to be insightful also for more general causal inference problems. A long JMLR paper [245] extensively studies the performance of a variety of approaches, suggesting that distinguishing cause and effect is indeed possible above chance level.

For the multivariate setting, we have developed a fully differentiable Bayesian structure learning approach based on a latent probabilistic graph representation and efficient variational inference [258]. Other new results deal with discovery from heterogeneous or nonstationary data [119], meta-learning [343], employing generalized score functions [477], or learning structural equation models in presence of selection bias [546], while [192] introduced a kernel-based statistical test for joint independence, a key component of multi-variate additive noise-based causal discovery.

Apart from such 'classical' problems, we have extended the domain of causal inference in new directions: e.g., to assay causal signals in images by inferring whether the presence of an object is the cause or the effect of the presence of another [519]. In a study connecting causal principles and foundations of physics [233], we relate asymmetries between cause and effect to those between past and future, deriving a version of the second law of thermodynamics (the thermodynamic 'arrow of time') from the assumption of (algorithmic) independence of causal mechanisms.

Within time series modeling, new causal inference methods reveal aspects of the arrow of time [544], or allow for principled causal feature selection in presence of hidden confounding [330]. We have applied some of these methods to analyse climate systems [161] and Covid-19 spread [354], see also [115].

More information: https://ei.is.mpg.de/project/causal-inference

Causal Representation Learning

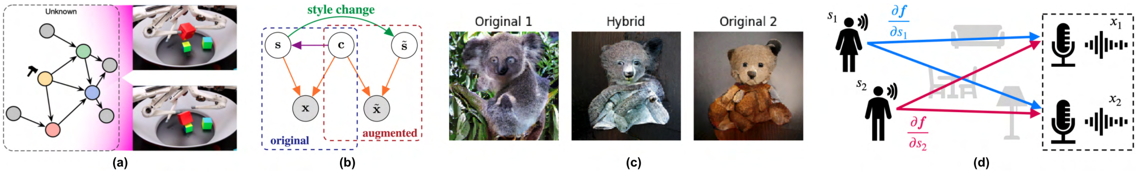


Figure 2.8: (a) Causal representation learning aims to infer abstract, high-level causal variables and their relations from low-level perceptual data such as images or other sensor measurements [107]. Recent work in this direction includes: (b) a proof that self-supervised learning isolates the invariant (content) representation c that is shared across views (e.g., obtained via data augmentation) [260]; (c) a method for extracting causal structure from trained deep generative models that allows for interventions leading to novel "hybrid" data [370]; and (d) a new instantiation of the principle of independent mechanisms suitable for unsupervised representation learning [259].

Causal representation learning aims to move from statistical representations towards learning causal world models that support notions of intervention and planning, see Fig. (a) [107].

Coarse-grained causal models Defining objects that are related by *causal models* typically amounts to appropriate coarse-graining of more detailed models of the world (e.g., physical models). Subject to appropriate conditions, causal models can arise, e.g., from coarse-graining of microscopic structural equation models [512], ordinary differential equations [489], temporally aggregated time series [513], or temporal abstractions of recurrent dynamical models [462]. Although models in economics, medicine, or psychology typically involve variables that are abstractions of more elementary concepts, it is unclear when such coarse-grained variables admit causal models with well-defined interventions; [512] provides some sufficient conditions.

Disentanglement A special case of causal representation learning is disentanglement, or nonlinear ICA, where the latent variables are assumed to be statistically independent. Through theoretical and large-scale empirical study, we have shown that disentanglement is not possible in a purely unsupervised setting [423] *(ICML'19 best paper)*. Follow-up works considered a semi-supervised setting [383], and showed that disentanglement methods learn dependent latents when trained on correlated data [303].

Multi-view learning Learning with multiple views of the data allows for overcoming the impossibility of purely-unsupervised representation learning, as demonstrated through identifiability results for multi-view nonlinear ICA [418] and weakly-supervised disentanglement [365]. This idea also helps explain the impressive empirical success of self-supervised learning with data augmentations: we prove that the latter isolates the invariant part of the representation that is shared across views under arbitrary latent dependence, see Fig. (b) [260].

Learning independent mechanisms For image recognition, we showed (by competitive training of expert modules) that independent mechanisms can transfer information across different datasets [471]. In an extension to dynamic systems, learning sparsely communicating, *recurrent* independent mechanisms (RIMs) led to improved generalization and strong performance on RL tasks [309]. Similar ideas have been useful for learning object-centric representations and causal generative scene models [381],[597],[355].

Extracting causal structure from deep generative models We have devised methods for analysing deep generative models through a causal lens, e.g., for better extrapolation [325] or creating hybridized counterfactual images, see Fig. (c) [370]. Causal ideas have also led to a new structured decoder architecture [602] and new forms of gradient combination to avoid learning spurious correlations [328].

New notions of non-statistical independence To use the principle of independent causal mechanisms as a learning signal, we have proposed two new notions of non-statistical independence: a general group-invariance framework that unifies several previous approaches [484], and an orthogonality condition between partial derivatives tailored specifically for unsupervised representation learning, see Fig. (d) [259].

More information: https://ei.is.mpg.de/project/causal-representation-learning

Accountability and Recourse

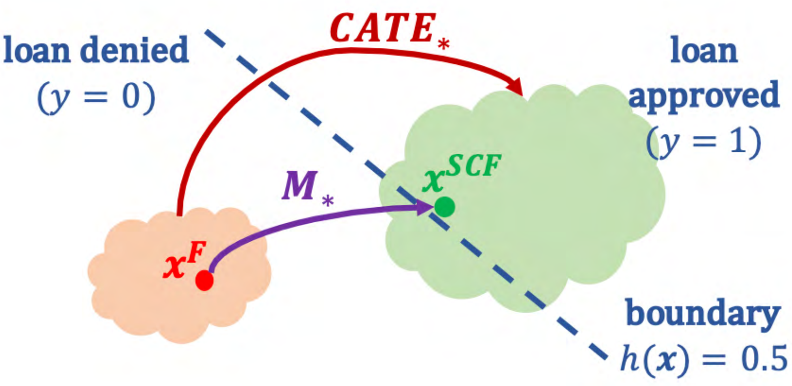


Figure 2.9: Recourse aims to offer individuals subject to automated decision-making systems a set of actionable recommendations to overcome an adverse situation. Recommendations are offered as actions in the real world governed by causal relations, whereby actions on a variable may have consequential effects on others. This figure illustrates point- and subpopulation-based algorithmic recourse approaches.

This research lies at the intersection of causal inference, explainable AI, and trustworthy ML. Given the increasing use of often intransparent ("blackbox") machine learning models for consequential decision-making, it is of growing societal and legal importance. In particular, we consider the task of enabling and facilitating algorithmic recourse, which aims to provide individuals with explanations and recommendations on how best (i.e., efficiently and ideally at low cost) to recover from unfavorable decisions made by an automated system. We address the following questions:

How can we generate recourse explanations for affected individuals in diverse settings? Several works have proposed optimization-based methods to generate nearest counterfactual explanations (CFE). However, these methods are often restricted to a particular subset of models (e.g., decision trees or linear models), only support differentiable distance functions, or poorly handle mixed datatypes. Building on theory and tools from formal verification, we proposed a novel algorithm for generating CFEs (MACE) [386], which are: i) model-agnostic; ii) datatype-agnostic; iii) distance-agnostic; iv) able to generate plausible and diverse CFEs for any individual (100% coverage); and v) at provably optimal distances. We also offer another solution with similar characteristics, this time using mixed-integer linear programs [327].

What actionable insight can be extracted from a CFE? Next, we explored one of the main, but often overlooked, objectives of CFEs as a means to allow people to act rather than just understand. We showed that actionable recommendations cannot, in general, be inferred from CFEs. We formulated a new optimization problem for directly generating minimal consequential *interventions* (MINT), offering exact recourse under the knowledge of an underlying causal model [331] and probabilistic recourse when only knowledge of the causal graph is available [368] or under potential confounding [249].

How does offering recourse affect other stakeholders? We argue that giving the right of recourse to individuals should not be considered independently of its effect on other stakeholders (e.g., model deployer and regulators), or in relation to other desirable properties (e.g., fairness, robustness, privacy, and security). In a follow-up work, we explore the fairness and robustness of causal algorithmic recourse, positioning these properties as complementary (but not implied through) fair and robust prediction [326]. Our experiments show how one may obtain recourse generating solutions that are fair and robust. Finally, we summarized the state of the field of recourse in a review paper [604].

More information: https://ei.is.mpg.de/project/accountability-recourse

Fairness

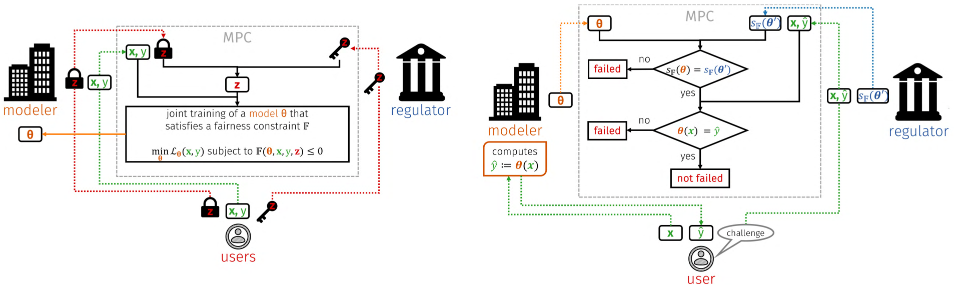


Figure 2.10: Protocols based on secure multi-party computation to learn (left) and verify (right) a fair model using only encrypted sensitive attributes; for details, see [474].

If algorithmic decision-making processes are becoming automated and data-driven in consequential domains (e.g., jail-or-release decisions by judges, or accept-or-reject decisions in academia), there are concerns of the potential unfairness of these systems towards people from certain demographic groups (e.g., gender or ethnic groups). We aim to contribute insights and, where possible, remedies.

Forms of legally problematic discrimination are commonly divided into several categories, e.g., "disparate treatment" (or direct discrimination), and "disparate impact" (or indirect discrimination). Despite the variety of proposed solutions, e.g., "fairness by unawareness", "demographic parity", etc., most of the existing criteria are observational: they depend only on the joint distribution of predictor, protected attribute, features, and outcome, and are formulated as potentially approximate conditional independencies.

Instead, we proposed a preference-based notion of (un)fairness, which is inspired by the fair division and envy-freeness literature in economics and game theory [490]. This definition provides a more flexible alternative to previous notions that are mostly based on parity of distributions of outcomes.

We also propose novel fairness criteria that distinguish between different causal models underlying the data, despite identical observations distributions. We present training methods to achieve fair classifiers that come with theoretical guarantees under certain regularity assumptions [500].

Moreover, we mitigate unfairness by developing flexible constraint-based frameworks to enable the design of fair margin-based classifiers [144]. We contribute a general measure of decision boundary unfairness, which serves as a tractable proxy to several of the most popular computational definitions of unfairness. We can thus reduce the design of fair margin-based classifiers to add tractable constraints on their decision boundaries.

Avoiding both disparate impact and disparate mistreatment is a major challenge, due to tensions that arise in the intersection of privacy, accountability, and fairness. By encrypting sensitive attributes, we show how a fair model may be learned, checked, or have its outputs verified and held to account, without users revealing their sensitive attributes, cf. the above figure and [474].

Despite fairness definitions and mechanisms, there is a lack of ML methods to ensure accuracy and fairness in human decision-making. In this context, each decision is taken by an expert who is typically chosen uniformly at random from a pool of experts. We showed that a random assignment may result in undesirable results for both accuracy and fairness, and propose an algorithm to perform an assignment between decisions and experts that jointly optimizes for both [460].

Finally, decisions made for humans bias the dataset labels towards those that are observed. In absence of ground truth labels, we propose to directly learn decision policies that maximize utility under fairness constraints and thereby take into account how decisions affect which data is observed in the future [384].

More information: https://ei.is.mpg.de/project/fairness

Robotics

Figure 2.11: We studied a single robot playing table tennis against a human or ball gun in the past. In 2018, we migrated to a new setup with sufficient space for two robots opposing each other. We aim to achieve collaborative table tennis play with the Barrett WAM robot arm and our muscular robots as well as compare performance of motor and muscular actuation using methods from robotic skill learning.

Creating autonomous robots that can learn to assist humans in daily life situations is a fascinating challenge for machine learning. While this aim has been a long-standing vision of artificial intelligence, we have yet to create robots that can learn to accomplish many different tasks triggered by environmental context or higher-level instruction. We thus focus on the solution of basic problems in robotics by developing domain-appropriate machine-learning methods.

While many machine learning methods work in theory, in simplified simulations and textbook control plants, it is essential to study real robot systems to understand the learning of high-performance motor skills. We focus on the problem of learning robot table tennis as our "Drosophila" to gain insights that we hope will be generalizable. These tasks have a number of components that are representative of tasks encountered by natural intelligent systems, including perception and action in rapidly changing and uncertain environments.

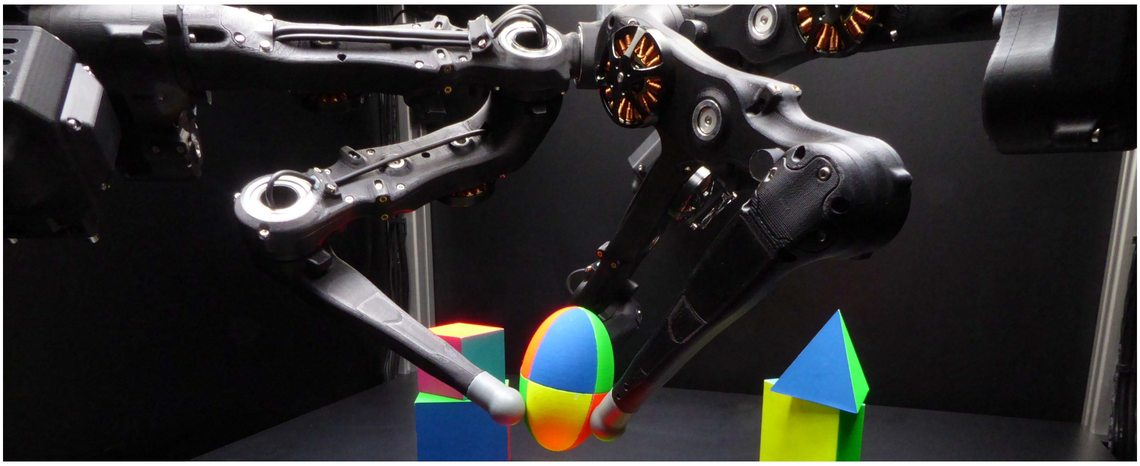
Learning approaches have to generalize a complex hitting behavior from relatively few demonstrated trajectories, which do not cover all ball trajectories or desired hitting directions. Our recent work on capturing trajectory distributions using probabilistic movement representations [141] opens new possibilities for robot table tennis. We have presented several methods to adapt probabilistic movement primitives, e.g., for adapting hitting movements learned in joint space to have a desired end-effector position, velocity, and orientation [62], as well as to find the initial time and duration of the movement primitive to intercept a moving object like the table tennis ball [141].

Another line of robot table tennis research is to explore new robot morphologies. To this end, we developed a lightweight robot actuated by pneumatic muscles [71] that enabled us to return and smash table tennis balls using model-free reinforcement learning from scratch [2]. This new robot exerts highly accelerated motions while inherently assuring safety, eventually opening up new ways to think of acquiring high-speed motor skills.

We have worked on various other questions of robot motion control with the context of robot table tennis in real robot experiments on the Barrett WAM. Among these approaches, we have studied the properties of optimal trajectory generation in robot table tennis strikes [64], and learning striking controllers [165]. We have also demonstrated how a table tennis serve can be captured and successfully reproduced [163].

More information: https://ei.is.mpg.de/project/robotics

Real-World Robot Benchmark



Dexterous object manipulation remains an open problem in robotics, despite the rapid progress in machine learning during the past decade. To a large extent, this is due to the high cost of experimentation on real systems and the lack of benchmarks that are shared across research institutions. We address this problem by designing an open-source robotic platform, called Trifinger [22], that can easily be built by researchers around the world using off-the-shelf components and 3D-printed parts for a cost of about $5000. This platform consists of three robotic fingers capable of dexterous object manipulation (the finger design is based on the leg of a quadruped also developed in-house [3]).

To allow researchers that are not able to build their own platform to conduct research in robotics, we host 8 Trifinger platforms at MPI-IS [600]. Researchers anywhere in the world are able to control the platforms remotely by submitting code that is executed automatically much like on a compute cluster.

Despite having finished the development of this robotic platform only recently, it has already given rise to a number of initiatives and publications, some of which we discuss below.

Robotics Competition We hosted a competition (https://real-robot-challenge.com/), where teams from anywhere in the world accessed our platforms to tackle challenging tasks, and we published the dataset collected during this competition (consisting of hundreds of robot hours) [600]. This competition gave rise to novel algorithms for robotic manipulation and has already lead to follow-up work by some of the participants, e.g., [598].

Transfer Learning Building agents that can transfer learned models, representations (e.g., of images), and skills (e.g., pushing an object) to unseen scenarios is one of the remaining key challenges in artifical intelligence. So far, the research community mostly evaluated such algorithms on small, synthetic toy problems. In contrast, using the Trifinger platform we can generate a continuum of realistic tasks that can be designed to share any desired amount of structure (for instance, two tasks may be defined to use identical or different objects). In [24] we generated a dataset containing robot motions in different regimes (e.g., high-speed vs low-speed), such that researchers can assess whether the dynamics learned under one regime transfer to another. We built a simulation of the Trifinger where numerous properties of the world, such as gravity and object colors, sizes, and shapes can be modified [321]. This facilitates research into causal representations and models that transfer to unseen scenarios or even to the real robot. In [320] and [26] we conducted large-scale studies of disentangled representations in more realistic settings than previous work. We observed that disentanglement was a good predictor for out-of-distribution (OOD) task performance.

More information: https://ei.is.mpg.de/project/robot-benchmark

Learning for Control

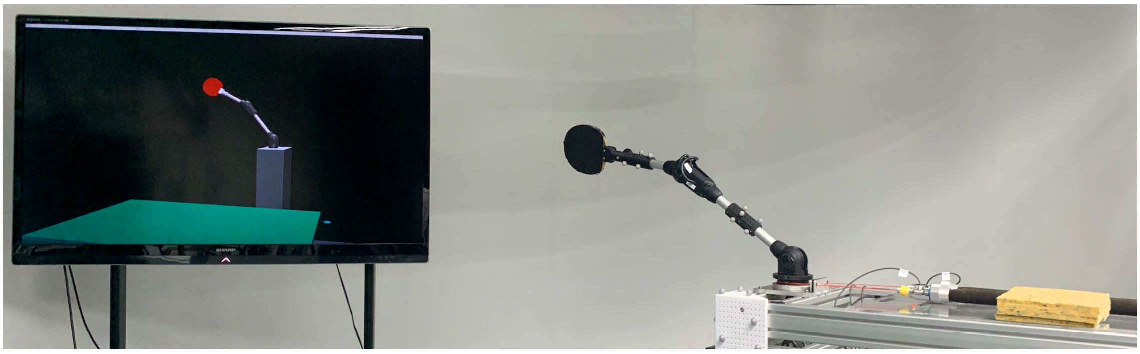


Figure 2.12: Our muscle-based robotic arm is a testbed for Learning for Control. While it offers unique possibilities in terms of high accelerations, extreme speeds and variable stiffness actuation, classical control methods are known to struggle with these abilities.

Control of complex plants or systems, especially robots actuated by pneumatic artificial muscles, is challenging due to nonlinearities, hysteresis effects, massive actuator delay, and unobservable dependencies such as temperature. Such plants and robots require much more from the control than classical methods can deliver. Therefore, we aim to develop novel methods for learning control that can deal with high-speed dynamics and muscular actuation.

Highly dynamic tasks that require large accelerations and precise tracking usually rely on accurate models and/or high gain feedback. Learning to track such dynamic movements with inaccurate models remains an open problem. To achieve accurate tracking for such tasks in a stable and efficient way, we have proposed a series of novel adaptive Iterative Learning Control (ILC) algorithms that are implemented efficiently and enable caution during learning [165].

Muscular systems offer beneficial properties to achieve human-comparable performance in uncertain and fast-changing tasks [71]. Muscles are backdrivable and provide variable stiffness while offering high forces to reach high accelerations. Nevertheless, these advantages come at a high price, as such robots defy classical approaches for control. We have built a muscular robot system to study how to control musculoskeletal robots using learning. We have shown how probabilistic forward dynamics models can be employed to control complex musculoskeletal robots incorporating model uncertainty of the forward model [186]. We were able to perform the accuracy demanding task of robot table tennis with this setup using model-free RL [2]. The work introduced a hybrid simulated and real training (HYSR) that enabled long-term training without resetting the real environment and incorporating prerecorded data for better transfer to the real task.

In addition, we have continued to work on reinforcement learning problems at the intersection of control and machine learning. We have extended several approaches in reinforcement learning for continuous control (NAF, Q-Prop, IPG, TDM) to handle function approximations with significantly improved sample efficiency [533],[506],[501],[480],[463]. We were able to show that our approach scaled to learning a door opening task [504].

Aside from fundamental algorithmic problems such as sample efficiency and stability, we also proposed algorithms that enable learning on real-world robots with fewer human interventions during learning. In [479], we propose the Leave No Trace (LNT) algorithm that significantly reduced the number of hard resets required during learning. Lastly, we contributed to the field of hierarchical reinforcement learning with the HIRO algorithm [445], a scalable off-policy HRL algorithm with substantially improved sample efficiency, and HiTS [257] that improves temporal abstraction for non-stationary environments.

More information: https://ei.is.mpg.de/project/learning-4-control

Stochastic and Robust Optimization

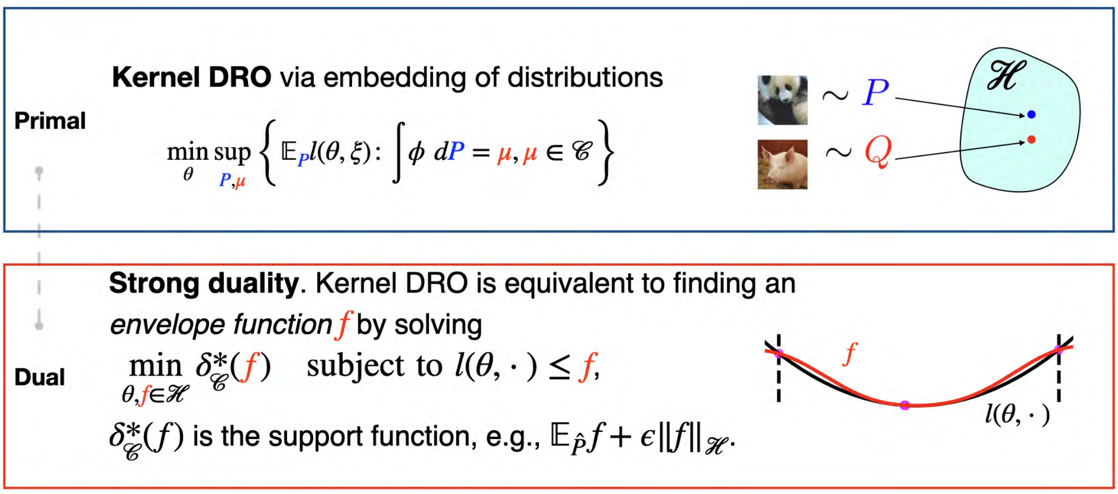


Figure 2.13: Illustration of the ideas behind Kernel Distributionally Robust Optimization

This project focuses on the mathematical optimization foundations of machine learning and control algorithms, and more broadly, data-driven algorithmic decision-making. We are especially motivated by addressing the lack of robustness and data distribution shift issues.

Our starting point is the standard *sample average approximation* (SAA), equivalent to empirical risk minimization (ERM). It optimizes the objective

$$\min_{\theta} \frac{1}{N} \sum_{i=1}^{N} l(\theta, \xi_i),$$

where l is the optimization objective, θ is the decision variable, and $\xi_i \sim P_0$ independent and identically distributed (i.i.d.) empirical data. ERM is the workhorse of modern machine learning. However, it is not suitable for safety-critical tasks since it does not guarantee generalization to new samples that do not come from P_0.

Instead of ERM, we explicitly robustify against data distribution shift using *distributionally robust optimization (DRO)*

$$\min_{\theta} \sup_{P \in \mathcal{C}} \mathbb{E}_{\xi \sim P} l(\theta, \xi),$$

where $\mathcal{C}$ is a set of distributions, referred to as an uncertainty *set*. We established a kernel framework for DRO – the *Kernel DRO* [329], and show that the DRO problem can be exactly reformulated into a kernel learning problem. The intuition is to find a smooth kernel function that majorizes the original loss, as demonstrated in the illustration above.

The above work is closely related to and synergistic with our statistical learning projects. For example, we can use the aforementioned Kernel DRO algorithm constrained by an MMD uncertainty set

$$\min_{\theta} \sup_{\mathrm{MMD}(P, \hat{P}_N) \leq \epsilon} \mathbb{E}_{\xi \sim P} l(\theta, \xi),$$

where the threshold ϵ can be chosen as a finite-sample error bound of our previous analyses [539],[211],[540].

In addition to our focus on robust optimization, we also explore other optimization topics such as [298],[359].

More information: https://ei.is.mpg.de/project/optimization

Computational Imaging

Figure 2.14: Super-resolution aims at estimating a high-resolution image from a single low-resolution input (left). Traditional methods tend to produce over-smoothed images that lack high frequency textures and do not look natural (second picture). One focus of our research was the development of algorithms that are able to create realistic textures (third picture) rather than a pixel-accurate reproduction of ground truth (right picture).

Handheld video cameras now being available in every smartphone, images and videos have become ubiquitous. The amount of visual content on the internet has been ever increasing and digital images and videos have become the main carrier of information over the last few decades.

We are interested in a range of signal and image processing problems both in computational photography and scientific imaging. Our focus is on methods that aim at computationally enhancing the quality of images and recovering probable original images by undoing the adverse effects of image degradation such as blur. Advances in neural networks have transformed computer vision and the field of digital image restoration has been no exception to this rule.

An intriguing problem in image restoration is super-resolution, aiming at recovering a high-resolution image from low-resolution input. Many traditional performance measures such as peak-signal-to-noise ratio (PSNR) correlate poorly with the human perception of image quality. Algorithms minimizing these metrics thus tend to produce over-smoothed images that lack high-frequency textures and do not look natural despite yielding high PSNR values. By focussing on realistic textures rather than pixel-wise accuracy we achieved a significant boost in image quality even at high magnification ratios [523] (see figure above). Enforcing time consistency led to novel approaches for the problems of video super-resolution [486] and video prediction [520].

Another focus area has been the problem of blind deblurring. Images often exhibit blur due to unwanted camera shake or moving objects in the scene. Removing the blur is hard as neither the sharp image nor the motion blur kernel is known. We have developed efficient recurrent network architectures that propagate information between multiple consecutive blurry observations which helps restore the desired sharp image or video [466],[511],[526],[510]. The modulation transfer function (MTF) plays an important role for lens quality assessment and non-blind deblurring. We have developed a framework to directly estimate it from natural images [478].

In another line of work we applied image processing to magnetic resonance images [502],[190]. Moreover, we have worked on MRI sequence generation [105], hardware optimization [139] and acceleration of acquisition processes [146]. In [146] a novel way of MRI image reconstruction using a forward model of the shim coil-modulated imaging process was used. An optimization-based approach was employed in [190] to improve the quality of MR images by compensating for subject motion-induced artifacts. In [105] a differentiable digital twin of the entire MRI measurement and reconstruction apparatus was proposed, which allowed for novel ways to design and improve MRI sequences.

Recently we have entered the field of acoustic computer-generated holography (CGH). Acoustic CGH is concerned with the computation of 3D-printed plastic devices that modulate the phase of passing ultrasound waves in order to generate desired intensity patterns with possible applications in the medical sciences and one-shot manufacturing. Casting the computation of holograms as an inverse problem allows us to employ tools from image processing in this context.

We have also begun to study optical machine learning methods, seeking to identify components of machine learning systems that can more elegantly (and faster) be implemented using optics.

More information: https://ei.is.mpg.de/project/computational-imaging

Neuroscience

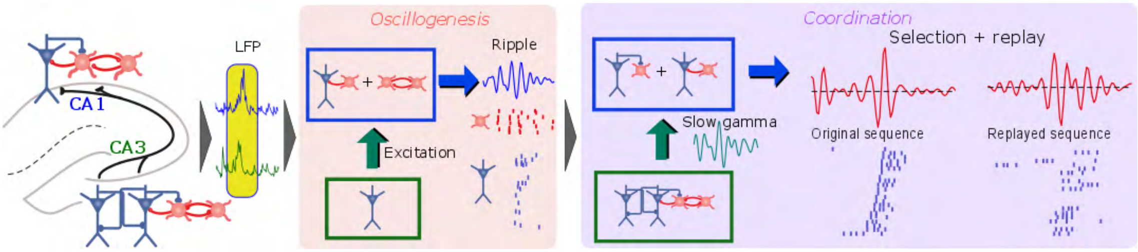


Figure 2.15: The mechanisms involved in replay of memory traces in the hippocampus. Left: connectivity of excitatory (blue) and inhibitory (red) cells in regions CA3 and CA1. Center: key circuits involved in generating synchronized neuronal activity. Right: circuits involved in generating replays of sequential activity of a sparse population encoding a memory trace. See [184].

Brain networks are characterized by a dense connectivity that generate complex dynamics and high dimensional data. Machine learning helps us uncovering their organization and function in multiple ways.

The analysis of three-dimensional (3D) electron microscopy data allowed reconstructing with high spatial resolution the morphological features of neurons and their connections [151]. Such detailed properties need to be incorporated in biologically realistic computational models to uncover brain mechanisms. However, the complexity of such models does not provide direct answers, but instead requires interpretation assisted by sophisticated data analysis techniques. This is well illustrated by our investigation of the replay of *memory traces* in the hippocampus [184], in which key neural circuits underlying the replay of memorized events during sleep are uncovered with the help of supervised machine learning.

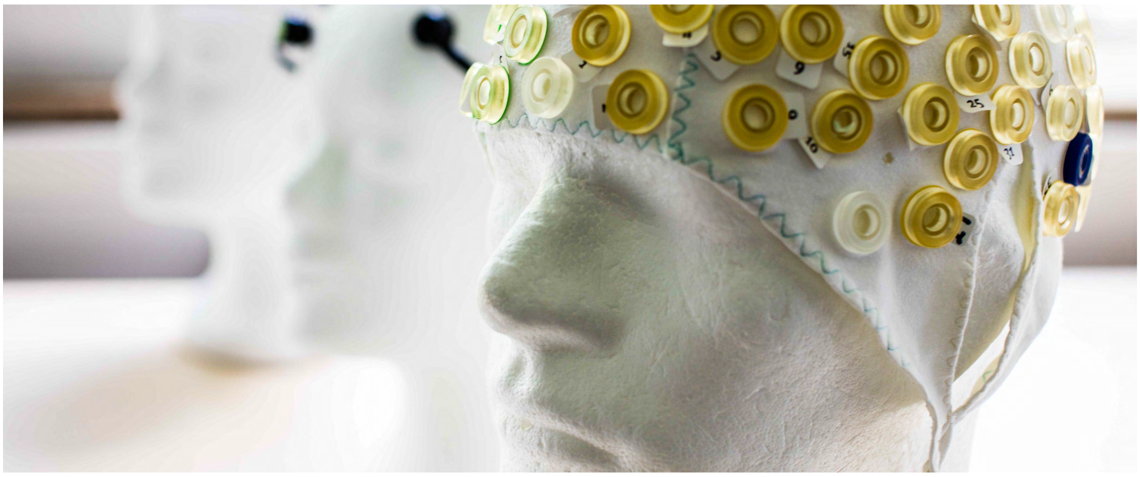
These computational modelling studies need to be further complemented by extensive analyses of large-scale recordings in order to detect and uncover the role of transient interactions between multiple regions across the whole brain. Our causal inference methods were used in this context to improve our understanding of how memory trace replay participates in brain-wide phenomena that consolidate new memories during sleep [133].

Another fascinating question of current neuroscience is uncovering the representations encoded by neurons in higher level regions such as the prefrontal cortex (PFC). Machine learning algorithms enabled unprecedented characterizations of these representations during conscious visual perception. This has been done notably through the use of unsupervised learning approaches such as Non-Negative Matrix Factorization [182] as well as supervised learning techniques that allow assessing the perceptual information content of neural populations [112].

Finally, high-dimensionality of electrophysiology and neuroimaging data is a major challenge for their analysis. We addressed it with novel theoretical frameworks providing neuroscientists with highly interpretable multivariate analyses techniques. In particular, MultiView independent component analysis [351] allows for example to incorporate neuroimaging data originating from multiple subjects to fit identifiable probabilistic models of brain response to stimuli. Moreover, we developed a statistical framework based on random matrix theory and point processes to assess the significance of multivariate measures of the coupling of spiking activity recorded simultaneously in large ensembles of neurons and mesoscopic electric field activity [114]. This tool leverages high-dimensional statistics in order to efficiently compute interpretable analyses of the most recent multi-channel electrophysiological recording technologies [113].

More information: https://ei.is.mpg.de/project/neuroscience

Brain-Computer Interfaces



Brain-computer interfaces (BCIs) hold promise in restoring communication for completely locked-in stage (CLIS) patients in late stages of amyotrophic lateral sclerosis (ALS). Despite more than two decades of research, however, late-stage ALS patients remain incapable of operating BCIs, arguably because such systems currently rely on brain processes that are impaired as a result of disease progression. To establish communication with CLIS-ALS patients, it is thus crucial to, first, understand how ALS affects neurophysiological as well as cognitive processes and, second, develop BCI systems that target brain processes which remain functional into late stages of the disease.

In a series of studies, we have investigated how ALS affects neural and cognitive processes. In particular, we were able to show that the neural correlates of self-referential processing are already impaired in the early stages of ALS, i.e., neural deficits emerge before cognitive deficits manifest in overt behavior [209]. Following up on this work, we recorded electrophysiological signals in two CLIS-ALS patients and demonstrated that the locked-in stage is accompanied by a major slow-down of the brain's dominant rhythm [178]. The cognitive implications of this slow-down are yet to be understood.

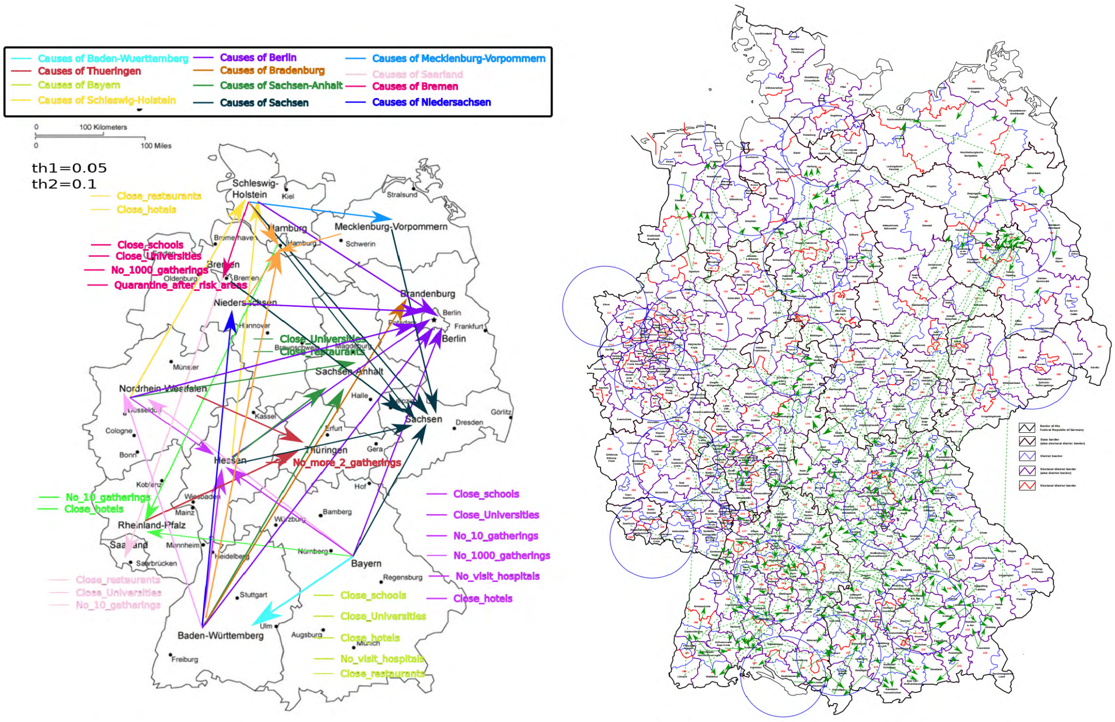
Based on these insights, we developed more accessible BCI control strategies for late-stage ALS patients by targeting brain processes that are likely to remain functional into late disease stages [549]. We successfully validated this system in a long-term study with two ALS patients, who achieved stable communication for more than one year [231].

To translate this system from lab to home use, we have pioneered a transfer learning approach for BCIs that drastically reduces the amount of training data while maintaining decoding accuracy [239] and developed a novel brain-decoding feature, based on task-induced frequency modulations of canonical brain rhythms, that is particularly useful for low-channel setups [210].

To evaluate the unsupervised use of this system across multiple days, we developed an open-source framework that couples an easy-to-use application with consumer-grade recording hardware [369]. A large study showed that participants were able to use the system without expert supervision, and results indicated that the framework can enable research on BCI robustness, environmental effects, and behavioral correlates, all of which could hardly be captured in traditional laboratory settings. These advances should enable us to build performant cognitive BCIs with off-the-shelf hardware, eventually leading to BCI systems available for large-scale application outside of laboratory environments.

More information: https://ei.is.mpg.de/project/brain-computer-interface

Medical Applications



(a) Federal state level & policies causal analysis. (b) District-level causal analysis.

Figure 2.16: Causal paths of the spread of Covid-19 among the German federal states (from [354])

Translation and application of state-of-the-art machine learning methods to medical applications is a central aspect of the department's effort to make methodological developments available to the broader scientific community and to contribute to solving machine learning challenges in the medical domain. Together with regional and international collaboration partners from medicine we conducted projects mainly focusing on medical image analysis, causal analysis of disease formation and recently analysis of epidemiological COVID-19 data.

Medical Image Analysis Our overall goal in this field is the development and implementation of machine learning algorithms that solve relevant medical problems in a robust and explainable way. Among other projects, we focused on the analysis of complex, multiparametric imaging data from different sources such as histopathology and PET/MRI [215], uncertainty estimation and explainability of deep learning models for medical image analysis [288] and federated learning aiming for cross-institutional learning and data protection [108].

Causal Analysis of Medical Data Causality plays an important role for medical decision making and knowledge discovery. In a series of projects, recently mainly addressing data concerning the COVID-19 pandemic, we were able to translate causal learning methods to large medical and epidemiological data sets and illustrate the practical significance of these methods. Specifically, we addressed challenges in data interpretation [108], investigated disease outcome prediction models from a causal viewpoint [115], [111] and studied epidemiological models of disease spread [318], [354], [599],[603].

Personalized Medicine Our membership in a Marie Curie Training network has led us to take part in (and win) the *ENCODE Imputation Challenge* aiming to help build a comprehensive list of functional elements in the human genome from data produced by various types of genomics assays.

More information: https://ei.is.mpg.de/project/medical-applications

Psychology

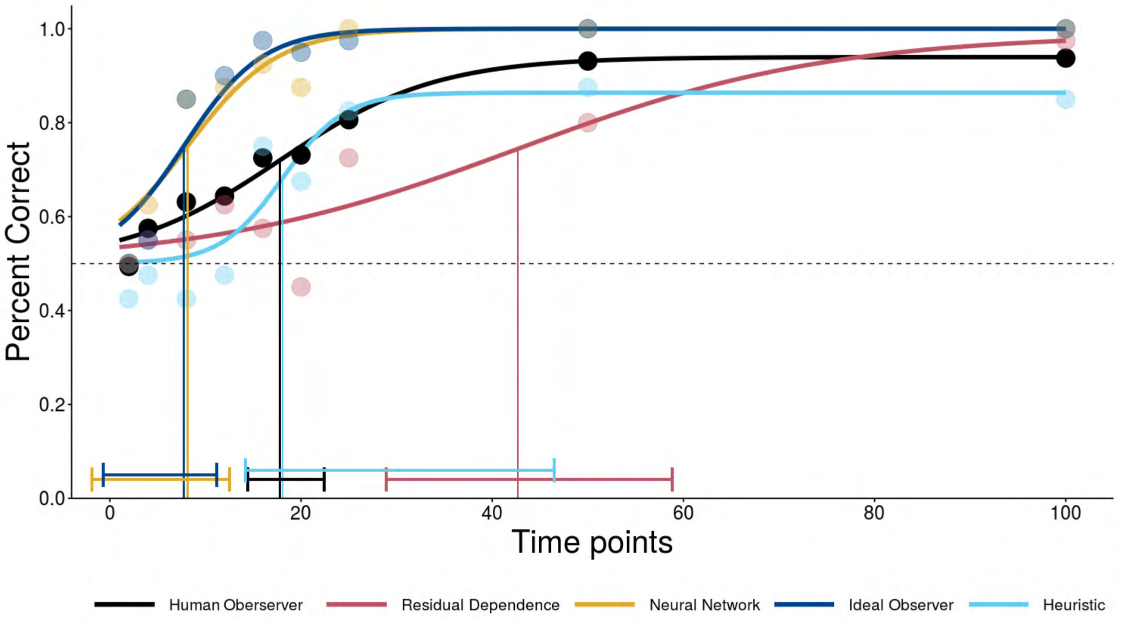


Figure 2.17: Experiments on the identification of the direction of the time series of a moving object on trajectories of different lengths. Black dots represent human accuracy pooled over all subjects. Colored dots represent different algorithms. Performance gets worse towards shorter time series. The vertical colored lines mark the 75% threshold for the psychometric fits and the corresponding 95% confidence intervals are shown at the bottom. The horizontal dashed line marks the chance accuracy (50%).

Much of the research in cognitive science and an increasing fraction of that in machine learning agree that truly intelligent behaviour requires causal representation of the world. A central research question is which behaviourally relevant input data support causal inference algorithms of human perception: what are the critical cues in complex, high-dimensional real-world data impinging on our sensory systems that our causal inference algorithms run upon?

Recent ML algorithms exploit the dependence structure of additive noise terms for inferring causal structures from observational data [544], e.g., to detect the direction of time series; the arrow of time. This raises the question whether the subtle asymmetries between the time directions can also be perceived by humans.

We show [411] that human observers can indeed discriminate forward and backward autoregressive motion with non-Gaussian additive independent noise, i.e., they appear sensitive to subtle asymmetries between the time directions. We employ a so-called frozen noise paradigm enabling us to compare human performance with four different recent ML algorithms. Our results suggest that all human observers use similar cues or strategies to solve the arrow of time motion discrimination task, but the human algorithm is significantly different from the three machine algorithms we compared it to.

Together with the results of an additional experiment [136]-using classical as well as modified Michotte launching displays-we now believe that the human ability to "see causes” is at least in our settings an early, a perceptual rather than a late, or deliberate, cognitive ability.

Another project of interest to psychology studied how to enhance human learning in spaced repetition schemes as used, e.g., in language learning [164].

More information: https://ei.is.mpg.de/project/psychology

Learning on Social Networks

Social media and online social networking sites contain opinionated, inaccurate or false facts that may get refuted over time. Spread of misinformation may have confused and misled voters in the last U.S. presidential election or the Brexit referendum. To address this problem, online platforms deploy evaluation mechanisms for their users to further curate information within these platforms. For example, users can remove inaccurate contents from *Wikipedia*, mark a correct answer as verified in *Stack Overflow* and flag a story as misinformation in *Facebook* and *Twitter*.

We developed a unified computational framework [551] that leverages the temporal traces left by the aforementioned examples of noisy evaluations to estimate robust, unbiased and interpretable notions of information reliability and source trustworthiness. The key idea is that unreliable contents are often removed quickly while reliable contents remain on platforms such as *Wikipedia* for a long time. Similarly, information contributed by sources which systematically spread misinformation are often removed quickly on a wide range of entries, while contents contributed by thrustworthy sources remain on a platform for a long time. By applying our framework to *Wikipedia* data, we are able to answer questions such as whether bbc.co.uk provides more reliable information compared to newyorktimes.com in *Wikipedia* entries related to the U.S politics, and at which point in time a particular *Wikipedia* entry, such as *Barack H. Obama*, was unreliable due to ongoing controversies.

Next, we focused on developing a machine learning method to detect and reduce the spread of harmful misinformation in online social networking sites through the power of the crowd and fact-checking [487]. Given limited reviewing resources, the main question is how to prioritize questionable content. Some cases of misinformation are not identified until a large number of users have been already exposed to it. However, many cases may only have a limited impact on people and unnecessarily consume reviewing resources for fact-checking. To address these challenges, we developed a robust methodology with provable guarantees to minimize the impact of potentially harmful contents on a large number of people. Results of applying this algorithm on datasets from *Twitter* and *Weibo* suggest that our method can identify cases of misinformation earlier than alternative methods and also uses fact-checking resources more efficiently.

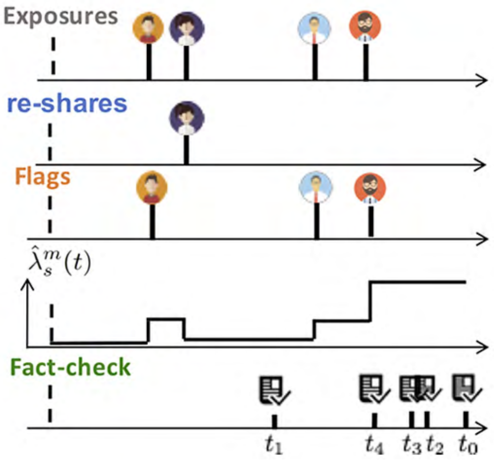


Figure 2.18: Fact checking of content on social networks using observed exposure, reshare and flag events. The rate of fact checking, $\hat{\lambda}_s^m(t)$, is updated after every observed event.

Fact-checking and removing content from social platforms are not always possible since not all potentially harmful content can be fact-checked in time. For many platforms it is still desirable to reduce circulation of such potentially harmful content. Facebook and Twitter often resort to modifying their ranking algorithms to reduce distribution of contents that present evidence of harm but are not yet fact-checked. In our next work in this series [374], we present a probabilistic Reinforcement Learning method to reduce the impact of harmful content over a specific time horizon by modifying any existing blackbox ranking algorithm. We apply this algorithm on data from Reddit and demonstrate that modifying rankings of comments of a post can minimize the spread of misinformation and improve the civility of online discussions.

More information: https://ei.is.mpg.de/project/learning-on-social-networks

2.3 Equipment

Computing Infrastructure

The desktop computing environment of the Department of Empirical Inference is based on Intel PCs, and currently uses centrally managed operating systems Ubuntu Linux, Microsoft Windows, and Mac OS X.

Until recently, storage for research data shares and home directories was provided solely by two department file servers. There is currently a transition toward usage of the NetApp cluster storage operated by the central IT facilities. This solution is shared with the other departments and research groups of the institute. This storage provides hourly snapshot backups. The Empirical Inference owns half (i.e., 120TB) of the data capacity of this cluster. Off-site storage from RZ Garching is offered for long-term archival of scientific data.

The Empirical Inference department used around 32% of the central high performance computing cluster in recent years. Researchers in the department also have access to a powerful supercomputer with a peak performance of more than 20 PFLOPS in the Max Planck Computing and Data Facility in Garching.

Robot Learning Lab: High-Speed Robot Arms

The **Robot Learning Lab** studies high-speed compliant control for learning tasks such as table tennis, using a maintenance-intensive set-up. A tendon-driven pneumatic artificial muscle robot arm was developed in-house to study antagonistically actuated joints, allowing for light-weight segments, incorporating strong pneumatic muscles, and using co-contraction for compliant control. We use this robot to show the beneficial impact of passive compliant muscular actuation in real-world robotics applications.

The software is based on the robot programming framework o80 and makes use of a custom four-camera high-speed vision setup that reliably detects table tennis balls at (200 Hz). A ten camera Vicon motion capture system enables to precisely track objects equipped with markers at 300 Hz. Strong LED lighting, with adjustable intensity and color, support tracking of objects at such frame rates.

For dexterous manipulation tasks, we developed a *TriFinger* robot setup. The design is focused on robustness and safety, permitting safe operation without human supervision and training reinforcement learning algorithms directly on the real robots. We have eight such platforms in total. They can be accessed remotely via a job submission system based on HTCondor, thus allowing external collaborators to use the robots as well as the organisation of the "Real Robot Challenge" which enabled safe robotics research even during Covid-19.

Brain-Imaging Equipment

The **Brain-Computer Interfaces (BCI) Lab** worked in two main areas: Clinical, high-fidelity electroencephalography (EEG) studies, and large-scale EEG studies with lower-fidelity consumer devices. We have an electromagnetically shielded cabin (mrShield by CFV) for high-fidelity, low-noise laboratory studies. Two 128-channel amplifiers enable high-density EEG, eye (EOG), and muscle (EMG) recordings inside and outside of the laboratory.

For large-scale EEG studies, we have acquired a stock of 34 Muse EEG headbands (InteraXon, Canada). These lower-fidelity consumer devices are ergonomic and easy to use. When paired with a computer or iPad, patients can autonomously participate in large-scale studies at home, with researcher involvement limited to experimental design and data analysis.

Computational Imaging

In computational imaging, it is desirable to develop image processing algorithms that work not just on synthetic but also on real data. To record data for varying setups and with controlled distortions, we use several SLR, CMOS, and CCD cameras with a variety of lenses as well as tele scopes (including a 12" Astro Physics Riccardi-Honders) that allow us to work on real-world astronomical image sequences affected by turbulence. For quality assessment and quantitative comparisons, we use an image quality analysis system (iQ Analyer by Image Engineering). Additionally, we have developed a precise test-panel that allows us to efficiently measure the properties of imaging optics (such as MTF) in a single shot.

More information: https://ei.is.mpg.de/pages/equipment

2.4 Awards & Honors

2021

Francesco Locatello, ETH Medal for his PhD Thesis (2021)

Karimi, Amir-Hossein: received the Google PhD Fellowship in Machine Learning 2021

Bernhard Schölkopf received the 2020 BBVA Frontiers of Knowledge Award. Due to the pandemic, the award ceremony was postponed to September 2021.

Georgios Arvanitidis, best Student Paper Award, at *Robotics: Science and Systems (R:SS)*, 2021, for the paper: "Learning Riemannian Manifolds for Geodesic Motion Skills", by Hadi Beik-Mohammadi, Søren Hauberg, Georgios Arvanitidis, Gerhard Neumann, Leonel Rozo

Gary Becigneul: Dieter-Rampacher-Prize 2020

2020

Krikamol Muandet, best Paper Award, International Conference on 3D Vision (3DV), 2020, for the paper "Grasping Field: Learning Implicit Representations for Human Grasps", by Karunratanakul, K., Yang, J., Zhang, Y., Black, M., Muandet, K., Tang, S

Bernhard Schölkopf awarded with "Deutscher KI-Innovationspreis" on October 1, 2020.

Stefan Bauer elected CIFAR Azrieli Global Scholar. The research group leader at MPI-IS is one of thirteen early-career researchers that have been elected. He will join the "Learning in Machines & Brains" CIFAR research program.

Bernhard Schölkopf receives Marsilius Medal and holds Marsilius Lecture "Symbolische, Statistische und Kausale Intelligenz" at the University of Heidelberg, Germany.

Alex Hawkins-Hooker, **Mateo Rojas-Carulla**, **Bernhard Schölkopf** and **Gabriele Schweikert** are one of the winning teams of the Encode Imputation Challenge.

Sebastian Weichwald (recent graduate of EI Department): won the Causality 4 Climate NeurIPS competition together with his team members.

2019

Niki Kilbertus wird im Rahmen des #KI50 Projekts der Gesellschaft für Informatik (GI) als einen von zwei "Newcomer des Jahres" in der Kategorie "Informatik"gekürt

Bernhard Schölkopf: Appointed as Full Member of the Heidelberg Academy of Sciences of the State of Baden-Württemberg

Bernhard Schölkopf receives the Körber European Science Preis 2019.

Francesco Locatello, Stefan Bauer, Bernhard Schölkopf et. al.: ICML best paper award 2019 for the paper "Challenging Common Assumptions in the Unsupervised Learning of Disentangled Representations"

Bernhard Schölkopf: honoured as one of the leading minds in German AI research.

Francesco Locatello: 2019 Google PhD Fellowship for Machine Learning Award.

Jan Peters has been elected IEEE Fellow.

2018

2018 Best Paper Award at the International Conference on Advances in System Testing and Validation (**Jan Peters** et. al.)

Olivier Bousquet, Leon Bottou: Test of Time Award, 2018 Neural Information Processing Systems conference, for their 2007 paper on "The Tradeoffs of Large Scale Learning" reporting work originally started in 2003 when Olivier Bousquet was a member of our lab.

Bernhard Schölkopf receives the Landesforschungspreis 2018 for Basic Research by the State of Baden-Württemberg.

Dominik Janzing, Jonas Peters, Bernhard Schölkopf: Causality in Statistics Education Award (American Statistical Association).

Bernhard Schölkopf: Gottfried Wilhelm Leibniz-Preis 2018, Deutsche Forschungsgemeinsschaft (DFG).

2017

Bernhard Schölkopf: ACM Fellow for contributions to the theory and practice of machine learning.

Matej Balog, Nilesh Tripuraneni, Zoubin Ghahramani, Adrian Weller: Honorable Mentions at ICML 2017 for their paper: "Lost Relatives of the Gumbel Trick".

2016

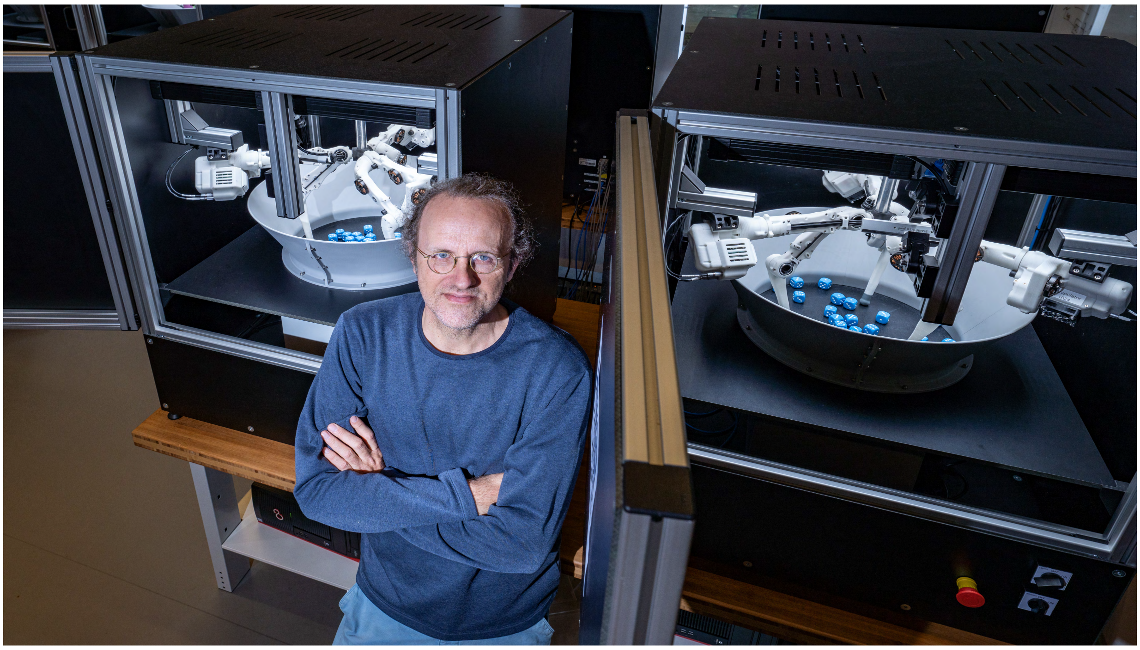
Moritz Grosse-Wentrup, **Vinay Jayaram**: IEEE Brain Initiative Best Paper Award at the IEEE SMC 6th Workshop on Brain-Machine Interface Systems, at the Systems, Man, and Cybernetics Annual Conference in Budapest.

Daniel, C.; van Hoof, H.; Neumann, G..; **Peters, Jan**: Best Student Paper Award of ECML-PKDD 2016 for their paper: "Probabilistic Inference for Determining Options in Reinforcement Learning".

Jonas Peters: elected New Member of the German "Young Academy".

Bernhard Schölkopf: has been elected member of the Leopoldina (German National Academy of Science).

2.5 Director profile: Bernhard Schölkopf



Biography

Bernhard Schölkopf studied Physics, Mathematics and Philosophy in Tübingen and London. In 1994 he joined Bell Labs to work on a Ph.D. with Vladimir Vapnik. Following researcher positions at GMD, Microsoft Research, and a biotech startup, Schölkopf started his lab at the Max Planck Institute for Biological Cybernetics (Tübingen) in 2002. In 2011, he co-founded the Max Planck Institute for Intelligent Systems. He has been program chair of NeurIPS and COLT and is co-editor-in-chief of the flagship journal in machine learning (JMLR). With Alex Smola, he initiated the Machine Learning Summer Schools series in 2002, which has meanwhile been organized, by various teams, 40 times. He is one of the most cited researchers in Computer Science.

Awards & Honours

2020	BBVA Frontiers of Knowledge Award (with I. Guyon and V. Vapnik)
2019	Körber European Science Prize
2019	Fellow, Canadian Institute for Advanced Research (CIFAR)
2019	Hector Science Award
2018	Causality in Statistics Education Award, American Statistical Association (with D. Janzing & J. Peters), for the monograph *Elements of Causal Inference*
2014	Royal Society Milner Award, London
2013	XXVIIIth Courant Lectures, New York University
2012	Academy Prize, Berlin-Brandenburg Academy of Sciences and Humanities
2011	Max Planck Research Award of the Alexander-von-Humboldt-Stiftung (with S. Thrun)
2011	Posner Lecture, Neural Information Processing Systems Conference
2011	Annual Brain Computer Interfacing Research Award (with M. Grosse-Wentrup)
2010	Inclusion in the list of ISI Highly Cited Researchers (Category: Engineering)
2006	J. K. Aggarwal Prize, International Association for Pattern Recognition
1998	Annual dissertation prize of the German Society for Computer Science (GI)
1992	Lionel Cooper Memorial Prize of the University of London
1992 – 1997	Studienstiftung des deutschen Volkes

Appointments

2019 – present	ELLIS Board Member & President
2019 – present	Affiliated Professor, ETH Zürich
2018 – present	Managing Director, MPI for Intelligent Systems, Stuttgart & Tübingen
2017 – 2018	Spokesperson, Cyber Valley (4 Months)
2017 – present	Distinguished Amazon Scholar
2015	Overseas Visiting Scholar, St John's College, Cambridge
2015 – present	Co-Director of the Max Planck ETH Center for Learning Systems
2015 – present	Member of the Max Planck Campus Triumvirate, Tübingen
2010 – present	Honorary professor, University of Tübingen, Dept. of Physics
2002 – present	Honorary professor, TU Berlin, Dept. of Computer Science
2001 – present	Scientific member of the Max Planck Society

Memberships

Machine Learning in Science, Cluster of Excellence, University of Tübingen; Image-Guided and Functionally Instructed Tumor Therapies, Cluster of Excellence, University of Tübingen; Data-integrated Simulation Science, Cluster of Excellence, Stuttgart University; Tübingen AI Center (Co-Director); Deutsche Mathematiker Vereinigung (DMV); Association for Computing Machinery (ACM, Fellow); Institute of Electrical and Electronics Engineers (IEEE, Senior Member); Heidelberg Academy of Sciences and Humanities; Leopoldina - German National Academy of Sciences.

Board Memberships

Foundations and Trends in Machine Learning (since 2007); Co-editor-in-chief of Journal of Machine Learning Research (JMLR); Advisory Committee Chair, LMB Program of the Canadian Institute of Advanced Research (2014 – 2019); ACM Heidelberg Laureate Forum Committee (2014 – 2015); Co-founder of DALI – Data, Learning, and Inference (2015 –); Core Committee Member, MPI for Biological Cybernetics (2015 –); Editorial Board Member of ACM Books (2016 –); The Future of AI – A New York University Symposium on Science, Technology, Reason and Ethics (2016); Initial Training Network for Machine Learning for Personalized Medicine (MLFPM); Forum Scientiarum at the University of Tübingen; Machine Learning Summer Schools (MLSS); International Machine Learning Society (IMLS, 2006-2019); Neural Information Processing Systems Foundation (NeurIPS); IEEE Global Initiative for Ethical Considerations in the Design of Autonomous Systems, Committee on Reframing Lethal Autonomous Weapons Systems (2016); IEEE John Von Neumann Medal Committee (2018 – 2022); Global Forum on Artificial Intelligence for Humanity (GFAIH) Program Committee (2019); Jury Member, Engineering and Tech, Falling Walls Conference (2020); Royal Society Milner Award Committee (2020 – 2022); Advisory Board Member, Leibniz Kolleg, University of Tübingen (2021 – 2023); Co-Chair of the 1st Conference on Causal Learning and Resoning (CLeaR) (2022).

Keynote, Conference, and Public Talks

Machine Learning for Signal Processing (MLSP), Vietri sul Mare (2016); International Conference on Machine Learning (ICML), Sydney (2017); Asian Conference on Machine Learning (ACML), Seoul (2017); Postel Lecture, UCLA (2018); SIAM International Conference on Data Mining (SDM), San Diego (2018); International Conference on Learning Representations (ICLR), Vancouver (2018); Falling Walls Conference, Berlin (2018); Annual IST/ÖAW Lecture, Vienna (2019); United Nations Workshop on Militarization of AI, New York City (2019); GI Tagung / KI, Kassel (2019), IEEE International Conference on Acoustics, Speech and Signal Processing, Toronto (2021); Bitkom, Germany (2021); G20 AI Summit, Genova (2021).

Links

Link to CV on website: https://ei.is.mpg.de/~bs

3 HAPTIC INTELLIGENCE

3.1 Research Overview

Figure 3.1: The Haptic Intelligence Department at the Stuttgart site of the Max Planck Institute for Intelligent Systems in October of 2021. The screens held across the front row show seven team members who could not be physically present for the photograph.

When you touch objects in your surroundings, you can discern each item's physical properties from the rich array of **haptic cues** you experience, including both the tactile sensations arising in your skin and the kinesthetic cues originating in your muscles and joints. For example, picking up a **glass of champagne** refines your visual estimates of the glass's location, size, shape, and weight while also making you rapidly aware of the temperature, stiffness, smoothness, and friction of its surfaces. Feeling how these haptic sensations develop in response to your motions enables you to not only perceive the glass's material properties but also manipulate it fluidly, whether your goal is to hand it to a friend, bring it to your own lips to drink, place it upside-down in your dishwasher, or rotate it under a flow of hot water as your other hand scrubs it clean.

Over the course of life, humans leverage their rich sense of touch to master a wide variety of **physical tasks**, from everyday necessities like buttoning a jacket to difficult feats such as sculpting a marble statue or inserting a needle into a patient's vein. Many tasks are challenging when first tried, but practice usually enables one to improve the resulting interaction and optimize one's motions so they become almost automatic. You can gain some appreciation for the complexity of tasks that normally feel effortless, such as slicing bread or brushing your teeth, by trying to complete them with your non-dominant hand. Similarly, even the simplest manual skills become almost impossible if you lose your tactile sensitivity due to local anesthetic or a lack of blood flow. The **crucial role of the sense of touch** is also deeply appreciated by researchers working to create **autonomous robots** that can competently manipulate everyday objects and safely interact with humans in unstructured environments. Such systems rarely take advantage of haptic cues and thus often struggle to match the perception, manipulation, and interaction capabilities of humans.

Although humans experience this sense coherently, touch stems from a wide range of distributed mechanical, thermal, and pain receptors. Each type of mechanoreceptor responds most strongly to a different category of stimulation, with overlapping characteristic frequency ranges that go from steady state all the way up to 1000 Hz. Much about the sense of touch is understood, and many other aspects still need to be investigated. The most notable differences between touch and the more well-understood senses of vision and hearing are that **exploring the world through touch requires action** and that **what one feels greatly depends on how one moves**. It is also helpful to consider that vision has high spatial acuity and only moderate temporal acuity, while hearing is the opposite; different aspects of haptic perception lie along this spatiotemporal continuum between vision and hearing. Because we don't yet fully understand haptic interaction, few **computer and machine interfaces** provide the human operator with high-fidelity touch feedback or carefully analyze the physical signals generated during an interaction, limiting their usability.

The Haptic Intelligence Department of the Max Planck Institute for Intelligent Systems aims to **elevate and formalize our understanding of haptic interaction** while simultaneously **inventing helpful human-computer, human-machine, and human-robot systems** that take advantage of the unique capabilities of the sense of touch. We pursue this goal by undertaking research projects in the five main research fields of **fingertip haptics**, **haptic interface technology**, **teleoperation interfaces**, **physical human-robot interaction**, and **touch sensing**.

The specific projects we pursue take shape through a **bottom-up process** that draws on the experience and interests of the primary researcher, the expertise and creativity of our director and other HI department members, ideas from our collaborators both within and outside of MPI-IS, and recent discoveries in haptics and related areas. The resulting projects typically fit well within one of the above fields or bridge two of them, such as fingertip haptics + haptic interface technology or physical human-robot interaction + touch sensing; many projects are inspired by specific medical applications. Each project has a **lead researcher** who is a research scientist, postdoctoral fellow, doctoral student, or master's thesis student. This person will generally be the first author of resulting publications, and Dr. Kuchenbecker will generally be the last author. Depending on the demands of the project, this pair may be supported by one or more other researchers, visiting scientists, engineers, technicians, student research assistants, and/or interns. Our department has grown to a steady-state size of about 30 members, including about eight postdoctoral scientists, fifteen doctoral students, five engineers and technicians, and a steady flow of visiting scientists, interns, and student workers.

Members of the HI department enjoy working in our diverse international research environment. Our current team is **gender balanced** (eighteen women and seventeen men) and hails from **eighteen countries** around the world (Austria, Bulgaria, Canada, China, Colombia, France, Germany, India, Iran, Israel, Italy, Malaysia, the Netherlands, South Korea, Turkey, the USA, Uruguay, and Vietnam). Because we pursue highly **interdisciplinary** projects, we welcome applications from people in a wide range of fields. Many of our current department members have a background in mechanical engineering, biomedical engineering, electrical engineering, and/or computer science. Dr. Kuchenbecker uses an online system to let her team members book meetings on demand, aiming to meet with each person at least every two weeks. This time is spent discussing the recent progress, challenges, and future goals for each of the researcher's projects. When she travels or is otherwise occupied, she often assigns technical triplet meetings between researchers in lieu of these individual research meetings.

We hold **department meeting** for 90 minutes every other week, using Zoom to enable participation from home, Tübingen, Zürich, Pittsburgh, and many other locations. Other institute researchers, staff members, and future employees often join as guests. Our recurring agenda covers personnel changes, publication activities, awards and media attention, third-party funding, internal logistics, recent scientific talks, and upcoming events. Each attendee then spends one to two minutes giving an **individual update** on his or her recent activities, including accomplishments, goals, and a lesson (something they recently learned that others could benefit from). As a rotating task, a lab member writes down funny things that are said during each group meeting, and our director emails out an edited version of these **quotes** along with her typed **minutes** from the meeting.

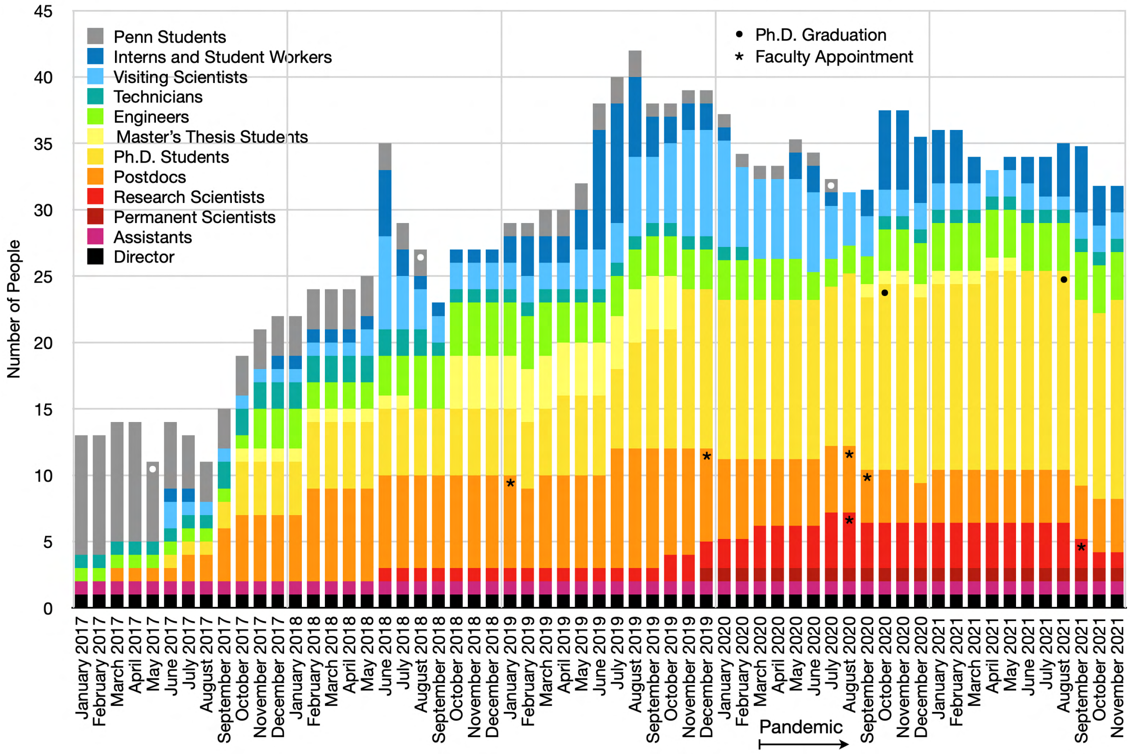


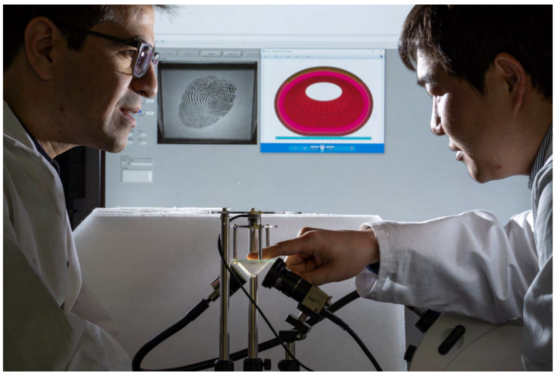
Figure 3.2: The development of the number of people in the Haptic Intelligence Department from our start in January of 2017 through November of 2021. The graduation dates of five doctoral students are highlighted with round markers, and stars mark the appointments of four of our postdoctoral researchers and two of our research scientists as independent scientists at academic research institutions.

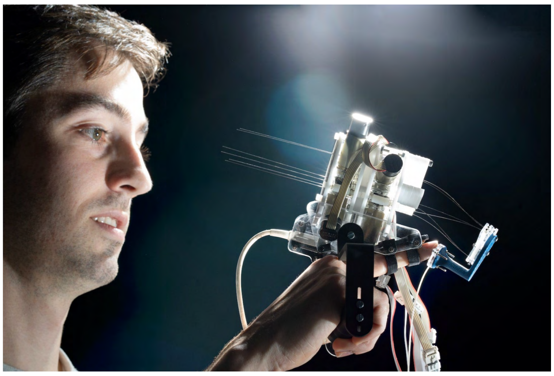
Our primary publishing targets are full-length **journal articles** in a range of research fields and **top-tier conference papers** in fields related to computer science. We use hands-on **demonstrations** of our technology and peer-reviewed **short papers** (often works in progress, late-breaking reports, or workshop papers) as stepping stones to longer-format papers, beneficially gathering feedback from other researchers early in the process to increase the chances of high-impact contributions. To increase visibility for our activities and gain experience formally presenting research, our scientists frequently attend conferences in haptics, human-computer interaction, human-robot interaction, and robotics.

To help people prepare for conference presentations, thesis defenses, and job talks, the HI Department frequently holds **presentation club**. The presenter practices his or her talk, answers a large volume of questions similar to what they might expect in the target presentation venue, and then receives constructive suggestions from the group on how the presentation could be made more effective. In other weeks, presentation club includes reports from people who recently attended a conference, an interactive discussion of a particular paper, a brainstorming session for one of our research projects, or tips from lab members on tools helpful for research. Presentation club is coordinated by a lab member who serves at least six months in this position. Other key **departmental leadership roles** that rotate include Demo Coordinator, Human Subjects Coordinator, Internship Wizard, and Poster Coordinator. Working together in these ways helps us advance human understanding of touch cues and discover new opportunities for their use in interactions between humans, computers, and machines.

3.2 Research Fields

3.2.1 Fingertip Haptics





Human **fingertips** are marvelously sensitive to minute variations in surface properties and contact conditions, providing the soft medium that enables dexterous manipulation. Although we use them constantly, fingertips are not yet fully understood, nor are all the mechanisms that underpin **haptic** perception, action, and learning. How do the geometrical and material properties of a fingertip affect its physical interactions and the way those interactions are perceived? We investigate both natural finger-surface contact and fingertip interactions with different kinds of haptic interfaces.

Some of our work in this research field aims to unravel the **complex phenomena of contact** between skin and natural objects, investigating physics, perception, and the link between them. We also investigate the mechanisms used to display **artificial haptic cues** in order to understand and thereby improve their performance. Such projects often employ high-fidelity external motion, force/torque, and acceleration sensors that capture the physical details of the interaction as it unfolds. Finally, we seek to invent and understand **new haptic rendering technologies for the fingertips**, so that we can better control their mechanical and perceptual effects on the human user.

More information: https://hi.is.mpg.de/field/fingertip-haptics

3.2.2 Haptic Interface Technology

Haptic interfaces are **mechatronic systems** that modulate the physical interaction between a human and his or her tangible surroundings so that the human can act on and feel a virtual and/or remote environment. How can such systems vividly reproduce the perceptual experience of touching real objects and provide feedback that helps the user improve his or her motor skills? We seek to answer these questions by carefully studying existing technologies and inventing new haptic interfaces.

Since the start of the field of haptics in the early 1990's, three distinct archetypal **haptic interface categories** have emerged: grounded kinesthetic haptic interfaces, ungrounded haptic interfaces, and surface haptic interfaces. Although they differ in key ways, they all function in the same overall manner: the haptic interface's mechanical, electrical, and computational elements work together to monitor and modify the user's physical interaction with his or her tangible surroundings.

We do research on all three categories of haptic interfaces. In the relatively well-established area of **grounded force-feedback devices**, we mainly seek to understand, share, and benchmark the diversity of past designs to accelerate haptic device innovation and enable standardized performance comparisons. We are also inventing new high-performance haptic actuation systems for grounded devices. In the newer areas of **ungrounded and surface haptic interfaces**, we aim to expand what is possible by inventing, refining, and carefully evaluating new devices. Such work often includes hardware design, actuator and sensor selection, calibration, control optimization, application design, system integration, and human studies.

More information: https://hi.is.mpg.de/field/haptic-interface-technology

3.2.3 Teleoperation Interfaces

Commonly used in minimally invasive robotic surgery and hazardous material handling, telerobotic systems empower humans to manipulate items by remotely controlling a robot. The user sends commands and receives multimodal feedback via the **teleoperation interface**, which is where we focus our attention. How can such systems support the operator to perform tasks with outcomes that are as good as (or even better than) those accomplished via direct manipulation? We work to create new ways to capture operator input, deliver haptic feedback, and otherwise augment the operator's abilities, and we systematically study how these technologies affect the operator.

Remotely accomplishing complex tasks such as surgical suturing benefits from a rich bidirectional interface that is optimized for human capabilities. Because the addition of force feedback tends to drive bilateral teleoperators unstable, most such systems include no haptic cues; the operator thus has to learn to rely on what he or she can see. We work on inventing and refining **clever ways of stably providing haptic feedback** during teleoperation, often by focusing on tactile rather than kinesthetic cues. A main thrust of this work centers on vibrotactile feedback of the robot's contact vibrations, as this approach is both simple and highly effective. We are also looking into how **visual augmented reality** can enrich the operator's experience in minimally invasive robotic surgery.

Importantly, we study how the addition of these novel technologies affects the operator over both **short and long time scales**. Having direct access to physical contact information changes the processing required for one to complete a task. Our investigations in this domain also show that the haptic signals captured during teleoperation contain significant information about the **manual skill** of the operator currently controlling the robot.

More information: https://hi.is.mpg.de/field/teleoperation-interfaces

3.2.4 Physical Human-Robot Interaction

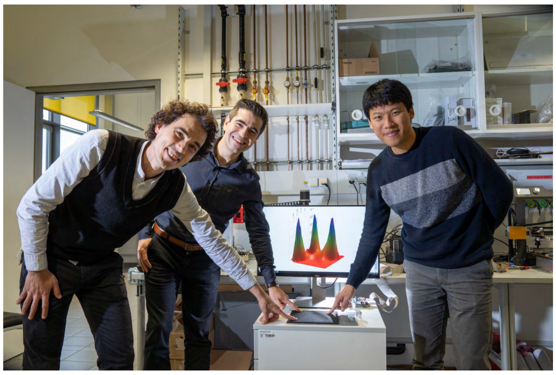
While autonomous robots excel at repetitive tasks in controlled environments, the world in which most humans live is messy, constantly changing, and filled with other people. Important opportunities exist for helping humans in these **unstructured environments**, particularly as our population ages, but new approaches are needed for robots to be as successful inside homes, clinics, and hospitals as they already are in factories. We are thus working to discover whether and how physical human-robot interaction can benefit humans by designing, building, and evaluating new systems targeted at particular user populations.

We are interested in robots that **physically interact** with both objects and people to accomplish useful tasks, taking advantage of novel strategies to detect and understand contact. Many physical interactions that transpire between humans, such as object handovers and hugs, have **strong social dynamics** that have been carefully studied. Robots that skillfully take part in such interactions may be able to work more effectively with and around humans. We are interested in how such robots should behave, and how people react to them in different scenarios.

Social-physical human-robot interaction (spHRI) may have a special role to play in clinical and therapeutic settings, where patients need to perform repetitive physical activities to improve their skills. We envision robots that function as an exercise partner or coach, interacting with the user both physically and socially in a natural and engaging manner. We are also creating algorithms that enable a human to teach a robot new manual tasks, which is again a task that has both physical and social aspects.

More information: https://hi.is.mpg.de/field/physical-human-robot-interaction

3.2.5 Touch Sensing



Humans and animals possess sophisticated skin that not only protects the body but is also exquisitely sensitive to physical contact. In contrast, most robots have **no tactile sensing**, since commercial touch sensors tend to be expensive, difficult to integrate into real robots, and rather limited in size, robustness, sensitivity, and/or reliability. How can we give robots an **effective sense of touch**, both at their fingertips and across their broad body surfaces? We purse a range of approaches to create practical tactile sensors for robots and deeply understand the tactile data generated during physical interactions between robots, humans, and physical objects.

We are working to create robust tactile sensors that can be **easily manufactured** and provide **useful contact information**. Some projects in this domain focus on covering the large surfaces of a robot's body with soft sensors that detect only normal force. Other projects aim to deliver much finer tactile sensation like the fingertip. We also frequently investigate new ways of using the **rich time-series data** from new and existing tactile sensors to increase a robot's haptic intelligence.

More information: https://hi.is.mpg.de/field/touch-sensing

3.3 Selected Research Projects

Finger-Surface Contact Mechanics in Diverse Moisture Conditions

Saekwang Nam, Gokhan Serhat, Yasemin Vardar, David Gueorguiev, Katherine J. Kuchenbecker

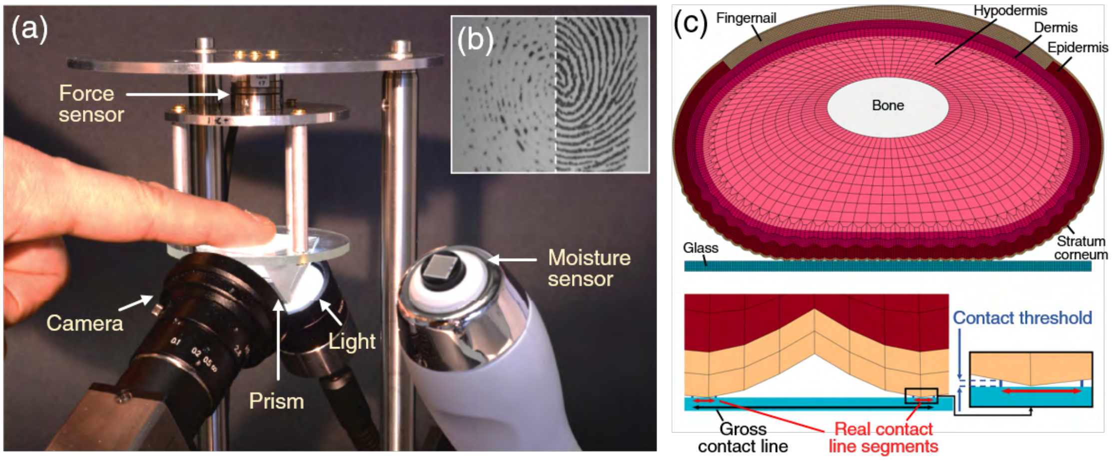


Figure 3.3: (a) One apparatus to measure three-dimensional contact forces, fingerprints over time, and finger moisture. (b) Two captured images showing the real contact area with a dry (left) or moist (right) finger. (c) One of our fingertip finite element models in frictional contact with a surface and the associated contact area calculation.

The finger's instantaneous contact state with a surface is strongly affected by its peripheral environment. *Fluid on the contact surface and the secretion of sweat from the fingerpad's glands cause particularly profound effects* because the outer layer of skin easily absorbs moisture. To elucidate fundamental aspects of tactile interaction, we study how moisture affects the finger's material properties, the contact area, the creation of friction, and perception.

First, we have built a series of **apparatuses** to measure three-dimensional finger contact forces, contact images, and fingerpad moisture [612, 622, 709]. The camera captures clear fingerprint images by means of a reflection-based optical design that contrasts between contact and non-contact areas. We are presently developing a transparent real-time moisture sensor to include in future setups.

We used one setup to investigate the **influence of different wetting conditions** on the initial contact evolution. The area measurements showed that the chosen fluid can drastically alter the real contact area (where the fingerprints touch the glass); however, gross contact area (the entire oval-shaped area over which contact occurs) was only slightly affected. To explore the causes of this phenomenon, we investigated the combined effects of tissue elasticity, skin-surface friction, and fingerprint ridges on contact area using a detailed finite element model. The simulations revealed the dominant influence of the elastic modulus over friction and an unusual contact phenomenon.

We used another apparatus and a three-dimensional finite element model to study how **sweating** affects the development of gross contact area [612, 701]. Four **key material properties** of our model were optimized to fit the measurements obtained from a participant repeatedly pressing on a glass plate in dry, natural, and moist finger conditions. The results showed that the softness of the bulk tissue reduces as the finger becomes more hydrated, and the epidermis of the moist finger is softest.

Finally, we investigated how contact mechanics relate to perception by studying why people sometimes perceive **a sensation of stickiness** when pulling their finger away from a surface [622, 709]. We asked nine participants to actively press their finger on the glass plate of our apparatus. Our analyses showed that finger-surface adhesion builds with pressing time, causing a larger normal impulse during detachment and thus a more intense stickiness sensation.

More information: https://hi.is.mpg.de/project/understanding-fingerpad-moisture-and-friction

Perceptual Integration of Contact Force Components During Tactile Stimulation

David Gueorguiev, Katherine J. Kuchenbecker, Julien Lambert (Université catholique de Louvain), Jean-Louis Thonnard (Université catholique de Louvain)

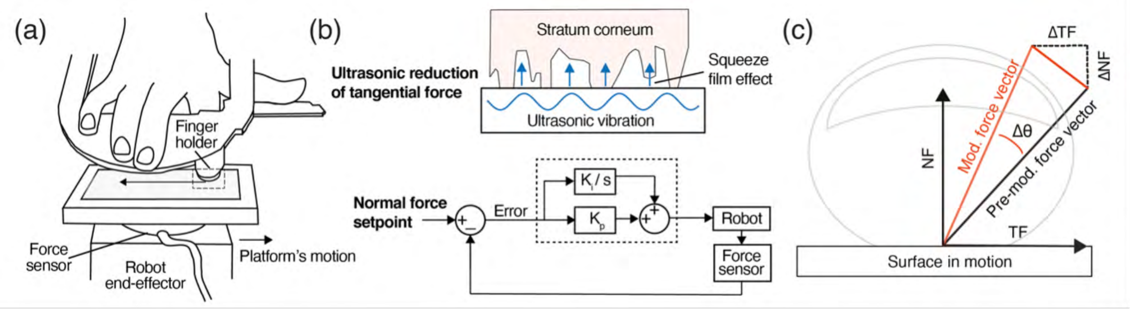


Figure 3.4: (a) The experimental apparatus used to move the surface under the finger. (b) Upper: tangential force (TF) is modulated by ultrasonic vibrations that create a microscale air film between the surface and the skin and thereby reduce the finger-surface friction. Lower: diagram of the controller that modulates normal force (NF). (c) Illustration of the modulation of the contact-force vector when changes are induced.

The contact forces we experience when our body interacts with objects provide **essential sensory cues** that help us understand the world and adapt our behavior. Sliding contact in particular arises in most daily activities, for example, when we feel the smoothness of fabric before buying clothing or when we slide our finger against the screen of a smartphone to move between pictures.

Humans are very sensitive to frictional changes while sliding the fingertip across a flat surface. Despite these observations, it is unclear *how the three-dimensional mechanical deformations induced by haptic exploration are processed by different skin receptors and the brain*. This collaborative project with UCLouvain aims to quantify the respective **contributions of the normal force and the tangential force** to the human perception of tactile stimulation. We induce variations of the normal force with a force-controlled robotic platform during passive stimulation of the finger while simultaneously modulating the tangential force with an ultrasonic haptic display that can reduce the finger-surface friction. By coupling these two technologies, we can generate independent variations of the normal and tangential force components that do not occur during natural interactions [710].

The first result of these experiments showed that humans detect changes in the normal force without interference from the concomitant tangential force variations [651]; however, we also found a higher sensory threshold than is usually observed for force perception. A second study showed that *humans most probably rely on the amplitude of the three-dimensional force vector to perceive changes in the contact force on their skin*, rather than previously hypothesized metrics like the coefficient of friction. These studies elucidated which parameters are the most efficient at **conveying force cues** to the human brain, a result that can both explain and benefit the design of haptic interfaces.

More information: https://hi.is.mpg.de/project/tangential-force-vs-friction-coefficient

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Understanding the Perception of Electrovibration

Yasemin Vardar, Shao-Wen Wu, Luzia Knoedler, Katherine J. Kuchenbecker

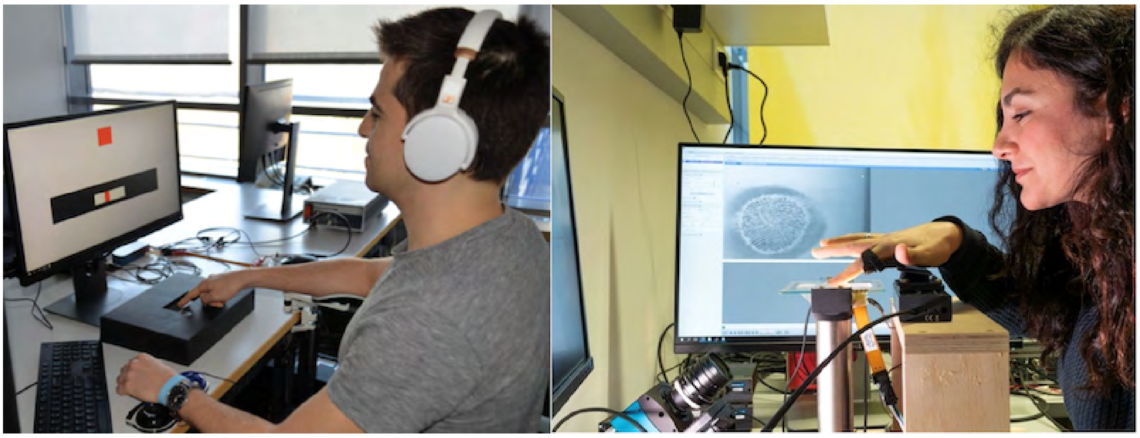


Figure 3.5: Our setups for investigating the haptic rendering technique of electrovibration. We measure the smallest electrovibration forces that participants can reliably feel (left) while interacting with a display using diverse contact conditions, along with the finger-pad deformations caused by these forces (right).

Researchers worldwide want to discover how to generate **compelling tactile sensations** on touchscreens to increase the usability of mobile devices and other interactive computer systems. One technique for generating such sensations is to control the friction force between the screen and the finger-pad of the user via electrostatic actuation; this haptic rendering approach is commonly called **electrovibration**. When an alternating voltage is applied to the conductive layer of a touch screen, an attractive force is generated between its surface and the user's finger. Systematic modulation of the voltage creates various haptic effects.

This project aims to shed light on our limited knowledge of how finger motion (stationary or moving), finger pressing force, and contact by multiple fingers affect electrovibration perception and the underlying physical mechanisms of these perceptions.

In our first study [617, 683, 694], by conducting **psychophysical experiments** and simultaneously measuring **contact forces**, we proved for the first time that *both the finger's motion and contact by a second finger significantly affect what the user feels*. At a given voltage, a single moving finger experiences much larger fluctuating electrovibration forces than a single stationary finger, making electrovibration much easier to feel during interactions involving finger movement. Indeed, only about 30% of participants could detect the stimulus without motion. Part of this difference comes from the fact that relative motion greatly increases the electrical impedance between a finger and the screen. In contrast to some theories, we found that threshold-level electrovibration did not significantly affect the coefficient of kinetic friction in any conditions.

Currently, we are investigating the effects of electrovibration on the contact evolution of finger-pad area. Our preliminary results indicate that the real contact area increases as a function of the alternating electrovibration force, again suggesting that electrovibration perception is mediated by temporal neural mechanisms rather than an overall increase in friction.

More information: https://hi.is.mpg.de/project/understanding-the-physics-behind-electroadhesion

Dynamic Models and Wearable Tactile Devices for the Fingertips

Gokhan Serhat, Ifat Gertler, Katherine J. Kuchenbecker

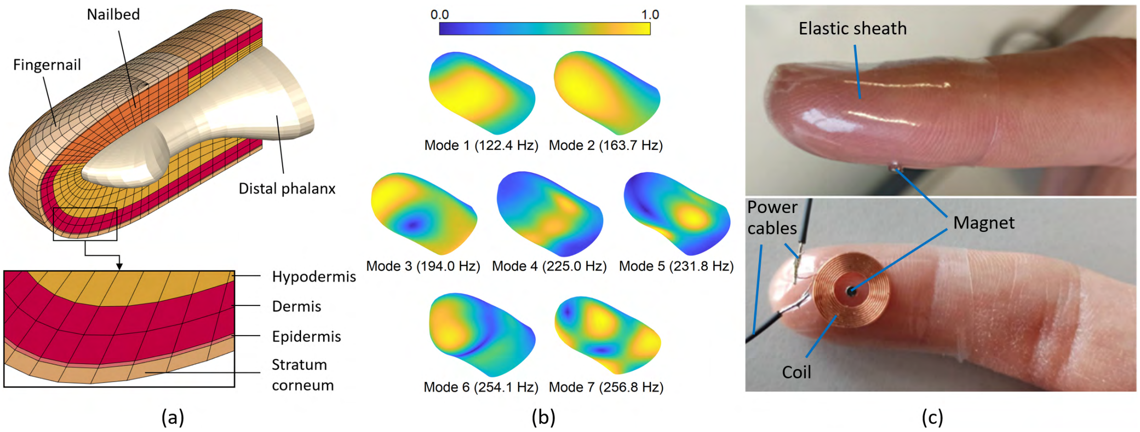


Figure 3.6: Dynamic analysis of the human fingertip and a wearable vibrotactile device partially inspired by these analyses. (a) DigiTip, our high-fidelity finite element model of the fingertip. (b) The first seven free vibration modes predicted by DigiTip. (c) A wearable haptic device created from a thin silicone finger sheath with an embedded magnet for delivering vibrotactile feedback.

Humans regularly use their fingertips to physically explore and manipulate their surroundings. For example, healthy adults can distinguish a near infinite range of textures and can quickly compensate when a grasped object slips unexpectedly. The fingertips exhibit this **very high tactile sensitivity** because they are densely enervated with receptors that detect mechanical stimuli ranging from steady-state deformations up to 1000 Hz vibrations.

Hence, significant scientific effort has been devoted to understanding fingertip deformation mechanics and designing glove-like haptic interfaces, but these efforts have rarely been coordinated or even informed by each other. *This project investigates the dynamic characteristics of the human fingertip and simultaneously uses that knowledge to develop a wearable device that can provide high-fidelity vibration feedback.*

To deeply understand the dynamics of the human fingertip, we used prior anatomy and biomechanics studies to create a **detailed three-dimensional finite element model named DigiTip** [616]. This model was used to compute the **free and forced vibration responses**, which illuminate the deformation of the human fingertip in haptic interactions involving oscillating stimuli. Given the amount of prior research conducted on human fingertips, it is surprising that these free vibration modes have never before been reported in the literature.

We have recently used this understanding to invent a new type of **wearable vibrotactile device**: an elastic sheath comfortably holds an embedded permanent magnet on the skin while AC current through a nearby coil generates strong, clear vibrations. Experiments with human participants confirmed that this design achieves exceptional transmission of expressive vibratory signals, as it adeptly stimulates the fourth vibration mode of the human fingertip. We adapted our DigiTip model to match one particular finger and added the soft elastic film and magnet. The *excellent agreement between the resulting simulated and experimentally measured vibrations* shows the usability of computational models in predicting soft tissue dynamics and characterizing vibratory haptic devices.

More information: https://hi.is.mpg.de/project/dynamic-models-and-wearable-tactile-devices

Novel Designs and Rendering Algorithms for Fingertip Haptic Devices

Eric Young, David Gueorguiev, Katherine J. Kuchenbecker, Claudio Pacchierotti (CNRS, Rainbow Team, Irisa and Inria Rennes Bretagne Atlantique)

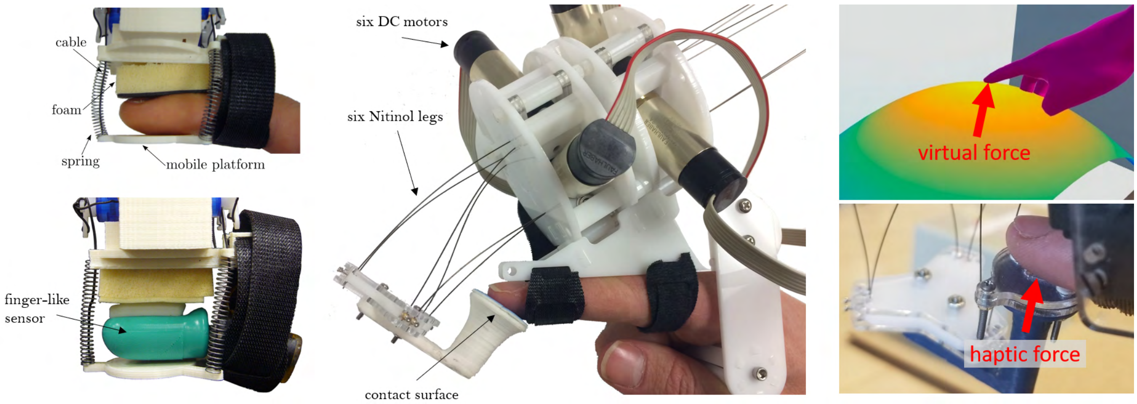


Figure 3.7: This project introduces a wide assortment of fingertip haptic devices and their rendering algorithms. Left: a three-degree-of-freedom (3-DOF) device that can render haptic sensations to a human finger (top) or a finger-like sensor for data collection (bottom). Middle: our 6-DOF fingertip haptic device that renders rich contact sensations by controlling the lengths of six elastic legs. Right: an example of a virtual interaction rendered by this 6-DOF device.

Wearable haptic devices have seen growing interest in recent years, but providing realistic tactile feedback is a challenge not to be solved soon. Daily interactions with physical objects elicit complex sensations at the fingertips. Furthermore, human fingertips exhibit a broad range of physical dimensions and perceptive abilities, adding increased complexity to the task of simulating haptic interactions in a compelling manner. Through this project (see [670] for summary), *we aim to provide hardware- and software-based solutions for rendering more expressive and personalized tactile cues to the fingertip*.

We are the first to explore the idea of rendering **6-DOF tactile fingertip feedback** via a wearable 6-DOF device, such that any fingertip interaction with a surface can be simulated. We demonstrated the potential of parallel continuum manipulators to meet the requirements of such a device [663], and we presented a motorized version named the Fingertip Puppeteer, or Fuppeteer for short [628]. We then used this novel hardware to simulate different lower-dimensional devices and evaluate the role of **tactile dimensionality** on virtual object interaction [646]. The results showed that *higher-dimensional tactile feedback may indeed allow completion of a wider range of virtual tasks, but that feedback dimensionality surprisingly does not greatly affect the exploratory techniques employed by the user*.

It is also essential to examine how to meet the small size and low weight requirements for wearable haptic interfaces. We used principal component analysis to find the minimum number of an existing device's actuators that are required to render a given tactile sensation with minimal estimated haptic rendering error [630].

Finally, we have also explored the idea of **personalizing fingertip tactile feedback** for a particular user. We presented two generalizable software-based approaches to modify an existing data-driven haptic rendering algorithm to more accurately display tactile cues to fingertips of different sizes [621]. Results showed that *both personalization approaches significantly reduced force error magnitudes and improved realism ratings*.

More information: https://hi.is.mpg.de/project/6dof-tactile-fingertip-display

Shape-Changing Devices for Motion Guidance

Adam Spiers, Naomi Tashiro, Eric Young, Robert Faulkner, Bernard Javot, Katherine J. Kuchenbecker, Samantha Melnyk, Tamara Rosales, Yasaman Tahouni (Institute for Computational Design and Construction, University of Stuttgart), Tiffany Cheng (Institute for Computational Design and Construction, University of Stuttgart), Dylan Wood (Institute for Computational Design and Construction, University of Stuttgart), Achim Menges (Institute for Computational Design and Construction, University of Stuttgart)

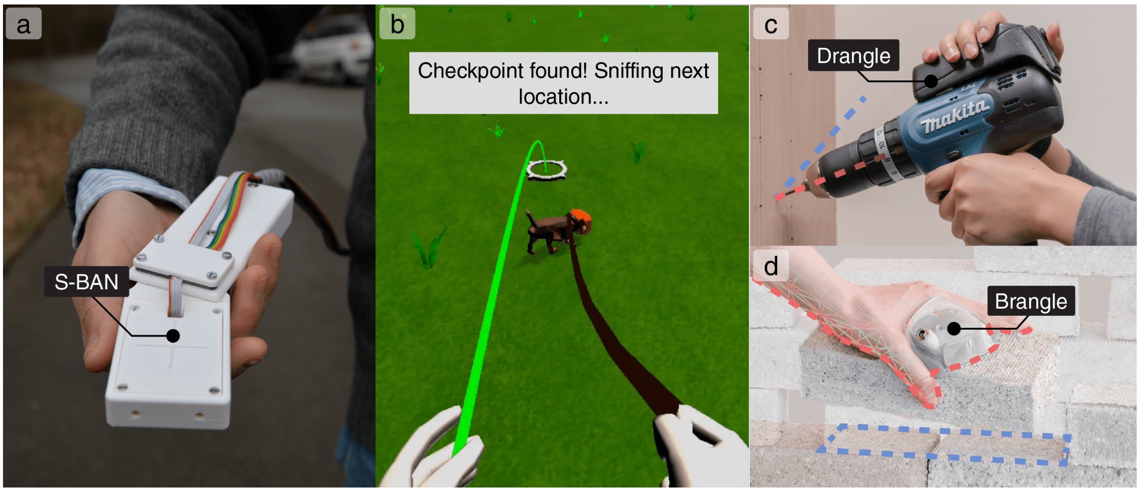


Figure 3.8: Our three shape-changing haptic interfaces. (a) The S-BAN is a handheld device that modifies its shape to communicate guidance directions to pedestrians. (b) The virtual reality environment used to evaluate S-BAN navigation. (c) A user drills a hole at a specified angle while feeling shape-changing guidance from Drangle. (d) A user places a brick at a desired angle using cues presented by Brangle.

Haptic devices are a promising alternative to devices with visual feedback, which demands one's gaze and is inaccessible to vision-impaired people, and audio feedback, which can mask or be masked by environmental sounds and is inaccessible to hearing-impaired people. **Shape-changing devices** are a subset of haptic interfaces that provide tangible feedback by physically transforming their shape; this transformation can easily be perceived by the body part contacting the device.

We are exploring how such devices can be used to guide **human motion**, such as rotation and translation. Shape-changing feedback can be particularly intuitive for this task because the device itself can rotate and translate to different poses in the hand of the user. We created three shape-changing devices that assist people with real-world tasks: the S-BAN (Shape-Based-Assistance for Navigation) provides navigation guidance, and Drangle and Brangle guide users in construction tasks.

The **S-BAN** is a new handheld haptic device that can pivot left/right and extend/retract its body [715], opening up possibilities and questions around spatial data representation through touch. To date, we have tested the feedback of the S-BAN via perceptual studies and embodied navigation tasks in virtual reality, where user performance with the S-BAN was compared to other navigation modalities. Results indicated *highest user sensitivity to guidance cues in the cardinal directions and equivalent navigation efficiency, slower navigation time, and a more elevated gaze* when compared to vision-based guidance from a smartphone proxy.

Drangle helps a user orient a drill when drilling angled holes, and **Brangle** guides a user to place bricks in a desired arrangement [675]. Both devices use graded bidirectional edge-changing cues to guide the user to the target angle. In a user study, participants understood the shape-changing feedback and enjoyed using both devices. *Users strongly preferred Drangle over a mechanical drill guide, and they found Drangle's fingertip feedback more intuitive than Brangle's palmar cues.* Future work includes integrating such devices into systems that can improve construction workflows relevant to IntCDC.

More information: https://hi.is.mpg.de/project/shape-changing-devices-for-motion-guidance

Exploring and Benchmarking Grounded Force-Feedback Devices

Hasti Seifi, Farimah Fazlollahi, Gunhyuk Park, Katherine J. Kuchenbecker, Michael Oppermann (University of British Columbia), John Sastrillo (University of British Columbia), Jessica Ip (University of British Columbia), Ashutosh Agrawal (IIT Guwahati), Karon E. MacLean (University of British Columbia)

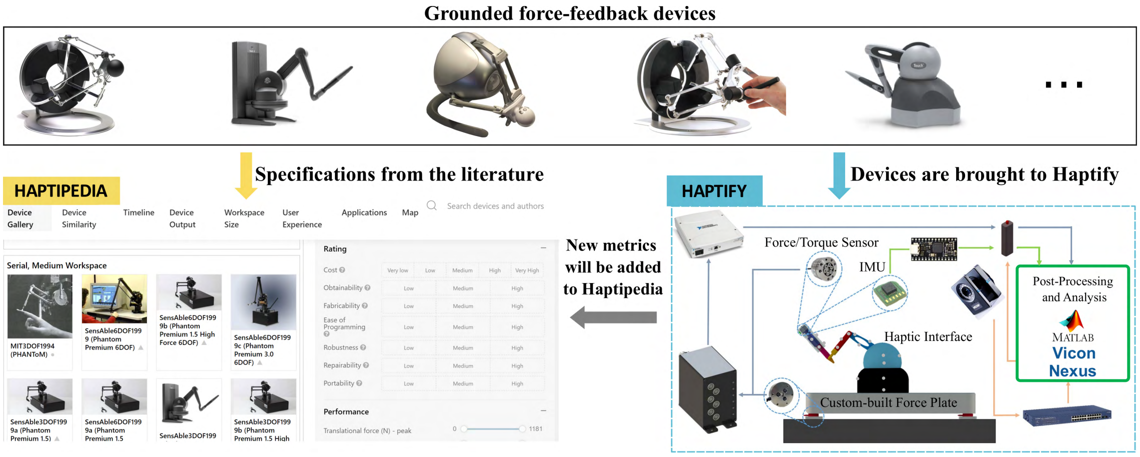


Figure 3.9: Haptipedia enables designers with different backgrounds and goals to browse and explore over 100 grounded force-feedback (GFF) devices. Haptify experimentally measures key benchmarking metrics for GFF devices using precise motion, force, and vibration sensors. Including these new metrics will let Haptipedia users know how each device actually performs.

A **grounded force-feedback (GFF)** device is a mechatronic system mounted to a stationary surface that measures the user's motion and/or force and outputs forces and/or motions in response so that the user can feel a virtual or remote environment. Over the last three decades, researchers have invented hundreds of GFF devices. However, to design a novel device or select one that is suitable for a given task, researchers need efficient ways of **accessing standardized performance specifications** of existing devices. We created Haptipedia and Haptify to facilitate this process.

Haptipedia (http://haptipedia.org/) is an online **taxonomy**, **database**, and **visualization** of more than 105 GFF devices [661, 724, 725]. Haptipedia's design was driven by both a systematic review of the haptic device literature [661] and rich input from a diverse group of haptic designers [648]. We iteratively developed Haptipedia by screening 2,812 haptics publications, selecting 105 papers that described a haptic device. We extracted attributes from device documentations, built a GFF taxonomy, database, and visualization, and evaluated them with users. With Haptipedia, designers can **browse** a growing database of GFF devices, **examine** their design trade-offs, and **repurpose** them into novel devices and interactions.

Haptify is our **measurement-based benchmarking system** for GFF devices with three main sensing components: a motion-capture system, a custom-built force plate, and a sensing end-effector [699]. We carefully chose these **external sensors** to work for almost all existing devices in Haptipedia. Our approach to examining GFF devices is inspired by real use cases, in which the device is placed on a table and the human user moves the device end-effector while the device is either off (passive mode) or rendering virtual content (active mode). We use Haptify's measurements to **define new metrics** for evaluating GFF device performance, such as global free-space forces and parasitic vibrations. These metrics enable one to **quantitatively compare** how devices feel to the user during similar tasks. We will soon run a study to identify the physical interrogations that expert hapticians employ when evaluating a GFF device and link Haptify measurements with interview data [679].

More information: https://hi.is.mpg.de/project/haptipedia-and-haptify

Halbach-Ring Motor Design

Bernard Javot, Vu Nguyen, Katherine J. Kuchenbecker

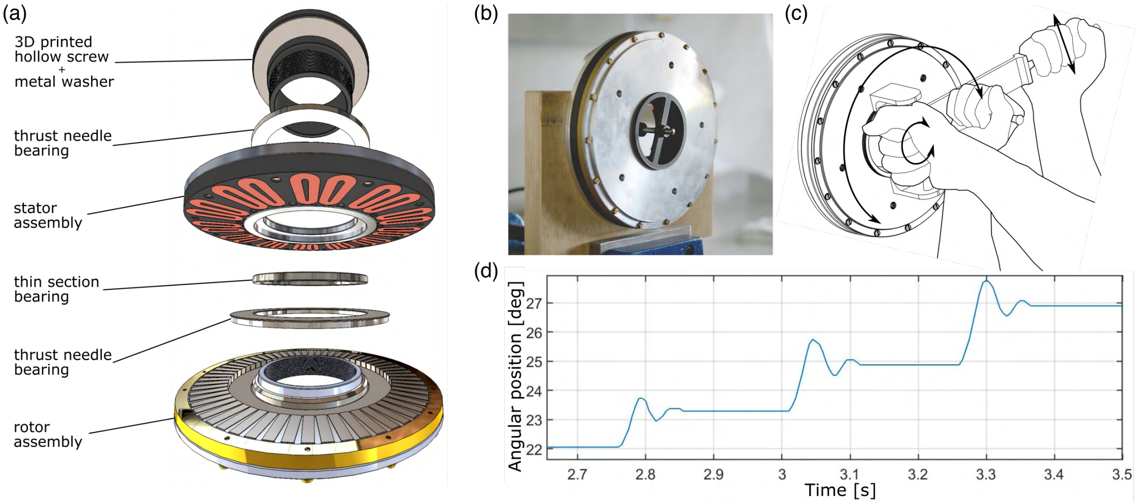


Figure 3.10: We have invented a new high-performance motor for haptic applications. (a) Exploded view of the motor design. (b) Photograph of the fabricated motor. (c) Illustration of how such a motor could be used for three possible force-feedback devices. (d) Three step responses (1.2°, 1.6°, and 2°) of the motor in closed-loop position control.

Quality **force-feedback** devices should supply haptic cues that are both strong and crisp. Delivering such sensations requires *the use of high-torque-density motors that rotate smoothly and are capable of operating at near-zero speeds at any angular position*. Currently available electric motors fall short of these requirements in direct-drive operation and must thus always be used with a mechanical transmission, which is complex, bulky, and encumbering.

In this project, we design and evaluate a new motor structure: a **brushless ironless motor** using a **Halbach-magnet ring** and a **planar Lorentz-coil array** [742]. The strengthened magnetic field on one side of the magnet ring varies sinusoidally along the circumference of the ring. Our design takes advantage of this attribute by *using the two-phase Lorentz coils to interact with the field and thus generate a constant torque at any angular position*. This two-phase design allows for a planar coil arrangement instead of overlapped coils as with existing three-phase designs. The two-phase planar coils can be separately made to enhance the fill factor (i.e., effective volume of copper divided by total coil volume) and geometrical accuracy. The motor's torque constant has been both analytically calculated and experimentally verified through torque measurements.

This motor outperforms existing Halbach ring and cylinder motors with a torque constant of 0.78 Nm/A, a record in the field. With a constant amplitude of the two-phase currents, the standard deviation of the measured torque around a full spatial period of the magnet array is within 3% of the nominal torque. We validated our motor design by commanding step responses with and without a torque disturbance at random angular positions. We used a proportional-integral-derivative controller with a refreshing frequency of 200 Hz.

Ongoing work focuses on more detailed characterization of our new motor's performance compared to the state of the art. Future research will explore the use of this motor in common haptic applications such as upper-limb rehabilitation or the steering wheel of a driving simulator.

More information: https://hi.is.mpg.de/project/halbach-ring-motor-design

Gait Rehabilitation Through Haptic Feedback

Siyao Hu, Nataliya Rokhmanova, Katherine J. Kuchenbecker, Krista Fjeld (SUNY Stony Brook University), Erin Vasudevan (SUNY Stony Brook University), Peter B. Shull (Shanghai Jiao Tong University), Eni Halilaj (Carnegie Mellon University)

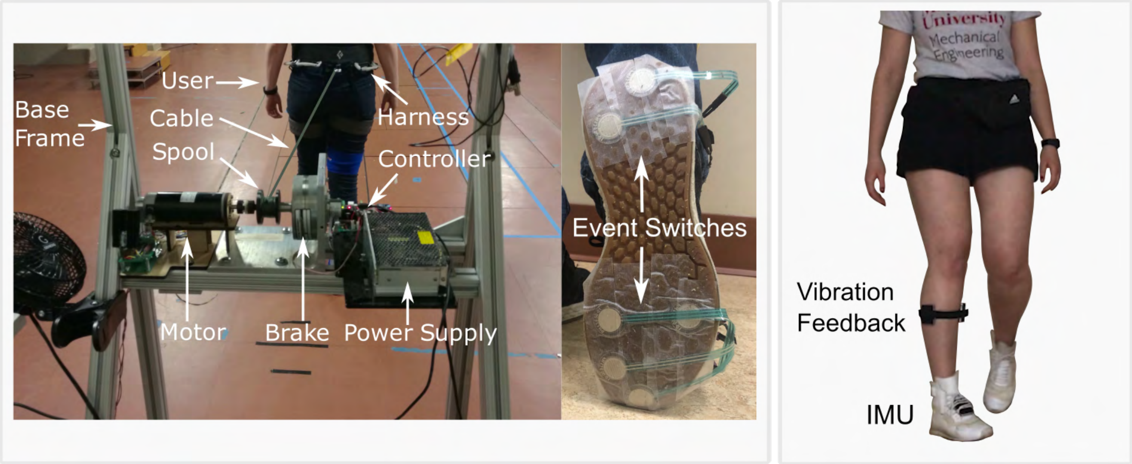


Figure 3.11: Wearable sensors, haptic actuators, and simple real-time feedback algorithms can be used to deliver haptic cues to a walking person. Our Gait Propulsion Trainer (left) periodically resists the user's forward progress to try to improve gait speed and symmetry, while a new commercial wearable biofeedback system (right) uses vibrations to try to improve knee loading.

Restoring healthy gait after injury, stroke, or joint disease is a core part of the rehabilitation process. Novel haptic devices provide an opportunity to supplement current medical practice to improve walking speed, symmetry, or joint loading in clinical populations. These devices can be used in-clinic, such as our **Gait Propulsion Trainer (GPT)**, and some could also support at-home treatment, such as **wearable biofeedback**.

Walking speed and symmetry are high priorities for people with hemiparesis from stroke. Invented through a collaboration with Stony Brook University, the GPT helps such individuals by applying *periodic stance-phase resistance* as the user walks overground [671]. It consists of two main components: (1) the stationary device provides resistance forces via a cable that tethers the pelvis to a magnetic-particle brake [664], and (2) the wearable system detects gait events via foot switches to control the timing of the resistance forces [613]. A preliminary study was conducted with a 24-year-old female with left-side hemiparesis and gait asymmetry following pediatric traumatic brain injury. GPT resistance increased paretic leg propulsive forces generated in late stance by 25% over baseline values, and increased propulsion persisted when GPT resistance was removed in post-braking trials. The results of other GPT studies are being analyzed.

Unlike stroke, knee osteoarthritis is a degenerative disease whose progression is exacerbated by knee loading. Targeted gait retraining to decrease joint loading is an effective conservative treatment strategy that has previously been limited to laboratory settings. To enable ubiquitous rehabilitation in natural environments, we are working to characterize efficacy and user response to a *wearable haptic biofeedback device* developed by SageMotion, LLC [688]. Insights from ongoing experiments with this system will inform our invention of new hardware and software for haptic gait rehabilitation.

With increased characterization of the long-term effects of gait retraining on hemiparetic or osteoarthritic gait, these emerging devices can help reshape the rehabilitation process for improved clinical outcomes.

More information: https://hi.is.mpg.de/project/gait-rehabilitation-through-haptic-feedback

Vibrotactile Playback for Teaching Sensorimotor Skills in Medical Procedures

Ravali Gourishetti, Gokhan Serhat, Ifat Gertler, Katherine J. Kuchenbecker

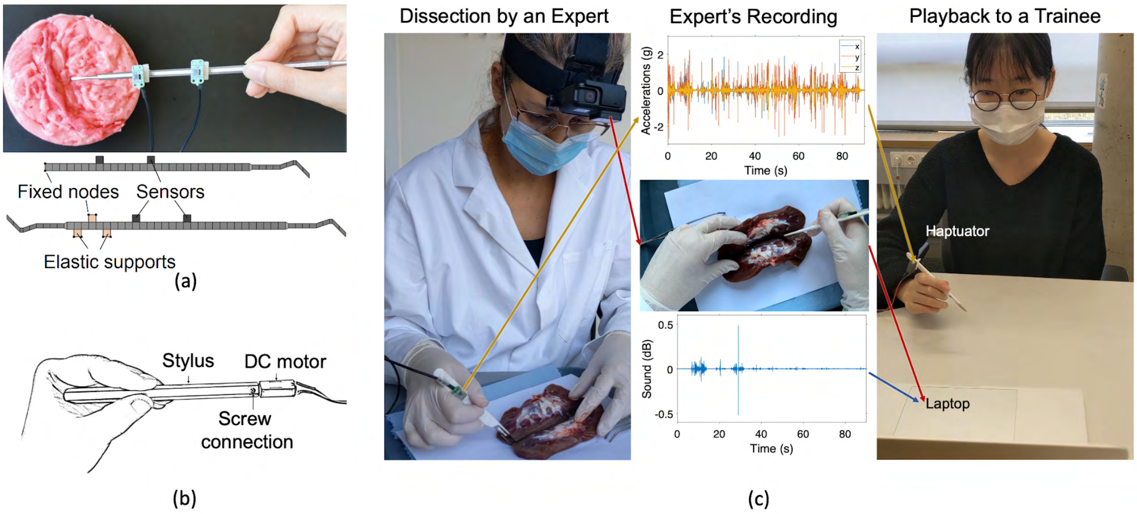


Figure 3.12: We are investigating several aspects of a medical training technique that records and replays instrument vibrations along with video and audio. (a) A finite element model used to optimize the location of the vibration sensor. (b) Our new approach to vibrotactile actuation using a DC motor. (c) An expert dissecting a pig kidney (left); the vibrations recorded from the scalpel (top middle); one first-person image (center middle), and the corresponding audio signal (bottom middle); a trainee experiencing the recorded interaction via a laptop and an actuated tool (right).

Clinicians perform many tasks that require **complex sensorimotor skills**, which are challenging and take time to master. Experts strongly recommend using simulators for training, as the patient's safety is of top priority. However, creating effective simulators requires a deep understanding of both engineering and medicine. Considering these challenges, we developed *a method to capture clinically relevant vibrotactile cues without disrupting the procedure and replay these cues along with video and audio for training* [680].

We attach a small accelerometer to the tool to robustly measure the rich physical contact vibrations felt by the expert without disturbing their movements. We seek to **optimize the location of the accelerometer** to maximize its vibration-sensing capability in the frequency range relevant to touch. For this goal, we characterize the dynamic properties of the selected medical tool by utilizing finite element analysis along with physical experiments [691]. We plan to validate the effectiveness of the optimized accelerometer placement through comparisons with other configurations during actual tool use. Finally, we process the contact vibrations measured with an optimally placed accelerometer and record them with the corresponding sound and video.

For training, we replay the audio, video, and vibration signals using a **vibrotactile actuator** along with a display. Listening to and watching the tool interacting with the tissue while also feeling what the expert felt provides a realistic experience with many advantages compared to physical and virtual simulators. Commonly used vibrotactile actuators are either expensive or have limited vibration output amplitudes. To tackle these problems, we designed *a cost-effective DC-motor-based vibrotactile actuation system that can generate high-fidelity haptic feedback on a stylus*. We plan to use this compact and effective actuation approach for replaying the recorded vibrotactile cues.

More information: https://hi.is.mpg.de/project/vibrotactile-playback-for-teaching-sensorimotor-skills

Dimensional Reduction from 3D to 1D for Realistic Vibration Rendering

Hojin Lee, Gunhyuk Park, Guney Tombak, Katherine J. Kuchenbecker

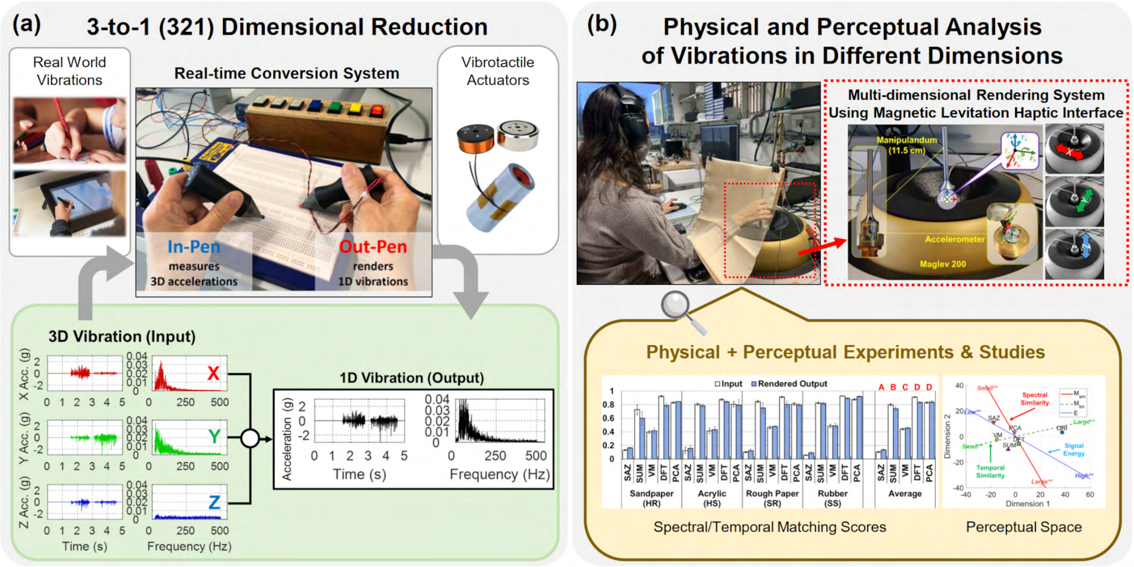


Figure 3.13: We are studying ways to reduce a real 3D vibration to a perceptually equivalent 1D vibration. (a) The concept and our real-time conversion system. (b) Our analysis of multi-dimensional vibrations using a magnetic levitation haptic interface.

Unconstrained tool-mediated interaction with a surface generates **3D vibrations** that contain high-frequency accelerations in all Cartesian directions. These vibrations convey rich task information, so they need to be captured and portrayed for the user to feel in both virtual and remote interactions. To limit system cost and complexity, haptics researchers often *reduce 3D vibrations into 1D signals and render them using a single-axis actuator* as humans cannot easily perceive the direction of vibrations. Such **three-to-one (321) reduction** can be performed using many different algorithms that have rarely been compared.

This project investigates the quality of **321 conversion methods** by analyzing the properties of their input and output vibrations. We established a **real-time conversion system** that simultaneously measures 3D accelerations and plays corresponding 1D vibrations [719, 732]. A user can interact with various objects via a stylus that contains a three-axis accelerometer. The captured signals are then reduced to 1D by different algorithms and rendered by a standard voice-coil actuator. Objective analysis and subjective user ratings confirmed that *more sophisticated conversion methods such as DFT321 perform better* than the common approach of choosing a single-axis signal [655].

We also developed a novel **multi-dimensional vibration rendering system** that can accurately generate 3D vibrations using a commercial magnetic levitation haptic device. We quantitatively and qualitatively verified its performance at rendering recorded 3D vibrations [698]. The system was then used to conduct experiments to compare human perception between the original 3D and different 1D versions of the same vibration signal. Ongoing work assesses the characteristics of all common 321 algorithms by establishing perceptual spaces.

This project provides many practical results for both real-time haptic teleoperation and offline haptic processing. For instance, our findings can contribute to medical teleoperation systems by offering a simple but realistic 321 method that allows surgeons to feel vibrotactile feedback from remote surgical robots.

More information: https://hi.is.mpg.de/project/reducing-3d-vibrations-to-1d

Minimally Invasive Surgical Training with Multimodal Feedback and Automatic Skill Evaluation

Fabian Krauthausen, Katherine J. Kuchenbecker, Maria Paola Forte, Haliza MatHusin, Jeremy D. Brown (Johns Hopkins University), Sergio Machaca (Johns Hopkins University), Eric Cao (Johns Hopkins University), Jaimie Carlson (University of Pennsylvania), Yousi A. Oquendo (University of Pennsylvania), David I. Lee (University of Pennsylvania), Thane A. Blinman (Children's Hospital of Philadelphia), Ernest D. Gomez (University of Pennsylvania; Beth Israel Deaconess Medical Center, Harvard Medical School)

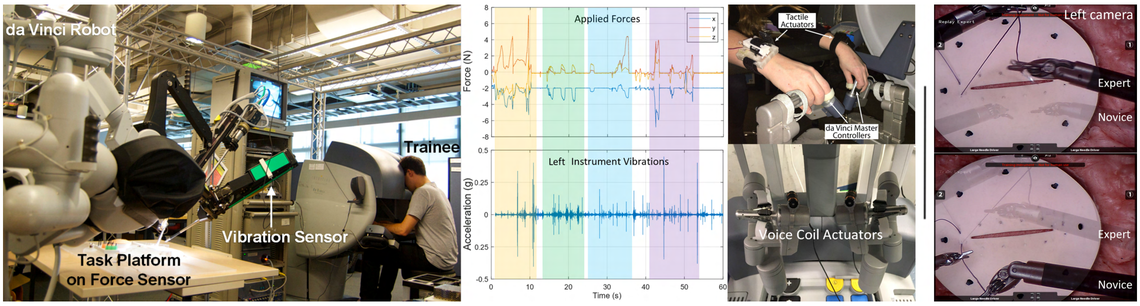


Figure 3.14: We are investigating technical approaches for improving training in robotic surgery. From left to right: Vibration sensors are attached to the arms of a da Vinci surgical system, and a force sensor is placed below the task. Vibration and force signals are used for surgical skill evaluation. Trainees also feel the vibrations as vibrotactile feedback played by voice-coil actuators, while force feedback is rendered through tactile actuators. Visual augmented reality allows training with pre-recorded expert performances.

Minimally invasive surgery (MIS) allows surgeons to perform procedures through tiny incisions, thus reducing healing time compared to traditional open surgery. In robot-assisted MIS (RMIS), surgeons control the instruments from a console. Consequently, besides the advantages of using a robotic platform, RMIS has one main drawback: the lack of haptic feedback, which is critical in manipulation tasks.

We explored the **effects of haptic feedback while training** in RMIS. First, we investigated vibrotactile feedback using VerroTouch, a previously developed system that allows the surgeon to feel the instruments' vibrations at the operator's manipulators. The vibrotactile feedback did not increase or decrease the trainee's workload [692]; ongoing work is examining impacts on learning. We also explored force feedback and created bracelets that squeeze the operator's wrists proportionally to the force applied by the surgical instruments. *Participants applied significantly less force on the task materials when receiving the feedback* [665, 717].

We identified two additional challenges when training in RMIS: the quantitative evaluation of surgical skills and the limits of existing simulators.

Currently, **surgical skill assessment** is mainly conducted through manual video evaluation, which is time-consuming and subject to bias. For MIS, we developed a motion-tracking system and machine-learning algorithm to evaluate trainee performance during suturing tasks. *The automatic ratings closely matched human expert ratings* [634]. For RMIS, we showed that surgical skill can be estimated through completion time, force applied to task materials, and vibrations generated at the surgical instruments [636, 692].

Finally, training with physical **simulators** requires experts to supervise the process. In RMIS, using a robotic console offers the possibility of evaluating surgical skills in real time and training in virtual and augmented reality. However, current virtual simulators result in lower skill transfer to actual surgeries. As such, we hypothesize that *augmented reality simulators could combine the advantages of physical and virtual approaches*. After an early prototype [738], our final developed platform allows expert surgeons to record surgical procedures with multiple modalities and novice surgeons to replay and train with the multimodal recordings, including visual, auditory, and vibrotactile feedback [674].

More information: https://hi.is.mpg.de/project/minimally-invasive-surgical-training

Intraoperative AR Assistance for Robot-Assisted Minimally Invasive Surgery

Guido Caccianiga, Maria Paola Forte, Ravali Gourishetti, Bernard Javot, Fabian Krauthausen, Katherine J. Kuchenbecker, Tobias Engler (Tübingen University Hospital), Ernest T. Gomez (Beth Israel Deaconess Medical Center, Harvard Medical School)

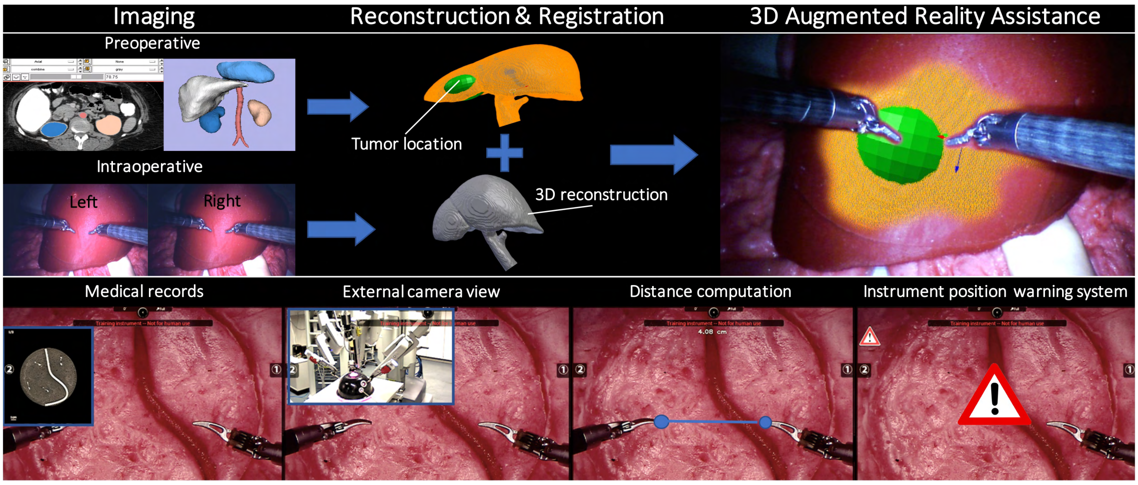


Figure 3.15: We are investigating new approaches for augmented reality in robotic surgery. Top: We envision combining preoperative and intraoperative data to register a liver tumor (shown in green) on the patient's anatomy and track it in real time. Bottom: Our AR functions assist the surgeon by overlaying 2D preoperative data and intraoperative cues (a live view of the operating room, the 3D distance between points selected with the instruments, a warning symbol for out-of-view instruments).

Following recent advances in optics, digital image acquisition, and computer vision, **augmented reality** (AR) applications are being vigorously researched and effectively deployed in several areas of the healthcare industry. In **robot-assisted minimally invasive surgery** (RMIS), AR has the potential to reduce the surgeon's cognitive load and thereby increase focus and efficiency by delivering computational, diagnostic, and visualization tools directly in the surgeon console.

In current clinical practice, AR is successfully applied to neurological surgery for navigation and guidance; after preoperative data are matched with the intraoperative scene via a registration process, the surgeon can superimpose the preoperative data onto the patient's anatomy. In RMIS, soft tissues and deformable organs in the abdomen make accurate superimposition and tracking extremely challenging. As such, we aim to achieve **accurate registration and tracking** by performing a robust anatomical 3D reconstruction of the intraoperative scene. We believe *the resulting image-based guidance will have the potential to help surgeons during critical steps of minimally invasive procedures*.

We have also explored **novel uses and interaction methods** for AR in RMIS [610, 708, 716]. In particular, we developed four voice-controlled functions to view 2D preoperative images, view a live video of the operating room, measure 3D distances, and warn users about instruments that have moved outside the visual field. A user study with eight experienced RMIS surgeons performing dry-lab lymphadenectomy showed that *the functions improved the procedure*; surgeons particularly appreciated the possibility of accessing patient images on demand, measuring distances intraoperatively, and interacting with the functions using voice commands. Our low-cost platform can be easily integrated into any surgical robot equipped with a stereo camera and a stereo viewer [676].

More information: https://hi.is.mpg.de/project/robust-visual-augmented-reality-in-robot-assisted-surgery

Arm-Motion-Based Telerobotic Construction with Vibrotactile Feedback

Yijie Gong, Mayumi Mohan, Haliza MatHusin, Valerio Ortenzi, Ecda Erol, Katherine J. Kuchenbecker

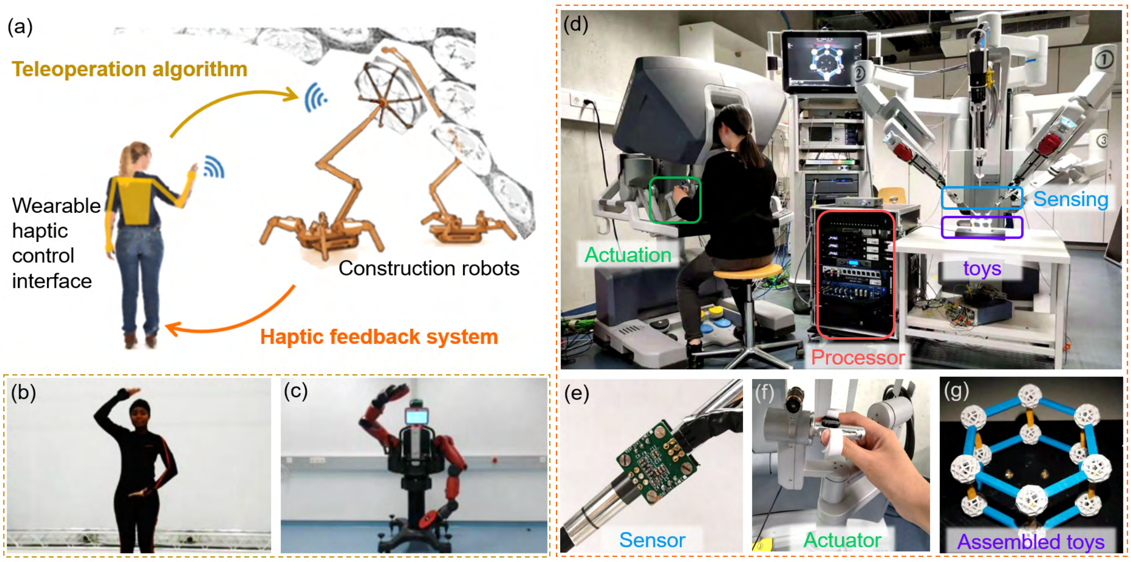


Figure 3.16: We are investigating natural haptic teleoperation for on-site assembly of long-span buildings. (a) The envisioned interaction scenario. (b) An operator wearing an inertial motion-capture suit. (c) A Baxter robot using our retargeting algorithm to follow the operator's arm motions. (d) Our audio-based haptic feedback system and the setup for a user study on construction using a da Vinci robot. (e) A three-axis accelerometer mounted on a robotic tool. (f) A haptic actuator attached to the handle. (g) Construction toys assembled in the study.

Construction machines are usually controlled through joint-space interfaces that are not intuitive or dexterous. In the context of the IntCDC Excellence Cluster, we envision *allowing **teleoperation** of such machines through natural arm motions, and we seek an effective and robust method for providing haptic feedback to facilitate teleoperated **construction activities***. As such, we are developing an advanced telerobotic system with haptic perception for operators in on-site construction. It has two subsystems: **a motion-mapping interface** and **a wearable vibrotactile feedback system**.

We believe the operator should be able to control a construction robot through natural arm motions. We are thus developing a motion-mapping interface that senses the operator's arm movements and commands the robot's arm to move in a similar way. The operator's arm is tracked using an Xsens Link, an inertial motion-capture system. The algorithm is formulated as a constrained optimization problem that minimizes the retargeting error, defined as the error between the pose of the human and that of the robot. We used a Baxter Research Robot as our platform for testing the initial prototype of this algorithm. We are working to adapt the algorithm for use with the IntCDC mini-crane in combination with our haptic feedback system.

The wearable vibrotactile feedback system enables the operator to feel the physical vibrations of the teleoperated machine as it moves and makes contact with other objects on the construction site, improving on our haptic feedback approach from robotic surgery. Our robust system uses accelerometers, an audio mixer, a stereo audio amplifier, and haptic actuators. As an initial validation, we ran a user study using a wired version on a da Vinci robot. Participants performed an assembly task with construction toys in three haptic feedback conditions: no vibrations, one-axis vibrations, and three-axis vibrations. The quantitative and qualitative measures were significantly improved when participants received haptic feedback.

More information: https://hi.is.mpg.de/project/arm-motion-based-telerobotic-construction-and-vibrotactile-feedback

Prendo: Analyzing Human Grasping Strategies for Visually Occluded Objects

Valerio Ortenzi, Katherine J. Kuchenbecker, Maija Filipovica (University of Birmingham), Diar Abdlkarim (University of Birmingham, Obi Robotics Ltd, United Kingdom), Tommaso Pardi (University of Birmingham), Chie Takahashi (University of Cambridge), Alan M. Wing (University of Birmingham), Massimiliano Di Luca (University of Birmingham)

Figure 3.17: Example of a trial in our VR experiment. A KUKA LBR iiwa robot is offering a hammer to the human participant. Top row, left to right: The participant awaits the start of the trial with their hands in the designated area. Then they approach the object held by the robot and grasp it. For explanation only, we depicted the contact points in cyan a posteriori, i.e., the cyan points were not visible during the actual trial. Bottom row, left to right: After the participant has made contact with the object, they answered two questions. The bottom rightmost picture shows an aggregate of the contact points of multiple participants for this scene. Each participant is coded with one color.

Humans display exemplary skill in manipulating objects and can adapt to highly diverse situations. For example, a human handing over an object modulates their grasp and movements to accommodate their partner's capabilities, which greatly increases the likelihood of a successful transfer.

State-of-the-art robot behavior lacks this level of understanding, resulting in interactions that force the human partner to shoulder the burden of adaptation, sometimes even in very awkward and unfavorable postures.

This project investigates how visual occlusion of the object being passed affects the quantitative performance and subjective perception of a human receiver.

We performed an experiment in virtual reality (VR) where each of the three tested objects (hammer, screwdriver, and scissors) was individually presented in a wide variety of poses to the participants [642]. We developed an open-source grasp generator [644] to devise forty physically realistic scenes with diverse occlusion levels for each of the objects.

The participants were tasked with taking a test object from the hand of the virtual robot as if they were to use it. After each trial they were asked to rate the holdability and direct usability of the object given the grasp they had just performed. We carefully analyzed the user's hand and head motion, the time to grasp the object, the chosen grasp location, and the participant ratings. Results show that visual occlusion significantly impacts the grasping strategy of a human receiver and decreases the perceived holdability and direct usability of the object [642].

Our findings lay the groundwork for enriching robot grasping with further knowledge needed to choose the most appropriate grasp for a given task considering visual occlusion and its effects on the human receiver. This new facet to robot intelligence could benefit many HRI scenarios that involve collaborative robotics, such as Industry 4.0 and healthcare.

More information: https://hi.is.mpg.de/project/prendo

Learning Upper-Limb Exercises from Demonstrations

Siyao Hu, Katherine J. Kuchenbecker, Rochelle Mendonca (Columbia University), Michelle J. Johnson (University of Pennsylvania)

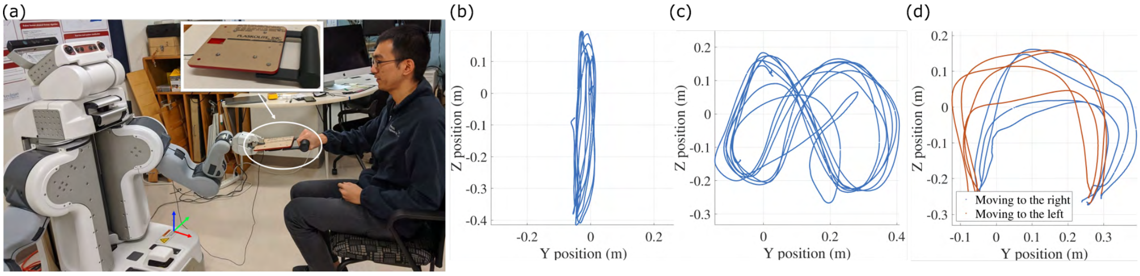


Figure 3.18: (a) A user sitting in front of the PR2 robot. They each use one hand to hold an object that was specifically designed for upper-limb exercises for patients with stroke. Example trajectories from the (b) 1D, (c) 2D, and (d) pick-and-place exercises tested in the study.

Compared to conventional upper-limb therapies, robotic devices can offer multiple advantages in physical training and rehabilitation. Automation can reduce the workload of rehabilitation professionals and augment their ability to provide care to patients by facilitating intensive and repeatable exercise. Additionally, robots can provide objective assessments of a patient's progress using onboard sensors.

In the scope of this research, we developed a learning-from-demonstration (LfD) technique that enables a general-purpose humanoid robot to lead a user through object-mediated upper-limb exercises [614]. Built upon our prior research [625], our approach requires only tens of seconds of training data from a therapist teleoperating the robot to do the task with the user.

We model the robot behavior as a regression problem: during training, the joint distribution of robot position, velocity, and effort (force output at the end-effector) are modeled by a Gaussian mixture model (GMM), and during testing, desired robot effort is regressed from the current state (position and velocity) from the GMM. Compared to the conventional approach of learning time-based trajectories, our state-based strategy produces customized robot behavior and eliminates the need to tune gains to adapt to the user's motor ability.

This approach was evaluated through a user study involving one occupational therapist and six people with stroke [614]. The therapist trained a Willow Garage PR2 on three example tasks for each client: i) periodic 1D motions, ii) periodic 2D motions, and iii) episodic pick and place operations. Both the person with stroke and the therapist then repeatedly performed the tasks alone with the robot and blindly compared the state- and time-based controllers learned from the training data.

Our results show that working models were reliably learned to enable the robot to do the exercise with the user. Furthermore, our state-based approach enabled users to be more actively involved, allowed larger excursion, and generated power outputs more similar to the therapist demonstrations. Finally, the therapist found our strategy more agreeable than the traditional time-based approach. More detailed descriptions of this project's algorithms and results can be found in the Ph.D. thesis of Siyao Hu [671].

More information: https://hi.is.mpg.de/project/learning-upper-limb-exercises-from-demonstrations

Intuitive Social-Physical Robots for Exercise

Mayumi Mohan, Cara Nunez, Haliza MatHusin, Coco Langens, Katherine J. Kuchenbecker, Naomi T. Fitter (Oregon State University), Michelle J. Johnson (University of Pennsylvania)

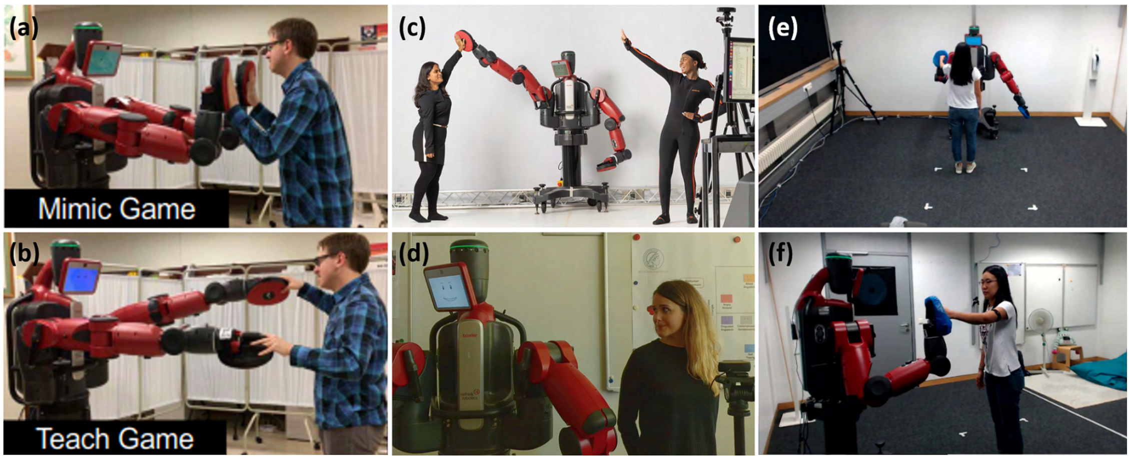


Figure 3.19: We are creating and evaluating ways in which robots can get people to do physical activity. (a, b) An end-user playing two of our eight exercise games with Baxter. (c) An operator teleoperating Baxter's arms to give a high-five to an end-user. (d) Baxter imitating an operator's head movement and facial expression. (e, f) An end-user interacting with Baxter within the Robot Interaction Studio.

Physical activity plays a critical role in maintaining one's health. Past research has shown that well-designed **robots can motivate users** to perform regular exercise and physical therapy.

To understand how people respond to exercise-based interactions with a robot, we developed eight exercise games for the Rethink Robotics Baxter Research Robot. These games were developed with the input and guidance of experts in game design, therapy, and rehabilitation, and via extensive pilot testing [736, 739]. Results from our game evaluation study with 20 younger and 20 older adults support the potential use of bimanual humanoid robots for social-physical exercise interactions [623, 726]. However, these robots must have customizable behaviors and end-user monitoring capabilities to be viable in real-world scenarios.

Novel robot behaviors can be created using **teleoperation**. We are creating an interface that allows a therapist operator to control Baxter in a physically and emotionally expressive manner [718]. Baxter's arm and head movements are based on measurements from Xsens, an inertial motion-capture suit worn by the operator. Ongoing work centers on optimization-based kinematic retargeting in real time. The robot's head and face can simultaneously be teleoperated via emotion recognition on a video of the operator.

The end-users of our robotic exercise coach will be monitored via the Robot Interaction Studio, a platform for enabling **minimally supervised human-robot interaction**. This system combines Captury Live, a real-time markerless motion-capture system, with a ROS-compatible robot to estimate user actions in real time and provide corrective feedback [689]. We evaluated this platform via a user study where Baxter sequentially presented the user with three gesture-based cues in randomized order [645]. Without instructions, we found that the users tended to *explore the interaction workspace*, *mimic Baxter*, and *interact with Baxter's hands*.

Our next step is to enable experts in exercise therapy to prototype a wide range of social-physical interactions for Baxter using our teleoperation interface [682]. These teleoperated behaviors can be recorded and then autonomously learned and repeated. We envision scenarios in a community rehabilitation center where a robot in the Robot Interaction Studio acts as an exercise partner or coach for an end-user.

More information: https://hi.is.mpg.de/project/intuitive-social-physical-robots-for-exercise

Haptic Empathetic Robot Animal (HERA)

Rachael Burns, Katherine J. Kuchenbecker, Hasti Seifi, Hyosang Lee, Robert Faulkner, Sophia Haass, Fayo Ojo, Neha Thomas, Keshav Garg

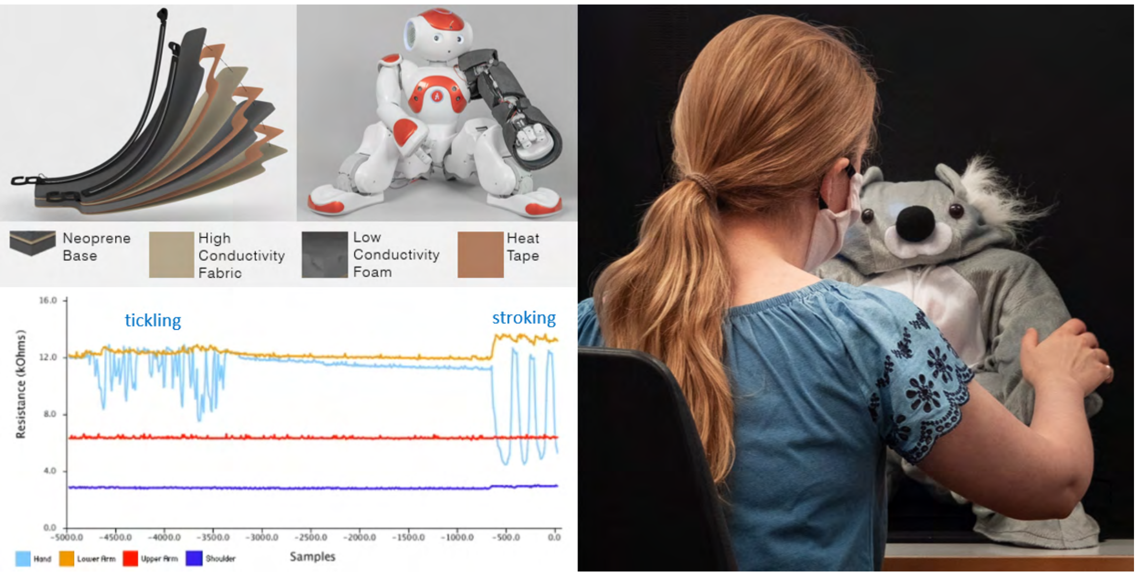


Figure 3.20: HERA's arm is fitted with custom fabric-based tactile sensors to detect social touch gestures. Left: These sensors are robust, easy to make, pleasant to touch, and sensitive to gestures such as tickling and stroking. Right: The sensors are secured on top of the robot's plastic exterior and are hidden underneath a soft koala suit.

Social touch is a key aspect of our daily interactions with other people. We use social touch to gain attention, communicate needs, and convey emotions. However, **children with autism** may have difficulty utilizing social touch. They may be touch-averse and wary of contact with others. Alternatively, they may be touch-seeking and may unknowingly touch their interaction partner in an unsafe way, e.g., too tightly or too frequently. These children are often taught about safe touch by an occupational therapist or similar care professional. While the use of socially assistive robots as educational tools during therapy is increasingly gaining interest, these robots have very limited touch perception, if any at all.

Inspired by the successes of deep-touch pressure therapy and animal-assisted intervention in autism education and care, we propose a touch-perceiving robot animal for children with autism. Our research objective is to test the hypothesis that *a robot animal augmented with tactile sensing can help children with autism learn safe and appropriate touch behavior during social interaction* [678, 684, 685, 731]. We refer to this koala-like robot companion as the Haptic Empathetic Robot Animal, or HERA.

We established seven key **touch-sensing guidelines** that a therapy robot should meet through in-depth interviews with eleven autism specialists [619, 695]. For our initial robot prototype, we enclosed the commercially available humanoid robot NAO inside a koala suit. Based on our guidelines, we then created a **tactile perception system** composed of fabric-based tactile sensors [702, 703] and a gesture classification algorithm. This system can identify the social touch action and force level performed on the robot. HERA will react on both short-term and long-term time scales using an **emotional response algorithm** designed to reinforce appropriate social touch behavior. To further serve as an educational tool, HERA's personality and behavior will be customizable to generate reactions appropriate for each child's learning needs.

More information: https://hi.is.mpg.de/project/haptic-empathetic-robot-animal-hera

HuggieBot: Evolution of an Interactive Hugging Robot with Visual and Haptic Perception

Alexis Block, Hasti Seifi, Katherine J. Kuchenbecker, Sammy Christen (ETH Zurich), Shari Y. Kuchenbecker (R. W. Research Inc.), Roger Gassert (ETH Zurich), Otmar Hilliges (ETH Zurich)

Figure 3.21: We designed, built, and evaluated a series of autonomous hugging robots. Left: HuggieBot 2.0 [647] ready for a hug. This custom human-sized hugging robot has two padded arms, an inflated torso, and a face screen mounted to a rigid frame. Center: HuggieBot 2.0 hugging a user. A camera above the screen visually senses the user at the start of the interaction, and torque sensors on the shoulder flexion and elbow flexion joints are used to embrace the user with a comfortable pressure. Right: The eleven hugging design guidelines that have been validated through this project.

Hugs are complex interactions that must adapt to the height, body shape, actions, and preferences of the hugging partner. Because hugs are known to greatly benefit humans, we created a series of hugging robots that use visual and haptic perception to provide enjoyable interactive hugs. Each improved version of HuggieBot was evaluated by measuring how users emotionally and behaviorally responded to hugging it.

Building on research both within and outside of human-robot interaction, this project proposed eleven guidelines of natural and enjoyable robotic hugging. These eleven guidelines are essential to delivering high-quality robot hugs [669]. We present these guidelines for designers to follow when creating new hugging robots to enhance user acceptance.

In our initial work with HuggieBot 1.0 [631, 730, 733, 741], we evaluated user response to different robot physical characteristics and hugging behaviors. We then iteratively created three versions of an entirely new robotic platform, referred to as HuggieBot 2.0 [647], 3.0 [686], and 4.0 [681]. To enable perceptive and pleasing autonomous robot behavior, we investigated robot responses to four human intra-hug gestures: holding, rubbing, patting, and squeezing [608]. We developed a real-time perceptual algorithm that detects and classifies user actions with 88% accuracy. The algorithm utilizes microphone and pressure sensor data collected from the robot's inflatable sensing torso, which we have named HuggieChest [706, 713]. We also created a probabilistic behavior algorithm that chooses natural robot responses in real time.

The results of our five user studies validated our eleven hugging guidelines and informed the iterative design of HuggieBot [669]. Users enjoy robot softness, robot warmth, and being physically squeezed by the robot. Users dislike being released too soon from a hug and equally dislike being held by the robot for too long. Adding haptic reactivity definitively improves user perception of a hugging robot; the robot's responses and proactive intra-hug gestures were greatly enjoyed. In our last study, we learned that HuggieBot can positively affect users on a physiological level and can be comparable to hugging a person. Participants consistently have more favorable opinions about hugging robots after prolonged interaction with HuggieBot in all our research studies.

More information: https://hi.is.mpg.de/project/huggiebot-evolution-of-an-interactive-hugging-robot-with-visual-and-haptic-perception

Efficient Large-Area Tactile Sensing for Robot Skin

Hyosang Lee, Gokhan Serhat, Bernard Javot, Katherine J. Kuchenbecker, Huanbo Sun, Georg Martius, Kyungseo Park (Korea Advanced Institute of Science and Technology), Jung Kim (Korea Advanced Institute of Science and Technology), Hyunkyu Park (Korea Advanced Institute of Science and Technology)

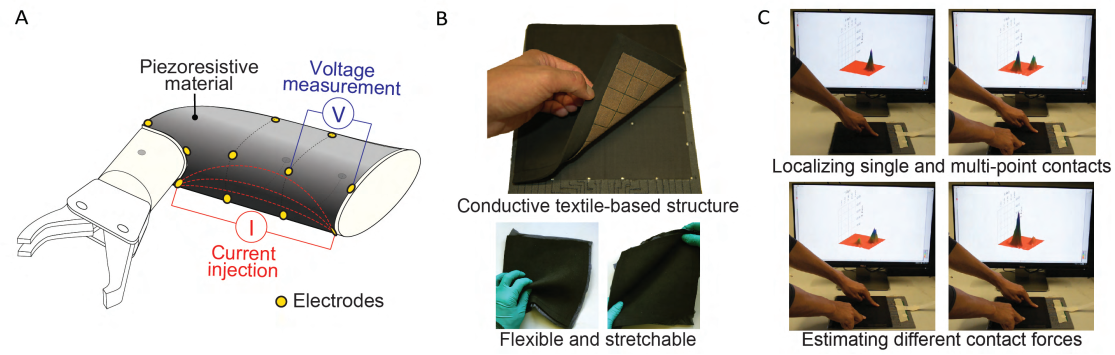


Figure 3.22: We have pioneered large tactile sensors based on electrical resistance tomography (ERT). (A) The key concept of our sensing approach. (B) A sensor prototype made of conductive textiles. (C) Demonstrations of our system's ability to sense multiple contact locations and force magnitude.

Being able to perceive physical contact is essential for intelligent robots to work well in cluttered everyday environments. Since physical contacts can occur at any location, *a successful tactile sensing system should be able to cover all of a robot's exposed surfaces*. Most researchers have pursued the creation of large tactile skin by using many sensing elements that are each responsible for a region; however, deploying many sensing elements is not efficient considering manufacturability, cost-effectiveness, and durability.

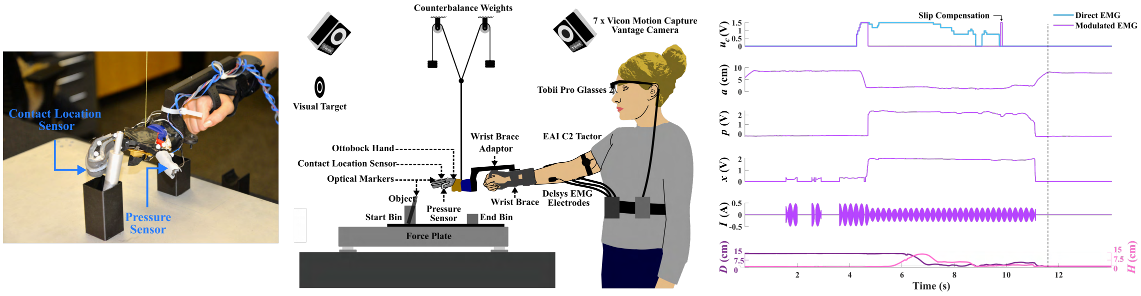
This project aims to *build a robot skin that combines a sensor design and a computational approach to achieve efficient large-area tactile sensing*. The key principle is using a piezoresistive material with a small number of distributed point electrodes; current is injected between successive pairs of electrodes, and the resulting voltage distribution is measured at other electrodes. We used this approach with conductive textiles to create several flexible and stretchable tactile sensor prototype [615, 658, 702, 723, 745]. They successfully estimate contact location, contact shape, and normal force magnitude over a broad region.

This project opened up two subprojects to enhance large-area tactile sensing performance. The first subproject was optimizing the current injection and voltage measurement by considering the temporal locality of contacts across a large area [618]. This subproject achieved a tactile sensing framerate over 400 Hz, which is five times faster than the conventional method. The second subproject was enhancing the contact estimation performance using sim-to-real transfer learning [607, 650]. This subproject demonstrated that a multiphysics model of the sensor could substantially improve the contact information estimation performance when combined with deep neural networks. In the future, we plan to apply this tactile sensing approach on a real robot surface to demonstrate a whole-body robot skin.

More information: https://hi.is.mpg.de/project/large-scale-fabric-based-tactile-sensor

Haptic Feedback and Autonomous Reflexes for Upper-limb Prostheses

Neha Thomas, Farimah Fazlollahi, Katherine J. Kuchenbecker, Jeremy D. Brown (Johns Hopkins University)



(a) (b) (c)

Figure 3.23: The studied task required the user to pick up and move the metal cylinder using a myoelectric prosthesis in the absence of direct vision. (a) Ottobock SensorHand Speed featuring custom-built contact-location and pressure sensors. (b) Experimental setup including an adapter and counterbalance weights to allow use by non-amputee individuals. (c) Traces of select signals from a participant who received vibrotactile feedback and used the prosthesis with reflexes enabled. From top to bottom: raw and reflex-modulated motor command to close the prosthetic hand, hand aperture, pressure sensor, contact-location sensor, current to vibrotactor, and lastly, the distance of the object to the end bin (purple line) and height of the object (pink line).

Upper-limb loss prevents amputees from being able to carry out many day-to-day tasks that are necessary for ensuring a good quality of life. Although commercially available prosthetic limbs can replace some of the lost motor function of the healthy limb, the lack of sensory feedback causes amputees to rely heavily on vision to estimate haptic information like contact, slip, and stiffness. This visual crutch prevents object manipulation in a variety of scenarios that healthy individuals take for granted. For example, being able to pick up a pen from a desk while watching a lecture is a task amputees would be unable to do due to a lack of haptic sensation.

For a prosthesis user to pick up an object without direct vision, we hypothesized that they would need to know where on their prosthetic hand they are touching the object, so that they can appropriately adjust the orientation and placement of their hand. We further hypothesized that imbuing a prosthesis with its own reflexes to prevent adverse events like object slip or excessive grasping force can also improve the performance of dexterous tasks. To realize such a system, we built a pressure sensor for use in the autonomous control loop and developed a novel contact-location sensor. This sensor's signals provide a continuous indication of single-site contact location, which can be fed back to the user in a variety of ways, such as through vibrotactile feedback or distributed pressure feedback.

We investigated the ability of participants to use a myoelectric prosthesis in a reach-to-pick-and-place task without using direct vision. Several combinations of haptic feedback and reflex controllers were tested. Initial results comparing the standard myoelectric prosthesis to a prosthesis with reflex control and vibrotactile feedback show that the combination of tactile feedback and control significantly improve performance consistency [643].

More information: https://hi.is.mpg.de/project/haptic-feedback-and-autonomous-reflexes-for-upper-limb-prostheses

Surface Interactions as Probability Distributions in Embedding Spaces

Behnam Khojasteh, Ben Richardson, Yasemin Vardar, Katherine J. Kuchenbecker, Christian Wallraven, Friedrich Solowjow , Sebastian Trimpe

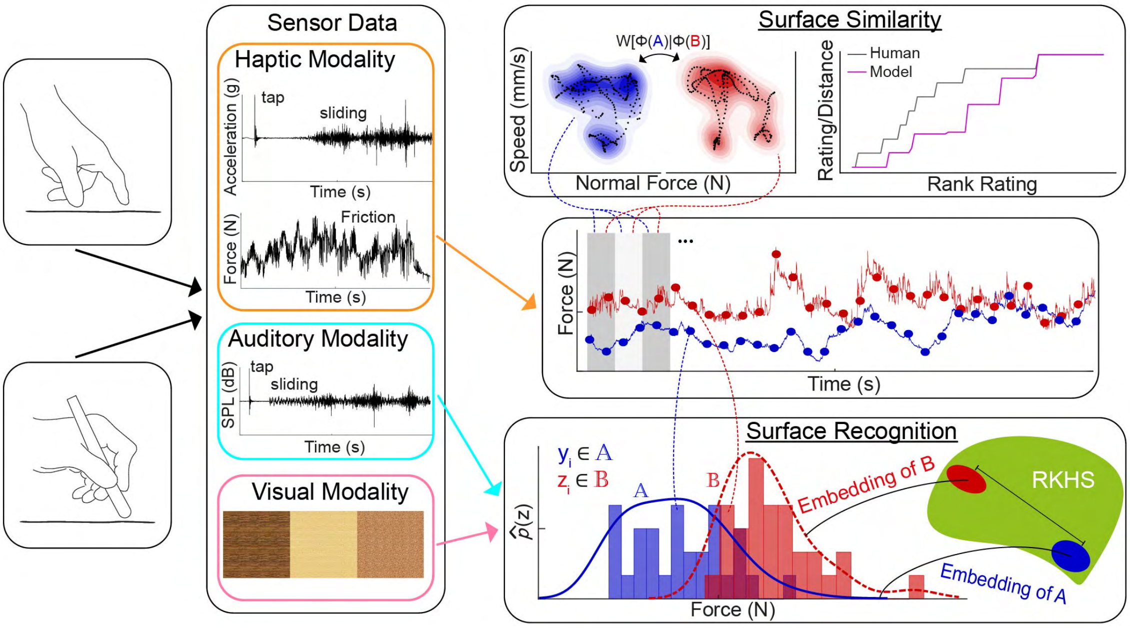


Figure 3.24: Sensor readings are recorded from finger-surface and tool-surface interactions. For surface similarity learning, the Wasserstein metric is used to compute distances between distributions of embedded features that are extracted from windows of interaction data. The embedding function is learned to match those distances to human similarity ratings. For surface classification, the kernel two-sample test is used to compare distributions of interaction data via kernel mean embedding.

When humans touch a surface with their bare finger or via a tool, they feel a rich array of haptic cues revealing its texture (e.g., friction and roughness) and material properties (e.g., deformability). Despite the rich information available from these interactions, research on surface perception and identification has generally either forgone interaction-specific analysis in favor of general surface descriptors or represented interactions as a large set of expertly crafted features taken over full interactions. In this research, we investigate how the physical data generated throughout entire interactions can represent surfaces in both perceptual and classification tasks.

We believe a natural way to consider full interactions is to analyze the **underlying distributions** of the contact-elicited signals, though such an approach has rarely been pursued before. We consider a variety of methods to represent these distributions and use **probability distance metrics** to compare interactions.

In our perceptual experiment, human subjects explore pairs of surfaces and rate the similarity of each pair while finger-surface interaction data are recorded [657]. We partition the signals into overlapping windows and extract eight simple physical features (e.g., average force and vibration power) from each window. We learn a *projection of the features into low-dimensional space such that the Wasserstein distances between pair-wise distributions match the perceived surface-pair dissimilarities*.

For the surface classification task, a human drags a tool over a surface while various sensory information is captured (e.g., force and vibration) [693]. By treating the interaction as a stochastic dynamical process, we can measure the underlying generative distributions of the surfaces by sparsely sampling over time or frequency. We perform the *kernel two-sample test on extracted samples with the maximum mean discrepancy (MMD) metric via kernel mean embedding*. As a result, we are able to classify a large number of surfaces in an automated fashion.

More information: https://hi.is.mpg.de/project/surface-interactions-as-probability-distributions-in-embedding-spaces

Insight: a Haptic Sensor Powered by Vision and Machine Learning

Huanbo Sun, Katherine J. Kuchenbecker, Georg Martius, Iris Andrussow

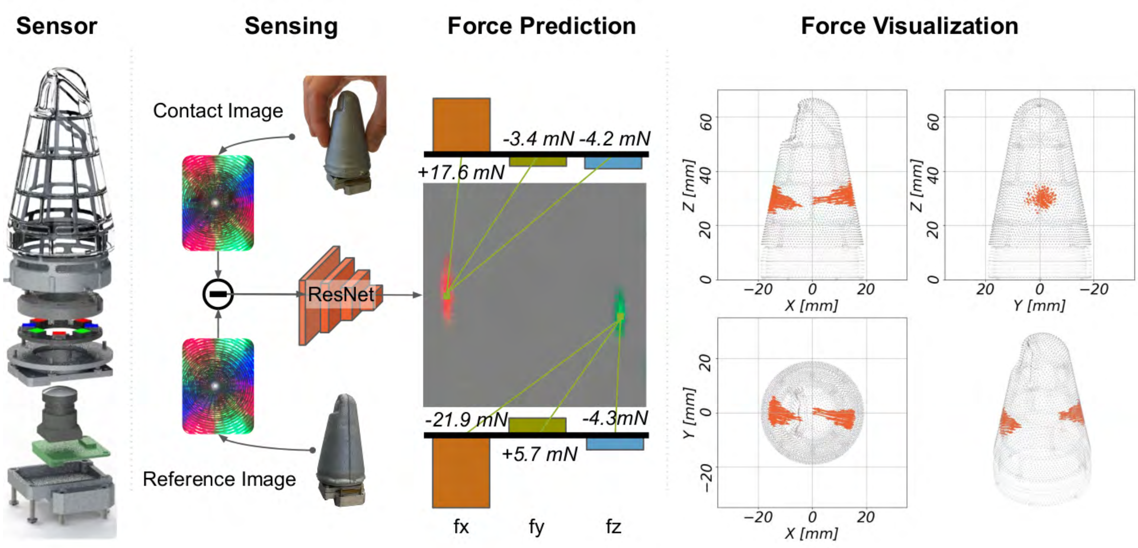


Figure 3.25: We introduce a new soft haptic sensor that uses vision and learning to accurately estimate where and how it is being contacted. The sensor constantly records images from the inside using a camera. Feeding these images and a reference image into a trained deep neural network makes it possible to estimate the directional force distribution all over the sensing surface.

Robots need detailed haptic sensing that covers their complex surfaces to learn effective behaviors in unstructured environments. However, state-of-the-art sensors tend to focus on improving precision and sensitivity, increasing taxel density, or enlarging the sensed area rather than prioritizing system robustness and the usability of the sensed haptic information. By considering the goals and constraints from a fresh perspective, we have designed **a robust**, **soft**, **low-cost**, **vision-based**, **thumb-sized 3D haptic sensor** named ***Insight***; it continually supplies the host robot with a **directional force-distribution map** over its entire conical sensing surface [609].

Insight uses an internal monocular camera, photometric stereo, and structured light to detect the 3D deformation of the easily replaceable flexible outer shell, which is molded in a single layer over a stiff frame to guarantee sensitivity, robustness, and a soft contact surface [744]. The force information is inferred by a deep-neural-network-based machine-learning method that maps images to the spatial distribution of 3D contact force (normal and shear), including numerous distinct contacts with widely varying contact areas [743].

Extensive experiments show that Insight has an **overall spatial resolution of 0.4 mm**, **force magnitude accuracy around 0.03 N**, and **force direction accuracy around 5 degrees** over a range of 0.03-2 N. It is sensitive enough to feel its own orientation relative to gravity, and its tactile fovea can be used to sense object shapes. The presented hardware and software design concepts can be extended to achieve robust and usable tactile sensing on a wide variety of robot parts with different shapes and sensing requirements. Ongoing work aims to reduce Insight's size, increase its framerate, and add other haptic sensing modalities such as vibration.

More information: https://hi.is.mpg.de/project/insight-a-haptic-sensor-powered-by-vision-and-machine-learning

3.4 Awards & Honors

2021

Director **Katherine J. Kuchenbecker** has been named an IEEE Fellow effective January 1, 2022, for contributions to interactive haptic systems and robotic touch perception

Ph.D. student **Alexis Block** is selected as a 2021 Computing Innovation Fellow (CIFellow) to support her postdoctoral research with Veronica Santos at UCLA in the USA

Postdoc **Yitian Shao** receives a two-year Humboldt Research Fellowship to support his postdoctoral research in the HI Department

Postdoc **Yitian Shao** wins the 2020 EuroHaptics Society prize for the best Ph.D. thesis in the field of haptics; he earned his doctorate with Yon Visell at UCSB in the USA

Ph.D. student **Saekwang Nam** and **Katherine J. Kuchenbecker** jointly win Honorable Mention for their *IEEE Transactions on Haptics* short paper at the 2021 IEEE World Haptics Conference

Ph.D. student **Rachael Bevill Burns** wins Honorable Mention for Best Research Lightning Talk at the IMPRS-IS Boot Camp

Ph.D. students **Alexis Block, Rachael Bevill Burns**, and **Mayumi Mohan** are selected to participate in the Gordon Research Seminar on the Future of Robotics: Possibilities for Transforming Healthcare

Ph.D. student **Rachael Bevill Burns** wins first place at the HRI 2021 Student Elevator Pitch Competition

Ph.D. student **Rachael Bevill Burns** is selected to participate in the HRI Pioneers 2021 Workshop

2020

Ph.D. student **Saekwang Nam** receives a KIST Europe Scholarship Award from the Korean Scientists and Engineers Association in Germany

Ph.D. student **Saekwang Nam** and **Katherine J. Kuchenbecker** jointly win the EuroHaptics 2020 Award for Best Poster

Senior Research Scientist **Ad Spiers** receives an Outstanding Reviewer Award from the *IEEE Robotics and Automation Letters*

2019

Postdocs **David Gueorguiev** and **Hasti Seifi** win a 9,500 USD grant from the IEEE Robotics and Automation Society to create a hands-on, standalone teaching module on haptic devices

Research Scientist **Hyosang Lee**, visiting Ph.D. student **Kyungseo Park**, Prof. Jung Kim of KAIST, and **Katherine J. Kuchenbecker** jointly win the Best Poster Award at the 2019 IROS ROBOTAC workshop

Ph.D. student **Rachael Bevill Burns** wins Second Place for Best Research Lightning Talk at the IMPRS-IS Boot Camp

Stanford Ph.D. student **Cara Nunez** receives a ten-month DAAD scholarship to do research with the HI Department as a visiting Ph.D. student

JHU Ph.D. student **Neha Thomas** receives a ten-month Fulbright grant to do research with the HI Department as a visiting Ph.D. student

Korea University Ph.D. students **Jeong-Hyun Cho** and **Young-Eun Lee** each receive a six-month grant to do research with the HI Department as a visiting Ph.D. student

Postdoc **Yasemin Vardar** wins the 2018 EuroHaptics Society prize for the best Ph.D. thesis in the field of haptics; she earned her doctorate with Cagatay Basdogan at Koc University in Turkey

Ph.D. students **Alexis Block** and **Maria-Paola Forte** win ROSCon 2019 diversity scholarships

2018

Ph.D. student **Mayumi Mohan** is selected to participate in the HRI Pioneers 2019 Workshop

Ph.D. student **Alexis Block** wins a 2,500 USD research grant from the IEEE Technical Committee on Haptics

Postdoc **Yasemin Vardar** is selected to participate in the MPG's Sign up! career-building program

Postdoc **Hasti Seifi** wins the 2017 EuroHaptics Society prize for the best Ph.D. thesis in the field of haptics; she earned her doctorate with Karon MacLean at UBC in Canaca

Visiting Professor **Brent Gillespie** receives a Humbold Research Award

Postdoc **Hyosang Lee** is selected to participate in the RSS Pioneers 2018 Workshop

Postdoc **Hyosang Lee** receives a fellowship from the South Korean National Research Foundation to support his postdoctoral research in the HI Department

Postdoc **Hasti Seifi** receives a two-year fellowship from the National Sciences and Engineering Research Council (NSERC) of Canada to support her postdoctoral research in the HI Department

Rachael L'Orsa receives a four-month DAAD scholarship to visit the HI Department

Alexis Block is elected as co-general chair of the HRI Pioneers 2019 Workshop

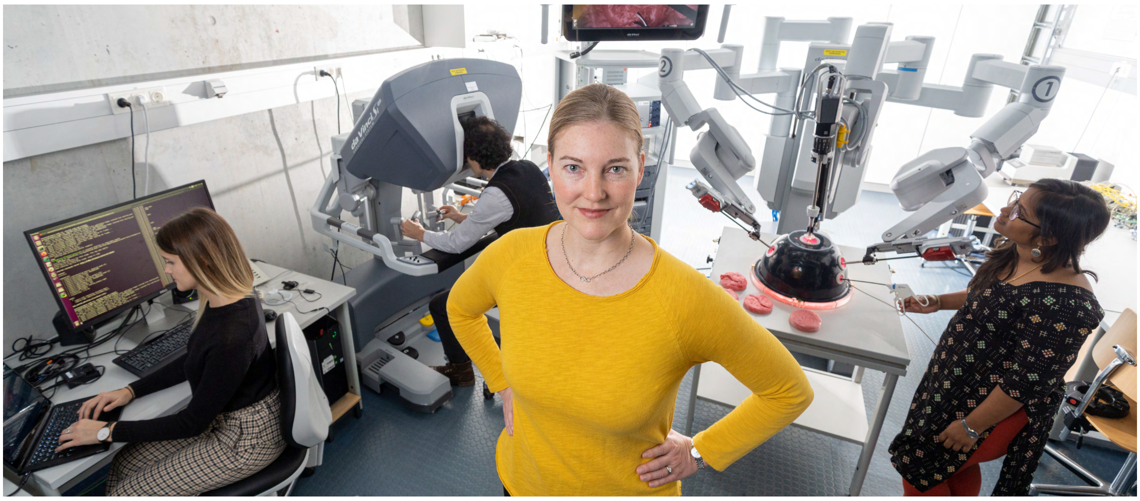
2017

Alexis Block is selected to participate in the HRI Pioneers 2018 Workshop

A paper by Ph.D. student **Eric Young** and **Katherine J. Kuchenbecker** is a finalist for the Best Poster Paper Award at the 2017 IEEE World Haptics Conference

Rachael Bevill Burns is selected to receive a grant from the Whitaker International Program to do research with the HI Department

3.5 Director profile: Katherine J. Kuchenbecker



Biography

Katherine J. Kuchenbecker earned her B.S., M.S., and Ph.D. in Mechanical Engineering from Stanford University in 2000, 2002, and 2006, respectively. After ten months as a postdoc at the Johns Hopkins University, she became the Skirkanich Assistant Professor of Innovation in the Department of Mechanical Engineering and Applied Mechanics (MEAM) at the University of Pennsylvania. She earned tenure and was promoted to Associate Professor in 2013, at which point she took on a secondary appointment in Computer and Information Science. She served as MEAM Undergraduate Curriculum Chair from July 2013 to June 2016 and held the Class of 1940 Bicentennial Endowed Term Chair from July 2015 to December 2016.

In January 2017 Katherine joined the Max Planck Society as a Scientific Member and Director at the Stuttgart site of the Max Planck Institute for Intelligent Systems. She has served as Spokesperson for the International Max Planck Research School for Intelligent Systems (IMPRS-IS) since its inception in 2017. She was Managing Director for the institute's Stuttgart site from January 2018 through December of 2020, and she was overall Managing Director from July 2019 through December 2020. She is a principal investigator in the DFG-funded excellence cluster on Integrated Computational Design for Construction and Architecture (IntCDC) at the University of Stuttgart and MPI-IS, in the BMBF-funded Tübingen AI Center, and in the new Stuttgart ELLIS Unit.

The four Ph.D. students who were working with Katherine when she moved to Germany have all earned their doctoral degrees. Naomi Fitter is now an Assistant Professor at Oregon State University in the USA. Alex Burka is at Exyn Technologies, Siyao Hu is at Amazon Robotics, and Eric Young is at Bright Machines. Alexis Block, her first MPI-IS doctoral student, graduated from ETH Zürich in August of 2021 and is now a postdoc at UCLA in the USA; the institute nominated Alexis for the 2021 Otto Hahn Medal, which is the doctoral dissertation prize of the Max Planck Society. Looking back, Katherine's third Ph.D. student from Penn, Heather Culbertson, is now an Assistant Professor at the University of Southern California in the USA, and she won the IEEE Technical Committee on Haptics Early Career Award in 2021.

Jeremy Brown, the postdoc working with Katherine when she moved, is now an Assistant Professor at the Johns Hopkins University in the USA. Seven of her MPI-IS postdoctoral researchers and research scientists have left the institute to take new jobs. One went to industry (Valerio Ortenzi, now a Senior Technical Program Manager at Unity Technologies in Denmark), and the other six went to independent scientific positions: Gunhyuk Park is an Assistant Professor at Gwangju Institute of Science and Technology (GIST) in South Korea, David Gueorguiev is a CNRS Researcher at the Institute for Intelligent Systems and Robotics in France, Ad Spiers is a Lecturer at Imperial College London in the UK, Yasemin Vardar is an Assistant Professor at TU Delft in the Netherlands, Hasti Seifi is an Assistant Professor at the University of Copenhagen in Denmark, and Hyosang Lee is a Cyber Valley Group Leader at the University of Stuttgart. Notably, three of the last four EuroHaptics Ph.D. Thesis Award winners have joined her lab as postdocs.

Appointments

Nominated as an Honorary Professor, University of Stuttgart, 2021
Adjunct Professor, University of Pennsylvania, 2019 – present

Awards & Honours

2021	Elevated to IEEE Fellow
2021	Honorable Mention, Best ToH Short paper (with co-author), IEEE World Haptics Conference
2020	Best Poster (with co-author), EuroHaptics Conference
2019	Best Poster (with co-authors), IROS RoboTac Workshop
2014	Lindback Award for Distinguished Teaching, University of Pennsylvania
2013	Best Demonstration Award (by committee vote, with co-authors), SIGGRAPH Asia
2013	Best Paper Silver Award (with co-authors), Advances in Computer Entertainment (ACE)
2013	Best Cognitive Robotics Paper Award (with co-authors), IEEE ICRA
2013	Best Demonstration (by audience vote, with co-authors), IEEE World Haptics Conference
2012	IEEE Robotics and Automation Society Academic Early Career Award
2012	Best Demonstration (three-way tie, with co-authors), IEEE Haptics Symposium
2009	National Science Foundation CAREER Award

Organization & Community Service

- Co-organizer, Workshop on the Future of Tactile Sensing: Applications and Challenges, 2021
- Program Committee, IEEE World Haptics Conference, 2017, 2019, and 2021
- Member, President’s Council on Equal Opportunities, Max Planck Society, 2020 – present
- Leader, Gender Equality Plan Committee, MPI-IS, 2020 – present
- Awards Chair, IEEE Haptics Symposium, 2020
- Member, Cooperation Council (Kooperationsrat), University of Stuttgart, 2018 – present
- General Co-chair, IEEE Haptics Symposium, 2016 and 2018
- Evaluator, NCCR Robotics, Switzerland, 2016 – present
- Co-chair, IEEE RAS Technical Committee on Haptics, 2015 – 2017

Memberships

Founding Member, Stuttgart ELLIS Unit, 2021 – present
Senior Member, IEEE, 2018 – 2021

Startup Activity and Board Memberships

2014 – present	Co-founder and Chief Science Advisor of Tactai, Inc.
2016 – 2019	Co-founder and Chief Science Advisor of VerroTouch Medical, Inc.

Keynote, Conference, and Public Talks

- Semi-plenary talk, IEEE Conference on Decision and Control (CDC), 2021
- Tutorial (teaching-focused keynote), Conference on Robot Learning (CoRL), 2020
- Plenary talk, IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2019
- Keynote, IEEE International Conference on Rehabilitation Robotics (ICORR), 2019
- Keynote, AsiaHaptics, 2018
- Keynote, Robotics: Science and Systems (RSS), 2018
- Keynote, IEEE Virtual Reality (VR), 2018

Links

Link to CV on website: https://hi.is.mpg.de/~kjk

4 PERCEIVING SYSTEMS

4.1 Research Overview

Computer vision is often treated as a problem of pattern recognition, 3D reconstruction, or image processing. While these all play supporting roles, our view is that the goal of computer vision is to *infer what is not in the picture* – to recognize the unseen. This is different from the Aristotelian view that the goal of vision is "to know what is where by looking." We see vision as the process of inferring the causes and motivations behind the images that we observe; that is, we want to infer the story behind the picture.

The most interesting stories involve people. Consequently, our research focuses on understanding humans and their actions in the world. We aim to recover human behavior in detail, including human-human interactions, and human interactions with the environment.

Humans interact with each other and manipulate the world through their bodies, faces, hands and speech. If computers are to understand humans and our behavior, then they are going to have to understand much more about us than they currently do. For example, they need to recognize when we are picking up something heavy and might need help. They need to understand when we are distracted. They need to understand that changes in our behavior may signal medical or psychological problems.

To teach computers to see us, we develop datasets, tools, models, and algorithms to recover human movement in unconstrained scenes at a level not previously possible. From single images or videos, we estimate full 3D body pose, including the motion of the face and the pose of the hands. We also recover the 3D structure of the world, its motion, and the objects in it so that human movement can be placed *in context.* We are not just interested in pose but also what the person is in contact with, what they are holding, where they are looking, who they are interacting with, and what they may do next.

This is quite different from previous work in which the human body is treated as a sparse set of joints, removed from the world around it, and 3D scene analysis happens on static scenes without humans. We think the interesting research problems involve analyzing human behavior when people are present in, and interacting with, the 3D world. By building 3D models of people and how they move, we are able to place them in context and reason about the physical and semantic contraints on their behavior.

We also seek to go deeper and understand the goals behind people's movements. To this end we relate natural language descriptions of human behavior to 3D movement. Our work aims to learn from video and language how people behave and then create virtual humans that exhibit natural behavior in virtual 3D scenes.

To advance this agenda, Perceiving Systems combines computer vision with machine learning and computer graphics to *capture*, *model*, and *synthesize* digital humans. We see the virtual human as more than a useful artifact. We see it as a tool for understanding ourselves. If we can simulate a virtual human in a virtual world behaving in ways that are indistinguishable from a real human, then we assert that we have captured something fundamental about what it means to be human.

4.1.1 Perceiving Systems: 2016-2021

In the last six years we have participated in a sea change in the field that has left no aspect of the department untouched. Prior to 2016, there was very little work on human pose and shape estimation that exploited deep neural networks; now everything does. However, deep networks are not the only sea change. Prior to 2016, the field of human pose estimation focused, almost exclusively, on estimating the major 2D or 3D joint locations of the body. In contrast, Perceiving Systems had been pursing a different approach – one focused on representing and estimating the 3D surface in the body in realistic detail. We made a sustained and concerted effort to move the field in our direction because we were confident that it was critical to addressing the core problem of understanding human-scene interaction.

At the end of 2015, we took the first step by releasing the SMPL body model. SMPL is a 3D statistical model of human body shape and pose that is learned from thousands of 3D body scans. We had built several body models prior to SMPL but they were not designed for wide adoption. SMPL was different; it was built to be used. Most importantly, we built SMPL on industry standard methods like linear blend skinning (LBS) and corrective blend shapes. That is, SMPL was designed, from the ground up, to be compatible with game engines and graphics packages. SMPL is also friendly for computer vision research because it is compact and differentiable.

We realized that for the world to adopt SMPL, however, we had to teach it how. This makes the story of SMPL's success the story of the last six years. This success has been driven by a key philosophy of the department

> *Build what you need.*
> *Use what you build.*

With each new result, we try to build on top of it in multiple ways and, by so doing, teach others how to build their own solutions. While SMPL was the kernel, it was everything we built to make SMPL *useful* that made it a success. Central to this strategy was a commitment to making almost all of our code and data available to the community. We also ran multiple tutorials at major conferences, and supported many on-line materials, to help build a community of users.

Based on this, it is fair to say that the dominant paradigm in the field has now changed from the estimation of joints to the estimation of *bodies*. As we knew, this has enabled the community to tackle new problems involving human-scene contact, appearance estimation, neural rendering, and implicit surface modeling. We also know that this is not the end. The community has not yet really begun to tackle issues of human-human interaction, goal understanding, and realistic synthesis of behaving avatars.

Six years ago, we had a 3D model of the body but little more. That model did not have articulated hands or an expressive face. It could not model infants, children, or animals. We had no way to model clothing and no way to estimate the model from images or videos. There was no good way to animate the model. The story of the last six years is really one of taking the raw material of SMPL and building an entire research ecosystem around it to enable the analysis of 3D humans and animals in image data.

Today SMPL and its many variants are widely used in academia and industry. It was a foundational tool for two spin-offs (Body Labs and Meshcapade) and has been licensed by six of the top ten NASDAQ companies as well as dozens of others. It is now the de facto standard for 3D body modeling.

Below, we summarize the work of the last six years with a focus on this story of human behavior in 3D scenes. Our research is roughly organized into themes related to modeling, capture, synthesis, and applications. This, of course, is not the whole story of Perceiving Systems. A fuller picture of our work over this period is provided in the project descriptions and our website.

4.1.2 3D Humans and Animals

Our approach to understanding humans and their behavior is grounded on 3D models of the body and its movement. Such models facilitate reasoning about human-object interaction, contact, social touch, and emotion. They make explicit what is implicit in images – the form of the body and its relationship to the 3D world. Consequently, we are developing ever more accurate and detailed models of the human body.

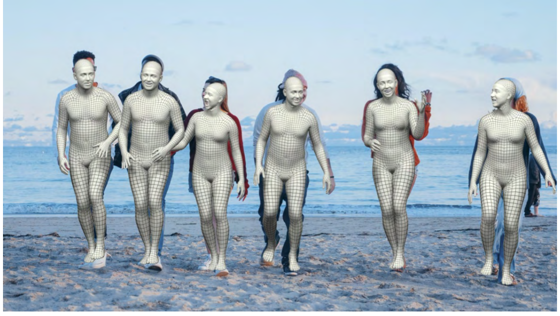


Figure 4.1: Bodies are not a collection of joints and bodies are not a skeleton. Bodies have shape, can move, can express emotion, and can interact with the world. Hence virtual bodies need faces and hands and the ability to move and use them. Our latest work regresses the SMPL-X body model [851] from an image, capturing realistic body shape, articulated hands, and detailed face shape and expression [797].

Specifically, we learn realistic 3D models of human body shape and pose deformation from thousands of detailed 3D scans. To go beyond SMPL, we have learned a face model (FLAME [782]) using a novel dataset of 4D facial sequences. FLAME captures realistic 3D head shape, jaw articulation, eye movement, blinking, and facial expressions. Similarly, we developed MANO [781], a 3D hand model learned from around 2000 hand scans of different people in many poses. We have combined SMPL, FLAME and MANO into a single model, SMPL-X [851], resulting in an expressive model of humans that can be animated and fit to data as seen in Fig. 4.1.

Within the SMPL family of models, we have also learned models of soft-tissue deformation [786], infants (SMIL [763]) and animals (SMAL [888]). Like SMPL, MANO and SMAL have become the de facto standard models of hands and animals, respectively, effectively opening up new avenues of research in computer vision.

These classical models, based on triangulated meshes, however, are not flexible enough to easily model complex clothing and changes in topology. Consequently, we are developing 3D articulated models of clothed humans based on *implicit functions*. These are neural networks that characterize occupancy in 3D space or the signed distance to the surface of the person.

Figure 4.2: Modeling people in varied and dynamic clothing is challenging using classical 3D mesh representations. Consequently, we learn an *implicit* model of shape (bottom) that is topologically flexible by learning a locally pose-aware signed distance function, parametrized by a neural network.

Figure 4.2 shows an example of constructing an animatable avatar from a set of raw 3D scans. This SCANimate method [818] learns an implicit-surface model of a clothed human that includes pose-dependent clothing deformations. To enable this, we exploit geometric cycle consistency to transform raw scans into a canonical pose. The key to this is to extend the classical notion of linear blend skinning from the surface of a mesh to a full 3D volume. The resulting *blend* *fields* are themselves implicitly represented by neural networks. SCANimate provides a foundation for learning implicit models of dressed humans and was a candidate for the best paper award at CVPR 2021.

SCANimate is one of several recent methods that we have developed with collaborators, laying a foundation for implicit digital humans. These methods include LEAP [821], SNARF [804], MetaAvatar [802], Grasping Fields [367]. Also SCALE [819] and PoP [806] pursue a related, topologically flexible, representation of bodies based on point clouds. Like implicit shape models, these allow complex and varying topology but have the advantage of being fast to render and compatible with existing graphics tools.

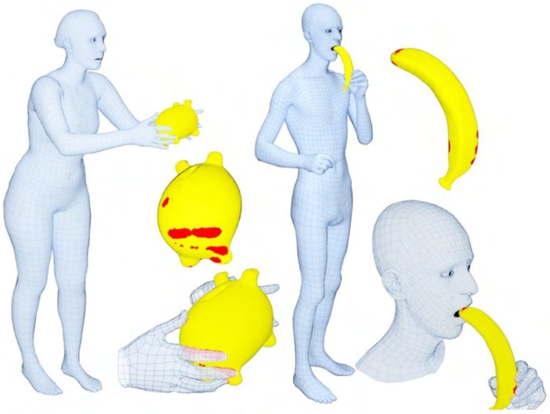


Figure 4.3: We are in constant contact with the world and our own bodies. When manipulating objects, this contact involves many parts of the body and not just the hands. For example, we grasp a cup and bring it in contact with our mouth to drink. The GRAB dataset [827] captures this full-body contact (shown here in red) together with body and object shape and pose.

4.1.3 Modeling Contact

In real estate the only three things that matter are location, location, location. In understanding human behavior it is contact, contact, contact. To address this, we have exploited our SMPL-X body model and MANO hand model in multiple ways to capture and model contact with the world and with the body.

In collaboration with colleagues at INRIA, we have generated a synthetic training set of hands interacting with 3D objects. Using this data, we train neural networks to simultaneously estimate both 3D hand pose and 3D object shape. We observe that these two processes are synergistic and that estimating them together produces better results because occlusion and contact can be modeled. Specifically, we train the model in such a way that we penalize hand-object interpenetration and encourage contact when parts of the hand are close to an object surface.

While the field has focused on hand-object grasping, we note that such interactions are just a fraction of our contact with the world. In fact, interactions with objects can involve multiple parts of the body – both hands, the mouth, the ears, or just about any part of the body. To study *whole-body* grasping, we captured the GRAB dataset [827], which is one of the richest and most complex mocap datasets available. It includes multiple subjects interacting with objects in natural ways and includes detailed labeling of fine-grained contact between the body and objects.

We leverage this to learn neural networks that predict grasps for novel objects. GrabNet uses a coarse network to get a rough hand pose and then a refinement network iteratively improves the grasp. We also explore implicit representations of grasping by using a neural network to represent the proximity between the hand and object. This novel *Grasping Field* representation [367] enables effective grasp generation with novel objects. The work won the Best Paper Award at 3DV 2020.

To capture more natural human-scene contact in the context of real scenes, we created the PROX dataset [845]. Here we exploit a 3D scan of the scene and an RGB-D sequence to estimate 3D human pose while penalizing interpenetration and encouraging contact. From this dataset, one can learn statistical models of how humans interact with scenes.

People also touch themselves and others. They touch their face 23 times an hour, they cross their arms and legs, put their hands on their hips, etc. In TUCH [817] we create novel datasets of images with ground truth self-contact information. One such dataset uses crowd sourced data of people mimicking a contact pose represented by a 3D mesh. We extend 3D human pose fitting methods to include object contact, and exploit this during neural network training. This work was a candidate for the Best Paper Award at CVPR 2021.

4.1.4 Faces and Expressions

Like hands, faces are critical to understanding human behavior. The estimation of 3D face shape from a single image must be robust to variations in lighting, head pose, expression, facial hair, makeup, and occlusions. Robustness requires a large training set of in-the-wild images, which by construction, lack ground truth 3D shape. Consequently, to train a network without any 2D-to-3D supervision, we developed *RingNet* [849], which learns to compute 3D face shape from a single image. Our key observation is that an individual's face shape is constant across images, regardless of expression, pose, lighting, etc. RingNet uses a novel loss that encourages the face shape to be similar when the identity is the same, yet different for different people.

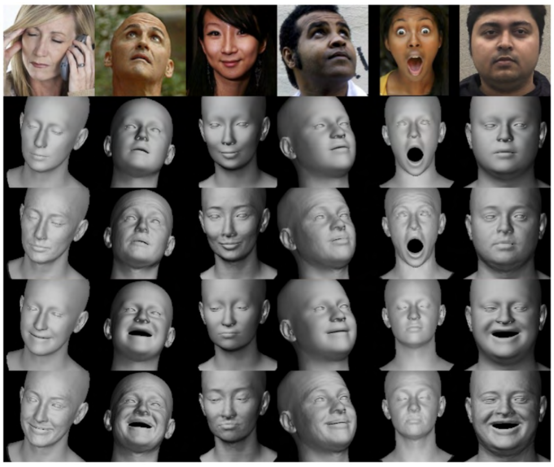


Figure 4.4: DECA [752] is trained to regress face shape and animatable details from in-the-wild images. From top to bottom: Input image, coarse 3D shape reconstruction, detailed shape reconstruction, animation of the coarse shape, predicted details for the animated shape.

With DECA [752], we go further to recover the detailed wrinkles of the face (Fig. 4.4). Beyond previous work, this detail information is animatable and is learned purely from in-the-wild images without 3D training data. DECA infers a detail code for an individual that enables us to change their expression while maintaining realistic wrinkles. We have combined this idea with our SMPL-X body model in PIXIE [797], enabling the regression of full 3D humans with detailed facial expressions (Fig. 4.1). This combined body and face representation serves as a foundation for the analysis of human behavior.

4.1.5 3D People from Images/Video

We view the *capture* of 3D human pose and shape is the foundation for behavior analysis as well as many applications in medicine, sports, games, and the Metaverse. While we make extensive use of motion capture and 4D scans in our Capture Hall, our ultimate goal is to capture human behavior in video. To that end, we have developed many methods over the last six years that define the current state of the art in the field. These methods can be broadly categorized into “top down” fitting methods and “bottom up” regression methods (though much of our work uses a hybrid of these approaches).

SMPLify [898] is the core optimization-based method that fits SMPL to image evidence. The basic objective function includes a term that computes the difference between 2D joint locations detected in the image and the projection of SMPL's 3D joints. This is combined with pose and shape priors and a self-intersection penalty. This basic method is a workhorse that can be modified to include silhouettes [875], semantic segmentation [815], multi-view images [846, 875], RGB-D [845], video [875], scene contact [845], self-contact [817], and a perspective camera [810]. The SMPLify-X version estimates the SMPL-X body and uses many improved components.

While fitting is highly flexible, it is also slow. Consequently, we have developed numerous methods to directly regress SMPL and SMPL-X models from image pixels. The first method to do this was HMR [869], which included two key novelties that made it work. First, it learned to regress 3D human pose and shape using only 2D image features by exploiting adversarial training. We used our strong models of human shape and pose to train the adversary to detect when HMR predicted an unrealistic human. Second, HMR introduced an iterative refinement scheme to improve the estimate of human pose in steps. We extended this idea to video with VIBE [833], which used a temporal GRU representation and a temporal discriminator that is trained with mocap data.

The next big advance was SPIN [840] , which combined HMR and SMPLify in a training loop. The regressed result from HMR is used to initialize SMPLify, which takes a few optimization steps, improving the pose and shape estimate.

These improved results are then fed back into the network training. In this way, SPIN is able to exploit the pixel-level accuracy of SMPLify but with the speed of regression networks. Many methods in the field are now built on this concept.

Figure 4.5: Examples of full-body expressive pose and shape estimation with PIXIE. Left to right: Input image, pose and coarse face shape, with detailed face shape. Note how PIXIE is robust to occlusion by the image frame and clothing.

While most methods focus on regressing SMPL parameters, we want to know more about people. Consequently, we regress SMPL-X with detailed faces and hands [851] . The problem is that regression networks take downsampled image regions of the body in which the hands and face are very low resolution. Moreover, hands and faces are often occluded or the hands are blurred due to motion. To address these issues, we developed two attention-based methods that use the body pose to guide attention to the hands and face [797, 828]. Sub-networks then receive high-resolution crops of these hand and face regions. PIXIE [797] is the latest version and it includes a moderator that assesses how reliable the sub-networks are. It is also trained with information about gender so that it automatically produces gender-appropriate body shapes. PIXE represents the current state-of-the-art in human pose and shape regression for single people (Fig. 4.5).

Figure 4.6: ROMP regresses multiple 3D people in realtime using a purely bottom-up architecture.

People, however, often appear in crowds (Fig. 4.6) and this causes several problems for current regression methods. First, they all rely on a top-down person detector to find people and crop them before passing them to the network. When people occlude each other, it can be hard for the network to infer the correct pose. Second, the computational cost of this top-down detection approach scales linearly with the number of people in the image, making realtime performance difficult. Third, such methods cannot exploit the overall scene context to reason about people in depth. ROMP [799] addresses these problem by using a purely bottom-up approach that estimates the centers of all people in the scene along with the SMPL parameters for each center. ROMP runs in real time even with many people in the video, and enables more explicit reasoning about depth and occlusion.

4.1.6 Putting 3D People in 3D Scenes

While much of our work focuses on the capture and modeling of humans and their motion, how do we know if our models are any good? What does it mean to have a good model of humans and their behavior? We argue for something akin to a Turing Test for avatars. Specifically, given a novel 3D scene, a digital human should be able to interact with that scene in a way that is indistinguishable from real human behavior. This is fundamentally an AI-complete problem and, consequently, is a long-term research goal. While fully realistic digital humans remain may be far off, we are making concrete progress today. Our core research is focused in three directions: neural rendering to create realistic looking humans, generating 3D human motion conditioned on high-level goals, and putting 3D people into 3D scenes with natural behavior. This will be critical to many applications including computer games, animation, XR, and the Metaverse.

Figure 4.7: POSA [816] takes a 3D scene and posed human scans and places the scans in the scene such that their contact and semantic interactions make sense. To do so, POSA relies on a novel, body-centric, generative model of human-scene contact that is trained from the PROX dataset.

We initiated this new line of research in 2021 with our paper on “Generating 3D People in Scenes without People” [834] and have followed this up in a series of papers. Our most recent work, POSA [816], exploits the PROX dataset to learn a body-centric representation of human-scene contact and contact semantics. This allows us to take commercial 3D scans of people and put them into 3D scenes as shown in Fig. 4.7. POSA does so by fitting a 3D SMPL-X model to the scans. Our learned body-centric contact model is pose dependent and allows us to sample plausible contact information for the SMPL-X body. POSA then searches the scene for places where the pose and contact makes physical and semantic sense. After placing SMPL-X in the scene, we replace it with the original scan.

4.1.7 Movement and Language

Putting static people into static scenes is only the beginning. What we really seek is to understand and model what is behind human movement; that is, the goals, motives, emotions, and plans that drive human movement. This would then allow us to create avatars that can interact with novel worlds based on high-level goals.

A first step towards understanding human motion is being able to predict it. To that end, we train deep neural networks on motion capture data to generate realistic human movements. These may predict motion based on the past [820, 879, 884] (Fig. 4.8) or generate it conditioned on linguistic descriptions [805]. To train neural networks to generate human motion, we need training data. To that end, we used MoSh to transform multiple datasets of mocap markers into a common SMPL body representation, resulting in the AMASS dataset [843]. This gives us sufficient training data for deep networks to be effective.

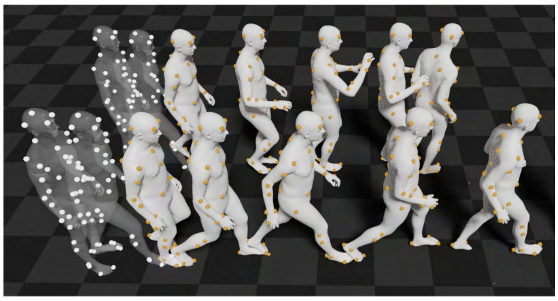


Figure 4.8: MOJO [820] predicts human motion from a short sequence of past motions. Uniquely, we do not predict the joints or the joint angles. Instead we predict 3D points on the surface of the body; that is, we turn the problem into one of point-cloud prediction. This enables us to fit a SMPL body at every prediction step, effectively projecting the solution back in the space of valid bodies.

To relate movement to language, however, we need to know what people are dong in AMASS. To that end, we labeled rendered sequences from AMASS and had crowd workers label the actions at the frame level. The resulting BABEL dataset [814] has fine-grained action labels that are much more diverse than in previous datasets and have a long tail. This makes the problem of recognizing and synthesizing human movement conditioned on action challenging.

SAMP [809] is our first attempt to put together everything that we know: motion capture, 3D body models, human-scene interaction, scene affordances, high-level goals, and movement generation. We gather mocap of a person interacting with various 3D objects and then augment this data by changing the objects, while using inverse kinematics to preserve contact. This creates a large and varied training set. SAMP predicts how an avatar should interact with novel 3D objects and then plans a trajectory through the scene to achieve its goals. This has many of the key pieces of our desired solution: the ability to "perceive" the affordances of the scene, the ability to generalize high-level goals to new scenes, and the ability to plan and execute a sequence of actions to achieve a goal.

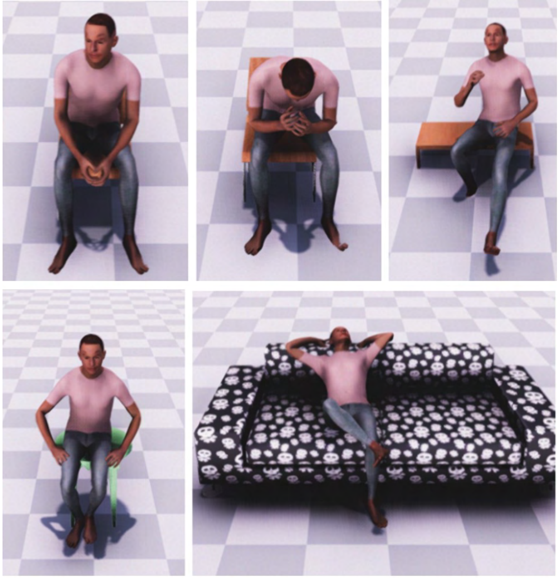


Figure 4.9: With SAMP [809], we trained an avatar to perform actions like sitting or lying down on a wide variety of surfaces. SAMP is able to generalize these actions to previously unseen objects to achieve its goals. The generated motions are diverse and realistic.

While there is still much to be done to make this truly human-like, all of our work on *capture*, *modeling*, and *synthesis* is building in this direction.

4.1.8 Beyond Mocap

Most methods for capturing human motion are restricted to laboratory environments and/or limited volumes. Most do not take into account the complex and rich environment in which humans usually operate. Nor do they capture the kinds of everyday motions that people typically perform. To enable the capture of natural human behavior, we have to move motion capture out of the laboratory and into the world.

To that end, we pursue different technologies. In the lab, we have developed SOMA [803] to automate the mocap process and make it easy to extract detailed and realistic 3D humans from mocap data. Our work here is focusing on extracting expressive SMPL-X bodies with detailed face and hand motion. We also capture objects and scenes to put human motion in context.

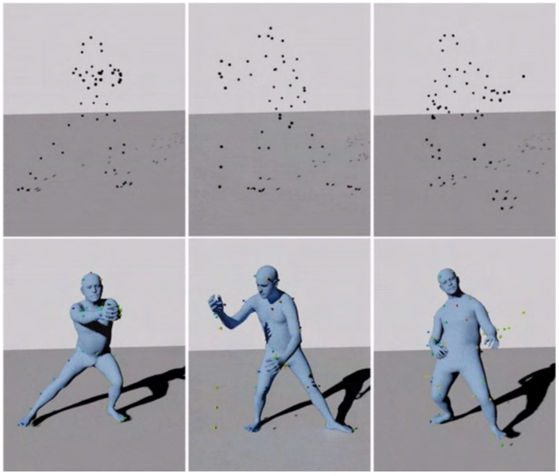


Figure 4.10: SOMA [803] takes a raw motion capture point cloud with noisy and missing data (top), labels the data, and solves for the 3D body shape and pose using MoSh++ (bottom). To do so, SOMA exploits synthetic training data, a stacked transformer architecture, and an optimal-transport layer.

To move outside the lab, we use inertial measurement units (IMUs) worn on the body [774, 788]. These give information about pose and movement, but wearing a full suite of sensors is impractical. Thus, we developed methods to estimate full body motion from as few as six sensors worn on the legs, wrists, belt and head. Our most recent methods use deep neural networks to estimate pose from IMU measurements in real time in unconstrained scenarios [774].

IMUs however suffer from drift so we combine IMU data with a single hand-held video sequence. In video we can detect the 2D joints of the body and use these to eliminate drift. We associate the IMU data with 2D data and solve for the transformation between the sensors. Using this, we crated the popular 3DPW dataset [861], which contains video sequences with high-quality reference 3D poses. 3DPW is widely used to train and test video-based human pose and shape methods.

To go fully markerless outdoors, we have developed autonomous flying motion capture systems [759]. With AirCap, multiple micro-aerial vehicles coordinate their activities to detect and track a person, while estimating their 3D location with on-bard processing. We then use the captured video offline to estimate the 3D human pose, shape, and motion. The challenge here is to deal with noise in the camera calibration since the location of the flying cameras is only approximate. Our novel solution jointly solves for the 3D body and the camera parameters [846].

Figure 4.11: Flying motion capture of humans and animals presents many challenges: tracking, calibration, and autonomous control to name few. To enable long flight times and quiet operation, we are developing a 3D motion capture system based on lighter-than-air vehicles. Such blimps present new challenges beyond existing fixed roter vehicles since they are deformable and susceptible to wind.

Most recently, we have developed autonomous control algorithms for lighter-than-air vehicles (Fig. 4.11). Blimps have advantages over common multi-copters but are more complex to control. We have developed novel methods for automous control and have been testing these in real flight conditions [813]. These control methods together with our AirCap pose estimation methods [846] form the foundation of our blimp-based system to capture animal movement in natural conditions.

4.1.9 Impact and Outreach

While our focus is on basic research, we want to have an impact beyond our core academic discipline of computer vision. Consequently, we pursue collaborations that allow our work to have a broader impact.

For example, we develop applications in medicine and psychology in collaboration with medical colleagues. Specifically, we have collaborative efforts to relate the distribution of adipose tissue in the body to the risk of diabetes and cardiovascular disease [748, 790]. We have also developed a 3D model of infants and use it to track their movement to aid the early diagnosis of cerebral palsy [758, 867].

Our 3D body model has also played an important role in understanding people's perception of their own and other's bodies. We focus, in particular, on body shape perception in people with eating disorders or overweight. We have created tools that make it easy for psychologists to create 3D body stimuli for VR [770] and desktop applications [749, 753, 754]. These tools have led to insights about how women who suffer from anorexia nervosa see their body and the bodies of others [778–780].

Figure 4.12: The Grevy's zebra is near extinction. We have developed a novel neural network that can estimate their 3D shape, pose, and texture from images without ground truth 3D training data [844].

We are also collaborating with researchers on animal conservation. Our SMAL model [888] of 3D animal shape and pose allows researchers to extend work on human pose and shape estimation to animals. Our most recent work focuses on directly regressing the shape, pose, and texture of an animal from a single image [844] (Fig. 4.12). Specifically, we work with Wildbook on a project to protect the Grevy's zebras in Africa. Our ultimate goal is to analyze herd shape and behavior from our flying capture systems.

We are also active in patenting, technology licensing, and startups. We have spun off two companies based on our 3D body model technology. One of these, **Body Labs Inc.**, was acquired by Amazon in 2017. This was one of the top 10 most profitable spinoffs for Max Planck in their history. Several Amazon products based on our technology are now in use by customers. The second startup, **Meshcapade GmbH**, started in 2018 and has been profitable from the start. Meshcapade is focused primarily on delivering 3D body shape models and applications to the clothing industry.

We also make code and data available for research purposes, open source, or for commercial license. For example, we are responsible for many widely used datasets and evaluation benchmarks that help push the state of the art and provide insight into what works, how well, and why. In the past, we have played central roles in many influential datasets and evaluations in the field including Middlebury Flow, Sintel, KITTI, HumanEva, FAUST, JHMDB, and others. Over the last six years, our most significant datasets include

- Dynamic FAUST: precise 4D scans of people in motion;
- 3DPW: 3D poses in the wild for training and evaluating human pose and shape estimation;
- SURREAL: images of synthetic humans for training deep networks;
- NoW Challenge: images of faces with 3D ground truth and an evaluation system;
- ObMan: data and code for 3D hand-object reconstruction from an RGB image;
- CAPE: 3D meshes of dressed humans for training models of clothed humans;
- PROX: data of 3D humans interacting with 3D scenes with contact;
- GRAB: data of 3D human-object whole-body grasps;
- AMASS: large dataset of mocap datasets in a unified SMPL-based representation;
- BABEL: AMASS motions with fine-grained action labels;
- AGORA: ground truth SMPL-X bodies for photo-realistic images of people.

This is just a sampling. Additionally, almost all our code is on-line. For a full list of code and data, see https://ps.is.mpg.de/code

4.1.10 The Past and Future

While, the department has always focused on human pose, shape, and motion, we have also done many other things over the last six years. We are known, for example, for our work on optical flow estimation and have also worked on problems like stereo and albedo estimation. One can think of these as “low level” problems in the sense that one does the same thing at every pixel in the image and one can evaluate the measure metric accuracy of the result. Problems like these are now relatively well solved by deep neural networks given sufficient training data. We have contributed to this with methods like SpyNet [880] for estimating optical flow or Competitive Collaboration [855] for self-supervised learning of flow, depth, and camera motion. Our most recent work shows that popular neural networks for optical flow estimation are vulnerable to adversarial attacks [839].

While these low-level problems may not be full “solved”, the path to solving them is relatively clear, making them less interesting for Perceiving Systems. Our current work is focused on what one might call “mid-level” problems; 3D human pose and shape estimation falls in the class. These mid-level problems involve nonuniform processing in the image but still use metric accuracy for evaluation. This metric quality means that it’s relatively easy to train neural networks to solve this problem if one has labeled data. What makes human pose and shape interesting to us is that it is hard to get such labeled data.

Longer term, we see an even richer range of “high-level” problems that can now be attacked. These correspond to our broad goal of inferring “what’s not in the image." In our case, we are interested in human behavior. What are they doing? Why are they doing it? What is their emotional state? What might they do next? The answers are not directly observable in the pixels. Progress on these problems will be slower because the output of our methods will not be so easily measurable. Ultimately, however, addressing these problems is critical if we are to build artificial agents that teach us about ourselves.

4.1.11 About Us

Figure 4.13: Perceiving Systems is highly international, diverse, and collaborative.

The Perceiving Systems department was founded in January 2011 and today has over 50 members from all over the world (not including guest scientists). This includes support staff, technicians, Ph.D. students, interns, undergraduates, and scientists at various career stages. We have over 100 alumni including 12 graduated Ph.D. students. Many of our alumni have gone on to academic positions, founded companies, or joined major research laboratories. In particular, 11 of our former students or postdocs now hold faculty positions.

We take diversity seriously and, between 2016 and 2018, 30% of our papers had female first authors and 50% had at least one female author. Between 2019 and 2021, 38% of our papers had a female first or last (senior) author, while 61% of papers had at least one female author.

Over the last six years, the department hosted two group leaders, Siyu Tang and Aamir Ahmad, whose groups focused on "Holistic Vision" and "Robot Perception" respectively. Both scientists are now professors: Tang at ETH Zürich and Ahmad at the University of Stuttgart. Ahmad continues with the department at 20% time to run his group synergistically with his university group. Details about these groups can be found on our website: https://ps.is.mpg.de/field/robot-perception-group and https://ps.is.mpg.de/field/holistic-vision-group

We have regular sabbatical and long-term visitors. Between 2016 and 2019 we hosted Cordelia Schmid (INRIA) as a Humboldt Professor, and Andrew Blake (Samsung and FiveAI), Hedvig Kjellström (KTH) and Daniel Scharstein (Middlebury University) as sabbatical visitors. Of course, during the pandemic, we paused our sabbatical program but continued an active Zoom lecture series and continued to host interns remotely. In the last six years, we have hosted 123 invited speakers, 38% of whom were women. A full list is here https://ps.is.tuebingen.mpg.de/talks

In what follows, we present a sampling of our research projects over the last six years, with a focus on the most recent work (2019-2021). Our website provides information about many other projects as well as greater detail: https://ps.is.tue.mpg.de

A broader view of the department activities, including our videos, can be found on our social media pages:

- Facebook: https://www.facebook.com/PerceivingSystems/
- Twitter: https://twitter.com/PerceivingSys
- Youtube: https://www.youtube.com/c/MichaelBlackMPI
- Bilibi (China): https://space.bilibili.com/1724740870

4.1.12 Facilities and Capture Team

Our Capture Hall supports a large range of equipment and experiments in roughly 830 square meters. During 2016–2021 we captured $4,257,686$ 3D scans broken down into over $2M$ full body scans, $1.5M$ face scans, $273K$ hand scans, $162K$ foot scans, over 400 object scans, and 41 full scene scans. In addition, we have collected over 20 hours of motion capture data and over 50 hours of multi-camera data.

Keeping this running is a professional staff of human subjects coordinators, scanner technicians, and software engineers who support the custom software that processes all this data. Additionally, we employ a vibrant team of undergraduates who get involved in labeling data, helping with trials, and engaging in research.

We used the pandemic as an opportunity to reorient and retool the Capture Team for the future. During this time, it was hard (or impossible) to capture subjects in the lab. Consequently, we shifted focus to capture on the Internet, manual labeling, and the use of crowdsourcing platforms such as Amazon Mechanical Turk as a key source of data. Our 3D and 4D capture systems remain critical to obtain high-quality data, but the future of our capture efforts will increasingly focus on “in the wild” data.

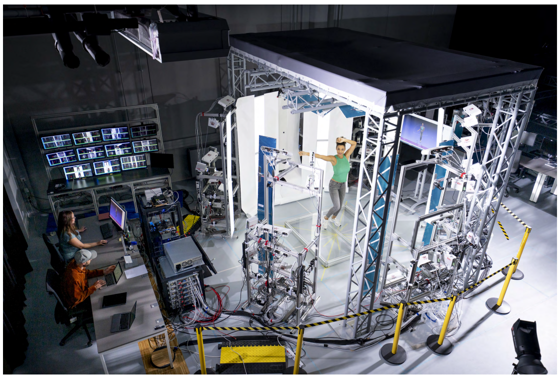


Figure 4.14: The 4D body scanner captures 3D meshes of the full body at 60 fps.

A core pice of equipment in this facility is our 4D body scanner (Fig. 4.14) made by 3dMD, which was the first of its kind that could capture the full range of human movement, in 3D, at 60 fps. At each time instant the system captures a 3D point cloud with about $150k$ points. We capture people both in minmal clothing and in normal street clothes. The scan data is then processed so that our 3D body model is aligned to the data to produce detailed meshes that are in correspondence across people and poses.

The full body scanner has limited resolution on the face and hands. Given the importance of the face and hands in communication and manipulation, we also run dedicated 4D face and hand scanners (Fig. 4.15). We also have a 4D foot scanner that captures a full 3D view of the foot during contact. The system images the bottom of the foot through a glass plate so that the deformation of the shape is captured.

Figure 4.15: Our new 4D hand scanner is opperated in collaboration with the Haptic Intelligence department. It is able to capture two hands interacting with objects.

Our 4D systems give us great detail about the 3D body, but we also want to relate this to images of people. One source of images is fashion websites but these do not come with ground-truth body shape. Consequently, we built a photo studio (Fig. 4.16) that enables us to recreate fashion photos ourselves with a key advantage – we also scan the participants with our 4D systems so that we know their true shape.

Figure 4.16: Our new photo studio allows us to reproduce commercial-quality fashion images, like those found on Internet shopping sites.

To study human interaction and more complex behaviors, we have a large motion-capture space with a Vicon marker-based motion capture system consisting of 54 high-resolution Vantage V16 cameras (Fig. 4.17). This system has the highest density of mocap cameras in Europe, enabling us to resolve tiny markers on the face and hands while minimizing the effects of occlusion.

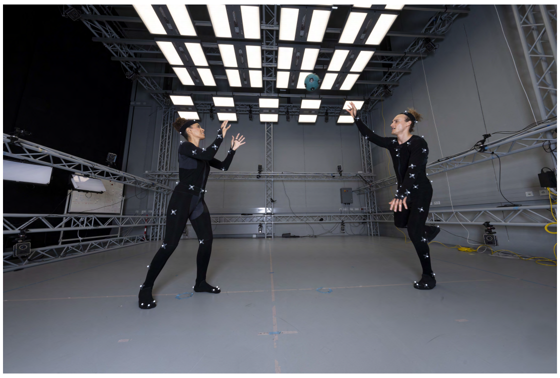


Figure 4.17: Our motion capture space includes a 54-camera Vicon motion capture system a multi-camera video capture system and specially designed lighting system.

Synchronized with the Vicon system is a multi-camera system consisting of 16 cameras, produced by IOI Industries, each with a maximum resolution of 12 megapixels, all controlled through 4 FPGA-based DVR recorders with a recording rate of 2240MB/s and a capacity of 88TB. The system provides multiple interfaces for synchronization: TTL, LTC, IRIG and GPS (for large distance applications outdoors). With tripods and our collection of lenses, the cameras can be used at any location, indoors and outdoors. For example, together with collaborators in Sweden, we have used the system to capture horses in motion.

Together with Norka Automation, we developed a unique lighting solution that delivers 12K lux of light to the capture volume and enables data recording at a high frame rate while minimizing motion blur. The bright light is tolerable because we pulse it such that it is synchronized with the cameras' shutter open times. The lighting operates at a frequency of 240Hz, making the light appear dim to the human eye.

In addition, we maintain a collection of technologies including IMU suits, Tobii eye-tracking glasses, RGB-D sensors, foot-pressure sensors, audio recording equipment, XR headsets, an Artec hand-held scanner, and a LEICA laser scanner to capture large spaces. We also maintain a fleet of micro-aerial vehicles that include custom octo-copters and helium-filled blimps.

This facility and its equipment provides us the opportunity to study human communication, human-human contact, and human-object interaction with unprecedented detail.

4.2 Selected Research Projects

Faces and Expressions

Timo Bolkart, Michael Black, Anurag Ranjan, Soubhik Sanyal, Tianye Li, Javier Romero, Cassidy Laidlaw, Yao Feng, Haiwen Feng, Partha Ghosh

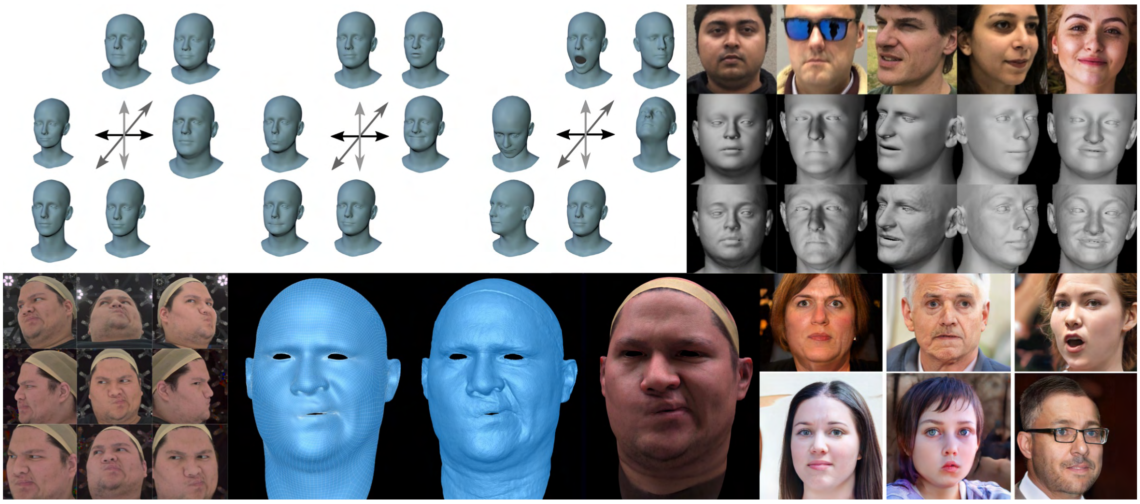


Figure 4.18: Analysis and Synthesis of 3D Faces: Top left: FLAME [782] captures 3D face shape, pose, and expression shape variations. Top right: DECA [752] reconstructs animatable 3D faces from 2D images with FLAME's parameter control. Bottom left: ToFu [801] reconstructs high-fidelity 3D faces from calibrated multi-view images. Bottom right: GIF [824] generates realistic face images with FLAME's parameter control.

Facial shape and motion are essential to communication. They are also fundamentally three dimensional. Consequently, we need a 3D model of the face that can capture the full range of face shapes and expressions. Such a model should be realistic, easy to animate, and easy to fit to data. See [761] for a comprehensive overview of different facial representations.

To that end, we train an expressive 3D head model called FLAME from over 33,000 3D scans. Because it is learned from large-scale, expressive data, it is more realistic than previous models. To capture non-linear expression shape variations, we introduce CoMA [863], a versatile autoencoder framework for meshes with hierarchical mesh up- and down-sampling operations. Models like FLAME and CoMA require large datasets of 3D faces in dense semantic correspondence across different identities and expressions. ToFu [801], a geometry inference framework that facilitates a hierarchical volumetric feature aggregation scheme, predicts facial meshes in a consistent mesh topology directly from calibrated multi-view images three orders of magnitude faster than traditional techniques.

To capture, model, and understand facial expressions, we need to estimate the parameters of our face models from images and videos. Training a neural network to regress model parameters from image pixels is difficult because we lack paired training data of images and the true 3D face shape. To address this, RingNet [849] directly learns this mapping using only 2D image features. DECA [752] additionally learns an animatable detailed displacement model from in-the-wild images. This enables important applications such as creation of animatable avatars from a single image. Our NoW benchmark enables the field to quantitatively compare such methods for the first time.

Classical rendering methods can be used to generate images using FLAME but these look unrealistic due to the lack of hair, eyes, and the mouth cavity (i.e., teeth or tongue). To address this, we are developing new neural rendering methods. GIF [824] combines a generative adversarial network (GAN) with FLAME's parameter control to generate realistic looking face images.
More information: https://ps.is.mpg.de/project/human-face-analysis

Hands-Object Interaction

Dimitrios Tzionas, Omid Taheri, Javier Romero, Nima Ghorbani, Gul Varol, Cordelia Schmid, Korrawe Karunratanakul, Jinlong Yang, Yan Zhang, Krikamol Muandet, Siyu Tang, Michael Black, Yana Hasson, Igor Kalevatykh, Ivan Laptev

Figure 4.19: (Left) We use a dataset of 3D hand scans to learn MANO, a statistical model of 3D hand shape. We combine MANO with our SMPL body model to build the holistic SMPL+H model. We register SMPL+H (pink) to 4D scans (white); the results look natural even for missing data or finger webbing in scans. (Middle) We train ObMan, a deep network with a MANO layer, to estimate 3D hand and object meshes from an RGB image of grasping, while encouraging contact and discouraging penetrations. (Right) We capture GRAB, a dataset of real whole-body grasps (blue, yellow), i.e. of people interacting with objects using their body, hands and face. We use GRAB to train GrabNet, a network that generates grasping hands (gray) for unseen objects (yellow).

Hands allow humans to interact with, and use, physical objects, but capturing hand motion is a challenging computer-vision task. To tackle this, we learn a statistical model of the human hand [781], called MANO, that is trained using many 3D scans of human hands and represents the 3D shape variation across a human population. We combine MANO with the SMPL body model and FLAME face model to obtain the expressive SMPL-X model, which allows us to reconstruct realistic bodies and hands using our 4D scanner, mocap data, or monocular video.

MANO can be fit to noisy input data to reconstruct hands and/or objects [912],[793] from a monocular RGB-D or multiview RGB sequence. Interacting motion also helps to recover the unknown kinematic skeleton of objects [897].

To directly regress hands and objects, we developed ObMan [852], a deep-learning model that integrates MANO as a network layer, to estimate the 3D hand and object meshes from an RGB image of grasping. For training data, we use MANO and ShapeNet objects to generate synthetic images of hand-object grasps. ObMan's joint hand-object reconstruction allows the network to encourage contact and discourage interpenetration.

Hand-object distance is central to grasping. To model this, we learn a Grasping Field [367] that characterizes every point in a 3D space by the signed distances to the surface of the hand **and** the object. The hand, the object, and the contact area are represented by implicit surfaces in a common space. The Grasping Field is parameterized with a deep neural network trained on ObMan's synthetic data.

ObMan's dataset contains hand grasps synthesized by robotics software. However, real human grasps look more varied and natural. Moreover, humans use not only their hands, but also use the body and face during interactions. We therefore capture GRAB [827], a dataset of real whole-body human grasps of objects. We use a high-end MoCap system, capture 10 subjects interacting with 51 objects, and reconstruct 3D SMPL-X [851] human meshes interacting with 3D object meshes, including dynamic poses and in-hand manipulation. We use GRAB to train GrabNet, a deep network that generates 3D hand grasps for unseen 3D objects.

More information: https://ps.is.mpg.de/project/hands-in-action

Implicit Representations

Michael Black, Jinlong Yang, Qianli Ma, Shunsuke Saito, Siyu Tang, Korrawe Karunratanakul, Krikamol Muandet, Yan Zhang

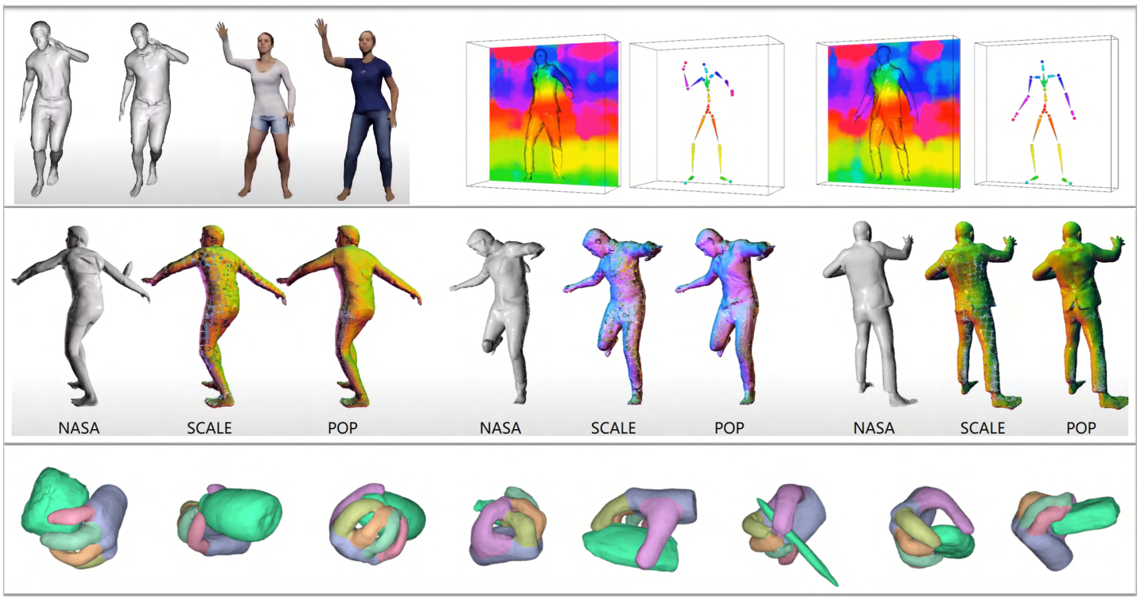


Figure 4.20: (Top to bottom) Deep implicit shapes for modeling clothed humans. A novel articulated point cloud shape representation of clothed bodies. Implicit representations for contact and interaction modeling.

While triangulated meshes are the dominant 3D representation in computer graphics, their fixed topology makes them ill-suited to modeling humans in clothing, where the topology varies between garments and over time. They also do not directly model distances between surfaces, which are central to human-scene interaction.

Recent work on deep implicit functions provides us with an alternative in which shape is defined using a deep neural network that defines either the occupancy at every point in a 3D volume or the signed distance to the object surface. The surface can then be extracted as the zero level set of this function.

Implicit functions are flexible in both resolution and topology, making them suitable to model clothed humans. A key step is to extend the notion of linear blend skinning from the surface of the mesh to the full 3D volume. Learning a 3D human entails learning skinning fields that allow posing and un-posing the body such that pose-dependent shape changes can be learned in a canonical pose space.

We explore these ideas in three recent papers: LEAP [821], SNARF [804], and SCANimate [818]. SCANimate learns an implicit model directly from raw 3D scans and is trained with a cycle-consistency loss as self-supervision.

Current implicit representations are slow for inference. To address this, we propose two novel point cloud representations (SCALE [819] and POP [806]), where the surface is implicitly defined by the points. While SCALE models a single clothed person, POP is trained to model a wide variety of clothing.

We also extend implicit representations to model hand-object interaction. For each point in space, if we know its signed distance to the hand and the object, we can infer the interaction between them. If both are zero, then the hand is touching the object; both positive, no contact; both negative, interpenetration occurs. Specifically, we learn a GraspingField [367] from which we can generate various grasping hand poses for given objects.

More information: https://ps.is.mpg.de/project/implicit-representations

Animal Shape and Pose

Silvia Zuffi, Angjoo Kanazawa, Michael Black, Nadine Rueegg, Omri Ben-Dov, Haiwen Feng, Paul Soubiran, Sergi Pujades

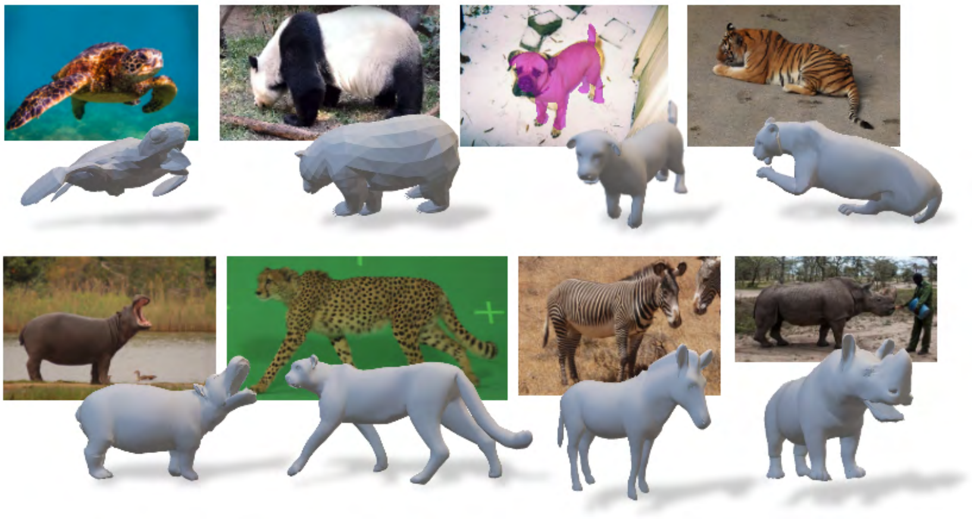


Figure 4.21: Our work estimates the shape and pose of animals from images and video. To achieve this, we learn 3D articulated shape models from 3D scans and 2D images.

In the past 20 years impressive advances have been made in capturing, modeling and tracking the human body in 3D, thanks to the availability of large amounts of 3D body scans and mocap data. Animals have received much less attention, despite many applications in biomechanics, biology, neuroscience, robotics, smart farming, and entertainment. The main reason for the lack of methods for the 3D modeling and tracking of animals is that the methods derived for the human body cannot be easily applied to animals: animals are not cooperative, cannot be brought to the lab in large numbers, and current scanners cannot be taken into the wild. It is also challenging to capture significant motion of animals using motion capture equipment.

In this project we develop methods to learn 3D articulated statistical shape models that can represent a wide variety of species in the animal kingdom, allowing intra- and inter-species analysis of 3D shape and the automatic and non-invasive assessment of animal shape and pose from images and video.

From scans of toy animals, we learn the SMAL (Skinned Multi Animal Linear) model [888], a 3D articulated statistical shape model able to represent animal shapes for different species: big cats, dogs, cows, horses, zebras, and hippos. To capture animals outside the SMAL space, we developed SMALR (SMAL with Refinement) [888]. SMALR estimates a detailed 3D textured mesh using a small set of uncalibrated, non-simultaneous images of the animal. We are also developing species-specific models for dogs, rats and horses exploiting different modalities.

Today animal motion is mostly captured indoors for domestic species with marker-based systems. We are exploiting our 3D articulated animal shape models to develop markerless motion capture systems that can capture the shape and articulated motion of wild animals in their natural environment. In this context, we have applied our technology to capture the shape, pose, and texture of the Grevy's zebra from in-the-wild images [844] using a novel neural-network regressor. The approach learns the zebra shape space during training using a photometric loss.

More information: https://ps.is.mpg.de/project/capturing-animal-shape

Clothing Capture and Modeling

Michael Black, Qianli Ma, Jinlong Yang, Siyu Tang, Gerard Pons-Moll, Sergi Pujades, Shunsuke Saito, Chao Zhang

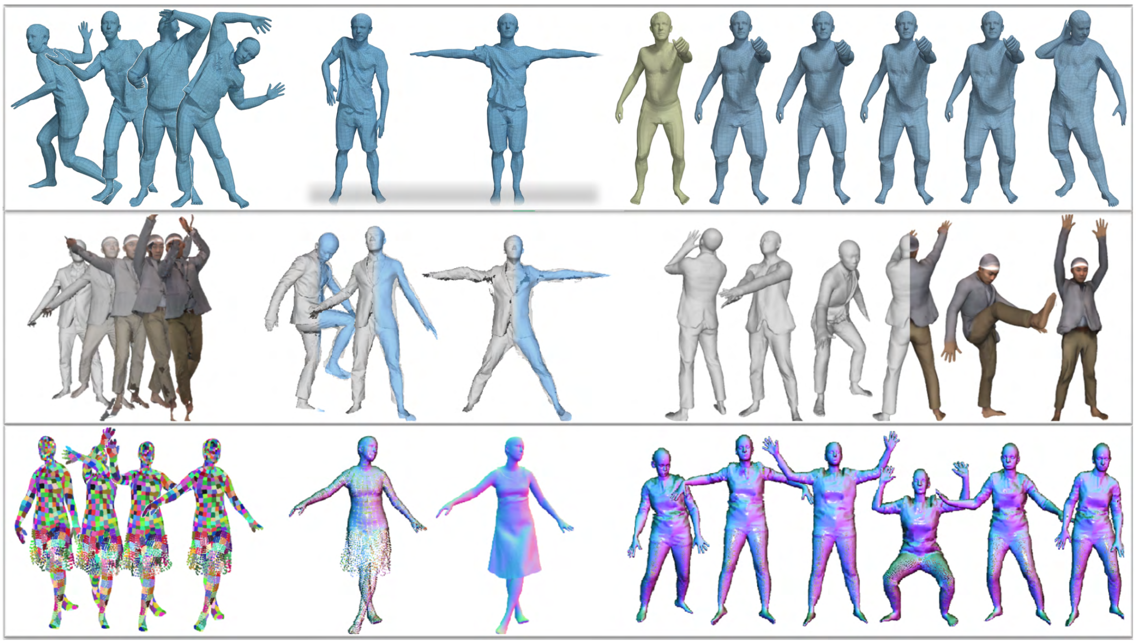


Figure 4.22: We explore different 3D shape representations to model clothed humans: mesh (top row), implicit function (middle row), and point cloud (bottom row)

While body models like SMPL lack clothing, people in images and videos are typically clothed. Modeling clothing on the body is hard, because of the variety of garments, varied topology of clothing, and the complex physical properties of cloth. Standard methods to dress 3D bodies rely on 2D patterns and physics simulation. Such approaches require expert knowledge and are labor intensive. We seek to capture garments on people "in the wild" and then realistically animate them. Consequently, we take a data-driven approach to learn the shape of clothed humans.

To learn a model of 3D clothing, we use both synthetic data from clothing simulation [806] and scans captured in our 4D body scanner [785]. We estimate the body shape under the clothing using BUFF [893] and then model how clothing deviates from the body.

With this data, we learn how clothing deforms with body pose. For example, CAPE [832] uses a conditional mesh-VAE-GAN, that is conditioned on pose, to learn clothing deformation from the SMPL body model. CAPE can then add pose-dependent clothing deformation to an animated SMPL body.

CAPE requires registered 3D meshes, which are challenging to obtain for clothing, and is tied to the topology of SMPL. To address these issues, we use implicit surface models. SCANimate [818] takes raw 3D scans are un-poses them to a canonical pose with the help of the estimated underlying body as well as a novel cycle-consistency loss. The canonicalized scans are then used to learn an implicit shape model that extends linear blend skinning to blend **fields**, defined implicitly in 3D space.

Implicit models lack compatibility with standard graphics pipelines. To address that, we propose two models, SCALE [819] and POP [806], that are based on point clouds and extend deep point cloud representations to deal with articulated human pose. The points are explicit but the surface through them is implicit. POP goes beyond previous methods to model multiple garments, enabling the creation of an animatable avatar, with pose-dependent deformations, from a single scan. These point-based models are readily rendered as images using neural rendering methods; see Neural Rendering for more information.

More information: https://ps.is.mpg.de/project/clothing

Expressive Body Models

Michael Black, Dimitrios Tzionas, Timo Bolkart, Ahmed Osman, Vassilis Choutas, Georgios Pavlakos, Nima Ghorbani

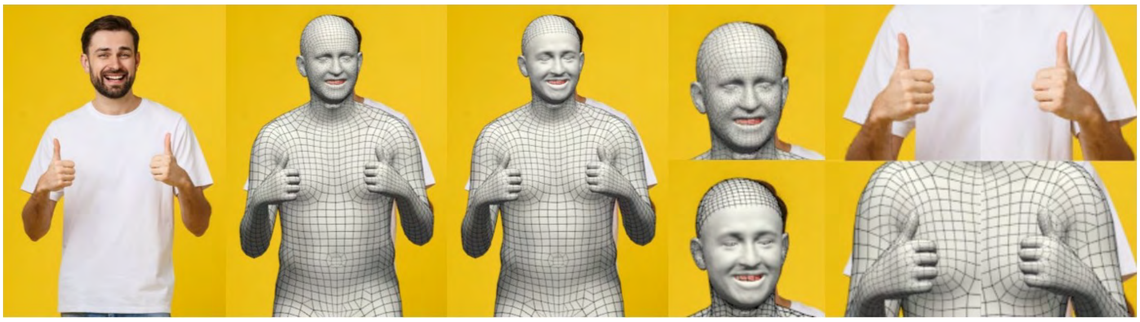


Figure 4.23: Bodies are not a collection of joints. Bodies have shape, can move, can express emotion, and can interact with the world. Hence virtual humans need emotional faces, realistic hands, and the ability to move and use them. Here we combine the SMPL-X body with a detailed face model (DECA) and train a regressor (PIXIE) to robustly recover body shape and pose, detailed face shape, and accurate hand pose from a single image.

Until recently, human pose has often been represented by 10-12 body joints in 2D or 3D. This is inspired by Johannson's moving light displays, which showed that some human actions can be recognized from the motion of the major joints of the body. We have argued that such representations are too impoverished to model human behavior. Humans express their emotions through the surface of their face and manipulate the world through the surface of their bodies.

Consequently, Perceiving Systems has focused on modeling and inferring 3D human pose and shape (HPS) using expressive 3D body models that capture the surface of the body either explicitly as a mesh or implicitly as a neural network. Such 3D shape models allow us to capture human-scene contact and provide information about a person related to their health, age, fitness, and clothing size.

We introduced the SMPL body model in 2015 [**smpl:2015**] and made it available for research and commercial licensing. SMPL is realistic, efficient, posable, and compatible with most graphics packages. It is also differentiable and easy to integrate into optimization or deep learning methods. Since its release, it has become the de facto standard in the field and is widely used in industry and academia.

SMPL also has limitations, some of which have been addressed by STAR [829], which is learned from thousands more 3D body scans and has local pose corrective blend shapes.

We have steadily improved on SMPL adding hands and faces to create SMPL-X [851]. Most recently we have combined this with the detailed facial model from DECA [752] to increase expressive realism. We always combine these models with methods to estimate them from images. Our most recent neural regression recent method, PIXIE [797], uses a moderator to assess the reliability of face and hand regressors before integrating the body, face, and hand features.

Current work is extending these models to include clothing. For example, CAPE [832] uses a convolutional mesh VAE to learn a generative model of clothing that is compatible with SMPL. See also our work on learning implicit models of clothed 3D humans.

This work on modeling humans is the foundation for our analysis of human movement, emotion, and behavior.

More information: https://ps.is.mpg.de/project/expressive-body-models

Regressing Humans

Michael Black, Angjoo Kanazawa, Muhammed Kocabas, Georgios Pavlakos, Chun-Hao Paul Huang, Joachim Tesch, Lea Müller, Ahmed Osman, Siyu Tang, Vassilis Choutas, Timo Bolkart, Dimitrios Tzionas, Nikos Kolotouros, Sai Kumar Dwivedi

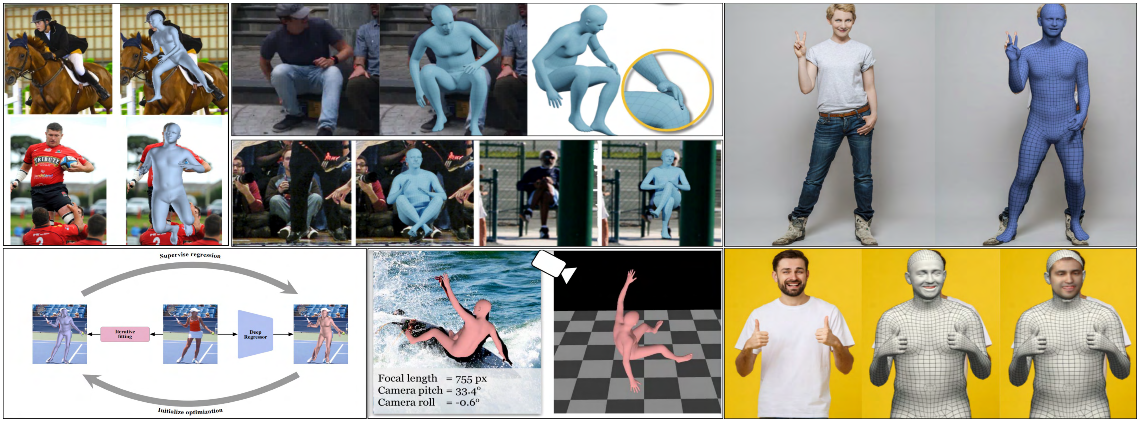


Figure 4.24: Regression of 3D bodies from images. Left: HMR [869] (top) and SPIN [840] (bottom) are foundational methods. Middle: Recent work improves results by considering self-contact (top, TUCH [817]), training for robustness to occlusions (middle, PARE [811]), and estimating perspective camera parameters (bottom, SPEC [810]). Right: We also regress expressive bodies with articulated hands and faces (top, ExPose [828]), including detailed face shape (bottom, PIXIE [797]).

Estimating the full 3D human pose and shape (HPS) directly from RGB images enables marker-less motion capture and provides the foundation for human behavior analysis. Classical top-down model fitting approaches have several limitations, they require pre-computed keypoints, which are difficult to obtain in complex scenarios and for bodies with occlusions, they are computationally slow (>30 seconds per image), and these methods are easily trapped in local minima. In contrast, regression methods directly learn the mapping between image pixels and 3D body shape and pose using a deep neural network.

The first HPS regressor, HMR [869], is trained using only a 2D joint reprojection error by exploiting an adversarial loss that encourages the model to produce SMPL parameters that are indistinguishable from real ones. VIBE [833] generalizes HMR to videos by using a temporal discriminator learned from AMASS [843]. SPIN [840] uses the current regressor to initialize optimization-based fitting, which then serves as supervision to improve the regressor in a collaborative training framework.

Our recent work builds on HMR and SPIN, addressing their limitations. PARE [811] learns to predict body-part guided attention masks to increase robustness to partial occlusions by leveraging information from neighboring, non-occluded, body-parts. SPEC [810] learns a network to estimate a perspective camera from the input image, and uses this to regress more accurate 3D bodies. TUCH [817] augments SPIN during training with 3D bodies that are obtained by exploiting discrete contacts during pose optimization, improving reconstruction performance for both self-contact and non-contact poses.

Typical HPS regressors work in two stages: they detect the human and then regress the body in a cropped image. ROMP [799] replaces this with a single stage by estimating the likelihood that a body is centered at any image pixel along with a map of SMPL parameters at every pixel. ROMP estimates multiple bodies simultaneously and in real time.

Most methods regress SMPL parameters. ExPose [828] estimates SMPL-X, including hand pose and facial expression, using body-part specific sub-networks to refine the hand and face parameters with body-driven attention. PIXIE [797] goes further, introducing a moderator that merges the features of different parts. PIXIE also increases realism by estimating gendered body shapes and detailed face shape.

More information: https://ps.is.mpg.de/project/3d-pose-and-shape-from-images

Optimizing Human Pose and Shape

Michael Black, Christoph Lassner, Javier Romero, Martin Kiefel, Federica Bogo, Peter Vincent Gehler, Angjoo Kanazawa, Georgios Pavlakos, Vassilis Choutas, Nima Ghorbani, Timo Bolkart, Ahmed Osman, Dimitrios Tzionas

Figure 4.25: Human inference via optimization. (Left) SMPLify estimates configurations of the SMPL body model from 2D body joints detected in images. (Middle) SMPLify-X estimates SMPL-X from whole-body 2D landmarks; note the expressive face and fingers. (Right) SMPLify-X humans (yellow) penetrate 3D objects; PROX (gray) extends it to use a 3D scene scan to encourage contact between bodies and objects, while discouraging inter-penetrations.

While data-driven methods for directly regressing 3D humans from 2D images are widely popular, optimization-based methods continue to play an important role. While typically slower than regression methods, optimization approaches require no training data, can be quickly adapted to new problems, and produce image-aligned results. In our view, the two approaches are not competing, but rather, complimentary.

Optimization-based approaches directly fit a 3D body model like SMPL to image observations (e.g., detected joint locations, edges, silhouettes, semantic segmentations, etc.). We introduced the first such method, SMPLify [898], which optimizes SMPL pose and shape to minimize the 2D error between detected joints and projected SMPL joints. Because of the inherent ambiguity in estimating 3D from 2D, SMPLify introduced a pose prior trained on mocap data and a term that discouraged self-penetration.

With SMPLify-X [851] we extend this concept to estimate the expressive SMPL-X model by fitting it to 2D landmarks from OpenPose. SMPLify-X introduced several improvements including a gender classifier so that the estimated body shapes better matched the image. We also introduced a better VAE-based pose prior, VPoser, trained on AMASS, and we improved the interpenetration detection.

Because images with ground-truth human pose and shape are hard to obtain, these optimization methods provide critical pseudo ground truth for training deep regression networks. For example, we use SMPLify-X to obtain SMPL-X fits to images and use these to train ExPose [828]. With SPIN [840], we showed that an even tighter integration of regression and optimization is valuable and synergistic. SPIN uses a regressor to initialize SMPLify, which is then run for a few optimization steps, improving the fit. These improved fits are then used to retrain the regressor. By doing this in a loop, we incrementally obtain better training data and a better regressor. This training approach is now widely used.

The basic SMPLify(-X) approach is easily adapted to new problems making it a foundational tool in our research. For example, we extended it to perform multi-view fitting and use silhouettes [875], which we exploited to create the AGORA [815] and SPEC-MTP [810] datasets. We use it with aerial vehicles to simultaneously solve for camera extrinsics and body pose in multi-view images [846]. We adapted it to RGB-D images by including a depth loss and scene contact constraints in the objective function, enabling the creation of the PROX dataset [845]. We added constraints related to self-contact and exploited this to create the training and test data for TUCH [817].

More information: https://ps.is.mpg.de/project/optimizing-human-pose-and-shape

Humans from Video

Michael Black, Muhammed Kocabas, Nikos Athanasiou, Yinghao Huang, Federica Bogo, Christoph Lassner, Angjoo Kanazawa, Peter Vincent Gehler, Javier Romero, Ijaz Akhter, Sergi Pujades, Gerard Pons-Moll

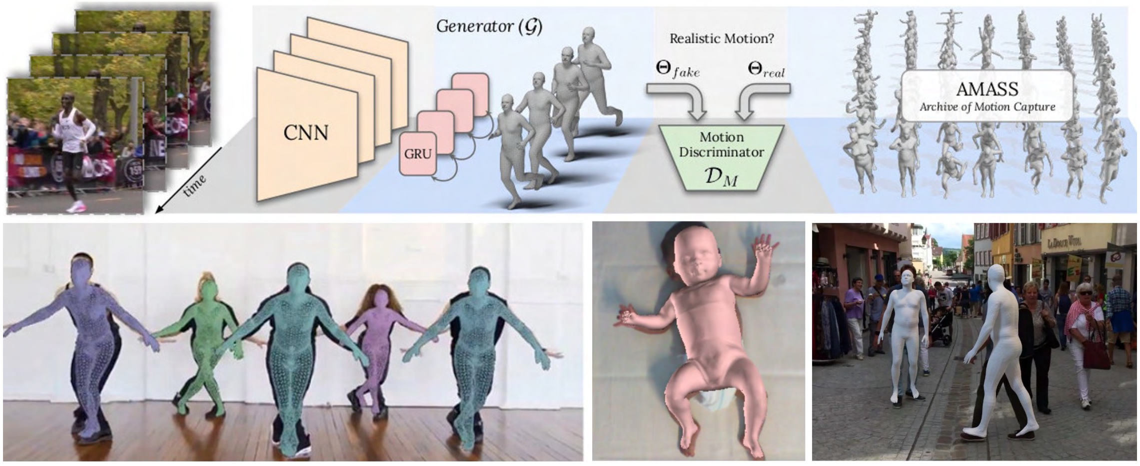


Figure 4.26: Top: VIBE regresses 3D human pose and shape from video using adversarial training by leveraging a large-scale human motion dataset (AMASS) to train a motion discriminator. Bottom left: output of VIBE. Bottom middle: SMIL estimates infant shape and motion from RGB-D videos to detect cerebral palsy. Bottom right: The 3DPW dataset combines IMU data with video to obtain high-quality pseudo ground truth 3D humans in video.

Humans are in constant motion. Interactions with the world and with each other involve movement. To capture, model, and synthesize human behavior we need to analyze it in video. Despite this, most methods for human 3D human pose and shape (HPS) estimation focus on single images. Intuitively, we should be able to exploit the regularity of human motion and the extra information provided by multiple video frames to improve HPS estimation compared to single-image methods. To that end, we are pursuing several lines or research to enable accurate markerless motion capture from unconstrained video "in the wild".

A key enabler of video-based analysis of motion is training data. To that end, we have exploited our 3D body models (SMPL, etc.) and MoSh, to create the large-scale AMASS dataset [843] of human motions in a common 3D representation. We used an early version of this to generate the SURREAL dataset [883], which contains rendered videos of people in motion. We used SURREAL, for example, to train methods to estimate the optical flow of people in video [762]. We also used AMASS to train a network to estimate 3D human pose from a sparse set of IMUs [774].

Synthetic datasets like SURREAL are not fully representative of real-world video. Consequently, we created the 3D Poses in the Wild dataset (3DPW) by combining IMU data with monocular video. IMUs are prone to drift but give 3D pose information. Videos give precise 2D alignment with image pixels but lack 3D. By combining these sources of information, 3DPW provides class-leading pseudo ground truth and is, consequently, widely used for training and evaluation.

To estimate 3D humans from video, we have pursued both optimization and regression approaches. Multi-View-SMPLify [875] optimizes 3D pose over time using a generic DCT temporal prior. In contrast, VIBE [833] uses a GRU-based temporal architecture to regress SMPL from video. VIBE exploits discriminative training using AMASS [843] to help the network generate motions that resemble true human movement.

With SMIL [763], we capture the motion of infants in RGB-D sequences but go further to use the sequences to learn the 3D shape model. By analyzing the movements of the infants, we provide an assessment related to cerebral palsy [760],[758].

More information: https://ps.is.mpg.de/project/humans-from-video

AirCap: 3D Motion Capture

Aamir Ahmad, Eric Price, Nitin Saini, Guilherme Lawless, Elia Bonetto, Roman Ludwig, Igor Martinovic, Yilin Ji, Michael Black, Aamir Ahmad

Figure 4.27: Real image sequence (top left). Estimated 3D pose and shape (top right). Two of our MAVs cooperatively detecting and tracking a person on-board in real time (bottom left). Cropped ROIs of images from both MAVs and estimated 3D pose and shape overlaid on images (bottom center). DRL-based aerial mocap (bottom right).

The goal of AirCap is markerless, unconstrained, human and animal motion capture (mocap) outdoors. To that end, we have developed a flying mocap system using a team of aerial vehicles (MAVs) with only on-board, monocular RGB cameras. In AirCap, mocap involves two phases: i) online data acquisition, and ii) offline pose and shape estimation.

During online data acquisition, the micro air vehicles (MAVs) detect and track the 3D position of a subject [776]. To do so, they perform on-board detection using a deep neural network (DNN). DNNs often fail to detect small people, which are typical in scenarios with aerial robots. By cooperatively tracking the person our system actively selects the relevant region of interest (ROI) in the images from each MAV. Then cropped high-resolution regions around the person are passed to the DNNs.

Then, human pose and shape are estimated offline using the RGB images and the MAV's self-localization (the camera extrinsics). Recent 3D human pose and shape regression methods produce noisy estimate of human pose. Our approach [846] exploits multiple noisy 2D body joint detectors and noisy camera pose information. We then optimize for body shape, body pose, and camera extrinsics by fitting the SMPL body model to the 2D observations. This approach uses a strong body model to take low-level uncertainty into account and results in the first fully autonomous flying mocap system.

Offline mocap, does not enable active positioning of the MAVs to maximize the mocap accuracy. To address this, we introduce a deep reinforcement learning (RL) based multi-robot formation controller for MAVs. We formulate this problem as a sequential decision making task and solve it using an RL method [759].

To enable fully on-board, online, mocap, we are developing a novel, distributed, multi-view fusion network for 3D pose and shape estimation of humans using uncalibrated moving cameras.
More information: https://ps.is.mpg.de/project/aircap

Capturing Contact

Michael Black, Lea Müller, Chun-Hao Paul Huang, Ahmed Osman, Siyu Tang, Omid Taheri, Nima Ghorbani, Dimitrios Tzionas, Vassilis Choutas, Mohamed Hassan, Partha Ghosh, Joachim Tesch, Gul Varol, Cordelia Schmid

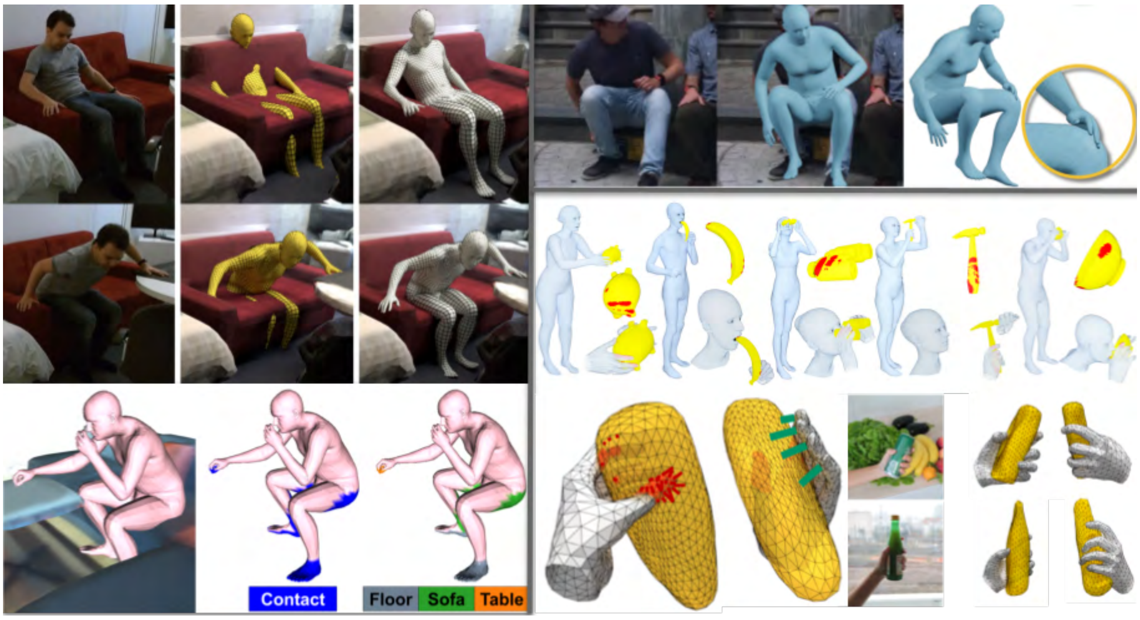


Figure 4.28: Contact plays an important role in understanding human-scene interactions and it takes many forms. Left: contact between the full body and furniture is used to improve monocular human pose and shape (HPS) estimation [845] and to learn a body-centric representation for human-scene interaction [816]. Top right: considering self-contact improves monocular HPS [817]. Middle right: a dataset of whole-body grasps [827]. Bottom right: contact between hands and hand-held objects helps reconstruct hands and objects jointly from images [852].

Understanding and modeling human behavior requires capturing humans moving in, and interacting with, the world. Standard 3D human body pose and shape (HPS) methods estimate bodies in isolation from the objects and people around them. The results are often physically implausible and lack key information. We view **contact** as central to understanding behavior and therefore essential in human motion capture. Our goal is to capture people in the context of the world where *contact is as important as pose.*

To study this, we captured the PROX dataset [845] using 3D scene scans and an RGB-D sensor to obtain pseudo ground truth poses with physically meaningful contact. Knowing the 3D scene enables more accurate HPS estimation from *monocular RGB* images by exploiting contact and interpenetration contraints.

Using the body-scene contact data from PROX, POSA [816] learns a generative model of contact for the vertices of a posed body. We use this *body-centric* prior in monocular pose estimation to encourage the estimated body to have physically and semantically meaningful scene contacts.

TUCH [817] explores HPS estimation with self-contact. We create novel datasets of images with known 3D contact poses or contact labels. Using these, and a contact-aware version of SMPLify-X [851], we train a regression network using a modified version of SPIN [840]. Not only is TUCH more accurate for images with self-contact, but also for non-contact poses.

To learn to regress 3D hands and objects from an image, we created the ObMan dataset by extending a robotic grasp simulator to MANO [781] and rendering images of hands grasping many objects. We trained a network to regress both object and hand shape, while encouraging contact and avoiding interpenetration.

To address detailed *whole-body contact* during object manipulation we used mocap to create the GRAB dataset [827]. GRAB goes beyond previous hand-centric datasets to capture actions like drinking where contact occurs between a cup and fingers as well as the lips.

More information: https://ps.is.mpg.de/project/capturing-contact

Inferring Actions

Michael Black, Yan Zhang, Michael Black, Krikamol Muandet, Abhinanda Ranjit Punnakkal, Arjun Chandrasekaran, Nikos Athanasiou, Alejandra Quiros-Ramirez, Siyu Tang

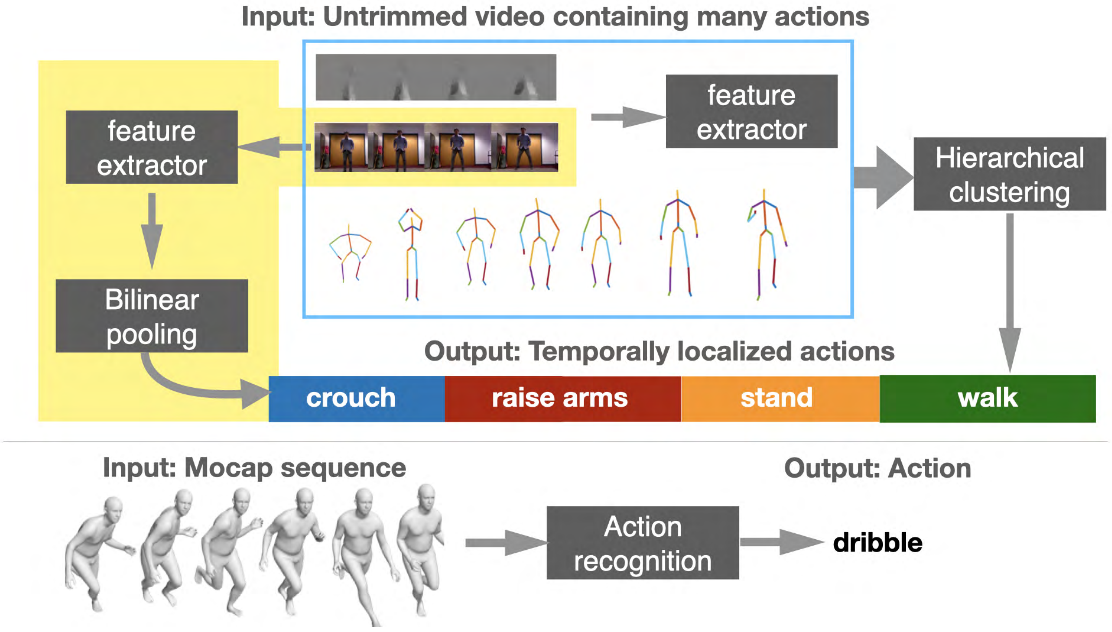


Figure 4.29: Top: Temporal Action Localization (TAL). The bilinear pooling algorithm [440] recognizes and localizes all actions in an RGB video (yellow background). The hierarchical clustering algorithm [860] uses both RGB and 3D joint positions for TAL (blue box). Below: The Action Recognition model in BABEL [814] predicts the action in a mocap sequence.

Human behavior can be described at multiple levels. At the lowest level, we observe the 3D pose of the body over time. Poses can be organized into primitives that capture coordinated activity of different body parts. These further form more complex actions. At the most abstract level, behavior can be described semantically in terms of actions and goals.

The BABEL dataset [814] contains labels of actions being performed by subjects in mocap sequences from AMASS [843]. BABEL is larger and more complex than existing 3D action recognition datasets, making the action recognition task challenging. BABEL has a long-tailed action distribution, significant intra-class variance, and frequently, multiple actions are performed simultaneously. These characteristics are similar to real-world data, suggesting that BABEL can drive progress in the field.

Human movements typically involve different successive actions. In addition to asking what actions are occurring, Temporal Action Localization (TAL) asks when these actions occur; i.e., the start and end of each action in the video.

Prior methods addressing TAL lose important information while aggregating features across successive frames. We develop a novel, learnable bilinear pooling operation to aggregate features that retains fine-grained temporal information [440]. Experiments demonstrate superior performance to prior work on various datasets.

Humans can readily differentiate biological motion from non-biological motion without training, even with sparse visual cues like moving dots. In this spirit, we perform behavior analysis at a low-level using a novel dynamic clustering algorithm [860]. Low-level visual cues are aggregated to high-level action patterns, and are utilized for the TAL task.

More information: https://ps.is.mpg.de/project/inferring-actions

Language and Movement

Mathis Petrovich, Abhinanda Ranjit Punnakkal, Arjun Chandrasekaran, Nikos Athanasiou, Alejandra Quiros-Ramirez, Siyu Tang, Gul Varol, Michael Black

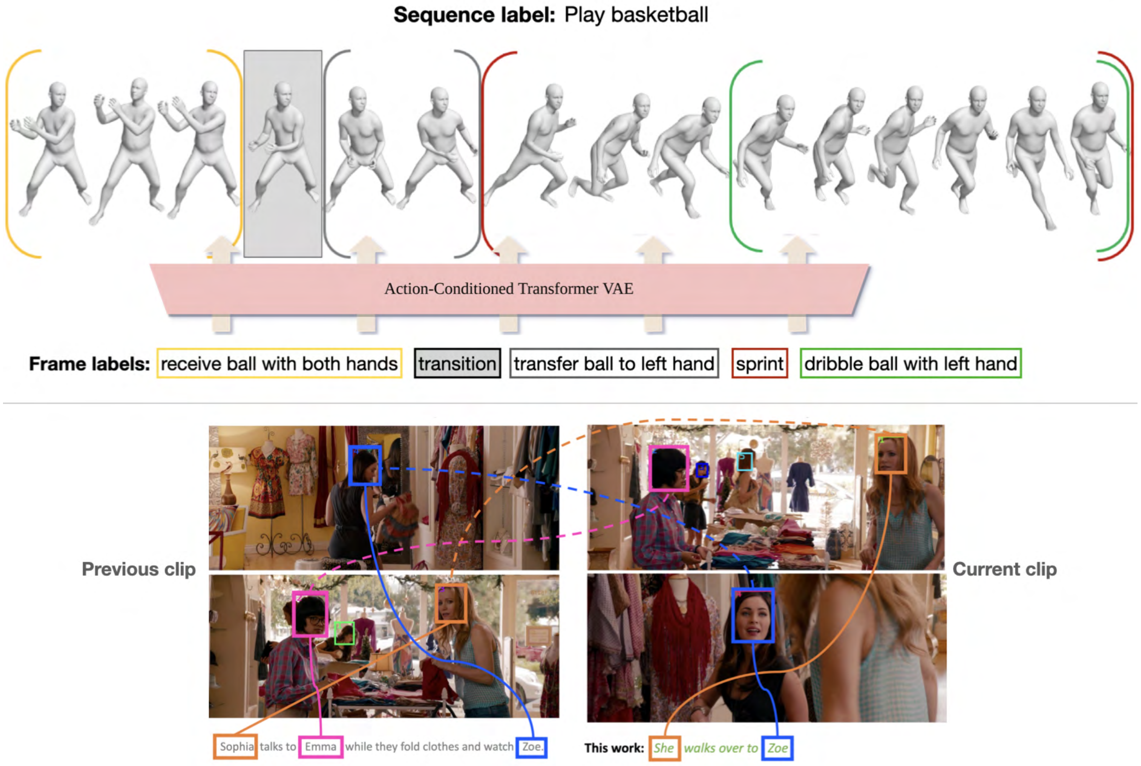


Figure 4.30: Top: Our goal is to generate 3D human movements that are grounded in actions using the BABEL dataset [814], which consists of dense frame-level action labels that correspond to 3D human movements. Bottom: We identify individual actors in a movie clip and synthesize natural language descriptions of their actions and interactions [889].

Understanding human behavior requires more than 3D pose. It requires capturing the semantics of human movement - *what* a person is doing, *how* they're doing it, and *why*. The *what* and *why* of human movement - the actions of a person, their goals, emotions, and mental states - are typically described via natural language. Thus, grounding human movement in language, is a key to modeling and synthesizing human behavior.

Progress in this requires 3D movement data that is precisely aligned with action descriptions. In BABEL [814] we label (>250) actions performed in (>43 hours) mocap sequences from AMASS [843]. Fine-grained "frame labels" precisely capture the duration of each action in a sequence. BABEL is being leveraged for tasks like action recognition, temporal action localization, and motion synthesis.

Since 3D mocap data will always be limited, we would like to learn language-grounded movement from video. Our approach identifies individual actors in a movie clip and synthesizes language descriptions of their actions and interactions [889]. The approach first localizes characters by relating their visual appearance to mentions in the movie scripts via a semi-supervised approach. This (noisy) supervision greatly improves the performance of a description model.

ACTOR [805] is an example of our work on synthesizing human movement, conditioned on action labels. Despite being trained with noisy data estimated from monocular video, ACTOR's transformer VAE architecture learns to synthesize diverse and realistic movements of varied length.

More information: https://ps.is.mpg.de/project/language-and-movement

Modeling Human Movement

Julieta Martinez, Judith Bütepage, Javier Romero, Hedvig Kjellström, Ludovic Righetti, Mohamed Hassan, Siyu Tang, Yan Zhang, Gul Varol, Mathis Petrovich, Michael Black

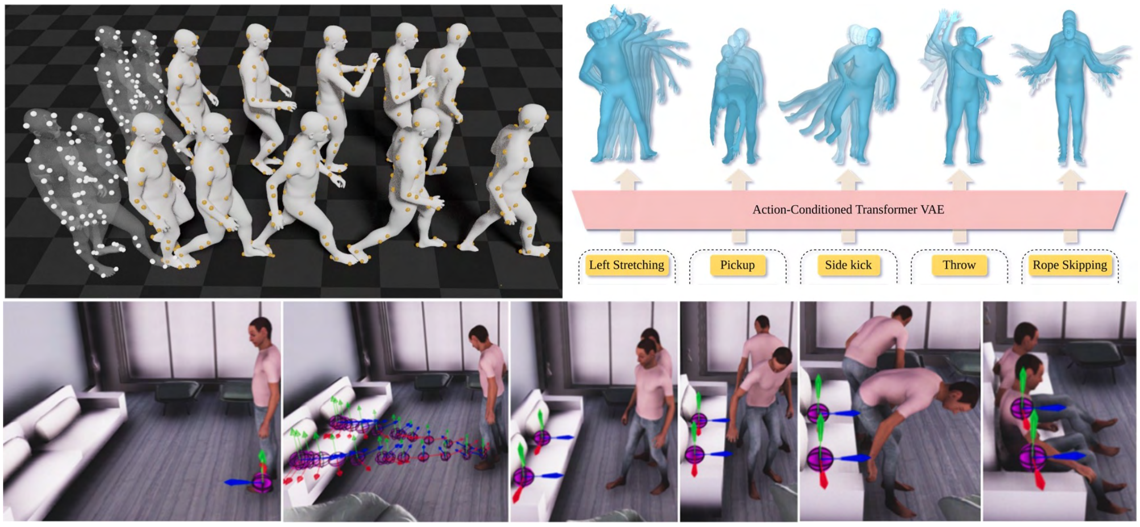


Figure 4.31: Clockwise from upper left: MOJO [820] predicts human movement given past movement. ACTOR [805] generates diverse human movements conditioned on an action label. SAMP [809] produces human motions to satisfy goals like "sit on the sofa".

A key goal of Perceiving Systems is to model human behavior. One way of testing our models is by **generating** movement.

One class of motion generation methods takes a short segment of human motion and predicts future motions; this is a classical time-series prediction problem but with unique physical constraints. We observed that many prediction methods suffer from "regression to the mean" and that state-of-the-art performance can be achieved by a simple baseline that does not model motion at all [879]. We have explored RNN-based methods [879] and a simple encoder/decoder architecture [884] to take past poses and predict future ones.

While prior work focuses on predicting joints, we note that these can be thought of as a very sparse point cloud; i.e., motion prediction methods are point-cloud predictors. Unfortunately, over time, these points tend to deviate from valid body shapes. Instead of joints, with MOJO [820], we predict virtual markers on the body surface. This allows us to fit SMPL to them at each time step, effectively projecting the solution back onto the space of valid bodies.

In many cases, we want to generate motion corresponding to specific actions. ACTOR [805] does this using an action-conditioned transformer VAE. By sampling from the VAE latent space, and querying a certain duration through a series of positional encodings, we synthesize diverse, variable-length motion sequences conditioned on an action.

Most synthesis methods, like those above, know nothing about the 3D scene. SAMP [809], in contrast, generates motions of an avatar through a novel scene to achieve a goal like "sit on the chair". SAMP uses a GoalNet to generate object affordances, such as where to sit on a novel sofa. A MotionNet sequentially predicts body poses based on the past motion and the goal, while an A* algorithm plans collision-free paths through the scene to the goal.

While ACTOR and SAMP take steps towards generating movement from high-level goals, many motions are governed by physics. Hence, we also explore physics-based controllers of human movement [775]. We envision a future that combines the best of both approaches with learned models of behavior combined with physical constraints coming from environmental interaction.

More information: https://ps.is.mpg.de/project/modeling-human-movement

Neural Rendering

Michael Black, Soubhik Sanyal, Sergey Prokudin, Javier Romero, Partha Ghosh, Timo Bolkart, Anurag Ranjan, Roy Uziel, Matthew Loper, Betty Mohler

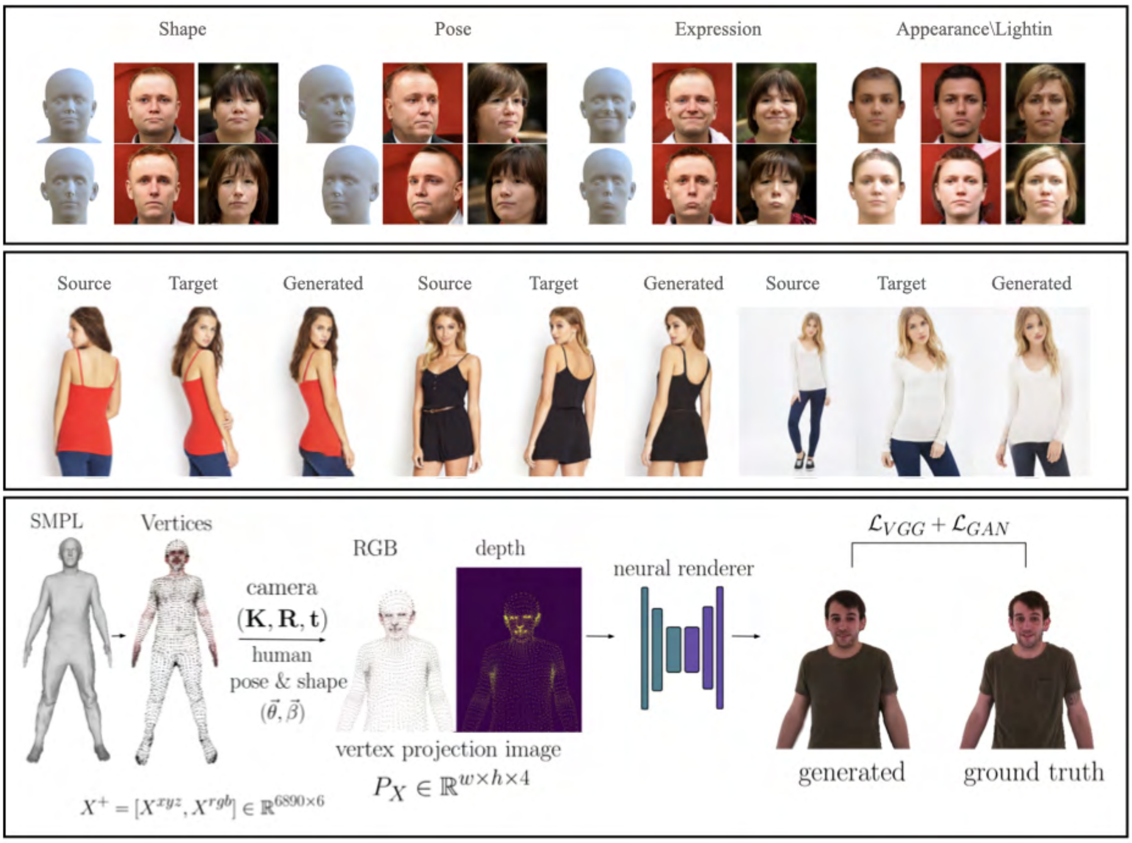


Figure 4.32: GIF [824] (top) generates realistic face images that are controlled by FLAME parameters. SPICE [800] (middle) learns to repose an image of a person without any paired training data by exploiting information about 3D bodies. SMPLpix [822] (bottom) generates realistic images of people from a sparse set of colored SMPL vertices.

Conventional graphics pipelines take a 3D model like SMPL, apply texture and material properties, light it, and render it as an image. Without expensive artist involvement, this results in unrealistic images that fall into the "uncanny valley". To address this, we develop neural rendering methods that keep the 3D body model but replace the rendering pipeline with neural networks. This approach keeps the flexibility of parametric models while producing realistic looking images without artist intervention.

GIF [824] generates realistic images of faces, by conditioning StyleGAN2 on the FLAME face model [782]. Given FLAME parameters for shape, pose, expressions, plus parameters for appearance, lighting, and an additional style vector, GIF outputs photo-realistic face images.

To generate images of people with realistic hair and clothing, we train SMPLpix [822] to transform a sparse set of 3D mesh vertices and their RGB values into photorealistic images. The 3D mesh vertices are controllable with the pose and shape parameters of SMPL.

SPICE [800] takes a different approach and synthesizes an image of a person in a novel pose given a source image of the person and a target pose. In contrast to typical approaches that require paired training data, SPICE uses only unpaired data. This is enabled by a novel cycle-GAN training method that exploits information about the 3D SMPL body.

The combination of parametric 3D models with neural rendering enables realistic human rendering with intuitive animation controls.

More information: https://ps.is.mpg.de/project/neural-rendering

Putting People into Scenes

Michael Black, Mohamed Hassan, Dimitrios Tzionas, Partha Ghosh, Joachim Tesch, Qianli Ma, Yan Zhang, Siyu Tang, Vassilis Choutas

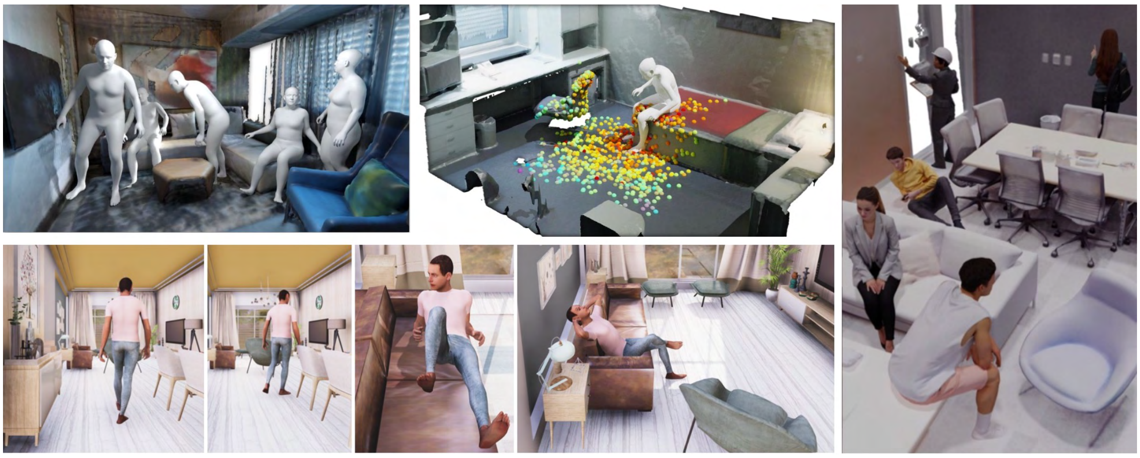


Figure 4.33: Clockwise from upper left: PSI [834], PLACE [825], POSA [816] and SAMP [809].

Humans live within a 3D space and constantly interact with it to perform tasks. Such interactions involve physical contact between surfaces that is semantically meaningful. Our goal is to learn how humans interact with scenes and leverage this to enable virtual characters to do the same. This is a challenging task for a computer as solving it requires that (1) the generated human bodies are semantically plausible within the 3D environment (e.g. people sitting on the sofa or cooking near the stove), and (2) the generated human-scene interaction is physically feasible such that the human body and scene do not interpenetrate while, at the same time, body-scene contact supports physical interactions.

While prior work focused on the body as a stick figure, we place full 3D SMPL-X bodies in scenes. The body surface is critical to establishing appropriate semantic and physical interactions. To create training data, we use the PROX dataset [845], which includes 3D SMPL-X bodies fit to real 3D scenes with ground truth contact information.

Our first work, PSI [834], uses a conditional variational autoencoder to predict semantically plausible 3D human poses conditioned on latent scene representations. We then refine the generated 3D bodies using scene constraints to enforce feasible physical interaction.

To synthesize realistic human-scene interactions, it is essential to represent the physical contact and proximity between the body and the world. With PLACE [825], we explicitly model the proximity between the human body and the 3D scene around it. Specifically, given a set of basis points on a scene mesh, we train a conditional VAE to synthesize the distances from the basis points to the human body surface.

POSA [816] flips this around to model human-scene interaction in a body-centric representation that enables it to generalize to new scenes. POSA augments SMPL-X such that, for every mesh vertex, it encodes (a) the contact probability with the scene surface and (b) the corresponding semantic scene label. We learn POSA with a VAE conditioned on the SMPL-X vertices, and train on the PROX dataset.

While the above methods produce static poses, SAMP [809] generates goal-directed human movement in novel scenes. Given a task like "sit on the sofa", SAMP uses a GoalNet to extract the affordances of the sofa. A MotionNet generates sequences of poses to achieve the goal, while an A* algorithm plans a collision-free path through the scene.

These methods are just the beginning but provide a path for creating digital humans that can behave autonomously in 3D worlds.

More information: https://ps.is.mpg.de/project/putting-people-into-scenes

Bodies in Society

Alejandra Quiros-Ramirez, Stephan Streuber, Silvia Zuffi, Matt Hill, Michael Black, Naureen Mahmood

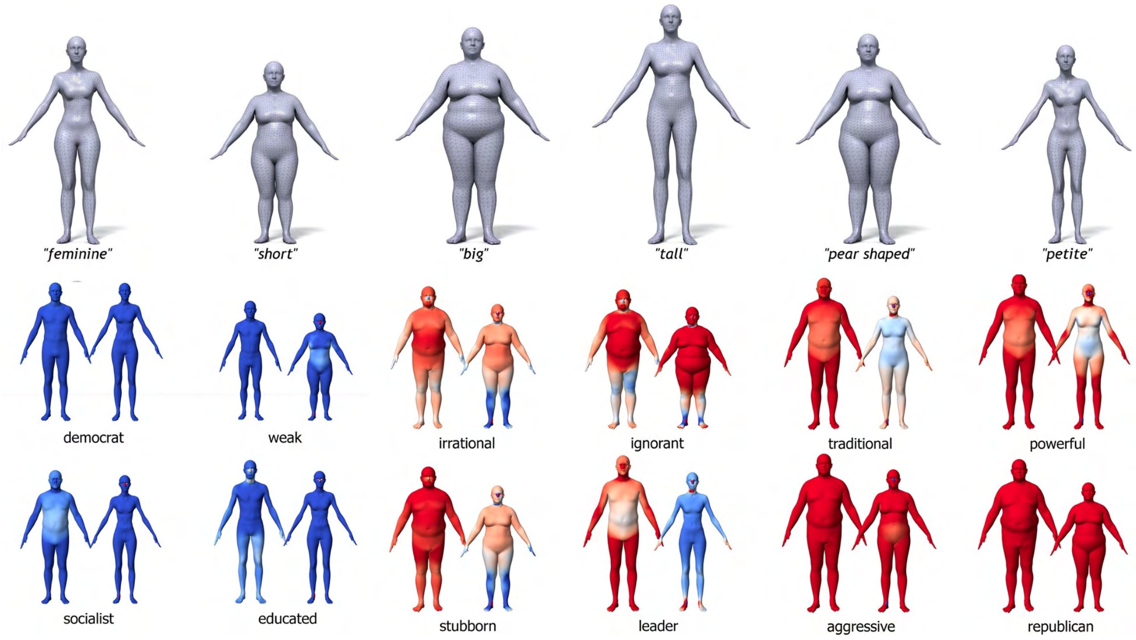


Figure 4.34: (top) Prototypical body shapes generated by BodyTalk, relating 3D shape to linguistic descriptions of shape. Shown are the most likely body shapes, conditioned on the words below them. (bottom) Each body pair illustrates the 3D mental representation associated with different political traits for male and female bodies. Blue indicates a geometric closeness to the Democrat stereotype, while red represents geometric closeness to the Republican stereotype.

Our bodies say something about us. We have names for body shapes like "hourglass" or "pear shaped" [789]. People also make social judgments based on body shape. To understand this we have developed methods to relate linguistic descriptions of people to 3D body shape [791].

Linguistic descriptions of body shape are naturally used to convey the physical appearance of people to others. For example, writers aim to create an image of a fictional character in the reader's mind with words, and crime witnesses are asked to verbally describe the appearance of the suspect to a sketch artist. Can we use this same procedure to recreate 3D human body shape? Do we share an understanding of 3D meaning of these shape descriptions?

We use crowdsourcing to generate attribute ratings of 3D body shapes corresponding to standard linguistic descriptions of 3D shape (for example, 'big', 'fit', 'feminine' or 'pear shape'). We also use non-shape words like 'ignorant', 'liberal', or 'Republican'. We then learn a function relating these ratings to 3D human shape parameters.

Given an image of a person, we use crowdsourcing to collect linguistic ratings of their body shape; this provides strong constraints on their 3D shape. These "crowdshaped" bodies are perceptually indistinguishable from bodies created from high-resolution scans and their metric accuracy is sufficient for many tasks.

Our model provides insight into social biases [773] based on body shape. In particular, in the absence of other information, people make judgements about leadership traits based only on body shape [750]. Voters find certain body shapes to be more trustworthy, more leader-like, more compassionate, or more conservative.

These findings can help raise awareness of unconscious biases in trait perception from body shape. Awareness is the first step in overcoming such biases that can affect decision making in elections, healthcare, the legal system, and education.

More information: https://ps.is.mpg.de/project/bodytalk

Bodies in Medicine

Michael Black, Sergi Pujades, Javier Romero, Marilyn Keller, Nikolas Hesse

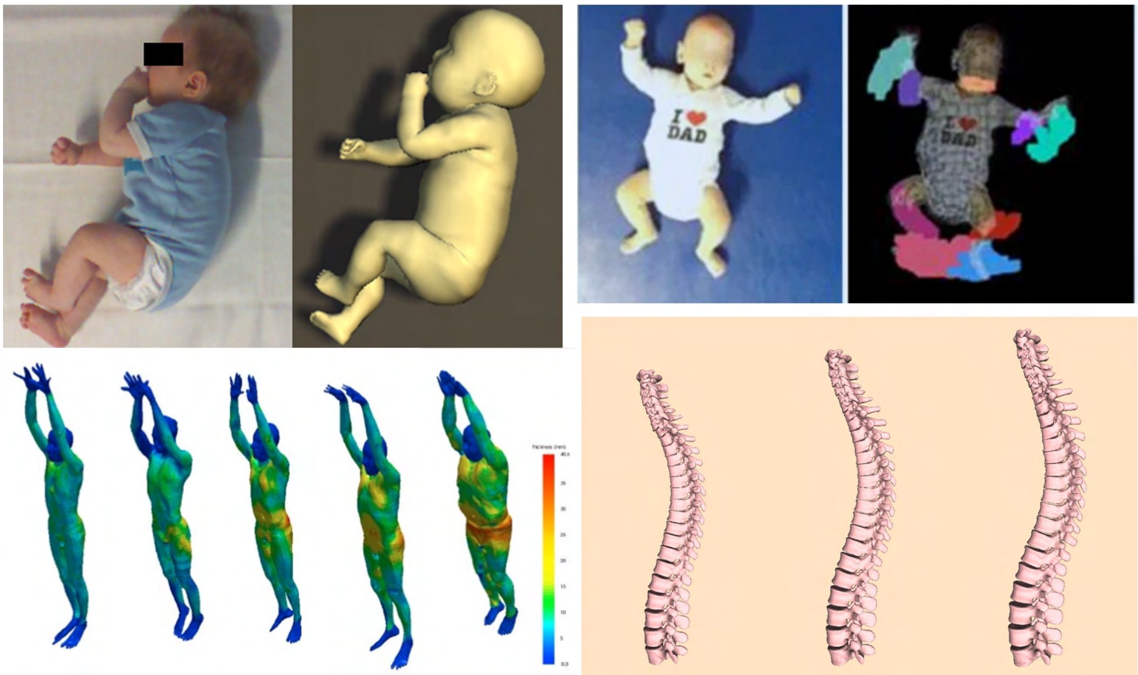


Figure 4.35: Top left: We learn an infant body model called SMIL from RGB-D sequences and use this to recover the shape and pose of freely moving infants. Top right: We use SMIL to track infant motion to assist with early diagnosis of cerebral palsy. Bottom right: Looking inside the body, we learn a model of spine shape and curvature. Bottle left: We align 3D bodies to MRI, segment the subcutaneous adipose tissue, and illustrate its thickness with a color code.

Body shape and movement are related to human health. Using our 3D models of body shape we analyze movement and shape to create non-invasive and deployable methods for analyzing human health.

For example, if Cerebral Palsy (CP) is detected early, there are effective therapies to minimize the impact in later life. CP can be diagnosed in infants based on their spontaneous, undirected movements. Unfortunately, this requires expert training that is not widely available. By automatically tracking infant movement, we can automate the early detection of CP. Methods for tracking adult 3D motion, however, do not work for infants due to their very different body shape.

Since we lack 3D scans of infants, we developed a novel method that learns an infant body shape model, called SMIL, directly from low quality, incomplete, RGB-D scan sequences and deployed this in hospitals where we scanned over 30 infants [867]. Using SMIL we track spontaneous infant movements in RGB-D sequences and train a method to automatically recognize pathological movements [758].

We also train methods to predict what is inside the body by observing the outside. Take, for example, the distribution of body fat. Visceral adipose tissue is correlated with disease while sub-cutaneous adipose tissue is relatively benign. We are developing methods to estimate this fat distribution purely from the surface shape of the body. To that end, we fit our 3D body models to full-body MRI scans [790] to model both the external surface and the subcutaneous fat layer.

To make predictions of the body composition of a person from a surface scan, a main challenge lies in the variance of the body shape due to the pose. In collaboration with the University of Hawai'i Cancer Center (US) we show how SMPL allows us to factor out pose variations from surface scan data, improving the accuracy of the body composition estimation [748].

More information: https://ps.is.mpg.de/project/medical-diagnosis

Learning Optical Flow

Michael Black, Andreas Geiger, Anurag Ranjan, Jonas Wulff, Deqing Sun, Varun Jampani, Laura Sevilla, Joel Janai, Fatma Güney

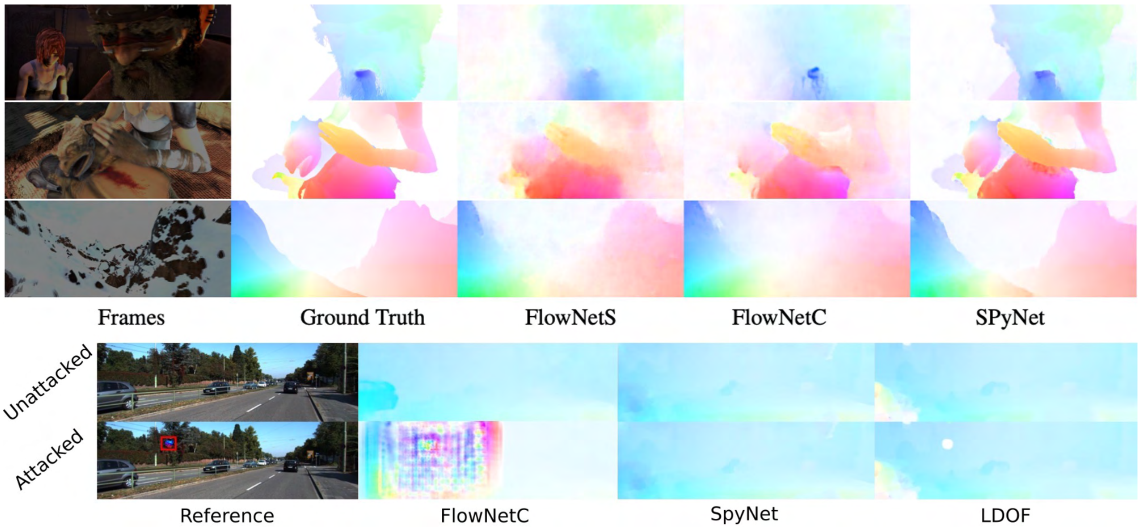


Figure 4.36: Top: Deep learning methods like SpyNet [880] now dominate optical flow estimation. Bottom: Unfortunately, many of these methods are easily attacked [839]. A small adversarial image patch (in the red square) can disrupt large parts of the flow field.

Optical flow is the projection of the 3D motion field into the 2D image plane and it is useful for a variety of applications. Advances in deep learning have rapidly improved the accuracy of optical flow methods. Despite this, they have several limitations that we have worked to resolve.

To deal with large image motions in a compact network, we developed the Spatial Pyramid Network (SpyNet) [880], which computes optical flow by combining a classical coarse-to-fine flow approach with deep learning. At each level of a spatial pyramid, the deep network computes an update to the current flow estimate. SpyNet is 96% smaller than FlowNet, is very fast, and can be trained end-to-end, making it easy to incorporate into other networks for tasks like action recognition [871].

We discovered that many existing deep flow networks are not robust to adversarial attacks, even when only a small portion of the image is corrupted [839]. We learn an optimal pattern that, when placed in the image, can cause widespread errors in the flow. This gives insights into the inner workings of these networks, points out potential risks, and suggests a path to making them more robust.

Deep networks also require significant amounts of training data, yet there are no sensors that give ground truth optical flow for real image sequences and synthetic data is currently unrealistic. Consequently, have developed methods for unsupervised learning.

To that end, we exploit the geometric structure of optical flow in rigid scenes. With Competitive Collaboration [855] we train four different networks that estimate monocular depth, camera pose, optical flow and non-rigid motion segmentation. These models compete and collaborate to explain the motion in the scene, producing accurate optical flow without explicit supervision.

The lack of proper occlusion handling in commonly used data terms is a major source of error in existing unsupervised methods. To address this, we use three consecutive frames to strengthen the photometric loss and explicitly reason about occlusions [862]. Our multi-frame formulation outperforms existing unsupervised two-frame methods and even produces results on par with some fully supervised methods.

Additionally, motion occlusion boundaries give important information about scene structure and we have worked on learning to detect these [902].

More information: https://ps.is.mpg.de/project/learning-optical-flow

Optical Flow and Human Action

Anurag Ranjan, Laura Sevilla, Yiyi Liao, Fatma Güney, Varun Jampani, David Hoffmann, Dimitrios Tzionas, Siyu Tang, Javier Romero, Andreas Geiger, Michael Black

(a) Our dataset (b) Results on synthetic scenes (c) Results on real world scenes

Figure 4.37: (Top) We learn human flow [865],[762] from synthetically generated flow fields and find that this generalizes to real videos of human movement. (Bottom) We fine tune an optical flow algorithm to produce flow that improves action recognition [871]. (Left columns) SpyNet. (Right columns) FlowNet. In each set, left to right: first image in sequence, original flow, flow when trained on action recognition, differences in the flow are focused on the human action.

Understanding human action requires modeling and understanding human movement. While we mostly focus on 3D human movement, what is directly observable in videos is the 2D optical flow. Previous work has shown that flow is useful for action recognition and, consequently, we explore how to better estimate human flow and improve action recognition.

Specifically, we train a neural network to compute single-human [865] and multi-human [762] optical flow. To enable this we create a new synthetic training database of image sequences with ground-truth human optical flow. For this we use the 3D SMPL body model, motion-capture data, and computer graphics to synthesize realistic flow fields; this effectively extends the SURREAL dataset [883]. We then train a convolutional neural network (SpyNet [880]) to estimate human optical flow from pairs of images.

The new network is more accurate than a wide range of top methods on held-out test data and generalizes well to real image sequences. When combined with a person detector/tracker, the approach provides a full solution to the problem of 2D human flow estimation.

Most of the top-performing action-recognition methods use optical flow as a "black box" input. In [871], we take a deeper look at the combination of flow and action recognition, and find that: 1) optical flow is useful for action recognition because it is invariant to appearance, 2) flow accuracy at boundaries and for small displacements is most correlated with action-recognition performance, 3) training optical flow needs to minimize classification error instead of the popular end-point-error (EPE) to improve action recognition, and 4) optical flow learned for action recognition differs from traditional optical flow mostly inside and at the boundary of human bodies.

More information: https://ps.is.mpg.de/project/optical-flow-and-human-action

AirCap: Perception-Based Control

Aamir Ahmad, Eric Price, Rahul Tallamraju, Roman Ludwig, Nowfal Manakkaparambil Ali, Igor Martinovic, Yu-Tang Liu, Halil Acet, Elia Bonetto, Michael Black, Aamir Ahmad

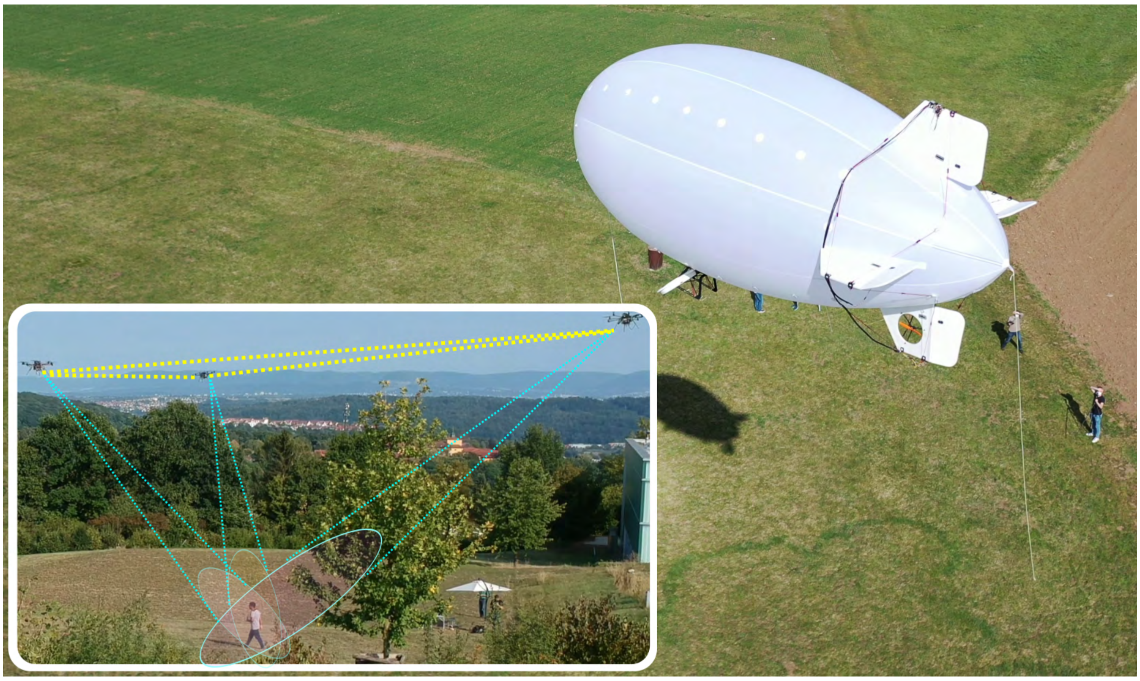


Figure 4.38: Perception-driven formation control of aerial robots tracking a person (inset). An autonomous blimp in flight, suitable for tracking animal subjects.

Flying mocap systems use aerial robots with on-board cameras that can localize and navigate autonomously. These robots must detect, track and follow the subject (human or animal) in real time. A key component of such systems is motion planning and control of multiple robots that ensures optimal perception of the subject while obeying other constraints, e.g., inter-robot and static obstacle collision avoidance.

We address this with decentralized convex model-predictive control (MPC) [768]. The micro air vehicles (MAVs) actively compute local motion plans producing optimal view-point configurations, which minimize uncertainty in the tracked estimate. We achieve this by decoupling the goal of active tracking into a quadratic objective and non-convex constraints corresponding to angular configurations of the MAVs w.r.t. the person. We derive this decoupling using Gaussian observation model assumptions within the cooperative tracking algorithm [776] [783]. We preserve convexity in optimization by embedding all the non-convex constraints, including those for dynamic obstacle avoidance, as external control inputs in the MPC dynamics [866]. We evaluate this with 3 MAVs in challenging scenarios.

Tracking animals is difficult with multi-rotor vehicles due to their noise and short flight time. Consequently, we developed a novel framework for modeling, simulation and control of helium-based blimps [813]. This addresses several unique properties of blimps, such as, i) dynamic deformation in response to aerodynamic and control forces, ii) susceptibility to wind and turbulence at low airspeed, iii) variability in airship designs regarding placement, direction and vectoring of thrusters and control surfaces. Based on simulated wind and deformations due to changes in ambient pressure and temperature as well as helium leakage, we predict substantial effects on controllability, verified in real world flight experiments. We are currently developing formation control strategies for blimps, where we address their non-linear, non-holonomic and time-delayed dynamics.

More information: https://ps.is.mpg.de/project/autonomous-mocap

Bodies and Eating

Simone Behrens, Simone Behrens, Anne Thaler, Betty Mohler, Stephan Streuber, Alejandra Quiros-Ramirez, Joachim Tesch, Javier Romero, Michael Black

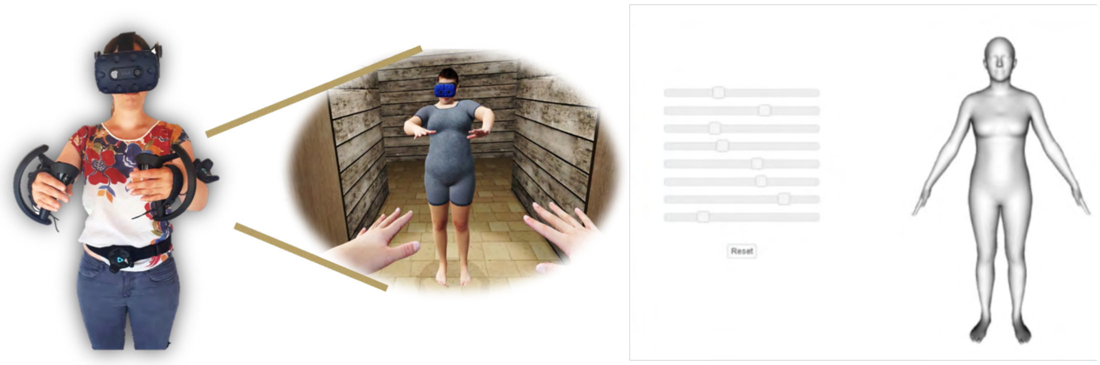


Figure 4.39: We combine realistic 3D body models with virtual reality to ask questions about how people perceive their own body shape and the shape of others. This has provided insight into how people with anorexia nervosa and overweight see themselves.

Body representation is an essential part of a person's self-concept and also shapes how we see the world. In individuals with eating disorders or overweight, a disturbed body representation plays a major role for the development and maintenance of the disorder. People with eating disorders or overweight typically are extremely dissatisfied with their body and cannot accept their body as it is. In this project, we cooperate with partners from the University Hospital Tübingen to develop ecologically valid methods for the assessment of body representation and new approaches for body image therapy.

In a first step, we created biometric figure rating scales [780], a desktop experiment [749],[754],[753] and a virtual reality mirror scenario [779],[778] to investigate how people with eating disorders perceive their body as well as other people's bodies. In a series of projects in cooperation with the university hospital Padova (IT) and the LVR hospitals Essen, we assessed >100 participants from the general population as well as >200 people with eating disorders and overweight. Our observations demonstrate that patients with eating disorders and overweight have accurate representations of how they look and how others look, i.e. other than previously assumed they do not misperceive bodies (own or other people's) as normal when they are not. However, we consistently observed that women with anorexia nervosa favored a much thinner body as ideal weight for themselves than healthy women.

In ongoing work, we are now exploring how virtual reality technology can support patients in accepting a healthy body weight for their own. To this end, we created a virtual reality setup that displays a semi-individualized biometric body with adjustable weight in a changing cabin. In a first study we demonstrated that experiencing the illusion of an overweight body can induce high arousal in healthy individuals with high weight and shape concern; i.e. the illusion is strong enough to be affectively relevant even for a subclinical group. Currently, we are exploring the effects of a virtual exposure to normal weight in patients with anorexia nervosa. Following the rationale of fear treatment, we expect that it might help them overcoming fear of weight gain and facilitate recovery.

More information: https://ps.is.mpg.de/project/bodies-and-eating

Markers to Avatars

Naureen Mahmood, Michael Black, Nima Ghorbani, Gerard Pons-Moll

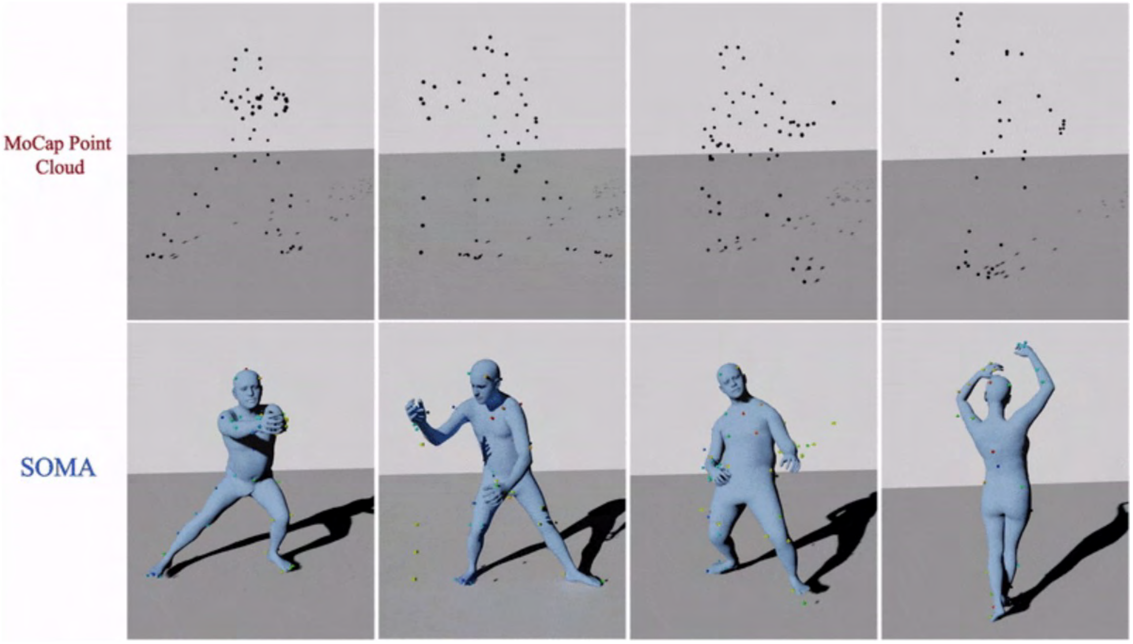


Figure 4.40: Bodies from mocap: SOMA takes a raw mocap point cloud and automatically cleans and labels the points. Once labeled, MoSh solves for the body shape and pose using SMPL (or SMPL-X). MoSh needs only sparse mocap marker data to create animations with a level of realism that is difficult to achieve with standard skeleton-based mocap methods.

Marker-based motion capture (mocap) is the "gold standard" for capturing human motion for animation and biomechanics. Unfortunately, the amount and quality of existing mocap data is small, limiting its use for deep learning. We address this with two key innovations: MoSh[1] and SOMA [803], which we use this to create a large dataset of human motions (AMASS [803]) with fine-grained action labels (BABEL [814]).

Traditional mocap can produce lifeless and unnatural animations. We argue that this is the result of "indirecting" through a skeleton. In standard mocap, visible 3D markers on the body surface are used to infer the *unobserved* skeleton in a process called "solving". The skeleton is used to animate a 3D model. While typical protocols place markers on parts of the body that move as rigidly as possible, soft-tissue motion always affects surface marker motion. Since non-rigid motions of surface markers are treated as noise, subtle information about body motion is lost.

MoSh (for Motion and Shape capture) replaces the skeleton with a 3D parametric body model. MoSh simultaneously estimates mocap marker locations on the SMPL body, estimates the body shape, and recovers the articulated body pose. By allowing soft-tissue deformations (DMPL) that vary over time, MoSh achieves high realism.

Mocap is also costly because human intervention is need to "clean" and "label" the capture data, which contains noise and missing markers. With SOMA we automate this process. Given a raw, noisy, and incomplete mocap point cloud, SOMA uses a stacked transformer architecture and a normalization layer to assign captured 3D points to markers on the body. The automatically labelled data is then fit with MoSh.

Using these techniques, we maintain the growing AMASS dataset, which converts many disparate datasets into a single unified SMPL-based representation. We have also built the BABEL dataset by acquiring fine-grained action labels for the motions in AMASS. The size of these datasets opens up human motion to deep learning architectures.

More information: https://ps.is.mpg.de/project/mosh

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[1] M. M. Loper, N. Mahmood, M. J. Black. MoSh: Motion and Shape Capture from Sparse Markers. *ACM Transactions on Graphics, (Proc. SIGGRAPH Asia)* **33** (6): 220:1–220:13, Nov. 2014.

4.3 Awards & Honors

2021

Timo Bolkart and **Victoria Fernandez Abrevaya** are recognized as ICCV 2021 *Outstanding Reviewers*.

PLoS ONE top 10% most cited papers, July 2021, for papers published in 2018. For the paper “Body size estimation of self and others in females varying in BMI”.

Best Paper Candidate, IEEE/CVF Conf. on Computer Vision and Pattern Recognition (CVPR), 2021, for the paper "SCANimate: Weakly Supervised Learning of Skinned Clothed Avatar Networks" by **Saito, S.**, **Yang, J.**, **Ma, Q.**, and **Black, M. J.**

Best Paper Candidate, IEEE/CVF Conf. on Computer Vision and Pattern Recognition (CVPR), 2021, for the paper "On Self-Contact and Human Pose" by **Lea Müller**, **Ahmed Osman**, **Siyu Tang**, **Chun-Hao Paul Huang**, and **Michael Black**.

Victoria Fernandez Abrevaya, Nikos Athanasiou, Michael Black, Timo Bolkart, Arjun Chandrasekaran, Vassilis Choutas, Partha Ghosh, Nikos Kolotouros, Dimitrios Tzionas, are recognized as CVPR 2021 *Outstanding Reviewers.*

Michael Black is elected to the German National Academy of Science Leopoldina.

2020

Soubhik Sanyal is recognized as an outstanding reviewer for ACCV 2020.

Best Paper Award, *International Conference on 3D Vision (3DV)*, 2020, for the paper "Grasping Field: Learning Implicit Representations for Human Grasps"**, by Karunratanakul, K., Yang, J., Zhang, Y., Black, M., Muandet, K., Tang, S.**

Partha Ghosh, **Shashank Tripathi, and Dimitrios Tzionas** receive the Outstanding Reviewer Award, European Conference on Computer Vision (ECCV), 2020

Michael J. Black: receives 2020 Longuet-Higgins Prize at the IEEE Conference on Computer Vision and Pattern Recognition (CVPR). The prize is given annually for "Contributions in Computer Vision that Have Withstood the Test of Time." Given for the paper: *Sun, D., Roth, S., Black, M. J., "Secrets of optical flow estimation and their principles," In IEEE Conf. on Computer Vision and Pattern Recognition (CVPR), pages: 2432-2439, IEEE, June 2010*

Nikos Kolotouros and **Dimitrios Tzionas** are recognized as CVPR 2020 *Outstanding Reviewers.*

2019

Dimitrios Tzionas is recognized as an ICCV 2019 *Outstanding Reviewer.*

2018

Siyu Tang receives the DAGM MVTec 2018 Dissertation Award at the German Conference on Pattern Recognition (GCPR) for her thesis "People Detection and Tracking in Crowded Scenes".

The paper "Neural Body Fitting: Unifying Deep Learning and Model-Based Human Pose and Shape Estimation" wins **Best Student Paper Award** at 3DV 2018.

Michael J. Black, *Alumni Research Award*, Department of Computer Science, University of British Columbia, 2018

CVPR 2018 Outstanding Reviewer awards for current and former PS members **Varun Jampani, Christoph Lassner, Juergen Gall, Yi-Hsuan Tsai, Julietta Martinez, Fatma Güney, Lars Mascheder, Gernot Riegler, Deqing Sun.**

Best Poster Award, Deutsche Gesellschaft für Essstörungen (DGESS), 2018, Körper Sprache: Sprachliche Repräsentation von Körpern bei Patientinnen und Patienten mit Essstörungen, by **Walder L., Quiros-Ramirez M.A., Mohler B., Black M.J., Keizer A., Zipfel S., Giel K., Mölbert S.**

2017

Andreas Geiger with collaborators from Daimler and Freiburg won the best student paper award at 3DV for the paper "Sparsity Invariant CNNs"

Siyu Tang: Winner of the CVPR 2017 Multi-Object Tracking Challenge

Varun Jampani, **Osman Ulusoy**, and **Silvia Zuffi.** Outstanding Reviewer Award. CVPR 2017.

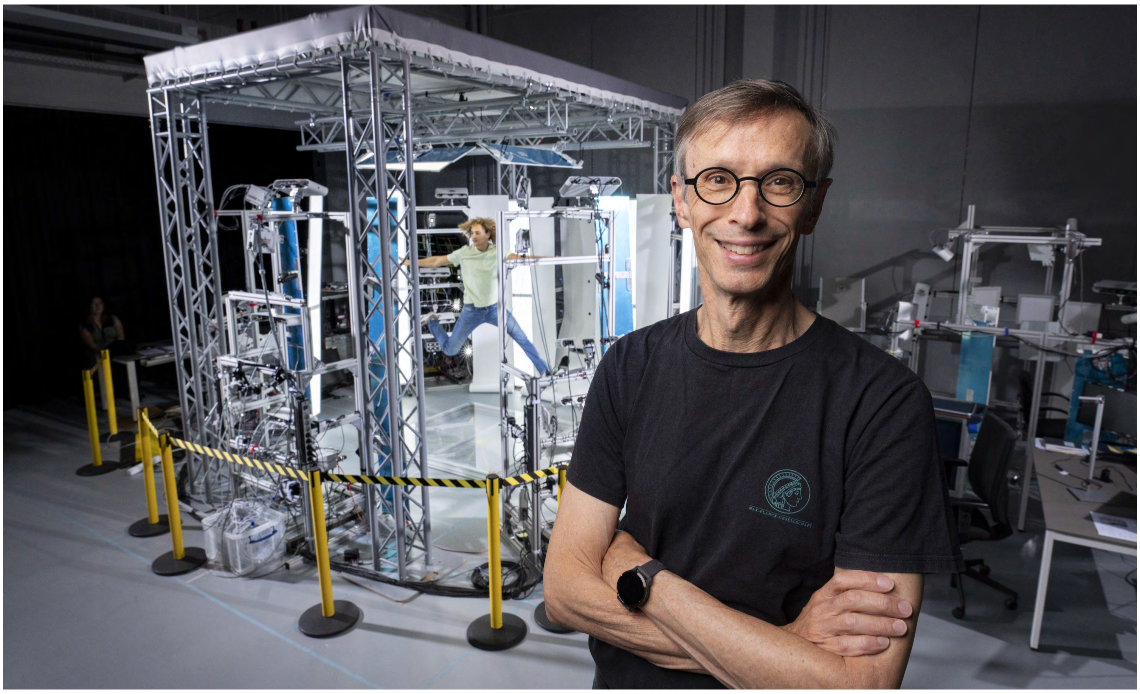
Best Paper Award, Eurographics 2017, for the paper Sparse Inertial Poser: Automatic 3D Human Pose Estimation from Sparse IMUs, by von Marcard, T., Rosenhahn, B., **Black, M. J., Pons-Moll, G.**

2016

Highly cited article: "A Quantitative Analysis of Current Practices in Optical Flow Estimation and the Principles Behind Them" by **Deqing Sun**, Stefan Roth, and **Michael Black**, is cited by Thompson Reuters as one of three highly cited articles published in the Int. J. of Computer Vision (IJCV) since 2014.

The FAUST dataset was awarded the "Dataset Award" at the Eurographics Symposium on Geometry Processing 2016. The award encourages and recognises the importance of the distribution of high-quality datasets on which geometry processing algorithms are tested. The creators of the dataset are **Federica Bogo, Javier Romero, Matthew Loper, and Michael Black**. The work originally appeared in the IEEE Conf. on Computer Vision and Pattern Recognition (CVPR) 2014.

4.4 Director profile: Michael J. Black



Biography

Michael J. Black received his B.Sc. in Honours Computer Science from the University of British Columbia (1985), his M.S. in Computer Science from Stanford University (1989), and his Ph.D. in Computer Science from Yale University (1992). As a graduate student he performed research at the NASA Ames Research Center, Aerospace Human Factors Research Division. After one year as an assistant professor at the University of Toronto, he joined the Xerox Palo Alto Research Center in 1993 as a member of research staff. He went on to managed the Image Understanding Area and found the Digital Video Analysis Area. In 2000 he joined the faculty of Brown University in the Department of Computer Science as an Associate Professor with tenure. He was promoted to Full Professor in 2004.

In 2011 he joined the Max Planck Society as a Scientific Member and one of the founding directors of the Max Planck Institute for Intelligent Systems in Tübingen, Germany. He is also an Honorarprofessor at the University of Tübingen. Black has played a central role in founding and growth of Cyber Valley and serves as its Speaker.

Black is a member of the German National Academy of Sciences Leopoldina and a foreign member of the Royal Swedish Academy of Sciences. He is the only researcher to have won all three major test-of-time awards in the field of computer vision: the 2010 Koenderink Prize (ECCV), the 2013 Helmholtz Prize (ICCV), and the 2020 Longuet-Higgins Prize (CVPR). His work has won several best paper awards and Honorable Mention for the Marr Prize in 1999 and 2005. His early work on optical flow has been widely used in Hollywood films. He has contributed to several influential datasets including the Middlebury Flow dataset, HumanEva, Sintel, FAUST, Dynamic FAUST, SURREAL, 3DPW, NoW Face Benchmark, AMASS, and more.

Black is also active in commercializing scientific results and has advised multiple startups. In 2013, he co-founded Body Labs Inc., which commercialized “the body as a digital platform" with technology licensed from his lab. Body Labs was acquired by Amazon in 2017, where he was a Distinguished Amazon Scholar until the end of 2021. In 2018, he was a founding investor in Meshcapde GmbH, which spun out of his department and is developing 3D body model technology for the apparel industry.

Appointments

01/2011 – present	Director at the Max Planck Institute for Intelligent Systems
05/2012 – present	Honorary Professor Department for Computer Science, University of Tübingen
09/2017 – 12/2021	Distinguished Amazon Scholar
04/2014 – 04/2016	Visiting Professor, Dept. of Inf. Tech. and Electrical Eng., ETH Zurich
01/2011 – 12/2020	Adjunct Professor, Dept. of Computer Science, Brown University

Awards & Honours (selected)

2021	Elected, *German National Academy of Sciences, Leopoldina*
2021	CVPR Best paper candidate, “SCANimate: Weakly Supervised Learning of Skinned Clothed Avatar Networks", by S. Saito, J. et. al
2021	CVPR Best paper candidate, “On Self-Contact and Human Pose" by L. Müller, et. al.
2020	Best Paper, International Conference on 3D Vision (3DV), for the paper “Grasping Field: Learning Implicit Representations for Human Grasps" by Karunratanakul, K., et. al.
2018	*Alumni Research Award*, Univ. of British Columbia
2017	Eurographics Best Paper, “Sparse Inertial Poser: Automatic 3D Human Pose Estimation from Sparse IMUs" by von Marcard, T., et. al.
2016	Dataset Award, Eurographics Symposium on Geometry Processing (SGP), for “FAUST Dataset" with F. Bogo, J. Romero, and M. Loper.

Organization & Community Service (selected)

- Spokesperson and member of the Executive Board, Cyber Valley, Feb. 2017 – Nov. 2017, Mar. 2018 – present.
- International Max Planck Research School for Intelligent Systems, Executive Board, since 2017.
- Thomas S. Huang Memorial Award Committee, CVPR 2021.
- Paper Awards Committee, ICCV 2019.
- PAMI Young Investigator Award Committee, 2016.
- External Advisory Committee (EAC), Stanford Mobilize Center, March 2020 – present.
- Co-organizer, SMPL made Simple, CVPR Tutorial, 2021.
- Co-organizer, CV4Animals: Computer Vision for Animal Behavior Tracking and Modeling, CVPR2021 workshop, June, 2021.
- Co-organizer, Scenes from Video (SfV) Workshops, Oct. 2017 and Sept. 2019.

Memberships (selected)

- German Academy of Sciences Leopoldina, since 2021
- ELLIS Fellow, since 2019
- Royal Swedish Academy of Science, since 2015
- MPI-ETH Center for Learning Systems, Member since 2015

Keynote, Conference, and Public Talks (selected)

- “Learning digital humans for the Metaverse", Keynote, *Int. Conf. on 3D Vision (3DV)*, Dec. 2021.
- “Estimating Human Motion: Past, Present, and Future", *40 Years DAGM - Invited Talks*, GCPR 2018.

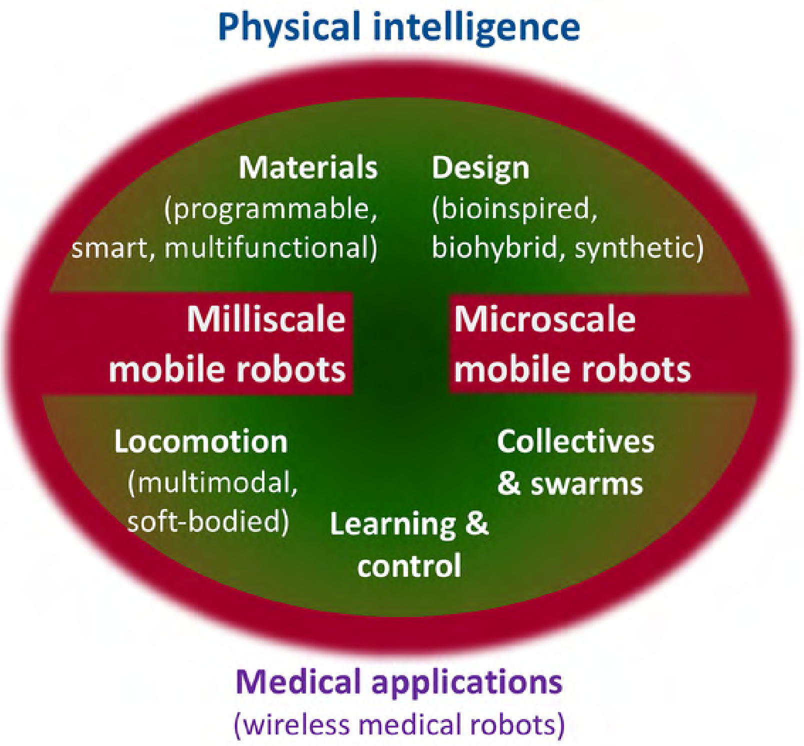
Links

Link to CV on website: http://files.is.tue.mpg.de/black/resume.pdf

5 PHYSICAL INTELLIGENCE

5.1 Research Overview

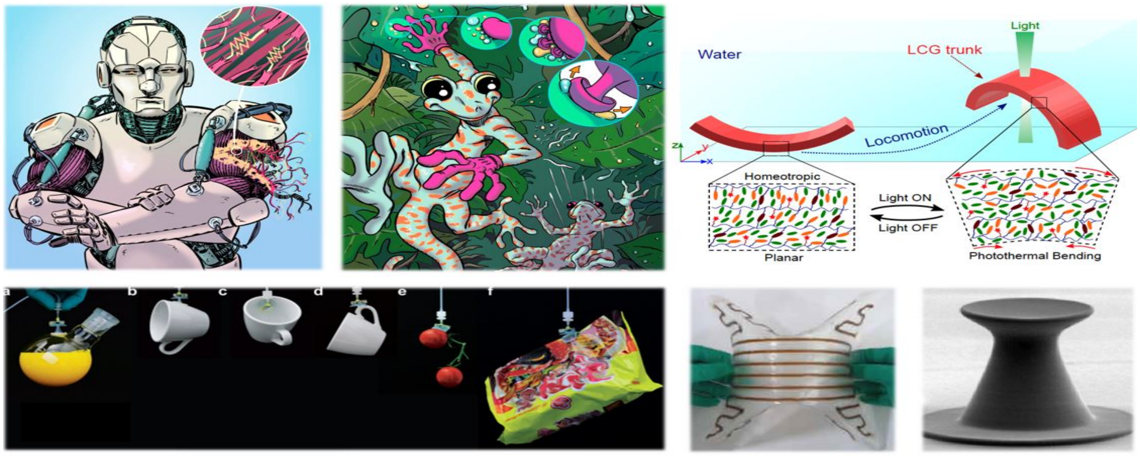
Main scientific mission of the Physical Intelligence Department is to understand the underlying principles of design, locomotion, control and physical intelligence of single and collectives of small scale-mobile robots made of multifunctional smart materials, structures and mechanisms. Since tiny wireless robots are inherently limited in on-board computation, actuation, powering, perception and control capabilities, their intelligence dominantly or completely comes from their body and collective physical intelligence. Therefore, our group is investigating new methods to create advanced physical intelligence capabilities in small-scale mobile robots using various design approaches, such as bioinspired (inspired by small-scale biological organisms), biohybrid (integrated with live biological cells or biomaterials) and fully abstract and synthetic design methods. As our societal mission and translational research focus, we aim to use these tiny robots as minimally invasive and implantable wireless medical robots inside our body to revolutionize medicine and healthcare. Such miniature medical robots would improve the quality of our life and save more lives of patients.



Our department has five main research thrusts currently to create new physical intelligence platforms at the small scale to understand them in detail and realize and implement them on novel milli- and micronscale mobile robots towards minimally invasive medical applications inside the human body. First, we investigate new physical intelligence methods using passive and active (stimuli-responsive) multifunctional material compositions, structures and mechanisms. Second, we study design, fabrication, locomotion and control of milliscale (insect-size) mobile robots with physical intelligence capabilities, such as shape/stiffness programmability, physical adaptation, adaptive locomotion and multifunctionality, enabled by their bioinspired soft or compliant smart body materials, structures and mechanisms. Third, we study design, fabrication, locomotion and control of micronscale (cell-size) mobile robots, which are much more challenging than the insect-size robots. Biohybrid designs integrate genetically engineered bacterium and alga type of microorganisms to the designed robot bodies to enable self-propulsion, taxis-based sensory locomotion control and active cargo transport and delivery type of functions adaptively in biological media. Synthetic microrobots are actuated by external magnetic fields, acoustic waves or light to swim or surface roll/crawl inside the complex fluids and tissues of the human body. Fourth, since single microrobots are hard to see and limited with their payload carrying capability and applied forces to the environment, a large number of these mobile microrobots is designed to self-organize at the air-water interface or inside liquids and controlled remotely to have a reconfigurable morphology and collective navigation and manipulation capabilities. Finally, we implement the developed milli- and microscale mobile robot design, fabrication and control methods with physical intelligence capabilities in minimally invasive medical applications inside the human body. Medical imaging-based tracking, localization, actuation and control of such single or collectives of wireless medical robots inside the complex, deep and tight sites of the human body are investigated in vitro, ex vivo and in vivo in preclinical small-animal models for specific target high-impact clinical applications.

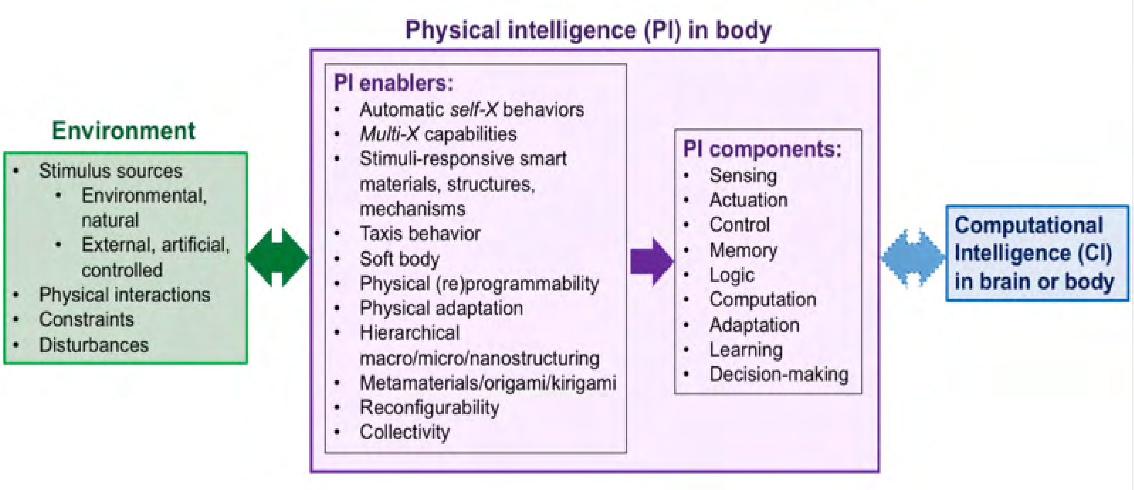
5.2 Research Fields

5.2.1 Physical Intelligence



As one of the core research questions of our department, we aim to understand the underlying principles of physical intelligence (PI) of single and collectives of biological organisms at milli- and micrometer length scales, and realize advanced PI capabilities on small-scale mobile robots using such principles.

At millimeter length scales with limited on-board computation, communication, control, actuation and powering capabilities at the current technological stage, PI in body becomes as important as computational intelligence (CI) in brain or body [951]. Body PI is tightly coupled to CI in the brain or body at the millimeter and larger length scales. At micrometer length scales, current autonomous machines do not have on-board computation and powering capabilities so that PI becomes the only or main option. Therefore, for example, autonomous microswimmers need to interact with their operation environment to get their fuel or harvest energy from their environment, and sense and follow specific stimuli in their microenvironment to reach to a target location and deliver their cargos, such as drugs, using their stimuli-responsive and shape-programmable smart materials and structures.



To achieve advanced PI capabilities in small-scale robots for given specific applications and tasks, there are many possible enablers and design considerations. In general, there are some key enablers that can be implemented to create advanced PI capabilities in a miniature robot:

- Encoding automatic **self-X** capabilities (e.g., self-adaptation, self-response, self-regulation, self-propulsion, self-healing, self-powering, self-cleaning, self-degrading, self-growing, self-replicating, self-cooling, self-oscillation, self-assembly, self-organization) in the robot body with no or minimal CI interference by integrating passive or active smart materials, structures or mechanisms.
- Encoding **multi-X** capabilities (e.g., multifunction, multistability, multilocomotion, multiterrain, multimodality, multiphysics) in the robot body, where the same or different material compositions, structures and mechanisms and physical forces or effects can induce multiple functions or behaviors at the same time to minimize the sensing, actuation, control and learning complexity for each specific function and behavior.
- Encoding various other advanced PI components and properties in the agent body, such as logic operations, memory, computation, decision making, reconfigurability, modularity, physical (re)programmability, physical adaptation, smart structuring (e.g., multistable structures, metamaterials, origami, kirigami, tensegrity), hierarchical multi-length scale structuring, smart mechanisms, taxis behavior and collective and emergent behavior. Such capabilities would require minimal or no CI.

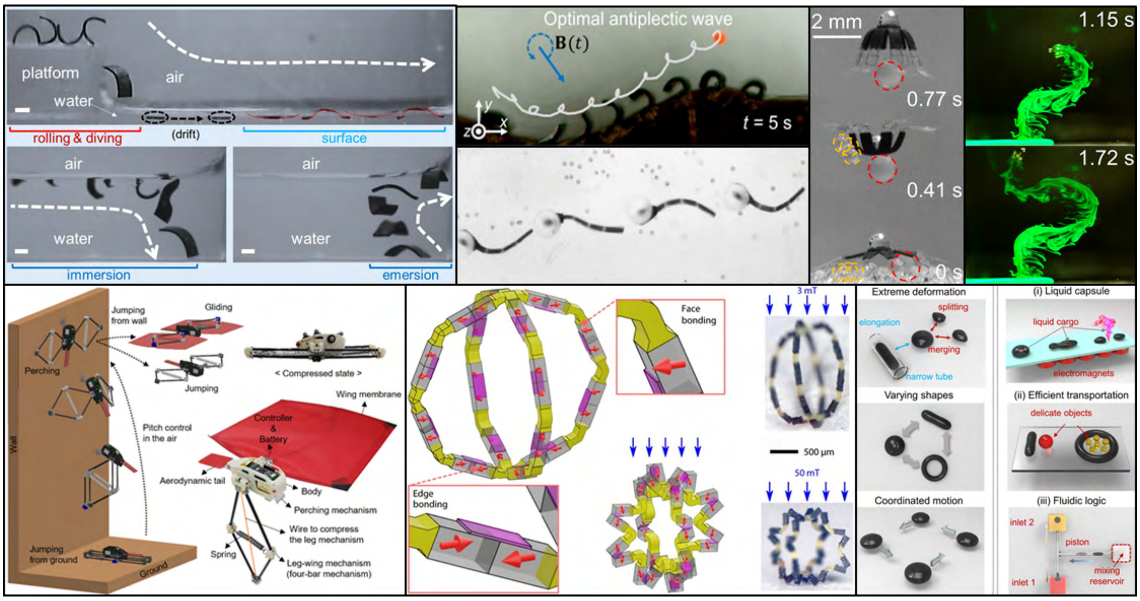
For above PI approaches, possible functional smart materials for robot bodies consist of stimuli-responsive or multifunctional synthetic polymers (e.g., hydrogels, liquid crystal elastomers, shape memory polymers, soft composites, magneto-elastic materials, piezoelectric polymers), metals (e.g., shape memory alloys, liquid metals), ceramics (e.g., piezoelectric), textile fabric, biomaterials (e.g., chitosan, cellulose, gelatin, silk, proteins, cells, tissues), and micro/nanomaterials-based composites (e.g., carbon fiber composites, ferrofluids, magneto/electrorheological fluids, micro/nanoscale particle/disc/wire/fiber/tube/crystal-filled polymers).

Many approaches have been proposed in our group to create PI for small-scale robots through designing the smart, adaptive and multifunctional body material compositions, structures and mechanisms. For example, we have been designing passive or active isotropic or anisotropic materials and structures in the robot body to enable self-adaptive, self-regulatory, self-degrading, self-cleaning, and other automatic behaviors. Using passive elastomeric materials, our group has pioneered elastomertic microfiber arrays-based adhesives and gripping materials inspired by biological micro-hairs on the body of animals and plants. Inspired by the biological micro-hairs, we have been designing and manufacturing elastomeric microfibers for reversible, fast, energy-efficient, compact and mechanically controlled adhesion and friction on a wide range of surfaces. We have recently optimized their three-dimensional (3D) fiber morphology for achieving maximum reversible adhesion using machine learning-based efficient optimization methods. Such surfaces can enable PI for robotic soft grippers by automatic surface 3D morphology adaptation and mechanically controlled switchable adhesion. Also, we designed such microfiber surfaces as liquid super-repellent surfaces against water, oil and all other liquids in the environment to enable self-cleaning and non-icing of the robot body surfaces. Prof. Sitti founded a startup (nanoGriptech, Inc.) in 2012 in USA, which has commercialized such gecko-inspired adhesives for a wide range of industrial and consumer applications with a brand name Setex®.

Our group has also pioneered self-healing and self-propelling protein-based soft actuators and robot materials, liquid crystal elastomers as stimuli-responsive, multifunctional, multimodal and stiffness-programmable PI materials on the robot bodies, liquid Gallium droplets behaving as a smart switchable phase-changing adhesive surfaces, and 3D-printed stiffness-programmable cellulose materials towards smart architectural surface applications as other PI examples.

More information: https://pi.is.mpg.de/field/physical-intelligence

5.2.2 Mobile Millirobotics



We have three focus areas in our mobile millirobotics research thrust currently. The first one is on soft-bodied millirobots with multimodal, adaptive and multifunctional locomotion in complex environments towards minimally invasive wireless soft medical robot applications. The second focus is on developing 3D microfabrication methods that can achieve unprecedented soft millirobot designs. The third focus is on design and control of bio-inspired millirobots as robotic models of the biological systems with physically intelligent body mechanisms.

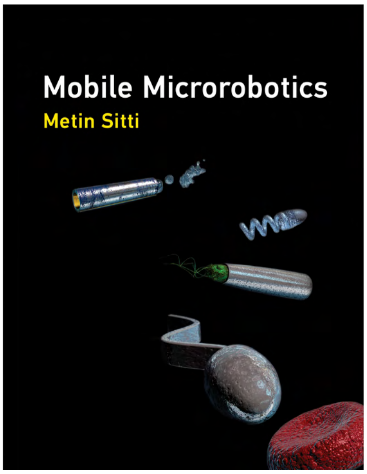
Soft-bodied mobile millirobots: Soft-bodied robots are promising as physical intelligence platforms, where their shape-programmable soft bodies can enable efficient, adaptive and multifunctional dynamics in complex confined environments. We explore a wide range of soft robot actuation methods, while our group has pioneered magnetic soft composite materials (i.e., magneto-elastomers) as soft actuators for medical applications. Inspired by soft-bodied small-scale animals, we have proposed a sheet-shaped magneto-elastic millirobot that can navigate in confined spaces with multimodal and adaptive locomotion, an ephyral jellyfish-inspired robot that can utilize the soft robot body and fluid interactions for multifunctional non-contact object manipulation and efficient propulsion, a larval fish-inspired robot that can produce adaptive body undulation for energy-efficient swimming, and an artificial cilia array that can realize highly efficient fluid transportation using metachronal waves at low Reynolds numbers. Moreover, using a probabilistic learning methods, locomotion performance of such soft millirobots is optimized for different locomotion modes and conditions.

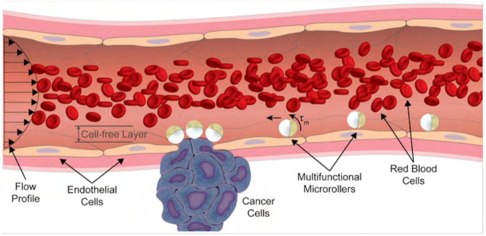
3D fabrication of soft-bodied mobile millirobots: To realize advanced physical intelligence capabilities in our magnetic soft millirobots, we have proposed novel 3D microfabrication strategies. We have developed a heat-assisted fabrication technique that can realize high-throughput magnetic (re)programming at a high resolution, and a jig-assisted 3D assembly-based fabrication technique that can fabricate complex soft machines with multimaterials, 3D complex geometries and magnetic programming, and 3D-to-3D shape morphing capabilities.

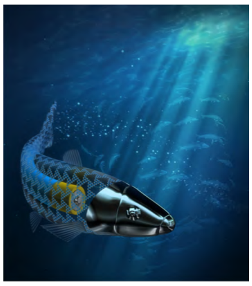
Bio-inspired multimodal locomotion with morphological intelligence: Inspired by a vampire bat, we have developed a miniature robot that can jump and glide as a multimodal locomotion system. Next, we have investigated the desert locust to study the morphological intelligence of its feet producing a significant chance to reengage with diverse real-world surfaces. Such study demonstrates the potential contribution of physical intelligence in solving complex dynamic locomotion problems.

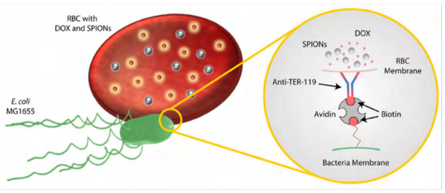
More information: https://pi.is.mpg.de/field/mobile-millirobots

5.2.3 Mobile Microrobotics







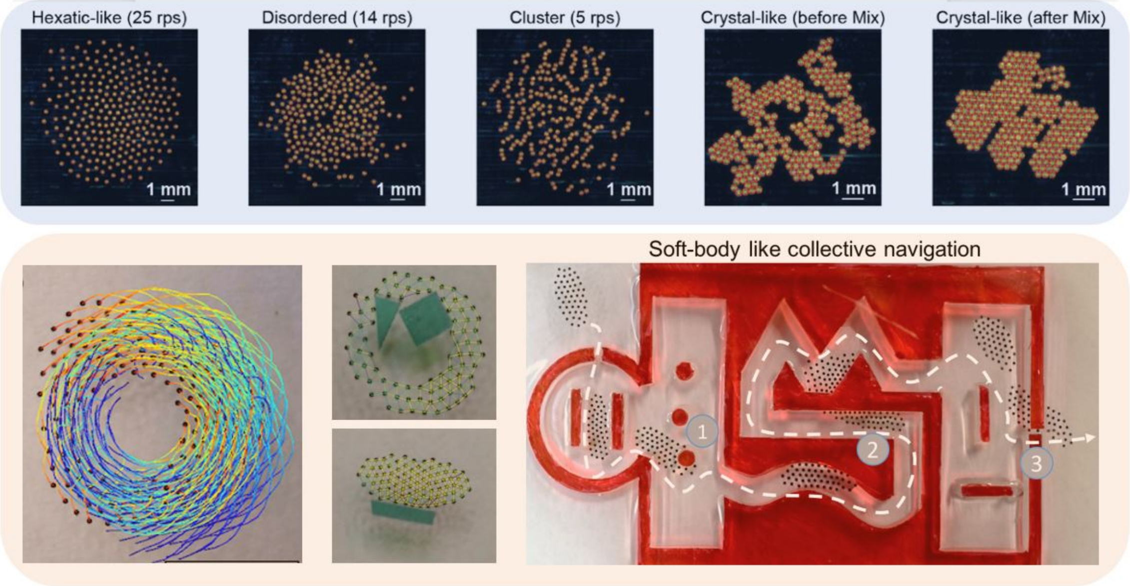


Micronscale mobile robots are much more challenging than mobile millirobots, since it is almost impossible to integrate on-board computation, power, actuation, sensing and communication on them for meaningful operation durations. Moreover, scaling laws make the surface area- and length-related, short- or long-range physical forces (e.g., drag, surface tension, adhesion, friction, van der Waals forces) become much more dominant than the volume-related physical forces at the microscale [916]. Even, the robot motion becomes much more stochastic going down to a few micrometer length scales due to the Brownian motion and other stochastic effects. Therefore, we need to propose new design, fabrication, locomotion and control approaches and methods to create mobile microrobots for given target applications and tasks.

As the first approach, we propose **biohybrid** designs that integrate genetically engineered bacterium and alga type of microorganisms to the designed robot bodies to enable self-propulsion, taxis-based sensory locomotion control and active cargo transport and delivery type of functions adaptively in biological media. Biohybrid microrobots exploit the cell's inherent capability of harnessing biochemical energy in the microenvironment or inside the cell to power mobility and sensing. We exploit the microorganisms that can achieve high propulsion speeds, thereby providing high thrust power to the microrobots. Integrated physical bodies enable remote steering and targeted cargo delivery for functional tasks. These microrobots are highly stochastic and can be fabricated at high volumes cost-effectively. We have shown that bacteria-powered red blood cells and synthetic particles loaded with cancer drugs can be steered towards a target location, and bacteria sensing (e.g., chemotaxis, aerotaxis, pH-taxis) can be used to accumulate them to the tumor cell regions. Then, triggered light or other stimulus is used to deliver the drug on-demand in the target location effectively (around 3-4 orders of magnitude more effective than the same-size passive drug particles). We have demonstrated such local on-demand effective drug delivery functions in vitro.

As the second approach, **synthetic** mobile microrobots are actuated by external magnetic fields, acoustic waves or light to swim or surface roll/crawl inside the complex fluids and tissues of the human body. Our group uniquely brings together new functional materials with design and engineering strategies to develop fully synthetic microrobots that can dynamically interact with the environment. Fabrication of microrobots presents unique challenges concerning design, fabrication process, and encoding operational capabilities. Conventional microfabrication techniques usually provide relatively simple geometric structures, such as tubes, spheres, and surfaces, with limited design flexibility and function. Therefore, we combine 3D microprinting with tailor-made polymeric and hydrogel materials and nanocomposites to realize multi-responsive and multifunctional 3D complex microrobots that could not be conceivable with the alternative microfabrication methods.
More information: https://pi.is.mpg.de/field/mobile-microrobots

5.2.4 Microrobot Collectives

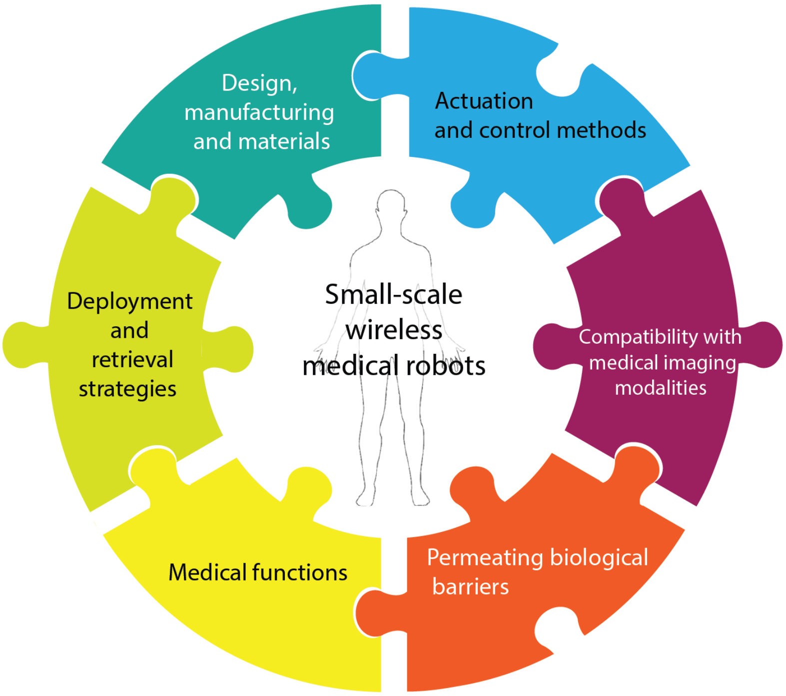


Single mobile microrobots have limited capabilities, such as the maximum cargo volume delivered to a target location and the maximum external force output, and are impossible or very hard to image and track using medical imaging modalities. Therefore, hundreds and even thousands of microrobot collectives are essential to design, navigate, control, and implement for diverse desired functions. However, current synthetic microrobots do not have on-board autonomy individually like in macroscale robot collectives. Therefore, new microrobot collective design and control methods need to be developed. Our main approach for creating synthetic microrobot collectives with programmable functionality and tracking capability is not to control each microrobot individually, but to control the **local** physical interactions among the microrobots through a **global** control input, which could enable their programmable self-organized collective formation, navigation and functions. Such approach entails design of local attractive/repulsive interaction forces (e.g., magnetic, capillary, electrostatic and hydrodynamic) among the robots to have programmable dynamic equilibrium states with different global actuation inputs. Such cohesive robot collectives can be navigated precisely using controlled external forces (e.g., magnetic, acoustic or light), while being tracked by medical imaging modalities.

We are exploring magnetic microrobot collectives to understand how to design and control such collectives for different tasks in complex environments. As the first platform, we have designed spinning magnetic micro-rafts, which have local pairwise interactions due to attractive angle-averaged magnetic dipole-dipole forces, repulsive angle-averaged capillary forces, repulsive hydrodynamic forces, and attractive magnetic forces to draw the rafts towards an external permanent magnet's axis of rotation. Such pairwise interactions can have different dynamic and static equilibrium states by controlling the spinning speed of the rafts globally, inducing different dynamic and static self-assembly formations. Next, external programmed permanent magnet arrays are used to induce local attractive or repulsive magnetic forces on magnetic robot collectives repelling each other at the air-water interface due to repulsive inter-magnetic forces and attracting each other due to attractive capillary forces. Such globally controlled local interactions induce different collective shape formations and move the robot collective by moving the external magnet array. Both cohesive robot formations can be navigated collectively through complex paths and manipulate large objects by programmable and reconfigurable formations and collective forces. Inside liquids, we have also demonstrated similar magnetic microrobot collectives and functions.

More information: https://pi.is.mpg.de/field/microbot-collective

5.2.5 Small-scale Wireless Medical Robots



Wireless small-scale mobile robots have the potential to transform medicine radically. Their small size and wireless mobility can enable access to and navigation in confined, small, hard-to-reach, and risky inner body sites. They can provide minimally invasive interventions and targeted diagnosis and therapy with high precision and efficiency. For example, active navigation of highly concentrated therapeutic and diagnostic agents to the site of action could represent a new state of the art, considering the limited delivery and distribution efficiencies offered by the systemic routes and local diffusion. Thus, we could minimize the effects of systemic toxicity and increase the overall delivery efficacy. Autonomous release of multiple types of payloads with programmable kinetics based on the environmental sensing of local cues in the living milieu could pave the way for microrobotic therapy and diagnosis form an orderly executed, programmable operation.

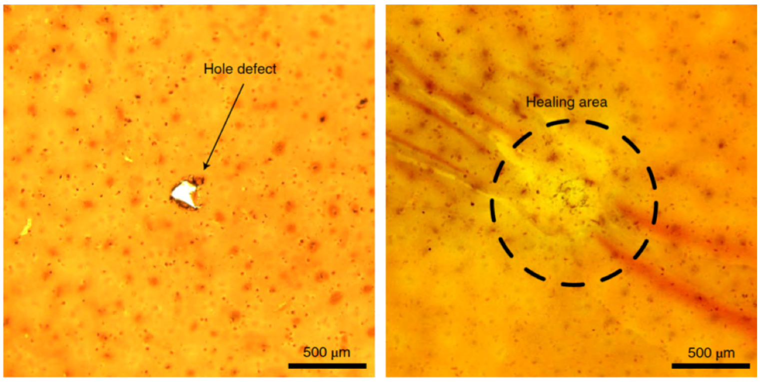
To pave the way for this transformation, our group seeks to understand and address the roadblocking scientific and engineering challenges towards developing wireless medical miniature robots. Our ultimate goal is to create a transforming impact in medicine by (1) improving the diagnostic or therapeutic capabilities of the current state-of-the-art, (2) offering a safer, less invasive, or implantable alternative in particular for patients with special conditions, or (3) enabling previously unthinkable or impossible new diagnostic or therapeutic capabilities. To reach this goal, we take an application-oriented systems approach by addressing all essential aspects that a microrobot needs to function safely in given in vivo conditions of a targeted medical problem. Therefore, our designs consider 3D body shape, material composition, manufacturing technique, permeation into biological barriers, deployment and retrieval strategy, actuation and control methods, medical imaging modality, and the execution of the prescribed medical tasks altogether at the same time. Each of the essential aspects requires specific design considerations, which must be reflected in the physical design of the medical robot. Therefore, all functional parts of the robot are highly interconnected and embedded in its material fabric in a tiny volume. Our group develops multidisciplinary methods by combining engineering with materials science and biology to simultaneously address the grand challenge of integrating these functional parts seamlessly to operate such medical robots inside the human body safely to achieve given target medical functions.

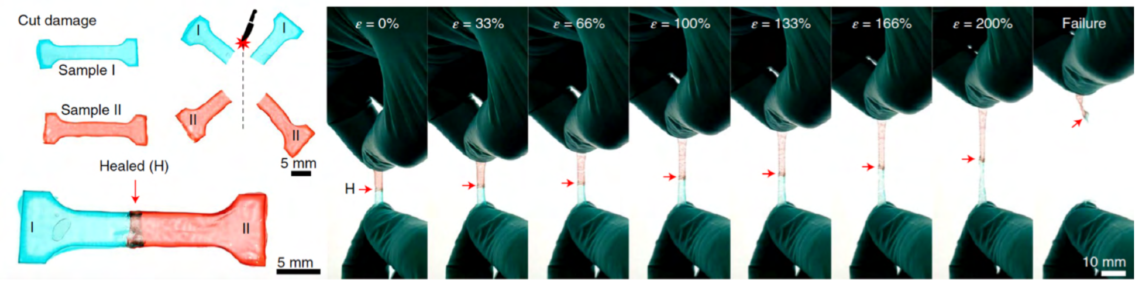
More information: https://pi.is.mpg.de/field/small-scale-wireless-medical-robots

5.3 Selected Research Projects

Protein-based multifunctional and self-healing robotic materials

Abdon Pena-Francesch, Joshua Giltinan





Traditional robots and actuators are typically composed of rigid and brittle materials. By contrast, in the growing field of soft robotics, flexible and largely deformable materials are explored to achieve compliance akin to that of biological systems. Compliance and complex deformation enable the soft robots to adapt to unpredictable surroundings, which makes these robots safer for physical interactions with humans and for operation in dynamic environments. Although soft machines are generally resistant to blunt damage (for example, impact, compression, and bending), they are vulnerable to mechanical damage (puncture, tear, and cutting) owing to their inherent softness, which limits their performance, reliability, and durability.

In our research, we are leveraging the properties of biological materials such as proteins to develop advanced materials to incorporate new functions to soft robots [1021]. Biological materials provide great control of their properties through structural changes, for example: we have developed self-healing soft actuators made from proteins that can self-heal micro- and macro-scale mechanical damage within seconds [978], with healing properties that surpass by several orders of magnitude those of other natural and synthetic soft materials. Here, we have used squid ring teeth protein in the wild and also genetically engineered form to optimize the self-healing and other mechanical properties. Using the same proteins, we have also developed V-shaped chemical motors that can self-propel in aqueous environments with high efficiency and respond to chemical cues in their environment. Here, we use the controlled diffusion of a fuel from the protein matrix to induce chemical surfactant-based Marangoni forces for fast and powerful propulsion. These high-performance protein-based materials can address current limitations in soft robotics, and find applications in drug delivery, self-healing artificial muscles, self-healing industrial grippers, environmental remediation, or personal protective equipment.

More information: https://pi.is.mpg.de/project/protein-based

Liquid crystal elastomers as novel smart small-scale robot materials

Yubing Guo, Jiachen Zhang, Wenqi Hu, Mingchao Zhang, Wei Feng, Muhammad Turab Ali Khan, Hamed Shahsavan, Zoey Davidson

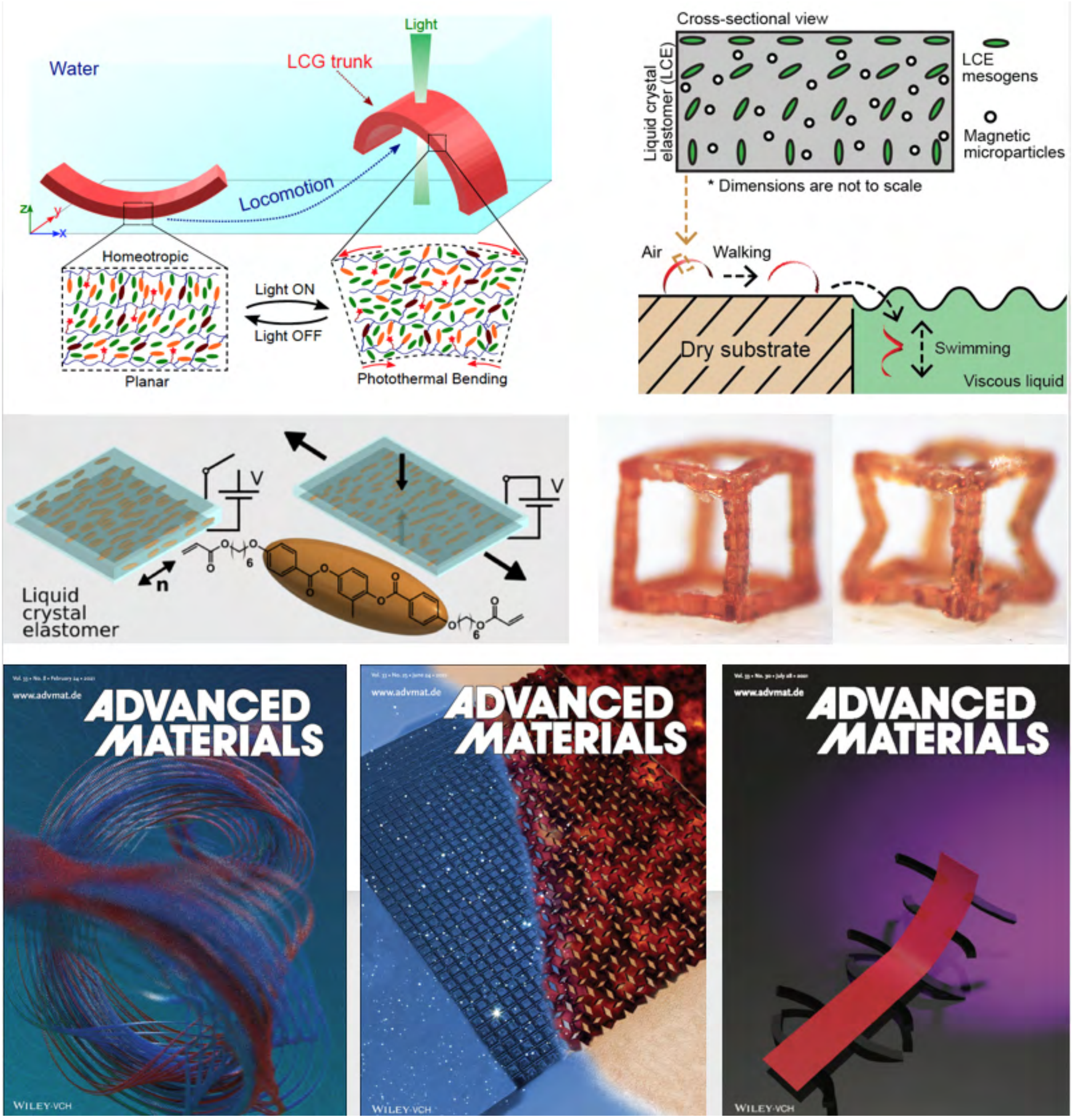


Figure 5.1: Stimuli-responsive liquid crystal elastomer (LCE) materials can be doped with magnetic microparticles for reconfigurable shape-morphing soft robots [954]. Next, LCE-actuated micro-metasurfaces, such as kirigami surfaces, are shown to enable tunable optically transpratent surfaces [945]. Also, thermo- and magneto-responsive bimorph materials enable environment-adaptable millirobots demonstrating advanced physical intelligence [**zhang2021stimuli**].

Liquid crystal elastomers (LCEs) are capable of reversible and programmable shape morphing in response to various external stimuli (e.g., temperature, chemicals) and capable of stiffness programming, which make them promising smart, soft and active small-scale robot materials. We aim to improve the physical intelligence and functionalities of small-scale robots by exploring programmable morphing modes and multi-stimuli responsiveness of LCEs. We have developed various strategies to develop LCE-based robot bodies for their applications in small-scale soft robotics.

We developed micro-scale LCE structures with programmable 3D geometries and 3D director fields, which enabled versatile shape morphing of soft machines. Firstly, we fabricated pixelated micro-channels with programmable orientations by using two-photon polymerization. These microchannels could be used to introduce arbitrary 2D alignment of thermotropic liquid crystals (LCs), lyotropic chromonic liquid crystals (LCLCs), and LCEs [1018]. We achieved designable 3D director fields by designing different microchannels on two confining surfaces. Micro-scale 3D LCE structures with arbitrary 3D director fields were fabricated using two-photon polymerization. We demonstrated how 3D director fields affect the shape-morphing ability of 3D LCE microstructures using a chemical solvent or temperature as a stimulus [977]. Additionally, we fabricated sub-millimeter scale cubic LCE voxels and assembled them into various 3D geometries. We then demonstrated designable shape morphing behaviors of these assembled 3D geometries with programmed director fields. Finally, we demonstrated switchable high-resolution polarization colors from LCE pixels with adjustable thicknesses [986].

We have been combining LCEs with magneto-elastomer materials to enable multimodal actuation and stimuli-responsiveness of miniature robot bodies. As the first strategy, we doped micro-scale magnetic particles (NdFeB) into LCE matrix to enable magneto-responsiveness [954]. We optimized the concentration of magnetic particles to preserve morphing modes of LCEs and to actuate LCEs with low magnetic fields. The optimized material was used to demonstrate LCE robotic structures, which were self-adaptable to changing environmental conditions or stimuli. As the second strategy, we developed a thermo- and magneto-responsive bimorph material by integrating the respective thermo-responsive LCEs with magneto-elastomers as respective active layers [**zhang2021stimuli**]. We applied three different configurations to achieve such bimorph actuator material. We demonstrated reconfigurable shape morphing of structures made up of such bimorph materials.

We have been also exploring three different topics: LCE-actuated micro-kirigami structures, shape programmable dielectric elastomers, and underwater actuation of liquid crystal gels. First, we utilized thermally actuated LCEs as artificial muscles to actuate kirigami microstructures remotely [945]. This strategy has significant potential in boosting the fundamental small-scale meta-structure research and the design of soft robots at the micro-scale. Second, we explored the large mechanical anisotropy of LCEs based on the local anisotropic elasticity and Poisson's ratio to achieve highly efficient and shape-programmable dielectric elastomer actuators [1030]. These electric field-driven elastomers were able to achieve a strain rate of 120% per second and energy conversion efficiency of 20%, and exerted force outputs over 700 times the elastomer weight at room temperature. Finally, we fabricated extremely soft light-driven liquid crystal gel robots by doping liquid crystal into liquid crystal networks to achieve highly efficient underwater locomotion (crawling, walking, jumping, and swimming) for the first time [995]. This study was the **Cozzarelli Prize Finalist** in the Engineering and Applied Sciences category in the PNAS journal in 2020, where 1 paper won the prize and our paper was the only finalist out of over 4000 papers published in PNAS in that year.

LCEs, combined with other smart actuator materials, structures and mechanisms, would enable advanced physical intelligence capabilities for small-scale and even large-scale soft robots, surfaces and devices.

More information: https://pi.is.mpg.de/project/LCE-robotics

Liquid-superrepellent, high-performance and 3D complex fibrillar adhesives

Cem Balda Dayan, Ville Liimatainen, Dirk Drotlef, Sungwoo Chun, Donghoon Son, Nagaraj Krishna-Subbaiah

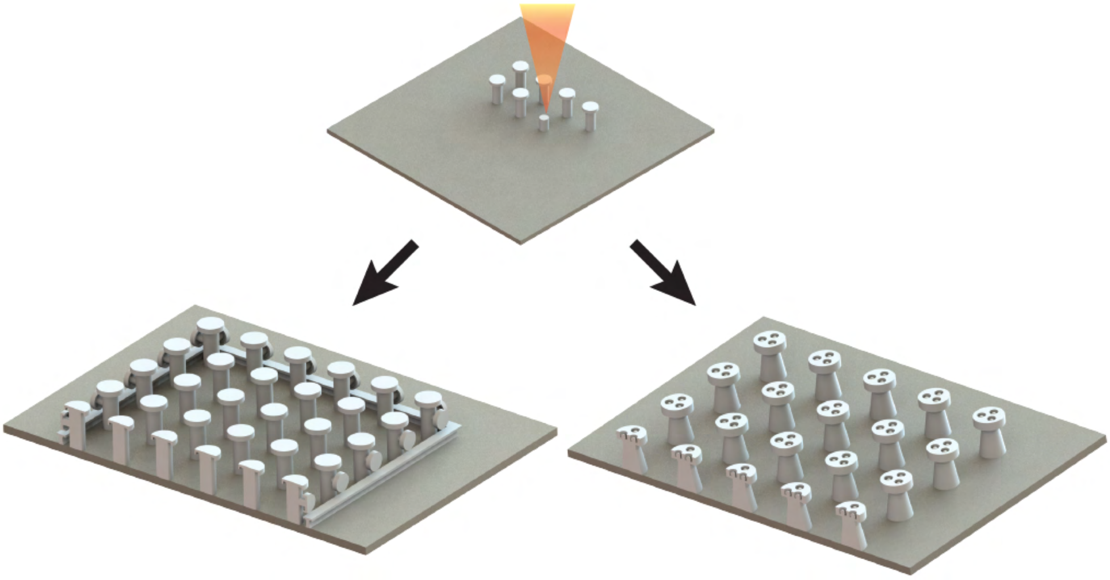


Figure 5.2: Direct 3D printing of two bio-inspired new microstructure-based adhesives using a custom-made elastomer resin. Springtail-gecko-inspired microstructures are designed for three simultaneous functionalities: top-surface liquid super-repellency, side-surface liquid-repellency, and strong dry adhesion. Next, octopus-gecko-inspired microstructures are designed for high adhesion on both underwater and dry conditions on synthetic skin.

Shape complexity and performance of the existing structural adhesives are limited by the used specific fabrication technique, such as molding. To overcome these limitations by proposing complex 3D microstructured adhesive designs, a 3D elastomeric microstructure fabrication approach has been implemented using two-photon polymerization [990]. A custom aliphatic urethane acrylate-based elastomer is used as the 3D printing material. We demonstrate two designs with two-combined biological inspirations to show the advanced capabilities enabled by the proposed fabrication approach and custom elastomer. The first design focuses on springtail- and gecko-inspired hybrid microfiber adhesive, which has the multifunctionalities of side-surface liquid super-repellency, top-surface liquid super-repellency, and strong reversible adhesion features in a single fiber array for the first time. The second design primarily centers on octopus- and gecko-inspired hybrid adhesive, which exhibits the benefits of both octopus- and gecko-inspired microstructured adhesives for strong reversible adhesion on both wet and dry surfaces, such as skin [934]. This fabrication approach could be used to produce many other 3D complex elastomeric structural adhesives for future real-world applications.

In our another study, we focus on increasing adhesion performance of gecko-inspired adhesives. We design bio-inspired composite microfibers for strong and reversible adhesion to smooth surfaces. The proposed microfibrillar patterns are composed of PDMS fibers decorated with vinylsiloxane mushroom shaped tips, which are additionally coated with an extremely soft and thin terminal layer of silicone based pressure sensitive adhesive. We demonstrated that mushroom tips coated with thin adhesive terminal layers can greatly enhance the adhesion through their optimal shape and enhanced load sharing. A high adhesion strength of 300 kPa together with superior durability on smooth surfaces are achieved, outperforming monolithic fibers by 35 times [1032].

More information: https://pi.is.mpg.de/project/superrepellent

Machine learning-based optimization of fibrillar adhesives

Donghoon Son, Ville Liimatainen

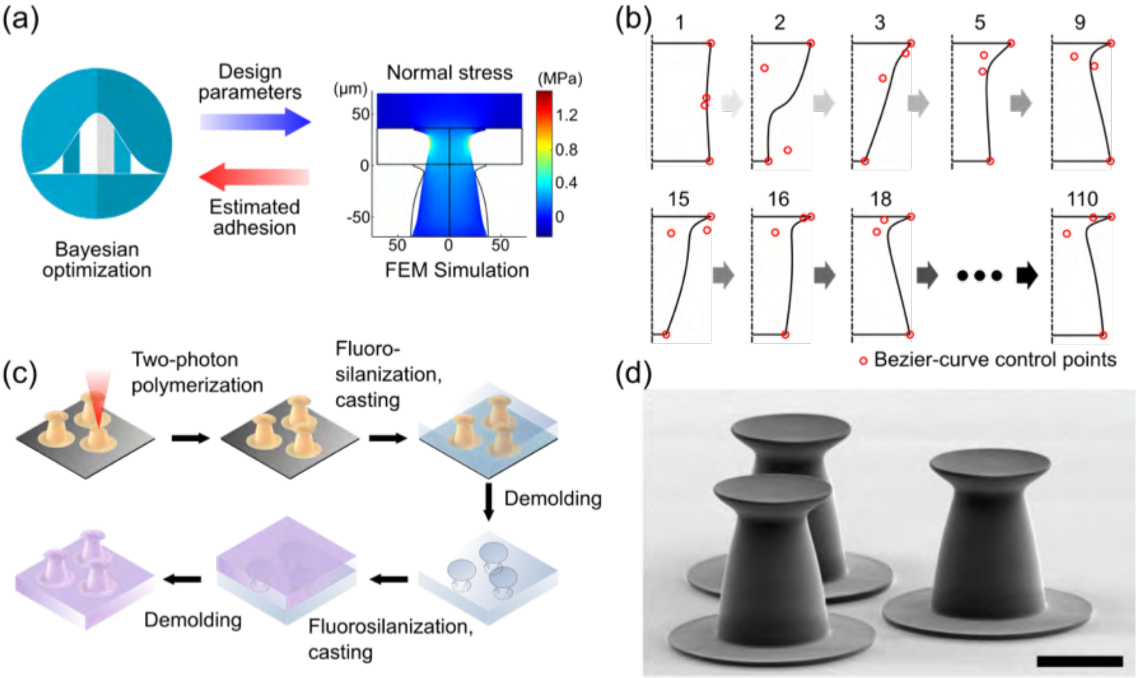


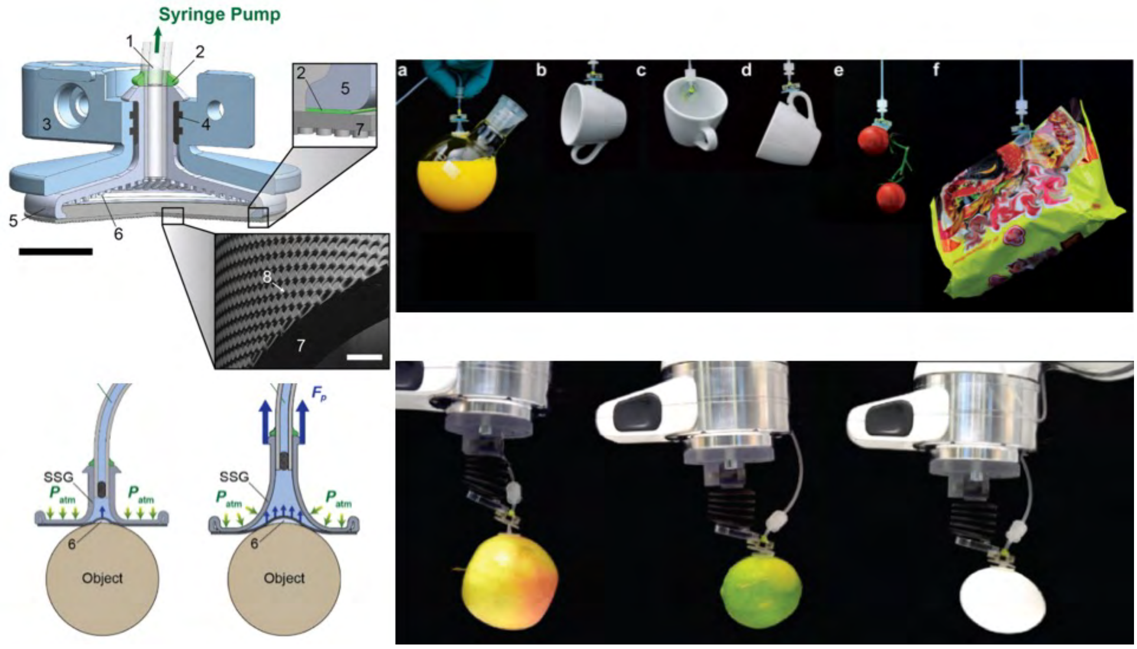
Figure 5.3: Design and fabrication process of the machine learning-based design of fibrils for maximal adhesion on smooth flat surfaces. A) A design optimization goal (e.g., maximize adhesion) along with the design constraints is supplied to the Bayesian optimization algorithm. The Bayesian optimizer provides design parameters to the simulator, and the simulator returns the estimated adhesion back using a finite element method (FEM)-based adhesion mechanics simulation. This process runs iteratively until the optimal design is achieved. B) The algorithm starts with a random shape and explores the broad design space by controlling Bezier-curve control points to maximize the estimated adhesive force from the FEM simulation. In each iteration, a comprehensive FEM simulation from the initial attachment to the detachment is performed. As the iteration number increases, the shape evolves to the best design. C) After the optimization, the best design is fabricated using two-photon polymerization and a subsequent double molding-based replication technique. D) The fabricated version of the optimal fibril design with the tip diameter of 70 µm (iteration number 110) is shown in a scanning electron microscope image (scale bar: 50 µm).

Objective of the project is to develop a machine learning technique to design optimal shape of adhesive fibril shapes [933]. Designing dry fibrillar adhesives is limited by a template-based design-approach using a pre-determined bioinspired T- or wedge-shaped mushroom tips. Here, we show a machine learning-based computational approach to optimize designs of adhesive fibrils, exploring a much broader design space. A combination of Bayesian optimization and finite element methods creates novel optimal designs of adhesive fibrils, which are fabricated by two-photon-polymerization-based 3D microprinting and double-molding-based replication out of PDMS. Such optimal elastomeric fibril designs outperform previously proposed designs by maximum 77% in the experiments of dry adhesion performance on smooth surfaces. Furthermore, finite-element analyses reveal that the adhesion of the fibrils is sensitive to the 3D fibril stem shape, tensile deformation, and fibril microfabrication limits, which contrast with the previous assumptions that mostly neglect the deformation of the fibril tip and stem, and focus only on the fibril tip geometry. The proposed computational fibril design could help design future optimal fibrils for different specific applications with less help from the human intuition.

More information: https://pi.is.mpg.de/project/machine-adhesives

Fibrillar adhesives- and suction-based robotic soft grippers

Sukho Song, Dirk Drotlef, Anastasia Koivikko, Cem Balda Dayan, Donghoon Son



For adhering to 3D surfaces or objects, current adhesion systems are limited by a fundamental trade-off between 3D surface conformability and high adhesion strength. This limitation arises from the need for a soft, mechanically compliant interface, which enables conformability to non-flat and irregularly shaped surfaces but significantly reduces the interfacial fracture strength. In this research, we overcome this trade-off with an adhesion-based soft-gripping system that exhibits enhanced fracture strength without sacrificing conformability to nonplanar 3D surfaces [**song2014soft**], [1110]. Composed of a gecko-inspired elastomeric micro-fibrillar adhesive membrane supported by a pressure-controlled deformable gripper body, the proposed soft-gripping system controls the bonding strength by changing its internal pressure and exploiting the mechanics of interfacial equal load sharing.

Next, we have proposed a suction-based soft robotic gripper where suction is created inside a self-sealing, highly conformable and thin flat elastic membrane contacting a given part surface [939]. Unlike previous our works involving microfabrication or assembly of active components to improve suction performance, our soft suction gripper can be manufactured by simply attaching the membrane onto the gripper body. The proposed soft suction gripper can self-reconfigure the effective suction area without using any active components. The reconfigurability allows the soft suction gripper to achieve robust attachment to a broad range of 3D geometries with textured surfaces. We have also shown that we can 3D print such pneumatically actuated soft suction grippers with an elastomer film [936].

More information: https://pi.is.mpg.de/project/softgrip

3D assembly-based fabrication of complex, soft, multimaterial millirobots

Wenqi Hu, Jiachen Zhang, Ziyu Ren, Ren Hao Soon, Immihan Ceren Yasa, Zemin Liu

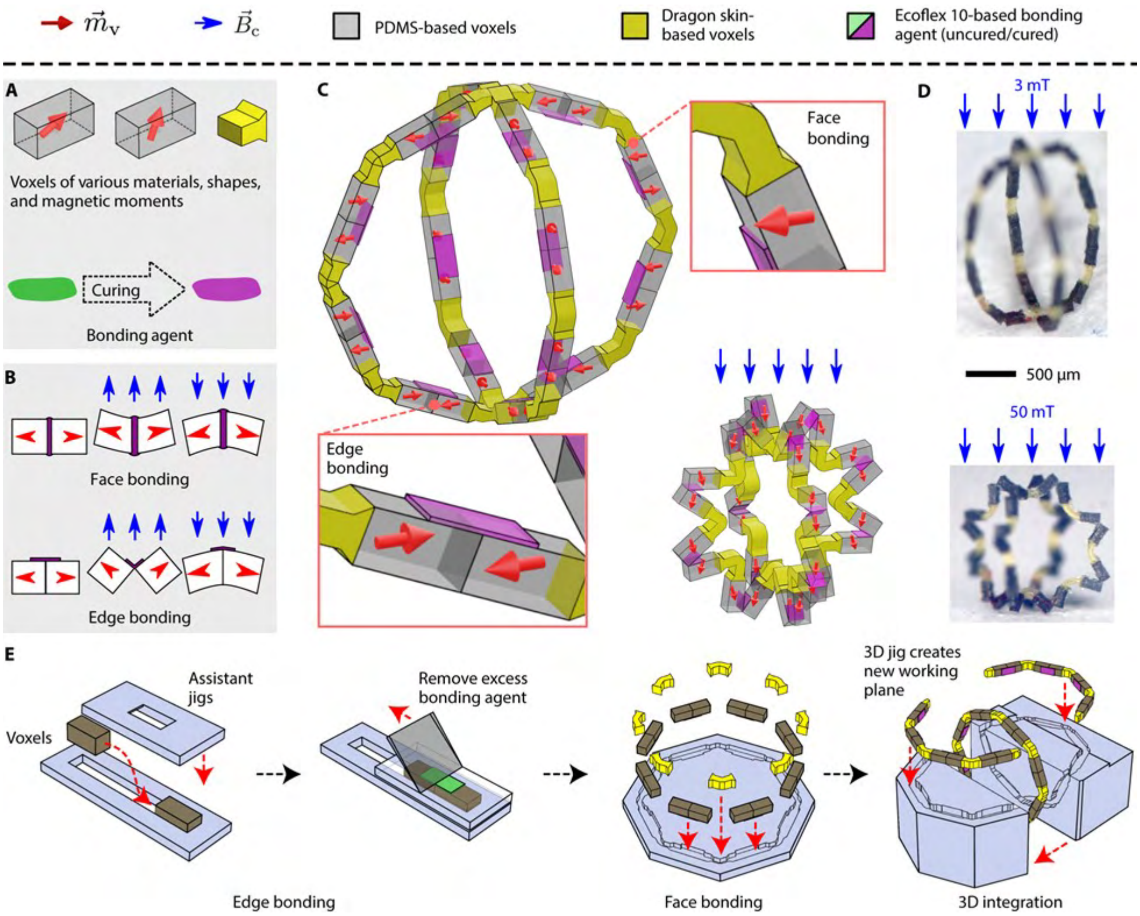


Figure 5.4: Jig-assisted 3D assembly approach for fabrication of magnetic soft millirobots. A) Voxels with different materials, shapes, and magnetization profiles are integrated together by a bonding agent. B) The bonding agent is applied to connect neighboring voxels using face and edge bonding, which respond to the external magnetic field differently. C) An assembled example soft machine with two interconnected circular rings, which experimentally shows 3D mechanical metamaterial characteristic of having a negative Poisson's ratio D). E) Representative steps of the jig-assisted assembly process for the 3D ring.

When the size of soft-bodied machines approach the sub-millimeter scale, their designs and functionalities are severely constrained by the available fabrication methods, which only work with limited materials, geometries, and magnetization profiles. To free such constraints, we propose a jig-assisted approach to 3D assemble microscale building blocks, **voxels**, to fabricate soft millimachines with non-magnetic/magnetic multimaterials, 3D complex geometry and magnetic programming, and 3D-to-3D shape morphing [950].

This proposed approach helps us concurrently realize diverse characteristics on the machines, including programmable shape morphing, negative Poisson's ratio, complex stiffness distribution, directional joint bending, and remagnetization for shape reconfiguration. This project enlarges the machine design space and enhances the machine functionality substantially. It enables the creation of functional machines with complex designs that are tailored to specific biomedical applications, which are previously difficult to achieve, including peristaltic pumping of biological fluids and transport of solid objects, active targeted cargo transport and delivery, liquid biopsy, and reversible surface anchoring in tortuous tubular environments withstanding fluid flows, all at the sub-millimeter scale. This project advances the achievable complexity of 3D magnetic soft machines and boosts their future capabilities.

More information: https://pi.is.mpg.de/project/3Dassembly

Shape-programmable soft millirobots with multimodal adaptive locomotion

Wenqi Hu, Ziyu Ren, Ren Hao Soon, Zemin Liu, Li Mingtong, Chong Hong

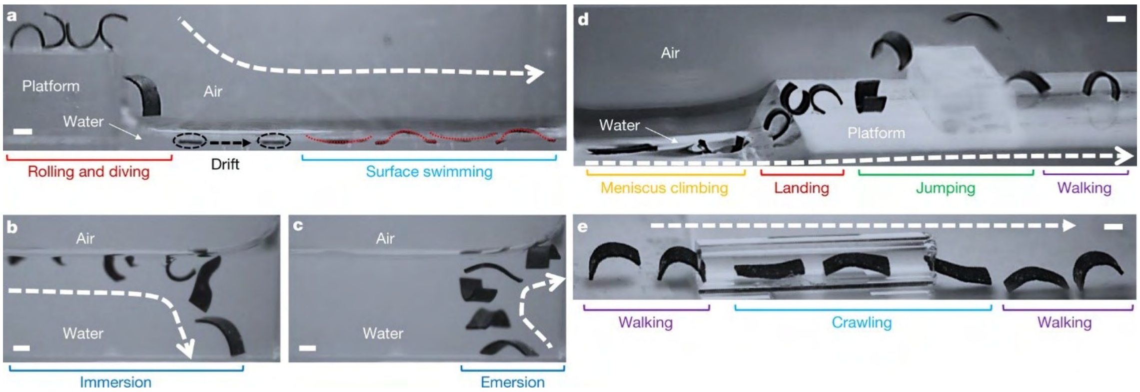


Figure 5.5: Our multimodal locomotion demonstration using a sheet-shaped soft millirobot moving over diverse liquid and solid environments. A) The soft robot rolls and dives from a solid platform into the adjacent water pool, where it drifts away along the water meniscus. The undulating robot then swims rightwards. B, C) The robot rotates, disengages from the water surface, sinks, and subsequently swims up from the pool bottom to emerge again at the water–air interface. D) The robot climbs up a water meniscus, lands on the solid platform, jumps beyond a standing obstacle, and walks away. E) The robot walks towards a tubular tunnel that impedes its walking gait. The robot then switches to the crawling mode to cross the tunnel, and finally walks away. The locomotion modes were sequentially captured in four separate videos owing to the restrictions of the workspace. Only one robot is used in this illustration. Scale bars: 1 mm.

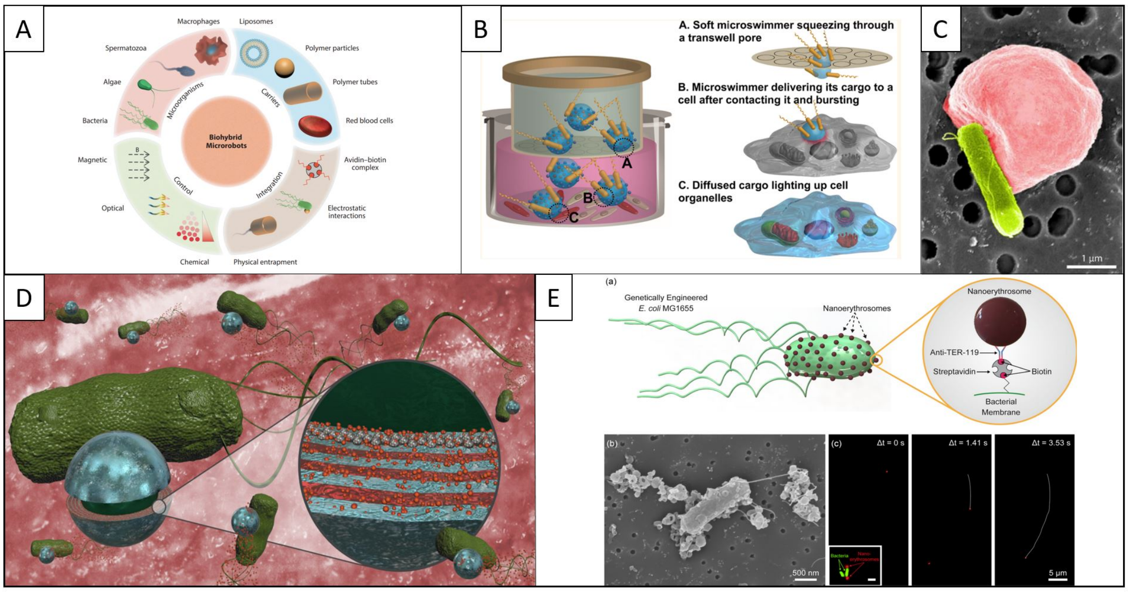
In previous studies, the shape-programmable magnetic materials have only been programmed for a small number of specific applications, as previous work can only rely on human intuition to approximate the required magnetization profile and actuating magnetic fields for such materials. We proposed a universal programming methodology that can automatically generate the desired magnetization profile and actuating fields for soft materials to achieve desired time-varying shapes. The universality of the proposed method can, therefore, enable other researchers to fully capitalize the potential of shape-programming technologies, allowing them to create a wide range of novel soft active surfaces and devices that are critical in robotics, material science, and medicine [1117].

By using the above methodology, we then addressed a grand challenge facing the existing small-scale robots: multi-locomotion in complex terrains. Previous miniature robots have very limited mobility because they are unable to negotiate obstacles and changes in texture or material in unstructured environments. In our research, we demonstrate magneto-elastic soft millimeter-scale robots that can swim inside and on the surface of liquids, climb liquid menisci, roll and walk on solid surfaces, jump over obstacles, and crawl within narrow tunnels. These robots can transit reversibly between different liquid and solid terrains, as well as switch between locomotive modes. They can additionally execute pick-and-place and cargo-release tasks. The locomotion capability of these robots in fluid-filled confined spaces was particularly investigated as body sites are physically constrained and filled with stagnant (e.g., mucus) or flowing (e.g., blood) biological fluids [1074]. By utilizing the interaction between the dynamic soft-bodied deformation and the surrounding environments, these robots can transit between undulatory crawling mode and the undulatroy swimming mode, and can realize helical surface crawling mode that can go against or withstand the fluid flow in a cylindrical tube. With the in-depth understanding of their locomotion mechanism, we further proposed a series of design and control strategies to enhance their locomotion performance towards different working environments [941].

More information: https://pi.is.mpg.de/project/Shape-programmable

Bacteria-powered biohybrid microswimmers

Mukrime Birgul Akolpoglu, Saadet Baltaci, Oncay Yasa, Yunus Alapan, Ajay Vikram Singh, Byung-Wook Park, Babak Mostaghaci



Bacterial biohybrids are formed by integration of motile bacteria with synthetic robot bodies. The potential of bacterial microrobotic applications lies in their autonomously functioning biological units, which provide active propulsion and environmental sensing capabilities, and also in their steerability using external stimuli [1043]. Specific bacteria species have been already tested in the clinics for cancer treatment, which we aim to take to the next level by integrating such bacteria to our biohybrid microrobots for more targeted, multimodal, controlled, and effective treatment.

We have designed and characterized various bacteria-powered biohybrid microrobots for targeted active delivery of drugs with high efficiency production, controllability and low cytotoxicity. We have developed various biohybrid platforms with synthetic cargoes, such as microparticles [1093], microtubes [1106], red blood cells (RBCs) [1066], microemulsions [1094], nanoerythrosomes [994], magnetic nanoparticles, and nanoliposomes. By using mild physical interactions to conjugate artificial cargoes to bacterial cells, such as biotin-streptavidin complex [1094] and electrostatic interactions, we have developed magnetically controllable bacterial biohybrid platforms for various delivery applications [1102]. We have investigated magnetotactic [1095],[**carlsen2014magnetic**], pH-tactic and chemotactic [1103] behavior of bacterial biohybrids and demonstrated hyperthermia applications using near-infrared light sources and cyanine dyes [1066]. Recently, we prepared bacteria-powered biohybrid microswimmers by conjugating E. coli cells with whole RBC or nanoerythrosomes, which are RBC-based nanovesicles [994]. Also, we have engineered a bacterial biohybrid platform with magnetic nanoparticles and functional nanoliposomes, where we have showed precise magnetic controllability, magnetic targeting, localization, extracellular matrix invasion, hyperthermia and pH-based delivery of drugs in 3D tumor microenvironments.

More information: https://pi.is.mpg.de/project/bacteriabots

Wireless magnetic millirobots navigating inside brain and other soft tissues

Musab Cagri Ugurlu, Donghoon Son

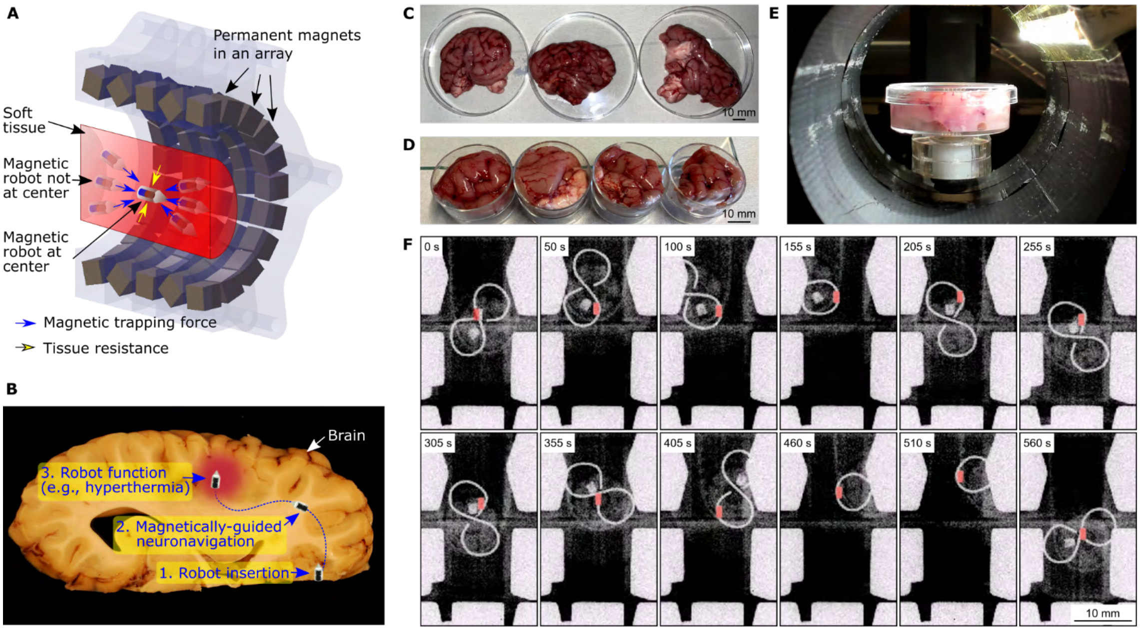


Figure 5.6: A) Schematic of the half-sectioned magnet array. B) Application scenario of the proposed robotic tissue navigation system. Prepared fresh porcine whole C) and quarter-cut D) brain tissues. E) Cut piece of a porcine brain attached to the robotic motion stage during the ex vivo path-following experiments. F) X-ray fluoroscopy image snapshots of a complete path-following experiment on an ∞-shaped path in the porcine brain. Robot is colored in red to make it distinguishable.

Creating strong magnetic forces to penetrate tissues in a very controlled and stable manner has been the challenge in medical robotics, especially due to the exponentially (on the order of 4) increasing magnetic forces on the robot toward the magnetic source, which is intrinsically unstable in the control aspect. This may result in the magnetic robot flying toward the magnetic source during a surgical operation when the localization and control systems are not extremely well designed with high bandwidths. In this study, we propose to solve this challenge by creating a robot actuation system with a stable magnetic force trap to drive a wireless magnetic robot inside soft tissues. This system can create very strong magnetic forces, which can enable locomotion inside soft tissues. It consists of an array of permanent magnets to generate a special magnetic field map that creates a magnetic force trap inspired by Halbach and Aubert arrays. Here, we propose a custom magnet array to create a stable magnetic force trap that can capture a magnetic robot at an area in 3D space leveraging mechanical interactions with a soft tissue at a point in 3D space with high magnetic gradients for driving it inside soft tissues. The magnet array generates a strong magnetic force toward the area of attraction in the array on the robot that deviates from the area of attraction. In addition, the induced magnetic torques align the robot's orientation toward the center of the array, which facilitates the sliding motion of the robot toward the center. Our experimental results show that this approach enables open-loop stability of magnetic millirobots in soft tissue phantoms and ex-vivo porcine brain tissue. Furthermore, by combining the array with a robotic 3D positioning system, the path-following of complex trajectories in soft tissues are demonstrated in concert with visual monitoring using 2D fluoroscopic x-ray medical images. In the future, the proposed design of the magnet array and robotic system under a fluoroscope could be used for creating a new generation of wireless medical millirobot systems for navigation and diverse medical functions, such as local and controlled drug delivery, cauterization, biopsy, and neural stimulation in brain and other soft tissues.

More information: https://pi.is.mpg.de/project/millirobots-navigating

MRI-powered wireless medical millirobots

Mehmet Efe Tiryaki, Onder Erin, Martin Phelan, Jelena Zinnanti, Senol Mutlu, Mehmet Berk Bilgin

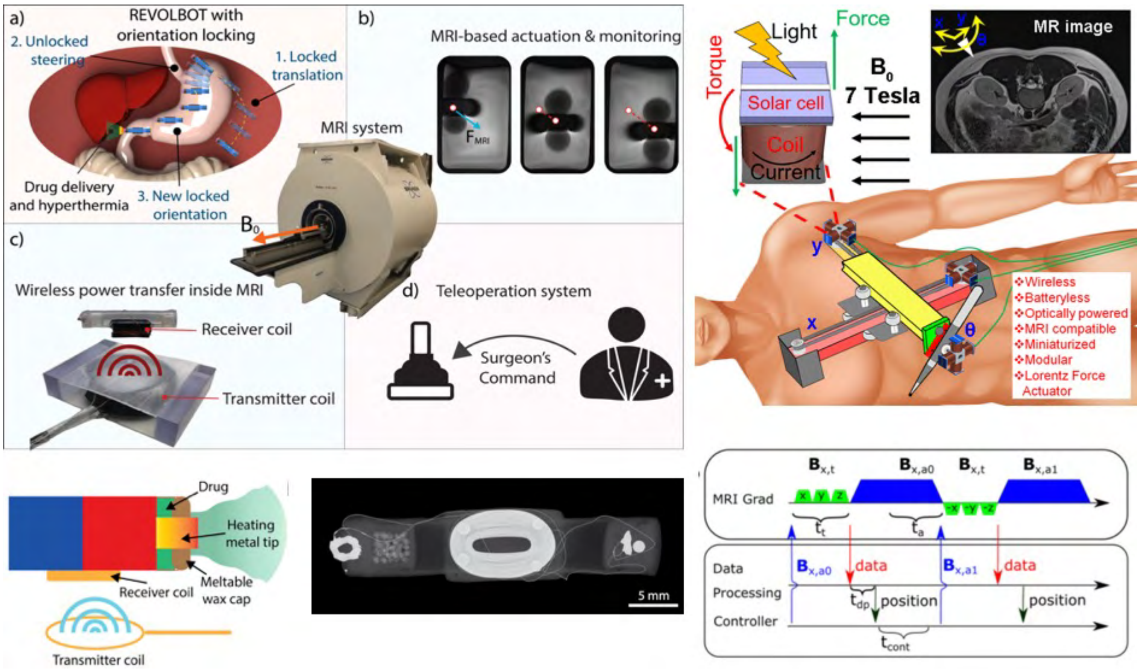


Figure 5.7: MRI-powered wireless medical robotic systems using the 7-Tesla small animal MRI in our laboratory. MR imaging sequence performs two-way communication with the robotic software. Wirelessly heated MRI capsule robot can be navigated inside ex-vivo tissues and deliver drugs and conduct hyperthermia on demand with remote doctor control. Also, light-driven MRI Lorentz coil actuators are proposed as wireless actuators inside MRI scanners.

Wireless miniature magnetic robots have the potential to reshape the traditional understanding of minimally invasive medical operations with their ability to access hard-to-reach, risky, and unprecedented regions in the human body. However, designing wireless microrobotic systems compatible with medical imaging modalities is still a major challenge towards future applications of microrobots. Therefore, the researchers have combined the microrobot actuation system with various medical imaging techniques, such as magnetic resonance imaging (MRI), ultrasound imaging, and X-ray imaging. Among these imaging modalities, the MRI attracts special attention due to its ionizing radiation-free nature and its superior image resolution of soft tissues compared to the other modalities. In addition to imaging capabilities, MRI hardware can also be used for actuating magnetic robots usig the existing magnetic gradient coils with up to 100 mT/m uniform gradients exerted [1000].

We have developed various wireless milli- and microrobots powered and tracked using an our 7 Tesla (7T) small-animal MRI scanner. There are two main approaches to use MRI's hardware to actuate wireless robotic systems: magnetic gradient force-based 3D pulling [1019],[947],[937] and Lorentz force-based rotation [961]. We have demonstrated closed-loop control magnetic particles down to hundreds of micrometer size scales using magnetic pulling-based actuation [982] and MRI-based robot tracking via specially design MR imaging and actuation sequences. In addition, we designed LC-coupled wireless magnetic capsule robots to perform drug delivery and hyperthermia in ex-vivo tissues [947]. We are also developing a Lorentz torques-based actively bent catheters and light-powered wireless actuators [961] operating inside MR scanners towards minimally invasive miniature robot applications.

More information: https://pi.is.mpg.de/project/MRIbots

Bioinspired cilia arrays for fluid pumping and object transport inside the body

Xiaoguang Dong, Guo Zhan Lum, Wenqi Hu, Ziyu Ren

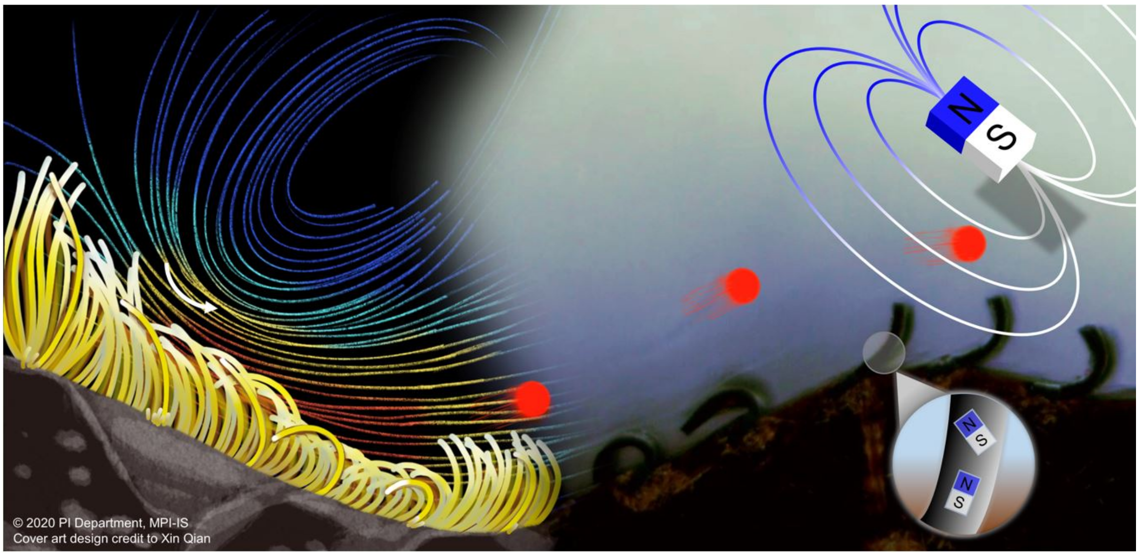


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Figure 5.8: Inspired by biological cilia (left), a generic design method enables creating magnetically actuated cilia arrays (right) with optimally coordinated movement, which help study challenging scientific hypothesis and enable highly efficient fluidic devices with unprecedented capabilities of pumping and mixing viscous synthetic and biological fluids wirelessly.

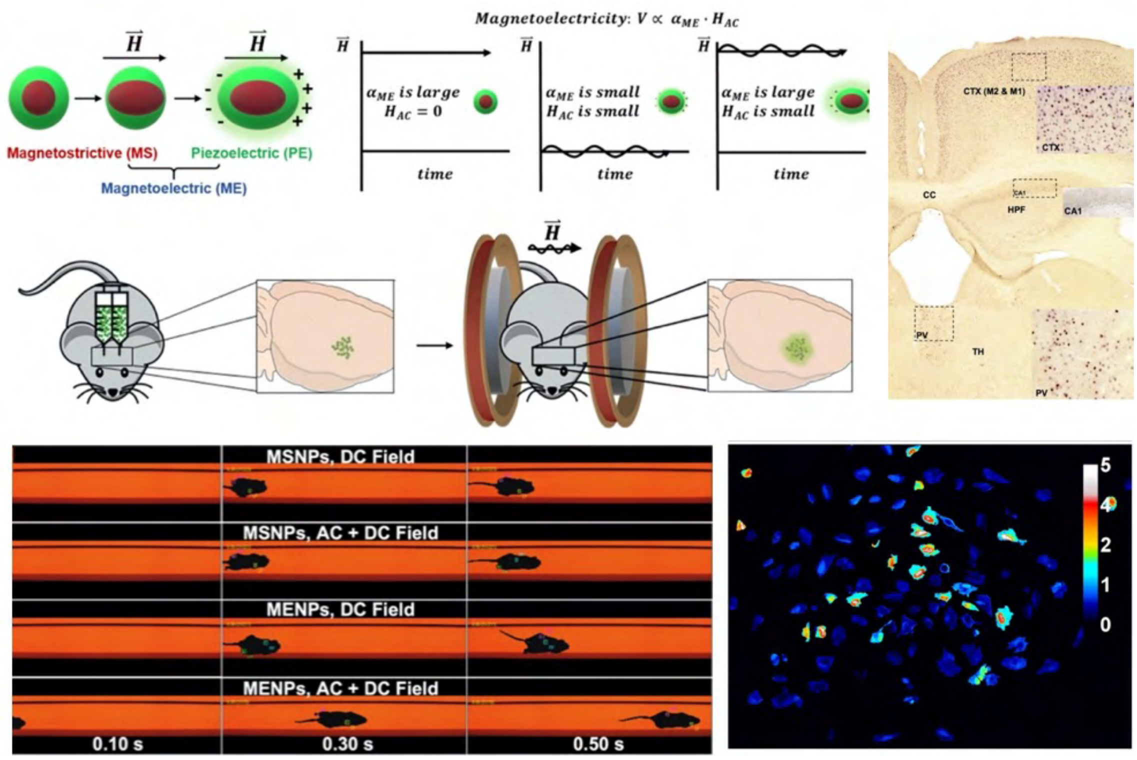
Coordinated non-reciprocal dynamics in biological cilia is essential to many living systems, where the emergent metachronal waves have been hypothesized to enhance net fluid flows at low Reynolds numbers (Re). Experimental investigation of this hypothesis is critical but currently missing, as biological systems are not fully viable for extensive controlled experiments. One promising solution is to use small-scale soft devices with programmable motions as a bioinspired platform to model and study their biological counterparts by controlled experiments at larger length scales while keeping the essential nondimensional parameters (e.g., Re) the same. These bioinspired soft devices can also enable unprecedented microfluidic functionalities for lab-on-a-chip and medical applications. So far, many small-scale artificial cilia have been proposed for emulating motions produced by biological cilia arrays. However, at small-length scales, designing and controlling both the complex individual ciliary motion and the overall coordinated dynamics within collective artificial cilia arrays pose a grand scientific challenge.

Here we report a class of miniature soft devices with both programmable non-reciprocal motion and collective metachronal coordination, by designing and actuating sub-millimeter scale ferromagnetic-elastic sheet arrays inside viscous fluids [968]. By intrinsically emulating biological ciliary dynamics using such magnetic cilia arrays, we found that only antiplectic metachronal waves with wave vectors in a specific range could enhance fluid flow compared with the synchronized case, revealing the quantitative relationship between metachronal coordination and the induced fluid flow. Such findings further enable various artificial cilia arrays as fluidic devices with unique functionalities at low Re, including a biomimetic cilia array capable of propagating optimal metachronal wave on curved surfaces (like coral reefs), a device for mixing viscous fluids rapidly and completely, and devices for pumping viscous (bio)fluids in narrow channels. Our design method and developed soft miniature devices provide new opportunities for studying ciliary biomechanics and creating cilia-inspired wireless microfluidic pumping, object manipulation and lab- and organ-on-a-chip devices, mobile microrobots, and bioengineering systems.

More information: https://pi.is.mpg.de/project/cilia-array-device

Wireless neural stimulation using magnetopiezoelectric nanoparticles

Kristen Kozielski, Onder Erin, Yan Yu, Gilbert Hunter



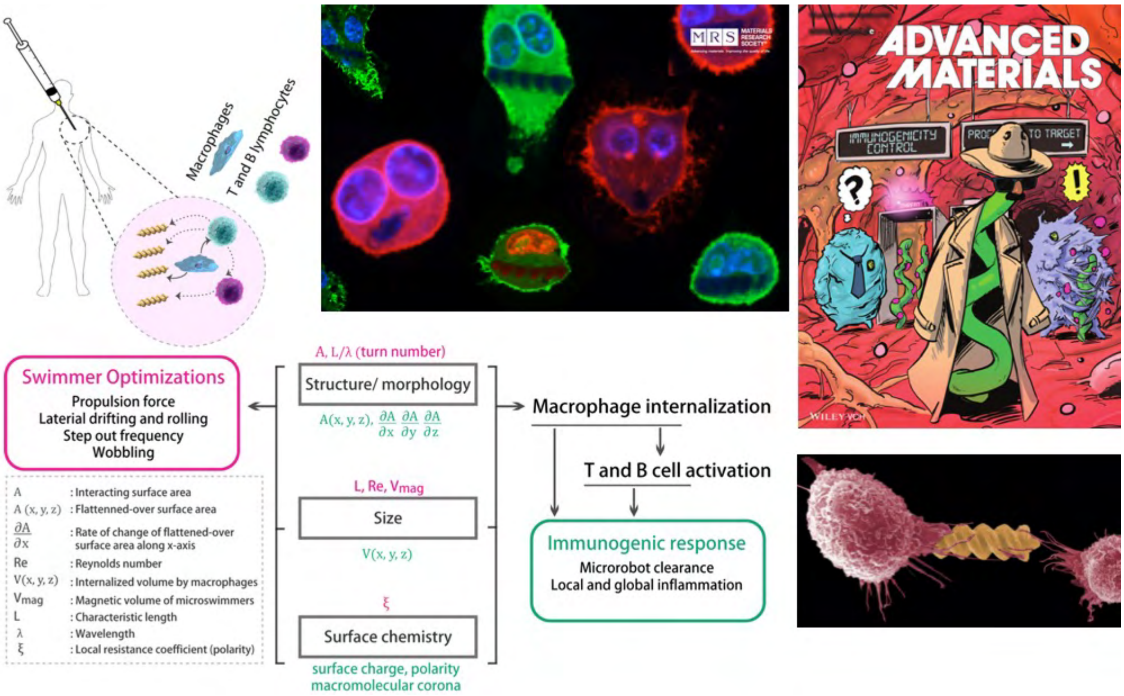
Electrical communication with and modulation of the central nervous system is essential to our current understanding of neurobiology and the diagnosis and treatment of neurological disorders. Efforts to make neural intervention mainly focus on developing less invasive, longer-lasting, and safer neural devices. A key challenge of such devices is powering, and wired-in powering can require that patients undergo surgical battery changes every 3 to 5 years in deep brain stimulation devices. Instead, neural devices that are remotely powered have emerged using magnetic induction, optoelectronic signaling, acoustic powering of piezoelectric materials, magnetic heating, and magnetoelectric materials. With certain degrees of success, each approach is limited by various anatomical or inherent phenomenological restrictions.

To achieve wireless neural stimulation, we have explored the potential of magnetoelectric nanoparticles (MENPs) [957]. We have shown proof-of-concept evidence that the non-resonant magnetic powering of MENPs locally modulates neuronal activity both in vitro and in a mouse model. We have also demonstrated that this modulation is sufficient to change animal behavior and to modulate other regions of the corticobasal ganglia-thalamocortical circuit. We will also explore wireless robotic neurostimulation methods, which could also enable stimulation at desired diverse locations by active position control.

More information: https://pi.is.mpg.de/project/wireless-stimulation

Immune cell interaction dynamics of medical microrobots

Hakan Ceylan, Nihal Olcay Dogan, Immihan Ceren Yasa, Abdon Pena-Francesch



Interaction dynamics of medical microrobots with their local live microenvironments are usually overlooked. Deployment of such micromachines in the body for extended durations can pose significant safety risks from their biocompatibility. When any synthetic material enters or stays inside the body, our immune system counteracts to eliminate it. To elucidate the interaction dynamics of medical microrobots with our immune system, we systematically explored the impact of the robot bosy morphology [983]. We found that the macrophages and immune cells from the spleen can recognize and differentially elicit an immune response to helix turn numbers of the microswimmers that otherwise have the same size, bulk physical properties, and surface chemistries. However, the same surface-borne design parameters are also critical for the locomotion performance of the microrobots. Our findings suggest that the structural optimization of medical microrobots for the locomotion performance and interactions with the immune cells should be considered simultaneously because they are highly entangled and can demand a substantial design compromise from one another.

Next, we have explored zwitterionic polymers as non-immunogenic stealthy microrobot materials [975]. Also, our recent efforts have focused on using patient-derivable autologous biomaterials as medical microrobot materials [932], since they can minimize any risk of cytotoxicity and immune responses as the body would recognize them as self. We have harvested the blood plasma, albumin, and platelet lysate from the patient's blood to create functional magnetic microrobots. We envision that a personalized design strategy can impact the design of various future medical robots and devices made of autologous biomaterials for their improved biocompatibility and intelligent functionality.

More information: https://pi.is.mpg.de/project/medical-microrobots

Self-assembling magnetic robots with dynamic boundaries

Utku Culha, Zoey Davidson, Massimo Mastrangeli

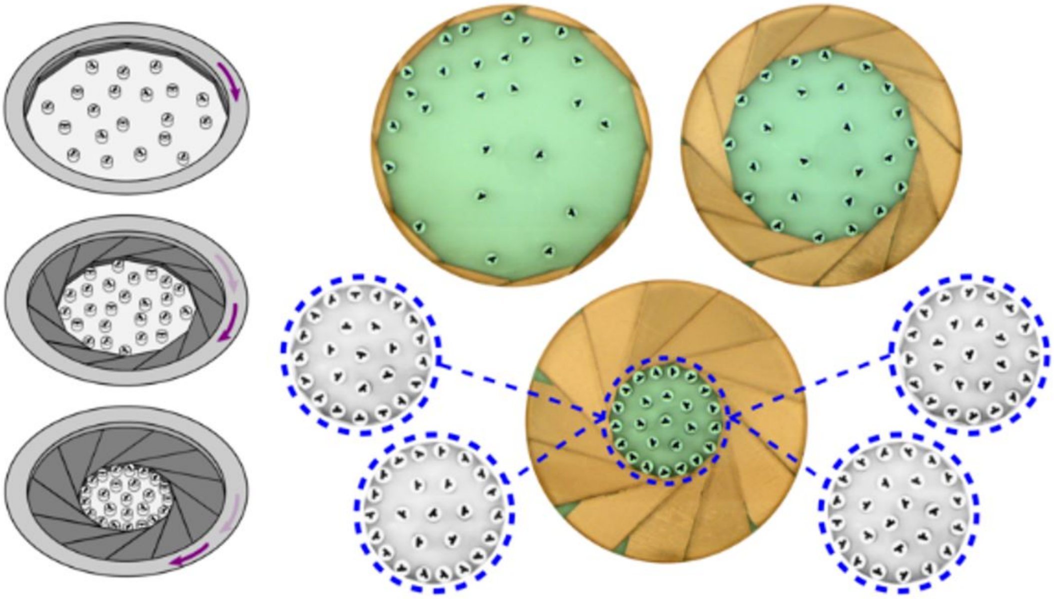


Figure 5.9: Moving boundaries confine magnetic particles into reprogrammable self-assembled patterns.

Self-assembly is an autonomous process where complex and functional structures are created in a bottom-up manner by the organization of a large set of components. Each component locally interacts with the others to create patterns, often with an unknown outcome: in the end, the patterns do not necessarily have a pre-conceived design. We aim to understand the underlying process of self-assembly. As this process continuously takes place both in living and non-living systems in a multitude of scales, our motivation is to understand the rules and dynamics of self-assembly. Specifically, we are interested in gaining the ability to control the self-assembly process to elucidate fundamental physics, and also to enable the fabrication of novel material systems and design of robotic systems. We propose a control approach that allows the programming of self-assembled patterns in a repeatable and reversible way [993]. We achieve this by confining magnetically repulsive millimeter-scale particles inside an orbitally shaken platform that provides a constant source of kinetic energy for the particles. Our confinement system compresses the freely moving particles via moving hard boundaries and traps them into diverse 2D patterns.

We exploit boundaries to steer self-assembly processes. The mechanical shaking in our system is functionally analogous to temperature in Brownian motion, and we could macroscopically simulate colloidal self-assembly processes. We showed that we can statistically program these 2D patterns by controlling the rate of particle compression. Moreover, our programming approach is reversible; meaning that after selecting one pattern, the system can be restored to its original state and reprogrammed to choose another. Our approach also shows the programming of material properties, as these patterns have unique elasticity and magnetic clutching properties. We show the correlation between confinement dynamics and resulting self-assembled structures, and also demonstrate the tuning of their mechanical and magnetic properties. By using our dynamic boundary regulation approach, we would like to use small-scale mobile robot swarms instead of particles and pave the way for a new approach for reconfigurable robotic systems.

More information: https://pi.is.mpg.de/project/dynamic-boundaries

Shape-encoded programmable dynamic assembly of mobile microrobots

Yunus Alapan, Mehmet Berk Yigit

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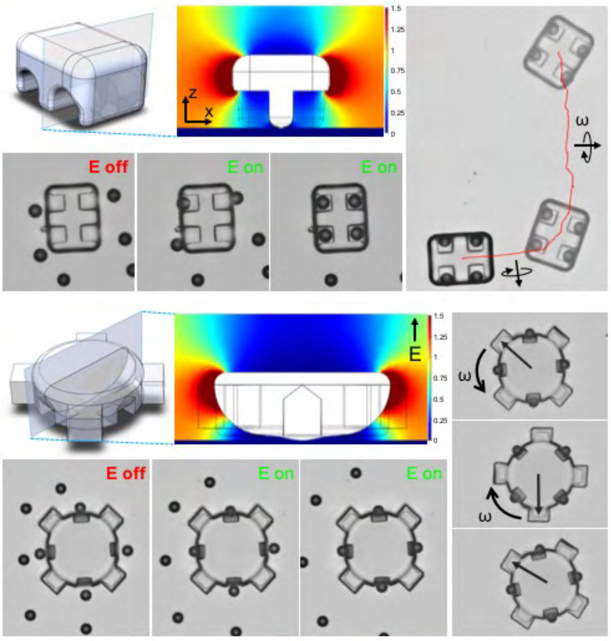
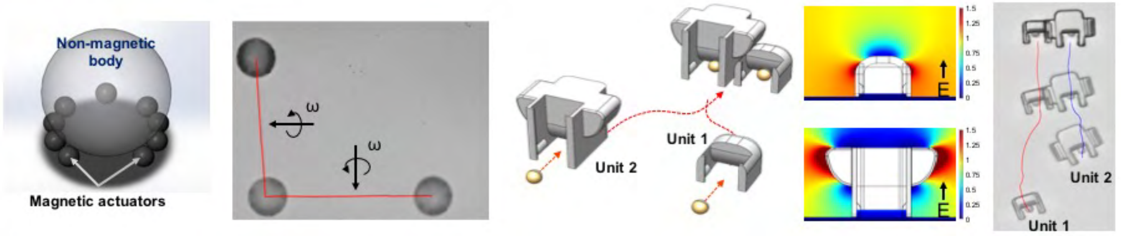
Self-assembled micromachines

PLASMONICS
Reaching ultralow lasing thresholds

ZEOLITES
Predicting structural transformations

PEROVSKITE SOLAR CELLS
With a little help from MXenes





Field-directed and self-propelled colloidal assembly have been used to build micromachines capable of performing complex motions and functions. However, integrating heterogeneous components into micromachines with specified structure, dynamics and function is required for building life-inspired complex hierarchical systems. In this project, we describe the dynamic self-assembly of mobile micromachines with desired configurations through pre-programmed physical interactions between structural and motor units [1026]. The assembly is driven by dielectrophoretic interactions, encoded in the three-dimensional shape of the individual parts. Micromachines assembled from magnetic and self-propelled motor parts exhibit reconfigurable locomotion modes and additional rotational degrees of freedom that are not available to conventional monolithic microrobots. The versatility of this site-selective assembly strategy is demonstrated on different reconfigurable, hierarchical and three-dimensional micromachine assemblies. Our results demonstrate how shape-encoded assembly pathways enable programmable, reconfigurable mobile micromachines. The design principle presented in this project will advance and inspire the development of more sophisticated, modular micromachines and their integration into multiscale hierarchical systems.

More information: https://pi.is.mpg.de/project/shape-assembly

Collective formation and cooperative behavior of magnetic microrobot collectives

Xiaoguang Dong

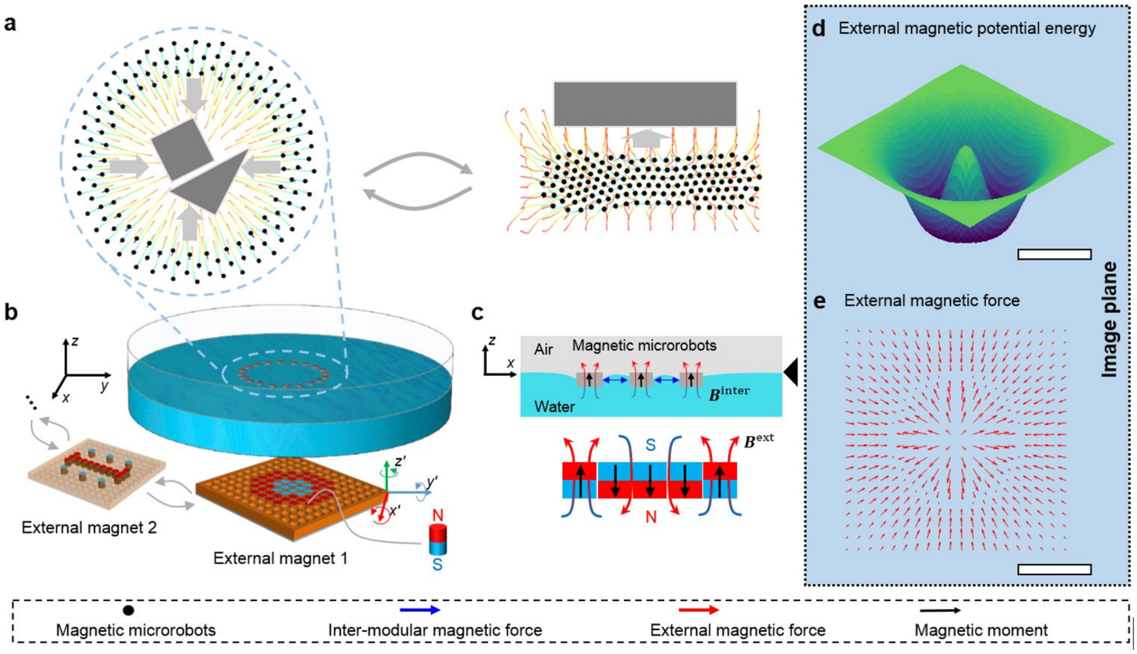


Figure 5.10: A generic design method enables controlling swarm magnetic microrobots with a significantly higher complexity in collective formation and more advanced functionalities compared with previous works.

Magnetically actuated mobile microrobots can access distant, enclosed, and small spaces, such as inside microfluidic channels and the human body, making them appealing for minimally invasive tasks. Despite their simplicity when scaling down, creating collective microrobots that can work closely and cooperatively, as well as reconfigure their formations for different tasks, would significantly enhance their capabilities such as manipulation of objects. However, a challenge of realizing such cooperative magnetic microrobots is to program and reconfigure their formations and collective motions with under-actuated control signals.

To tackle this challenge, this project presents a method of controlling 2D static and time-varying formations among collective self-repelling ferromagnetic microrobots (100 µm to 350 µm in diameter, up to 260 in number) by spatially and temporally programming an external magnetic potential energy distribution at the air-water interface or on solid surfaces. A general design method is introduced to program external magnetic potential energy using ferromagnets [1001]. A predictive model of the collective system is also presented to predict the formation and guide the design procedure. With the proposed method, versatile complex static formations are experimentally demonstrated and the programmability and scaling effects of formations are analyzed [1135]. We also demonstrate the collective mobility of these magnetic microrobots by controlling them to exhibit bio-inspired collective behaviors such as aggregation, directional motion with arbitrary swarm headings, and rotational swarming motion. Finally, the functions of the produced microrobotic swarm are demonstrated by controlling them to navigate through cluttered environments and complete reconfigurable cooperative manipulation tasks.

More information: https://pi.is.mpg.de/project/collective-formation

Acoustically-powered mobile microrobots

Amirreza Aghakhani, Oncay Yasa, Paul Wrede

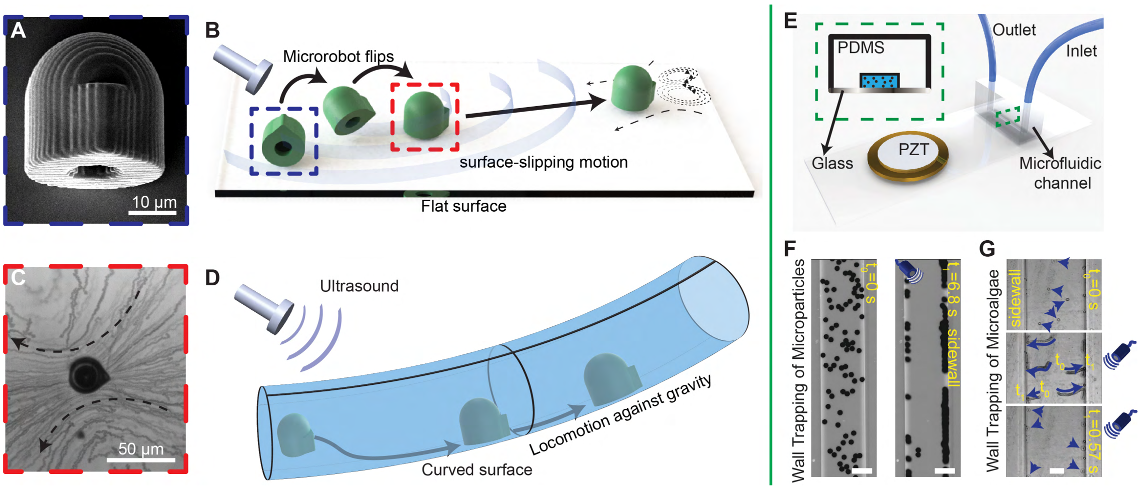


Figure 5.11: Overview of acoustically powered microrobots. A) Scanning electron microscope image of the 3D-printed microrobot. B) Locomotion mechanism of the robot under acoustic actuation. C) Microstreaming fluidic flow around the microrobot that causes the propulsion thrust. D) Propulsion of acoustic microrobots on curved surfaces. E) Schematics of the flexural wave-driven soft attractor walls. Wall trapping of F) polystyrene microparticles and G) microalgae swimmers under ultrasound waves.

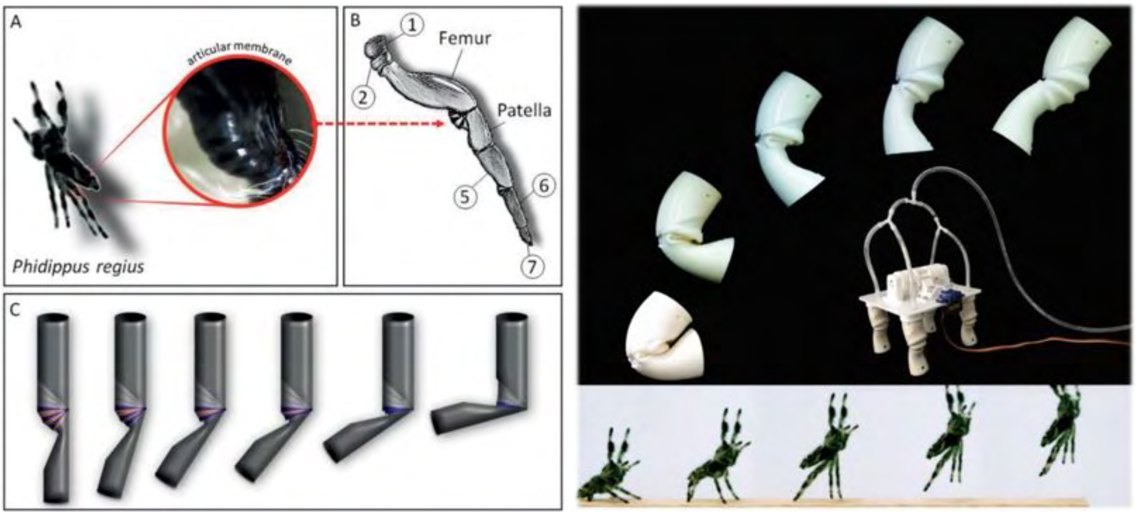
We propose acoustically powered microrobots that use a fast and unidirectional locomotion strategy, termed surface slipping, and can navigate on both flat and curved surfaces [996]. These microrobots have a 3D polymeric shell with a spherical cavity inside, whereupon immersing in fluid media an air bubble is trapped inside the cavity. By application of ultrasound waves at the resonance frequency of the bubble, the microrobot can generate asymmetric fluidic flow, leading to fast propulsion. They can harness the acoustic waves for propulsion at high speeds, up to 90 body lengths per second with a body length of about 25 µm. They can also generate a thrust force of about two to three orders of magnitude higher than that of microorganisms, such as algae and bacteria, enabling navigation inside the vascular capillaries with blood flow. For controlled steering under a uniform magnetic field, the microrobots were anisotropically coated with a magnetic nanofilm. Overall, the combination of acoustic powering and magnetic steering can be used as an efficient actuation mechanism to propel and navigate the microrobots in confined and hard-to-reach body location areas at high speeds.

Next, we reported a flexural wave-based acoustofluidic system for trapping micron-sized particles, cells, and potentially microrobots at the soft wall boundaries [960]. By exciting a standard microscope glass slide at its resonance frequency, we showed the wall-trapping action in sub-millimeter-size channels. We demonstrated the wall-trapping performance for the case of motile cells, such as Chlamydomonas reinhardtii microalgae. The flexural wave-driven acoustofluidic system described here provides a biocompatible, versatile, and label-free approach to attract particles, cells, and microrobots toward the soft walls.

More information: https://pi.is.mpg.de/project/acoustic-powered

Jumping spider leg folding mechanism and body fluid properties

Chantal Goettler, Guillermo Amador



Jumping spiders (Phidippus regius) are known for their ability to traverse various terrains fast and have targeted jumps within the fraction of a second to catch flying preys. Different from humans and insects, spiders use muscles to flex their legs, and hydraulic actuation for extension. By pressurizing their inner body fluid, they can achieve fast leg extensions for running and jumping. Here, we investigate the working principle of the articular membrane covering the spider leg joint pit [955]. This membrane is highly involved in the walking, grasping and jumping motions. We studied hardness and stiffness of the articular membrane using nanoindentation tests and developed preparation methods for scanning electron microscopy and histology to give detailed information about the inner and outer structure of the leg joint and its membrane. Inspired by the stroller umbrella-like folding mechanism of the articular membrane, a robust thermoplastic polyurethane-based rotary semi-fluidic actuator is demonstrated, which shows increased durability, achieves working angles over 120°, produces high torques which allows lifts over 100 times of its own weight and jumping abilities. The developed actuator can be used for future grasping tasks, safe human-robot interactions and multi-locomotion ground robot applications, and it could shed light into spider locomotion-related questions.

Next, we stdied fluid mechanics and rheology of the jumping spider body fluid [946], which has not been reported before. Spiders use their inner body fluid ("blood" or hemolymph) to drive hydraulic extension of their legs. In hydraulic systems, performance is highly dependent on the working fluid, which needs to be chosen according to the required operating speed and pressure. Here, we provide new insights into the fluid mechanics of spider locomotion. We present the three-dimensional structure of one of the crucial joints in spider hydraulic actuation, elucidate the fluid flow inside the spider leg, and quantify the rheological properties of hemolymph under physiological conditions. We observe that hemolymph behaves as a shear-thinning non-Newtonian fluid.

More information: https://pi.is.mpg.de/project/jumping-spider

Machine learning methods for soft millirobot design and control

Sinan Ozgun Demir, Utku Culha, Alp Can Karacakol, Abdon Pena-Francesch, Sebastian Trimpe

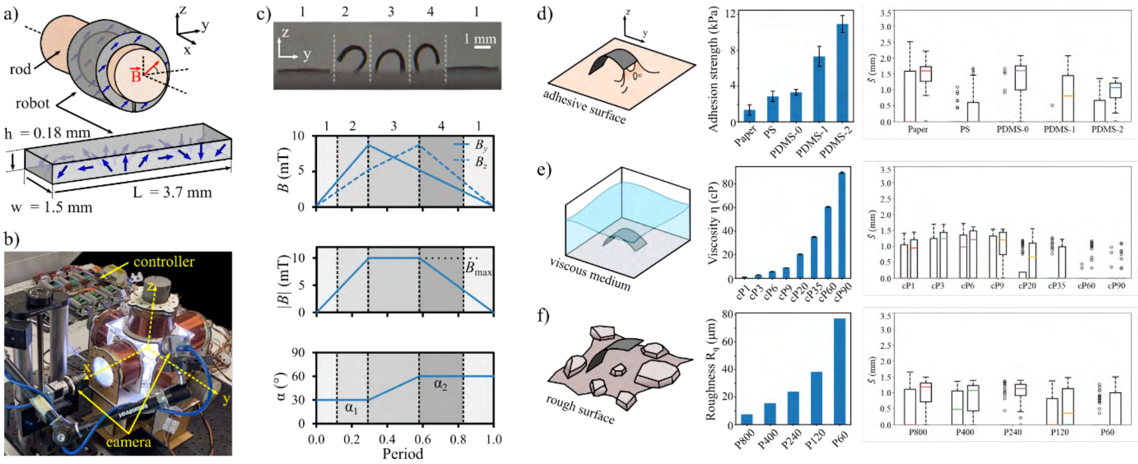


Figure 5.12: A) Magnetic soft millirobot is composed of non-magnetized ferromagnetic microparticles homogeneously distributed inside a silicone elastomer sheet, is rolled around a cylindrical rod, and magnetized with a uniform 1.8 T magnetic field (red arrow) with a 45° angle to the y-axis. B) Photo of the magnetic actuation and imaging system with six electromagnetic coils and two high-speed cameras. C) In a single actuation period of the walking gait, the magnetic soft millirobot follows the four consecutive gait states shown with the photos by the applied magnetic field. Learning performance of the walking gait parameters with the standard Bayesian optimization (left bars) and the mean transfer method (right bars) for the changing D) adhesion properties, E) test medium viscosity, and F) roughness values of the test surfaces.

Untethered small-scale soft robots have promising applications in minimally invasive surgery, targeted drug delivery, and bioengineering applications as they can directly and non-invasively access confined and hard-to-reach spaces in the human body. For such potential biomedical applications, the adaptivity of the robot control is essential to ensure the continuity of the operations, as task environment conditions show dynamic variations that can alter the robot's motion and task performance. The applicability of the conventional modeling and control methods is further limited for small soft robots due to their kinematics with virtually infinite degrees of freedom, inherent stochastic variability during the fabrication, and changing dynamics during real-world interactions. To address the controller adaptation challenge to dynamically changing task environments, we propose in [1132] using a probabilistic learning approach for a millimeter-scale magnetic walking soft robot using Bayesian optimization (BO) and Gaussian processes (GPs). Our approach provides a data-efficient learning scheme by finding the gait controller parameters while optimizing the stride length of the walking soft millirobot using a limited number of physical experiments. To demonstrate the controller adaptation, in [938], we test the walking gait of the robot in task environments with different adhesion properties, medium viscosities, and surface roughnesses. We also utilize the transfer of the learned GP model among different task spaces and robots and studied its effect on improving controller learning performance.

More information: https://pi.is.mpg.de/project/MLsoftirobot

Reconfigurable multifunctional ferrofluid droplet robots

Fan Xinjian, Xiaoguang Dong, Alp Can Karacakol

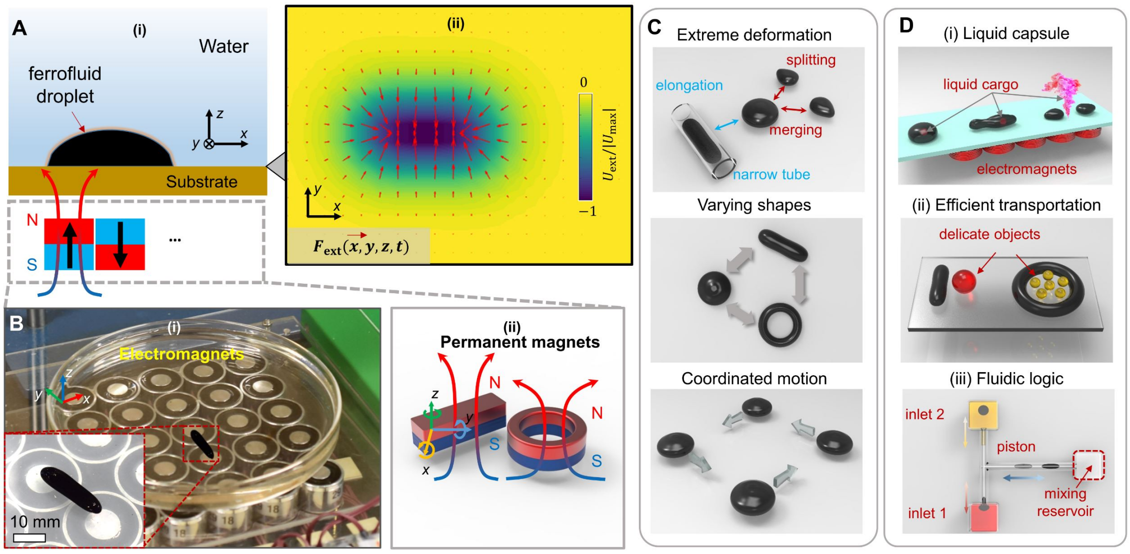


Figure 5.13: Newly developed electromagnetic actuator array-based control mechanisms enable reconfigurable and multifunctional ferrofluid droplet robots towards diverse biomedical and lab-on-a-chip applications.

Magnetically actuated miniature soft robots are capable of programmable deformations for multimodal locomotion and manipulation functions, potentially enabling direct access to currently unreachable or difficult-to-access regions inside the human body for minimally invasive medical operations. However, magnetic miniature soft robots are so far mostly based on elastomers, where their limited deformability prevents them from navigating inside clustered and very constrained environments, such as squeezing through narrow crevices much smaller than the robot size. Moreover, their functionalities are currently restricted by their predesigned shapes, which is challenging to be reconfigured in situ in enclosed spaces.

To tackle these challenges, we report reconfigurable multifunctional ferrofluid droplet robots (FDRs) with programmable morphology and cooperative behaviors by programming external magnetic fields spatiotemporally [969]. We first report the fundamental mechanism to control the complex shape-morphing behaviors and two-dimensional (2D) motions of ferrofluid droplets on solid substrates and in confined spaces, which allows producing much larger deformations (e.g., splitting) of these droplets compared with existing magnetic soft elastomeric robots, and on-demand complex shape-morphing ability compared with existing droplet robots. Then, we demonstrate that these droplet robots could have reconfigurable multiple functionalities, such as splitting and merging for cargo delivery, navigating through narrow channels much smaller than their sizes, and reconfiguring into different shapes for versatile and efficient 2D manipulation of delicate objects. Furthermore, the controllable splitting ability allows a single droplet to disassemble into multiple subdroplets, which can then coordinate their motions and complete cooperative tasks, such as working as a programmable fluidic-mixing device for addressable and sequential mixing of liquid chemicals. Therefore, our proposed reconfigurable multifunctional FDRs could open up a wide range of opportunities to enable diverse unprecedented functionalities that are essential for advanced lab/organ-on-a-chip and biomedical applications.

More information: https://pi.is.mpg.de/project/dropletrobots

Larval fish-like efficient undulatory swimming

Tianlu Wang, Ziyu Ren, Wenqi Hu, Li Mingtong

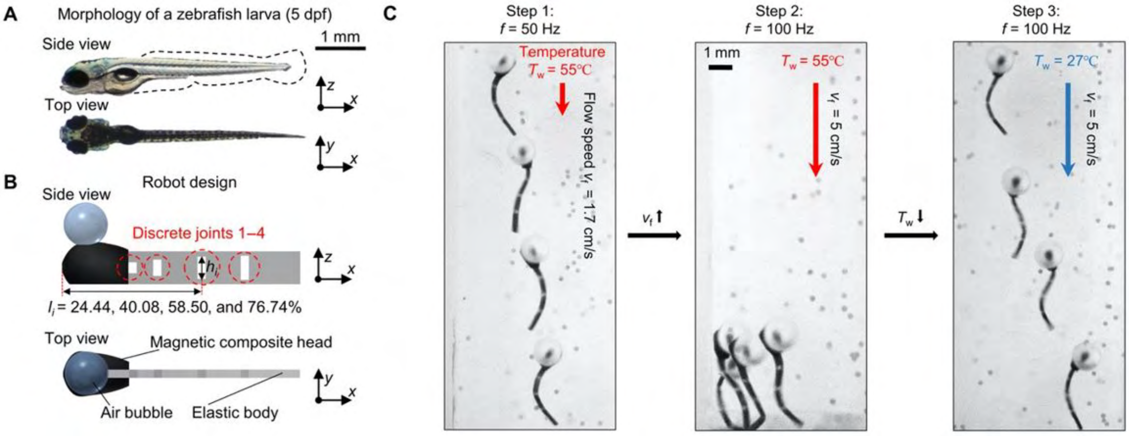


Figure 5.14: Proper combination of the body bending stiffness and actuation frequency enables the efficient undulatory propulsion in the intermediate flow regime. A, B) The robot design is inspired from the larval zebrafish and the magnetic actuation is utilized for its advantages in wireless nature, high-frequency actuation, and miniaturization. C) Together with the capability of stiffness adjustment for shape memory polymer, the efficient propulsion is demonstrated at the uniform body stiffness and high propulsion frequency.

Energy-efficient propulsion is a critical design target for robotic swimmers. Although previous studies have pointed out the importance of nonuniform body bending stiffness distribution (k) in improving the undulatory swimming efficiency of adult fish-like robots in the inertial flow regime, whether such an elastic mechanism is beneficial in the intermediate flow regime remains elusive. Hence, we develop a class of untethered soft milliswimmers consisting of a magnetic composite head and a passive elastic body with different k [948]. These robots realize larval zebrafish-like undulatory swimming at the same scale. Investigations reveal that uniform k and high swimming frequency (60 to 100 Hz) are favorable to improve their efficiency. A shape memory polymer-based milliswimmer with tunable k on the fly confirms such findings. Such acquired knowledge can guide the design of energy-efficient leading edge-driven soft undulatory milliswimmers for future environmental and biomedical applications in the same flow regime.

As one of the most widely spread locomotion modes, undulatory swimming exists in many organisms, ranging in size from sperm cells to whales. It results from the fluid-structure interaction, which involves the influence of the muscle contraction and the interactions between the fish body and the surrounding water. This can be shown by the mismatch between the body wave's transmission speed and the muscle contraction's propagation speed. Particularly, the axial muscle contraction can do both positive work to bend the body and negative work to stiffen the body. The negative work part and the body's physical properties, i.e., structural and material properties, determine the body bending stiffness distribution, k, which dictates the fluid-structure interaction. Using the proposed robotic platform in this study, we abstract and emulate a series of k configurations of larval fish-like swimming at the steady state and investigate their effects. This robotic platform can be further extended to investigate the effects of different k on biological larval fish and illustrate the importance of negative work in real larval fish swimming. This could help explain the effectiveness of their propulsion with usually higher frequencies and hint us to reexamine the roles of the homogeneously stiff notochord and the uniform body morphology on efficient undulatory swimming at the larval phase.

More information: https://pi.is.mpg.de/project/larval-fish

Soft-bodied jellyfish-like swimming

Ziyu Ren, Wenqi Hu, Tianlu Wang, Xiaoguang Dong

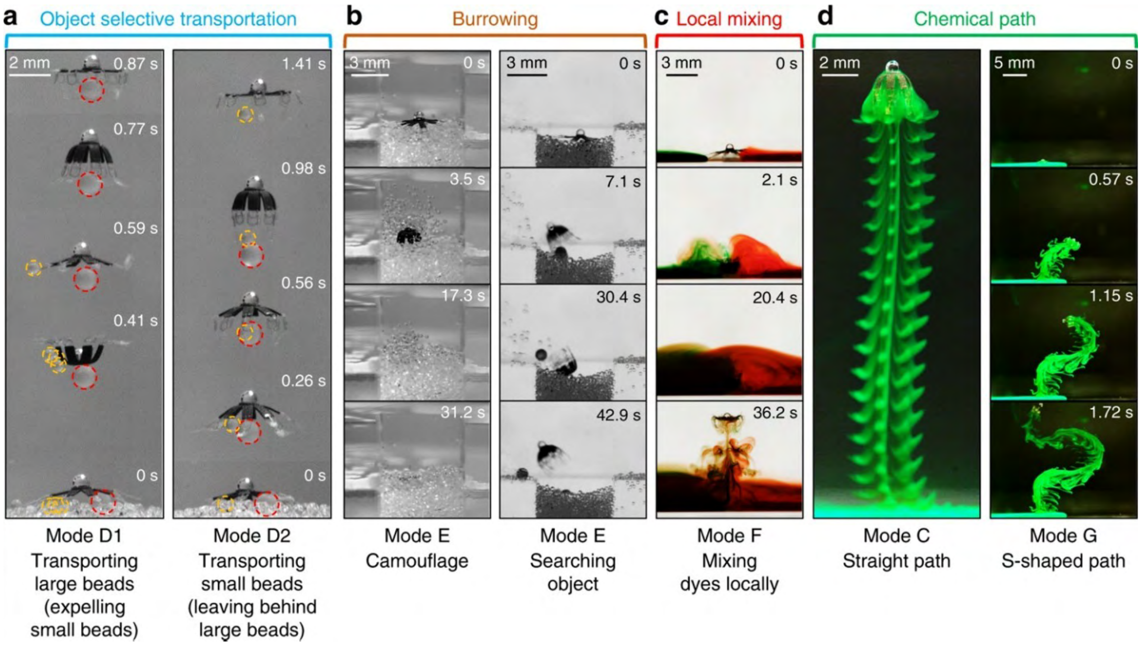


Figure 5.15: Four tasks realized by our jellyfish-inspired soft robot: A) Object selective transportation i) to transport large beads while expelling small beads and ii) to transport small beads and leave behind large beads; B) Burrowing for camouflage and searching in fine beads; C) Locally mixing two food dyes with different colors; D) Generating a desired concentrated chemical path while moving in a desired S-shaped path.

The advanced functions, e.g., object manipuiation, of the existing miniature swimming robots significantly decrease as the robot size gets smaller due to the limitations on their on-board components. To achieve the object manipulation function, microswimmers operating in the low Reynolds number (Re) regime have been proposed to incur controlled viscous fluidic flows to manipulate objects. However, it is unclear whether such approach is applicable in the moderate Re regime, where both inertial and viscous forces play critical roles. To realize the non-contact object manipulation in such regime, we propose a jellyfish-like soft millirobot, which could realize multiple functionalities by producing diverse controlled fluidic flows around its body using its lappets that are bent by remote magnetic fields. It can mimic the energy-efficient swimming kinematics and the prey capture behaviors of the ephyra jellyfish in nature.

This study particularly investigates the influence of different jellyfish-inspired swimming modes on the propulsion and object manipulation performances [1023]. The interaction between the robot's soft body and the surrounding fluid can incur different propulsion speeds, efficiencies, and flow patterns, and such interaction is utilized to achieve predation-inspired object manipulation capabilities towards different robotic tasks, such as selectively trapping and transporting objects of two different sizes, burrowing into granular media, enhancing the local mixing of two different chemicals, and generating a desired concentrated chemical path. Several medical functions, such as drug delivery, channel clogging, and patching to a target position under the ultrasound guidance have also been demonstrated with some adaptations in the robot design [1137]. This innovative study received the **best paper award** in Robotics Science and Systems Conference in 2019. This pioneering study exactly mimics the biological lappet kinematics, swimming, and predation type of functions in a soft robotic model for the first time. Such robotic model can be used to study the unknown behaviors of the jellyfishes.

More information: https://pi.is.mpg.de/project/jellyfish

Light-powered microswimmers

Varun Sridhar, Byung-Wook Park, Yunus Alapan

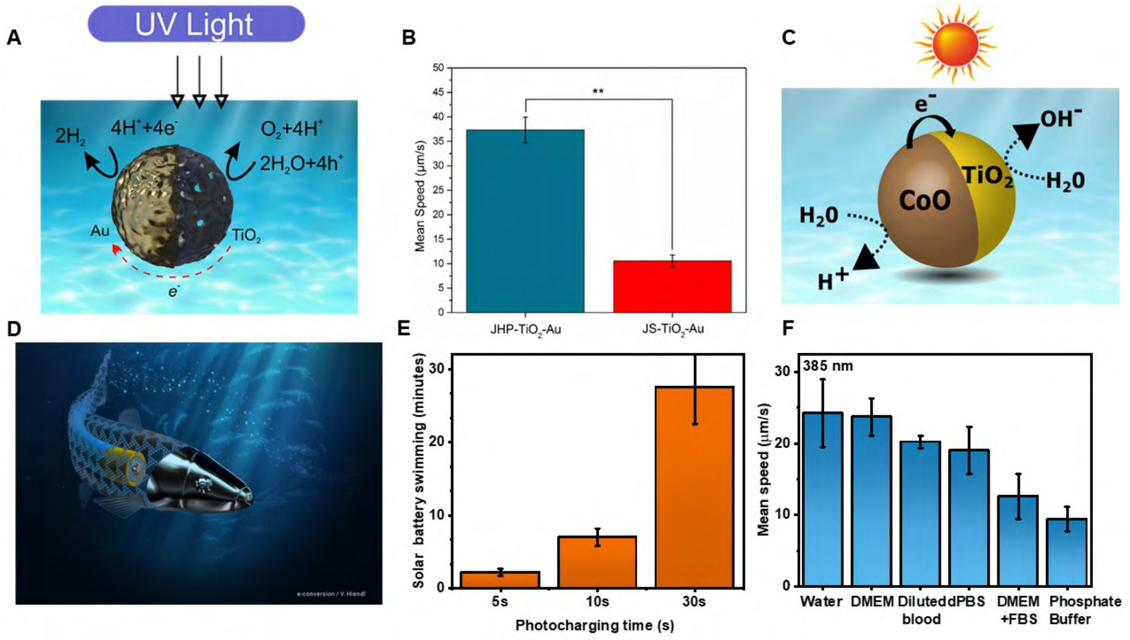


Figure 5.16: A) Janus hollow mesoporous TiO2 microswimmers for cargo carrying and B) their mean speed. C) CoO-TiO2 visible light-propelled microswimmers. D) Carbon nitride microswimmers, which can swim in dark up to 30 min and E) can have solar battery charging. F) Their mean speed in biological media.

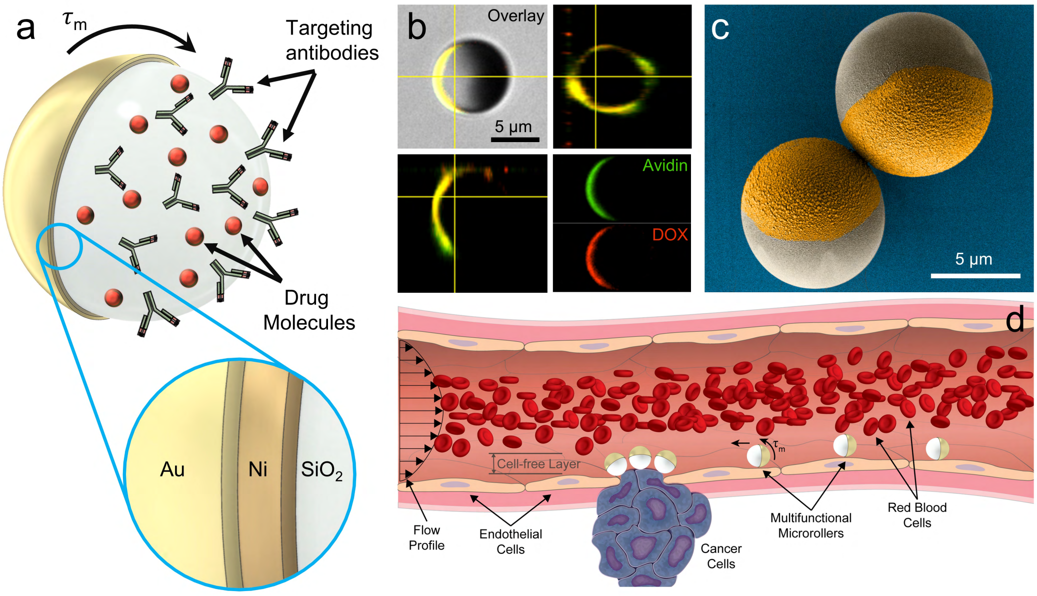
We have developed various photocatalytic light-driven swimmers by utilizing inorganic and organic (in collaboration with Bettina Lotsch's group) materials. On the inorganic microswimmers, we demonstrated the use of a hollow mesoporous TiO2 microswimmer that swims much faster than a solid TiO2 microswimmer under a low UV light intensity with only a small amount of fuel. The use of a mesoporous structure which has a large surface area, allows for faster swimming and ability to load drugs [1078]. We also present the use of a visible light responsive CoO-TiO2 microswimmer that swims in low visible light illumination without the need for any external fuels [987]. The microswimmers show visible light activity over a range of wavelengths from the UV to visible spectrum.

On the organic microswimmers, we demonstrated poly(heptazine imide) (PHI), a 2D carbon nitride material for the use as swimmers, they show efficient propulsion in aqueous media not only during but after illumination creating a solar battery swimming in dark. The mechanism of propulsion is also investigated in depth for different cap structures and different fuels. We find that oxygen reduction reaction is the driving reaction responsible for propulsion of all light-driven microswimmers [972]. The PHI microswimmers without the presence of any cap structures display propulsion in different ionic and biological media and cellular environments, such as diluted blood, without requiring additional fuels. The swimmers can even swim in high concentrations of ions such as 5 M NaCl. The swimmers can be loaded with a cancer drug with high loading efficiency without any passive release. Controlled drug release on demand is demonstrated in different pH conditions and can be triggered also by illumination while being sensitive to oxygen concentrations. This enables targeted and intelligent release of the drugs based on their environment. We also work on covalent organic frameworks which can be used in biological environments and which can carry large molecule cargos for tracking delivery due to their larger structural pores.

More information: https://pi.is.mpg.de/project/light-microswimmers

Magnetic surface microrollers in the blood stream

Ugur Bozuyuk, Yunus Alapan



Conventional drug delivery systems suffer from non-specific distribution of delivery agents throughout the body, resulting in low therapeutic efficiency and side effects for the treatment of diseases, such as cancer. To overcome such limitations, active therapeutic cargo delivery systems have emerged in the past decade, exploring the efficient targeting potential of such systems in biological media. Among active systems, magnetic microrobots have shown great promise thanks to their distinct advantages such as precise control capability.

Wireless magnetic microrobots possess significant potential to revolutionize the minimally invasive targeted medical applications at hard-to-reach, high-risk and deep regions inside the human body. The circulatory system is the natural fluidic transport network of the body, reaching all organs and the deepest tissues. Even though the circulatory system represents the ideal route for accessing the target disease locations, harsh physical conditions (e.g., blood flow) within the vessels impair the motion of cell-size microrobots. On the other hand, the surface motion of leukocytes, the only motile cells in the bloodstream, on vessel walls is enabled by their margination to the vessel wall and decreased flow velocities compared with the vessel centre. Therefore, vessel wall-enabled surface motion of leukocytes can be mimicked in surface-rolling microrobots for efficient propulsion in blood flow.

This research explores the navigation ability of magnetic surface microrollers in physiologically flow conditions for future endovascular medical applications. Specifically, we explore the upstream navigation potential of the magnetic microrollers using different materials and designs, understand the biological and hydrodynamic barriers [952] in blood vessels for efficient propulsion. We incorporate different drugs and antibodies to investigate the active targeting and delivery potential of the microrollers to the cells of interest [991]. Other than that, the medical imaging potential of surface microrollers is also being investigated with different imaging modalities to identify suitable techniques for imaging-guided endovascular delivery applications. Overall, we explore the biological barriers in blood vessels for the locomotion of the microrollers, and aim to develop a microrobotic system that can navigate the bloodstream and perform high-impact medical interventions in realistic settings.

More information: https://pi.is.mpg.de/project/surface-microrollers

Magnetic soft microrobots made of linked microactuator networks

Wenqi Hu, Xinghao Hu, Immihan Ceren Yasa, Ziyu Ren, Hakan Ceylan, Sandhya Rani Goudu

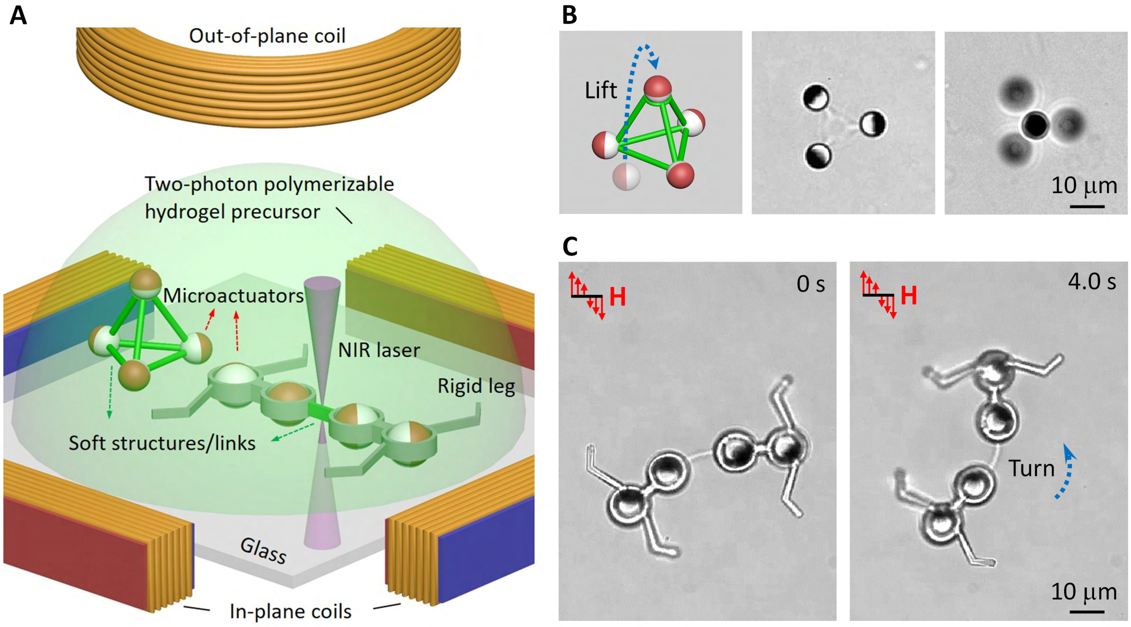


Figure 5.17: A) Soft micromachine fabrication strategy: fabrication process schematics of soft micromachines using a two-photon polymerization-based 3D microprinting system with an integrated electromagnetic coil setup. The microactuators (spherical Janus microparticles) are manipulated to reach a desired position and orientation and fixed there temporarily using 3D microprinting. Soft and rigid materials can be 3D-printed on a fixed microactuator to link it with various other fixed microactuators. B) Example 2D and 3D soft microactuator structures. C) Example legged soft microrobot with a soft body structure and rigid legs to walk on surfaces.

Soft mobile microrobots with overall sizes less than 100 micrometer would enable diverse programmed shape transformations and functions for future biomedical and organ-on-a-chip applications. However, fabrication of such machines has been hampered by the lack of control of microactuator's programmability. To address such challenge, we use two-photon polymerization to selectively link Janus microparticle-based magnetic microactuators by 3D printing of soft or rigid polymer microstructures or links [942]. Sequentially, we position each microactuator at a desired location by surface rolling and rotation to a desired position and orientation by applying magnetic field-based torques, and then 3D printing soft or rigid links to connect with other temporarily fixed microactuators. The linked 2D microactuator networks exhibit programmed 2D and 3D shape transformations, and untethered limbless and limbed micromachine prototypes exhibit various robotic gaits for surface locomotion. Furthermore, the microactuators can also be positioned in 3D space as a preliminary step towards 3D future configurations, either by levitating the microactuators in the vertical axis using 3D gradient fields or by a rolling motion along the 3D-microprinted hydrogel beam. The proposed fabrication strategy can enable new soft micromachine designs and applications at the cellular scales. By implementing this method layer-by-layer, 3D soft actuator networks can be also created in the future towards more complex soft microrobots.

More information: https://pi.is.mpg.de/project/soft-microrobots

Multimodal locomotion of bioinspired jumping-gliding robot (Multimo-Bat)

Hyun Gyu Kim, Matthew Woodward

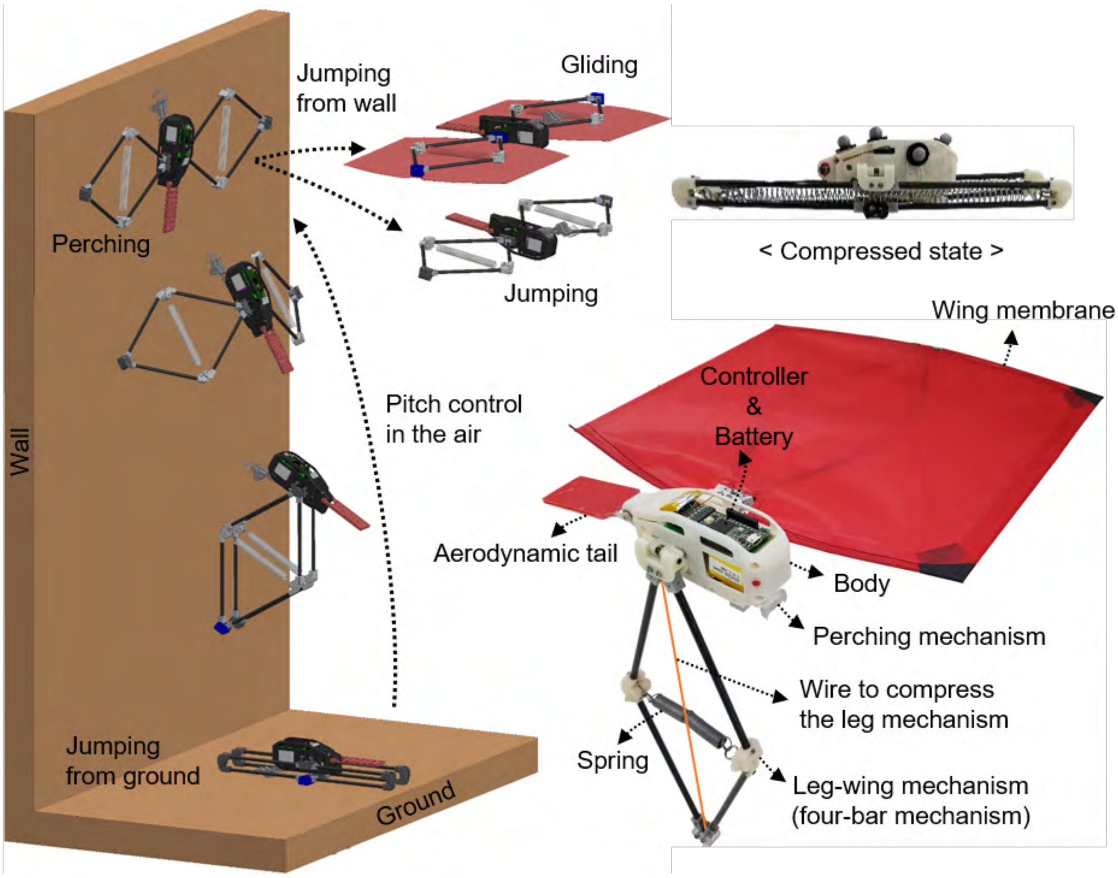


Figure 5.18: MutiMo-Bat: Multimodal robotic platform to integrate jumping, perching, and gliding motions. The jumping energy source comes from a spring in a four-bar mechanism. The robot has a clutch mechanism to store and release the jumping energy. The robot absorbs a perching shock and makes a stable engagement with the wall surface by using a claw. Wing membrane generates air drag force for the gliding motion. The aerodynamic tail controls the robot's pitch angle in air.

Mobility in unstructured environments is a significant challenge for robotic systems; however, there are creatures capable of operation in these environments. For example, flying squirrels, frogs, and snakes can jump from trees and glide to move to other trees. Woodpeckers can fly and perch on the bark. These integrated motions provide maneuverability to avoid danger from predators or obtain food. With the correct level of abstraction, these creatures can inspire designs that can improve the performance of their robotic counterparts.

The objective of this work is to design a single robotic platform and mechanisms for the motion integration from jumping, perching, and gliding motions. The benefit of our approach is that employing multiple locomotion strategies can significantly improve the mobility of systems operating in unstructured terrain. By utilizing an integrated approach for the addition of locomotion modes, the performance of individual modes can be preserved while reducing the additional structure and actuation required, therefore, improving overall system performance. We are also investigating the importance of an active tail in such multimodal locomotion systems to improve the robot stability and maneuverability. We are also adding perching, climbing and other locomotion modes to our MultiMo-Bat platform to challenge the robot design and control further.

More information: https://pi.is.mpg.de/project/multimo-bot

Information entropy to detect order in self-organizing systems

Gaurav Gardi, Wendong Wang, Vimal Kishore

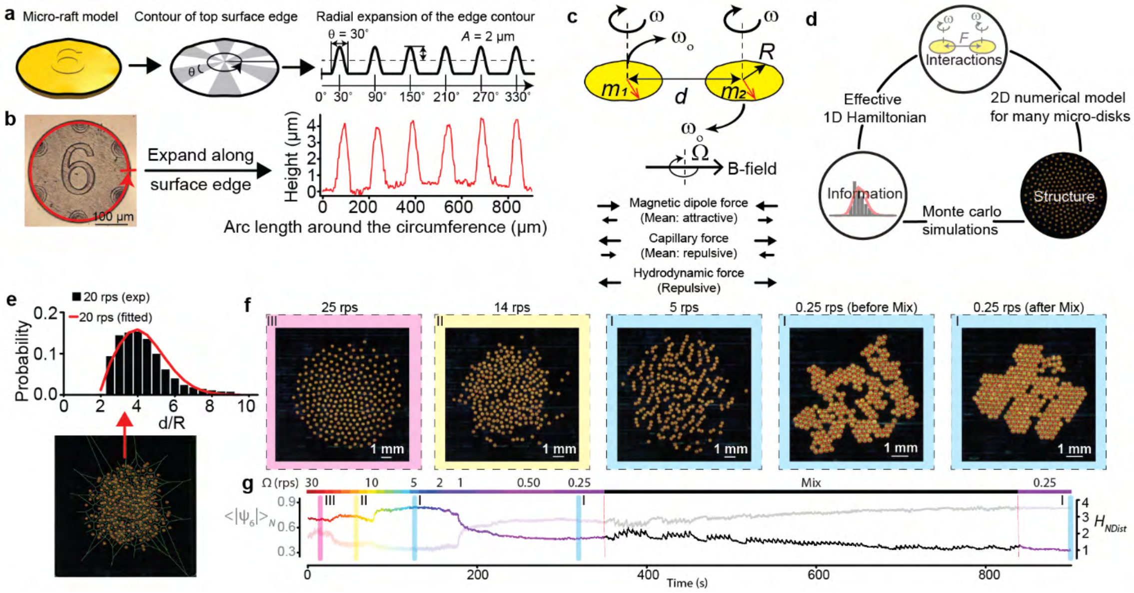


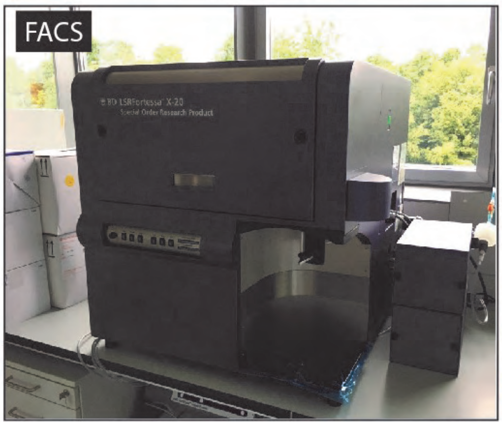
Figure 5.19: Local information relates to the order in patterns of a collective system. A) Parametric design of a 3D-printed micro-raft. B) Image of a micro-raft along with the measured edge height profile. C) The balance between pairwise interactions give rise to tunable patterns with diverse order. D) Schematic showing the relations between the interactions in the system, structure of the system and local information. E) Example of Voronoi tessellation and representative neighbor distance distribution. F) Sequence of collective pattern transition from hexatic-like to disordered to clustered patterns and finally to crystal-like ordered pattern. G) Hexatic order parameter and entropy by neighbor distances H_NDist characterizing the order in the patterns.

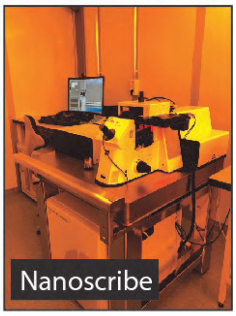
The application of the Shannon entropy to study the relationship between information and structures has yielded insights into molecular and material systems. Despite gaining valuable insights for such systems, much remains to be learned about the relationship between the abstract notion of information and its concrete manifestation in a structure. Using a model collective system, we seek to develop an information theoretic tool to detect order and relate it to the information content in the diverse patterns formed by equilibrium and non-equilibrium systems.

We use a self-organizing system made of hundreds of magnetic 300 μm-diameter micro-disks spinning at the air-water interface, as a model system. We design an intricate balance between the three main pairwise interactions in the system: capillary, magnetic dipole-dipole and hydrodynamic interactions. We seek to understand the relation between these mutual interactions, the structure, and the information contained in the diverse patterns formed by our system. The micro-disks can assemble into patterns with varying degree of order: hexatic-like, disordered and crystal-like ordered patterns and we can transition between these patterns by tuning the spinning speed of the external uniform rotating magnetic field. We have developed an information theoretic measure to quantify the degree of order in these patterns using the distribution of the neighbor distances. Intuitively, lower value of this measure means more order in the pattern. We anticipate that such measure will be useful for detecting self-organization in systems at different length scales, including cells, animals, humans, and robots, and that our experimental system could serve as a model system for testing non-equilibrium hypothesis.

More information: https://pi.is.mpg.de/project/information-entropy

5.4 Equipment





Our department conducts highly inter- and multidisciplinary research by maintaining robotics (physical), chemistry (wet bench), biology (certified S1 genetic engineering facility), medical imaging and research (in-vitro and ex-vivo small-animal imaging and testing), and microfabrication labs (class 10,000 facility) at the highest standards.

Synthesis and characterization of tailor-made responsive advanced materials and structures

We synthesize various organic and inorganic materials using wet benches in the dedicated chemistry lab. Our chemistry lab is equipped with a cross-polarized microscope (Axio Imager.Z2, Zeiss) and a PolScope (Polaviz) for characterizing and mapping liquid crystal elastomer (LCE) molecular orientations. We use a rheometer (Discovery HR-3, TA instruments) to measure the mechanical properties of LCEs and a differential scanning calorimeter (DSC) (DSC 2500, TA instruments) to characterize polymers. We have an analytical HPLC (1260 Infinity II Prime, Agilent) with a reverse phase column (C18) to rapidly characterize polymeric new materials we synthesize. We have an attenuated total reflection fourier transform infrared spectroscopy (Tensor II, Bruker) to monitor and characterize thin films.

Our dedicated cleanroom area has a spin coater (Laurell Technologies Corporation) and mask aligner (MJB-4 Suss, MicroTec) for photolithography. Most of our microrobots are 3D printed using two direct laser writing systems (Photonic GT, Nanoscribe GmbH) with a range of 1-300 μm and 100 nm resolution. The cleanroom hosts a Parylene coating system (PDS 2010, Specialty Coating Systems) to render devices and robots being fabricated biocompatible and implantable. The lab utilizes a plasma cleaner (PIE Scientific) for surface treatment of samples to clean contaminated surfaces, plasma activation of polymer coating, or etching for microfabrication. Also, in the central cleanroom of our institute, we have a roll-to-roll micro/nanostructure replication system (Coatema) to scale up the production of our micro/nanostructured materials and future robotic systems. We have a dedicated lab to support the research in adhesion and friction properties of engineered surfaces with a microscope (Axio Observer A1, Zeiss) and automated force transducer setups for measuring friction and adhesion and a Laser Microscope (VK-X200, Keyence) with the ability to scan surface profiles in 3D with a lateral resolution of 120 µm and an axial-resolution of about 0.5 nm. We use our scanning electron microscopy (SEM) (Gemini 500, Zeiss) to visualize microfabricated structures. We employ a critical point dryer (EM CPD 300, Leica) and a sputtering machine (EM ACE600, Leica) for sample preparation. For magnetic material characterization, a vibrating sample magnetometer (VSM) (EZ7, Microsense) is available to characterize the magnetization property and magnetize our magnetic materials at 1.8 Tesla. To characterize the surface wetting property of our materials/structures, we have a contact angle goniometer/tensiometer (Kruss DSA100 Drop Shape Analyzer).

Mobile millirobot fabrication and testing

To prototype, characterize, and test millimeter-scale rigid and soft robots, we have a physical lab equipped with essential tools and multiple SLA, FormLab, and extrusion-based 3D printers. We have a 60W CO2 laser cutter and engraver (Epilog) and an ultraviolet laser mill from (ProtoLaser U3, LPKF) with 25 µm resolution for cutting and shaping various thin materials. To actuate magnetic milli/microrobots, we have 6 custom-built magnetic actuation setups. One of them has five coils mounted on a Zeiss Axio Observer A1 inverted microscope. To investigate the interaction between miniature soft swimming robot bodies and fluids, we also have a customized magnetic setup integrated with the MicroPIV (micron-scale particle imaging velocimetry, Dantec). For magnetic manipulation of magnetic soft robots dexterously in 3D space, we have a 7-DOF robotic arm (Franka Emika) connected with a rotational permanent magnet towards clinical use. To characterize jumping-gliding and other robots moving fast and in the air in 3D, we built a cage system (5 m long x 3.2 m width x 4.8 m height) fully equipped with a Vicon system setup to track and characterize the robot movements in 6 DOF visually. Moreover, over 4 high-speed cameras (Phantom) up to 5000 fps are also available.

Mobile microrobot fabrication and testing

We have four biology labs (all S1) for mammalian and various eukaryotic (e.g., algae) and prokaryotic (e.g., E. coli) cell cultures and ten biological characterization labs (all S1). The culture labs are well-equipped with the basic infrastructure, including biosafety cabinets, incubators, autoclaves, and centrifuges. The characterization labs are equipped with a variety of biological optical microscopes. We have a Zeiss inverted microscope (Axio Observer A1, Zeiss), a Nikon Inverted microscope (ECLIPSE Ts2, Nikon), a Nikon inverted fluorescence microscope (ECLIPSE Ti-E, Nikon), a Nikon spinning-disk confocal microscope (Eclipse Ti-E equipped with Yokogawa CSU-X1 spinning disk, Nikon), a Leica stereomicroscope (M205 FA, Leica), and a Leica SP8 single-point confocal in combination with a widefield fluorescence microscope (Leica DMi8 plus SP8). All these microscopes are capable of supporting live-cell imaging for days. With these microscopes, we perform an extensive range of experiments, from toxicity tests of robots on cells and histology to long-term monitoring of robot-cell interaction, to high-speed imaging of bacteria swimming with robots attached, and to high resolution confocal 3D reconstruction of the robot-splenocyte interface. We use fluorescence-activated cell sorting (FACS) (LSRFortessa X-20, BD Biosciences) with five lasers to evaluate the immunogenic potential of our microrobots assessing surface markers of cells, cytokine levels, or simple live-dead applications. Besides these microscopes, we also have a quartz crystal microbalance (QCM) with dissipation (LOT-QuantumDesign) to study sensor devices, including multilayer buildup, drug uptake/release, and bacteria adhesion. We have a biological atomic force microscope system (AFM) (JPK) with an integrated fluorescent optical microscope to measure the surface property and topology of the microrobot materials or bodies. This tool is also used to characterize the physical properties of living and soft materials, such as bacteria, cells, hydrogels, and biopolymers. We perform various in vitro and ex vivo assays to test the toxicity and performance tests of our small-scale medical robots. These assays include Caspase-assays, live-dead-assays, cell-viability-assays, enzyme-linked immunosorbent assays (ELISA), which can be read out using the BioTek Synergy 2 Microplate Reader. We also set up a histology section with a semi-motorized rotary microtome (RM2245, Leica) for the preparation of 2-10 µm-thick tissue samples for routine histological staining as H&E (hematoxylin and eosin) staining, but also more specific immunohistochemistry staining for the evaluation of, e.g., tissue damage, oxidative stress, and infiltration of immune cells.

Medical imaging and testing

We have built a medical imaging facility to develop image-guided actuation, control, and tracking methods for wireless small-scale mobile robots in realistic tissue phantoms and inside small animals. State of the art medical imaging systems are operated mainly by the Medical Systems CSF staff. Currently, our facility is equipped with a 7 Tesla preclinical MRI Scanner (BioSpec 70/30, Bruker), which enables high-resolution 3D imaging, microrobot tracking, and magnetic robot actuation using the gradient coils. After completion of the MedLab, the MRI will move there, where it will be equipped with a state-of-the-art Bruker PET (positron emission tomography) insert for simultaneous PET/MR imaging. We will then be able to detect and track microrobots with high sensitivity. Also, changes in glucose metabolism, proliferation within specific tissues, and hypoxic potential can be assessed in disease models or upon treatment. Next, we have three X-ray-based imaging instruments with various features: preclinical in vivo microCT (Bruker SkyScan 1276), a closed X-ray cabinet (Kubtec XPERT 80-L), and an open mini C-arm (Hologic Fluoroscan InSight FD Flex).

To localize microrobots in realistic tissue phantoms and inside small animals, we have an in vivo imaging system (IVIS) (Perkin Elmer, Spectrum) for 2D and 3D fluorescence, bioluminescence and Cerenkov imaging. We have a multispectral optoacoustic tomography (MSOT) system (iThera Scientific inVision 512-TF) combined with ultrasound imaging for tracking of microrobots within blood vessels with high speed and precision. We also have a separate small-animal ultrasound (US) system (Fujifilm VisualSonics Vevo 3100) with a frame rate of up to 500 Hz and a resolution down to 50 µm, which offers anatomical, hemodynamic, functional, and molecular imaging data. We have an optical coherence tomography (OCT) system (Thorlabs), which allows the acquisition of cross-sectional images up to several millimeters deep into the tissue.

More information: https://pi.is.mpg.de/field/equipment

5.5 Awards & Honors

2021

15 journal articles of our group were selected as the Highly Cited Papers in Web of Science.

Hakan Ceylan and **Xiaoguang Dong** will join Mayo Clinic and Vanderbildt University, respectively, and **Abdon Pena-Francesch** joined University of Michigan, Ann Harbour as an assistant professor in USA.

Utku Culha and **Kristen Kozielski** joined Technical University of Munich as a chief scientist and assistant professor, respectively.

Jiachen Zhang, **Yubing Guo**, and **Xinghao Hu** joined the City University of Hong Kong, Beijing Institute of Technology, and Northwestern Polytechnical University, respectively as an assistant professor in China.

Yichao Tang received the 1000 Young Talents Award in China and joined Tongji University as a full professor.

Donghoon Son and **Sungwoo Chun** joined Pusan National University and Korea University, respectively as an assistant professor in S. Korea.

Jaekang Kim, Aniket Pal, Zhen Yin, Wei Feng, Yingdan Wu, and **Mingchao Zhang** received the Humboldt postdoctoral fellowship.

Savas Tasoglu received the Humboldt fellowship for experienced researchers.

Saadet Fatma Baltaci-Demir and **Siyeon Jang** received the DAAD PhD fellowship.

Jie Han, Chong Hong, Yingbo Yan, Fan Wang, Shuqi Wang, and **Xianglong Lyu** received the CSC PhD fellowship.

Wei Feng received the Best Paper Award in Bonic Robotics at the International Workshop on Bionic Engineering.

Hakan Ceylan selected as a **Young Academy Member** by Turkish Science Academy, 2021.

2020

Metin Sitti received the "Breakthrough of the Year" Award in the engineering and technology category of the Falling Walls World Science Summit in Berlin for the research breakthrough related to wireless medical robots inside our body.

Junghwan Byun: received a National Research Foundation of Korea (NRF) Fellowship.

Meng Li,Sungwoo Chun and **Shuaizhong Zhang** received the Humboldt Postdoctoral Research Fellowship.

Hakan Ceylan received the Günter Petzow Prize.

Hamed Shahsavan, Amirreza Aghakhani, Yubing Guo, Zoey Davidson, and **Metin Sitti** were the Cozzarelli Prize Finalist in the Engineering and Applied Sciences category in the PNAS journal for the research article entitled, "Bioinspired underwater locomotion of light-driven liquid crystal gels" (1 paper won the prize and our paper was the finalist out of over 4000 papers published in PNAS in 2020).

Immihan Ceren Yasa named as an Innovation Fellow at Novartis, Basel, Switzerland.

Wendong Wang joined University of Michigan - Shanghai Jiao Tong University Joint Institute as an assistant professor in China.

Vimal Kishore joined Banaras Hindu University as an assistant professor in India.

Hamed Shahsavan joined University of Waterloo as an assistant professor in Canada.

Hakan Ceylan named as a **College for Life Science Fellow** by Wissenschaftskolleg zu Berlin.

2019

Metin Sitti received the ERC Advanced Grant for the project titled, "SoMMoR: Soft-bodied Miniature Mobile Robots".

Ziyu Ren, Tianlu Wang, Wenqi Hu, and **Metin Sitti** received the Best Paper Award in the Robotics Science and Systems Conference for the research paper entitled, "A Magnetically Actuated Untethered Jellyfish-Inspired Soft Milliswimmer".

Morteza Amjadi joined Heriot-Watt University as an assistant professor in UK.

Matthew Woodward joined Tufts University as an assistant professor in USA.

Guillermo Amador joined Wageningen University as an assistant professor in Netherlands.

Jiachen Zhang and Yichao Tang received the Humboldt postdoctoral fellowship.

Musab Cagri Ugurlu received the Ministry of Education PhD fellowship from Turkey.

Xinjian Fan and **Mingtong Li** received the CSC PhD fellowship.

Hakan Ceylan and **Metin Sitti**'s medical microrobotics research was featured as among "5 amazing projects that will change the future of healthcare" by the PC Magazine.

2018

Hamed Shahsavan received the Canadian NSERC postdoctoral fellowship.

Wenqi Hu, **Guo Zhan Lum**, and **Metin Sitti** received the Innovator of the Year Award in medical devices topic by the Design & Elektronik Magazine in Germany due to the invention of soft medical robots.

Ahmet F. Tabak and **Metin Sitti** were the Best Medical Robotics Award Finalist in the IEEE Robotics and Automation Conference for the research paper entitled, "Mechanical Rubbing of Blood Clots Using Helical Robots Under Ultrasound Guidance".

Metin Sitti received the Rahmi Koç Medal of Science, in Turkey, which is given to one world-wide pioneering Turkish-origin scientist each year.

Wenqi Hu received the Günter Petzow Prize.

Abdon Pena-Francesch, **Zoey Davidson**, **Ville Liimatainen**, **Xinghao Hu**, **Yubing Guo**, and **Utku Culha** received the Humboldt postdoctoral fellowship.

Pelin Erkoç joined Bahcesehir University as an assistant professor in Turkey.

Chang-Kyu Yoon joined Ewha Womans University as an assistant professor in S. Korea.

Guo Zhan Lum joined Nanyang Technological University as an assistant professor in Singapore.

David Gracias received the Friedrich Wilhelm Bessel award from the Alexander von Humboldt foundation.

Sinan Özgün Demir received the Ministry of Education PhD fellowship from Turkey.

Hakan Ceylan, **Immihan Ceren Yasa** and **Metin Sitti** received the Science as Art Award of the Materials Research Society (MRS) in the Fall Meeting, Boston, USA.

2017

Donghoon Son and **Metin Sitti** were the Best Medical Robotics Award Finalist in the IEEE Robotics and Automation Conference for the research paper entitled, "Magnetically Actuated Soft Capsule Endoscope for Fine-Needle Aspiration Biopsy".

Byung-Wook Park joined Youngstown University as an assistant professor in USA.

Ahmet Fatih Tabak joined Bahcesehir University as an assistant professor in Turkey.

Massimo Mastrangeli joined Delft University of Technology as an assistant professor in Netherlands.

Hunter Bryant Gilbert joined Louisiana State University as an assistant professor in USA.

Yubing Guo, Yunus Alapan, and **Zoey Davidson** received the Humboldt postdoctoral fellowship.

Hamed Shahsavan received the NSERC from the National Sciences and Engineering Research Council of Canada.

Hakan Ceylan received the Masoumeh Ghaderi Best Talk Prize at the 5th annual workshop on Micro and Nanotechnologies for medicine: Emerging Frontiers and Applications in Boston, USA.

2016

Yunus Alapan and **Hunter Gilbert** received the Humboldt postdoctoral fellowship.

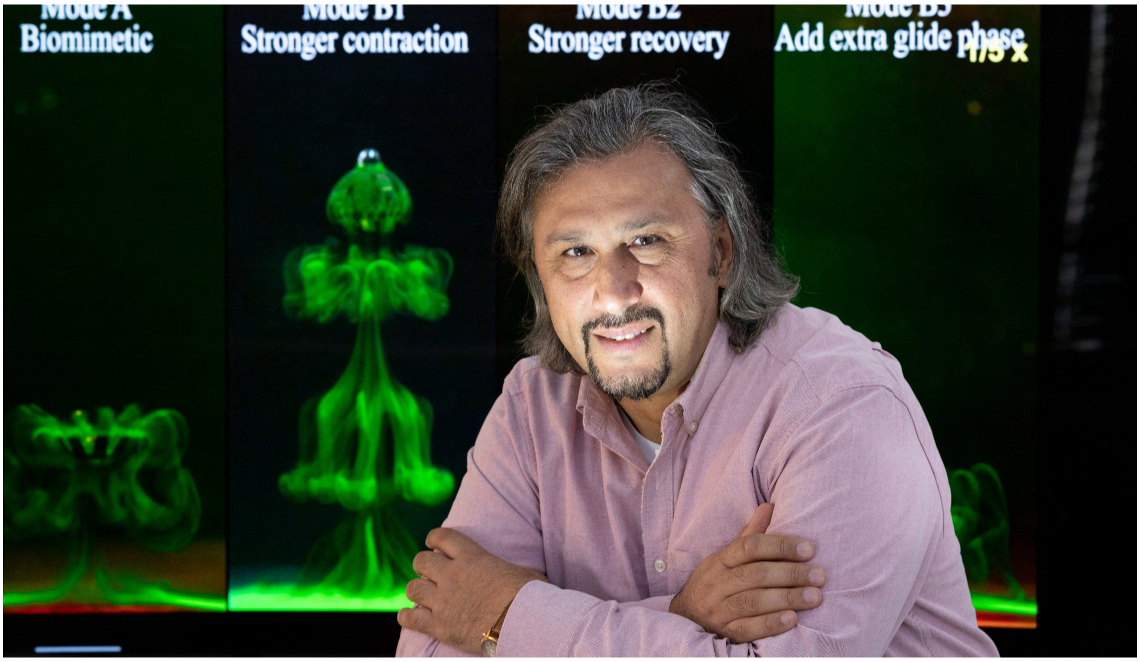
Alex Sprowitz joined Max Planck Institute for Intelligent Systems as an independent group leader in Stuttgart, Germany.

Zeinab Hosseini joined McMaster University as an assistant professor in Canada.

Kirstin Petersen joined Cornell University as an assistant professor in USA.

Wenqi Hu and **Hunter Gilbert** received the Humboldt postdoctoral fellowship.

5.6 Director profile: Metin Sitti



Biography

Prof. Dr. Metin Sitti is the director of the Physical Intelligence Department at the Max Planck Institute for Intelligent Systems in Stuttgart, Germany since 2014. He is also a professor at ETH Zurich and Koç University. He was a professor in the Department of Mechanical Engineering and Robotics Institute at Carnegie Mellon University in Pittsburgh, USA (2002-2014) and a research scientist at University of California at Berkeley, USA (1999-2002). During 2011-2012, he was a visiting professor at Harvard University, EPFL, and Sorbonne University. He received the BSc (1992) and MSc (1994) degrees in electrical and electronics engineering from Boğaziçi University, Turkey, and the PhD degree (1999) in electrical engineering from the University of Tokyo, Japan.

He has pioneered many research areas, including wireless miniature medical soft robots, gecko-inspired microfiber adhesives, bio-inspired miniature robots, and physical intelligence. He has published 2 books and over 480 peer-reviewed papers, over 320 of which have appeared in archival journals. These papers have been cited over 33,000 times in Google Scholar (h-index: 97). His group's research breakthroughs have been featured in the popular press, such as NY Times, Wall Street Journal, Le Monde, Economist, Der Spiegel, Forbes, Science, New Scientist, Science News, Nature News, and MIT Technology Review. He has given over 220 invited keynote, plenary or distinguished seminars in universities, conferences and industry. He has over 12 issued patents and over 16 pending patents. He founded a startup in USA in 2012 to commercialize his lab's gecko-inspired microfiber adhesive technology as a new disruptive adhesive material (branded as Setex®).

His group is one of the research partners of the Max Planck-Queensland Center the Materials Science of Extracellular Matrices, Max Plank–University of Toronto Centre for Neural Science and Technology, Max Planck-ETH Center for Learning Systems, European Centre for Living Technology, and Cyber Valley research consortium in the field of intelligent systems.

He has supervised and mentored over 67 (26 current) PhD students and 70 (18 current) postdoctoral researchers since 2002. Over 40 of his lab alumni became a faculty or group leader at Cornell, UMich, Mayo Clinic, UIUC, Vanderbilt, Tufts, Oregon State, Virginia Tech, WPI, ASU, LSU, Texas Tech (USA); Toronto, Waterloo, McMaster (Canada); ETH Zurich (Switzerland); MPI-IS, TUM (Germany); NTU (Singapore); Tampere (Finland); Bilkent, Hacettepe, Bogazici (Turkey); Sheffield, Heriot-Watt (UK); Delft, Wageningen (Netherlands); KIST, Hanyang, PNU, Korea (S. Korea); UMich-SJJI, CityU, Tongji, BIT (China); etc. Moreover, over 25 of his lab alumni are working in industry as senior researchers at Intuitive Surgical, Apple, Intel, Google, Novartis, BostonDynamics, Schlumberger, 3M, Proprio Vision, Arete Associates, nanoGriptech, etc.

Appointments

since 2021	Managing Director, Max Planck Institute for Intelligent Systems, Stuttgart
since 2020	Professor, Institute for Biomedical Engineering, ETH Zurich, Switzerland
since 2018	Professor, School of Medicine and College of Engineering, Koç University, Istanbul, Turkey
since 2017	Honorary Professor, SimTech, University of Stuttgart, Germany
since 2014	Director, Max Planck Institute for Intelligent Systems, Stuttgart, Germany
since 2015	Executive Board Member, Max Planck-ETH Center for Learning Systems (CLS)
(2017-2020)	Executive Board Member, International Max Planck Research School (IMPRS) on Intelligent Systems
(2019-2021)	Member, Perspectives Committee of the Max Planck Society
2015-2017	Managing Director, Max Planck Institute for Intelligent Systems
2002-2015	Professor, Department of Mechanical Engineering and Robotics Institute, Carnegie Mellon University, Pittsburgh, USA
1999-2002	Research Scientist, Department of Electrical Engineering and Computer Science, University of California, Berkeley, USA

Awards & Honours

- 15 journal articles of his group selected as the Highly Cited Papers in Web of Science (2021)
- Cozzarelli Prize Finalist in the Engineering and Applied Sciences category in the PNAS journal (2020)
- Breakthrough of the Year Award in the Engineering and Technology Category in Falling Walls World Science Summit (2020)
- Best Paper Award in the Robotics Science and Systems Conference (2019)
- ERC Advanced Grant (SoMMoR: Soft-bodied Miniature Mobile Robots) (2019)
- Rahmi Koç Science Prize (2018)
- Innovator of the Year Award in medical devices topic by the Design & Elektronik Magazine in Germany (2018)
- Best Medical Robotics Award Finalist in the IEEE Robotics and Automation Conference (2018)
- Best Medical Robotics Award Finalist in the IEEE Robotics and Automation Conference (2017)
- Best Poster Award in the Adhesion Conference (2014)
- IEEE/ASME Best Mechatronics Paper Award (2014)
- IEEE Fellow (2014)
- SPIE Nanoengineering Pioneer Award (2011)
- Best Paper Award in the IEEE/RSJ Intelligent Robots and Systems Conference (2009)
- Most Friendly Professor in Mechanical Engineering, selected by all seniors (2007)
- Distinguished Lecturer, IEEE Robotics and Automation Society (2006-2008)
- National Science Foundation CAREER Award (2005)
- Best Biomimetics Paper Award in the IEEE Robotics and Biomimetics Conference (2004)
- Best Video Award in the IEEE Robotics and Automation Conference (2002)
- Best Paper Award in the IEEE/RSJ Intelligent Robot Systems Conference (1998)
- Japanese Ministry of Education Fellowship during all PhD education (1996)

Organization & Community Service

- Vice Co-chair (2022) and Co-chair (2024) of Gordon Research Conference on Robotics
- Co-chair of International Conference on Manipulation, Automation and Robotics at Small Scales (MARRS) in 2018
- Co-chair of Workshop on Biomedical Applications of Micro/Nanotechnology in 2018
- Editor-in-Chief of Progress in Biomedical Engineering and Journal of Micro-Bio Robotics journals
- Associate Editor of Science Advances and Extreme Mechanics Letters journals

Memberships

- Fellow, IEEE
- Fellow, European Center for Living Technology
- Member, Turkish Academy of Sciences
- Member, Turkish American Scientists and Scholars Association (TASSA)

Startup Activity and Board Memberships

Founder and Board Chairman, nanoGriptech Inc., Pittsburgh, USA since 2012.
This start-up has commercialized his lab's gecko-inspired microfiber adhesive technology as a new disruptive adhesive material (branded as Setex®) for a wide range of industrial applications.

Keynote, Conference, and Public Talks

Keynote and plenary talks in conferences and workshops (selected)

- IEEE/RSJ International Conference on Intelligent Robots and Systems, 28 Sept. 2021
- International Embodied Intelligence Workshop, 24 March 2021
- Gordon Research Conference on Multifunctional Materials & Structures, 21 Jan. 2020.
- Gordon Research Conference on Robotics, USA, 17 Jan. 2020
- Summit on Oncology, Antalya, 16 Nov. 2019
- International Workshop on Active Matter for Soft Robotics, Brussels, 3 October 2019
- NSF Advanced Study Institute, Crete, 17 June 2019
- 4th Sino-German Symposium on Biomimetics, Bremen, 3 June 2019
- IEEE International Conference on Soft Robotics (RoboSoft), Seoul, 16 April 2019
- Adhesion Conference, USA, 18 Feb. 2019
- IEEE International Conference on Robotics and Biomimetics, Malaysia, 14 December 2018
- MRS Fall, Boston, 28 Nov. 2018
- Living Machines, Paris, 18 July 2018
- Karman Conference for 4D Printing, Cologne, 16 July 2018
- Hamlyn Symposium on Medical Robotics, London, 25 June 2018
- Reconfigurable Mechanisms Conference, Delft, 21 June 2018
- 1st BIGHEART Symposium, National University of Singapore, 19 June 2017

Distinguished seminars in universities and industry(selected)

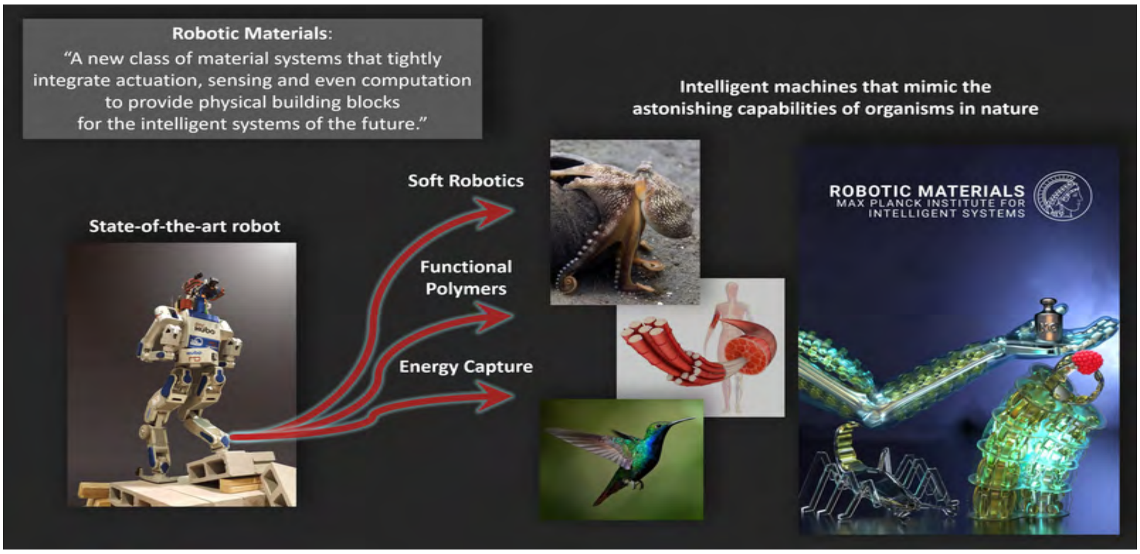
- ECLT Christmas Lecture, Venice, 20 December 2021
- Johns Hopkins University, 18 November 2021
- iCANX, 16 April 2021
- EMPA, Switzerland, 19 March 2021
- 3M, USA, 16 March 2021
- Sony Europa, Stuttgart, 22 Oct. 2020
- Edinburgh Robot Center, UK, 13 Oct. 2020
- Caltech, USA, 16 Jan. 2020
- Imperial College, Uk, 22 May 2019
- University of Leeds, UK, 13 March 2019
- University of Groningen, Netherlands, 6 Dec. 2018
- University of Toronto, 30 November 2018
- MIT, USA, 11 May 2018

Links

Link to CV on website: https://pi.is.mpg.de/~sitti

6 ROBOTIC MATERIALS

6.1 Research Overview



Robotic Materials:
"A new class of material systems that tightly integrate actuation, sensing and even computation to provide physical building blocks for the intelligent systems of the future."

Intelligent machines that mimic the astonishing capabilities of organisms in nature

Robots today rely on rigid components and electric motors based on metal and magnets, making them heavy, unsafe near humans, expensive, and ill-suited for unpredictable environments. Nature, in contrast, makes extensive use of soft materials, such as muscle and skin, and has produced organisms that drastically outperform robots in terms of agility, dexterity, and adaptability. The Robotic Materials Department aims to fundamentally challenge current limitations of robotic hardware, using an interdisciplinary approach that synergizes concepts from soft matter physics and chemistry with advanced engineering technologies to devise robotic materials that enable creation of intelligent machines that mimic the astonishing capabilities of organisms in nature. We pursue this goal in three main fields of research:

- **Soft Robotics.** One of our central goals is the development of new classes of actuators - a key component of all robotic systems - that replicate the sweeping success of biological muscle, a masterpiece of evolution featuring astonishing all-around actuation performance, the ability to self-heal after damage, and seamless integration with distributed sensing. Our fundamental research aims to allow practical applications for soft robotic systems that span from industrial automation, over medical and wearable robotics all the way to new types of human-machine interfaces.

- **Functional Polymers.** In this field of research, we develop new types of polymers with unusual combinations of properties, such as electrical conductivity paired with stretchability, transparency, biocompatibility and the ability to self-heal from mechanical and electrical damage - key features for future biologically inspired robotic systems.

- **Energy capture.** Our overall goal is the discovery of new energy capture principles that can provide power to remote or mobile intelligent systems, as well as - on larger scales - enable sustainable solutions for the use of waste heat from industrial processes or the use of untapped sources of renewable energy, such as ocean waves.

6.2 Research Fields

6.2.1 Energy Capture

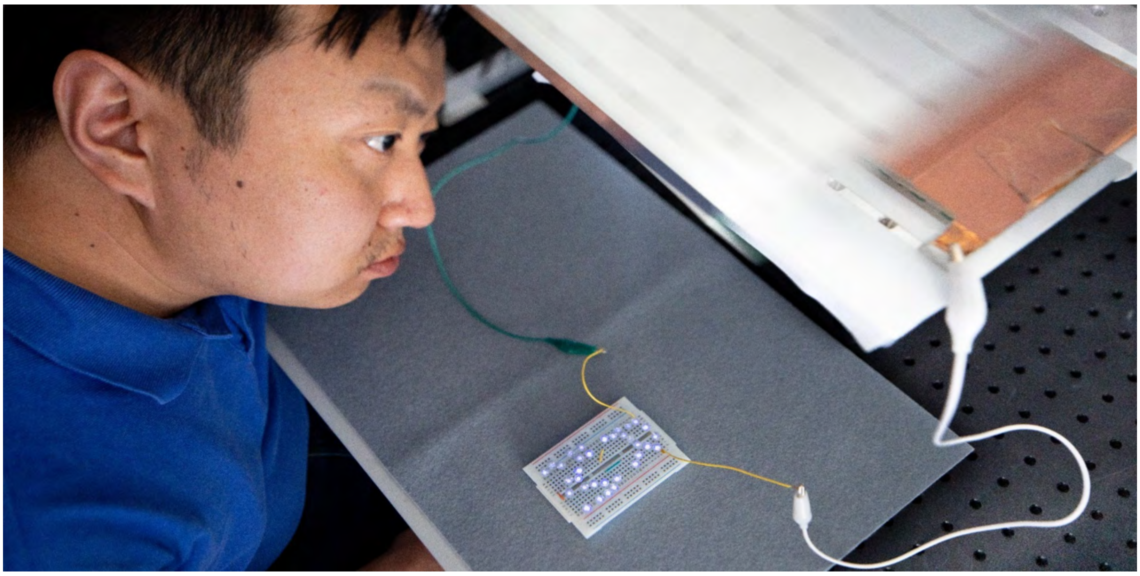


Figure 6.1: Dr. Steven Zhang demonstrating an electrostatics-based energy capture device that converts mechanical motion into electrical energy.

We are approaching an era of ubiquitous mobile intelligent systems, such as portable electronic devices, wearable or implanted biomedical devices, and autonomous robots - all these devices will depend on or benefit from energy capture systems that can harvest energy from ambient sources and convert it into electricity.

On a larger scale, due to climate change it is a global priority to economically and sustainably capture energy from currently unused, renewable sources. Not surprisingly, our perception of the sustainability of different methods of electrical energy generation typically places coal and wind power on opposite ends of the spectrum. At the same time, only few realize that almost every type of electricity generation today - from coal and nuclear, to renewables like hydro and wind - involves a traditional, electromagnetic generator in the final step converting mechanical to electrical energy. While electromagnetic generators excel under optimized conditions when a steady flow of fluid forces the generator to rotate rapidly, they are economically unviable for unused, extensive sources of renewable energy, such as ocean waves, where impedance mismatch necessitates complex power take-off systems, and where metallic components face rapid degradation in the harsh ocean environment.

Motivated by the evident need for effective and economical energy capture systems across different length scales, we aim to discover and to develop a deep understanding of fundamentally new principles to convert different forms of ambient energy, such as mechanical, thermal or chemical energy, into electrical energy that can power intelligent autonomous systems or enable sustainable and economical solutions for renewable energy.

More information: https://rm.is.mpg.de/field/energy-capture

6.2.2 Soft Robotics

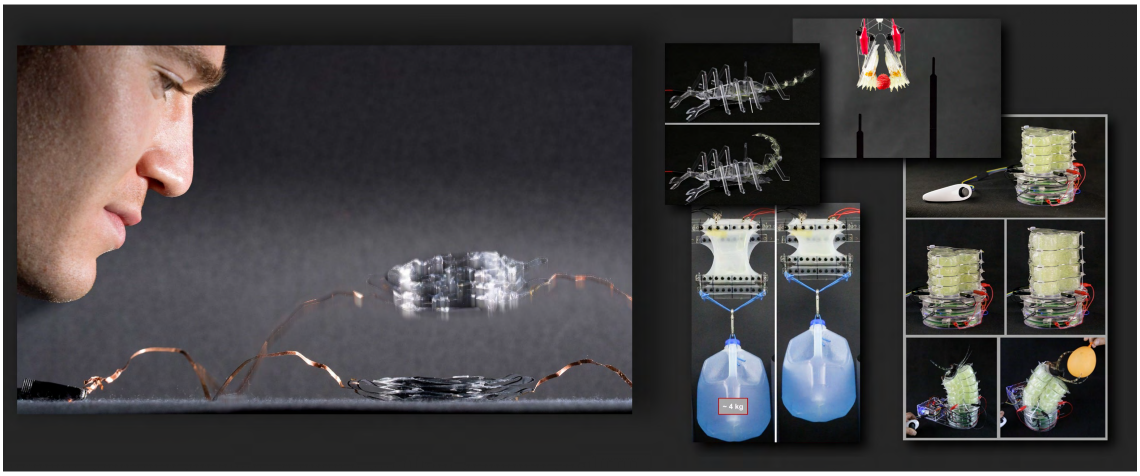


Figure 6.2: Zachary Yoder testing a high power-to-weight ratio stack of HASEL artificial muscles – a new platform technology pioneered by us.

Today's robotic systems excel at precise and repeatable tasks, and have become widespread in manufacturing and industrial environments. However, as demand grows for versatile and multi-functional robots, and as the physical distance between humans and robots continues to diminish, the rigid links and electric motors that make up these traditional robotic systems are becoming a limiting factor. The sensors and controls required to make them safer to operate around humans are complex, expensive, and error-prone, and their non-adaptable nature reduces their effectiveness in unpredictable environments.

Yet nature provides countless examples of organisms that can easily carry out tasks considered highly challenging for today's robots, such as manipulating a variety of objects or traversing varying terrain. These organisms are driven by soft muscles and surrounded by conformal, sensor-rich skin - a far cry from the electric motors and rigid links that make up traditional robotic systems. Biological muscle in particular is a masterpiece of evolution, as it powers the ultra-versatile arms of an octopus, is strong enough to move an elephant and fast enough for the wings of a hummingbird, self-heals after damage, and is seamlessly integrated with distributed sensing. Not surprisingly, these astonishing capabilities have inspired the creation of artificial muscles, which has been considered a grand challenge of science and engineering for centuries, dating back to the 1600's when Robert Hooke first recorded the idea, all the way to very recent papers appearing frequently in top journals.

Consequently, one of our central goals in this main field of research is the development of new classes of actuators - key components of all robotic systems - that replicate the sweeping success of biological muscle and that transform our ability to design robotic systems for entirely new fields of application. Our current research focus is to understand the fundamental principles and mechanisms, as well as robotics applications of a new class of self-sensing, high-performance artificial muscles, termed hydraulically amplified self-healing electrostatic (HASEL) actuators, a platform technology pioneered by us. HASEL artificial muscles feature high speed and efficiency as well as the capability to self-heal from electrical damage, and they harness a new electrohydraulic mechanism, where electrostatic Maxwell stress activates soft, hydraulic structures to achieve a wide variety of actuation modes. HASEL actuators show promise to become the first technology where all performance metrics and capabilities match or exceed those of biological muscle, thus being a prime candidate to solve a centuries-old grand challenge. Further, modeling results lay out a roadmap showing how to drastically improve performance of HASEL actuators, surpassing both biological muscle and traditional electromagnetic motors. With rich underlying physics and chemistry to be further explored, the HASEL technology is poised to create a vibrant new field of research that promises a variety of practical applications that will improve human quality of life.

Overall, in a broader and longer-term context, our research in this main field is driven by projects that simultaneously aim to solve practical problems in robotics and to answer the following fundamental research questions:

- What are the fundamental physical limits of electrical (or chemical/thermal/etc.) to mechanical energy conversion in robotic actuation systems? How close can specific actuation principles based on specific materials system get to those fundamental limits?
- Can we match or exceed performance of biological muscle with new actuation technologies to allow revolutionary new designs of bio-inspired intelligent systems across different length-scales?
- Which physical principles and mechanisms for transducers are versatile enough to be used in highly adaptable soft robotic systems, and which ones can mimic survival features such as self-healing and tight integration with sensing, as seen in biology?
- Can we exceed performance of traditional electromagnetic servo motors with new actuation technologies based on entirely new principles?
- Which physical principles and mechanisms for actuators allow the highest possible values for power/weight (or volume), energy/weight (or volume), energy efficiency and bandwidth of actuation?
- For specific actuation principles, can we push the underlying materials systems far beyond currently identified limits and maxima?
- What controls or machine learning methods will allow the creation of autonomous, bioinspired intelligent systems built from robotic materials, that can achieve levels of dexterity, agility and adaptability currently only seen in natural organisms?

More information: https://rm.is.mpg.de/field/bioinspired-soft-actuators-sensors-robots-and-machines

6.2.3 Functional Polymers

Figure 6.3: Dr. Alona Shagan explaining the materials properties and synthesis of PVDF-based terpolymers.

Human and animal bodies employ highly-functional, soft-matter-based biological architectures, such as skin, muscle and tendons, and drastically outperform today's robots in terms of agility and adaptability. Beyond these individual components of the body, it is particularly impressive to observe, how nature has managed to create extremely effective and reliable interfaces between different components with vastly different properties, such as bones and tendons. Intelligent machines of the future that match or even exceed the astonishing capabilities of natural organisms, will need to similarly be built from functional soft materials that combine multiple desirable materials capabilities, that autonomously adapt to environmental changes and that can repair themselves after damage.

From a technological point of view, future human-machine interfaces will need new classes of functional materials that can, for example, provide localized haptic feedback on touchscreens, requiring these materials systems to be transparent, conductive and stimuli-responsive, or that can reliably interface the human brain with electronic devices, requiring bioelectronic interfaces that provide effective and safe long-term connections with nervous tissue.

A further aspect of our research in this field is the sustainability of components used to build intelligent systems, which we aim to realize by developing biodegradable robotic materials – growing electronics and plastic waste pose environmental and health concerns, and we believe that it will become increasingly important to develop sustainable robotic materials that can be decomposed by bacteria or other living organisms after use thereby avoiding pollution.

Building upon a period of rapid progress in the synthesis and simulation of functional soft materials and in the design and fabrication of complex responsive structures, our department and its collaborators are aiming to devise new types of functional polymers with unusual combinations of properties, such as electrical conductivity paired with stretchability, transparency, biocompatibility, biodegradability, and the ability to self-heal from mechanical and electrical damage.

More information: https://rm.is.mpg.de/field/functional-polymers

6.3 Selected Research Projects

Liquid Crystal Elastomers with Enhanced Directional Actuation to Electric Fields

Philipp Rothemund, Christoph Keplinger, Hayden E. Fowler, Timothy J. White

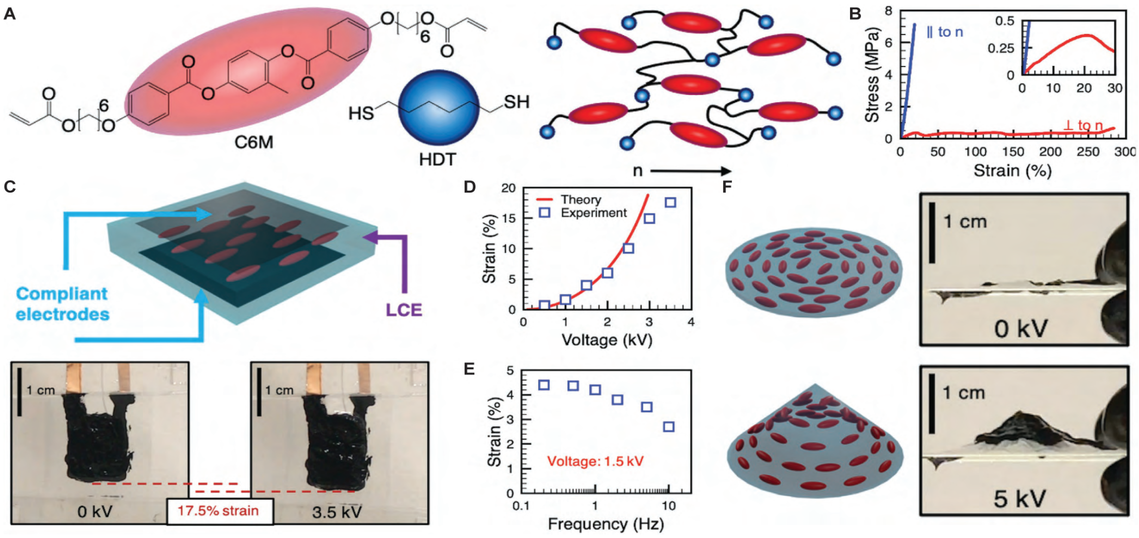


Figure 6.4: Liquid crystal elastomer (LCE) actuators. (A) Chemical structure of the LCE (B) Stress-strain curves of the LCE parallel and perpendicular to the liquid crystals (C) Upon application of voltage between the electrodes, a Maxwell stress elongates the LCE perpendicular to the liquid crystals. (D) Strain-voltage and (E) strain-frequency curves of a uniaxial LCE actuator. (F) Circular alignment of the liquid crystals leads to out-of-plane deformation.

Dielectric elastomer actuators are a class of soft actuators, which consist of compliant, elastomeric membranes and are coated on both sides with compliant electrodes. When a voltage is applied between the electrodes, a Maxwell stress arises, which leads to a reduction in thickness and an in-plane expansion of the membrane. The in-plane expansion is equal in all directions due to the isotropy of the material. To achieve directional actuation, dielectric elastomer actuators are therefore typically prestretched laterally and attached to rigid frames.

In this project [1172], we developed a liquid crystal elastomer for dielectric elastomer actuators with directional actuation. The material was synthesized by crosslinking the monomer 1,6-hexanedithiol with the liquid crystalline monomer 1,4-bis-[4-(6-acryloyloxy-hexyloxy)benzoyloxy]-2-methylbenzene. Parallel alignment of the liquid crystals leads to a stiffness ratio of 14:1 between the directions parallel and perpendicular to the alignment direction. In a dielectric elastomer actuator, this large anisotropy in stiffness, leads to uniaxial actuation without the need for a prestretch or a rigid frame.

With actuation strains of 20% at 6 kV, strain rates of 18%/s, and demonstrated actuation frequencies up to 10 Hz, the liquid crystal elastomer exhibited substantially improved electromechanical performance compared to previously reported dielectric elastomer actuators based on liquid crystals.

The alignment of liquid crystals can be patterned across the elastomer to achieve different types of deformation. Circular alignment of the liquid crystals leads to an out-of-plane deformation of the initially flat membrane into a cone. We demonstrated an array of three individually addressable out-of-plane actuators on a single membrane.

This work demonstrated the potential for liquid crystal elastomers in dielectric elastomer actuators that feature complex, programable three-dimensional deformation.

More information: https://rm.is.mpg.de/project/LCDEA

Electromechanics of planar HASEL actuators

Sophie Kirkman, Philipp Rothemund, Christoph Keplinger, Eric Acome

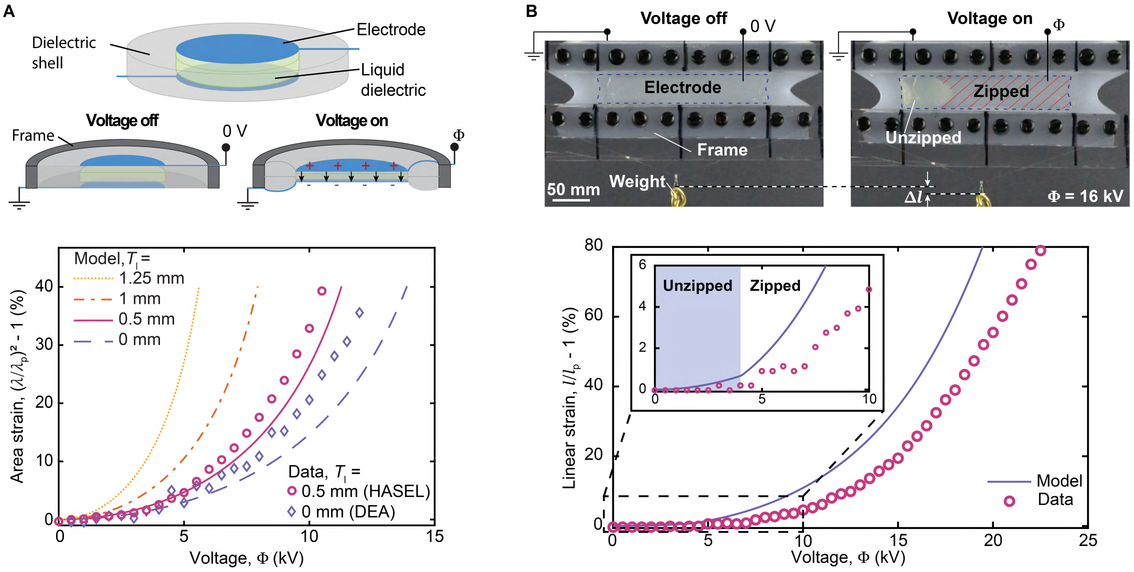


Figure 6.5: Electromechanics of planar HASEL actuators. A. The circular planar HASEL consists of a circular shell, which is filled with a liquid dielectric and covered on both sides with compliant electrodes. Upon application of a voltage, the electrode-covered region expands radially in-plane. B In the linear planar HASEL actuator, the shell has a rectangular shape. When a voltage is applied to this actuator it elongates linearly due to a combination of stretching and zipping of the shell.

Planar HASEL (hydraulically amplified self-healing electrostatic) actuators are stretchable, soft artificial muscles, with self-healing properties and muscle-like performance[1]. They have, with 70 J/kg, greater specific energies than natural muscle, and have achieved specific powers of 614 W/kg and linear strains of 124%. While planar HASEL actuators had demonstrated strong performance in experiments, the details of the underlying electromechanics had not yet been explored.

Planar HASEL actuators comprise a stretchable dielectric shell that is coated with compliant electrodes and filled with a liquid dielectric. Upon electrical activation, they expand in-plane. In experiments, two mechanisms of deformation are observed: elastic stretching of the shell and electrohydraulic "zipping", where the electrodes progressively come together. This project [1174] analyzed these mechanisms using two examples: a circular planar HASEL actuator that stretches equibiaxially, and a linear actuator that both stretches and zips.

To understand the quasistatic actuation behavior of planar HASELs, we used an energy minimization approach to derive a nonlinear electromechanical model for each geometry. For the circular HASEL actuator, we did a parametric study to elucidate the effect of the liquid layer. This analysis shows that the actuation behavior is similar to that of dielectric elastomer actuators (DEAs), and reveals how the added liquid layer in planar HASELs reduces their stiffness, allowing them to achieve greater strains than DEAs of the same dimensions. For the linear actuator, the model displays how the actuator only stretches until it reaches a critical voltage at which it starts to zip, drastically increasing strain. The derived models show good quantitative agreement with measured data. This work lays the foundation for the theoretical analysis of planar HASEL actuators, which consist of stretchable materials.

More information: https://rm.is.mpg.de/project/planar-electromechanics

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[1] E. Acome, S. K. Mitchell, T. Morrissey, M. Emmett, C. Benjamin, et al. Hydraulically amplified self-healing electrostatic actuators with muscle-like performance. *Science* **359** (6371): 61–65, 2018.

Spider-Inspired Electrohydraulic Actuators for Fast, Soft-Actuated Joints

Philipp Rothemund, Christoph Keplinger, Nicholas Kellaris, Yi Zheng, Shane K Mitchell, Garret M Smith, Kaushik Jayaram

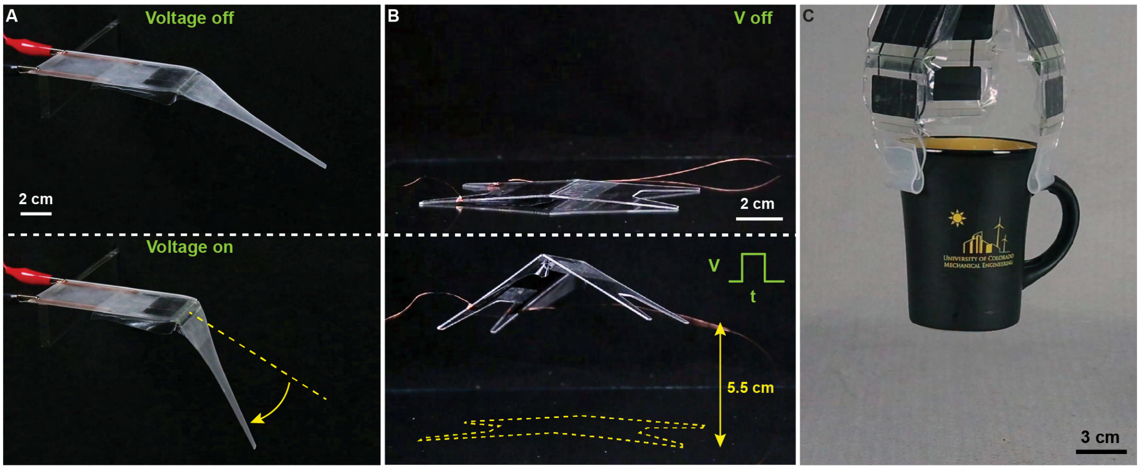

Figure 6.6: Spider-inspired electrohydraulic soft-actuated (SES) joints. (A) SES joints are rotational joints in which an electrohydraulic zipping mechanism generates rotation. (B) SES joints are powerful enough to make a robot jump ten times its height. (C) A gripper consisting of SES joints.

Unlike most animals, who rely on antagonistic pairs of muscles to move their joints, spiders use a hydraulic mechanism to extend their joints and they use muscles only for flexion. This lightweight hydraulic mechanism allows spiders to perform precise and coordinated, but also fast and powerful, motion. Developing robots that match the capabilities of spider joints remains a challenge to date.

Inspired by the hydraulic architecture of spider joints and based on the HASEL technology[2], we have developed low-profile, lightweight actuators for joints in articulated robots [1175]. Such a spider-inspired electrohydraulic soft-actuated (SES) joint is formed by attaching a thin-film shell, which is covered on both sides with compliant electrodes and filled with a liquid dielectric, to a robot joint. When a voltage is applied between electrodes, the resulting electric field causes the shell to zip together displacing the liquid dielectric. The resulting deformation of the shell flexes the joint.

We demonstrated SES joints with actuation angles up to 70º, blocking torques up to 70 mN·m, and specific torques up to 21 N·m/kg. The roll-off frequencies of these joints were as high as 24 Hz, and their specific powers reached 230 W/kg. Additionally, we derived a theoretical model for SES joints, which rationalizes these results and shows how their output performance can be further improved. Because of their electrohydraulic working principle, SES joints are backdrivable, and they exhibit a catch state, which drastically reduces their energy consumption compared with servo motors when holding a position under load.

SES joints can readily be integrated into articulated robots. We designed a low-profile robot that jumped ten times its height exploiting the high peak output power of SES joints. Multiple, individually addressable SES joints can be combined to design limbs with multiple controllable degrees of freedom. We used SES joints to construct a three-fingered gripper, which was able to grasp objects of various sizes and weights.

Their light weight and low profile together with their well-rounded performance make SES joints ideal building blocks for future mobile robotic systems with high outptut forces, high speed operation, and low power consumption

More information: https://rm.is.mpg.de/project/ses-joints

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[2] E. Acome, S. K. Mitchell, T. Morrissey, M. Emmett, C. Benjamin, et al. Hydraulically amplified self-healing electrostatic actuators with muscle-like performance. *Science* **359** (6371): 61–65, 2018.

6.4 Equipment

The Robotic Materials Department pursues highly interdisciplinary and predominantly experimental research at the intersection of materials science and robotics, with a current focus on soft robotics, functional polymers, and energy capture. To stimulate scientific excellence across all our projects, we have made and will continue to make substantial investments in our scientific equipment. We select every new piece of equipment balancing cost with both immediate impact on current research projects and the potential for longer-term usage beyond our current portfolio of projects.

Characterization of electromechanical trans-ducers (sensors, actuators, generators)

We own a large number of low and high voltage electrical power sources and amplifiers (including 3x TREK Model 610E amplifiers, 1x Matsusada AMPS-10B40, 1x Trek 50/12A), which allow us to excite transducers with voltages up to±50 kV and frequencies up to 40 kHz, Figure (6.7). For contactless measurement of high voltages (i.e., without influencing the system), we host three electrostatic voltmeters (TREK Model 341B, Figure 6.7) that can measure voltages of up to ±20 kV.

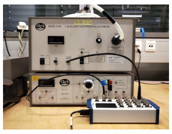


Figure 6.7: High-voltage power amplifier (bottom) and high voltage electrostatic voltmeter (top) for evaluation of electrostatic transducers.

To measure the force-output of our transducers and to excite them mechanically, we use three dual mode muscle lever systems (Model 310C-LR, Aurora scientific, Figure 6.8), which were originally designed to test the properties of animal muscles. These devices can supply forces up to 100 N and strokes up to 40 mm, at a frequency of up to 90 Hz.

Figure 6.8: Dual-mode muscle tester used for characterization of an electrohydraulic artificial muscle.

For the characterization at large strokes (up to 300 mm), we use two linear motors (DM01-37x120F-HP-R95_MS02 and DM01-37x120F-HP-R295, LinMot), which can generate forces up to 255 N (Figure 6.9). We further own three Keyence laser displacement sensors (LK-H157), which can measure the time-dependent displacement of our transducers at ultrahigh sampling rates of 390 kHz and resolution $\leq$20 µm.

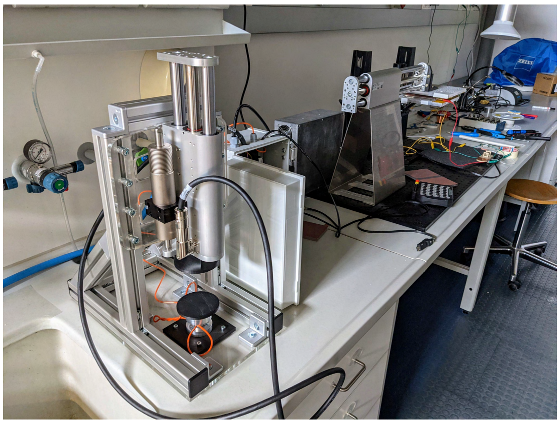


Figure 6.9: Custom-designed linear motors to characterize transducers.

Characterization of mechanical and electrical properties of materials systems.

For mechanical characterization, we own a universal testing machine (Figure X.4, Zwick-Roell Z010 TE All-Round-Line), which performs tensile and compressive tests on both stiff and stretchable materials. The frame allows testing of samples at forces of up to 10 kN. For soft, very stretchable materials such as hydrogels, the machine exhibits an extra-large maximum crosshead travel of 1.8m. The attached optical displacement sensor enables the contactless measurement (i.e., without influencing the sample) of large deformations up to 1 m, at an accuracy of ±1.5 μm. We also own a dynamic mechanical analyzer (Figure 6.10, DMA) (TA INSTRUMENT DISCOVERY DMA 850), which characterizes the time-dependent and temperature-dependent mechanical properties of materials. Our DMA can deliver continuous forces from 0.1 mN to 18 N and a maximum stroke of 10 mm, with a maximum frequency of 200 Hz. The built-in heating and cooling systems allow characterization at temperatures ranging from –160 °C to 600 °C.

Figure 6.10: Universal testing machine (left), with an attached optical displacement sensor and dynamic mechanical analyzer on an anti-shake table (right).

The dielectric properties of polymer films and dielectric fluids determine the performance and the electromechanical conversion efficiency of electrostatic transducers. Our dielectric spectrometer (Figure 6.11, Novocontrol Technologies Alpha-A High Resolution Dielectric-Impedance Gain Phase Analyzer) measures the voltage and frequency-dependent dielectric properties of both solids and liquids. At low voltages (up to 3 V_{rms}) the device measures the dielectric properties in a very wide range, from 3 μHz to 40 MHz. At high electric fields, the dielectric properties of materials can exhibit nonlinearities in their dielectric behavior. To study these nonlinearities, we also purchased a high-voltage interface, which measures dielectric properties in the frequency range of from 3 μHz to 10 kHz at voltages up to 1.4 kV_{rms}. The temperature of the sample can be controlled within the range of –160°C and 400°C to study the temperature dependence of the dielectric properties of a material.

The dielectric strength of polymer films and dielectric fluids limits their performance. We host a Matsusada high voltage supply unit that delivers a maximum voltage of ±120 kV (Matsusada AU series) for dielectric breakdown tests.

Figure 6.11: Dielectric spectrometer with high voltage controller, alpha-A phase analyzer, and liquid nitrogen tank.

Infrared and high-speed imaging.

A thermal imaging camera (VarioCam HD, InfraTec, Figure 6.12) serves as a tool to monitor temperatures, energy dissipation mechanisms, and flow of heat in transducers during operation (e.g., heat generated due to electrical dissipation, generation of plasma due to high electric fields) at rates of up to 240 fps. The information from the camera allows us to identify and eliminate weaknesses and bottlenecks in our transducer designs in order to improve their performance and reliability.

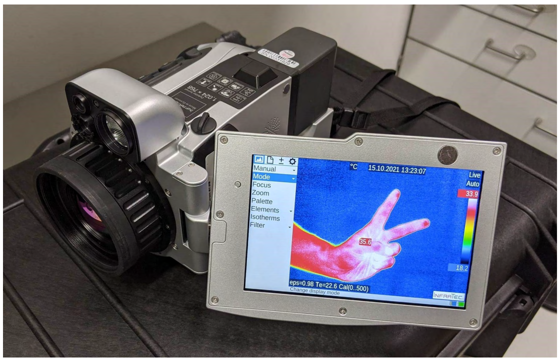


Figure 6.12: Infrared camera creating a temperature map of a human hand.

To capture ultra-fast processes and to measure quantitative performance metrics of transducers, such as bandwidth, actuation speed, or strain rates, we own two Phantom v2640 high speed cameras (Figure 6.13). The cameras record video at rates of 6600 fps (frames per second) at an image resolution of 2048 x 1920 and at up to 300,000 fps at reduced resolution. The camera is equipped with a fast shutter (142 ns) that allows us to capture ultrashort physical processes such as dielectric breakdown without motion blur.

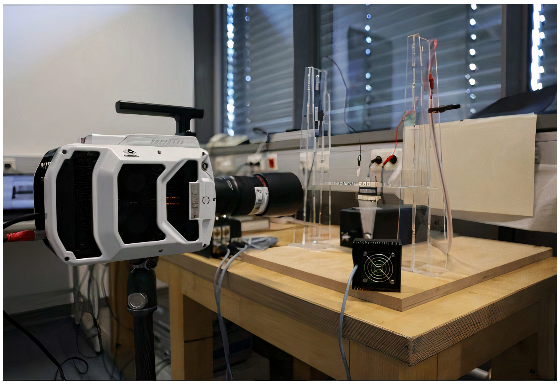


Figure 6.13: Setup of Phantom v2640 high-speed camera for high-speed video capture of an artificial muscle.

We use two Canon EOS R5 mirrorless digital cameras with a set of all-round and macro lenses, which allow us to record high resolution videos and photos.

Synthesis of functional polymers, fabrication of robotic materials.

We synthesize custom materials and new types of polymeric systems with properties such as self-healing. For the synthesis steps we have three laboratories equipped with chemical hoods and gas lines. We have micro-balances, a rotary evaporator (Heidolph, High-Vap Expert, Ultimate control) for the evaporation of solvents after a chemical reaction, and a high-speed vacuum planetary mixer (Thinky ARV-310) to mix solutions while simultaneously removing microbubbles, and vacuum ovens (Figure 6.14) to cure and anneal materials.

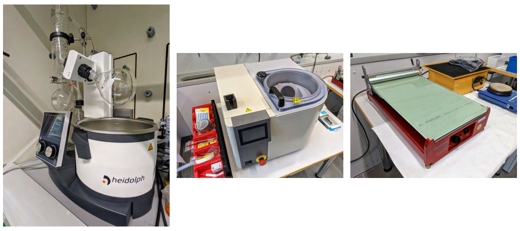


Figure 6.14: Equipment for synthesis and fabrication of functional polymers. (Left to right) Rotary evaporator, planetary mixer and thin film applicator.

Further, we own a wide range of equipment that allows the rapid prototyping of high-performance transducers using commercial and custom-made materials. With a heatable, thin-film applicator (Zehtner ZAA 2300H, Figure 6.14) we can fabricate homogeneous elastomeric and thermoplastic films with thicknesses that range from 10 µm to several millimeters. We built a custom CnC heat-sealer that bonds thermoplastic materials to each other. We also host a tabletop printing machine (Challenger 173, nsm Norbert Schlaefli) that allows the accurate (<100 µm positional accuracy), semiautomated deposition of conductive and dielectric layers using flexographic printing onto thin-film substrates. These machines serve as test-beds for the planned purchase of a roll-to-roll system for the precision fabrication of high-performance transducers based on a variety of materials systems.

Mobile robot arm platform.

We own a combination of a Franka Emika Panda robot arm and a Clearpath Ridgeback automated mobile platform, which together allow automated locomotion, manipulation, sensing, and planning functions in one robotic system. This system provides a platform for testing and demonstrating prototypes of new types of transducers in a state-of-art commercially available robotic system. For example, we can integrate in-house developed soft robotic grippers and biomimetic hands with the robot arm to show versatile manipulation of delicate objects. The robot arm not only allows us to gain scientific insights, but will also allow us to showcase our results to visitors.

Computing resources.

The department owns several high-performance computers and laptops that are specialized for complex numerical simulations of soft transducers. Computing resources are also used to process and analyze high resolution and high-speed videos.

6.5 Director profile: Christoph Keplinger

Biography

Christoph Keplinger is a director at the Max Planck Institute for Intelligent Systems (MPI-IS) in Stuttgart, Germany, where he heads the Robotic Materials Department. Additionally, he is an Eminent Visiting Professor of Soft Robotics at the University of Colorado Boulder, USA. Before joining the Max Planck Society in 2020, he was an Assistant Professor of Mechanical Engineering and a Fellow of the Materials Science and Engineering Program at the University of Colorado Boulder, where he also held an endowed appointment serving as Mollenkopf Faculty Fellow.

Building upon his background in soft matter physics (Ph.D., 2011, Johannes Kepler University Linz, Austria), mechanics and chemistry (Postdoc, Harvard University, USA), he leads a highly interdisciplinary research group at MPI-IS, with a current focus on (I) soft robotics, (II) energy capture and (III) functional polymers. His work has been published in top journals including Science, Science Robotics, PNAS, Advanced Materials and Nature Chemistry, as well as highlighted in popular outlets such as National Geographic and on TED.com. He has received prestigious awards including a 2017 Packard Fellowship for Science and Engineering, a 2021 Alexander von Humboldt Professorship (declined), and the 2013 EAPromising European Researcher Award from the European Scientific Network for Artificial Muscles. He is the principal inventor of HASEL artificial muscles, a new technology that will help enable a new generation of lifelike robotic hardware; in 2018 he co-founded Artimus Robotics to commercialize the HASEL technology, and has served as Chief Science Officer (CSO) of Artimus since its founding.

Current Appointments

08/2020 – present	Director, Max Planck Institute for Intelligent Systems
08/2020 – present	Eminent Visiting Professor of Soft Robotics, Department of Mechanical Engineering & Materials Science, University of Colorado Boulder

Awards & Honours

2020	Alexander von Humboldt Professorship (declined)
2019	Young Scientist Award, International Conference on Active Materials and Soft Mechatronics
2019	Talk featured on TED.com: “The artificial muscles that will power robots of the future”
2019	Featured in “Ten robotics technologies of the year”, selected by editors of *Science Robotics*
2018	Mollenkopf Faculty Fellowship, endowed position at the University of Colorado Boulder
2018	EAP-in-Action Best Demonstration Award, SPIE Smart Structures (EAPAD) conference
2017	2017 Packard Fellowship for Science and Engineering
2013	EAPromising European Researcher Award, European Scientific Network for Artificial Muscles
2012	Loschmidt Award, Chemical-Physical Society of Austria
2011	Award of Excellence, Austrian Federal Ministry for Science and Research

Organization & Community Service

2020 – present	Program Committee, SPIE Smart Structures (EAPAD) conference
2020 – present	Program Committee, ACTUATOR conference
2010 – present	Regular reviewer of grant proposals and peer reviewer for extensive list of leading journals including Nature, Nature Materials, Science, Science Robotics, etc.

Memberships

- Materials Research Society
- European Society for Electromechanically Active Polymer Transducers & Artificial Muscles
- SPIE international society for optics and photonics
- International Max Planck Research School for Intelligent Systems (IMPRS-IS)
- Max Planck ETH Center for Learning Systems (CLS)

Startup Activity and Board Memberships

Artimus Robotics Inc., Boulder, USA: Co-founder and Chief Science Officer (CSO), 2018 – present

Keynote, Conference, and Public Talks

- Invited Seminar, MaP Distinguished Lecture Series on Soft Robotics, ETH Zürich, Switzerland, 2021
- Invited Talk, IUTAM Symposium on Mechanics of Smart and Tough Gels, Austin, USA, 2021
- Invited Talk, RoboSoft 2021 - IEEE Int. Conference on Soft Robotics, New Haven, USA, 2021
- Invited talk & Live Keynote, MRS Fall Meeting, Boston, USA, 2020
- Invited Seminar, University of Rochester – Physics Colloquium, Rochester, USA, 2020
- Keynote Lecture, Int. Conference on Active Materials and Soft Mechatronics, Incheon, Korea, 2019
- Invited Talk, The Hamlyn Symposium on Medical Robotics, London, UK, 2019
- Invited Talk, EuroEAP 2019, Dresden, Germany, 2019
- Invited Seminar, Distinguished Lecture Series, EPFL School of Engineering, Lausanne, Switzerland, 2019
- Invited Seminar, Northwestern University - Physics Department Colloquium, Evanston, USA, 2019
- Invited Seminar, MIT Robotics Seminar, Boston, USA, 2018

Links

Link to CV on website: https://rm.is.mpg.de/~ck

7 AUTONOMOUS LEARNING

7.1 Research Overview

Already now robots are present in many areas, taking over tasks that are too dangerous, too repetitive, or require too high precision for humans. So far, however, robots used in practice are preprogrammed, i.e. use fixed and engineered control strategies. Since our world is complex and constantly changing, preprogrammed robots are limited to well-controlled situations. In mammals, innate information, which corresponds to the preprogrammed part in robots, is complemented substantially by learning and self-organization. Motivated by this, our research vision is to create autonomously learning and developing robotic agents to design versatile assistants for humans.

To fulfill this vision, we have to tackle an extensive range of open challenges. We believe that improvements at the fundamental level in learning theory and learning methods have the potential to solve many of our challenges. Paired with the increasing availability of data in the robotic domain, learning methods are becoming competitive with purely engineered solutions and will surpass them.

Taking inspiration from self-organization in nature that is evidently involved in building large and fault-tolerant systems from local interactions, our research investigates the theoretical basis for self-organized robot control using dynamical systems theory and information theory. Our improvements allow for efficient self-exploration of the sensorimotor capabilities [1217] and the extraction and recombination of behavioral primitives [1189].

To make robots able to quickly learn new skills, they have to extract as much information as possible from experience. Learning a model of its body and the environment can capture the information needed to master unknown future tasks. We investigate model learning [1214],[24] and suitable optimization and planning methods [1204] and their integration in reinforcement learning algorithms [1197, 1201]. This is a promising route for data-efficient learning on real robotic systems.

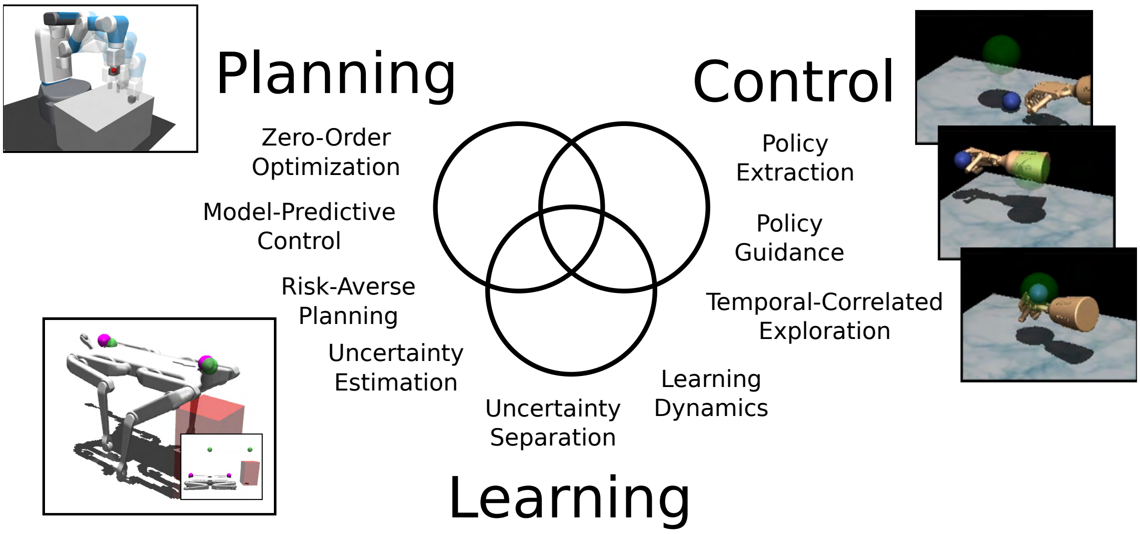
For autonomously learning agents, it is also important to set their own goals for improving their skills, such that a designer does not need to specify all details of the learning curriculum. In [1209] we propose a framework and a practical implementation of an intrinsically motivated hierarchical learner that attempts to gain control of its environment as fast as possible. Another important insight is that the knowledge of the causal influence of a robot on its environment can greatly accelerate learning. Our first contribution in this direction proposes a tractable quantity to autonomously identify the situation-dependent causal influence [271]. When learning from raw camera input in an unsupervised way, suitable representations have to be learned. In this context we study object-centric representations and suitable unsupervised reinforcement learning methods [1196, 1202]. Because unsupervised representation learning is generally very important for autonomously learning agents, we investigate commonly used algorithms from a theoretical perspective [1200, 1210].

A parallel strand of our research is on enhancing the capabilities of machine learning models for model learning and reasoning. We develop methods that attempt to identify the underlying relationships in data via concise symbolic or algebraic expressions [1214]. These methods are not only useful for autonomous agents but also enabe solving problems in the natural sciences. We investigate several exciting topics in physics with our collaborators [1181, 1188]. To enhance the reasoning capabilities of deep networks, we have been the first to propose a general and efficient method to embed combinatorial solvers as building blocks into neural networks [1207]. This new method has enabled us to improve the state of the art in several computer vision problems [1205, 1206] and generalization in reinforcement learning [1199].

To enable successful learning, robots need physical capabilities to percieve their surrounding. We contribute by designing new haptic sensors that are powered by machine learning [1190, 1215].

Model-based Reinforcement Learning and Planning

Cristina Pinneri, Sebastian Blaes, Marin Vlastelica Pogancic, Georg Martius



The goal of this project is to bring efficient learning-based control methods to real robots. A promising direction to learning from a few trials is to learn the transition dynamics in order to generate desired behavior. We train a deep network to model the interactions of the robot with the environment and then use model-based reinforcement learning or planning for control. In a first work, we have explored the use of our equation learning framework for the forward model and obtained unparalleled performance on a cart-pendulum system [1214]. However, we found that it does not scale yet to relevant robotic systems.

A widely used method in model-based reinforcement learning is the Cross-Entropy Method (CEM), which is a zero-order optimization scheme to compute good action sequences. In [1204] we have improved this method by replacing the uncorrelated sampling of actions with a temporal-correlated-based sampling (colored noise). As a result, we were able to reduce the computational cost of CEM by an order of magnitude while often yielding a significant performance increase in a variety of challenging robotic tasks (see figure).

Even with our improvements, it is still challenging to run such a planning method in real-time on a robot with a high update frequency. Thus, we set out to extract neural network policies from the data generated by a planning algorithm. A challenging task, as it turns out since naive policy learning methods fail to learn from such a stochastic planning algorithm. We have proposed an adaptive guided policy search method [1201] that is able to distill strong policies for challenging simulated robotics tasks.

The next step for running these algorithms on a real robot is to make them risk-aware. We extend the learned dynamics models with the ability to estimate their prediction uncertainty. In fact, we make them distinguish between uncertainty due to lack of data and inherent unpredictability (noise). We demonstrate on several continuous control tasks how to obtain active learning and risk-averse planning to avoid dangerous situations [1197]. This is an important step towards safe model-based reinforcement learning on real hardware.

More information: https://al.is.mpg.de/project/model-based-reinforcement-learning-and-planning

Intrinsically Motivated Hierarchical Learner

Sebastian Blaes, Marin Vlastelica Pogancic, Jia-Jie Zhu, Georg Martius

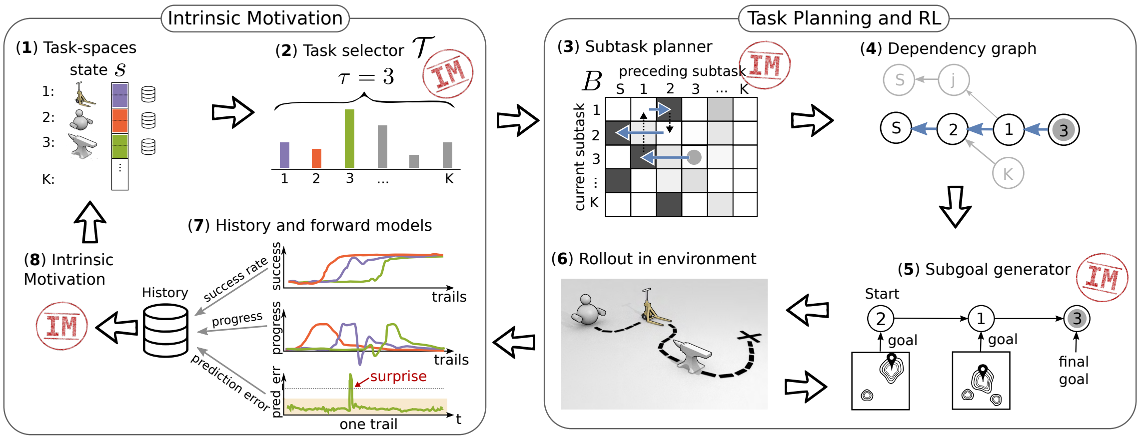


Figure 7.1: Overview of the CWYC method. All components except (1) are learned. The left part shows how intrinsic motivation is used to distribute learning resources among self-imposed tasks. Most resources are used where the agent can make progress. The right part depicts the planning pipeline used for actually executing a task in the environment.

True autonomy in the real world is not bound to a single task under fixed environmental dynamics. In fact, tasks are hardly ever clearly specified, e.g. through well-shaped rewards, and it really is left to the agent to determine what tasks to pursue in order to prepare for unknown future challenges.

In this work [1209], we equip a Reinforcement Learning (RL) agent with different abilities that support this self-organized learning process and make it sample-efficient. The goal is to have an agent that explores its environment and thereby figures out how to solve a number of tasks that require it to manipulate different parts of the observation space. Once the agent learns all tasks sufficiently well, we can ask the agent to solve a certain task by manipulating the corresponding part of the obervation space until a goal state is achieved. In the end, the agent should be capable of controlling all controllable parts of its environment.

The main abilities we equip the agent with are depicted in the figure and are described as follows: A task selector (part (2) in the figure) that allows the agent to distribute its available resource budget among all possible tasks it could learn (part (1)) such that, at any given time, most of the resource budget is spent on tasks that the agent can make the most progress in. A task planner (part (3)) that learns a potentially existing inter-dependency between tasks, i.e. if one task can be solved faster or is only enabled by another task. A dependency graph (part (4)) that the agent uses to plan subtask sequences that allow it to solve a final desired task. A subgoal generator (part (5)) that generates for each subtask in the plan a goal state that, if reached by the agent, makes it easier to solve the next subtask. All components are learned concurrently from an intrinsic motivation signal (part (8)) that is computed from the experience the agent collects while autonomously interacting with the environment (parts (6) & (7) in the figure).

In this work, we pair an explicit but general planning structure with data-driven learning to solve challenging control tasks, such as tool-use for manipulation. By extracting information about the interrelationship between components from the data, the agent's planner can specialize on the specific set of problems it faces in the current environment. One next step in this line of research is to make the planning structure itself more flexible so that it can be fully learned or dynamically adapted to better fit the specific needs of the problems at hand. Confronted with the open-ended learning setting, we select learning progress as the main driving force of exploration and as an additional training signal for differentiating between task-relevant and task-irrelevant information in the training data. Another future direction of research is to find other types of intrinsic motivation that can drive the exploration behavior of the agent.

More information: https://al.is.mpg.de/project/control-what-you-can

Symbolic Regression and Equation Learning

Alessandro Simon, Matthias Werner, Dominik Zietlow, Martin Oettel, Igor Lesanovsky, Sabine Andergassen, Georg Martius

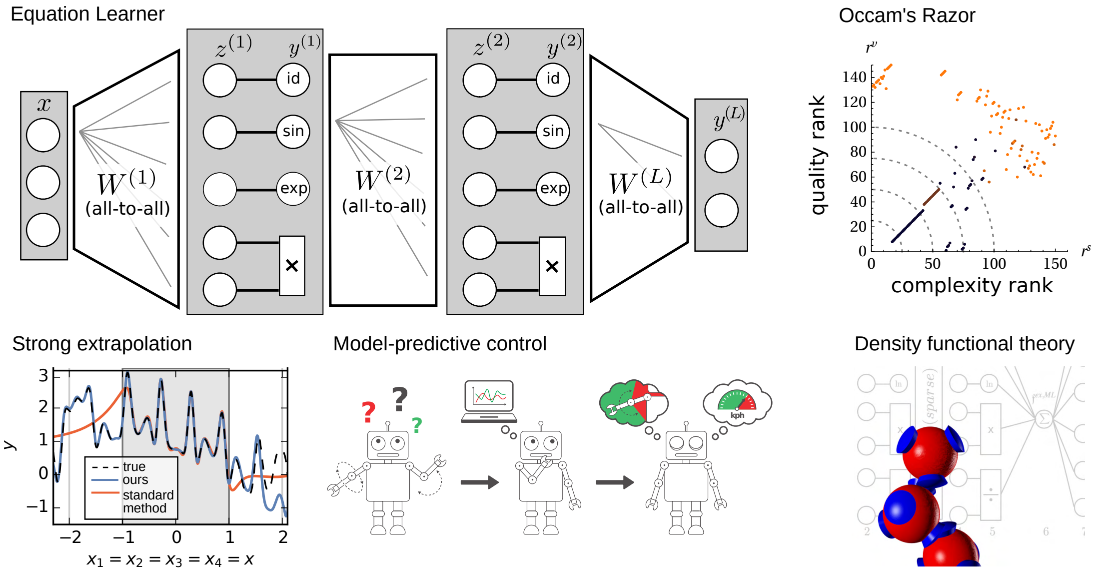


Figure 7.2: Finding concise analytical expressions for given data is also called symbolic regression. Our equation learning method does this also for systems with many degrees of freedom. We use it in several applications in physics and robotics.

When analyzing data in the context of natural sciences, the prime aim is often to gain understanding by distilling compact and interpretable analytic equations. Instead, contemporary supervised machine learning methods mostly produce unstructured and dense mapping functions from input to output with the aim to make accurate numeric predictions.

In this project, we aim to automate the extraction of concise functional equations from data by developing new machine learning methods. Our first method, called Equation Learner (EQL), is a modified feed-forward neural network containing algebraic base functions, such as cosine, multiplication, square root, exponential, and so forth[1] [1214]. Using a particular regularization and model selection scheme and sufficient domain priors[2], we can often discover the correct analytical expressions, which then enable strong extrapolation performance. In a proof of principle, we show that the equations of motion of a cart-pendulum robot can be identified after only 20 seconds of random interaction – enabling successful model-based control [1214].

The beauty of our approach is that it can be embedded in larger neural networks or other differentiable processing pipelines. This is a property that we exploit in a collaboration project with the University of Tübingen to create effective descriptions of fluid particles. We were able to create a machine learning system using EQL to find suitable density functionals for simple fluids [1188]. Currently, we are investigating fluids of particles with anisotropic potentials which are important in many applications, such as drug design.

In another collaboration, we are deploying machine learning methods to improve the understanding of quantum systems [1181]. Given a physical quantum system in which a subsystem is embedded in a larger system, we used neural networks to learn the generator of the subsystem's dynamics. Our analysis shows under which conditions Markovian generators are accurate and where long-term predictions can be made.

More information: https://al.is.mpg.de/project/symbolic-regression-and-equation-learning

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[1] G. Martius, C. H. Lampert. Extrapolation and learning equations. arXiv preprint https://arxiv.org/abs/1610.02995. 2016.

[2] M. Werner, A. Junginger, P. Hennig, G. Martius. Informed Equation Learning. 2021. eprint: 2105.06331.

Combinatorial Optimization as a Layer / Blackbox Differentiation

Marin Vlastelica Pogancic, Anselm Paulus, Michal Rolinek, Dominik Zietlow, Vít Musil, Georg Martius

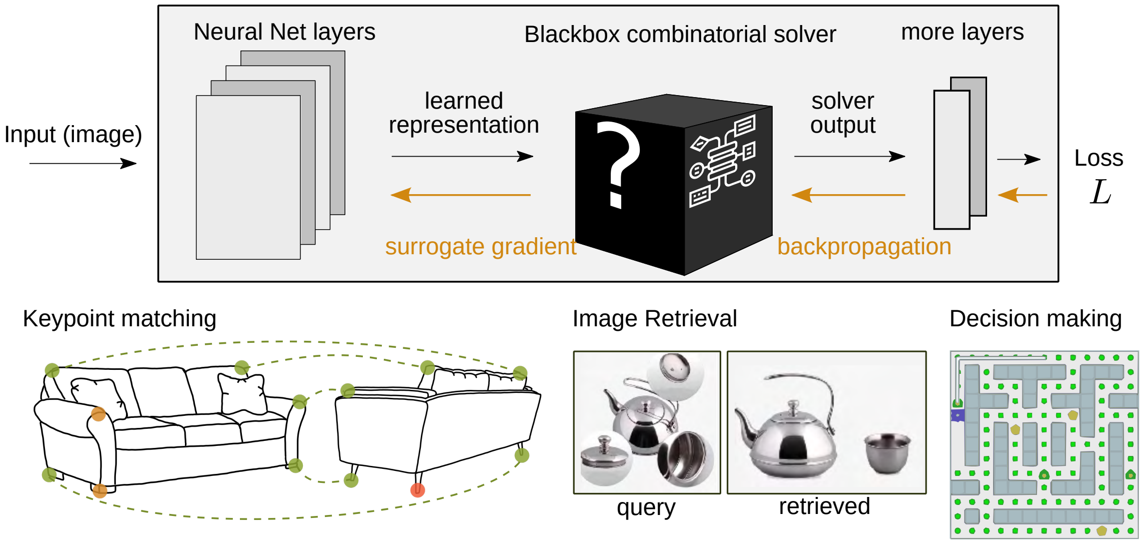

Figure 7.3: Schema depicting an architecture with an embedded solver on the top. Thanks to our surrogate gradient, training can be done as usual with stochastic gradient descent. The bottom row illustrates the applications we tackled so far: keypoint correspondence in pairs of images, directly optimizing ranked-ranked-based losses for improved image retrieval, and embedded planning for stronger generalization in reinforcement learning.

Deep learning has shown remarkable success in solving problems from high-dimensional raw input, such as image recognition or speech-to-text translation. However, deep learning is not particularly good when it comes to problems with a combinatorial nature, such as solving a puzzle, finding the shortest path or matching two sets of items. For each of these problems, computer scientists have developed highly optimized algorithms with correspondingly fast implementations in the field of combinatorial optimization. These methods require a perfect input representation and cannot be used on raw inputs as such.

In this work, we bring deep learning and combinatorial optimization together. Ideally, we would like to have the best of both worlds: having rich feature representations through deep neural networks and efficient algorithm implementations that enable combinatorial generalization. We have developed a method [1207] with which such algorithms can indeed be used as building blocks in deep neural networks. The original implementations do not need to be known or modified. Instead, it is enough to invoke them one time during the gradient computation on a modified input to obtain an informative gradient.

Equipped with our new method, called *Blackbox differentiation*, we tackled two real-world problems in computer vision: the keypoint correspondence problem and optimizing rank-based functions. The keypoint correspondence problem is about finding matching pairs of points in two or more images. Our architecture embedding a strong graph-matching solver [1205], is able to outperform the state of the art in this domain on several benchmarks. Another remarkable success of our method is that it allows computing gradients for ranking-based functions [1206] – commonly used in, e.g., object-retrieval. Our paper was nominated for the best-paper award at CVPR.

Enhancing reinforcement learning agents with planning algorithms as part of their policy networks is another exciting application [1199].

Recently, we conceptually enhanced our method with the ability to learn the type of combinatorial algorithm that should be solved [1198]. This is achieved by learning the constraints of an integer linear program.

More information: https://al.is.mpg.de/project/blackbox-differentiation-of-combinatorial-solvers

Super-resolution Sensing for Haptics

Huanbo Sun, Georg Martius

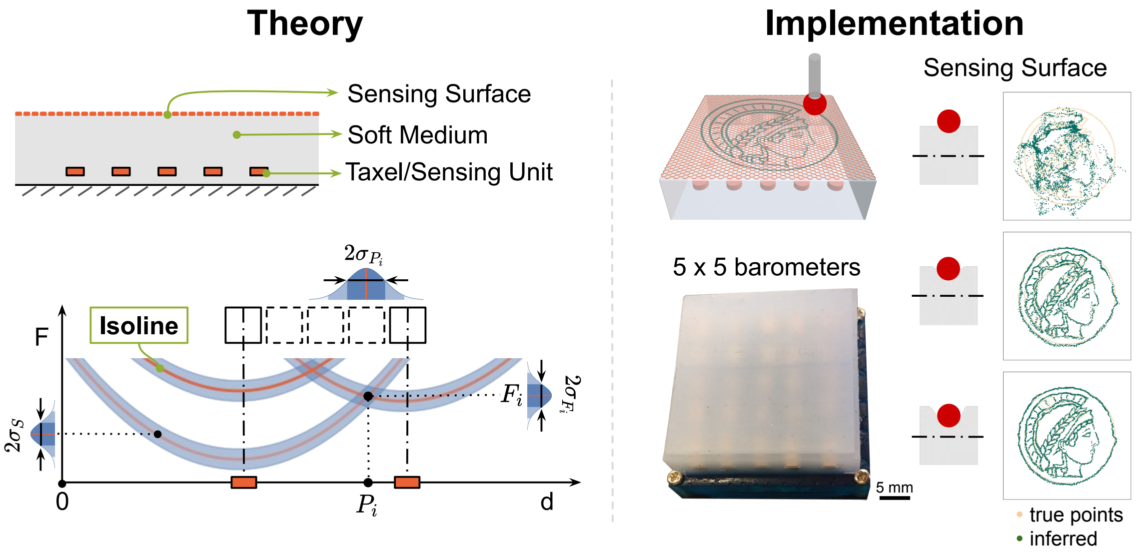

Figure 7.4: We introduce a theory to characterize, analyze, and predict force sensation at super-resolution for haptic sensors. Our theory is based on sensor isolines that directly assess the uniqueness of contact position reconstruction. A sensor design guided by this theory achieves a super-resolution factor of over 1200.

Haptic feedback is essential to make robots more dexterous and effective in unstructured environments. Nevertheless, high-resolution tactile sensors are still not widely available. When using a large number of physical sensing units we often face manufacturing challenges and wiring problems. Such complex hardware can also lead to durability issues as each additional component constitutes a potential point of failure.

We pursue a route towards high-resolution and robust tactile skins by embedding only a few sensor units (taxels) into a flexible surface material and use machine learning to achieve sensing with super-resolution accuracy. Our first successful robotic application was a large surface sensing on a robot limb [746, 747, 1190, 1215]. We then propose a theory for geometric super-resolution to guide the development of tactile sensors of this kind and link it to machine learning techniques for signal processing[3] as illustrated in the figure.

More information: https://al.is.mpg.de/project/superresolution-sensing-for-haptics

Representation Learning

Dominik Zietlow, Michal Rolinek, Georg Martius

Learning meaningful, low-dimensional representations of data is a challenging problem. Particularly for an autonomously learning system, representations learned from observations can play a crucial role. Consider for example a system that receives many images of faces and is capable of finding out that there are common factors explaining most of the visible characteristics, such as gender, or hair color. Variational Autoencoders (VAEs) can do this to an astonishing extent, but it was unclear why VAEs actually have this ability. We found that the reason is a byproduct of simplifying the learning objective to make the method tractable and suitable for applications [1210]. Interestingly, this insight allowed a new and tighter connection of VAEs to the classical method of principle component analysis. Furthermore, we then used this understanding to demonstrate that VAEs solely rely on the consistency of local structures in the datasets [1200]. In the future, we hope to utilize this knowledge for further advances in general data analysis.

More information: https://al.is.mpg.de/project/representation-learning

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[3] H. Sun, G. Martius. Theory and Design of Super-resolution Haptic Skins. *arXiv*, Aug. 2021.

7.2 Research group leader: Georg Martius

Biography

Georg Martius is leading the research group on Autonomous Learning at the Max Planck Institute for Intelligent Systems in Tübingen, Germany since 2017. He received his computer science Diploma degree from the University of Leipzig in 2005 and his Ph.D. in 2009 from the University of Göttingen, Germany. He was a postdoctoral fellow at the IST Austria and was a postdoctoral researcher at the Max Planck Institute for Mathematics in the Sciences in Leipzig, Germany. His research aims at creating autonomously learning and developing robotic agents that can help to create versatile assistants for humans. Methodologically, he focuses on machine learning for robotics, including internal model learning, reinforcement learning, intrinsic motivations, representation learning, differentiable combinatorial optimization, and haptics.

Awards and fellowships

- 2020 Best paper nomination at CVPR (IEEE Conf. on Computer Vision and Pattern Recognition) (26 out of 1470 accepted papers), virtual
- 2016 Distinguished oral presentation award on ICDL (IEEE Intl. Conf. in Developmental Learning), Cergy, France
- 2014 IST-Fellowship from Institute of Science and Technology Austria, Austria
- 2014 Best paper award at SAB (Intl. Conf. on Simulation of Adaptive Behavior), Castellon, Spain
- 2010 Best paper award at SAB 2010, Paris, France
- 2009 “Summa cum laude” (highest praise) for Dissertation, Göttingen, Germany

Education

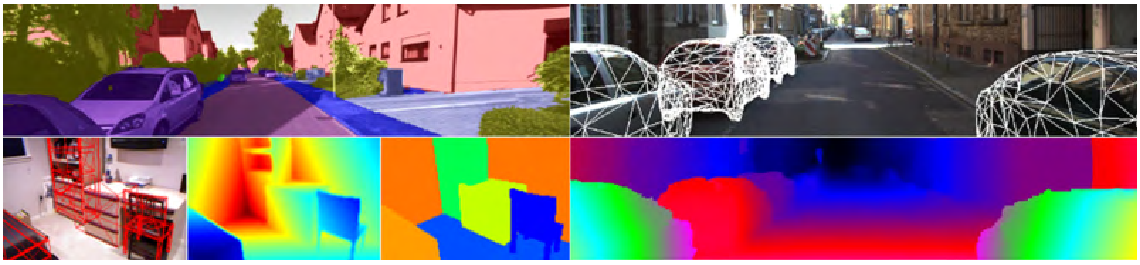
- 2009 Ph.D. (Dr. rer. nat.) Georg-August Universität Göttingen, Germany
- 2005 M.Sc. (Diploma) in Computer Science with minor in Physics, University of Leipzig, Germany
- 2002–2003 Visiting student at University of Edinburgh, Division of Informatics, UK

Employment (appointments) / Academic positions

from 2017	Independent Max Planck Research Group Leader, MPI for Intelligent Systems, Tübingen, Germany Faculty member of IMPRS-Intelligent Systems graduate school Faculty member of Max Planck ETH Center for Learning Systems
2015 – 2017	Independent postdoctoral Fellow at Institute of Science and Technology Austria, Klosterneuburg, Austria
2010 – 2015	Postdoctoral position at Max Planck Institute for Mathematics in the Sciences, Leipzig, Germany
2009 – 2010	Postdoctoral position at Max Planck Institute for Dynamics and Self-Organization, Göttingen, Germany
2005 – 2009	Graduate student at Bernstein Center for Computational Neuroscience (BCCN), Göttingen, Germany

8 AUTONOMOUS VISION

8.1 Research Overview



The **Autonomous Vision Group** is focused on 3D scene understanding, reconstruction, motion estimation, generative modeling and sensori-motor control in the context of autonomous systems. Our goal is to make artificial intelligent systems such as self-driving cars or household robots more autonomous, efficient, robust and safe. By making progress towards these goals, we also strive for uncovering the fundamental concepts underlying visual perception and autonomous navigation. Our research is guided by the following principles.

Representations: Our world is inherently three-dimensional as all physical processes (including image formation) occur in 3D and not in the 2D image plane. Thus, we strive for inferring compact 3D representations of our world from 2D or 3D measurements. To this end, we develop novel representations, learning frameworks, reconstruction and motion estimation algorithms.

Generative Models and Simulation: Generative models are at the core of understanding the fundamental processes underlying vision, building robust models and generating large amounts of training data for discriminative models. We investigate generative models (such as GANs and VAEs) from a theoretical perspective and apply them to tasks in the context of data generation for autonomous driving and beyond.

Prior Knowledge: Visual perception is a highly ill-posed task with many explanations for a single observation. We therefore investigate how prior knowledge (e.g., about the shape of objects, image formation or driving laws) can be incorporated into visual perception and autonomous navigation to make both tasks more robust. We also develop probabilistic representations which capture uncertainty in the output.

Learning from Little Data: High-capacity models such as deep neural networks require large amounts of annotated training data which limits scalability. To address this problem, we develop novel techniques for learning from little annotated data, including self-supervised models for geometry and motion estimation, methods for transferring labels across domains and techniques which incorporate a-priori knowledge into the structure of neural networks.

Empirical Risk Minimization: Many state-of-the-art computer vision models (e.g., 3D reconstruction) or sensori-motor control systems (e.g., self-driving cars) are trained using auxiliary loss functions instead of the actual task loss due to difficulties in representation or computational limitations. We work on end-to-end trainable models for these tasks which exploit task information in a data-efficient manner.

Datasets and Evaluation: We strongly believe that research is a collective effort that is only possible by sharing research results, code and data. We are therefore committed to publishing our results and code. Moreover, we construct novel datasets like KITTI or ETH3D to foster progress in the field and across research areas.

8.2 Research Fields

8.2.1 Neural Implicit Representations

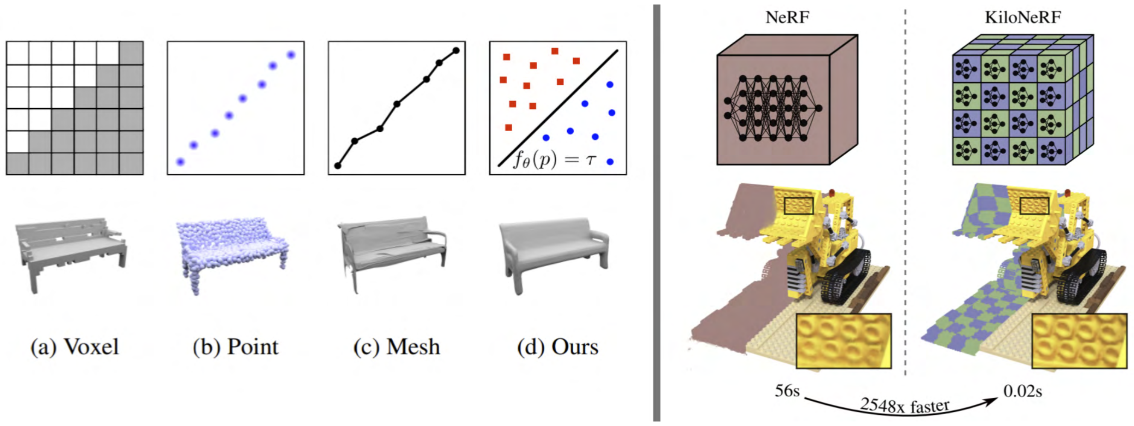


Figure 8.1: Left: By representing a scene as the decision boundary of a deep neural network we do away with the issues of classical 3D representations (voxel, point could and mesh). Right: Our hybrid between neural and voxel representation enables real-time rendering.

We live in a three-dimensional world, thus proper 3D understanding is crucial for autonomous systems like self-driving cars. But first, a suitable representation for the three-dimensional content of our world is required. Traditionally, point cloud, voxel or mesh representations are used, but point clouds lack connectivity information, voxels are memory hungry and meshes are hard to integrate into deep learning pipelines. To address these problems, we developed neural implicit representations (NIR), that compactly encode the geometry of a scene in the weights of a deep neural network (DNN) [1272].

We extended NIRs to handle time-varying topologies by introducing Occupancy Flow, a novel spatio-temporal representation of time-varying 3D geometry. Implicitly, our model yields correspondences over time, thus enabling fast inference while providing a sound physical description of the temporal dynamics [1265].

For texture reconstruction of 3D objects, we introduced Texture Fields, a novel representation that is based on regressing a continuous 3D function parameterized with a neural network. Texture Fields are able to represent high-frequency details and blend naturally with modern deep learning techniques [1264]. Further, we developed Surface Light Fields, where we additionally condition the neural network on the location and color of a small light source [1249]. This allows us to manipulate the light source and relight captured objects using environment maps.

By combining NIR with convolutional neural networks we can perform 3D reconstruction of large scenes from point clouds [1251]. The aforementioned works rely on 3D supervision, which might not be always available. We showed that by differentiably rendering our NIR, we can solve for the geometry and appearance of a scene even when only posed 2D images are available for supervision [1258]. In follow-up work, we increased the practicality of this method by removing the dependence on expensive-to-collect image masks [1238].

A downside of NIRs is that they cannot be efficiently rendered without prior conversion to a voxel or mesh representation. To tackle this issue, we designed a hybrid between NIRs and voxels. This representation can be rendered in real-time but still has a small memory footprint[1239].

Finally, we developed differentiable forward skinning for NIRs which enables the animation of articulated 3D objects like humans from posed meshes alone [1240].

More information: https://avg.is.mpg.de/field/neural-implicit-representations

8.2.2 Intermediate Representations for Autonomous Driving

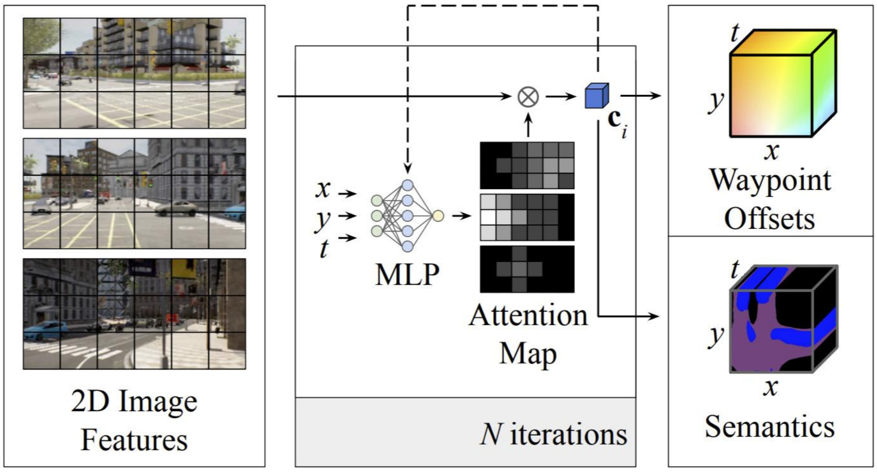


Figure 8.2: We developed Neural Attention Fields as intermediate representation for predicting waypoint offsets and Bird's Eye View semantics. Intermediate attention maps are used to iteratively compress high-dimensional 2D image features into a compact representation useful for the downstream task of autonomous driving.

For autonomous driving, raw sensor inputs (RGB images, LiDAR) are transformed into a high-level representation, that is more suitable for decision making on the road. However, it is not clear what is the most adequate intermediate representation and how to obtain a particular representation from raw inputs. We, therefore, studied several alternative representations and developed a learning pipeline for each representation to efficiently and accurately estimate it from the car's sensors.

Towards this goal, we trained a neural network that predicts from the RGB feed information useful for the self-driving task like distance to the centerline or to the lead vehicle [1274]. Since some of these affordances like the presence of a relevant red light also depend on the self-driving car's route we additionally condition the network on directional inputs. In the challenging CARLA simulation benchmark for goal-directed navigation, our approach is the first to handle traffic lights, speed signs and smooth car-following, resulting in a significant reduction of accidents.

How should representations from complementary sensors be integrated for autonomous driving? Geometry-based fusion has shown great promise for tasks such as object detection. However, for the driving task, the global context of the 3D scene is key, e.g. a change in traffic light state can affect the behavior of a vehicle geometrically distant from that traffic light. Geometry alone is therefore insufficient for fusing representations in driving models. To tackle this issue, we introduced TransFuser, a novel Multi-Modal Fusion Transformer, to integrate image and LiDAR representations using attention [1245]. Our approach achieves state-of-the-art driving performance on CARLA while reducing collisions by 76

With NEural ATtention fields (NEAT), we developed a novel representation that enables efficient reasoning about the semantic, spatial, and temporal structure for end-to-end imitation learning models [1236]. NEAT is inspired by our work on neural implicit representations [1272] and maps locations in Bird's Eye View (BEV) scene coordinates to waypoints and semantics, using intermediate attention maps to iteratively compress high-dimensional 2D image features into a compact representation. This allows our model to selectively attend to relevant regions in the input while ignoring information irrelevant to the driving task, effectively associating the images with the BEV representation. Visualizing the attention maps for models with NEAT intermediate representations provides interpretability.

More information: https://avg.is.mpg.de/field/intermediate-representations-for-autonomous-driving

8.2.3 3D Controllable Image Synthesis

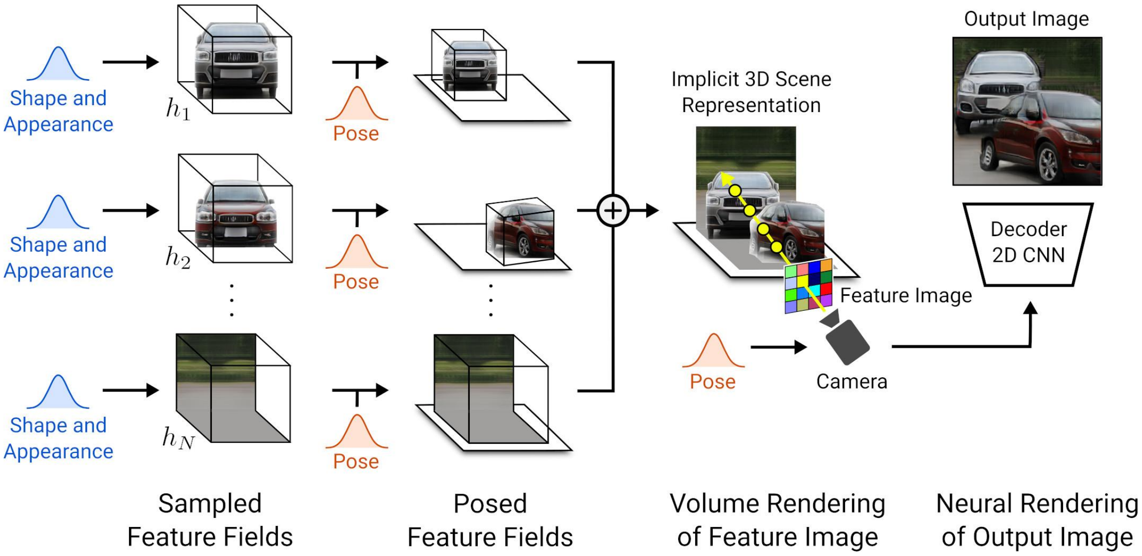


Figure 8.3: By representing scenes as Compositional Generative Neural Feature Fields, we gain explicit control over the pose and appearance of individual objects in synthesized images.

A generative model like a Variational Auto-Encoder (VAE) or Generative Adversarial Network (GAN) is able to synthesize diverse and high-quality images that closely resemble the images from the training dataset. However, the generation process of these models lacks controllability. In particular, users may want to adjust the 3D pose and size of objects in the synthesized images. Ideally, the scene's layout can be altered without changing other aspects like the overall geometry or texture of the individual objects.

Endowing a generative model with such 3D controllability requires 3D understanding. Traditionally, in 3D Reconstruction, geometry is inferred from a set of posed images of a single scene. In contrast, our algorithms observe images from multiple scenes. In the most challenging setting we studied, there is only a single image per scene given. Therefore, our research constitutes an important step towards gaining 3D understanding from arbitrary image collections.

In our pioneering work [1256], we were the first to develop a method that allows for synthesizing multi-object scenes that are consistent wrt. changes in viewpoint or object pose.

In our second work on the subject, we developed Generative Radiance Fields (GRAFs) [1248], a model capable of synthesizing images of complex objects with higher fidelity. This was achieved by using a neural radiance field (NeRF) for representing the 3-dimensional content of the scene. A NeRF is a deep neural network that maps 3D position and 2D viewing direction continuously maps these quantities to volumetric density and color. This scalable scene representation is strongly influenced by our works on neural implicit representations; please refer to the correspondent research project. Volumetric rendering of the NeRF representation ensures consistent synthesis results across viewpoints.

With Compositional Generative Neural Feature Fields (GIRAFFE) [1244] we extended GRAF's methodology to multi-object scenes. To enable the manipulation of individual objects, we represent each object with a separate feature field. Instead of color, we associate a feature vector with each 3D point. Volumetric rendering of the GIRAFFE results in a 2D feature image, which is converted by a convolutional network into the final image. This novel combination of volumetric and neural rendering leads to detailed results at a low cost.

For the work introducing GIRAFFEs, we received the best paper award at CVPR 2021.

More information: https://avg.is.mpg.de/field/3d-controllable-image-synthesis

8.3 Awards & Honors

2019

Andreas Geiger: Ausgezeichnet als Junge Elite - Top 40 unter 40 (Capital Business Journal)

2018

Andreas Geiger receives the IEEE PAMI Young Researcher Award

2017

Andreas Geiger with collaborators from Daimler and Freiburg won the best student paper award at 3DV for the paper "Sparsity Invariant CNNs"

Andreas Geiger wins the German Pattern Recognition Award 2017.

Heinz-Maier-Leibnitz Prize for **Andreas Geiger**.

8.4 Research group leader: Andreas Geiger

Biography

Andreas Geiger is a full professor at the University of Tübingen and a group leader at the Max Planck Institute for Intelligent Systems. Prior to this, he was a visiting professor at ETH Zürich and a research scientist in the Perceiving Systems department of Dr. Michael Black at the MPI-IS. He studied at KIT, EPFL and MIT and received his PhD degree in 2013 from the Karlsruhe Institute of Technology. His research interests are at the intersection of 3D reconstruction, 3D motion estimation and visual scene understanding with a particular focus on integrating rich prior knowledge and deep learning for improving perception in intelligent systems. In 2012, he has published the KITTI vision benchmark suite which has become one of the most influential testbed for evaluating stereo, optical flow, scene flow, detection, tracking, motion estimation and segmentation algorithms.

His work on stereo reconstruction and optical flow estimation has been ranked amongst the top-performing methods in several international competitions. His work has been recognized with several prizes, including the IEEE PAMI Young Investigator Award, the Heinz Maier Leibnitz Prize of the German Science Foundation DFG, the German Pattern Recognition Award, the Ernst Schoemperlen Award and the KIT Doctoral Award. In 2013, he received the CVPR best paper runner-up award for his work on probabilistic visual self-localization. He also received the best paper award at GCPR 2015 and 3DV 2015 as well as the best student paper award at 3DV 2017. In 2021, he received the best paper award at CVPR and the Mark Everingham Prize at ICCV. He is an associate member of the Max Planck ETH Center for Learning Systems and the International Max Planck Research School for Intelligent Systems, and serves as an area chair and associate editor for several computer vision conferences and journals (CVPR, ICCV, ECCV, PAMI, IJCV).

Awards & Fellowships

2021	IEEE Mark Everingham Prize
2021	CVPR Best Paper Award
2019	Young Elite - Top 40 under 40
2019	ERC Starting Grant
2018	IEEE PAMI Young Researcher Award
2017	Best Student Paper Award, International Conf. on 3D Vision (3DV)
2017	German Pattern Recognition Prize, German Conf. on Pattern Recognition (GCPR)
2017	Heinz Maier-Leibnitz Prize, Deutsche Forschungsgemeinschaft (DFG)
2015	Best Paper Award, International Conf. on 3D Vision (3DV)
2015	Best Paper Award, German Conf. on Pattern Recognition (GCPR)
2013	Best Paper Runner Up Award, Conf. on Comp. Vision and Pattern Recog.

Education

Sep 2008 - April 2013	Ph.D. in Computer Vision (Grade 1.0/1.0), Karlsruhe Institute of Technology, Germany
July 2008	Master Thesis (Grade 1.0/1.0), Massachusetts Institute of Technology, USA
Feb 2006	Bachelor Thesis (Grade 1.0/1.0), Ecole Polytechnique Fédérale de Lausanne, Switzerland
Oct 2003 - July 2008	Diploma (Grade 1.0/1.0), Karlsruhe Institute of Technology, Germany

Employment (appointments) / Academic positions

03/2018 – present	Professor (W3), University of Tübingen
06/2016 – 06/2021	Independent Max-Planck Research Group Leader, Max Planck Institute for Intelligent Systems
06/2016 – 02/2018	Visiting Professor, ETH Zürich
06/2013 – 05/2016	Research Scientist, Max Planck Institute for Intelligent Systems
06/2013 – 05/2016	Research and Teaching Assistant, Karlsruhe Institute of Technology

Links

Link to CV on website: https://avg.is.mpg.de/~ageiger

9 LOCOMOTION IN BIOROBOTIC AND SOMATIC SYSTEMS

9.1 Research Overview

Under the direction of Dr. Ardian Jusufi, the scientists and engineers of the independent Max Planck Research Group *Locomotion in Biorobotic and Somatic Systems* study natural locomotion and the organismic bauplan that enables the graceful movement of animals in unstructured environments. The researchers apply their biological discoveries from animal experiments, capturing real-world behavior, to the creation of life-like robots with the vision to make robot movement indistinguishable from the elegant and efficient movements of animals - overall expanding the biomimetic robotic potential in real-world applications. Their research is at the nexus of engineering, materials, and biosciences.

The group conducts research in a variety of areas, and stands out as having experts in biological sciences, robotics, and material technologies. While the majority of today's robots are still constructed using stiff and hard components, soft robotics seeks to integrate malleable, flexible components into synthetic systems. To do this, scientists rely on the morphological intelligence inherent in mammals, insects, and reptiles' body structures, which enables them to move effectively and robustly. The interactions of stronger or stiffer material with softer or more flexible tissues are of special importance; animal movement involves a flawlessly coordinated action of all materials. Jusufi and his colleagues believe that by using these natural design principles and integrating morphological intelligence into swimming or climbing robots, such machines will be able to deal with more complicated situations and overcome barriers more efficiently.

The group's research highlights include:

Investigating bio-inspired solutions for complex movement.

Here, we use non-invasive motion capture techniques to understand challenging locomotory behaviors including swimming, gliding, and perching in animals. Understanding each of these behaviors allows us to translate our findings to create novel biologically informed designs and mechanisms for robotic locomotion and thus making robotic movements more realistic and applicable in a variety of real-world situations. **Soft material manufacturing**.

A key requirement to create life-like robotic movements is to fabricate actuators and sensors that are soft and capable of generating movements that conventional rigid actuators cannot. We have drawn inspiration from how animals sense their environment and sensors that can track changes in body orientation to enhance the control of robotic systems.

However, the scientists' goal extends beyond that; understanding how animals move and why by developing life-like robots, they may be able to answer evolution's design choices, and allow the scientists to gain previously unknown insights into the animals' underlying sensory and locomotory mechanisms. Ultimately, the scientists want to acquire a better knowledge of both animals and technology.

9.2 Selected Research Projects

Soft Sensory Control of Robotic Fish

Ardian Jusufi, Fabian Schwab

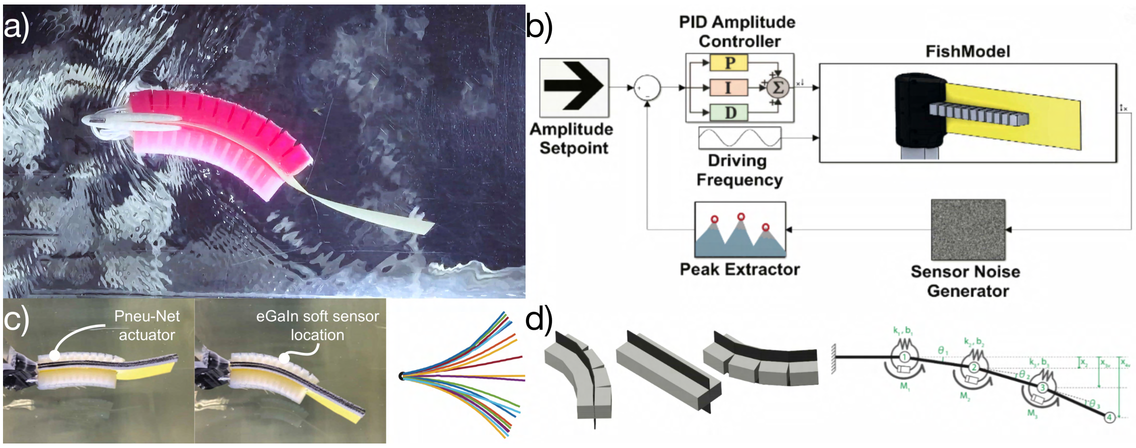


Figure 9.1: a) A pneumatic soft fish swims in a water tank b) Soft robotic fish undulation feedback controller. c) Soft sensors are placed on the outside edge of the PneuNet actuator to provide feedback and an example snapshots of midline kinematics as the feedback controller adjusts the robot's swimming amplitude. d) Lumped parameter model of a pair of antagonistic soft pneumatic actuators.

Soft robotics may be utilized to create new, more lifelike types of locomotion as well as to comprehend complex biomechanics using robotic model platforms. We built a fully soft robotic subcarangiform fish based on prior results on undulatory movement in fish, using antagonistic fast-PneuNet actuators and hyperelastic eutectic Gallium-Indium (eGaIn) implanted in silicone channels for strain sensing. These sensors are capable of measuring curvature because the electrical conductivity of the liquid metal reduces according to the silicone structure's stretching as the robot bends. As with its natural model, it advances in a wave-like pattern, with all components having a stiffness comparable to that of a fish body. To establish control, a simple, data-driven lumped parameter approach is proposed. This approach enables accurate yet lightweight computations that are customized using experimental data and a genetic algorithm. The model accurately predicts the robot's behavior over a wide range of driving frequencies and pressure amplitudes, taking into account the influence of the soft actuators' antagonistic co-contraction. The model is used to prototype an amplitude controller that is then deployed to the robot in order to reach the setpoint of a tail-beat amplitude using fully soft and real-time strain sensing. Knowing when a fish bends its caudal fin during swimming enables researchers to develop even more complex and life-like swimming robots.

More information: https://bio.is.mpg.de/project/soft_interface

Multi-Modal Aerial Locomotion with Soft Robotic Landing on a Wall

Ardian Jusufi, Robert Siddall

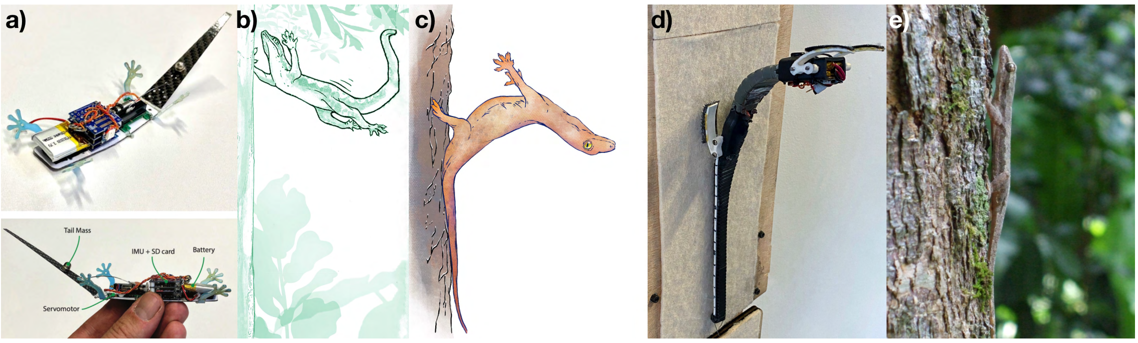


Figure 9.2: Images on multi-modal locomotion in the air and transition to a vertical substrate. Image descriptions from left to right. (a) Bio-inspired gecko robot capable of changing mid-air body pitch orientation using tail flexion. (b) Illustration of a lizard gliding in the field (Peter Bräm). (c) Illustration of Fall Arresting Response (Andre Wee). (d) Soft robotic lander (e) field photo of gecko post landing (Ardian Jusufi).

Landing on a vertical substrate after flight is one of the most dramatic transitions in multi-modal locomotion. Geckos' remarkable climbing abilities endow them with agility that is rarely matched in nature. They can rapidly climb up smooth vertical surfaces and even move on an upside-down ceiling due to their extremely specialized adhesive lamellae on their foot. In our most recent work, we discovered another gecko superpower: The multi-talented lizard known as *Hemidactylus platyurus* is capable of gliding and crash-landing on vertical trees.

In field studies in Southeast Asian rainforest, Dr. Ardian Jusufi deployed high-speed cameras and captured the gecko gliding from tree to tree, reaching a speed of up to 6 m/s (21 km/h) when landing on a tree. The animal cushions the impact by bending its torso backward by up to 100 degrees. The front foot lose grip during the bend and the back legs are the only ones that remain attached. Pushing the tail hard into the tree trunk, the gecko dissipates the energy. Lizards that have lost tails could not dissipate sufficient energy and fall from the tree. As a result, we postulate that the tail functions as a fifth leg, assisting the gecko in stabilizing itself following an impact. To validate the hypothesis, we developed the gecko-inspired robot, a physical model platform that enables a better understanding of the forces encountered by the animal. It has a flexible torso and a detachable tail, and is programmed to bend upon impact, pushing the tail into the wall. We launched the robot onto a vertical platform and measured the force applied to the robot's front and back feet upon contact. The longer the tail, the less force was required to move the back feet away from the surface. The lesser the applied force, the easier it is for the robot (and, most likely, the animal) to maintain its grip. However, without a tail, the pressures acting on the back feet become excessive, and the robot loses grip, bounces off, and falls from the platform. We were able to measure something with the robot that we could not with geckos in the field. The wall reaction forces at impact proved that the tail plays a crucial role in achieving hard landings after subcritical glides. Not only does our soft robotic lander contribute to the advancement of another field, but it also has the potential to improve robot mobility by enhancing robustness and simplifying control.

More information: https://bio.is.mpg.de/project/geckos-glide-crash-land-but-don-t-fall-thanks-to-tail

Robustness and Transition in aerial and terrestrial locomotion

Ardian Jusufi, Mrudul Chellapurath, Pranav Khandelwal, Fabian Schwab

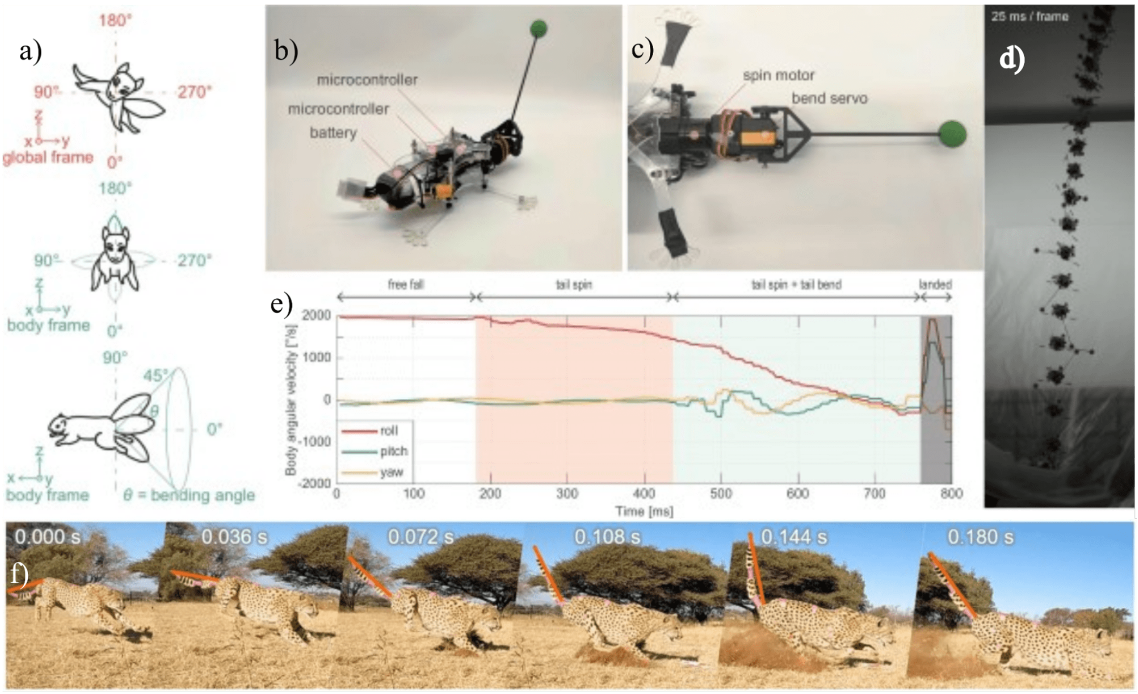


Figure 9.3: a) Definitions of body roll angle, tail spin angle, and tail bending angle, respectively. b) Overview of the squirrel-like robot. c) Tail actuation mechanism. d) A sequential photo of the dropping robot. After the tail started to be spun, body rotation speed decreased. e) Tail inertial stabilization. The spinning bent tail stabilized the body rotation before its landing. f) the cheetah pitches his tail upward while decelerating. The virtual tail is indicated in orange.

Depending on the species of animal the tail is attached to, it can have extraordinarily multifunctional purposes. Tails help the animals to navigate in challenging environments by providing more agility and maneuverability. For example, arboreal mammals like squirrels demonstrate impressive agility while jumping from branches to branches. In a recent YouTube video by Mark Rober, which went "viral", squirrels voluntarily visiting the YouTuber's garden cross parkour to earn a food reward. The squirrels were mechanically catapulted off of a track, inducing an initially uncontrolled rotation of the body. Interestingly, they skillfully stabilized themselves using tail motion, which ultimately allowed the squirrels to land successfully. We analyzed the mechanism by which the squirrels recover from significant body angular rates. From the analysis of videos, we observed that the squirrels first use their tail to stabilize their head to fix a landing site visually. Then the tail starts to rotate to help stabilize the body, preparing themselves for landing. To analyze further the mechanism of this tail use during mid-air, we built a multibody squirrel model as well as a squirrel robot and showed the righting strategy based on body inertia moment changes and active angular momentum transfer between axes.

Another example of the amazing use of the tail is found in the fastest terrestrial animal; cheetah. Researchers have analyzed their hunting behavior in the wild and attributed their hunting success to their ability to change direction and decelerate rapidly. The tails play a crucial role in the maneuverability in running cheetahs using inertial and aerodynamic effects to counter the unwanted rotation it induces. Using two approaches, motion capture of the animal, and robotic imitation, the role of the cheetah's tail in its maneuverability was studied (Fig. f).

More information: https://bio.is.mpg.de/project/robustness

Soft Actuator Composites

Ardian Jusufi, Hritwick Banerjee, Hongliang Ren, Manivannan Sivaperuman Kalairaj

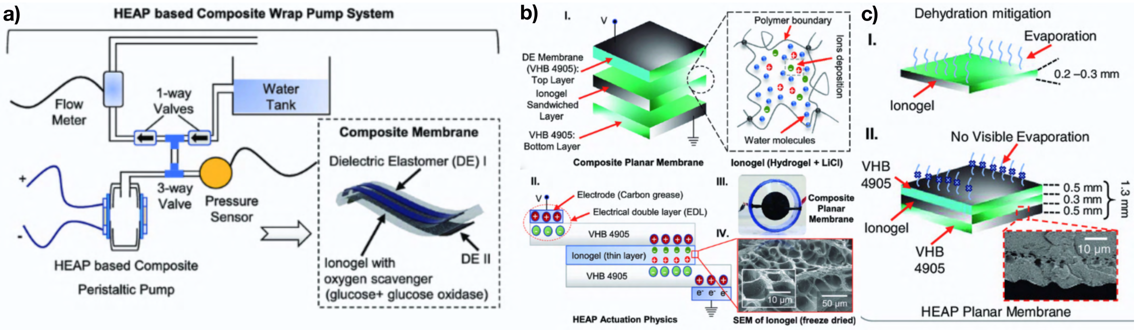


Figure 9.4: (a) HEAP-based composite wrap-up pumping system's working principle. (b) (I)-(II) Multilayered soft actuator composite with ionogel sandwiched with actuation physics. (III) Composite planar membrane's optical photograph with carbon grease electrode (black) that connects with the copper tape for electroactuation. (IV) Scanning electron microscopy (SEM) of freeze-dried ionogel demonstrating porous surface. (c) Schematic representation of the I) dehydration and II) antidehydration kinematics

We need artificial soft muscles to create new soft robots capable of securely interacting in close proximity with humans as well as performing complex tasks in spaces that are difficult to reach. These devices would ideally be entirely soft, as powerful as genuine muscles, and electrically driven to facilitate integration with the rest of the robot. Our recent work on soft actuator composites illustrates the advantages of using biocompatible polymers in conjunction with soft-active materials and presents performance assessment for cardiovascular trials and similar biofluid pumping applications. We discovered a material solution that depends on a well-established technology - a dielectric elastomer soft capacitor that deforms in response to an applied electric field. We present a novel design solution involving composite layering of hydrogel and electroactive polymer (HEAP), incorporating hydrogel-based ionotronics and achieving contraction forces comparable to those of real muscles by using a unique mix of nanoscale conductive particles and soft elastomers when high electric fields are applied. With dielectric elastomers (DE), we approximate actuator-like behavior in terms of non-hemolytic pumping action and higher energy density to develop more lifelike motion profiles for biorobotic physical models and biomedical assistive devices. In terms of pressure change, HEAP achieves the greatest value measured to date and the flow rate obtained with the HEAP multilayer composite materials is the third highest in the DE-based composite pumping system when taking relevant literature into account. Furthermore, novel surgical instruments, prostheses and artificial limbs, haptic gadgets, and more competent soft robots for exploration are all possible applications.

More information: https://bio.is.mpg.de/project/soft-actuator-composites

9.3 Research group leader: Ardian Jusufi

Biography

Dr. Ardian Jusufi has been leading the independent Max Planck Research Group for *Locomotion in Somatic and Biorobotic Systems* at the MPI-IS in Stuttgart since 2018. He is head of a Cyber Valley research group. Ardian is also faculty at International Max Planck Research School IMPRS-IS, as well as an Associate Faculty at the ETH Center for Learning Systems. He conducted his formal training at the University of California at Berkeley, USA, where he received his PhD in 2013. Dr. Ardian Jusufi was then a postdoctoral fellow at the University of Cambridge, UK. Next, he went to Harvard University, USA, to work as a postdoctoral researcher. After serving as a lecturer from 2016, Ardian joined MPI-IS in 2018 and has been an independent Max Planck Research Group Leader (Associate Professor).

Dr. Ardian Jusufi positions his highly interdisciplinary research at the interface of engineering, materials science, and biomechanics. He specializes on soft active materials, biomimetics, and robotics inspired by original biomechanical discovery. Ardian is a pioneer in the biorobotic investigation of robust locomotion of robots underpinned by his discoveries of tails as control appendages enabling rapid disturbance rejection and agile multi-modal transitions.

With a goal to achieve the dream of life-like movement, he integrates soft actuators and flexible sensors made of hyperelastic silicone elastomers (containing liquid metal) and embeds them into a diving, soft robotic fish, for instance. Their integration enables new skills in swimming and arboreal robots to increase their ability to overcome obstacles. In contrast to robots with mostly hard components, the musculoskeletal system is capable of adapting to multiple dynamic perturbations simultaneously. Life-like movement not only expands upon robot capability, it also enables original discovery in experimental biomechanics. His research integrates robotics, ’smart’ materials, with comparative biomechanics. In this spirit, Dr. Ardian Jusufi is a leader in the field of biorobotics enabled by biomimetic materials and mechanisms.

Awards & Fellowships

- **OutstandingTeaching Award** for G.S.Instructors – **U.C.Berkeley**.
- William V. Power Award –**U.C.Berkeley**.
- Fellowship for Prospective Researchers, Swiss National Science Foundation.
- Fellowship for Early Postdoc Mobility. Swiss National Science Foundation.
- Best Poster Presentation – 8^{th} International Symposium Adaptive Motion in Animals and Machines [AMAM], Japan.
- Best Presentation Competition, Runner-up, Soc. Int. Comp. B. Annual main conference.
- Queens’ College Postdoctoral Research Associate, Cambridge University.
- Darwin College Postdoctoral Research Affiliate, Cambridge University.

Education

- Dr. Ardian Jusufi conducted his formal training at Univeristy of California at Berkeley, USA, where he received his PhD in 2013.

- After graduation, Dr. Ardian Jusufi was a postdoctoral research fellow at the University of Cambridge, UK, in 2013 and 2014.
- He was also a Postdoctoral Researcher at Harvard University School of Engineering and Applied Sciences in 2015 and 2016.

Employment (appointments) / Academic positions

- Postdoctoral Fellow at the University of Cambridge, Queens' College.
- Postdoctoral Fellow at Harvard University.
- Lecturer, University of Technology Sydney.
- Subsequently he joined as a Max Planck Research Group Leader in March 2018 at MPI-IS, Stuttgart, where he has been leading a Cyber Valley research group since.

Links

Link to CV on website: https://bio.is.mpg.de/~ardian

10 DYNAMIC LOCOMOTION

10.1 Research Overview

Legged animals outperform legged robots albeit limited muscle power density and sensorimotor conduction velocity responsible for comparably slow reflexes. We see that animals run faster and more efficiently, and incorporate higher agility in a smaller building volume. But **how does the animal's neurocontrol orchestrate legs and body**, what role plays morphology, and **how are animals not overwhelmed by a control task that requires high-end computers**, kilo-hertz rate sensory feedback, and complex mathematical models **in robots**?
At the Dynamic Locomotion Group, sharing our research results and tools is the goal and we contribute to the open-source robots Oncilla robot [1323] and Solo robot [3] through the Open Dynamic Robot Initiative. We developed a rugged, light-weight, and customizable foot sensor ('FootTile') to reliably sense touch-down timing and stance phase loading. Arrays of our waterproofed sensor sense the instantaneous center of pressure during locomotion in natural terrain[1331].

We developed a robot leg with animal-like leg segmentation and a modular spring-tendon network. We find that the animal-like spring-tendon configuration hops with a below-average cost of locomotion of animals [1321]. With a hopping robot and boom-guide we recreated an environment that alters the effect of gravity. The gradually changing cost landscape shows how learning of hopping locomotion can be guided through a sequential increase of environment loading or the robot's complexity [1336].

A close look reveals hysteresis loops in muscles' work cycles also during negative power conditions (active braking or damping). We examine viscous, physical damping that produces forces based on joint velocity without need for high-frequency sensory feedback [1317]. In a numerical simulation study, we provide evidence that small amounts of intrinsic, viscous damping can improve locomotion [1316].

We research the trunk's subtle swaying motion in the fore-aft direction and its consequence to bipedal running. Previously, ground reaction forces were documented that intersect in a virtual point above the human trunk's center of mass. We predict feasible running gaits with a virtual point below the center of mass and characterize related actuator characteristics [1332]. With collaborators from locomotion research, we then show that human runners display a virtual point below, in certain locomotion conditions [1318]. We applied our model to bird-type and theropod-type trunk morphologies [1319].

Fluid-based (hydraulic, pneumatic) actuation is an omnipresent tool in engineering; less known is that animals and plants integrate fluidic actuation as well. Several spider-leg joints are potentially actuated by hemolymph. Inspired by a highly structured membrane in spider leg joints, we develop a spider-inspired rotary rolling diaphragm actuator [1312] which shows highest mechanical efficiency, independent from actuator speed and load.

With large feedback delays in animals, how can mechanosensory information trigger feedback loops timely? Intra-spinal sensing minimizes feedback delay, and intra-spinal accessory lobes in birds have been hypothesized to act as such sensors. We mapped the topology of the surrounding soft tissues and identified morphologies in small birds (quail) that are candidates to support accessory-lobe-based, intra-spinal sensing [1314].

We merge leg designs featuring mechanical elasticities (springs) and active compliance (feedback- and model-based virtual spring) leading to a new class of hybrid joint actuation that allows low control frequencies; the hybrid-actuated leg is controllable with sensory update frequencies around 50Hz, compared to typical, active robot leg compliance at 200Hz and beyond [1313].

10.2 Selected Research Projects

Viability, Learning and Robust Natural Dynamics

Alexander Badri-Sprowitz, Steve Heim

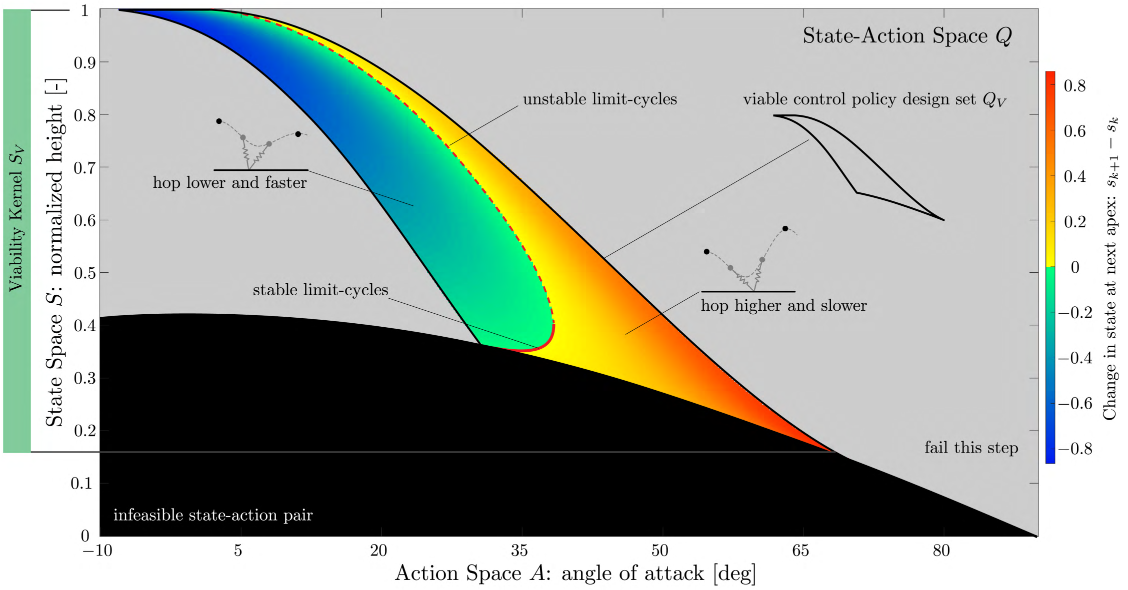


Figure 10.1: We can find the structure of the natural dynamics of a system by moving into the state-action space (shown is the state on the y-axis and action on the x-axis). The colored region shows the space available for designing a viable control policy.

To quantify the effect of natural dynamics on the policy learning problem, we formalize our work using the concept of viability. Unlike traditional control, viability analysis starts by defining a set of failures instead of a target. The viable set (also known as the viability kernel) is then the set of all states which can remain inside the set, and therefore avoid failure for all time.

While finding the viable set does not shed any information on convergence or optimality, **it also requires no definition of an objective, the reward function or even the policy parameterizatio**n. This **allows us to begin quantifying robustness to failure for a system design prior to designing** or learning the actual control policy.

We currently find that systems that are more robust to noise in action space are also more amenable to learning control policies, and allow more flexibility. This allows us to compare different designs of the mechanical system as well as low-level controllers (such as reflexes) [1322].

More information: https://dlg.is.mpg.de/project/viability-learning-and-robust-natural-dynamics

Spider inspired rotary rolling diaphragm actuation

Alexander Badri-Sprowitz, Jonas Hepp, An Mo, Chantal Goettler, Farimah Fazlollahi,

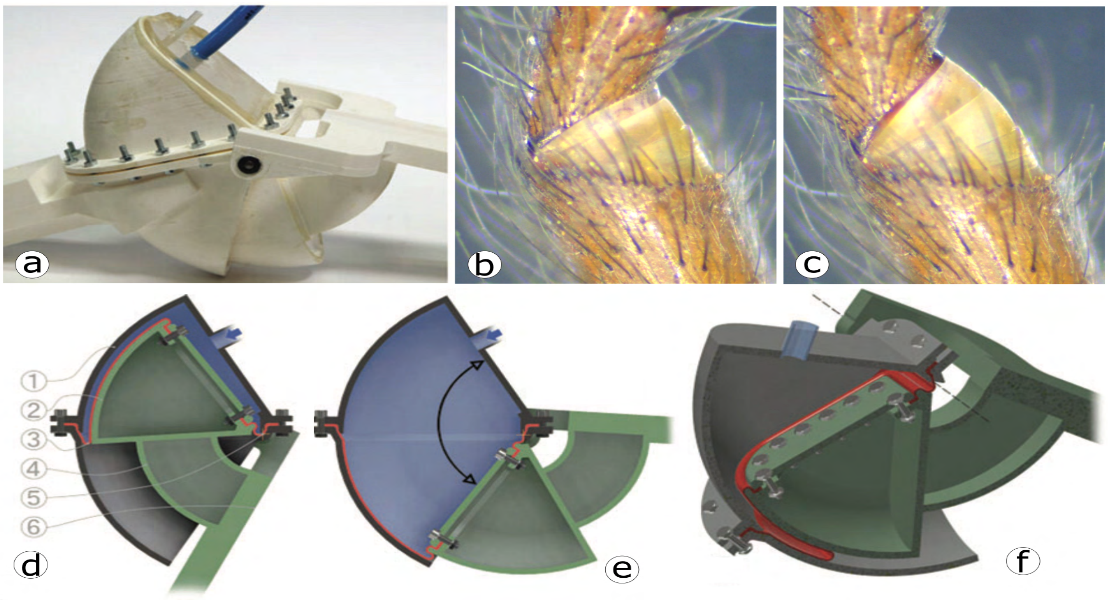


Figure 10.2: Figure shows a) rotary rolling diaphragm (RRD) actuator, b) flexed spider joint with membrane, c) extended spider joint - five membrane segments are visible, d) RRD actuator joint flexed, e) RRD actuator extended by internal fluid pressure, and f) RRD joint in perspective view. The diaphragm is shown in red, the fluid space in blue. The prototype was 3d printed, and can be built MRI compatible.

Fluidic actuation evolved in animals and plants. We are fascinated by the **membrane structure found in the femur-patella, and tibia-metatarsus joints of spiders** [1339]. These joints are hypothesized to **open hydraulically by pressurized blood** (hemolymph). The joint's arthrodial or articular membrane is potentially formed from a single, folded membrane transferring energy from fluid pressure into joint extension torque.

Standard engineered fluid actuators typically mount o-rings between moving parts, as friction seals. These actuators work with good efficiency at high pressure. However, at low working pressure or at low speed, the seal's Coulomb friction and stiction are significant, cause inefficient actuation, and require dedicated control. Alternatively, telescopic diaphragm actuators with high efficiency and linear force characteristics exist, but only for linear actuation.

Inspired by the spiders' arthrodial joint membrane, we hypothesized that **spiders might apply a rotary implementation of diaphragm-fluid actuation**. Our engineered rotary rolling fluidic diaphragm is custom-designed from a silicone rubber reinforced fabric with anisotropic tensile characteristics. The diaphragm follows the actuator's toroidal shape to unroll smoothly.

The rotary fluidic actuator outputs a constant torque throughout its stroke. In comparison, monolithic rotary soft robot actuators show a change in torque over output angle. Stiction and Coulomb friction are avoided by design; the rotary diaphragm seal is rolling during the actuator's stroke. The rotary rolling diaphragm actuator is compact with a low mechanical complexity from a single actuator chamber.

Our implementation outputs 6 Nm torque at a working pressure of 50 kPa (0.5 bar), with a working angle range of 100 degrees. **The rotary rolling diaphragm shows a 95% mechanical efficiency**, compared to seal-type fluidic actuators with an efficiency between 60-90%.

The spider-inspired rotary rolling diaphragm actuator can be used as a compliant actuator in soft robots, or as a stiff transmission device, depending on fluid and working pressure [1312, 1341].

More information: https://dlg.is.mpg.de/project/Spider-Inspired-Rotary-Rolling-Diaphragm-Actuation

Legged robots

Alexander Badri-Sprowitz, Felix Ruppert, An Mo, Alborz Aghamaleki Sarvestani, Steve Heim, Benedikt Gyoerfi, Milad Shafiee-Ashtiani, Bernadett Kiss

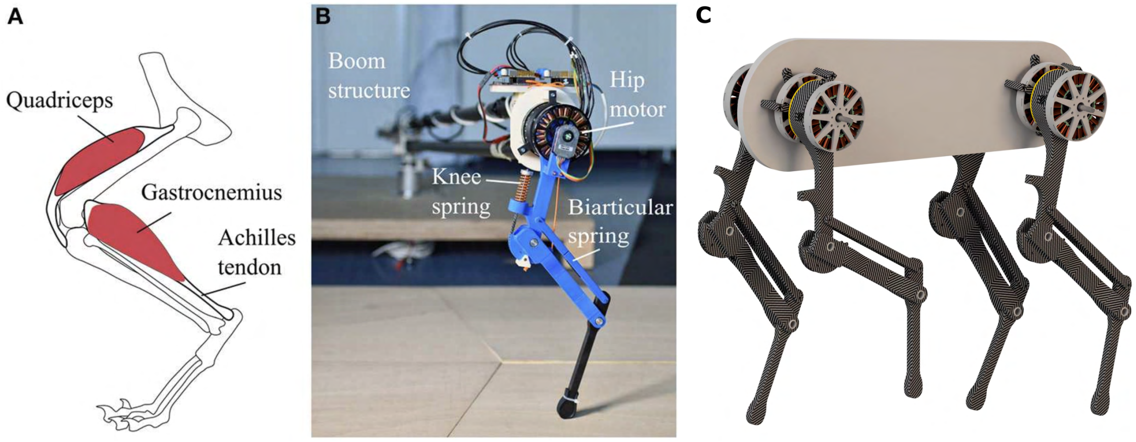


Figure 10.3: Bioinspired leg design for hopping and quadruped robots. A) A schematic presentation of a cat's hind leg, with the quadriceps (monoarticulate) and the gastrocnemius (biarticulate) muscle-tendons shown. B) The elasticity and connectivity of both muscles are presented by spring-tendons inserting between the femur and the lower leg (knee spring), and the femur and the ankle (biarticular spring). C) A possible quadruped configuration with four spring-loaded legs.

Legged animals outperform legged robots albeit limited muscle power density and sensorimotor conduction velocity of biological tissue. **Animals run faster and more efficiently,** seemingly effortless in natural terrain, **and incorporate higher agility in a smaller building volume.**

But how do leg and trunk designs interact with neurocontrol, and how is the animal's control effort reduced? We aim to understand these interactions also to improve the locomotion robustness and efficiency of bioinspired legged robots. For example, we test how leg stiffness and coupling through ligaments and tendons change the performance of robot legs. We develop mechanics, mechatronics, and control in-house, and analyze the resulting performance, and gait kinematics, and dynamics of bioinspired robots. **With robots and simulation models, we systematically investigate design and control parameters and establish a connection between form/morphology and function/legged locomotion**.

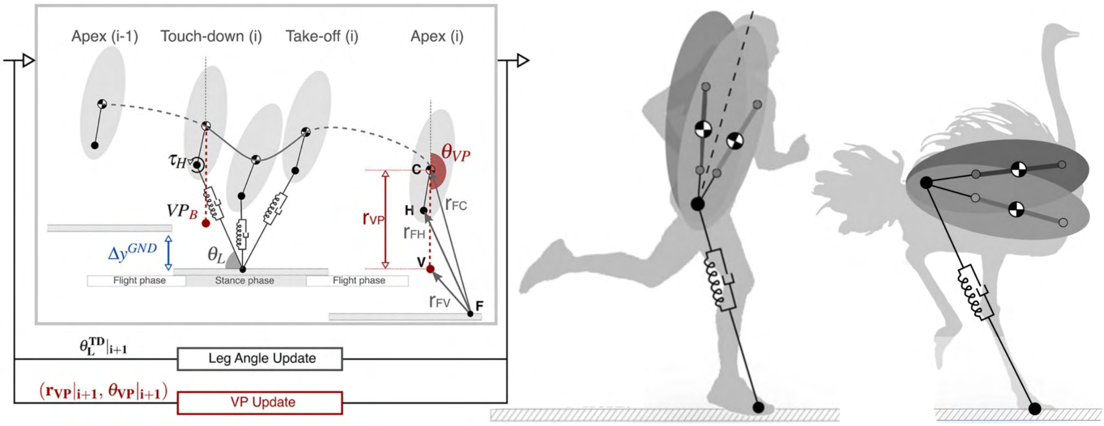
We are inspired by the muscle-tendon network structures in the hind limbs of **cats; the Quadriceps applies torque at the knee joint, while the Gastrocnemius muscle-tendon inserts torque into the knee and ankle joint**. Previous work suggested joint power transfer as a possible function of biarticular muscle tendons. We **hypothesized that the Gastrocnemius muscle-tendon functions as a leg-angle elasticity,** contrary to it being mounted in leg length direction.

Indeed, in experiments, we show that the Gastrocnemius-like spring-tendon effectively stores and releases energy inserted by the robot's leg angle (hip) actuator. We compare a pantograph leg with and without a Gastrocnemius-like spring-tendon. The **biarticular-elastic leg hops with a cost of transport of 0.8 J/N/m (64% CoT of a natural runner of equal body mass),** compared to the single-spring configuration with a cost of transport of 1.3 J/N/m (net CoT). Hence, the biarticular-elastic leg configuration has a clear energetic advantage at hopping locomotion [1321].

More information: https://dlg.is.mpg.de/project/Legged-robots

Trunk motion and virtual point control in bipedal locomotion

Alexander Badri-Sprowitz, Oezge Drama, Alborz Aghamaleki Sarvestani



We investigate the functional demands of bipedal running with a focus on trunk orientation and virtual point mechanics. **Bipedalism evolved in reptiles, avians, theropods, and primates**. Amongst bipeds, birds and humans demonstrate exceptional agility, locomotion efficiency, and terrain traversability despite having limitations in actuation and sensory delays [Alexander, 1992, More et al. 2010]. The **trunk accounts for 1/2 the humans' body mass, and 3/4 of a bird's mass**. With a small support base (feet), the trunk and its orientation become an integral part of bipedal legged locomotion generation, beyond the task of trunk stabilization. We utilize a spring-loaded inverted pendulum model which we extend by a rigid trunk, similar to the T-SLIP model by Maus et al., 2008.

We implement **VP controllers with a VP above (VPA) or below (VPB) the center of mass**. We research bipedal VP running in the following scenarios: downhill and step-down running for human-like morphology (numerical simulations), human step-down running (experiments and numerical simulations), human running on level ground (numerical simulations), and running with bird-like trunk orientation (numerical simulations) [1315, 1318, 1319, 1332].

We show that positioning the VP below the center of mass (CoM) can explain the forward trunk pitching during human running. We show that the VP method can stabilize single step-down perturbations up to 40cm, and downhill grades up to 20-40 degrees at speeds of 2-5 m/s. A VP below the CoM leads to a synergistic work between the hip and leg, reduces leg loading, but increases peak hip torque. Camouflaged step-down perturbations affect the location of the VPB in simulation and human experiments. Our simulation results suggest that a VPB can encounter the step-down perturbations and bring the system back to its initial equilibrium state. Adjusting the VP vertically redistributes joint loads, and potentially improves locomotion energy efficiency.

More information: https://dlg.is.mpg.de/project/Trunk-and-Virtual-Point-in-Bipedal-Locomotion

Shaping the reward landscape without shaping the reward

Alexander Badri-Sprowitz, Steve Heim, Felix Ruppert, Alborz Aghamaleki Sarvestani

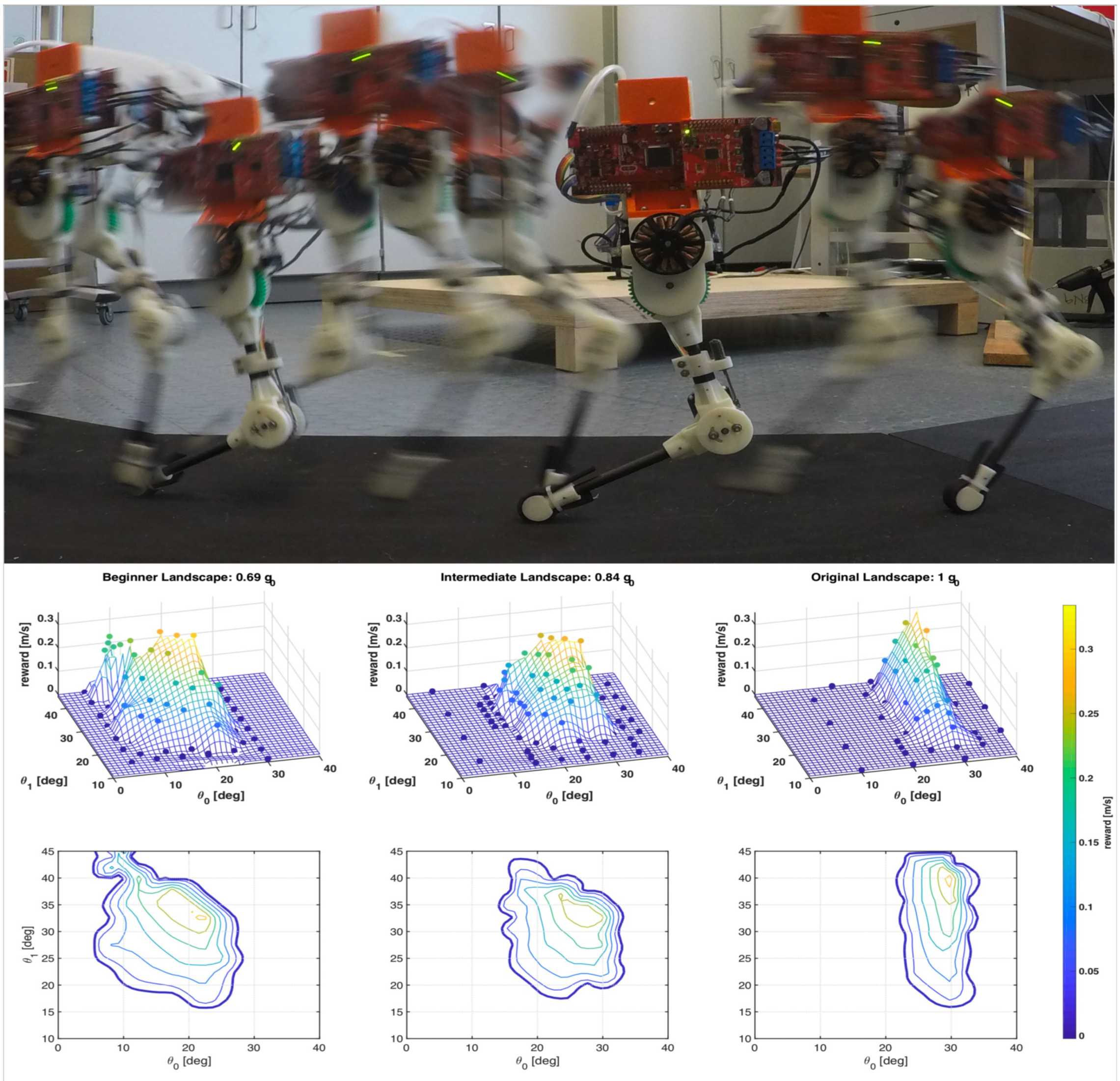


Figure 10.4: We can empirically map the true reward landscape of our monoped hopping robot, and observe the change of the landscape due to the modified effective weight of the system.

In reinforcement learning, tasks that are difficult to learn are often made more amenable by shaping the reward (cost) landscape. This is typically done by adjusting the reward signal R in the Markov Decision Process, composed of (S, A, P, R, γ), where S is the state-space, A is the action-space, P is the probability transition matrix (i.e. the system dynamics), R is the reward signal and γ is the discount factor.

We formalize and show the effectiveness of changing other parts of the MDP, in particular the dynamics P and the initial state conditions S_0. **The concept of training wheels, first formalized by [Randløv, 2001], uses instead a temporary adjustment of the system dynamics**. As a practical example, we show that mechanically adjusting the weight of a hopping robot influences its reward landscape, resulting in learning that can occur more reliably and with less initial tuning [1336].

In a simple simulation, we show that state initialization can play an important role in state initialization. Indeed, **we show that state initializations that are doomed to fail can not only be useful to learn effective policies, but they can result in much more reliable as well as quicker learning** [1335].

More information: https://dlg.is.mpg.de/project/shaping-the-reward-landscape-without-shaping-the-reward

Velocity dependent forces in legged locomotion

Alexander Badri-Sprowitz, An Mo, Steve Heim, Fabio Izzi

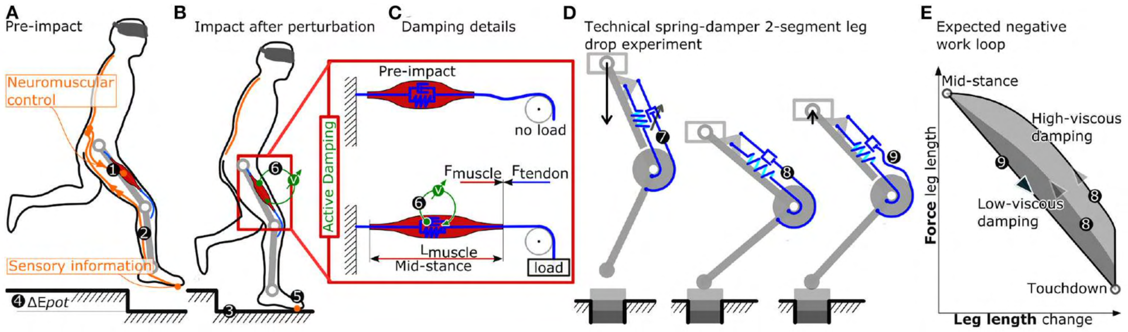


Figure 10.5: A) The nerve conduction velocity in organic tissue is limited (More et al., 2010). B) In case of perturbations like an unexpected step-down, delayed sensory information can be lead to falling. C) We hypothesize that 'smart' actuators like muscles possess internal mechanisms leading to muscle force based on the muscle extension velocity. D) We implement a two-segmented leg with a parallel spring-damper. A) The nerve conduction velocity in organic tissue is limited (More et al., 2010). B) In case of perturbations like unexpected step-down, delayed sensory information can be lead to falling. C) We hypothesize that muscles possess internal mechanisms creating muscle force based on the extension velocity. D) We develop a two-segmented leg with a parallel spring-damper. E) Energy dissipated by viscous damping.

Muscle models and experimental observations suggest that **locomotion stability might benefit from physical, viscous damping** in muscle-tendon tissue. Contrary to active damping, **physical damping is inert to delays in neuromuscular control, and noise** caused by sensing, actuation, or information transmission.

We investigate how to exploit physical damping in a leg drop experiment; the stance phase of legged locomotion can be separated into a drop component and a leg angle component. The numerical simulations suggest that adjustable and viscous damping deals best with ground perturbations, compared to Coulomb damping.

In two hardware implementations we test a commercial, off-the-shelf hydraulic damper, and a custom-made, rolling diaphragm damper. We separate the dissipated energy into its components with the help of a dedicated experimental design. We quantitatively identify energy dissipation from the early impact (unsprung-mass effects), viscous damping, Coulomb damping, and orifice adjustments. Viscous, hydraulic **dampers react velocity-dependent, and create an instantaneous, physically adaptive response** to ground-level perturbations **without sensory input**[1] [1317].

In [1316], we present **a new simulation model with a damping term that can be adjusted without retuning other model parameters**. We compare how increased damping affects stability for unexpected ground-height perturbations. Our measure of task-level stability allows trajectories to be compared quantitatively instead of only being separated into a binary classification of "stable" or "unstable".

Our simulation study results show that increased damping contributes significantly to task-level stability; however, this benefit quickly plateaus after only a small amount of damping. **Low intrinsic damping values observed in experiments may have stabilizing benefits**, and are not simply minimized for energetic reasons.

More information: https://dlg.is.mpg.de/project/damping-in-legged-locomotion

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[1] A. Mo, F. Izzi, D. F. B. Haeufle, A. Badri-Spröwitz. Viscous Damping in Legged Locomotion. May 2020.

Lumbosacral organ morphology and function

Alexander Badri-Sprowitz, Viktoriia Kamska, An Mo, Fernanda Bribiesca Contreras

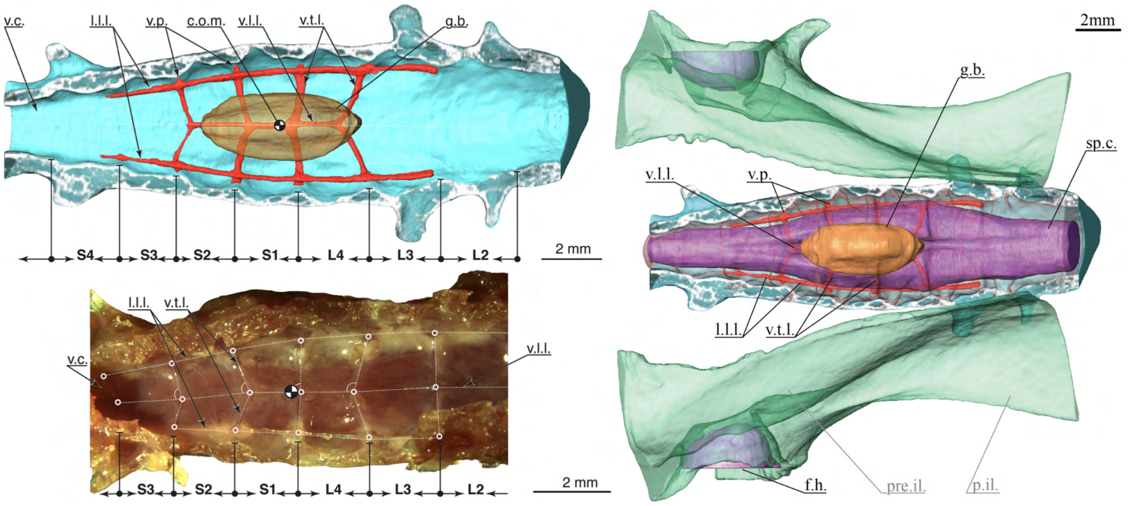

Figure 10.6: Tissues of the lumbosacral region in birds, digitally and classically dissected, here shown for a quail. The glycogen body (g.b.) with a slightly higher-than water density is supported by a ligament network (v.l.l, v.t.l, v.p., l.l.l). The entire lumbosacral organ (LSO) soft-tissue structure is submerged in spinal cord fluid. Not shown here: accessory lobes with potential mechanosensing function, protruding pair-wise from the spinal cord into the spinal canal.

Birds are diverse and agile vertebrates; they fly and glide through the air, run on the ground, swim and dive in the water, and perch and jump through trees. Birds also show an unusual and unique morphology; an enlargement of the spinal canal in the lumbosacral region. The soft tissue structure involved potentially presents a sensing organ; the **’lumbosacral organ’ (LSO)** [Necker 2002]. Our definition of the LSO includes the spinal cord, a glycogen body positioned in the dorsal bifurcation of the spinal cord, pairs of accessory lobes, a network of denticulate ligaments that support the spinal cord and the glycogen body, and a series of semi-circular canals formed by fused lumbosacral vertebrae.

The unusual feature clustering suggests that the LSO might be involved in bird’s hindlimb neurocontrol of locomotion, likely in addition to the vestibular system. As an intraspinal mechanosensor, the **LSO would propagate feedback almost instantaneously to relevant motor control centers in the spinal cord hemispheres** nearby.

The precise LSO mechanosensing mechanism is still unknown. **We mapped the anatomy with an approach combining traditional gross dissection and 3D imaging** (micro-CT and MRI). We recorded three-dimensional data supporting the hypothesis that the glycogen body and the spinal cord could oscillate vertically within the spinal canal. The glycogen content seems to increase the glycogen body’s density, potentially adjusting LSO sensitivity.

We suggest **the LSO is reminiscent of a mass-spring accelerometer damped by spinal cord fluid**. Previous work pointed out the proximity of accessory lobes to neurocontrol units in the spinal cord relevant for locomotion control (i.e., [Eide 1996]). We are now developing models to investigate the LSO soft material response to locomotion.

More information: https://dlg.is.mpg.de/project/lumbosacral-organ-morphology-and-function

10.3 Awards & Honors

2018

Charlotte le Mouel receives a DAAD postdoctoral fellowship, and joins the Dynamic Locomotion Group. Congratulations, and welcome!

Steve Heim receives an ICRA 2018 RAS Travel Grant. Congratulations!

2017

Steve Heim receives "Outstanding Poster Award" at AMAM2017 on "Towards understanding how changing morphology influences learning". Congratulations!

10.4 Research group leader: Alexander Badri-Sprowitz

Biography

Alexander Badri-Spröwitz is leading the Dynamic Locomotion Group at the MPI for Intelligent Systems in Stuttgart, Germany since 2016. He received his Mechatronics degree from Ilmenau Technical University in 2005 and his Ph.D. in 2010 from the Swiss Federal Institute of Technology Lausanne (EPFL), Switzerland. He was working as a postdoctoral researcher at EPFL, Oregon State University (OSU), USA, and Royal Veterinary College (RVC), UK, and at MPI-IS in Stuttgart. He is a member of the Max Planck Research School for Intelligent Systems and an associate member of the Max Planck ETH Center for Learning Systems. He received two research grants from the Deutsche Forschungsgemeinschaft (DFG) for research related to human-legged locomotion. He aims at understanding the principles underlying legged locomotion in animals and robots, with a focus on biomechanics and neurocontrol. He is developing bioinspired legged robots and numerical models to reproduce legged locomotion in machines, and he is developing novel bioinspired actuators, sensors, and control concepts that leverage the advantages of bioinspired legged machines.

Education

2010	Ph.D (Dr. Sc.), Manufacturing Systems and Robotics, from Ecole Polytechnique Federale de Lausanne (EPFL), Lausanne, Switzerland
2005	MSc equiv. (Diplom-Ingenieur) in Mechatronics, Ilmenau Technical University, Ilmenau, Germany

Employment (appointments) / Academic positions

from 2016	Independent Max Planck Research Group Leader, MPI for Intelligent Systems, Stuttgart, Germany
2014-2016	Postdoctoral researcher at MPI-IS, Stuttgart, Germany
2013-2014	Postdoctoral researcher in shared project at Oregon State University (Dynamics Robotics Laboratory), Corvallis, USA and Royal Veterinary College (Structure & Motion Lab), Hatfield
2011-2012	Postdoctoral researcher at EPFL (Biorobotics Laboratory), Lausanne, Switzerland
2006-2010	Phd candidate researcher at EPFL (Biorobotics Laboratory), Lausanne, Switzerland
2005-2006	Researcher and teaching assistant at Ilmenau Technical University, Ilmenau, Germany
2004-2005	Six month research stay at National Institute of Advanced Industrial Science and Technology (AIST), Neuroscience Research Institute Tsukuba, Japan
2003-2004	Six month internship at National Institute of Advanced Industrial Science and Technology (AIST), Neuroscience Research Institute Tsukuba, Japan

Links

Link to CV on website: https://dlg.is.mpg.de/~sprowitz

11 EMBODIED VISION

11.1 Research Overview

Intelligent agents such as robots require the ability to learn and adapt within their environment. Our group investigates novel methods for learning to understand dynamic 3D scenes and their functioning, and uses this knowledge to perform complex tasks such as autonomous navigation and object manipulation. Traditional approaches often integrate perception and control components engineered for specific tasks and scenarios. In contrast, we aim at systems that learn to act and perceive from raw sensor measurements such as images or tactile information and action experience acquired in their environment. We investigate computer vision methods and end-to-end trainable architectures for learning task-relevant representations that allow agents to plan their actions.

Computer Vision for Embodied Agents: Interpreting visual information plays a key role in autonomous systems that act purposefully in their environment. We develop approaches for visual scene reconstruction and understanding in intelligent systems. Specifically, we are interested in computer vision methods for simultaneous localization and mapping, and 3D and dynamic scene understanding. We also investigate approaches for self-supervised learning and adaptation in order to increase the flexibility of systems.

Learning and Perception of Dynamics Models for Control and Planning: In recent years, learning-based approaches have gained traction due to their prospects of enabling robotic agents to learn their skills through interaction and exploration in the environment. This way, robots could adapt faster to novel situations and learn more generalizable representations than manually engineered approaches. In contrast to model-free approaches, which learn policies and value functions with an implicit understanding of the environment, our paradigm is to make environment models explicit and learn these models for model-based control and planning. Challenges in this regard are to learn generalizable models which transfer to a variety of environments and systems, to achieve sample-efficient learning, and to enable robust approaches which are aware of the uncertainty of models.

11.2 Selected Research Projects

Learning for Model-Based Control and Planning

Jörg Stückler, Jan Achterhold

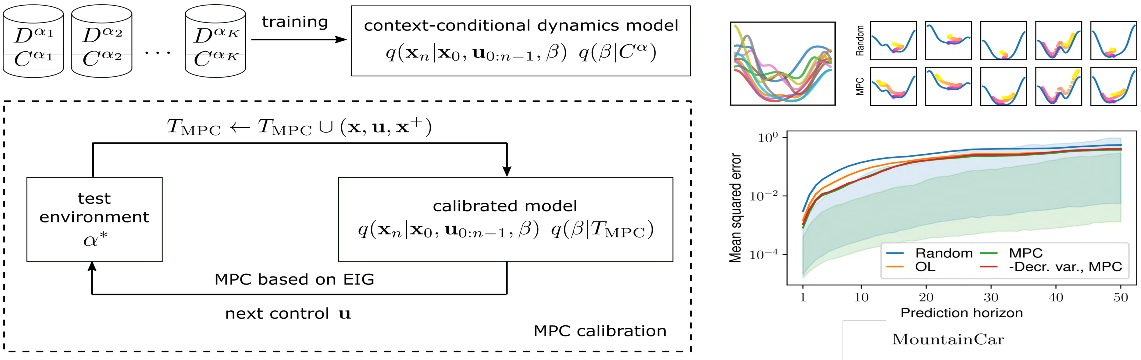

Figure 11.1: Learning of families of dynamics models which are conditioned on context variables β in Explore-the-Context [1349]. The models can be used for system identification using model-predictive control (MPC) with an expected information gain based objective.

Complex everyday environments pose a challenge to the implementation of autonomous robots that purposefully act in these environments. A classical approach for developing autonomous robots is to hand-craft object and environment models that are used for control and planning. These models, however, are typically limited by the implicit assumptions the engineers make about the properties and functioning of the environment, such that the designed system might not generalize to unseen tasks and situations. In this project, we aim to overcome these limitations by enabling agents to learn dynamics models from observations and interaction experience for scene understanding, control and planning.

In Deep Gaussian Latent Process Dynamics (DLGPD [1353]) we develop a novel method which encodes pairs of images of a simulated inverted pendulum into latent states using deep learning and learns action-conditional transition and reward models as Gaussian Processes on the latent states. A CNN decodes back the latent states into images for self-supervised learning. The hyperparameters of the GPs and the parameters of the neural network are trained jointly. The approach achieves more sample-efficient transfer learning to modified environments (different pendulum mass, inverted sign of the applied torques) than a purely deep learning based approach, since the GPs can be conditioned on new transition examples in the modified environments.

In Explore-the-Context (EtC [1349]) we presented a novel method for dynamics model learning which learns a whole family of dynamical systems. This can be useful for environments in which a range of hidden parameters can vary and determine the dynamics model. We learn a probabilistic neural model which encodes a set of example transitions in the environment into a context variable. The probabilistic dynamics model is conditioned on this context variable. We demonstrate that the probabilistic model can be used for planning actions using model-predictive control with expected information gain as objective. In this way, the agent chooses efficient actions to identify the system. Once the context variable is identified, the trained models can also be used for model-predictive control to achieve task goals.

More information: https://ev.is.mpg.de/project/learning-for-model-based-control-and-planning

Physics-based Scene Understanding

Jörg Stückler, Michael Strecke, Rama Kandukuri, Jan Achterhold

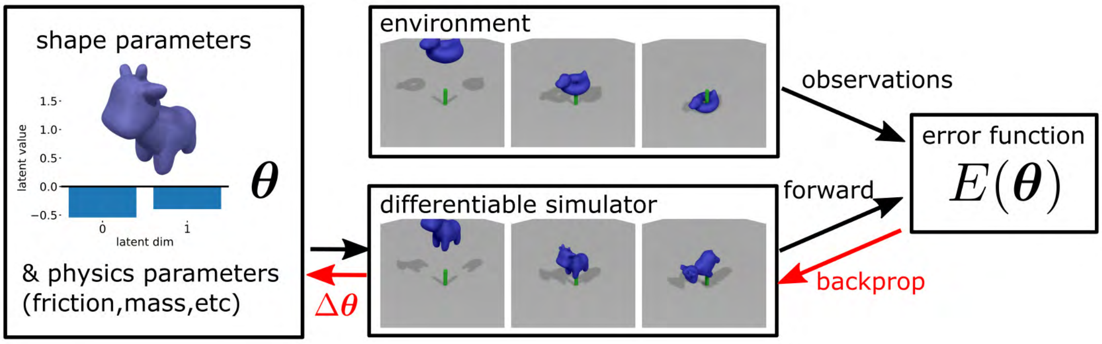

Figure 11.2: Differentiable rigid body dynamics with implicit shapes (DiffSDFSim [1347]).

In this project, we investigate methods for giving intelligent robots an understanding and a sense of physics about their environment. By this, the robots could obtain plausible 3D scene reconstructions and predict the outcome of interactions with the environment. In Zhu et al. [1355], we present a method which learns to embed videos using a variational recurrent neural network into a latent state representation which can be interpreted for dynamics and appearance quantities. We optimize the latent codes of the network using total correlation objectives to improve the disentanglement of the learned latent state representation. We also study the effects of partial supervision to recover latents that model dynamics properties.

In Kandukuri et al. [1350],[1345] we embed a differentiable physics simulation into a deep neural network which we train on video sequences in a self-supervised way. The differentiable physics engine is based on a time-stepping velocity- and constraint-based formulation and can model 3D geometric shape primitives such as boxes, cylinders and spheres. It includes collision, friction and joint constraints. The predicted velocity in each time step is found by solving a linear complementarity problem which can be differentiated at the solution. While a CNN encoder embeds images into the physical positions of objects, the dynamics is propagated by the differentiable physics simulation. The method learns the parameters of the CNN and can concurrently recover physical paramters such as mass or friction. The inductive bias by the physics simulation achieves better accuracy and generalization than a pure neural network based approach in prediction performance of future states and video frames.

We also propose a differentiable physics simulation coined DiffSDFSim [1347] which can simulate the motion and collisions of arbitrary watertight shapes. We represent the shapes using signed distance functions. We demonstrate that shape parameters can be recovered together with physics parameters like mass and friction or external forces on the objects from sample trajectories or depth image sequences in several scenarios such as objects bouncing against a wall, falling on another object, or wrenches applied on the objects.

More information: https://ev.is.mpg.de/project/physics-based-scene-understanding

Visual Simultaneous Localization and Mapping

Jörg Stückler, Michael Strecke, Haolong Li

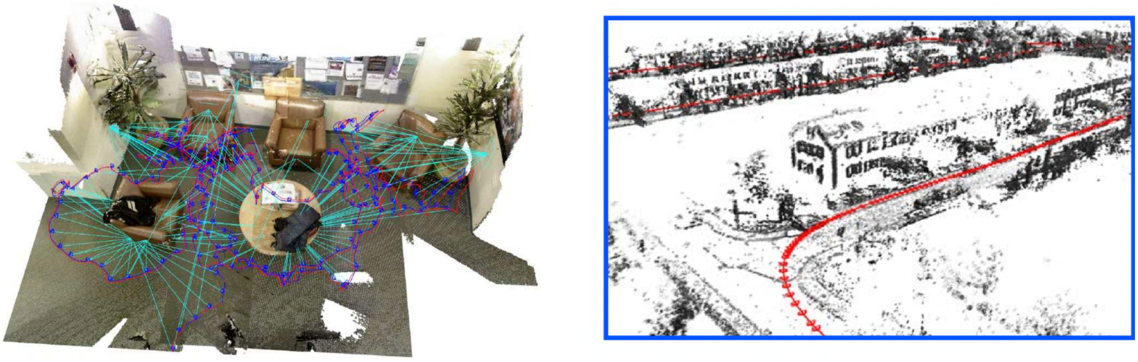

Figure 11.3: Left: RGB-D SLAM with maps that combine keyframes with planar objects. Right: Monocular visual odometry using deep-learning based monocular depth estimation.

Simultaneous localization and mapping or structure-from-motion is an important subfield in computer vision and robotics. It enables the 3D reconstruction of unknown environments from moving cameras and allows for localizing in the built map. We investigate direct visual SLAM approaches that enable robots to acquire 3D maps of the environment and localize in the maps in real-time. For instance, in[1], we combine keyframe-based direct SLAM with tracking and mapping of planar objects in a single optimization framework. The addition of planar objects provides semantic information in the map, reduces drift during camera tracking and improves the estimated map and trajectory estimate. Deep Virtual Stereo Odometry (DVSO,[2]) is a hybrid direct method that uses a learned model for monocular depth prediction as prior for direct monocular SLAM in a classical optimization pipeline. The model predicts dense depth from single images which is used to initialize depth and regularize the depth estimation during optimization.

Cameras record images with a limited framerate (e.g., 30Hz), and a reference image or 3D reconstruction is required to estimate the motion relative to these references. Inertial measurement units well complement cameras with their higher frame-rate measurements which directly sense linear accelerations and rotational velocities in 3 axes. Visual-inertial SLAM approaches seek to combine both sensing modalities for more robust and accurate tracking than each sensing modality alone. In [1346] we present a novel approach to visual-inertial SLAM which estimates camera motion and 3D reconstruction in a two-layer hierarchical pipeline. On the lower visual-inertial odometry layer, camera motion, 3D reconstruction of keypoints, and IMU sensor biases are estimated in a sliding window approach for a set of recent frames and selected keyframes. Older frames are marginalized from the optimization window to keep their estimates as prior information. The global mapping layer optimizes all key frame poses and a 3D reconstruction of keypoints using probabilistic summaries of the accumulated estimates and sensor information between the keyframes from the visual odometry layer. With loop-closing constraints, the mapping layer can compensate for drift accumulated in the visual odometry layer and achieve a more accurate overall estimate of trajectory and map.

More information: https://ev.is.mpg.de/project/visual-simultaneous-localization-and-mapping

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[1] L. Ma, C. Kerl, J. Stueckler, D. Cremers. CPA-SLAM: Consistent Plane-Model Alignment for Direct RGB-D SLAM. In *IEEE International Conference on Robotics and Automation (ICRA)*, 2016.

[2] N. Yang, R. Wang, J. Stueckler, D. Cremers. Deep Virtual Stereo Odometry: Leveraging Deep Depth Prediction for Monocular Direct Sparse Odometry. In *European Conference on Computer Vision (ECCV)*. oral presentation, preprint https://arxiv.org/abs/1807.02570, 2018.

3D Scene Reconstruction and Understanding

Jörg Stückler, Cathrin Elich

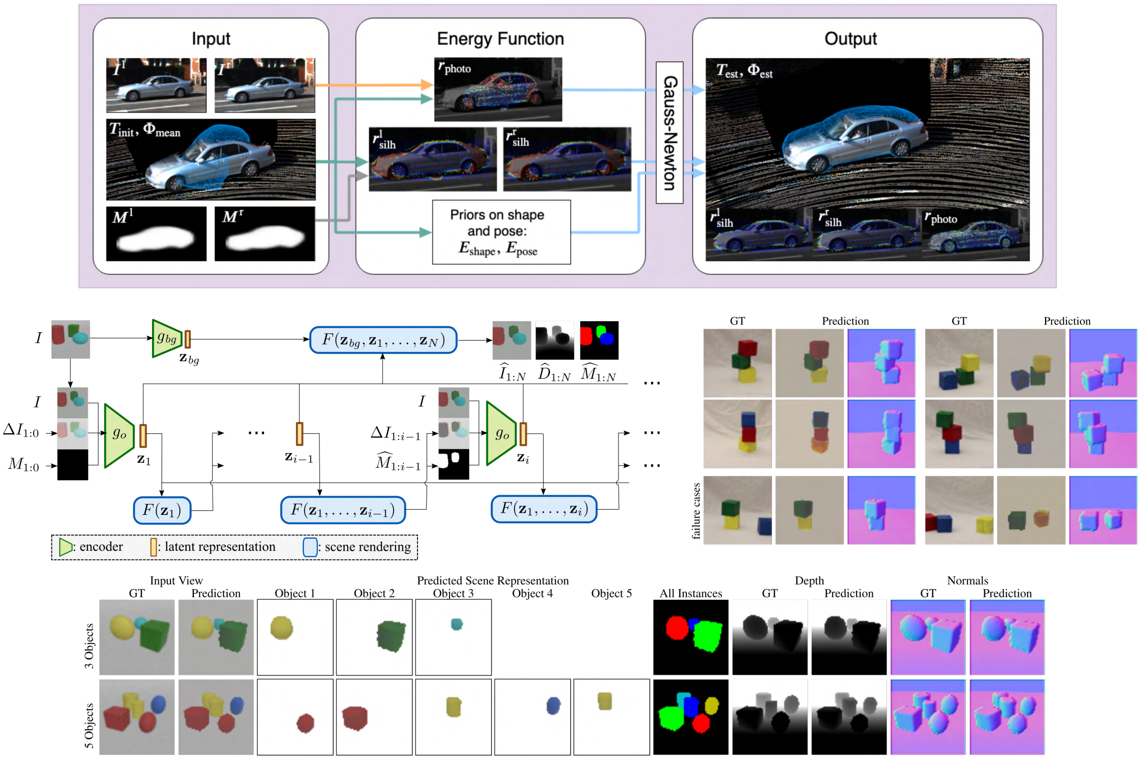

Figure 11.4: Top: direct shape alignment into stereo images using PCA shape priors [1354]. Bottom: Multi-object scene parsing and reconstruction using deep shape priors.

Representing scenes at the granularity of objects is a prerequisite for scene understanding and decision making. For instance, for autonomous driving, the ability to parse scenes into static and moving objects and obtain 3D information can be useful to reason on possible actions and collision-free paths. In DirectShape [1354], we propose a novel method for determining the pose and shape of vehicles in stereo images which does not require a dense stereo reconstruction. Instead a shape space of vehicle objects represented in a low-dimensional PCA embedding is fitted into the stereo images using direct image alignment principles. We demonstrate that our approach improves a variety of deep learning based 3D object detectors which are used to initialize the pose estimate of the objects.

In Elich et al.[3] we use deep learning based shape spaces of various object categories including typical household objects. We devise a deep learning based encoder-decoder architecture which parses RGB images recursively into individual objects alongside their shape parameters, texture, 3D position, and orientation. The decoder is implemented by a differentiable renderer which renders the signed distance field representation of the objects and their texture back into images. This way, the model can be trained in a self-supervised way on RGB-D images. The method achieves competitive results in object segmentation and image reconstruction compared to previous approaches which do not use explicit 3D representations.

In a collaboration with the Computer Graphics group at University of Tuebingen, we developed a meta-learning approach for multi-view stereo reconstruction [1351]. Through meta-learning, the method is trained to adapt better to novel datasets by self-supervised learning.

More information: https://ev.is.mpg.de/project/3d-scene-reconstruction-and-understanding

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[3] C. Elich, M. R. Oswald, M. Pollefeys, J. Stueckler. Weakly Supervised Learning of Multi-Object 3D Scene Decompositions Using Deep Shape Priors. Tech. rep. 2020.

Dynamic Scene Understanding

Jörg Stückler, Michael Strecke, Haolong Li

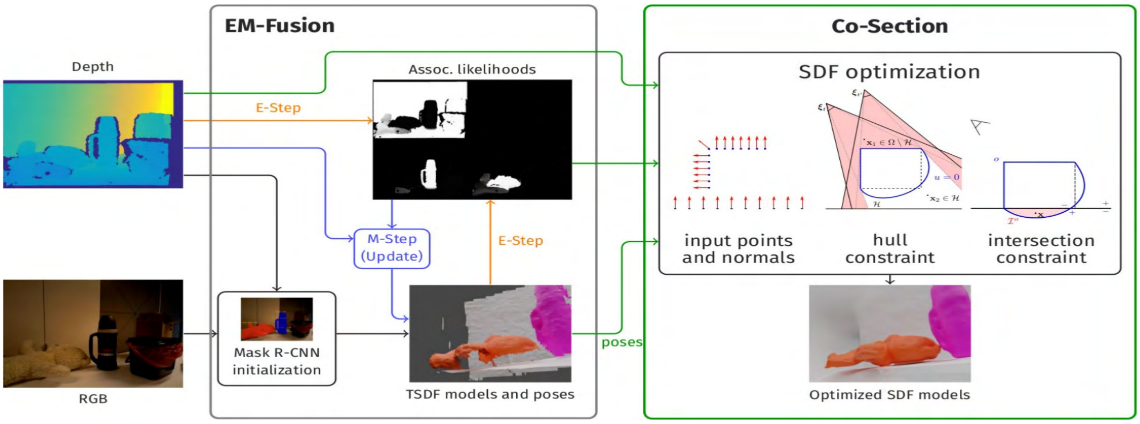


Figure 11.5: Simultaneous localization and 3D mapping of dynamic objects with EM-Fusion [1356], and shape completion using visual hull and object intersection constraints in Co-Section [1352].

When agents interact with their environment, or act in dynamic scenes, they require the ability to observe moving objects. Early approaches to SLAM treat dynamics as outliers and are mostly concerned with mapping and localizing with respect to the static environment. We pursue methods that can detect moving parts of the scene, and track and reconstruct these as separate objects.

In EM-Fusion [1356] we propose a tracking and mapping approach which segments objects based on semantic instance segmentation and motion cues. In an expectation-maximization framework, the approach incrementally estimates 3D maps of the segmented objects represented in signed distance fields (SDF), and tracks the motion of the objects by aligning the depth measurements on the objects with the SDF maps. The EM approach provides probabilistic soft associations of image pixels to objects which can make mapping and tracking more robust and accurate than hard decisions.

EM-Fusion only maps the visible parts of the objects. In Co-Section [1352] we proposed a method for completing the shapes with visible hull and object intersection constraints in a physically plausible way. The approach is based on a variational method which optimizes the SDF maps from data, plausibility and regularization terms. For instance, we demonstrate that the method allows for closing the contour of an object towards the support surface when the object is placed on a table.

For high rate and high dynamic range tracking, event-based cameras which measure logarithmic intensity changes at each pixel asynchronously are promising devices. In [1348] we present a 3D object tracking method which can estimate the 6-DoF motion of objects on short time intervals. It combines tracking using events on one layer with photometric image frame alignment on a second optimization layer. In experiments with synthetic data, we demonstrate that the combination of both event- and frame-based alignment can outperform pure event- or frame-based tracking for fast moving objects. In future work we aim at scaling the method to longer sequences with real data.
More information: https://ev.is.mpg.de/project/dynamic-scene-understanding

11.3 Awards & Honors

2020

Rama Kandukuri, **Jan Achterhold**, and **Joerg Stueckler** received an Honorable Mention at GCPR 2020 for their paper "Learning to Identify Physical Parameters from Video Using Differentiable Physics"

11.4 Research group leader: Jörg Stückler

Biography

Joerg Stueckler received his Diploma (equiv. M.S.) in Computer Science from the University of Freiburg (2007), and his Ph.D. in Computer Science from Bonn University (2014). As a postdoc, he performed research in the Computer Vision groups of the Technical University of Munich and RWTH Aachen University. In 2017/2018, he spent one semester as a visiting professor in the Department of Computer Science at the Technical University of Munich for the Chair of Computer Vision and Artificial Intelligence. Since April 2018, he is leader of the independent Max Planck Research Group on Embodied Vision at the Max Planck Institute for Intelligent Systems in Tuebingen. Dr. Stueckler investigates research topics in computer vision, machine learning and robotics. In computer vision and robotics, he is most known for his research on 3D scene understanding and localization and mapping. Dr. Stueckler is the recipient of the 2015 Georges Giralt Award for the best PhD thesis in European robotics.

Awards

- Best Paper Honorable Mention at German Conference on Pattern Recognition 2020
- Georges Giralt PhD Award 2015 by euRobotics aisbl
- 1. Place RoboCup@Home in 2011, 2012, and 2013
- Finalist KUKA Service Robotics Best Paper Award at IEEE ICRA 2011

Fellowships

- MPI-ETH Center for Learning Systems, Associated Member, since 2018
- International Max Planck Research School on Intelligent Systems, Faculty Member, since 2018

Education

2014	Dr. rer. nat. in Computer Science, Rheinische Friedrich-Wilhelms-Universität Bonn
2007	Diploma in Computer Science, Albert-Ludwigs-Universität Freiburg

Employment (appointments) / Academic positions

04/2018 – present	Max Planck (Cyber Valley) Independent Research Group Leader at the MPI for Intelligent Systems
10/2017 – 03/2018	Visiting Professor, Department of Computer Science, Technical University of Munich
10/2015 – 10/2017	Postdoctoral Researcher, Computer Vision Group, RWTH Aachen University
09/2014 – 09/2015	Postdoctoral Researcher at Chair for Computer Vision and Pattern Recognition, Technical Univerity of Munich
04/2008 – 08/2014	Research Associate at Chair for Autonomous Intelligent Systems, University of Bonn
10/2007 – 04/2008	Research Associate in Research Group on Learning Humanoid Robots, University of Freiburg

Links

Link to CV on website: https://ev.is.mpg.de/~jstueckler

12 HUMAN ASPECTS OF MACHINE LEARNING

12.1 Research Overview

With the widespread use of machine learning (ML) algorithms in everyday life, it is essential to study the human aspects of these algorithms. ML algorithms are increasingly used to make critical decisions that influence our day-to-day life: banks and credit rating agencies assess the default risk of individual customers; government agencies aim to improve public safety, health care, and education; last but not least, advertisers target specific groups to increase sales efficiency. All these ML processes interact with and affect human beings to an extent far beyond that of classic computer programs. It is necessary to study the implications of these processes on humans and vice versa.

The human aspects of ML group focus primarily on two topics. The first relates to ethics and fairness in machine learning, emphasizing exploring ways to prevent bias and discrimination in decision-making. The second explores ways of building teams between machine learning and humans to make better joint decisions.

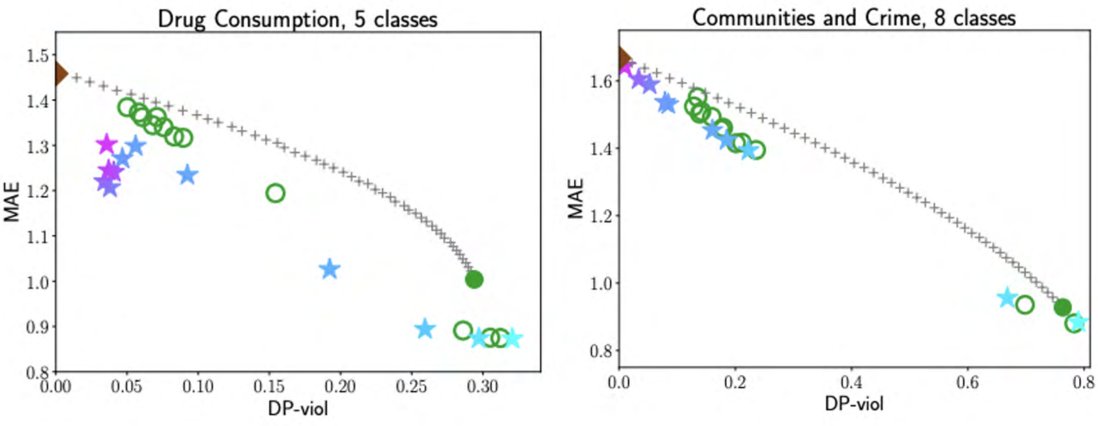
One of the central research goals in machine learning is to design machines that can make decisions in much the same way humans do. However, machine learning algorithms can only make decisions based on the data they have been fed - they then reproduce biases in the data in their decision-making. This poses a challenge, particularly in areas where the use of machine learning and artificial intelligence impacts people's lives. For instance, many banks use algorithms to determine their customers' credit scores and thus to make decisions about loan applications. However, given that these algorithms are trained with historical data that can be biased and incomplete, their recommendations can be unfair or discriminatory. We design ML models that ensure fair and unbiased decisions.

In addition to developing machine learning systems that make decisions based on principles of fairness, our group also aims to explore methods that will enable a collaborative synergy between humans and machines when they make joint decisions. For instance, in medical diagnosis, the physician might get help from a machine that analyzes all the patient's historical data and predicts their medical needs. To build more effective hybrid human-ML models, we build meta-algorithms that shape humans and ML's decision-making dynamic.

12.2 Selected Research Projects

Pairwise Fairness for Ordinal Regression

Samira Samadi, Matthäus Kleindessner, Muhammad Bilal Zafar, Krishnaram Kenthapadi, Chris Russell



Ordinal regression can be understood as multi class classification over an ordered label set. For example, consider a hiring scenario, where given a job applicant's features, such as their prior experience or education, we want to predict a label in bad, okay, good, excellent. Perhaps surprisingly, fairness for ordinal regression has not been studied to date. The order information not only entails that different kinds of misclassifications should be weighted differently, but also has certain implications when we try to be fair in such a prediction task. For example, an applicant that should be scored as 'okay' would feel treated unfairly if misclassified as bad, but probably not if they were misclassified as good. Or it might be acceptable to misclassify all excellent applicants from a minority group as good as long as all other excellent applicants from other (majority) groups are misclassified in the same way.

In this project[1] we focus on two group fairness notions adapted from the literature on fair ranking and present a strategy to learn a predictor that is accurate and approximately fair according to either one of these notions. Typically a trade-off exists between accuracy and fairness, and our strategy allows us to control this trade-off via a parameter. In extensive experiments, we show that for different choices of the parameter we typically obtain predictors with different accuracy-vs-fairness performance and our strategy allows us to explore the trade-off. Often, our strategy compares favorably to state-of-the-art methods for ordinal regression that do not take fairness into account in that it yields predictors that are only slightly less accurate, but significantly more fair than the predictors produced by those methods.

One of measures of fairness that we consider here is pairwise demographic parity (Pairwise DP). Pairwise DP is the requirement that it is as likely for a point sampled from one protected group to be preferred over a point sampled from a second group as it is for the converse to happen (e.g., a female applicant being considered better than a male applicant happens just as likely as a male applicant being considered better than a female one). The figure above describes an example of our methods performance compared to an state-of-the-art method on two publicly available datasets: "Drug Consumption" and the "Communities and Crime". The performance is measured with respect to the accuracy of prediction measured by mean absolute error (MAE) and violation of pairwise DP (DP-viol). Stars indicate performance of our algorithm for different parameter values. Circle indicates the performance of a classical technique for ordinal regression known as the proportional odds model and + line is the baseline.

More information: https://hml.is.mpg.de/project/pairwise-fairness-for-ordinal-regression

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[1] M. Kleindessner, S. Samadi, M. B. Zafar, K. Kenthapadi, C. Russell. Pairwise Fairness for Ordinal Regression. *arXiv preprint arXiv:2105.03153*, 2021.

12.3 Research group leader: Samira Samadi

Biography

I am a research group leader at the Max Planck Institute for Intelligent Systems (MPI-IS). My research background is in machine learning and algorithm design with a recent focus on developing fair and efficient ML models. More broadly, I study the interactions between humans and AI and use my findings to design AI systems that augment humans' abilities rather than replacing them. I got my Ph.D. from the School of Computer Science at Georgia Tech.
I am also a faculty at the International Max Planck Research School (IMPRS-IS) and an associated faculty at the Max Planck ETH Center for Learning Systems (CLS).

Awards & Fellowships

- Georgia Tech College of Computing Ph.D. Dissertation award (honorable mention), 2021.
- ARC Fellowship Georgia Tech, 2017
- Provost Doctoral Entrance Award, University of Waterloo, 2014
- Computer Science Merit Scholarship, University of British Columbia, 2012
- Ranked 281th in Iran's University Entrance Exam among about 500,000 students, 2007

Education

- Ph.D. in Computer Science, Georgia Institute of Technology, Atlanta, US. 2020
- M.Sc. in Computer Science, University of British Columbia, Vancouver, Canada. 2014
- B.Sc. in Mathematics, Sharif University of Technology, Tehran, Iran. 2012

Employment (appointments) / Academic positions

Sept 2020 – Now	Independent Research Group Leader, Max Planck Institute for Intelligent Systems
Spring 2019	Research Intern, Microsoft Research NYC
Spring 2018	Research Intern, Toyota Technological Institute at Chicago
Summer 2016	Research and Developement Intern, Sentient Technologies, San Francisco
2014 – 2015	Visiting Research Associate, University of Waterloo

Links

Link to CV on website: https://hml.is.mpg.de/~ssamadi

13 INTELLIGENT CONTROL SYSTEMS

13.1 Research Overview

The Intelligent Control Systems (ICS) group aims to develop machine learning and decision algorithms for machines in the physical world. Our research often starts with fundamental theoretical questions on learning and control, leading us to develop new methods and algorithms, which we finally implement and demonstrate on physical machines such as robots, vehicles, and other autonomous systems.

When learning on physical machines, some special challenges arise, which are different from other machine learning domains typically involving pure software or computer systems. For example, learning in the real world often has to cope with imperfect and relatively small data sets, because physical systems cannot be sampled arbitrarily and exhibit high-dimensional and continuous state-action spaces. A constant stream of data (e. g. from sensors) requires online and lifelong learning, but often on embedded hardware with limited computational resources. Finally, theoretical guarantees on safety, robustness, and reliability are essential for physical learning systems, but often not available in standard machine learning. These are some of the fundamental challenges that arise when artificial intelligence meets the physical world - and that drive our research. In addition to learning, control, and decision making for a single physical system, we are also interested in distributed and networked problems, for example, where multiple intelligent agents cooperate to achieve a common goal. How can a team of robots efficiently coordinate their actions? What information should they exchange, and when? And how to design for limited embedded resources such as bandwidth, computation, or energy? These are some of the questions that we address in this research direction.

As we seek to bridge computational and physical intelligence, research at ICS is highly interdisciplinary. In particular, we combine and intersect the disciplines of machine learning, systems & control theory, applied mathematics, and robotics. The main directions of the research at ICS can be summarized as:

- **Learning-based control:** machine learning and control theory for learning on physical systems with guarantees;
- **Distributed intelligence:** learning, control, and cooperation across multi-agent and cyber-physical networks;
- **Resource efficiency:** achieving high performance control and learning with limited resources (embedded computation, small data, communication bandwidth, energy).

History of the group

The ICS group was founded in February 2018, when Sebastian Trimpe was appointed as a Max Planck Research Group Leader (W2) at MPI-IS Stuttgart. The Max Planck Research Group is primarily funded through the Cyber Valley initiative. Since its start, the ICS group grew rapidly to around eight PhD and postdoctoral researchers, as well as many students and interns. In May 2020, Sebastian Trimpe accepted a full professorship at RWTH Aachen University, where since he has been building up a new Institute for Data Science in Mechanical Engineering. ICS has been continued for a transition period with the agreed end date of April 2022. With several researchers transitioning from Stuttgart to Aachen, the ICS group formed the foundation for an entire new institute at RWTH.

We are grateful for the opportunities that we have had at MPI-IS. The ecosystem allowed us to grow quickly, form a strong team, and have impact in several new research directions at the intersection of Machine Learning and Automatic Control.

13.2 Selected Research Projects

Learning Safety Constraints and Safe Learning

Steve Heim, Alexander von Rohr, Sebastian Trimpe

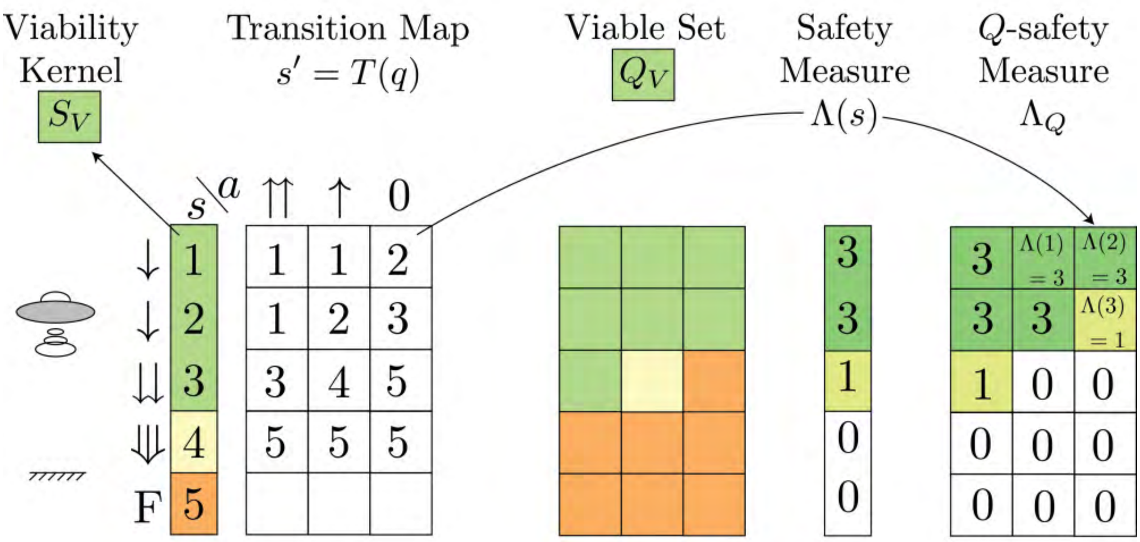

Figure 13.1: A toy example from [1320] illustrating all the key objects: the viability kernel S_V, the viable set Q_V, the safety measure $\Lambda(s)$ and the Q-safety measure Λ_Q. Both S_V and Q_V are highlighted in green. We also highlight state-action pairs which result directly in failure in orange, and those that are unviable in yellow. The arrows and illustration are only to help with intuition.

To deploy learning algorithms in robots for real-world situations, it is vital to provide safety guarantees of the learned behavior. Although failures are often easy to classify (e.g., a legged robot has fallen if the body touches the ground), the actual state-space constraints (e.g., the robot is stumbling and can no longer catch itself) often are not. Consequently, safe learning algorithms often use heuristics, conservative approximations of the constraint function, or require substantial model-based knowledge.

We formalize sharp constraints in our paper [1320] using viability theory, and show that we can learn this constraint in a model-free setting by making use of a measure taken over the set of viable state-action pairs. While safety can only be guaranteed after learning the constraint has converged, failures can be greatly reduced during learning by using the constraint estimate.

We shed more light on the topic in [1377] by examining how constraint-learning interacts with a nominal, task-relevant control policy. We show that exploration is not necessary to learn the constraint: following the nominal policy greedily fulfills the minimum exploration requirements

More information: https://ics.is.mpg.de/project/learning-safety-constraints-and-safe-learning

Event-triggered Learning

Friedrich Solowjow , Dominik Baumann, Sebastian Trimpe

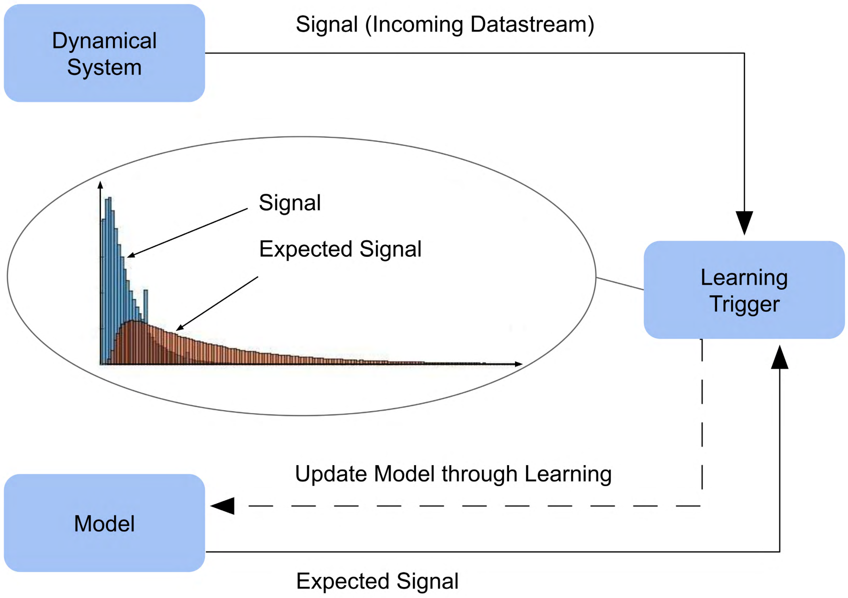

Figure 13.2: Abstraction of the event-triggered learning framework. Structured decisions about when to learn are obtained based on a comparison of a model-based reference signal and incoming data from the system.

The ability to learn is an essential aspect of future intelligent systems that are facing uncertain environments. However, the process of learning a new model or behavior often does not come for free, but involves a certain cost. For example, gathering informative data can be challenging due to physical limitations, or updating models can require substantial computation. Moreover, learning for autonomous agents often requires exploring new behavior and thus typically means deviating from nominal or desired behavior. Hence, the question of when to learn is essential for the efficient and intelligent operation of autonomous systems.

Event-triggered learning (ETL) was proposed in our publication [1395] for making principled decisions on when to learn new dynamics models and applied for efficient communication in distributed systems. Information exchange in distributed systems is a key aspect in solving collaborative tasks. Communication often takes place over wireless networks, and therefore, needs to be used carefully to avoid overloading the network. Dynamical models are deployed to predict other agents' behavior and therefore, accurate models are essential to reduce communication effectively. We developed a stochastic trigger to decide when to learn a new model and derive statistical guarantees that the triggering happens at the right time. In a collaboration with TU Berlin, we validated the proposed method experimentally on IMU sensor networks [1367].

While effectively reducing communication in distributed systems, the developed ideas are more general and address in their core the question when to learn with possible extensions in different directions. Among others, in [1362], we investigate their generalization to cost signals. Using different performance signals to perform decisions in reinfocement learning is an important aspect of ongoing research in which we link the exploration-exploitation trade-off to ETL.

More information: https://ics.is.mpg.de/project/event-triggered-learning

Structured Robot Dynamics Learning

Andreas Rene Geist, Sebastian Trimpe

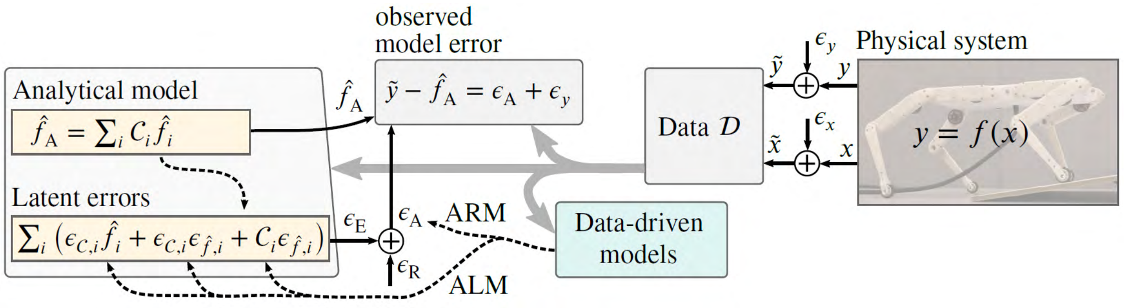

Figure 13.3: Data-driven models can approximate the output error of an analytical physics model (ARM) as well as reduce latent errors inside the analytical physics model (ALM).

The computation of a robot's actions via model-based control approaches requires an accurate robot dynamics model. Robot dynamics are often considerably influenced by physical phenomena such as friction, elasticities, and contacts. These phenomena can be environmental dependent as well as unknown a-priori, which in turn aggravates analytical physics modeling. As an alternative approach, recent works resort to learning dynamics solely from input-output data using regression models such as neural networks or Gaussian processes (GP). Yet, data sets that stem from physical systems are often limited in size and information value which aggravates data-driven modeling.

In this project, we explore the idea of combining analytical physics with data-driven regression for the identification of non-linear robot dynamics, which we refer to as structured modeling. In [1359], we survey literature on structured robot dynamics modeling and distinguish these into:

- Analytical output residual modeling (ARM), in which a data-driven model approximates the residual (target function) of an analytical physics model.
- Analytical latent modeling (ALM), in which a data-driven model replaces a latent function (target function) *inside* an analytical physics model.

Compared to ARM, ALM can be more sample-efficient by: i) reducing the complexity of the target function; ii) reducing the dimensionality of the target function; and iii) enabling the inclusion of physics knowledge into the data-driven model.

We further delve into ALM in [1383], in which a GP is linearly transformed using implicitly constrained rigid-body dynamics. We further extended the proposed modeling framework in [1376] by combining a rigid-body dynamics library with GP regression and automatic differentiation in PyTorch. Currently, we investigate how ALM may improve on the sample efficiency of parametric data-driven modeling and plan to provide practical guidelines for the synthesis of structured robot dynamics models.

More information: https://ics.is.mpg.de/project/robot-dynamics-synthesis

13.3 Research group leader: Sebastian Trimpe

Biography

Since February 2018, Sebastian Trimpe is a Max Planck Research Group Leader (W2) at MPI-IS Stuttgart. He leads the independent Max Planck Research Group on Intelligent Control Systems, which has been established within the Cyber Valley Initiative and focuses on fundamental research at the intersection of control, machine learning, distributed systems, and robotics. Trimpe obtained his PhD (Dr. sc.) degree in Dynamic Systems and Control from ETH Zurich in 2013 with Raffaello D'Andrea as his advisor. Previously, he received a B.Sc. degree in General Engineering Science in 2005, a M.Sc. degree (Dipl.-Ing.) in Electrical Engineering in 2007, and an MBA degree in Technology Management in 2007, all from Hamburg University of Technology. In 2007, he was a research scholar at the University of California at Berkeley.

In 2020, Trimpe took on a full professorship (W3) at RWTH Aachen University. He is now Professor for Data Science in Mechanical Engineering and has begun building the corresponding institute, which he also heads. Over the course of 2020 and 2021, Trimpe transitions his research group in Stuttgart, where he keeps a co-affiliation.

Awards & Fellowships

- 2020 Future Prize by the Ewald Marquardt Stiftung for innovations in control engineering
- 2019 Best Paper Award of the International Conference on Cyber-Physical Systems
- 2019 Best Demo Award of the International Conference on Information Processing in Sensor Networks
- 2016 Top Four Finalist for Best Student Paper Award (as advisor and co-author), International Workshop on Discrete Event Systems
- 2014 KlarText! Klaus Tschira Award for achievements in public understanding of science
- 2011 IFAC Congress Interactive Paper Prize (best out of 450 interactive papers
- 2005 General Engineering Award for the best undergraduate degree
- 2002-07 Scholarship from the German Academic National Foundation (Studienstiftung)

Education

2013	PhD (Dr. sc.), ETH Zürich, Switzerland, advisor: Raffaello D'Andrea
2007	MSc (Dipl.-Ing.), Electrical Engineering, TU Hamburg, Germany
2007	MBA, Technology Management, TU/NIT Hamburg, Germany
2007 (04-11)	Visiting Student Researcher, University of California Berkeley, USA
2005	BSc General Engineering Science, TU Hamburg, Germany

Employment (appointments) / Academic positions

since 2020	Full Professor (W3) and Head of Institute for Data Science in Mechanical Engineering, RWTH Aachen University
since 2020	Member of Board of Directors, Center for Artificial Intelligence, RWTH Aachen University
02/2018 - 04/2022	Max Planck Research Group Leader (W2), Max Planck Institute for Intelligent Systems, Stuttgart (since 05/2020 as part-time side-appointment)
10/2016 - 01/2018	Senior Research Scientist &Group Leader, AMD, MPI-IS
09/2013 - 09/2016	Research Scientist, Autonomous Motion Deptartment (AMD) MPI-IS
03/2013 - 08/2013	Postdoctoral Researcher & Lecturer, ETH Zürich

Links

Link to CV on website: https://ics.is.mpg.de/~strimpe

14 ORGANIZATIONAL LEADERSHIP AND DIVERSITY

14.1 Research Overview

Recent economic (e.g., shift from large organizations to decentralized networks of individuals and small businesses), technological (increased use of machine learning algorithms in the workplace), and societal changes (e.g., #MeToo and #TimesUp movements) require organizations to adapt to the transforming nature of work by challenging assumptions, changing corporate cultures, and altering the way work is performed. The "Organizational Leadership and Diversity" group aims to 1) investigate the use of artificial intelligence (AI) tools in the workplace to unleash the true potential of diversity and inclusion (D&I), 2) develop ways to mitigate bias in human-machine partnership in the workplace, and 3) explore the nature of leadership in the AI age.

Consistent evidence suggests that diversity and inclusion leads to improved organizational outcomes, such as the increased quality of decision-making, better hiring results, reduced employee turnover, and higher employee engagement. Furthermore, D&I increases creativity on both the individual and team level, drives radical innovation, and relates to higher financial performance. Despite the pronounced benefits of D&I, most organizations still struggle with implementation of D&I, leaving the question of how organizations can create meaningful change in this area. The research group answers this question by investigating the possible use of AI tools to promote D&I. For example, AI can be implemented to use inclusive language in job descriptions, recommend jobs that job-seekers might not have considered for themselves, provide blind ranking of applicants, build diverse slates of candidates, scrutinize the history of hiring, promotion, termination, and bonus decisions, and audit pay practices. We use qualitative and quantitative methods to explore what AI tools are suitable for promoting D&I and how they can be implemented in a responsible, ethical manner.

The second area of research is to develop ways to mitigate bias in human-machine partnership in the workplace. Previous research suggests that AI tools can be biased against people of color as well as women. As individuals also have their own unconscious biases, would human-machine partnership be more helpful or harmful, especially in high-risk work scenarios? We explore how humans interact with AI to better understand under what conditions combining the inputs of humans and machines produces the most accurate results.

The third area of research looks into ways how the use of AI is changing the nature of leadership. AI tools have been increasingly implemented in organizations across industries to enhance decision-making, fundamentally changing workflows, roles, and responsibilities of leaders. Indeed, AI tools seem to supplant many "hard" elements of leadership, especially those connected with collecting, synthesizing, and processing of vast amounts of information. However, previous research suggests that the increased use of AI at the workplace also strengthens the role of leaders' soft skills, such as the leader's adaptability to constant changes, his/her ability to provide followers with a clear and appealing vision, and the willingness to learn from both inside and outside the organization. We focus on exploring what leadership capabilities and skills are necessary for leaders to successfully deal with the challenges in the age of AI. In addition, we investigate how AI tools can be used to enhance leadership development.

14.2 Selected Research Projects

Value-Driven Leadership Approaches to Managing Organizations

Ksenia Keplinger, Sheila Hanson

One of the main concerns of modern organizations is ethics, where only few institutions have not been affected by abuse of power. Recent history (e.g., Volkswagen emissions scandal, BP Deepwater Horizon oil spill, Wells Fargo account fraud, Theranos bankruptcy) highlights ethical breakdowns in organizations, which call organizational leaders to strive to behave responsibly, be an example for their followers, and to re-gain trust with them. The leaders' behavior sets the stage for incorporating values into day-to-day operations in order to improve the relationship between leaders and followers. This project brings together various values-driven leadership approaches to managing organizations and offer leaders and managers strategies to mitigate ethical challenges. For inspiration, we look at the historical examples, such as moral leadership of the Benedictines, members of a religious order that has been founded in the sixth century. The Benedictines were able to establish their own businesses in various industries and successfully manage in the times of hardship. Using the example of Benedictine leadership, we explore how different leadership styles (ethical, servant, authentic leadership) can co-exist and complement each other in organizations that have been operating for more than 1,500 years. The results suggest that moral leadership of the Benedictines does include elements of ethical, authentic and servant leadership but goes beyond them by specifically delineating (religious) values that both leaders and followers adopt to develop trust relationships. Further, the Benedictines offer guidance for the selection of leaders, mentoring of followers, and finding meaning in work and entrepreneurial activities. Benedictine leadership also offers ideas how the implementation of religious values can help leaders and followers make decisions in morally challenging situations. These insights can be useful for leaders and entrepreneurs beyond the religious sector.

More information: https://ld.is.mpg.de/project/value-driven-leadership-approaches-to-managing-organizations

When Managers Become Robin Hoods: A Mixed Method Investigation

Ksenia Keplinger, Russell Cropanzano, Daniel Skarlicki, Thierry Nadisic, Marion Fortin, Phoenix von Wagoner

Figure 14.1: When a manager perceives that his/her subordinate has been treated unfairly, s/he behaves as Robin Hood by attempting to compensate the victim. This often happens without the consent of senior leadership and can involve rule breaking. Examples of Robin Hood behaviors include providing a gift from the department's budget and giving days off to compensate the victim for working during the strike.

The purpose of this project is to explore when and why managers take steps to informally compensate subordinates whom they deem to have been unfairly treated by senior leaders. These Robin Hood (RH) behaviors are 1) triggered by a manager's perception of the subordinate's mistreatment, 2) an attempt to allocate the victim something extra that belongs to the company, and 3) can involve rule breaking. Drawing from deontic justice theory, we proposed and tested a theory of RH in four studies. In Study 1, we examined the premise of our definition and identified key RH behaviors using qualitative interviews. Managers freely admitted that they engaged in RH behaviors by allocating organizational resources to workers in response to an injustice committed by senior leadership. Some managers saw themselves as engaging in wrongful conduct, but for "good reasons," so they felt that their actions were justified. In Study 2, we surveyed 265 participants, who reported observing RH behaviors at the workplace, and investigated different types of justice that can motivate RH. The findings confirmed Hypothesis 1 that RH can be triggered by interpersonal injustice (perceptions that the subordinate has been treated with a lack of dignity and respect by senior leadership) or by distributive injustice (perceptions that the subordinate has received an outcome that is low in fairness). These types of justice differ with respect to their moral relevance, with interpersonal justice being more likely to trigger moral concerns than distributive. In experimental Studies 3 and 4 (184 and 119 participants, respectively), we confirmed Hypothesis 2 that the effect of injustice on RH is a function of the strength and salience of the manager's moral identity. When moral identity is high, interpersonal justice predicts RH regardless of the level of distributive justice. When moral identity is low, the two types of justice similarly predict RH.

More information: https://ld.is.mpg.de/project/when-managers-become-robin-hoods-a-mixed-method-investigation

14.3 Research group leader: Ksenia Keplinger

Biography

Since August 2020, Ksenia Keplinger leads the newly established independent research group "Organizational Leadership & Diversity" at the Max Planck Institute for Intelligent Systems in Stuttgart. Prior to this, she first was a postdoctoral researcher and then a faculty member at the University of Colorado Boulder, USA. She earned her Ph.D. in Business Studies at the Johannes Kepler University of Linz, Austria, in 2016, completed a Master's degree in Finance and Managerial Accounting at the same university in 2010, and received a Bachelor's degree in International Economics in 2007 at the Higher School of Economics in Russia. During her studies, she worked for several tech companies, and these experiences motivated her to pursue fundamental interdisciplinary research at the intersection of leadership, diversity, and artificial intelligence. Her research aims to support organizational leaders in using artificial intelligence to unleash the true potential of diversity and inclusion. Her research has been featured in leading peer-reviewed outlets, including Business Ethics Quarterly, PLoS One, and Harvard Business Review.

Awards & Fellowships

Dec 2016	**Award of Excellence** from the Austrian Federal Ministry for Science and Research
Dec 2016	**Recognition Award for Women in Research** from the Dr. Maria Schaumayer Foundation
Dec 2011	**Ludwig Scharinger Award** from the Johannes Kepler University of Linz
Nov 2011	**VOEWA Academic Award** from the Association of Austrian Business Graduates
Oct 2011	**REHAU Business Award** from REHAU Group

Education

Oct 2010 - July 2016	**Ph.D., Business Studies (Focus on Organizational Behavior)** (with highest distinction) Johannes Kepler University of Linz, Austria (Feb13 - Feb15 - parental leave)
Oct 2007 - Oct 2010	**M.S (Mag.), Finance and Management Accounting** (with highest distinction) Johannes Kepler University of Linz, Austria
Sep 2003 - Jun 2007	**B.S., International Economics** (with highest distinction). National Research University - Higher School of Economics, Russia

Employment (appointments) / Academic positions

Aug 2020 - present	**Researcher Group Leader** Max Planck Institute for Intelligent Systems, Stuttgart, Germany
Aug 2019 - Aug 2020	**Scholar in Residence** (Faculty position with research, teaching, and service duties) University of Colorado Boulder, Leeds School of Business, Boulder, US
Aug 2016 - Aug 2019	**Postdoctoral Researcher** University of Colorado Boulder, Boulder, US (Jun18 - Dec18 - parental leave)
Aug 2015 - Aug 2016	**Research Associate** University of Colorado Boulder, Boulder, US

Link to cv on website: https://www.is.mpg.de/person/kkeplinger

15 LEARNING AND DYNAMICAL SYSTEMS

15.1 Research Overview

The current paradigm in supervised machine learning is to fit high-capacity models to large amounts of data. Prior information, such as causal structures, first-principles, or a-priori known symmetries, is often discarded, and as a result, the predictions may not generalize to unforeseen situations, i.e., situations that are not adequately captured with the training data. This is particularly relevant for the use of machine learning in cyber-physical systems (such as self-driving cars, the smart grid, or transportation systems), where safety and reliability is a primary concern. We propose to analyze the problem of decision-making for these systems, which includes investigating and developing data-driven methods that explicitly incorporate prior knowledge from physics.The incorporation of prior information might also lead to an efficient quantification of prediction uncertainties and can potentially be exploited by optimization algorithms for fast decision-making. As a result, the research contributes to a safe and reliable deployment of machine learning algorithms in cyber-physical applications.

Our past research included the following machine learning aspects:

1) Predictions: In our previous work,[1], we investigated how prior knowledge from physics can improve the predictions of deep neural networks. More precisely, for the prototypical problem of fluid flow predictions, we showed that models preserving Lyapunov stability tend to generalize better. The work highlights that incorporating even basic properties such as Lyaunov stability, can already improve predictions.

2) Decisions: Mathematical optimization represents the basis for rational decision-making and lies at the heart of most machine learning methods. While algorithms for convex optimization problems are well understood, there are many open questions regarding the design of efficient algorithms for nonconvex problems. In previous work,[2],[3], we rigorously analyzed and quantified the convergence rate of optimization algorithms with momentum, for both convex and nonconvex functions. Thus, our work not only develops an intuitive and qualitative understanding of acceleration - a phenomenon, which researchers have struggled to explain for a long time - but generalizes beyond the convex setting. This might enable fast-converging algorithms for many problems encountered in machine learning and artificial intelligence.

3) Experiments with real-world testbeds: We build cyber-physical systems for testing and evaluating our learning and decision-making algorithms. We showed in experiments with various robotic testbeds (balancing robot, different flying vehicles, robot for playing table tennis) that incorporating prior knowledge leads to efficient and safe learning,[4],[5],[6].

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[1] M. M. N. B. Erichson, M. Mahoney. Physics-informed Autoencoders for Lyapunov-stable Fluid Flow Prediction. In *Machine Learning and the Physical Sciences Workshop, Conference on Neural Information Processing Systems*, 2019.

[2] M. Muehlebach, M. I. Jordan. Optimization with Momentum: Dynamical, Control-Theoretic, and Symplectic Perspectives. *Journal of Machine Learning Research* **22** (73): 1–50, 2021.

[3] M. Muehlebach, M. I. Jordan. Continuous-time Lower Bounds for Gradient-based Algorithms. In *Proceedings of the International Conference on Machine Learning*, 2020.

[4] M. Muehlebach, R. D'Andrea. Nonlinear Analysis and Control of a Reaction Wheel-based 3-D Inverted Pendulum. *IEEE Transactions on Control Systems Technology* **25** (1): 235–246, 2016.

[5] C. Sferrazza, M. Muehlebach, R. D'Andrea. Learning-based parametrized model predictive control for trajectory tracking. *Optimal Control Application and Methods* **41** (6): 2225–2249, 2020.

[6] M. Muehlebach, R. D'Andrea. The Flying Platform - A Testbed for Ducted Fan Actuation and Control Design. *Mechatronics*, 2017.

15.2 Selected Research Projects

First-order optimization under nonlinear constraints

Michael Mühlebach

Optimization plays an essential role in machine learning by providing a theoretical foundation on which algorithms, systems, and datasets can be brought together at unprecedented scales. The focus in recent years has been on unconstrained optimization and first-order algorithms, as this has sufficed for many applications in pattern recognition. In particular, theoretical work on rates, lower bounds, and choice of step sizes has focused on the unconstrained setting. This is despite the important role of constraints in applications: Emerging problems in machine learning involve decision-making in the real world, which often includes safety constraints, economic constraints, and constraints arising from the presence of multiple decision-makers. Similarly, control-theoretic problems often involve interactions with physical, biological, and social systems, whose laws can be expressed as fundamental constraints.

This project aims at developing learning-friendly first-order algorithms that can handle nonlinear constraints. We follow analogies between constrained optimization and non-smooth dynamical systems, where the iterate is represented by a point mass. This leads to a new class of algorithms, where the velocity instead of the position of the point mass is constrained. The algorithmic consequence is that optimizations over the entire feasible set are replaced with sparse, local and convex approximations (even if the feasible set is nonconvex), which reduces the per-iteration complexity and thus expands the range of potential applications. Our research quantified the convergence properties of the resulting algorithms, both in theory as well as with numerical experiments on benchmark problems, [**constraints_in_first-order_optimization**]. We demonstrated that despite the local approximation of the feasible set, the methods still exhibit approximately linear convergence, where the scaling of the rate with the conditioning of the problem is similar to the unconstrained case. In our numerical experiments we observed significant speedups (an order of magnitude) compared to the state-of-the-art interior point method CVXOPT. Our latest research expands towards momentum-based methods, practical applications in machine learning, and the treatment of saddle-point problems.

More information: https://lds.is.mpg.de/project/First-order-optimization-under-nonlinear-constraints

15.3 Awards & Honors

2021

Michael Mühlebach: Extension of Branco Weiss Fellowship until the end of 2023.

15.4 Research group leader: Michael Mühlebach

Biography

Michael Muehlebach studied mechanical engineering at ETH Zurich and specialized in robotics, systems, and control during his Master's degree. He received the B.Sc. and the M.Sc. in 2010 and 2013, respectively, before joining the Institute for Dynamic Systems and Control for his Ph.D. He graduated under the supervision of Prof. R. D'Andrea in 2018 and joined the group of Prof. Michael I. Jordan at the Unversity of California, Berkeley as a postdoctoral researcher. In 2021 he started as an independent group leader at the Max Planck Institute for Intelligent Systems.

He is interested in a wide variety of subjects, including machine learning, dynamical systems, and optimization. During his Ph.D. he developped approximations to the constrained linear quadratic regulator problem and applied them to model predictive control. He also designed control and estimation algorithms for a balancing robot and a flying machine. His postdoctoral research is concerned with analyzing momentum-based optimization algorithms from a dynamical systems point of view.

He recieved the Outstanding D-MAVT Bachelor Award for his Bachelor's degree and the Willi-Studer prize for the best Master's degree. His Ph.D. thesis was awarded with the ETH Medal and the HILTI prize for innovative research. He was also awarded a Branco Weiss Fellowship and an Emmy Noether Fellowship, which funds his research group.

Awards & Fellowships

- Emmy Noether Fellowship 2020
- HILTI Prize for Innovative Research 2019
- ETH Medal 2018
- Branco Weiss Fellowship 2018
- Willy Studer Award 2013
- Outstanding D-MAVT Bachelor Award 2011

Education

- M. Sc. ETH Zurich, Switzerland, 2011-2013
- B. Sc. ETH Zurich, Switzerland, 2008-2011

Employment (appointments) / Academic positions

2021	Independent group leader, Max Planck Society, Germany
2018-2020	Postdoctoral researcher, UC Berkeley, USA
2014-2018	Ph. D., ETH Zurich, Switzerland

Links

Link to CV on website: https://lds.is.mpg.de/~mmuehlebach

16 MOVEMENT GENERATION AND CONTROL

16.1 Research Overview

Research statement

What are the algorithmic principles that would allow a robot to run through a rocky terrain, lift a couch while reaching for an object that rolled under it or manipulate a screwdriver while balancing on top of a ladder? By answering these questions, we try to understand **the fundamental principles for robot locomotion and manipulation** that will endow robots with the robustness and adaptability necessary to efficiently and autonomously act in an unknown and changing environment.

Our research assumption is that understanding how robots should move is a necessary step towards autonomy and **a comprehensive theory of robot movement is needed**. This theory should have at least three important properties:

1. it can be used to control any robot with legs and arms for both manipulation and locomotion tasks,
2. it allows robots to constantly improve their performances as they experience the world,
3. it is fully automated, (i.e. no need for time-intensive engineering each time a new robot is used or a new task needs to be performed).

With this goal in mind, our research agenda follows several complementary directions that define a consistent research program for the generation of movements in autonomous robots. In particular, we explore problems related to high performance torque control, contact interactions, reactive motion planning and movement learning and we apply our research to both locomotion and manipulation problems.

16.2 Selected Research Projects

Whole-body control of legged robots

Ludovic Righetti, Majid Khadiv, Avadesh Merduri, Julian Viereck, Elham Daneshmand, Felix Grimminger

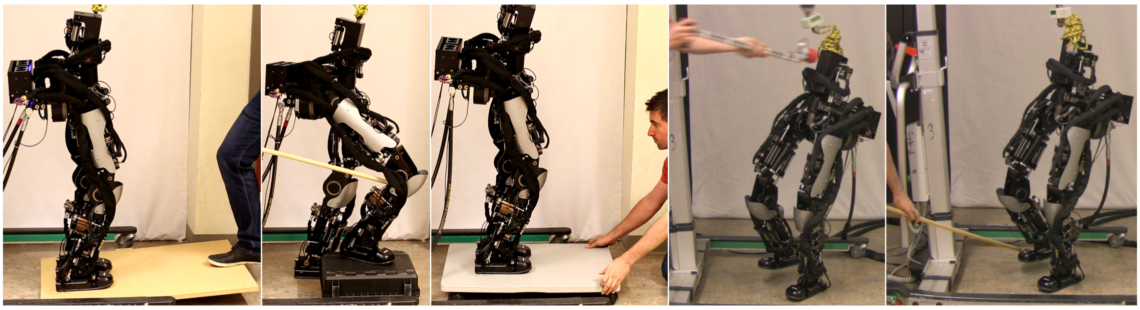


Figure 16.1: The robot is balancing while different kinds of disturbances are applied to its mechanical structure. At each millisecond an optimization problem is solved that decides which joint torques are to be applied in order to realize feedback controllers that a) stabilize the robot after a push while b) generating admissible forces on the ground. With our whole-body controller the robot remains in balance despite comparably strong pushes.

Legged robots are expected to locomote autonomously in an uncertain and potentially dynamically changing environment. Active interaction with contacts becomes inevitable to move and apply forces in a goal-directed way and withstand unpredicted changes in the environment. Therefore, we need to design algorithms that exploit interaction forces and generate desired motions of the robot leading to robust and compliant interaction with the environment. In this context, the choice of a control strategy for legged robots is of primary importance as it can drastically improve performance in face of unexpected disturbances and therefore open the way for agile robots, whether they are locomoting or performing manipulation tasks.

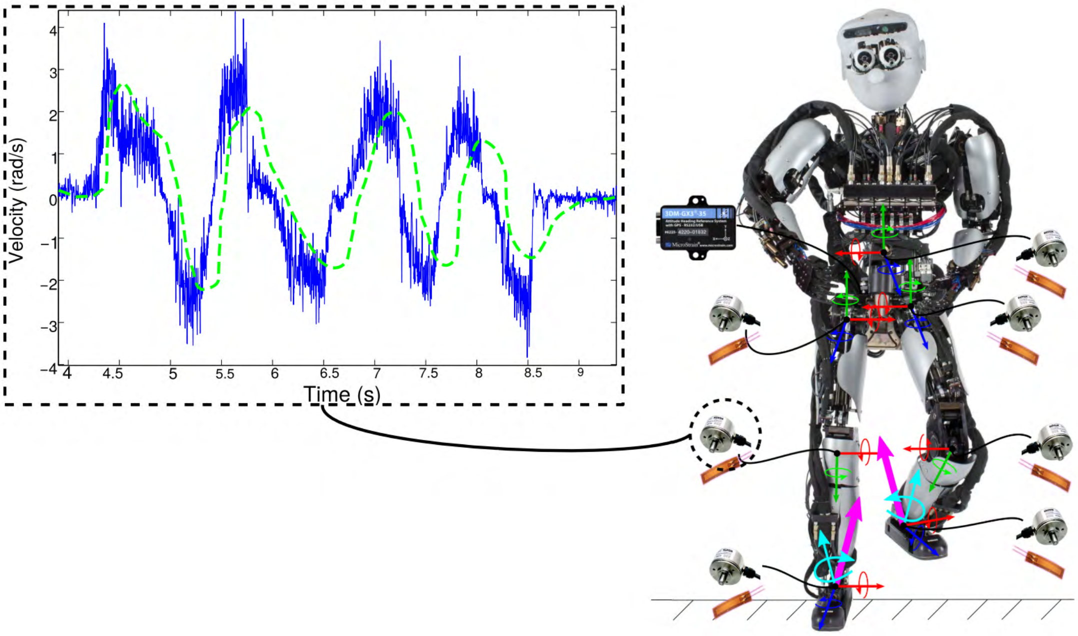
In the theoretical part of our work, we develop algorithms based on dynamic models to control any robots with arms and legs. Our controllers allow for simultaneous control of robot motion and contact interactions in a unified framework. This allows, for example, optimization of contact forces while walking on uneven terrain. In the experimental part of our work, we implement these algorithms on state-of-the-art machines and show the capabilities and limitations of the algorithms when dealing with imperfect models, sensor noise and actuation limitations.

Our experiments show that our humanoid robot can balance with very good performance. It withstands strong pushes and rapid displacements of the ground support. Our experiments demonstrate that our algorithms are robust to dynamic model inaccuracies, sensor noise and actuator bandwidth limitations and it opens the way to more general controller formulations through optimization.

More information: https://mg.is.mpg.de/project/model-based-control-of-floating-based-robots

Sensor fusion for legged robots

Ludovic Righetti, Majid Khadiv, Shahram Khorshidi, Ahmad Gazar, Nick Rotella, Alexander Herzog



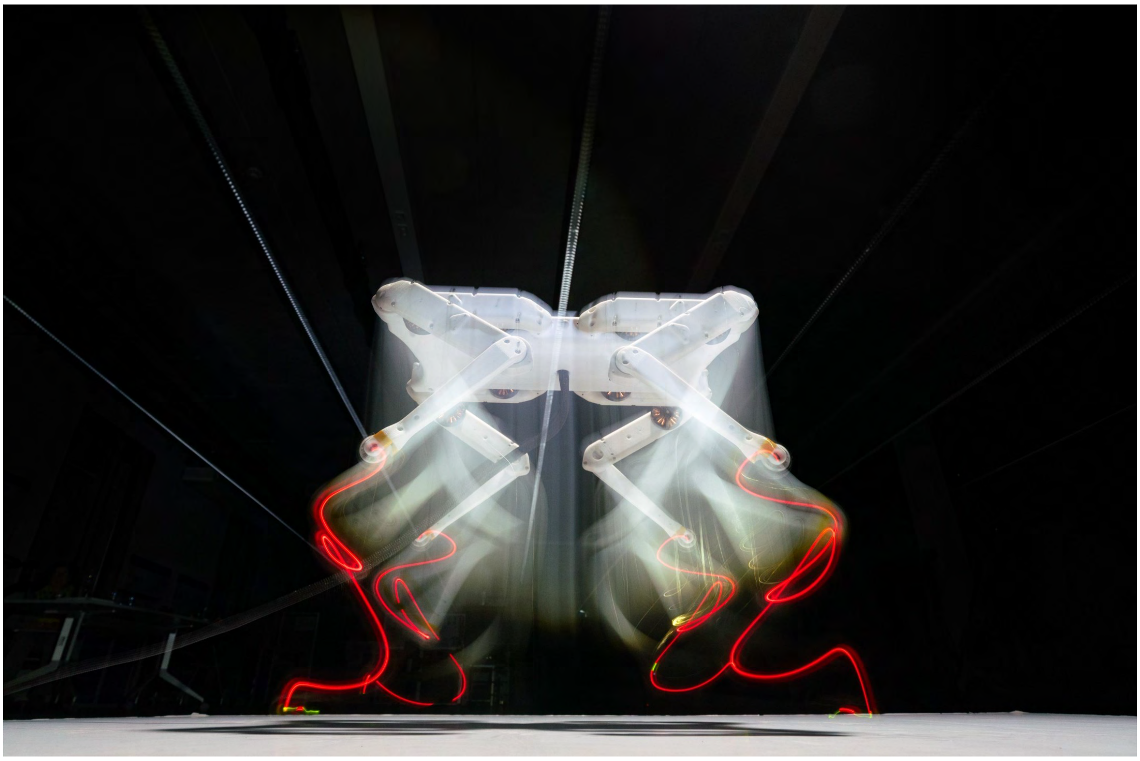
In this project, we explore the problem of fusing sensor information from inertial, position and force measurements to recover quantities fundamental for the feedback control of legged robots. Our final goal is to find a systematic way of fusing multiple sensor modalities to improve the control of legged robots.

- Our theoretical work studies the observability properties of nonlinear estimation models to better understand the fundamental limitations of sensor fusion approaches for legged robots
- We design novel estimators combining multiple sensor modalities (inertial, position and force) to provide accurate estimates of important quantities, such as the position and orientation of the robot in space, its center of mass and angular momentum or any external forces applied on the robot. We demonstrate through numerical simulation and real robot experiments that our estimators can significantly improve the control performance.
- We also investigate machine learning techniques to automatically extract sensory information, for example, to learn how to classify the contact states of a robot using unsupervised learning

More information: https://mg.is.mpg.de/project/sensor-fusion-for-legged-robots

Multi-contact trajectory optimization

Ludovic Righetti, Majid Khadiv, Maximilien Naveau, Ahmad Gazar, Julian Viereck, Bilal Hammoud, Elham Daneshmand, Brahayam Ponton, Sean Mason, Alexander Herzog

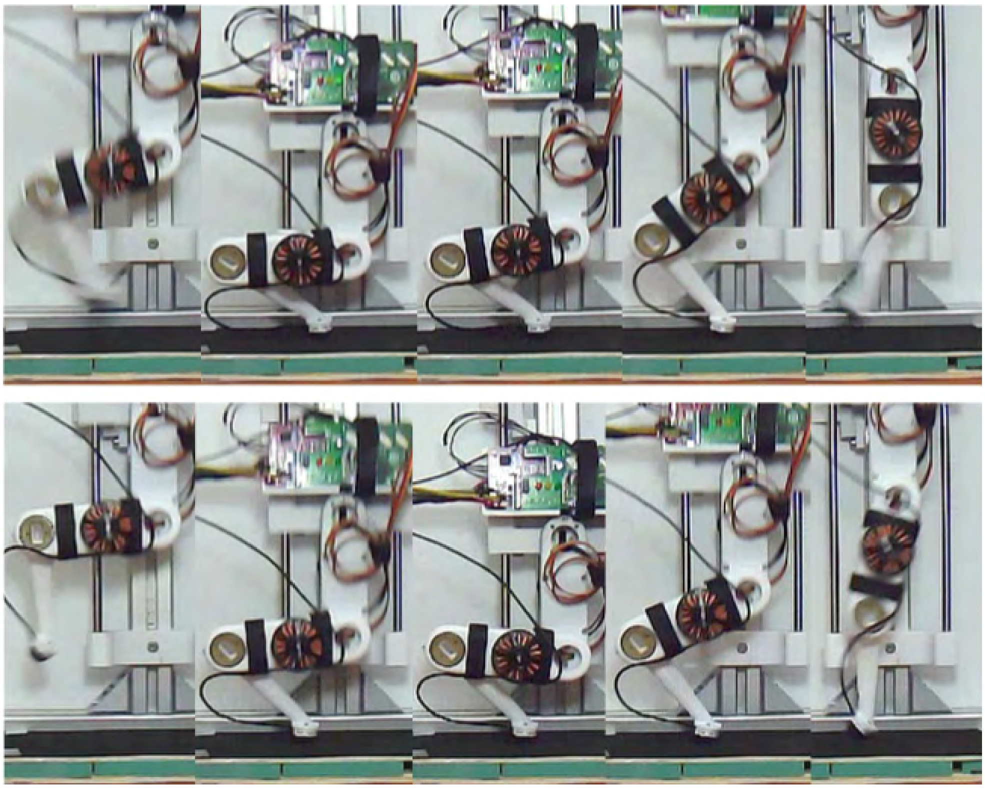


In this project, we investigate the problem of computing movements for robots with arms and legs in intermittent contact with their environment that are physically correct. Our approach uses trajectory optimization and optimal control techniques. In particular, we study how the physics of mechanical systems impose a structure to the underlying optimization problem. This can be leveraged to find computationally efficient algorithms that optimize for the centroidal-momentum dynamics of the robot, contact timing, locations and forces as well as whole-body motions. Our ultimate goal is to demonstrate such techniques in real-time on complex multi-contact tasks.

More information: https://mg.is.mpg.de/project/multi-contact-trajectory-optimization

Learning contact dynamics

Ludovic Righetti, Julian Viereck, Avadesh Merduri, Felix Grimminger, Majid Khadiv



In this project, we are interested in using machine learning techniques to handle robot behaviors with hard impact dynamics and contacts, such as walking, jumping or catching a ball. We investigate reinforcement learning techniques to learn dynamic motions under contact. We also use statistical learning tools to find representations for contacts that can be efficiently incorporated in estimation and control algorithms.

More information: https://mg.is.mpg.de/project/learning-contact-dynamics

16.3 Awards & Honors

2021

Sarah Bechtle won best student paper award at the International Conference of Pattern Recognition 2020 (ICPR2020)

2018

Ludovic Righetti was designated by New York University Provost's Office, together with the Tandon School of Engineering as the **Vivian G. Prins Global Scholar** at New York University for 2018-2019.

2017

Cédric de Crousaz receives an ETH Medal 2017 for his excellent master thesis, which he did at the Autonomous Motion Department (supervision by Ludovic Righetti and Sebastian Trimpe).

Julian Viereck receives the ETH Medal for his outstanding master thesis on "Learning to Hop Using Guided Policy Search" (Handed out to <2.5 % of all master theses per year at ETH Zurich). He did his master thesis at the Movement Generation and Control Group under the supervision of A. Herzog and L. Righetti.

2016

The paper "A Convex Model of Humanoid Momentum Dynamics for Multi-Contact Motion Generation" by Brahayam Ponton, Alexander Herzog, Stefan Schaal and Ludovic Righetti was Finalist for the Best Interactive Session Award at the 2016 IEEE-RAS International Conference on Humanoid Robotics. 10 finalists out of 283 submitted / 186 accepted papers.

The paper "Stepping Stabilization Using a Combination of DCM Tracking and Step Adjustment" by Majid Khadiv, Sébastien Kleff, Alexander Herzog, Ali Moosavian, Stefan Schaal and Ludovic Righetti was Finalist for the Best Paper Award at the 4th RSI International Conference on Robotics and Mechatronics (ICROM).

Ludovic Righetti receives the Heinz Maier-Leibnitz Prize 2016. It is awarded by the German Research Foundation (DFG) and the German Federal Ministry of Education and Research. It is considered the most prestigious award in Germany for early career researchers across all disciplines who have established an independent scientific career since having gained their doctorates.

Ludovic Righetti receives the IEEE-RAS Early Career Award (Academic) for "his contributions to the theory of, and experiments in, robot locomotion and manipulation". It is awarded by the IEEE Robotics and Automation Society to "individuals in the early stage of their career who have made an identifiable contribution or contributions which have had a major impact on the robotics and/or automation fields".

16.4 Research group leader: Ludovic Righetti

Biography

Ludovic Righetti is an Associate Professor in the Electrical and Computer Engineering Department and in the Mechanical and Aerospace Engineering Department at the Tandon School of Engineering of New York University and a Senior Researcher at the Max-Planck Institute for Intelligent Systems (MPI-IS) in Tübingen, Germany.
He leads the Machines in Motion Laboratory , where his research focuses on the planning and control of movements for autonomous robots, with a special emphasis on legged locomotion and manipulation. He is more broadly interested in questions at the intersection of decision making, automatic control, optimization, applied dynamical systems and machine learning and their application to physical systems.

He studied at the Ecole Polytechnique Fédérale de Lausanne (Switzerland) where he received an engineering diploma in Computer Science (eq. M.Sc.) in 2004 and a Doctorate in Science in 2008 under the supervision of Professor Auke Ijspeert. Between March 2009 and August 2012, he was a postdoctoral fellow at the Computational Learning and Motor Control Lab with Professor Stefan Schaal (University of Southern California). In September 2012 he started the Movement Generation and Control Group at the Max-Planck Institute for Intelligent Systems in Tübingen, Germany where he became a W2 Independent Research Group Leader in September 2015. He moved to New York University in September 2017.

Awards & Fellowships

- 2021 Piero Zamperoni Best Overall Student Paper Award for Sarah Bechtle at the IEEE International Conference for Pattern Recognition 2021
- 2020 IEEE Senior member grade elevation
- **2019 Invited Keynote Speaker** at the IEEE-RAS International Conference on Humanoid Robots
- **2019 Google Faculty Research Award**
- 2018 Vivian G. Prins Global Scholar at New York University (2018-2019)
- 2016 **Heinz Maier-Leibnitz Prize** Awarded by the German Research Foundation (DFG) and the German Federal Ministry of Education and Research.
- 2016 **IEEE Robotics and Automation Society Early Career Award**, $1,000 prize for individual *"for contributions to the theory of, and experiments in, robot locomotion and manipulation"* Awarded by the IEEE Robotics and Automation Society to "individuals in the early stage of their career who have made an identifiable contribution or contributions which have had a major impact on the robotics and/or automation fields".
- 2016 Finalist for the Best Interactive Session Award at the IEEE-RAS International Conference on Humanoid Robotics, 10 finalists out of 283 submitted / 186 accepted papers.
- 2016 Finalist for the Best Paper Award at the 4th International Conf. on Robotics and Mechatronics.
- 2014 **European Research Council Starting Grant**, For the project CONT-ACT: Control of contact interactions for robots acting in the world.
- 2012 Finalist for Best Paper Award at the IEEE-RAS International Conference on Humanoid Robotics, 5 finalists out of 233 submitted / 133 accepted papers.
- 2011 **IROS Best Paper Award**, IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). The paper was also nominated for best student paper award (for P. Pastor).

- 2010 **Georges Giralt PhD Award** for the best PhD thesis in Europe in the field of robotics. Awarded by the European Robotics Research Network, EURON (now euRobotics).
- 2006 Finalist for the best student paper award at the IEEE-RAS International Conference on Robotics and Automation (ICRA). 3 student finalists out of 1756 submitted / 680 accepted papers

Education

2008 **Doctorate in Science** (Equivalent to Ph.D.), Thesis: *Control of locomotion using dynamical systems: design methods and adaptive frequency os- cillators*, **Received the Georges Giralt PhD Award**, Advisor: Prof. Auke J. Ijspeert. Computer Science Department, Ecole Polytechnique Feédérale de Lausanne, Switzerland

2004 **Engineering Diploma in Computer Science** (Equivalent to M.Sc.) Thesis: *Control and Synchronization with Nonlinear Dynamical Systems for an application to Hu- manoid Robotics*, **Received the Jean Landry Award**, Advisor: Prof. Auke J. Ijspeert Computer Science Department, Ecole Polytechnique Feédérale de Lausanne, Switzerland

Employment (appointments) / Academic positions

Sept 2017	**Associate Professor** New York University, USA, Department of Electrical and Computer Engineering and Department of Mechanical and Aerospace Engineering (Joint Appointments)
Sept 2017	**Senior Researcher**, Max-Planck Institute for Intelligent Systems, Germany
2015-2017	**W2 Independent Research Group Leader**, Max-Planck Institute for Intelligent Systems, Germany
2012-2015	**Group Leader**, Autonomous Motion Dept., Max-Planck Institute for Intelligent Systems, Germany
2011-2012	**Postdoc**, Autonomous Motion Dept., Max-Planck Institute for Intelligent Systems, Germany
2009-2012	**Visiting Researcher**, Computational Neurosciences Laboratories, ATR, Japan
2009-2012	**Postdoc** Computer Science Department, University of Southern California, USA

Links

Link to CV on website: https://mg.is.mpg.de/~lrighetti

17 NEURAL CAPTURE AND SYNTHESIS

17.1 Research Overview

The main theme of the research group is to capture and to (re-)synthesize the real-world using commodity hardware. It includes the modeling of the human body, tracking, as well as the reconstruction and interaction with the environment. The digitization is needed for various applications in AR/VR as well as in movie (post-)production. Teleconferencing and working in AR/VR is of high interest and will have a high impact on the society. It will change the way we communicate, how and where we work and live. A realistic reproduction of appearances and motions is key for such applications, to enable an immersive interaction. Especially, capturing natural motions and expressions of a human as well as the photorealistic reproduction of images under novel views are very challenging. But with the rise of deep learning methods and, especially, neural rendering, we see immense progress to succeed in these challenges.

For these neural rendering methods, the underlying representation of appearance, geometry and motion are of paramount importance. Within this research group, we work on novel neural scene representations that allow for controllability, editability as well as for generalization and composition. Specifically, we concentrate on 3D representations for humans that can capture the fine scale details of the body shape, facial expressions, hair, and the dynamics of clothing. With respect to the controllability, we work on motion synthesis approaches that can drive these reconstructions based on a variety of input modalities, like video, audio, or only text.

As the goal is to reconstruct and synthesize humans in their environments, we also investigate techniques to reconstruct objects and scenes. Especially for scenes, we work with incomplete data (due to occlusions, or regions that are not observable) which has to be completed. While recent approaches for geometry completion show promising results, the texture and appearance completion is a very challenging and unsolved problem. Besides static objects and scenes, people also interact with non-rigid objects. Tracking and reconstructing these, especially, with neural non-rigid tracking (where parts of a non-rigid tracking pipeline are learned) produce state-of-the-art results[1][2]. Still there are a lot of open challenges that we are working on, especially, the reconstruction of the appearance, as well as the tracking and reconstruction from RGB-data only.

The development of algorithms for photo-realistic creation or editing of image content comes with a certain responsibility, since the generation of photo-realistic imagery can be misused. Therefore, we collaborate with researchers from the digital multi-media forensics field to improve the detection of synthetic or manipulated images and videos. Here, the insights of our motion capturing and person specific motion signatures help detection methods to generalize to unseen manipulation methods [1444]. Furthermore, we contribute and manage large-scale manipulation datasets that are generated by our synthesis methods, which allow researchers to train and benchmark their detection methods.

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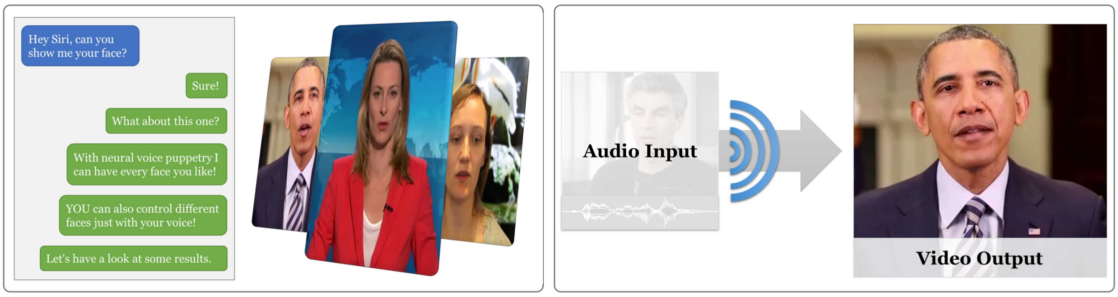
[1] A. Bozic, P. Palafox, M. Zollöfer, A. Dai, J. Thies, et al. Neural Non-Rigid Tracking. In *NeurIPS*, 2020.

[2] A. Bozic, P. Palafox, M. Zollöfer, J. Thies, A. Dai, et al. Neural Deformation Graphs for Globally-consistent Non-rigid Reconstruction. In *IEEE/CVF Conf. on Computer Vision and Pattern Recognition (CVPR)*, 2021.

17.2 Selected Research Projects

Multi-modal Motion Synthesis

Justus Thies, Balamurugan Thambiraja



Hey Siri, can you show me your face?

Sure!

What about this one?

With neural voice puppetry I can have every face you like!

YOU can also control different faces just with your voice!

Let's have a look at some results.

Facial Animation for Digital Assistants

Audio-driven Facial Reenactment

Figure 17.1: The multi-modal motion synthesis of human expressions, head pose and hand gestures is essential for generating the visual appearance of a conversational AI (left), or voice-driven reenactment (right). Especially, implicit facial attributes are challenging to synthesize and are often ignored in recent publications.

A key aspect of digital humans is the capture and synthesis of motions. In this project, we will work on the multi-modal synthesis of human motion, especially, generating videos or an animated 3D avatar from text or audio inputs. We will focus on the synthesis of natural motions of human faces and bodies. A target application is a conversational AI for which we aim to synthesize an according visual appearance.

In the context of audio-driven facial reenactment[3], synthesizing plausible lip motions during speech pauses, generating eye gaze motions as well as eye blinks, and motions of the upper body is a challenging problem. While lip motions have a strong correlation to the audio signal, implicit facial attributes (eye gaze/blink, head pose) only provide a weak correlation. These implicit facial attributes require a long temporal context. We will, therefore, explore recent advances in sequence modelling (especially, transformer networks), to synthesize these attributes. In addition to the facial attributes, synthesizing hand gestures that fit to the audio signal will be explored. In the motion synthesis field, motion matching is a key concept to generate character animations and gestures (especially used in games). We will investigate, if we can incorporate ideas from RetrievalFuse [1441] to such a framework, and whether it is possible to learn a dictionary of motion sequences. Furthermore, the person-specific motion synthesis will be analyzed, and how a motion generator can be conditioned on a specific talking style and emotion.

More information: https://ncs.is.mpg.de/project/Multi-modal-Motion-Synthesis

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[3] J. Thies, M. Elgharib, A. Tewari, C. Theobalt, M. Nießner. Neural Voice Puppetry: Audio-driven Facial Reenactment. In *Computer Vision – ECCV 2020*, 2020.

Representing Controllable Human Avatars

Justus Thies, Jalees Nehvi, Wojciech Zielonka

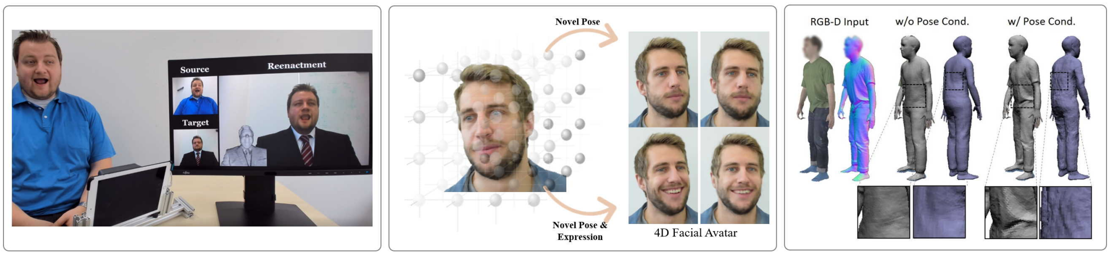

Image-based Avatars Dynamic Neural Radiance Fields Explicit Dynamic Surface Function Networks

Figure 17.2: The representation of a digital double of a human that offers controllability as well as editability is a key challenge in the field. Representations range from classical image-based rendering techniques to learned implicit or explicit models that store geometry and appearance information in a deep neural network.

Representing controllable 3D human avatars, reconstructing, and displaying them photo-realistically is a core challenge in the research field of digital humans. In this project, we analyze person-specific as well as generalized implicit and explicit representations for the human body that can be reconstructed using commodity hardware (e.g., a Webcam or a Kinect depth sensor). We focus on representations that allow us to control the expressions and pose of the body as well as the viewpoint (e.g., needed for teleconferencing applications in AR/VR). With dynamic surface function networks [1443], we introduced a technique which can handle pose dependent surface changes of the body. This explicit representation of the surface allows for fast rendering and can be integrated into existing pipelines that rely on mesh-based representations. While this approach only handles the geometry, we explore extensions to represent the color to enable reconstruction and animation only based on RGB inputs. Besides these explicit representations for geometry and appearance, we will work on implicit representations like NeRFace[4], that can also be used for real-time applications. Implicit representations have the advantage that they are not based on a specific template mesh and can adapt to topological changes. Especially, modelling the hair and the mouth interior with learned implicit functions will be examined. To enable real-time reconstructions of such representations, we will explore implicit representations that rely on fused features, similar to our TransformerFusion [1440]. In [1442], we analyze neural parametric models (NPM), a neural-network-based implicit surface representation that is generalized over a population of human 3D scans. In contrast to PCA-based body models like SMPL, the NPM model is able to represent humans in clothing and can be used to reconstruct a human from a single depth image. If multi-view data is available, our neural deformation graph approach[5] shows promising results, not only for the reconstruction of humans, but also for animals and general objects. Within this project, we also focus on the generalization of neural scene representations for the human head. Especially, the disentanglement of the shape space (representing the identity of a person) and the expression space, as well as the color space and illumination will be examined. To this end, we explore ideas from metric learning (i.e., contrastive learning) that also show great success in face recognition. Specifically, we want to understand, whether a learned metrical space can be used to represent the identity of a person for a generative task (i.e., estimating the shape of the face from an identity code) and whether we can learn similar representations for the expressions and the illumination.
More information: https://ncs.is.mpg.de/project/representing-human-avatars

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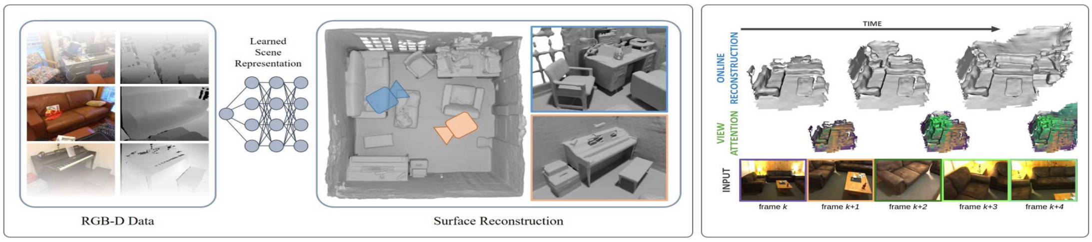
[4] G. Gafni, J. Thies, M. Zollöfer, M. Nießner. Dynamic Neural Radiance Fields for Monocular 4D Facial Avatar Reconstruction. In *IEEE/CVF Conf. on Computer Vision and Pattern Recognition (CVPR)*, 2021.

[5] A. Bozic, P. Palafox, M. Zollöfer, J. Thies, A. Dai, et al. Neural Deformation Graphs for Globally-consistent Non-rigid Reconstruction. In *IEEE/CVF Conf. on Computer Vision and Pattern Recognition (CVPR)*, 2021.

Reconstructing and Synthesizing Objects and Scenes

Justus Thies



Neural RGB-D Surface Reconstruction

Transformer-based 3D Reconstruction

Figure 17.3: The reconstruction of room-scale scenes using state-of-the-art RGB-D- and RGB-based methods.

To enable teleconferencing in VR or AR, we need to reconstruct the environment and the objects we want to interact with. Within this project, we concentrate on static as well as on non-rigid objects and scenes, and aim for the photo-realistic reproduction of this content (i.e., novel view point synthesis, as well as scene editing and composition). To this end, we work on novel neural rendering techniques that reconstruct both geometry and appearance[6][7][8][9][10][11]. Our preliminary work 'Neural RGB-D Surface Reconstruction'[12], reconstructs room-scale scenes using an implicit representation that is learned for a specific scene. It shows superior reconstruction results of the geometry in comparison to state-of-the-art methods. In TransformerFusion [1440], we enable interactive reconstructions of a static scene based on an RGB video sequence. While it shows state-of-the-art results, it lacks details in the reconstructed geometry. A promising direction is to combine this RGB-based approach with RetrievalFuse [1441] which reconstructs scenes from a stream of depth maps. The core idea of RetrievalFuse is to leverage high-resolution geometry patches from a database to reconstruct and complete a room from a sparse pointcloud. While this method works for the geometry, color is still challenging. To get a consistent prediction of the surface color of unobserved regions, we explore recent graph-based methods in conjunction with a dictionary of textures.

While the above-mentioned techniques are designed for static objects and scenes, we also work on general non-rigid tracking and reconstruction methods. Similar to neural rendering, we propose to learn components of non-rigid tracking pipelines, also known as neural non-rigid tracking[13]. To represent the deformation of a general object, we propose the use of a neural deformation graph[14]. This deformation graph explicitly models the deformation of an arbitrary object and allows for deformation editing. A key challenge is to adapt these methods that reconstruct the geometry based on RGB-D data, to be applicable to RGB inputs only. This also requires the capture of the appearance of the objects.

More information: https://ncs.is.mpg.de/project/reconstructing-objects-and-scenes

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[6] J. Thies, M. Zollhöfer, M. Nießner. Deferred Neural Rendering: Image Synthesis using Neural Textures. *ACM Transactions on Graphics 2019 (TOG)*, 2019.

[7] V. Sitzmann, J. Thies, F. Heide, M. Nießner, G. Wetzstein, et al. DeepVoxels: Learning Persistent 3D Feature Embeddings. In *Proc. Computer Vision and Pattern Recognition (CVPR), IEEE*, 2019.

[8] J. Thies, M. Zollhöfer, C. Theobalt, M. Stamminger, M. Nießner. Image-guided Neural Object Rendering. In *International Conference on Learning Representations*, 2020.

[9] H. A. Alhaija, S. K. Mustikovela, J. Thies, M. Nießner, A. Geiger, et al. Intrinsic Autoencoders for Joint Neural Rendering and Intrinsic Image Decomposition. In *3DV*, 2020.

[10] J. Huang, J. Thies, A. Dai, A. Kundu, C. Jiang, et al. Adversarial Texture Optimization from RGB-D Scans. In *Proceedings IEEE Conf. on Computer Vision and Pattern Recognition (CVPR)*, 2020.

[11] A. Dai, Y. Siddiqui, J. Thies, J. Valentin, M. Nießner. SPSG: Self-Supervised Photometric Scene Generation from RGB-D Scans. In *IEEE/CVF Conf. on Computer Vision and Pattern Recognition (CVPR)*, 2021.

[12] D. Azinovic, R. Martin-Brualla, D. B. Goldman, M. Nießner, J. Thies. Neural RGB-D Surface Reconstruction. *ArXiv*, 2021.

[13] A. Bozic, P. Palafox, M. Zollöfer, A. Dai, J. Thies, et al. Neural Non-Rigid Tracking. In *NeurIPS*, 2020.

[14] A. Bozic, P. Palafox, M. Zollöfer, J. Thies, A. Dai, et al. Neural Deformation Graphs for Globally-consistent Non-rigid Reconstruction. In *IEEE/CVF Conf. on Computer Vision and Pattern Recognition (CVPR)*, 2021.

17.3 Research group leader: Justus Thies

Biography

Justus Thies is heading the independent research group 'Neural Capture and Synthesis' at the Max Planck Institute for Intelligent Systems (MPI-IS). Before joining the MPI-IS in 2021, he was a postdoctoral researcher at the Technical University of Munich (TUM), where he helped to build up the Visual Computing & Artificial Intelligence Group of Prof. Matthias Nießner. He received his PhD from the University of Erlangen-Nürnberg in 2017 for his research on marker-less motion capturing of facial performances and its applications. His research group focuses on AI-based performance capturing of humans (digital humans), the reconstruction of scenes and non-rigid objects, humans are interacting with, and the synthesis of photo-realistic image and video content which allows for video editing/synthesis, as well as interactions in AR/VR (e.g., telepresence in VR). Thus, his work combines methods from the Computer Vision, the Machine Learning and the Computer Graphics field. He publishes regularly at top tier conferences with broad impact not only in the research community but also in public media.

Awards & Fellowships

- 2021: EUROGRAPHICS Junior Fellow
- 2019: Research Highlight (Communication of the ACM)
- 2017: Nominee for the GI Dissertation Award (Gesellschaft für Informatik).
- 2017: Excellent graduation with honors (PhD thesis).
- 2016: SIGGRAPH: Best Emerging Technologies Award for the Face2Face Live Demo.

Education

04/2014–04/2017	PhD in Computer Science, University of Erlangen-Nürnberg, Germany. Topic: Face2Face: Real-time Facial Reenactment. Advisor: Günther Greiner
10/2011–02/2014	Master of Science, University of Erlangen-Nürnberg, Germany. Topic: Interactive Model-based Reconstruction of the Human Head. Advisor: Günther Greiner
10/2008–10/2011	Bachelor of Science, University of Erlangen-Nürnberg, Germany. Topic: Deformation Transfer of Triangular Meshes. Advisor: Günther Greiner
09/1999–07/2008	Abitur (University Entrance Qualification), Burghardt-Gymnasium, Buchen, Germany.

Employment (appointments) / Academic positions

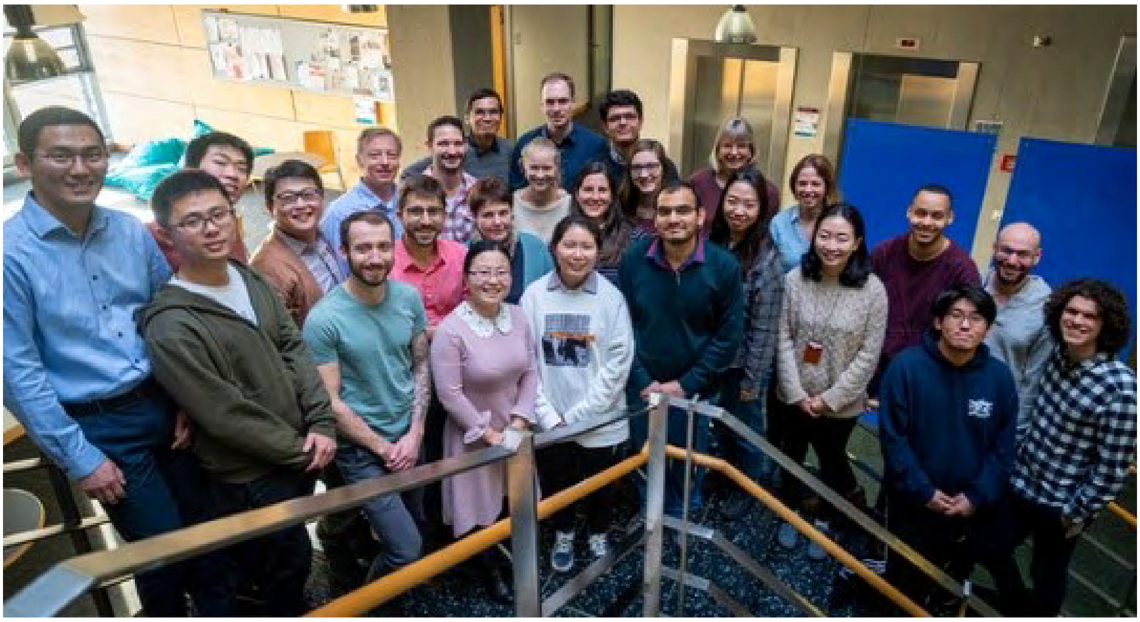
04/2021–present:	Researcher Group Leader, Max Planck Institute for Intelligent Systems, Tübingen, Germany
09/2017–03/2021:	Postdoctoral Researcher, Technical University of Munich, Garching, Germany
04/2014–08/2017:	Research Employee, University of Erlangen-Nürnberg, Erlangen, Germany

Links

Link to CV on website: https://ncs.is.mpg.de/~jthies

18 MICRO, NANO, AND MOLECULAR SYSTEMS

18.1 Research Overview



The independent Max Planck Research Group headed by Peer Fischer, who is also a Full Professor of Physical Chemistry at the Univ. of Stuttgart, combines research on the physics and chemistry at small scales, with the development of new nano and micro-scale fabrication methods, alongside original engineering approaches to realize novel “Micro Nano and Molecular Systems”. The group has broad interests and currently consists of 20 (PhDs and Postdocs) physicists, chemists, material scientists, and biomedical, electrical and mechanical engineers. In the period of this review, three Humboldt Postdoctoral Fellows as well as a Minerva Fellow joined the group. Twelve former students and postdocs (6 in the period of the report) have secured faculty positions around the world. The lab has won major research grants (ERC AdG, ERC PoC, EU-ITN, Volkswagen Foundation, MPG-Fraunhofer, BMBF, German Israeli Foundation, DFG) with >4.3 Mio € of competitive third party funding in the past six years.

A focus of the lab are the development of new technologies, and the group has been very successful in patenting several inventions, including a novel way to generate ultrasound fields in 3D and a way to develop organ phantoms. In the period of this report, ten patents have been published. Five patents have already been successfully licensed to a US-Israeli Startup company focusing on targeted delivery, where Prof. Fischer serves as a Senior Scientific Advisor. The company is a cooperation partner of the lab, and it has secured substantial funding in two rounds from leading Silicon Valley venture capital firms. In addition, another spin-off is being prepared via Max Planck Innovation that leverages technology to build realistic (materials, haptics, appearance and imaging contrast) organ models for training and robotic surgical instruments. This effort has been supported by an ERC-Proof-of-Concept Grant. Full surgeries, including the successful resection of a prostrate, have been performed with the phantoms in operating theatres using the same medical instruments as are used in regular surgeries.

The group is also visible internationally. In the period of the report, Prof. Fischer has been appointed an Adjunct Professor in Korea, a Member of the International Advisory Board of the Institute of Medical Robotics at Shanghai Jiao Tong University, and he continues to serve as an Editorial Board Member of Science Robotics. In the past six years Prof. Fischer has won several awards and distinctions, including an ERC Advanced Grant, a World Technology Award, a Steinhofer Prize, and a Fellowship of the Royal Society of Chemistry (FRSC). He has presented named lectures and seminars (Steinhofer Freiburg Germany, NanQiang Xiamen China, CMTI Bangalore India, Juan Lasheras UC San Diego), received an endowed lectureship at UT Austin, and he has given ten keynote and plenary talks. Most recently, he has been named a Distinguished Lecturer by the Sigma Xi scientific research honor society.

In the reporting period, Fischer and his group have published > 65 peer-reviewed journal articles of which several are ISI highly cited papers. In what follows, only a brief overview of some research projects is given (due to page restrictions). The projects are motivated by fundamental questions, or they led to the discovery of new effects and technologies.

18.2 Selected Research Projects

First spatial modulator and projector for ultrasound

Zhichao Ma, Kai Melde, Athanasios Athanassiadis, Tian Qiu, Peer Fischer

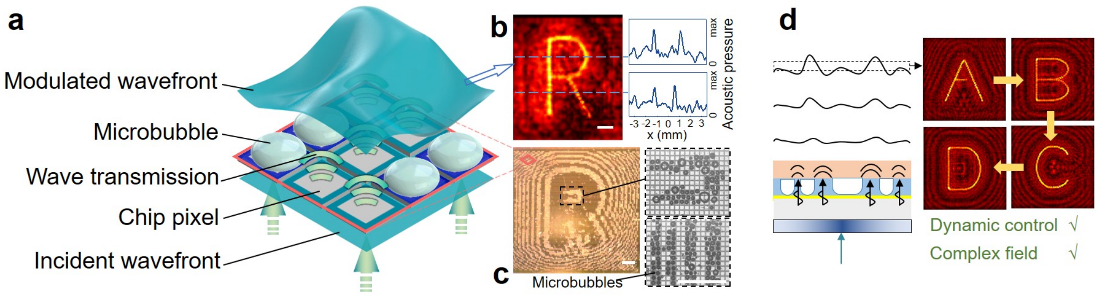


Figure 18.1: Spatial ultrasound modulator (SUM). (a) Schematic of the idea. A CMOS chip is used to form digitally controlled microbubble arrays. A bubble in water can block ultrasound, thereby causing amplitude modulation of the wave. (b) Experimental hydrophone scan of the acoustic field in the target plane, modulated by the bubble array on the surface of the SUM (c). Refreshing the CMOS chip allows an “ultrasound movie” to be projected (d). Scale bars are all 1 mm.

Introduction and problem: Ultrasound is widespread with applications ranging from medical imaging and industrial inspection to therapy and tissue ablation in surgery. While sophisticated technologies exist to detect and analyze ultrasound, the generation and projection of ultrasound is still fairly basic. Compared to optical systems, where one can use million-pixel light projectors (and spatial light modulators), ultrasonic systems typically consist of a few sound generators that can steer or focus a beam, but not project changeable patterns and images. For surgical applications, for instance, it is important to have a projection system that can be used to dynamically generate complex beam shapes (e.g. bent or elliptical or multi-focus beams). The challenge is that the sound speed cannot be easily modified in most materials, unlike in optics where the refractive index within a liquid crystal display can be changed using an electric field. The state of the art, therefore, uses as many ultrasound generators (transducers) as is technically possible. This is at best a few hundred, but is far too few to create complex fields.

Our invention: While most materials show little variation in their ultrasound response, even a 20 micron air bubble can effectively block ultrasound transmission in water. Our idea is to generate microbubble patterns and use these to realize an ultrasound projector. We worked with our collaborators at IMS Chips in Stuttgart to implement spatial amplitude control of an ultrasound wave with a CMOS chip. The chip has 10,000 electrodes that can be individually activated to generate a microbubble locally. Hence, each electrode functions as a pixel in this projector that can be locally blocked or unblocked, as shown in the Figure. The pattern of bubbles modifies the wavefront of the ultrasound wave passing through the chip. We were thus able to realize the first dynamic high resolution projector for ultrasound and the work has appeared in Nature Comm. 11, 4537 (2020) [1467].

Discussion and Outlook: We have won a competitive Max Planck-Fraunhofer grant to develop new ultrasound technologies. Our ultrasound modulator permits complex acoustic images to be projected in water and to be changed on-the-fly. Because ultrasound means pressure, we can also generate sophisticated pressure patterns and manipulate objects like cells. We are working on a robust implementation with even higher resolution and simpler control. Our goal is to be able to dynamically project high power ultrasound fields for robotic control and medical applications.

More information: https://pf.is.mpg.de/publications/2020ma or
https://pf.is.mpg.de/project/first-spatial-modulator-and-projector-for-ultrasound

Organ phantoms for surgical training and quantitative assessment

Dandan Li, Moon-Kwang Jeong, EunJin Choi, Xiangzhou Tan, Tian Qiu, Peer Fischer

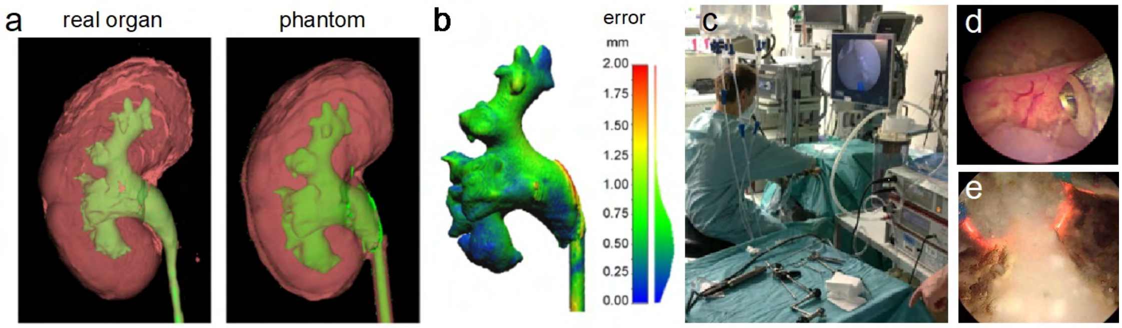


Figure 18.2: Realistic organ phantoms for medtech and surgical training. (a) CT scan of kidney phantoms showing the same anatomy as a human kidney. (b) 3D reconstruction of the collecting system shows high precision of the phantom with an average spatial error of only 0.5 mm. (c) A surgeon performs a surgery on our phantom in an operating theatre. (d-e) Several surgical procedures have been successfully simulated using our phantoms, including an endoscopic laser surgery (d), and electrocautery surgery (e).

Introduction and problem: The traditional way of surgical training - "see one, do one, teach one"- should be replaced by modern model-based surgical simulation. Models (phantoms) are safer for patients, offer a wider choice of disease models and a smoother learning curve. Animal models are often unrealistic and may be ethically problematic. Therefore, to train medical personnel, test new procedures, and to develop new medical instruments, realistic *in vitro* human-like organ models are needed. This is especially so for robotic surgery, where there is high demand for such technology. The challenge of making phantoms is that 3D printing materials are unsuitable (Young's modulus is too high) and most commercial models are too basic, with incorrect appearance and contrast in medical imaging, and do not offer a way to quantitatively assess the surgery.

Our approach: We combined our unique expertise in materials research and fabrication with the practical knowledge of our medical collaborators to build several organ models, including urinary tract models with bladder, kidney and prostate, as well as an aneurysm within a liver model. They are anatomically correct with fine 3D features, are made using customized biomimetic soft materials that show the correct imaging contrast (optical, X-Ray, and ultrasound), and offer a realistic surgical response (e.g. when cut, sutured or cauterized). We have also patented a method that permits the quantitative assessment of the surgery using a second contrast agent and imaging modality.

Results: In collaboration with the medical teams, we validated the organ phantoms under realistic surgical conditions and demonstrated their usefulness in endoscopic, laparoscopic, and robotic surgeries. Our materials are mainly hydrogels with additives and behave like real tissue. Different imaging methods were used during and after the surgical simulation and in some cases this was combined with machine learning to provide quantitative feedback to the trainees. We published Multiple journal and conference papers based on this project [1449],[1454],[1474].

Discussion and outlook: We were awarded an ERC Proof of Concept grant and filed two patents (1 granted, 1 pending) to protect the technology. Major medical device companies have contacted us and one leading endoscope manufacturer will run their first training at an international conference in Canada using our phantoms. With the support from Max Planck Innovation GmbH, a spin-off is being prepared

More information: https://pf.is.mpg.de/project/organ-phantoms-for-surgical-training-and-quantitative-assessment

The acoustic hologram towards ’one shot’ assembly of living matter

Kai Melde, Zhichao Ma, EunJin Choi, Nicolas Moreno Gomez, Peer Fischer

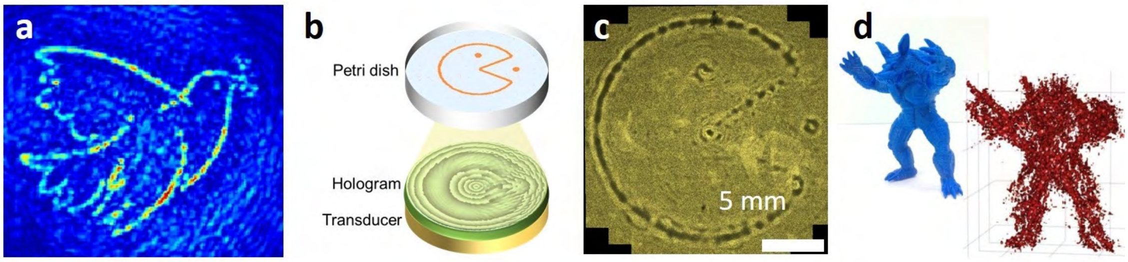


Figure 18.3: a) Pressure image in water generated by an acoustic hologram [1516]. b) Schematic for the assembly of cells in a petri dish in the shape of a pac-man and c) actual cell assembly with HCT-116 human colon cancer cells [1482]. d) Target 3D structure (blue) and 3D ultrasound pressure distribution (red) generated with three holograms.

Introduction and our invention: We have invented a radically new approach to generate ultrasound fields with orders of magnitude higher complexity than what has been possible to date [1516]. We demonstrated the first acoustic hologram, which is a diffractive element that defines the phase of a sound wave at each point across the entire wave-front. The desired phase pattern is encoded in the thickness distribution of a thin 3D printed polymer slab. Due to the difference in the speed of sound between the hologram and the surrounding medium (e.g. fluid) the passing wave will locally lead or lag at each point depending on the local thickness of the slab. The phase distribution that is needed to obtain an arbitrary target field can be computed by algorithms similar to those used in optical holography. Because we encode more than 20,000 unique points on the hologram, we obtain the most sophisticated pressure images to date (a) as compared to alternative methods can only utilize a few hundred (transducer elements). Since pressure fields can be used to manipulate particles and cells in solution, it is now possible to assemble an entire object just by switching on a single ultrasound transducer [1503]. We have been awarded an ERC Advanced Grant and a Max Planck-Fraunhofer cooperation grant to develop this entirely new form of bio-assembly. We collaborate on this project with the Empirical Inference Department at our institute and the Fraunhofer Institute for Biomedical Engineering.

Challenge: In order to assemble cells in the shape of the pac-man (b), it is necessary to compute the corresponding acoustic field and encode it in the holograms. In addition, it is challenging to exert enough force on the cells since cells mainly consist of water, resulting in a small acoustic contrast. Finally, if we want to assemble a 3D structure, then we must solve an incredibly complex inverse problem: how to encode an entire 3D object in the 2D phase distributions of a few holograms? This is a phenomenally complex optimization problem because of the astronomically large number of computational degrees of freedom.

Latest results: Our initial breakthrough is highly cited and has attracted considerable media interest [1516]. In addition, we have succeeded in exploiting a fluidic effect to assemble cells (c) in 2D [1479],[1482],[1559]. In collaboration with the Empirical Inference Department, we have also succeeded in obtaining computational solutions for 3D objects (d) and have assembled the first 3D cell structures.

Outlook: Our acoustic hologram work and our most recent results offer the possibility to directly assemble spheroids and possibly entire organoid structures in ‘one shot’ from a suspension of cells. Our method is much faster than alternative schemes and even offers the chance to design and build more complex cell systems with a view towards obtaining robotic living matter.

More information: https://youtu.be/MBdsAYbuszg or
https://pf.is.mpg.de/project/the-acoustic-hologram-towards-one-shot-assembly-of-living-matter

A wireless robot arm and the smallest micro- and nano-swimmers

Jan-Philipp Günther, Stefano Palagi, Tian Qiu, Fabian Adams, Peer Fischer

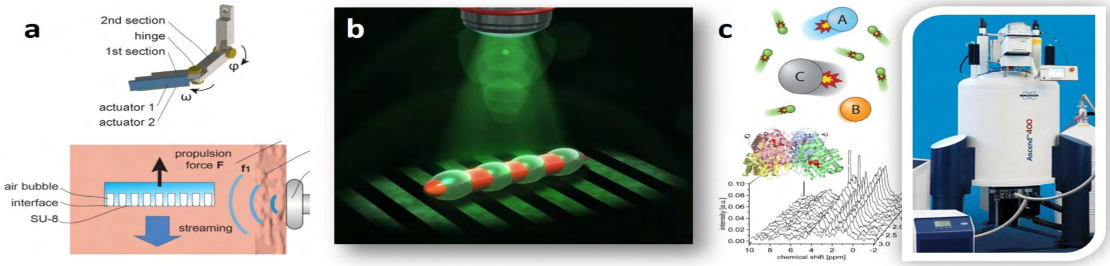


Figure 18.4: a) A surface containing microbubbles is excited with ultrasound and the recoil force moves a micro-robot arm. The actuator has many degrees of freedom – each surface has an array of bubbles with an unique size. b) A light actuated liquid crystal elastomer swims when the light-pattern excites a metachronal wave. c) It has been claimed that enzymes and molecules show enhanced motion (swimming) when they are catalytically active. Our precision measurements were able to address this fundamental question.

Problem: Actuation and motion of sub-mm devices and structures is challenging because it is difficult to transfer energy to small scales. In addition, reciprocal actuation does not lead to propulsion at low Reynolds numbers. New effective actuation mechanisms are needed for minimally invasive medical procedures as this relates to fundamental questions in chemistry.

A multi-degree of freedom wireless micro-robot arm: Endoscopy enables minimally invasive procedures in many medical fields, such as urology. However, current endoscopes are normally cable-driven, with an outer diameter of about 3 mm and only one bending degree of freedom. To avoid anesthesia in these procedures, it would be advantageous to develop an endoscopic camera arm that needs no cables or wires. This calls for a new kind of actuator. Our patented idea is to design functional surfaces that are excited by ultrasound to directly generate a force. We fabricate surfaces that contain thousands of resonant microbubbles and exploit acoustic streaming, which we show can actuate a 1 mm robot arm (Figure). We used our actuator to successfully move a mm-sized Naneye camera in a rabbit bladder *ex vivo* [1504],[1515],[1533],[1561].

Smallest micro-swimmer: A major challenge in robotics is the development of actuation schemes that mimic the versatility of biological locomotion. This is especially important at the micro-scale where traditional actuators are not feasible [1500]. Microorganisms perform sophisticated periodic body-shape changes, e.g. they beat cilia to generate metachronal waves. We developed the first fully-artificial swimming micro-robot capable of self-propulsion (no external forces or torques). In an international collaboration, we implemented multiple gaits (mimicking either symplectic or antiplectic metachrony of ciliate protozoa) in soft micro-robots made from liquid crystal elastomers, which show a fast phase transition under illumination. The LCE actuation scheme is quite general [1484] and can be optimized with learning [1393]. The work appeared in Nature Materials and is an ISI highly cited paper [1522].

Fundamental studies on nano-swimmers: Chemical reactions on the surface of microparticles can cause local concentration gradients, which causes fluid flow around the particle. Momentum conservation requires that the particle moves in the direction opposite to these flows. This form of "active matter" is known as chemical motors, which can autonomously swim and self-organize [1508]. Several publications have claimed that these concepts extend to enzymes and molecules, and have reported enhanced diffusion in catalytically active molecules. Such a mechanism would have major implications for biochemistry. We used advanced fluorescence correlation spectroscopic techniques and pulsed-field gradient NMR to show that there is no enhanced diffusion [1460, 1487, 1496].

More information: https://pf.is.mpg.de/project/a-wireless-robot-arm-and-the-smallest-micro-and-nano-swimmers

Biocompatible nanorobotic systems for propulsion through biological tissues

Vincent Mauricio Kadiri, Zhiguang Wu, Tian Qiu, Hyeon-Ho Jeong, Debora Schamel, Peer Fischer

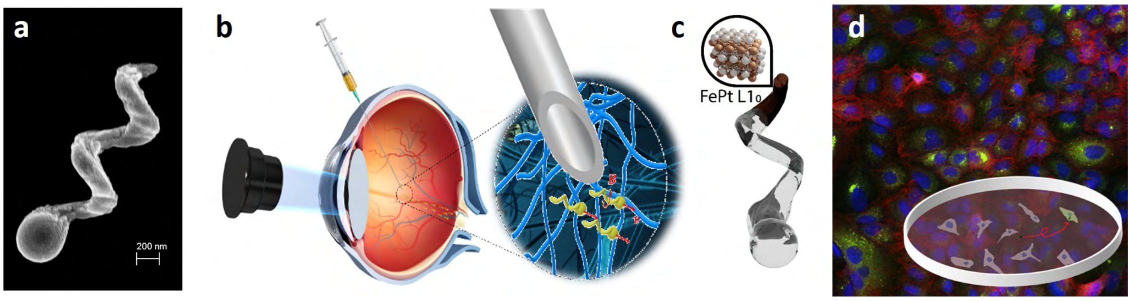


Figure 18.5: a) Single nanopropeller that can range in length from 90nm to 4μm. b) After application of a non-slip coating, a swarm of nanopropellers could be navigated through the vitreous of the eye over cm long distances. c) Fabrication with FePt yields biocompatible nanopropellers that are shown to d) be effective in transfection.

Introduction and problem: There is intense interest to develop nano-vehicles that can actively move through tissue and precisely deliver therapeutic agents to a targeted region. Micro- and nanopropellers - pioneered in our lab - provide a promising platform to achieve these goals. We have solved two major challenges using nano-vehicles in biological systems. The first challenge is biological tissues are difficult to traverse, such as the macromolecular networks in the vitreous of the eye. The second major challenge is that commonly used magnetic materials exhibit unacceptably high toxicity (nickel, cobalt), are difficult to fabricate (zinc ferrite), exhibit low chemical stability (iron corrosion), have weak magnetic moments (iron oxides), or cannot be fabricated/used at very small scales (neodymium iron boron (NdFeB) supermagnets).

Our approach: We have developed 3D nanofabrication tools that allow us to grow billions of cork-screw like nanopropellers from a wide range of materials and shown that the nanopropellers can be magnetically actuated and precisely steered. The helical microstructures were fabricated using physical vapor shadow growth via glancing angle deposition (GLAD).

Results: To enable propulsion through the vitreous of the eye, we have developed a method to apply an anti-adhesion coating [1493] to these nanopropellers. The propulsion through vitreous was achieved with a novel patented liquid perfluorocarbon coating scheme (inspired from the carnivorous Nepenthes pitcher plant) that prevents adhesion in tissue [1554]. A large swarm of nanopropellers was wirelessly navigated over cm-distances through the eye. We could use standard clinical OCT imaging for the observation of the propellers. The propulsion shows excellent directionality. The work has been published in Science Advances [1493], and has been highlighted by the international media. Our patents have been licensed by a start-up company in the US.

For magenetic nanoproparticle propulsion, we have succeeded in fabricating a fully biocompatible strong magnetic material. We incorporated a small section of iron-platinum and shown that we can anneal the structures to obtain the $L1_0$ phase, a very strong magnetic phase that rivals the magnetic strength of NdFeB, yet shows no cytotoxicity. We were able to use the propellers for the transfection of cells [1470].

Outlook: The extracellular matrix has a pore size of approximately 100-300 nm, and the propulsion mechanism reported herein is general and can therefore be applied to various porous biological media. In addition, a FePt has been identified as a superior magnetic material that shows great potential for use in micro-robotics and a diverse range of biomedical applications.

More information: https://www.youtube.com/watch?v=zygGq0tV0hg or
https://pf.is.mpg.de/project/biocompatible-nanorobotic-systems-for-propulsion-through-biological-tissues

18.3 Awards & Honors

2021

Jael George Mathew won the Best ePoster Prize at nanoGe from ACS Energy and Fuels with co-author Hannah-Noa Barad.

Peer Fischer has been named a Distinguished Lecturer by the Sigma Xi scientific research honor society.

Johannes Sachs wins the 2021 Springer dissertation award for his Ph.D. thesis.

Jan-Philipp Günther has won the the German Bunsen Society 2021 Agnes Pockels Ph.D. Award.

Vincent Kadiri has won Best Oral Award for his talk at the 2021 MRS Spring meeting.

Vincent Mauricio Kadiri receives the Alfred Landecker Democracy Fellowship.

2020

EunJin Choi receives the 2020 Athanasiou Student Paper Award from the Annals of Biomedical Engineering.

Vincent Kadiri selected to join Lindau Nobel Laureate meeting.

Peer Fischer has been appointed Adjunct Professor at the Gwangju Institute of Science and Technology (GIST), South Korea.

Zhichao Ma receives a Humboldt Postdoctoral Fellowship.

2019

Peer Fischer is CMTI Distinguished Lecturer at the Indian Institute of Science.

Peer Fischer is NanQiang lecturer at Xiamen University, China.

Kai Melde wins the 2019 Günter Petzow Prize.

Xiaolong Lu receives a Humboldt Postdoctoral Fellowship.

Hannah-Noa Barad receives a Minerva PostDoctoral Fellowship.

2018

Kai Melde won the "Excellent Communication Award" at the International Conference on Ultrasonics 2018 in Caparica Portugal.

Peer Fischer wins an ERC Advanced Grant from the European Research Council (2,5 M€).

2017

Eunjin Choi and **Hyeon-Ho Jeong**, respectively, received the 2017 scholarship awards from the Korean Scientists and Engineers Association in the FRG (VeKNI e.V).

Peer Fischer is named Steinhofer lecturer at the University of Freiburg and receives the associated prize of the Steinhofer-Foundation.

Tian Qiu, Stefano Palagi, and **Fabian Adams** win the Best Oral Paper Award, at the 10th Hamlyn Symposium on Medical Robotics, London 2017.

Jan-Philipp Günther and **Vincent Mauricio Kadiri** won the first poster prize on the NanoBioMater 2017 Summer School and International Conference for their contribution "Nanorheology and Nanopropellers in Biological Fluids".

Hyeon-Ho Jeong was awarded this year's Graduate Student Award at the 2017 E-MRS Spring Meeting in Strasbourg.

2016

Peer Fischer has received the 2016 World Technology Award for IT Hardware. Together with his group, he has developed new 3D nanofabrication methods and nanorobots, made the first reciprocal microswimmer, and realized the first swimming soft microrobot that moves using only body shape changes.

Hyeon-Ho Jeong was awarded the MRS Gold Graduate Student Award for a presentation on Chiral Plasmonic Nanosensors at the 2016 MRS Fall Meeting in Boston.

Tian Qiu has been granted the "National Award for Outstanding Self-financed Chinese Students Abroad 2015" by the China Scholarship Council (April, 2016).

18.4 Research group leader: Peer Fischer

Biography

Peer Fischer is a Professor of Physical Chemistry at the Univ. of Stuttgart and he heads the independent Micro Nano and Molecular Systems Lab at the Max Planck Institute for Intelligent Systems in Stuttgart. He received a B.Sc. in Physics from Imperial College London and a Ph.D. from the University of Cambridge (1999). He was a NATO (DAAD) Postdoctoral Fellow at Cornell University, before becoming a Rowland Fellow at Harvard, where he directed an interdisciplinary lab for five years. In 2009 he received an Attract Award from the Fraunhofer Society which led him to set up a photonics lab at the Fraunhofer Institute for Physical Measurement Techniques. In 2011 he moved his lab to the MPI-IS in Stuttgart, and since 2013 he is a Professor at the Univ. of Stuttgart. Peer Fischer won several prizes including an ERC Starting Grant in 2011, a World Technology Award in 2016, and an ERC Advanced Grant in 2018. He is an Editorial Board Member of the journal Science Robotics and a Fellow of the Royal Society of Chemistry. He has broad research interests including 3d nanofabrication & assembly, micro- and nano-robotics, active matter, interaction of optical, electric, magnetic, and acoustic fields with matter at small length scales, chirality, and molecular systems engineering.

Awards & Fellowships

2021	Distinguished Lecturer, Sigma Xi Scientific Research Honor Society.
2020	Adjunct Professor, School of Elec. Eng. and Comp. Sci., Gwangju Inst. of Science and Techn. (GIST), South Korea.
2020	Cockrell Engineering School endowed lectureship, Univ. of Texas at Austin, USA.
2019	Distinguished CMTI Lecture, (CeNSE), Indian Institute of Science; Bangalore, India.
2019	NanQiang Lecturer, Xiamen University, China.
2018	ERC Advanced Grant (start date 2/2019).
2017	Steinhofer Lecture and Prize, Steinhhofer Foundation, Univ. of Freiburg. awarded for *"fundamental contributions to the controlled 3D fabrication of artificial nanostructures and their biomedical application"*.
2016	Winner, World Technology Award, (IT Hardware), Los Angeles.
2016	Fellow of the Royal Society of Chemistry (FRSC).
2011	ERC Starting Grant (as consolidator).
2009	Attract Award, Fraunhofer Society, *"The »Fraunhofer Attract« grant is the excellence stipend programme of Fraunhofer. »Fraunhofer Attract« invites outstanding researchers to develop their ideas towards innovation.” (5 yrs., stayed until 9/2011).*
2004	Rowland Junior Research Fellow, Harvard University. *“Fellows are selected for their scientific achievement, their creativity, their resourcefulness as experimentalists”*.

Education

1999	Ph.D., Dep. of Chemistry, **University of Cambridge**
1995	B.Sc. Physics, (First Class Honours), **Imperial College London**

Employment (appointments) / Academic positions

Since 6/2013	tenured Full Professor of Physical Chemistry, **Univ. of Stuttgart**
Since 9/2011	tenured independent scientist and head of the Lab for Micro Nano and Molecular Systems, **Max Planck Institute for Intelligent Systems**
2011	Offer Assistant Professor, Boston University (declined)
2009 – 2011	**Fraunhofer Society**, Independent Attract Group Leader
2009	Offer Assistant Professor, Yale University (declined)
2009	Offer Assistant Professor, Univ. of Oregon (declined)
2004 – 2009	Rowland Institute, Principal Investigator and Rowland Fellow, **Harvard University**
2000 – 2004	NATO Postdoc. Fellow, Dep. Chem. and Appl. and Eng. Physics, **Cornell Univ.**

Activities

2021	Co-organizer: MRS Materials Research Society, "SM06: Materials and Fabrication Schemes for Robotics", MRS-Spring meeting
2020	Editorial Advisory Board: *MDPI Micromachines*
2019	International Advisory board, Institute of Medical Robotics at Shanghai Jiao Tong University (SJTU)
2019	Conference co-chair, International Conference on Micro/Nanomachines, Harbin China
2018	Tenure committe, Univ. of Stuttgart
2018	Editorial Advisory Board: *MDPI Robotics*
2018	Guest Editor, *Acc. of Chem. Res.*, Special Issue "Fundamental Aspects of Self-Powered Nano- and Micromotors" (with A. Sen and A. Balazs)
2018	Guest Editor, *Advanced Functional Materials*, Special Issue on "Micro- and Nanomachines on the Move" (with M. Pumera and J. Wang)
2018	Symposium organizer: MRS Materials Research Society, "Materials for Next-Generation Robotics", Boston
2017	Faculty of chemistry, research committee, Department of Chemistry, Univ. of Stuttgart
2016	Editorial Board: *Science Robotics*

Invited talks, publications and patents, mentoring

- >110 invited talks, 12 named lectures and keynote or plenary talks since 2016
- 138 peer-reviewed scientific publications
- 14 patents, 5 licensed to a start-up
- 20 PhD students (8 current), 36 PostDocs (10 current)
- 12 former group members (six since 2016) have secured faculty positions

Links

Link to CV on website: https://pf.is.mpg.de/~fischer

19 PHYSICS FOR INFERENCE AND OPTIMIZATION

19.1 Research Overview

The research goal of the Physics for Inference and Optimization group is *understanding, optimizing and predicting* relations between the microscopic and macroscopic properties of complex *large-scale interacting systems.* We pursue this agenda by addressing application-oriented problems of *inference and optimization on networks* via developing models and algorithms derived from **statistical physics principles**.

The two main motivations behind this interest are the idea that there is a pressing need for theory to be grounded in concrete applications in order to solve relevant scientific problems in rigorous ways, improving both methodological and domain-specific knowledge.

In addition, in recent years statistical physics has been able to provide new insights and novel approaches to problems in computer science.

Our approach is to address this problem with two main research questions that tackle this issue under different angles and together should provide a cohesive and coherent analysis of the problem:

- How can we exploit the *distributed* character of complex interacting systems to perform network optimization?
- How can we understand the mechanism leading to *large-scale pattern emergence* and thus perform robust and scalable inference?

The objective is that by answering these questions one can provide a comprehensive analysis of the bigger problem of understanding large-interacting systems in their different aspects.

Our research reflects this interdisciplinary approach and considers:

- *Developing theoretical models* capable of describing the mechanism driving the optimization or inference problems, assessing their properties and limitations.
- *Building efficient and scalable algorithms* to apply them leveraging various statistical physics tools such as message-passing techniques, variational inference or matrix product factorization.
- *Addressing data-rich open problems* involving domain experts from other disciplines. This is stimulated by the ongoing interactions with more empirically-oriented scientists from various disciplines.

19.2 Selected Research Projects

The richeness of modeling directed interactions in networks

Caterina De Bacco, Hadiseh Safdari, Martina Contisciani, Laura Iacovissi, Andrea Della Vecchia, Nicolo Ruggeri, Kibidi Neocosmos

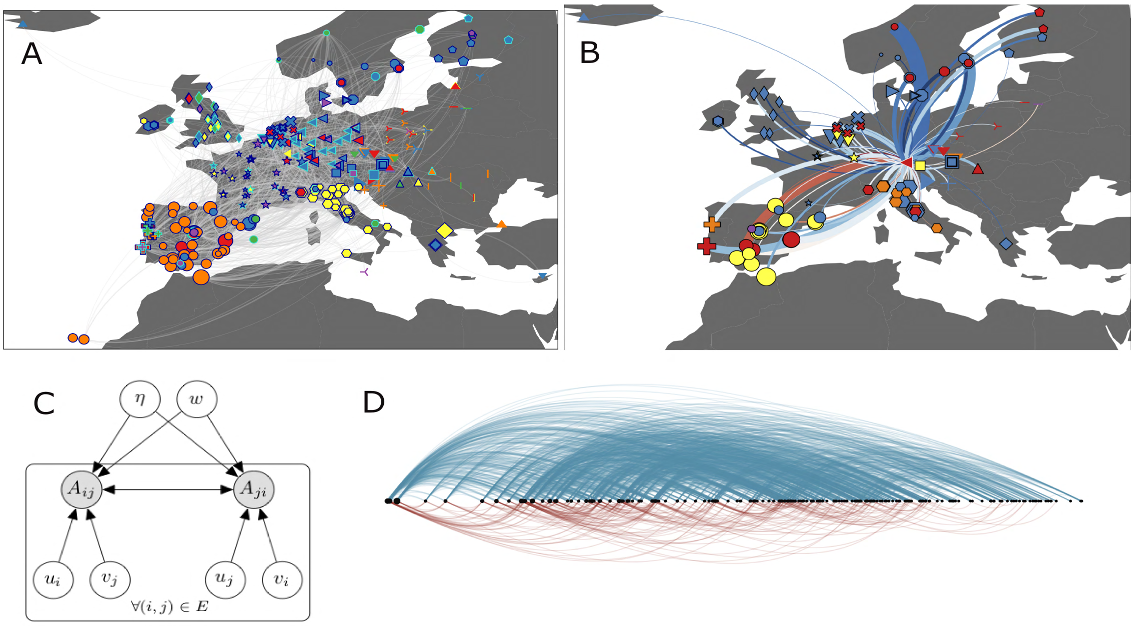


Figure 19.1: A: partition into communities inferred by the model [1566]. B: different reciprocity patterns of an individual node. C: graphical model of [1566], capturing both communities and reciprocity. D: example of hierarchy in directed networks.

Standard models for networks focus on modeling whether an interaction is observed or not between two individuals, regardless its direction. In other words, they are often applicable to undirected networks but do not consider the information contained in the direction. In fact, directed networks are often transformed into their undirected version, to be able to apply these methods. However, by doing this, one misses the opportunity to model rich patterns that are only observed in directed structures.

This is the case of reciprocity, the tendency of a pair of nodes to form mutual connections between each other. This is an important feature of many social relationships. Its impact ranges from affecting the development of exchange and power to determining the emergence of trust and solidarity. Popular generative models with latent variables have high predictive performance in recovering missing connections, but fail in the arguably simple task of recovering reciprocated edges. This highlights the value of properly modeling edge direction. It also unveils a deeper theoretical justification for this failure, in the common assumption made by generative models of conditional independence between edges. By making a minimal relaxation to this hypothesis, we showed that one can successfully model reciprocity, while preserving the nice properties of latent variable models [1566].

Another property inherent of directed networks is that of structural hierarchy. In certain applications, as in animal behavior or systems of endorsement, directed edges represent an outcome. For instance, an animal that attacks another signals an underlying strength, and therefore the presence of a hierarchy, between them. Modeling this type of structure requires moving beyond classical models, for instance combining physics principles with domain knowledge of how certain systems works[1],[1577],[1578].

More information: https://pio.is.mpg.de/project/the-richeness-of-modeling-directed-interactions-in-networks

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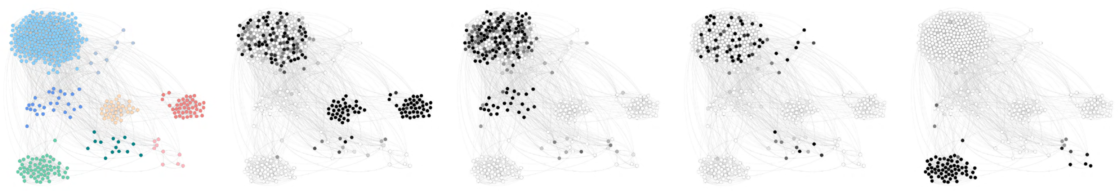
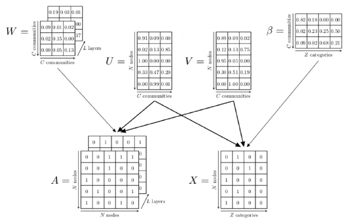
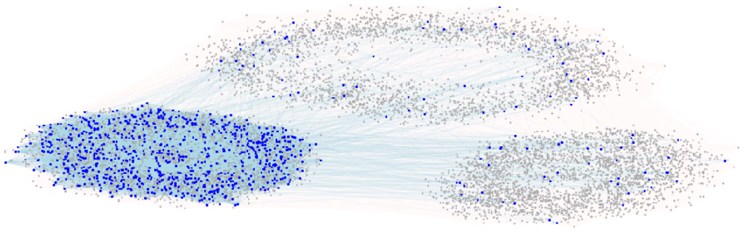
[1] C. De Bacco, D. B. Larremore, C. Moore. A physical model for efficient ranking in networks. *Science Advances* **4** (7), 2018. eprint: http://advances.sciencemag.org/content/4/7/eaar8260.full.pdf.

Combining different types of information to find patterns in networks

Caterina De Bacco, Hadiseh Safdari, Martina Contisciani, Nicolo Ruggeri, Nicolo Zottino, Laura Iacovissi, Sameh Othman







Networks are a powerful formalism to represent pairwise interactions between individuals. The basic type of information that can be stored is a binary one: does an interaction exist between two nodes or not? However, real dataset a much richer than this. Interactions can be of different types, as in multilayer networks. Edges can be weighted or have a timestamp regulating their existence in time. Nodes and edges can have attributes. The question is how to combine these various types of information to learn patterns.

We address this problem by considering probabilistic models with latent variables that capture correlations between the different types of input data. The idea is that when the extra information is correlated with the set of observed interactions, i.e. the network structure, then by effectively inferring latent variables one can recover one type of information from the other. On the contrary, when network structure and extra information are independent, learning one will hurt recovering the other.

We develop principled models that are able to combine the various source of information and automatically estimate relevant information from noise. In the context of multilayer network, one can formulate this problem in terms of measuring what layer helps predicting another[2]. This is also a principled method to measure whether using a multilayer formalism makes sense, or we should instead treat the layer as a collection of single-layer networks. Similarly, having access to several node attributes requires distinguishing the informative ones from those that are irrelevant [1570, 1574, 1580].

A closely related problem is that of sampling a subset of the network in an efficient way in order to properly recover structural properties, such as nodes' centralities [1571],[1569]. In this case, the problem is that the amount of information available is limited, and should then be selected in a principled way.

More information: https://pio.is.mpg.de/project/combining-different-types-of-information-to-find-patterns-in-networks

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[2] C. De Bacco, E. A. Power, D. B. Larremore, C. Moore. Community detection, link prediction, and layer interdependence in multilayer networks. *Physical Review E* **95** (4): 042317, 2017.

Optimal Transport for Routing Optimization on networks

Caterina De Bacco, Ibrahim Abdullahi Adinoyi, Daniela Leite, Diego Theuerkauf, Alessandro Lonardi

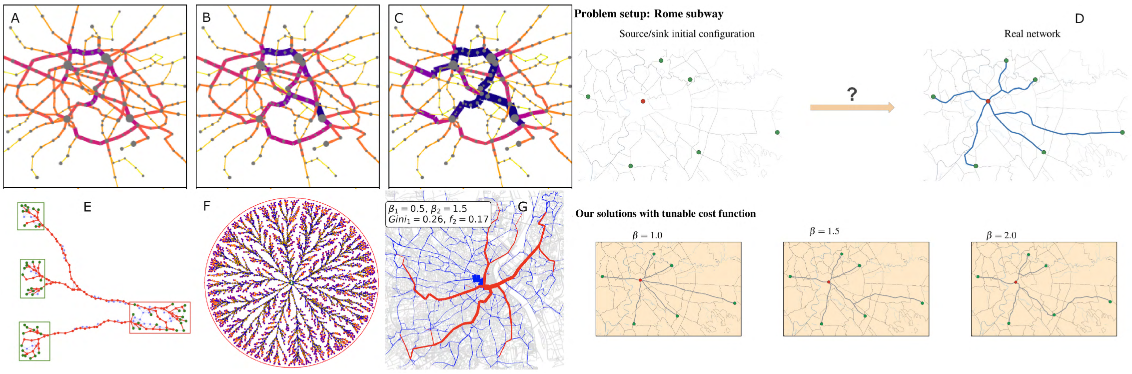


Figure 19.2: A-C: Paris metro traffic optimization with different cost functions. D: Rome metro network inferred by our algorithm. E-F: optimal network structures extracted by our algorithm, for different source/sink initial configurations. G: Bordeaux 2-layer network (bus + tram) flow optimization.

Optimizing traffic on a network is a relevant problem in situations where traffic congestion has a big impact on transmission performance. This can be traditionally formalized as a computationally-hard constrained optimization problem where interactions are non-local and a global optimization is required. Optimal transport theory provides a principled and computationally-efficient alternative to standard optimization methods to address this problem. However, most of the results derived in this context remain abstract and not applicable in practice.

On this basis, we adopt this approach from an application-oriented perspective, using theoretical principles to devise practical algorithms to tackle a variety of problems where the goal is to design optimal networks and optimizing flows on them.

For instance, we adapt this novel formalism to multi-commodity problems where mass of more than one type travels through a network [1567],[1576],[**mcopt_metro**], as in routing of passengers in urban transportation systems. Similarly, we extend this approach to multilayer systems with more than one transportation modes [1563] or to scenarios where the incoming and outgoing flow changes in time.

In addition, we take advantage of a model that extracts properly-defined networks from raw solutions in continuous space [1568] to investigate the structure of the optimal networks arising from this approach in realistic scenarios [1573] and propose an algorithm to automatically extract natural networks from images [1565].

Finally, as this formalism provides at no additional cost an efficient way to compute Wasserstein distances between networks, we investigate how this framework can be applied to problems beyond that of optimizing traffic. For instance, it can be used to measure similarities between images, as in classification tasks, similarities between layers in multilayer networks or to cluster similar nodes into groups.

More information: https://pio.is.mpg.de/project/optimal-transport-for-routing-optimization-on-networks

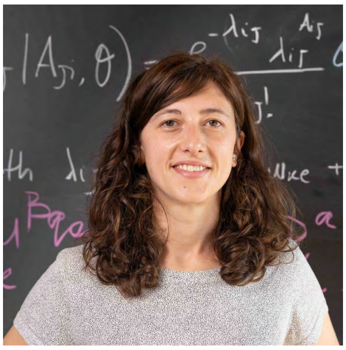
19.3 Awards & Honors

2021

Caterina De Bacco received the 2021 EPS Statistical and Nonlinear Physics Prize in the Statistical And Nonlinear Physics Division

19.4 Research group leader: Caterina De Bacco

Biography



Caterina De Bacco is a Cyber Valley Independent Research Group Leader. She leads the Physics for Inference and Optimization group at the Max Planck Institute for Intelligent Systems in Tuebingen.
She obtained a degree in Physics at University of Padova in 2012 and a PhD in Statistical Physics at Université Paris Sud 11 in 2015, with a Marie Curie ITN fellowship. After that, she was a Program Postdoc at the Santa Fe Institute from 2015 to 2017, and then spent one year in 2018 at the Data Science Institute, Columbia University, first as a Postdoc and then as a visiting faculty, before starting her group at MPI.
Her research focuses on studying large-scale interacting systems following two main research directions, inference and routing optimization on networks. Her research approach is based on addressing application-oriented problems involving domain experts from different disciplines via developing models and algorithms derived from statistical physics principles.

Awards & Fellowships

- 2021 European Pyshical Society, division for Statistical and Nonlinear Physics, awareded the Early Career Prize
- 2020-21 UKRI Economic and Social Research Council (ESRC) grant.
  Developing Latent Hierarchical Network Models for Cross-Cultural Comparisons of Social and Economic Inequality.
- 2015-17 John Templeton Postdoctoral Fellowship
- 2012-2015 Marie Curie Initial Training Network Fellowship

Education

2012-2015	PhD in Statistical Physics, LPTMS, Université Paris Sud 11, Paris
2010-2012	Master degree in Physics, Universitá di Padova, Padova
2010-2011	Erasmus at Imperial College, London, Imperial College International Degree
2007-2010	Bachelor degree in Physics, Universitá di Padova, Padova

Employment (appointments) / Academic positions

from 07/2018	Indipendent Research Group Leader, Cyber Valley, Max Planck Institute for Intelligent Systems, Tuebingen, Germany
2018	Visiting Faculty, Data Science Institute, Columbia University, Ney York, USA
2018	Postdoc at Data Science Institute, Columbia University, Ney York, USA
2015-2017	Postdoc at Santa Fe Institute, Santa Fe, USA

Links

Link to CV on website: https://pio.is.mpg.de/~cdebacco

20 PROBABILISTIC LEARNING GROUP

20.1 Research Overview

[The Probabilistic Learning group existed from mid 2019 to end 2020, when it moved to become a Chair at Saarland University. Prior to this, the group was part of the department of Empirical Inference between end 2017 and mid 2019. The following text covers the overall period and, as a result, some of the research contributions may ovelap with the ones of the department of Empirical Inference.]

The research focus of the Probabilistic Learning Group focuses on the development of trustworthy ML methods to be deployed in the real-world. Our research can be broadly categorized in three main topics: fair, interpretable and robust machine learning.

- ***Fair ML***: Our group has been a pioneer at establishing the methodological foundations of fairness and interpretability in ML, and especially, at providing algorithmic solutions to the limitations of common practices in these research areas, which often come at a high societal cost. Our recent contributions to *fair ML* include: i) new fairness definitions [490]; ii) flexible learning frameworks for the design of fair classifiers [144, 1585]; and iii) ML algorithms to enhance fairness and accuracy of human decision-makers [460]. More recently, we have shown the limitations of previous work on algorithmic fairness and propose a methodological paradigm shift from learning to predict to learning to decide, in order to ensure algorithmic fairness under realistic assumptions on the data collection process [384].

- ***Inperpretable ML***: In the context of *interpretable ML*, we have focused on developing methods to provide contrastive explanations and algorithmic recourse, i.e., to help an individual to, respectively, understand and revert an (unfavourable) algorithmic decision [386]. Our recent work on a causal view of algorithmic recourse has not only allowed us to prove the limitations of prior works [331], but also to guarantee recourse under realistic assumptions [368]. Our results were already being taught as seminal work at the prestigious University of Stanford (https://psych293.github.io/) while still in the peer-review process. Currently, our survey paper [386] is under review.

- ***Robust ML*:** A core goal of our research is to develop robust ML methods that can properly handle realistic assumptions and, especially, the complex nature of real-world data. We have extensively worked on ML for mixed continuous and discrete data (e.g., tabular data), as well as with missing data [1583, 1584][1586]—e.g., to the best of our knowledge, HI-VAE [1583] was the first deep generative model to handle both heterogeneous and missing data.

History of the Group

The Probabilistic Learning group at the MPI for Intelligent Systems was initially founded in 2017, as a result of the MPG Minerva Fast Track fellowship granted to Isabel Valera. Between 2017 and 2019, the group was hosted and funded by the Department of Empirical Inference, led by Prof. Schölkopf. In mid 2019, the group was finally established as an independent group at the MPI for Intelligent Systems. However, very shortly aftern then, in April 2020, Isabel Valera was appointed as a full professor at Saarland University, where the group now lives on in a new form, as the Chair of Machine Learning.

20.2 Selected Research Projects

Counterfactual explanations and algorithmic recourse

Isabel Valera

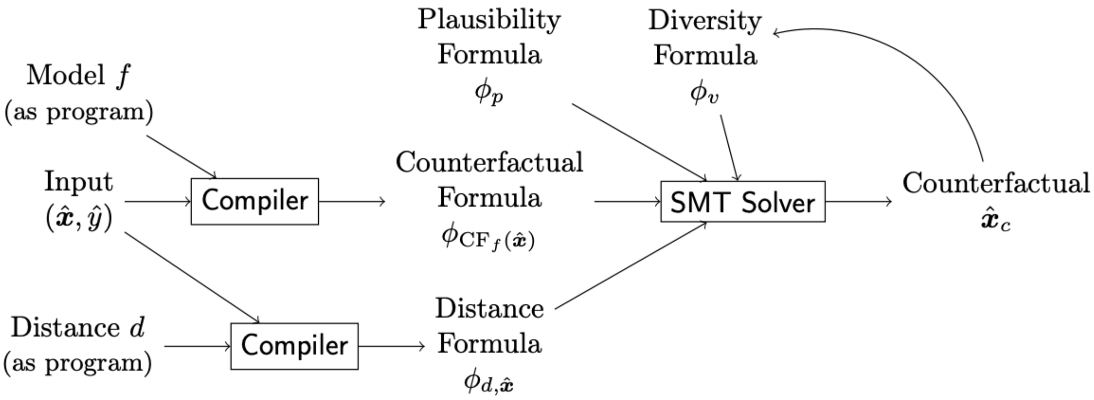


Figure 20.1: Architecture Overview for Model-Agnostic Counterfactual Explanations (MACE)

Machine learning is increasingly used to inform consequential decision-making (e.g., pre-trial bail and loan approval). In these settings, in addition to requiring models to be accurate and robust, socially relevant values such as fairness, privacy, accountability, and explainability play an important role in the adoption and impact of these technologies. In particular, when algorithmic decisions affect individuals, it becomes important to explain how the system arrived at its decision, and also suggest actions to achieve a favorable decision. Counterfactual explanations –“how the world would have (had) to be different for a desirable outcome to occur”– aim to satisfy these criteria.
Our research contributions to this field are twofold.

First, we focus on providing flexible approaches to generate (nearest) counterfactual explanations, i..e, to identify the set of features resulting in the desired prediction while remaining at minimum distance from the original set of features describing the individual. In [386], we abandoned the standard optimization approach to find nearest counterfactual explanations, as it these methods are often restricted to a particular subset of models (e.g., decision trees or linear models) and differentiable distance functions. Instead, we proposed a Model-Agnostic Counterfactual Explanations (MACE) approach that builds on standard theory and tools from formal verification to solve a sequence of satisfiability problems, where both the distance function (objective) and predictive model (constraints) are represented as logic formulae. As a result, MACE, depicted in Figure , allows generating optimal, plausile and diverse counterfactual explanations for a wide variety of machine leanring classifiers. Unfortunately, SMT solvers strugle to generate counterfactual explanations when the underlying classifiers is a complex neural network. To solve such a limitation, we recently provided a framework based on Mixed-Integer Programming (MIP) to compute nearest counterfactual explanations for the outcomes of neural networks, with both provable guarantees and runtimes comparable to gradient-based approaches [327].

Second, we focus on supporting individuals affected by an unfavourabkle decision to revert it, or in other words, on algorithmic recourse. Algorithmic recourse and counterfactual explanations are closely related terms, that the literature has often used in a exchangeable way. Unfortunately, as shown in our work [331], counterfactual explanations inform an individual where they need to get to (i.e., they help uindividuals to understand), but not how to get there (i.e., how to act to revert an unfavourable decision). In particular, we relied on causal reasoning to caution against the use of counterfactual explanations as a recommendable set of actions for recourse. Then, we showed that algorithmic recourse can be achieved by finding the set of causal interventions with minimal cost for the individual, shifting the focus from explanations to interventions. Such guarantees, however, only hold under perfect causal knowledge (i.e., perfect kenowledge of both the causal graph and struural equations) [368]. Unfortunately, in practice, the true underlying structural causal model is generally unknown. To address such a limitation, we then focused on relaxing the causal assumptions by, for example, accounting for uncertainty on the structural equations. Specifically, we proposed two probabilistic approaches to select optimal actions that achieve recourse with high probability given limited causal knowledge.

Our ongoing research in this area focuses on providing practical approaches for both counterfactual explanations and algorithmic recourse under realistic assumptions. Finally, we are pleased that our survey paper about the field is currently under revision [368].

Latent variable models for heterogenous data

Isabel Valera

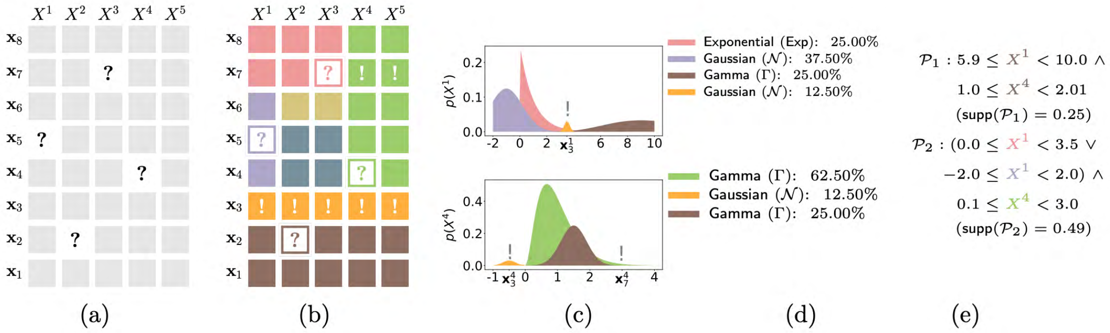


Figure 20.2: ABDA on a tabular dataset comprising samples from mixed continuous and discrete features, potentially containing missing values (denoted as “?”) (1a). The latent dependency structure inferred by ABDA induces a hierarchical partition over samples and features (i.e., a hierarchical co-clustering) given a learned Sum-Product Network (SPN) structure (b). Statistical data types and likelihood models are discovered by estimating each feature distribution as a mixture model over a dictionary of suitable and interpretable parametric model, e.g., Gaussian for real data, Gamma, Exponential distributions for positive data in (c-d). ABDA efficiently imputes missing entries as the most probable values by SPN inference routines. Anomalous entries (denoted as “!” in b-c), on the other hand, are presented to the user as low-likelihood samples that are relegated to micro-clusters or to the distribution tails. Moreover, ABDA allows to automatically discover complex dependency patterns, e.g. conjunctions of confidence intervals, by exploiting the correlations over the induced hierarchical co-clustering (e).

Latent feature modeling allows capturing the latent structure responsible for generating the observed features of a set of datapoints. It is often used to make predictions either for new observations or for missing information in the original data, as well as to perform exploratory data analysis. That is, to help exploring and understanding the latent structure in the data. However, although there is an extensive literature on latent feature models for homogeneous datasets, where all the attributes that describe each object are of the same (continuous or discrete) nature, there is scarce work on latent feature modeling for heterogeneous databases (e.g., tabular datasets).

Our work has focused on developing generative models, based on latent variable models for heterogenous data. More in detail, we consider datasets stored in an observation matrix $\mathbf{X}$ of size $N \times D$, where each of the N datapoints is defined by a set of D features, which each of them might be continuous (e.g., real-valued or positive real-valued) or discrete (either numerical or nominal, e.g., categorical or ordinal). Note that in such a case, the likelihood factorizes as

$$p(\mathbf{X}|\mathbf{Z}) = \prod_n \hat{} N \prod_d \hat{} D p(x_{nd}|z_n),$$

where the latent variable z_n is shared across all the D features for each observation n. Here, the goal and also the key challenge is to infer (or accurately approximate) the posterior distribution $p(\mathbf{Z}|\mathbf{X})$ under a flexible heterogenous generative model that accurately fit the data, while at the same time allowing for efficient inference.

To this end, we first introduced in [1584] a general Bayesian nonparametric latent feature model suitable for heterogeneous datasets, which presents several important properties. Firstly, it accounts for heterogeneous data while keeping the properties of conjugate models, which allows to infer the model in linear time with respect to the number of observations and features. Secondly, its Bayesian nonparametric nature allows us to automatically infer the model complexity from the data, i.e., the number of features necessary to capture the latent structure in the data. Thirdly, the latent features in the model are binary-valued, this facilitates the interpretability of the obtained latent features in exploratory data analysis. Importantly, this research contribution was accompanied with a software package called GLFM toolbox, which is made publicly available for other researchers to use and extend.

Second, with the aim to increase the flexibility of the generative model by accounting for non-linear statistical dependencies in the observed data, we leveraged the flexibility of Sum-Product Networks (SPNs) [1586]. The resulting model enabled making exploratory data analysis accessible at large without the supervision of an expert data scientist. As a consequence, we named our model as Automatic Bayesian Density Analysis (ABDA), as it allows for automatic and efficient missing value estimation, statistical data type and likelihood discovery, anomaly detection and dependency structure mining, on top of providing accurate density estimation. Figure 20.2 includes an example of the tasks that ABDA can automate.

The above two works, however, may not scale for very large datasets, as they rely on Gibbs sampling to perform posterior inference. Moreover, they expressiveness to fit complex data remains limited by the model. For this reason, our next step consited of leveraging the expresiveness of neural networs, and in particular, variational autoencoders (VAEs) to model heterogenous data. Specifically, in [1583], we proposed a general framework to design VAEs suitable for fitting incomplete heterogenous data. The proposed HI-VAE includes likelihood models for real-valued, positive real valued, interval, categorical, ordinal and count data, and allows accurate estimation (and potentially imputation) of missing data. Up to the best of our knowledge, the HI-VAE was the first generative neural network architecture to handle heterogenous and mising input features. As a result, this piece of work already accumulated over 120 citations (according to Google scholar).

Our current research in this topic is focusing in the learning methods of these models, especially on those realying on neural networks, and thus gradient-based optimization. In particular, we aim to mitigate that issues similar to negative transfer in multi-task learning (as a consequence of the gradient competintion acorss tasks) prevent the model to accurately fit the marginal distribution of, and the statistical dependencies among, all features.

20.3 Research group leader: Isabel Valera

Biography

From mid 2019 to the end of 2020, Isabel Valera led the Probabilistic Learning research group at the MPI for Intelligent Systems. This biography deliberately reflects her career path, which as shown below has been strongly inlfucenced by her time at the MPI for Intelligent Systems. First as a groupd leader at the Department of Empirical Inference from 2017 to 2019, then as the leader of a independent research group (2019-2020).
Since April 2020, Isabel Valera is a full Professor on Machine Learning at the Department of Computer Science of Saarland University in Saarbrücken (Germany), and Adjunct Faculty at MPI for Software Systems in Saarbrücken (Germany). She is also a scholar of the European Laboratory for Learning and Intelligent Systems (ELLIS). She has held a German Humboldt Post-Doctoral Fellowship, and a “Minerva fast track” fellowship from the Max Planck Society. She obtained her PhD in 2014 and MSc degree in 2012 from the University Carlos III in Madrid (Spain), and worked as postdoctoral researcher at the MPI for Software Systems (Germany) and at the University of Cambridge (UK).

Employment (appointments) / Academic positions

2020 – present	Full Professor of Machine Learning (W3), Saarland University, Germany.
2021 – present	Adjunct Faculty, Max Planck Institute for Software Systems (MPI-SWS), Germany.
2019 – 2020	W2 Independent Max Planck Research Group Leader, MPI-IS, Germany.
2017 – 2019	Research Group Leader, Department of Empirical Inference, MPI-IS, Germany.
2017	Research Associate, Department of Engineering, University of Cambridge, UK.
2015 – 2017	Post-Doctoral Researcher, MPI-SWS, Germany.

Education

2014	PhD. in Multimedia and Communications, Universidad Carlos III de Madrid, Spain. Supervisor: Dr. Fernando Perez-Cruz
2010– 2012	MSc. in Multimedia and Communications (Data and Signal Processing), Universidad Carlos III de Madrid, Spain.
2008 – 2009	Erasmus studies at Hannover university, Germany
2003 – 2009	BSc. on Electrical Engineering (Signal Processing and Communications), Universidad Politécnica de Cartagena, Spain.

Publications

Publications	32 papers in high-impact international conferences and journals of machine learning h-index: 21, i-10 index: 27, 2645 citations (Google Scholar 12/10/21)

Awards & Fellowships

2018 – 2019	Minerva Fast Track Fellowship, Max Planck Society, Germany.
2018	Nominated to the CNIL-Inria Privacy Award 2018.
2017	Best Paper Award Honorable Mention, WWW 2017.
2017	Best Paper Award, ICML 2017 Workshop on Human Interpretability.
2015 – 2017	Humboldt Post-doctoral Fellowship, Alexander von Humboldt Foundation. Host: Max Planck Institute for Software Systems (MPI-SWS), Germany

Teaching/Supervision Activities

2019 – present	Supervision of 5 PhD students
2019 – present	Supervision of 4 Master Theses (1 current)
2020 – present	Several Full Lecture Courses on Machine Learning
	Several Seminars, Invited Tutorials
2016	Co-organizer of a Machine Learning Summer Schools (MLSS)

Professional Activities (selected)

2022	Program Chair of the International Conference on Artificial Intelligence and Statistics (AISTATS), Spain.
2020	Pogram Chair of European Conference on Machine Learning and Principles and Practice of Knowledge Discovery in Databases (ECML-PKDD), Belgium.
2018 – present	Area Chair for Neural Information Processing Systems (3×), International Conference on Machine Learning (2×), Artificial Intelligence and Statistics (4×).

(Co-) Organization of Scientific Workshops

2021	ELLIS Workshop on Causethical ML
2021	ICML Workshop on Algorithmic Recourse
2021	ELLIS Workshop on Foundations of Algorithmic Fairness
2020	NeurIPS Workshop on Probabilistic Machine Learning
2019	NeurIPS Workshop on Human-Centric Machine Learning
2019	NeurIPS Workshop on Learning with Temporal Point Processes
2018	Data Learning and Inference Conference (DALI), Spain
2017	Data Learning and Inference Conference (DALI), Spain
2016	Women in Machine Learning Workshop (WiML), Spain

Links

Link to CV on website: https://plg.is.mpg.de/~ivalera

21 PROBABILISTIC NUMERICS

21.1 Research Overview

[The Probabilistic Numerics group existed from mid 2016 to early 2018, when it moved to become a Chair at the University of Tübingen. The following text covers only this period, and was already included in the SAB report 2019. It is included here unchanged for completeness. More recent developments from 2018 onwards can be found at our new webpage (https://uni-tuebingen.de/en/160189)]

Computation is Inference What does it mean to *compute* a number? For simple operations like divisions, floating point arithmetic gives a concise and formalized answer: A computer can compute such numbers in a fixed amount of time, to a specified precision. But the situation is more complicated when the quantity to be computed is described in terms of more advanced mathematical operations. There are no general solutions to tasks like finding the extremum of a function, the value of an integral, the solution to a linear system of equations, or to a differential equation. Methods designed to find approximate solutions to such jobs are known as *numerical algorithms.* Numerical methods are inherentely imperfect. They excel on some tasks and fail on others, and they do not always 'notice' the difference. Some numerical methods are expensive and slow, but work on a large class of problems. Others are fickle, specific to a small domain, on which they nevertheless work extremely well.

The computational cost of contemporary machine learning is dominated by such numerical tasks, and the properties of the algorithms used to solve them:

- Optimization methods (sgd, quasi-Newton, Frank-Wolfe,...) train and fit estimators,
- Integration algorithms (MCMC, free energy methods, quadrature,...) compute marginals, conditionals and expectations in probabilistic inference,
- Linear algebra tools (Gauss-Jordan, conjugate gradients, Cholesky decompositions,...) solve elementary tasks like least-squares estimation and do the heavy lifting in the innermost loop of many more high-level numerical methods
- Differential equations are solved to *simulate*, *predict* and *control* future states of the environment

As a young field, machine learning has been able to borrow many extremely well-designed numerical algorithms from other fields. Some of these (e.g. linear algebra subroutines) are so good that people have essentially stopped thinking of them as algorithms with properties and flaws, and blindly trust the black box. This confidence is not always justified, for machine learning and data science poses some new numerical challenges that are not addressed well by classic methods. An example is the strong computational noise caused by data sub-sampling in big-data applications, which can make advanced optimization methods (like quasi-Newton) essentially unusable in applications like deep learning.

The improve this situation, our group aims to develop and broaden the understanding of numerical algorithms for intelligent systems, *in* the language and the setting of probabilistic machine learning. Our core tenet is that machine learning not just poses new challenges for numerics, it can also offer its own contributions to their solution, because *numerical methods **are** elementary learning* *machines themselves.* A numerical method *estimates* an unknown, latent quantity (e.g. an integral), *given* the value of certain tractable, observable quantities (values of the integrand at discrete locations). So they solve an inference task. But numerical methods are not passive statistical estimators; they actively decide, often in a closed feedback loop, which numbers to compute. They thus really are elementary autonomous agents.

In our work, we phrase this active inference process probabilistically, as the actions of an agent equipped with a notion of uncertainty about its task, captured by a probability measure. Exact computations performed on a chip provide information about the analytically intractable task, yielding a *posterior* probability measure whose location and width should ideally provide a point estimate and meaningful surrounding uncertainty over the true solution. Such algorithms are known as **probabilistic numerical methods**. Over the past years, we have helped establish this young research field, together with international collaborators.

On the theoretical side, we have contributed in-depth analysis of classic numerical algorithms to show that probabilistic numerical algorithms can be as fast, reliable and flexible as the widely used classics - simply because the classics already *are* probabilistic numerical methods, they just are not usually presented in this way. They can thus serve as a point of reference from which one can venture out to create new functionality for contemporary challenges. We also showed that in some cases (like optimization for deep learning), the probabilistic viewpoint can help uncover the cause for failures and problems of state-of-the-art methods, and suggest fixes.

For practitioners, our algorithms offer tangible improvements, some of which have helped our work enter into industrial use. Our Bayesian optimization framework *Entropy Search* has been used for advanced experimental design in areas like robotics and automated machine learning. For deep learning, we have contributed several tools that automate algorithmic hyperparameters in the inner loop, freeing users from tedious and wasteful tasks like step-size adaptation (some of our work can also be directly accessed as code packages on our github page). As the theoretical foundations of probabilistic numerics continue to expand and improve, we now increasingly turn our attention to develop practical algorithms for and in machine learning.

Last but not least, we have also invested in the establishment of a dedicated research community. We created a community website and organized and supported several international workshops and meetings. Partly as a result of this, there is now a nascent by rapidly growing international community studying both the theory and practice of probabilistic numerics.

History of the Group

The Probabilistic Numerics group at the MPI for Intelligent Systems was initially founded and funded, in 2015, as an Emmy Noether Research group of the German Research Union (DFG). In late 2016, it became one of the first independent Max Planck Research Groups of the MPI for Intelligent Systems. In 2017 our work let to the award of an ERC Starting Grant, which in turn led to several offers from German universities to move the group to a more permanent home. In May 2018, Philipp Hennig was appointed as a full professor at the Eberhard Karls University of Tübingen, where the group now lives on in a new form, as the Chair for the Methods of Machine Learning.

21.2 Selected Research Projects

Probabilistic Methods for Linear Algebra

Philipp Hennig, Simon Bartels, Filip de Roos

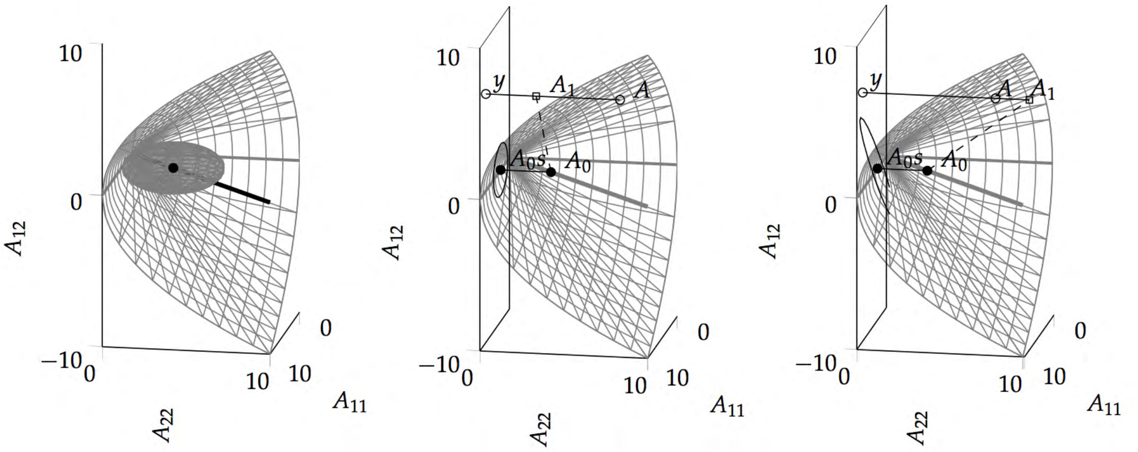


Figure 21.1: Probabilistic linear algebra methods assign matrix-valued probability measures to unknown matrix quantities; for example to elements of the positive definite cone.

Linear algebra methods form the basis for the majority of numerical computations. Because of this foundational, “inner-loop” role, they have to satisfy strict requirements on computational efficiency and numerical robustness.

Our work has added to a growing understanding that many widely used linear solvers can be interpreted as performing probabilistic inference on the elements of a matrix or a vector from observations linear projections of this latent object. In particular, this is true for such foundational algorithms as the method of conjugate gradients and other iterative algorithms in the *conjugate directions* and *projection method* classes [**hennig2015**].

Our ongoing research effort focusses on ways to use these insights in the large-scale linear algebra problems encountered in machine learning. There, the most frequent linear algebra task is the least-squares problem of solving

$$Kx = b$$

where K is a very large symmetric positive definite matrix (e.g. a kernel Gram matrix, or the Hessian of a deep network loss function). A key challenge in the big data regime is that the matrix — defined as a function of a large data-set — can only be evaluated with strong stochastic noise caused by data sub-sampling. Classic iterative solvers, particularly those based on the Lanczos process, like conjugate gradients, are known to be unstable to such stochastic disturbances, which is part of the reason why second-order methods are not popular in deep learning. In recent work we have developed and tested extensions to classic solvers that remain stable [**barhen16**] and tractable in this setting by efficiently re-using information across many interations [1600].

More information: https://pn.is.mpg.de/project/probabilistic-methods-for-linear-algebra

Controller Learning using Bayesian Optimization

Alonso Marco Valle , Sebastian Trimpe, Philipp Hennig, Alexander von Rohr, Jeannette Bohg, Stefan Schaal

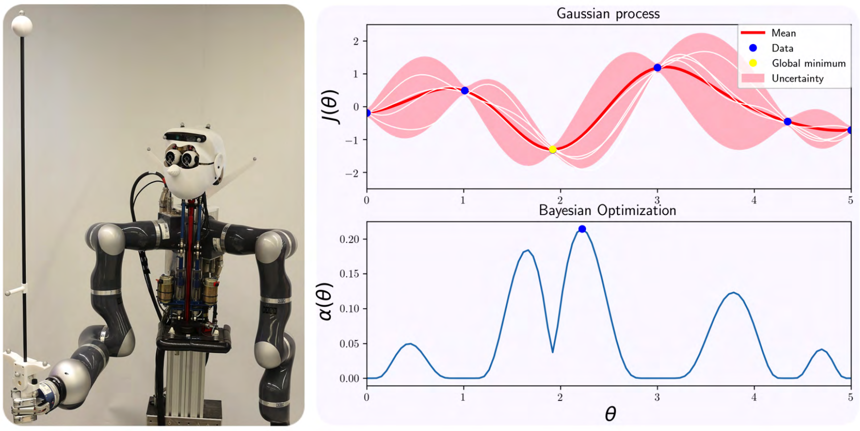


Figure 21.2: Left: Humanoid robot Apollo learning to balance an inverted pole using Bayesian optimization. Right: One-dimensional synthetic example of an unknown cost J(θ) modeled as a Gaussian process for controller parameter θ, conditioned on observed data points. The next controller to evaluate is suggested by the Bayesian optimizer where the acquisition function $\alpha(\theta)$ finds its maximum.

Autonomous systems such as humanoid robots are characterized by a multitude of feedback control loops operating at different hierarchical levels and time-scales. Designing and tuning these controllers typically requires significant manual modeling and design effort and exhaustive experimental testing. For managing the ever greater complexity and striving for greater autonomy, it is desirable to tailor intelligent algorithms that allow autonomous systems to learn from experimental data. In our research, we leverage automatic control theory, machine learning, and optimization to develop automatic control design and tuning algorithms.

In [73],[**marcomlpc15**],[**marco15**], we propose a framework where an initial controller is automatically improved based on observed performance from a limited number of experiments. Entropy Search (ES) [**hennigs2012**] serves as the underlying Bayesian optimizer for the auto-tuning method. It represents the latent control objective as a Gaussian process (GP) (see above figure) and sequentially suggests those controllers that are most informative about the location of the optimum. We validate the developed approaches on the experimental platforms at our institute (see figure).

We have extended this framework into different directions to further improve data efficiency. When auto-tuning real complex systems (like humanoid robots), simulations of the system dynamics are typically available. They provide less accurate information than real experiments, but at a cheaper cost. Under limited experimental cost budget (i.e., experiment total time), our work [46] extends ES to include the simulator as an additional information source and automatically trade off information vs. cost.

The aforementioned auto-tuning methods model the performance objective using standard GP models, typically agnostic to the control problem. In [39], the covariance function of the GP model is tailored to the control problem at hand by incorporating its mathematical structure into the kernel design. In this way, unforeseen observations of the objective are predicted more accurately. This ultimately speeds up the convergence of the Bayesian optimizer.

Bayesian optimization provides a powerful framework for controller learning, which we have successfully applied on very different settings: humanoid robots [73], micro robots [1393] and automotive industry [1370].

More information: https://pn.is.mpg.de/project/cont-learn-bayes-opt

Probabilistic Radiation Treatment Planning

Philipp Hennig, Mark Bangert, Niklas Wahl, Hans-Peter Wieser

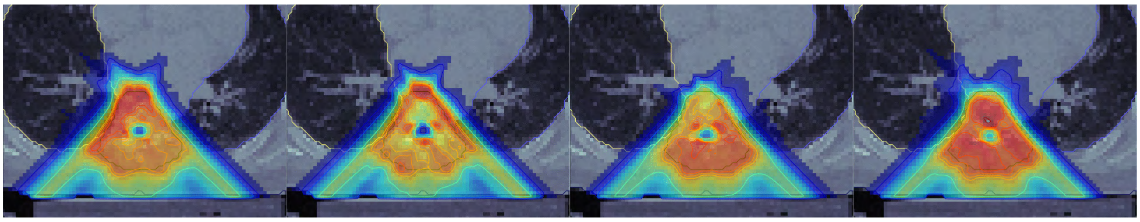


Figure 21.3: Several hypotheses for the dosis deposited in a spinal tumor under a traditional treatment plan. The samples are representative of an entire population simultaneously considered and optimized for reduced variance by the novel algorithm produced in this project.

Fast Probabilistic Treatment Planning for Radiation Tumor Therapy

Software solutions for scientific and technical tasks usually do not consist of a single computational step, but rather are a *pipeline* of computations. An ongoing collaboration between the research group on probabilistic numerics and the Optimization Group at the German Cancer Research Centre in Heidelberg has offered an opportunity for us to test mathematical ideas for the *propagation of uncertainty* through such chains of computation while also producing tangible medical results.

The semi-automated production protocol of treatment plans is an everyday occurence in clinical practice: Tumor patients who are scheduled for radiation treatment by their oncologist come in for an imaging session in a CT or MRI scanner. The resulting 3D image is annotated by a physician, outlining both tumor tissue and surrounding organs at risk of unwanted radiation damage. This volumetric data provides the input to an optimization algorithm, which sets the parameters of a treatment system (angles, energies, and shape of treatment beams). In advanced treatment systems, in particular those using heavy ions as the treatment probe, this optimization problem regular has several thousand parameters. Then the patient comes in for a sequence of treatments.

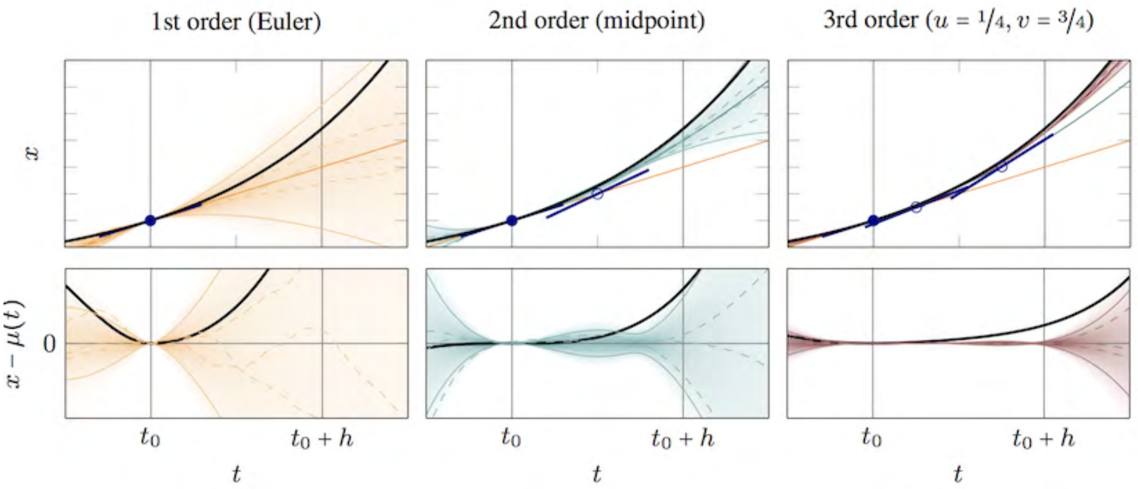
This entire process is subject to a host of sources of uncertainty, from the imaging process, through human labeling, the optimization algorithm itself, the mechanical imperfections of patient placement during treatment, to complicated and correlated physical and biological sources of uncertainty about the reaction of each cell to the delivered radiation dose.

In a number of sub-projects with our collaborators in Heidelberg, we were able to construct a framework for the analytical and numerically efficient computation and propagation of such input uncertainties [**bangertho2013**],[**bangertho2013_2**], that can separate the effects of various sources of uncertainty [1596], including highly nonlinear biological effects [1598] and efficiently propagate them through the optimization process [1601], to produce an improved treatment plan that is more robust to errors and reduces the risk of complications for patients. From the point of view of research in probabilistic numerics, this strand of work provides examples both for the feasibility and concrete useability of uncertainty propagation in compartmental computations: By casting each step of the pipeline in terms of structured Gaussian distributions, uncertainty from various sources can be tracked, monitored, and controlled at feasible computational overhead. There is a deeper philosophical inside hidden inside of these practical tools: Because probability theory does not differentiate between different types of uncertainty but captures everything the the universal language of probability measures, there is fundamental reason to distinguish between numerical, physical, experimental or philosophic uncertainty in computational practice, either. The kinds of uncertainty caused by finite data, by finite computational budget, imperfect physical measurements and even quantum-mechanical aspects of the interaction between accelerated heavy ions and DNA molecules all fit into one joint Gaussian distribution.

More information: https://pn.is.mpg.de/project/probabilistic-radiation-treatment-planning

Probabilistic Solvers for Ordinary Differential Equations

Philipp Hennig, Michael Schober, Hans Kersting



Solvers for ordinary differential equations (ODEs) belong to the best-studied algorithms of numerical mathematics. An ODE is an implicit statement about the relationship of a curve $x : \mathbb{R}_{\geq 0} \to \mathbb{R}^N$ to its derivative, in the form $x'(t) = f(x(t), t)$, where x' is the derivative of curve, and f is some function. To identify a unique solution of a particular ODE, it is typically also necessary to provide additional statements about the curve, such as its *initial value* $x(t_0) = x_0$. An ODE solver is a mathematical rule that maps function and initial value, (f, x_0) to an estimate $x(t)$ for the solution curve. *Good* solvers have certain analytical guarantees about this estimate, such as the fact that its deviation from the true solution is of a high polynomial order in the step size used by the algorithms to discretize the ODE.

One of the main theoretical contributions of the group is the development of *probabilistic* versions of these solvers. In several works, we established a class of solvers for initial value problems that generalize classic solvers by taking as inputs Gaussian distributions $\mathcal{N}(x(t_0); x_0, \Psi)$, $\mathcal{GP}(f; \hat{f}, \Sigma)$ over the initial value and vector field, and return a Gaussian process posterior $\mathcal{GP}(x; m, k)$ over the solution. We were able to show that these methods

- have the same (linear) computational computational complexity in solver's step-size h as classic methods [1595] (they are Bayesian filters)

- can inherit the famous local and global polynomial convergence rates of classic solvers [1594] (i.e. $\|m - x\| \leq Ch^q$ for $q \geq 1$)

- produce posterior variance estimates that are calibrated worst-case error estimates [1594] (i.e. $\|m - x\|^2 \leq Ck$). In Short, they produce meaningful uncertainty

- are in fact a generalization of certain famous classic ODE solvers (namely they reduce to explicit single-step Runge Kutta methods and multi-step Nordsieck methods in the limit of uninformative prior and steady-state operation, respectively. In practical operation, they offer a third, novel type of solver) [1595]

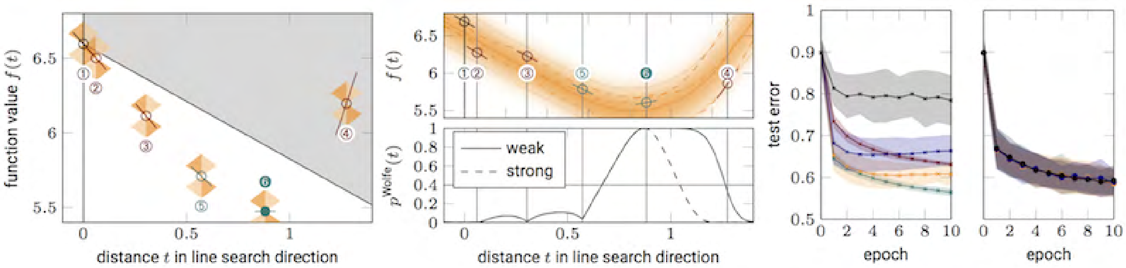
- they can be generalized to produce non-Gaussian, nonparametric output while retaining many of the above properties [1591].

Together, these results provide a rich and reliable new theory for probabilistic simulation that current ongoing research projects are seeking to leverage to speed up structured simulation problems inside of machine learning algorithms.

More information: https://pn.is.mpg.de/project/probabilistic-solvers-for-ordinary-differential-equations

Probabilistic Methods for Nonlinear Optimization

Philipp Hennig, Maren Mahsereci, Lukas Balles, Frank Schneider



Optimization problems arising in intelligent systems are similar to those studied in other fields (such as operations research, control, and computational physics), but they have some prominent features that set them apart, and which are not addressed by classic optimization methods. Numerical optimization is a domain where probabilistic numerical methods offer a particularly interesting theoretical contribution.

One key issue is computational noise. Big Data problems often have the property that computational precision can be traded off against computational cost. One of the most widely occuring problem structure is that one has to find a (local) optimum of a function L that is the sum of many similar terms, each arising from an individual data point y_i

$$L(x) = \frac{1}{N}\sum_{i=1}^{N} \ell(y_i, x)$$

Examples of this problem include the training of neural networks, of logistic regressors, and many other linear and nonlinear regression/classification algorithms. If the dataset is very large or even infinite, it is impossible, or at least inefficient, to evaluate the entire sum. Instead, one draws $M \ll N$ (hopefully representative) *samples* y_j from some distribution and computes the approximation

$$\hat{L}(x) = \frac{1}{M}\sum_{j=1}^{M} \ell(y_j, x) \approx L(x)$$

If the representers y_j are drawn independently and identically from some distribution, then this approximation deviates, relative to the true $L(x)$, by an approximately Gaussian disturbance.

Classic optimizers like quasi-Newton methods are unstable to these disturbances, hence the popularity of first-order methods, like stochastic gradient descent (sgd), in deep learning. But even such simple methods become harder to use in the stochastic domain. In particular, sgd and its variants exhibit free parameters (e.g. step-sizes / learning rates) in the stochastic setting, even though such parameters can be easily tuned automatically in the noise-free case. Thus, even at the world's leading large AI companies, highly trained engineers spent their work time hand-tuning parameters by repeatedly running the same training routine on high-performance hardware. A very wasteful use of both human and hardware resources. A NeurIPS workshop organized by us in 2016 highlighted the urgency of this issue.

The probabilistic perspective offers a clean way to capture this issue: It simply amounts to changing the *likelihood* term of the computation from a point measure on $L(x)$ to a *Gaussian* distribution $p(\hat{L} \mid L) = \mathcal{N}(\hat{L}; L, \Sigma)$. This seemingly straightforward formulation immediately offers an analytical avenue to understand why existing optimizers fundamentally require hand-tuning: While a point measure only has a single parameter (the location), a Gaussian has *two* parameters: mean and (co-) variance. But the latter does not feature in classic analysis, and is simply unknown to the algorithm. It is possible to show [895] that this lack of information can make certain parameters (such as step sizes) fundamentally un-identified. Identifying them not just requires new algorithms, but also concretely *computing* a new object: In addition to batch gradients, also batch *square* gradients, to empirically estimate the variance. Doing so is not free, but it has low and bounded computational cost [895], because it can re-use the back-prop pass, the most expensive part of deep learning training steps.

Over years we have built a series of tools that use this additional quantity to tune various learning hyperparameters such as the learning rate [**mahhen2015**] [1599] [578], batch size [895] and stopping criterion [784]. We have also contributed theoretical analysis for some of the most popular deep learning optimizers [1603] and are now working towards a new code platform for the automation of deep learning in the inner loop, to free practitioners hands to build models, rather than tune algorithms.

More information: https://pn.is.mpg.de/project/probabilistic-methods-for-nonlinear-optimization

21.3 Awards & Honors

2018

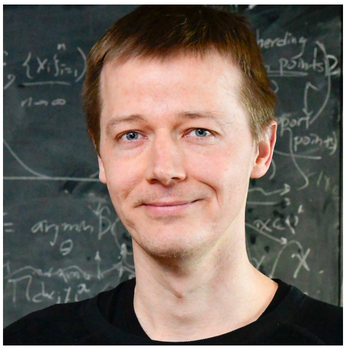
Philipp Hennig has been named as one of Germany's "40 under 40" influential young people in the category Science and Society.

2017

Philipp Hennig: ERC Starting Grant (Acronym: PANAMA)

21.4 Research group leader: Philipp Hennig

Biography



From mid 2016 to early 2018, Philipp Hennig led the Probabilistic Numerics research group at the MPI for Intelligent Systems. This biography deliberately reflects the status quo at the end of that period. More recent information pertaining his work after his move to the University of Tübingen can be found under the link at the bottom of this page.
Hennig studied Physics in Heidelberg, Germany and at Imperial College, London, before moving to the University of Cambridge, UK, where he attained a PhD in the group of the late Sir David JC MacKay for research on approximate inference methods. Since this time, he is interested in connections between computation and inference. He began his postdoctoral career at the MPI IS in the department for Empirical Inference, before his group received independent funding through the Emmy Noether programme of the German Research Union (DFG) in 2015.

An ERC Starting Grant awarded in 2017 triggered several offers for full professorships from German universities. In May 2018, Hennig accepted such an offer from the University of Tübingen, where he now holds the Chair for the Methods of Machine Learning. In November 2018, Capital Magazine listed Philipp Hennig as one of Germany's "40 under 40" influential young people in the category "Science and Society". Hennig retains an adjunct position at the MPI IS, in the Empirical Inference department.

Employment (appointments) / Academic positions

2018 – present	Full Professor for the Methods of Machine Learning (W3), Eberhard Karls University of Tübingen, Germany
2016 – 2018	W2 Independent Max Planck Research Group Leader, MPI-IS, Germany
2015 – 2016	Independent Emmy Noether Group Leader, MPI-IS, Germany
05/2015 – 01/2016	Parental Leave
2013 – 2015	Senior Research Scientist, Empirical Inference Department, MPI-IS, Germany
2011 – 2013	Research Scientist, Empirical Inference Department, MPI-IS, Germany

Education

2011	PhD, University of Cambridge (Robinson College / Cavendish Lab.), UK. Supervisor: Sir D.J.C. MacKay
2005 – 2016	Erasmus studies at Imperial College, London (*Quantum Fields and Fundamental Forces* program)
2007	Diploma in Physics, Ruprecht Karls University Heidelberg, Germany

Awards & Fellowships

2018	Named as one of Germany's *40 under 40 in Science and Society* by Capital Magazine
2017	ERC Starting Grant, 5 year project PANAMA
2015	Emmy Noether Fellowship of the German Research Union (DFG)

Publications and Talks

Publications	14 Refereed Journal, 29 Refereed Conference, 1 Ed. Book, 1 US Patent h-index: 22, i-10 index: 32, 1331 citations (Google Scholar 06/12/18)

Teaching/Supervision Activities

2012 – present	Supervision of 11 PhD students (3 graduated)
2004 – present	Supervision of 4 Master Theses (1 current)
2012 – present	Several Full Lecture Courses on Bayesian Machine Learning Several Seminars, Invited Tutorials
2017	Lecturer at Dobbiaco Summer School on Probabilistic Numerics
2012–13–15	Co- and Principal Organizer of three Machine Learning Summer Schools (MLSS)

Professional Activities (selected)

2013 – present	Member of Editorial Board, Journal of Machine Learning
2014 – present	Area Chair for Neural Information Processing Systems (3×), International Conference on Machine Learning (1×), Artificial Intelligence and Statistics (3×)
2017 – 2018	Member of the Exectuive Board for the International Max Planck Research School for Intelligent Systems (IMPRS-IS)
2014 – 2018	Steering Board, Max Planck-ETH Center for Learning Systems

(Co-) Organization of Scientific Workshops

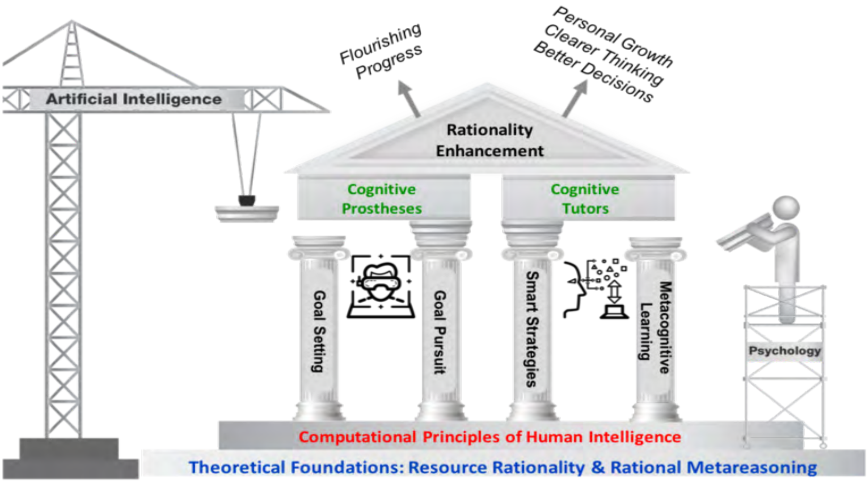
2017	ICERM workshop on Probabilistic Scientific Computing
2016	Dagstuhl Seminar: New Directions for Learning with Kernels and Gaussian Processes
2016	NIPS Workshop on Optimizing the Optimizers
2015	NIPS Workshop on Probabilistic Integration
2015	Workshop on Probabilistic Numerics for Differential Equations, Warwick
2015	Workshop on Probabilistic Numerics at DALI
2014	Roundtable on Probabilistic Numerics
2012	Inaugural NIPS workshop on Probabilistic Numerics

Links

Link to CV on website: https://uni-tuebingen.de/en/134782

22 RATIONALITY ENHANCEMENT

22.1 Research Overview



The Rationality Enhancement Group investigates the **computational principles of human intelligence** and develops **intelligent systems that help people realize their full potential**. Our diverse, interdisciplinary team combines methods from computational cognitive science, artificial intelligence, psychology, and human-computer interaction to strengthen the scientific and technological foundations for understanding, supporting, and improving the human mind.

To lay a solid foundation for this work, we have co-developed and extended the theoretical frameworks of resource rationality [1627] and rational metareasoning [1629]. To identify computational principles of human intelligence, we apply our theoretical frameworks to develop computational models of i)the cognitive mechanisms that enable people to set and achieve clever long-term goals and ii) the learning mechanisms that enable them to discover and continuously refine their algorithms. In doing so, we are reverse-engineering some of the learning algorithms that might contribute to people's general intelligence.

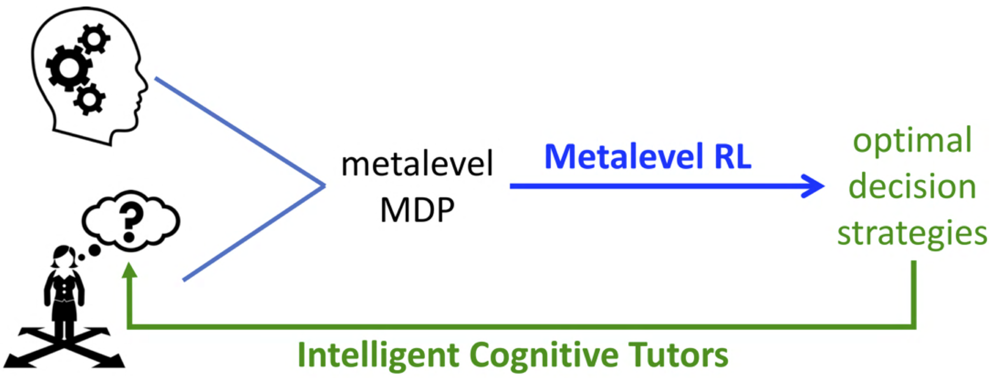
We take a unique approach to developing beneficial artificial intelligence in that all of our projects are grounded in computational models of human cognition. These models specify what people's goals are, what constitutes good thinking and decision-making, and why people often struggle to achieve their goals. To enable intelligent systems that help people realize their full potential, we pursue two complementary lines of research that focus on training people (intelligent cognitive tutors) and providing decision support (intelligent cognitive prostheses).

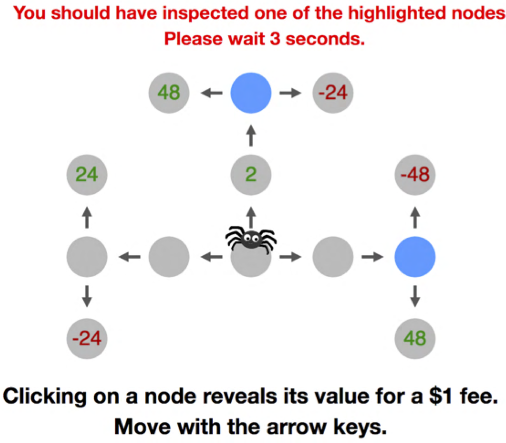
The overarching long-term aim of this research program is to help lay the scientific foundations for increasing people's capacity and motivation to make the world a better place in a way that is sustainable and conducive to their well-being. In addition to pursuing this goal through our research, we started the Life Improvement Science conference, whose first edition drew in 600 registered participants from many different countries and disciplines. To raise awareness for this emerging research field, we have also published an encyclopedia entry about Life Improvement Science [1662]. We are currently leading a broad collaborative project to identify the community's most important scientific questions.

22.2 Selected Research Projects

Intelligent Cognitive Tutors

Falk Lieder, Lovis Heindrich, Julian Skirzynski, Yash Raj Jain, Frederic Becker, Aashay Mehta, Saksham Consul, Jugoslav Stojcheski, Gabriela Iwama, Anirudha Kemtur, Maria Wirzberger, Anastasia Lado, Mike Prentice, Jean-Claude Passy, Ivan Oreshnikov, Lisa Eckerstorfer, Adrian Stock, Fred Callaway, Tom Griffiths, Paul Krueger, Bas van Opheusden, Priyam Das

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Clicking on a node reveals its value for a $1 fee.
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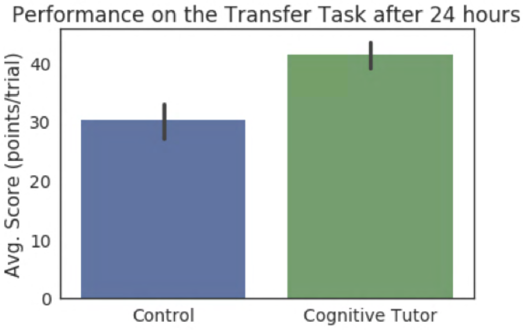

Teaching people how to make their own wise decisions is one of the most challenging goals of education. This project leverages artificial intelligence to address two key challenges in teaching decision-making skills: discovering smart decision strategies and teaching them at scale.

To discover smart decision strategies, we have developed a mathematical theory of optimal decision-making with limited time and bounded cognitive resources [1627] and cognitively inspired reinforcement learning methods for computing such strategies [1659][1]. To make it possible to teach the resulting automatically discovered strategies at scale, we develop called intelligent cognitive tutors. Our intelligent cognitive tutors help people internalize those strategies by having them practice decision-making with optimal feedback [1653, 1654][2], demonstrate the optimal strategies to them, and present them with automatically generated natural-language descriptions of those strategies [1622]. Our recent work has made our methods significantly more scalable to larger and more complex decision problems, more robust to errors in the model of the real world [1644], and more interpretable [1622]. We are currently extending this approach to partially observable environments. Moving forward, we will apply our approach to improve human performance in real-world problems, such as in hiring decisions.

Testing our intelligent cognitive tutors in large-scale online experiments demonstrated that our intelligent cognitive tutors can significantly improve the strategies and outcomes of human decision-making not only in the trained task but also in more complex decisions and in similar tasks in other domains [1653][2]. Unfortunately, we also found that people rarely apply the taught strategies to tasks that look very different from the trained task [1639].

Our work has primarily focussed on helping people overcome short-sighted biases in decision-making by discovering and teaching far-sighted planning strategies [1653][2]. However, our methods are very general. We have already successfully applied them to other types of sequential decision problems and the problem of choosing between multiple alternatives based on their attributes [1644, 1661]. In addition, we have developed a desktop app that helps people train their executive functions by giving them feedback on how well they succeed at staying focused on their goals as they work on their computers [1643].

More information: https://re.is.mpg.de/project/cognitive-tutors

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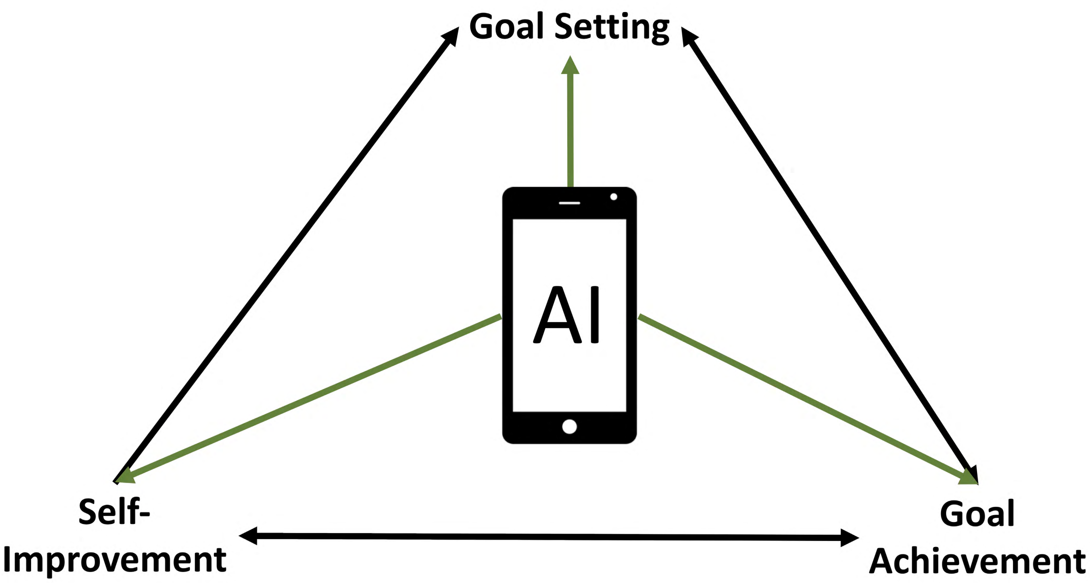
[1] S. Consul, L. Heindrich, J. Stojcheski, F. Lieder. Improving Human Decision-Making by Discovering Efficient Strategies for Hierarchical Planning. *Computational Brain & Behavior*, under review.

[2] F. Callaway, Y. R. Jain, B. van Opheusden, P. Das, G. Iwama, et al. Leveraging Artificial Intelligence to Improve People's Planning Strategies. *Proceedings of the National Academy of Sciences of the United States of America*, accepted conditional on minor revisions.

Intelligent Cognitive Prostheses

Falk Lieder, Mike Prentice, Victoria Amo, Valkyrie Felso, Florian Mohnert, Benjamin Prystawski, Jugoslav Stojcheski, Pin-Zhen Chen, Hernán González, Gabriela Iwama, Reena Pauly



Today's rapid technological advances present an unprecedented opportunity to augment the human mind with the help of technology. We refer to such technologies as *cognitive prostheses*. Our goal is to leverage insights from cognitive science to develop technologies that help humanity overcome its cognitive limitations and enable people to set better goals and pursue them more effectively. To achieve this goal, we are developing digital tools that help people make valuable contributions to society. Our tools assist people in each step from setting prosocial long-term goals [1634, 1637] and planning how to achieve them [1641] to making good decisions [1628, 1651, 1658], staying focused on the goal [1643], and overcoming psychological obstacles along the way [1633, 1645].

Our basic idea for leveraging AI to help people make better decisions is to align each action's immediate reward with its long-term value to make good decisions easier [1628]. We have developed a mathematical framework for designing incentive structures that can be used to guarantee that the rewards won't accidentally incentivize counter-productive behaviors and a computational method for computing incentives that make it as easy as possible for people to choose the course of action that is best in the long run. We are working on instantiating this approach in an intelligent productivity system that helps people plan their days, weeks, and months by computing optimal hierarchical plans and incentivizing the user's tasks and potential short-term goals accordingly. Initial results suggest that this is a promising approach to helping people prioritize their most important tasks and overcome procrastination [1628]. We are currently scaling up this approach[3],[4] and integrating it into a digital companion that helps people achieve their goals. We are also working towards incentivizing planning and goal-setting and computing personalized incentives based on inverse-reinforcement learning [1642]. In another project, we successfully applied this approach to incentivize self-directed learning [1636, 1658].

We combine these computational approaches with psychological theory to guide people towards socially beneficial goals [1634, 1637] and help them overcome psychological obstacles, such as self-defeating thoughts and emotions [1633, 1645].

More information: https://re.is.mpg.de/project/modeling-and-fostering-effective-goal-pursuit

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[3] S. Consul, J. Stojcheski, V. Felso, F. Lieder. Optimal To-Do List Gamification for Long Term Planning. Tech. rep. 2021, https://arxiv.org/abs/2109.06505.

[4] J. Stojcheski, V. Felso, F. Lieder. Optimal To-Do List Gamification. Tech.rep. 2020, https://arxiv.org/abs/2008.05228.

Computational Principles of Human Intelligence

Falk Lieder, Ruiqi He, Benjamin Prystawski, Yash Raj Jain, Gabriela Iwama, Florian Mohnert, Nishad Singhi, Mateo Tosic, Valkyrie Felso, Tom Griffiths, Fred Callaway, Peter Dayan

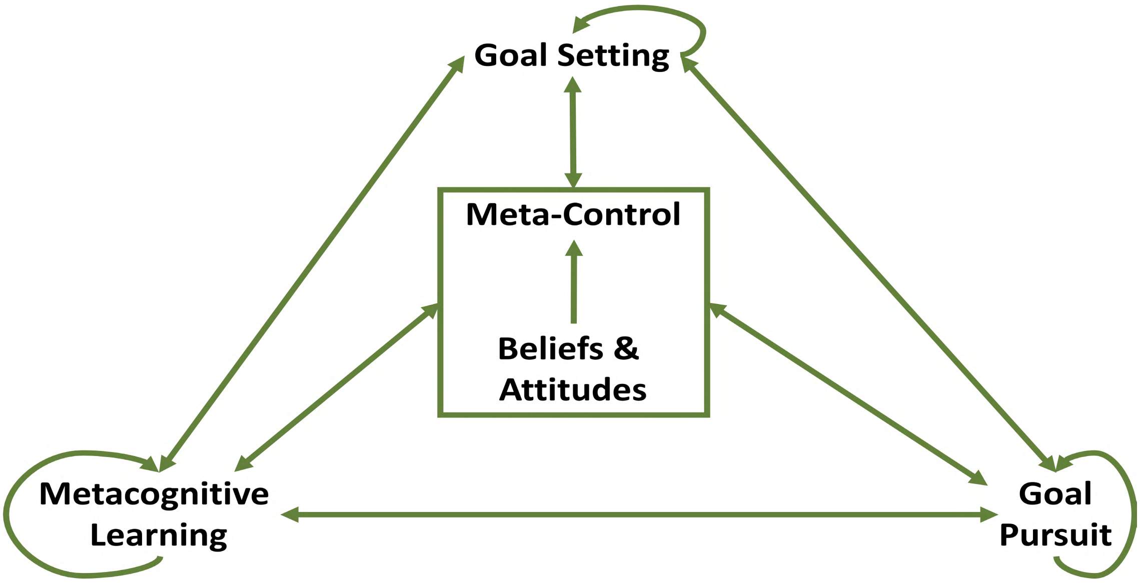
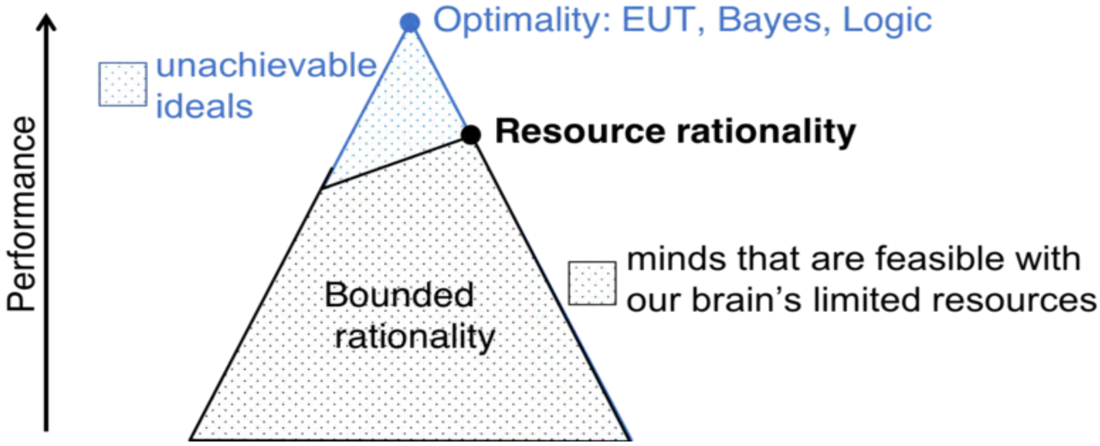


Figure 22.1: Meta-control, goal, setting, goal-pursuit, and metacognitive learning are essential to human intelligence. The REG reverse-engineers the underlying computational mechanisms.

Our research on the computational principles of human intelligence strives to elucidate and reverse-engineer two of the most impressive features of the human mind: **proactivity** and **metacognitive learning**. To reverse-engineer the underlying computational mechanisms, we have developed a new cognitive modeling paradigm called **resource-rational analysis** [1627] that many cognitive scientists have rapidly adopted.



Resource rationality and rational metareasoning

Our most influential scientific contribution so far has been to develop and establish the theory of resource rationality as a framework for modeling the computational mechanisms of human intelligence [1626, 1627, 1648] This new approach to cognitive modeling integrates the functional constraints imposed by the goal of a cognitive mechanism with the computational constraints imposed by people's finite time and bounded cognitive resources. This new approach to cognitive modeling has spread rapidly. The 16 articles in which we introduced and established it have been collectively cited more than 1400 times in the first six years.

One of our recent theoretical contributions has been to develop and test computational models of two important metacognitive abilities that contribute to people's resource-rationality, namely the adaptive control of reasoning and decision-making [1621, 1624, 1625, 1629, 1657] and metacognitive learning (see below; [1623, 1638, 1640, 1652]). The progress summarized here and in other sections of this report demonstrates that the Rationality Enhancement Group continues to successfully leverage the theory of resource-rationality to reverse-engineer, augment, and enhance human cognition.

Proactivity

An essential aspect of human intelligence is that people do not merely react to their environment. Instead, they often take the initiative to set and pursue their own goals. This is known as proactivity. To elucidate the computational principles of proactivity, the Rationality Enhancement Group has developed resource-rational models of how people pursue their goals [1621, 1649], new methods for elucidating the cognitive strategies of human planning [1656][5],[6], and a rational metareasoning model of how the brain decides when to engage the mechanisms of proactivity [1624]. To facilitate research on human planning, we developed a Bayesian method for inferring people's mental planning strategies from their overt behavior in an appropriately designed planning task [1656]. Using this method, we discovered that people make adaptive use of 79 planning strategies of 13 different types. In addition, we have developed a machine learning method for clustering and describing people's planning strategies automatically.

Metacognitive Learning

How does the human brain learn how to think and how to decide? What are the learning mechanisms that give rise to human intelligence and enable us to get better at what we do? How can this learning be promoted and accelerated? To answer these questions, we reverse-engineer how people learn when to use which cognitive strategy [1657][7],[8], how the brain learns to control its own information processing [1623][9], and how people discover and continuously refine their own cognitive strategies [1638, 1640, 1652, 1656][5]. To make this possible, we have developed new empirical and computational methods for measuring learning-induced changes in people's planning strategies [1656]. We have used these methods to characterize metacognitive learning empirically. We found that our models of metacognitive learning can capture not only how people's average performance improves with practice but can also predict the underlying qualitative changes in people's planning strategies [1638, 1640, 1652]. So far, this line of research has led to 9 publications and 399 citations.

In a follow-up project, we are currently investigating whether reflection can improve metacognitive learning and what the underlying mechanisms might be [1635]. The resulting psychological insights and technical advances lay a scientific foundation for leveraging technology to accelerate human learning and improve decision-making. Our initial results show that guiding people to systematically reflect on how they make their decisions by asking them a series of Socratic questions leads to instantaneous metacognitive learning.

More information: https://re.is.mpg.de/project/computational-principles-of-human-intelligence

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[5] Y. R. Jain, F. Callaway, T. L. Griffiths, P. Dayan, P. M. Krueger, et al. A Computational Process-Tracing Method for Measuring People's Planning Strategies and How They Change Over Time. *Behavior Research Methods*, under review.

[6] J. Skirzynski, Y. R. Jain, F. Lieder. Automatic discovery and description of human planning strategies. *Behavior Research Methods*, Sept. under review.

[7] F. Lieder, D. Plunkett, J. B. Hamrick, S. J. Russell, N. J. Hay, et al. Algorithm selection by rational metareasoning as a model of human strategy selection. In *Advances in Neural Information Processing Systems 27*, 2014.

[8] F. Lieder, T. L. Griffiths. Strategy selection as rational metareasoning. *Psychological Review* **124**: 762–794, 2017.

[9] F. Lieder, A. Shenhav, S. Musslick, T. L. Griffiths. Rational metareasoning and the plasticity of cognitive control. *PLOS Computational Biology* **14** (4): e1006043, 2018.

22.3 Research group leader: Falk Lieder

Biography

Falk Lieder leads the Rationality Enhancement group at the MPI for Intelligent Systems in Tübingen.
Following two Bachelor's degrees in Cognitive Science and Mathematics/Computer Science at the University of Osnabrück, he obtained his master's degree in Neural Systems and Computation at ETH Zurich. After working as a research assistant in Klaas Stephan's Translational Neuromodeling Unit at the University of Zurich he then completed his Ph.D. in Tom Griffiths's Computational Cognitive Science Lab at UC Berkeley. His dissertation was awarded the Glushko Dissertation Prize in Cognitive Science.

His interdisciplinary research combines computational modeling, behavioral experiments, and artificial intelligence to understand and improve human learning and decision-making. His most influential scientific contribution to date has been to develop and establish the cognitive modeling paradigm known as *resource-rational analysis* that has been rapidly adopted by the cognitive science community (14 publications, >1400 citations). In total, he has published 25 articles and 37 conference abstracts that have collectively been cited more than 2700 times. He has successfully acquired third-party funding from the National Science Foundation, the German Federal Ministry of Education and Research, the Cyber Valley Research Fund (2x), and the German Research Foundation (as external co-PI).

He was the lead organizer of the inaugural Life Improvement Science conference.

Awards & Fellowships

04/2020	Robert J. Glushko Dissertation Prize in Cognitive Science ($10,000)
09/2018	Best poster award of the 14th Biannual Conference of the German Cognitive Science Society
12/2017	Outstanding Paper Award, NIPS workshop on Cognitively Informed Artificial Intelligence
08/13–07/15	Berkeley Fellowship for graduate study (offered to the top 4% of prospective graduate students)

Education

- Ph.D. University of California, Berkeley, USA, Neuroscience, May 2018
- M.Sc. ETH Zurich, Switzerland, Neural Systems and Computation, 2012, with distinction
- Graduate Summer School Probabilistic Models of Cognition, 07/2011, UCLA
- B.Sc. University of Osnabruück, Cognitive Science, 2010, with distinction
- B.Sc. University of Osnabruück, Mathematics/Computer Science, 2010, with distinction

Employment (appointments) / Academic positions

since 07/2018:	Max Planck Research Group Leader, Max Planck Institute for Intelligent Systems, Tuübingen
10/2012-07/2013:	Research Assistant, Translational Neuromodeling Unit, University of Zurich, Switzerland

Links

Link to CV on website: https://re.is.mpg.de/~flieder

23 PHYSICAL REASONING AND MANIPULATION LAB

23.1 Research Overview

The general aim of the *Physical Reasoning and Manipulation* lab – as part of Toussaint's MPI Fellowship – are AI systems with the general competence to reason about anything achievable and possible in our Newtonian physical world.

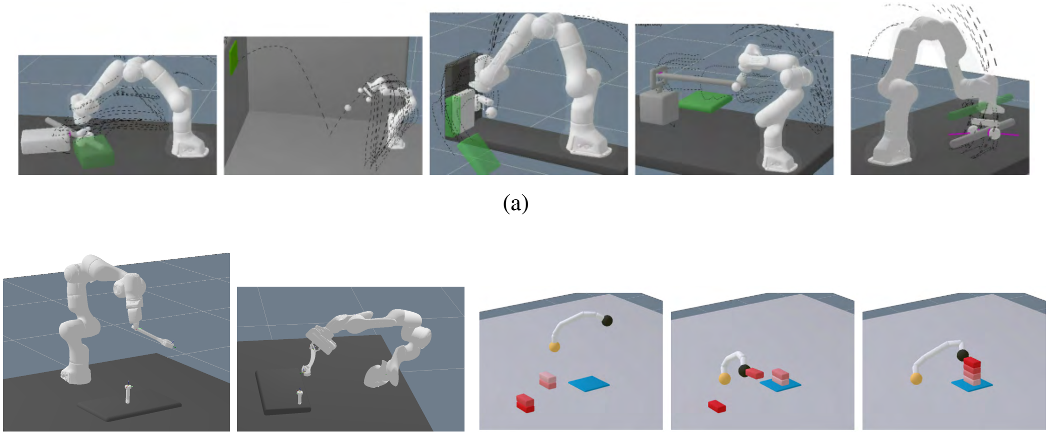
While contemporary research makes great progress in general reinforcement learning, general decision theory, and leveraging machine learning for decision making, we believe that there is lack of progress in specifically understanding physical competences, such as physical reasoning and problem solving, which are the foundation of natural intelligence.

This lack of porgress is a core reason for why robotics research cannot yet profit from modern AI to the same degree as other, more data-driven disciplines do. With our research we aim to fill this gab. Our leading research question is:

What does it need to enable general purpose physical reasoning and manipulation?

23.2 Selected Research Projects

Formalizing Physical Reasoning as Logic-Geometric Programming



(a)

(b)

(c)

Figure 23.1: Our Physical Reasoning Framework – Logic-Geometric Programming – applied to a) force-based manipulation planning, b) robot and tool morphology optimization, and c) hierarchical manipulation.

Our goal is to enable physical reasoning, i.e., the competence of general purpose problem solving in a Newtonian physical world. There are two fundamental questions to this end: 1) If reasoning is model-based, what kind of models do systems need to enable physical reasoning? In the cognitive sciences, this is related to the question of *Intuitive Physics* as a concept to enable efficient problem solving in our physical world. And 2), what computational paradigm should enable reasoning? In classical AI, planning & reasoning are often addressed as discrete search, esp. logic. However, physical reasoning requires to efficiently cope with continuous geometry and physics laws.

Our general approach assumes optimization as the core computational paradigm to enable reasoning, but extends this to also account for discrete decisions on discontinuous aspects of the physical world, such as which objects to interact with. To this end we developed a novel framework, called Logic-Geometric Programming (LGP), to combine the concepts of optimization theory and logic search.

The core scientific question becomes how to formulate physical reasoning problems within this framework, and how to devise efficient solvers.

While our first LGP formulations had shown its capability to solve mostly kinematic and stable tasks, like pick-and-place, we now pushed the boundary to include reasoning over general, also force-based, physical interactions. In [1607], we introduced novel physics models for reasoning, in particular a specific parameterization of wrench exchange between object surfaces which can be seamlessly integrated into LGP. This enables our robot to come up with motion plans that, e.g., push a box on the table to a target location. Moreover, we showed that the LGP framework can handle multi-physics descriptions for general physical reasoning, which include and integrate general force-based interactions, quasi-static dynamics, and pick-and-place type interaction modes.

In most of our work we assume a deterministic physics models for reasoning. However, in [1612], we extended the LGP formulation to stochastic domains so that it can tackle scenarios where disturbances are injected into actuators and/or the environment contains some sort of uncertainty. We converted the stochastic trajectory optimization into the posterior inference problem of optimal path distributions and approximated it as a mixture of Gaussians where each feasible logic profile defines a single Gaussian path distribution. The proposed framework enables many interesting things which only arise in stochastic domains: (i) A robot can prioritize various interaction modes taking uncertainty into account; for example, it prefers to push a box using two fingers instead of one because the uncertainty of the box's orientation can be greatly reduced that way. (ii) A robot can acquire contact exploitation behaviors for uncertainty reduction such as fixing its elbow on the table to get more precise hand motions. (iii) A robot can (probabilistically) combine multiple plans to construct a reactive controller to adaptively choose which plan to follow.

Concerning our solvers, a challenge is to achieve scalability to longer horizons or situations having many possible discrete decisions, because the size of a logic tree to be searched grows exponentially with those. To overcome this, in [1618], we proposed to introduce a hierarchy of LGPs at the discrete decision level for the purpose of providing efficient lower bounds of the underlying LGP problem. In the proposed framework which we call hierarchical LGP, a coarse level LGP is solved first that contains fewer constraints in the underlying NLP and the discrete decisions of this solution then condition a fine level LGP. This hierarchy turned out to greatly reduce the computation time in the experiments.

Finally, existing work on sequential manipulation planning, including the above ones, assumes the robot, environment and tools to be given. However, physical reasoning should include reasoning about what would be an optimal robot design, tool shape, or robot station geometry for a particular ensemble of manipulation tasks. Therefore, in [1609], we investigated if such static design parameters can be jointly optimized with the sequential manipulation trajectory. The proposed approach was demonstrated on a bin-picking/re-sorting industrial application and a wrench tool scenario and we found that design optimization can significantly improve on metrics such as penalizing velocities (path length) and joint torques.

Learning From Planning

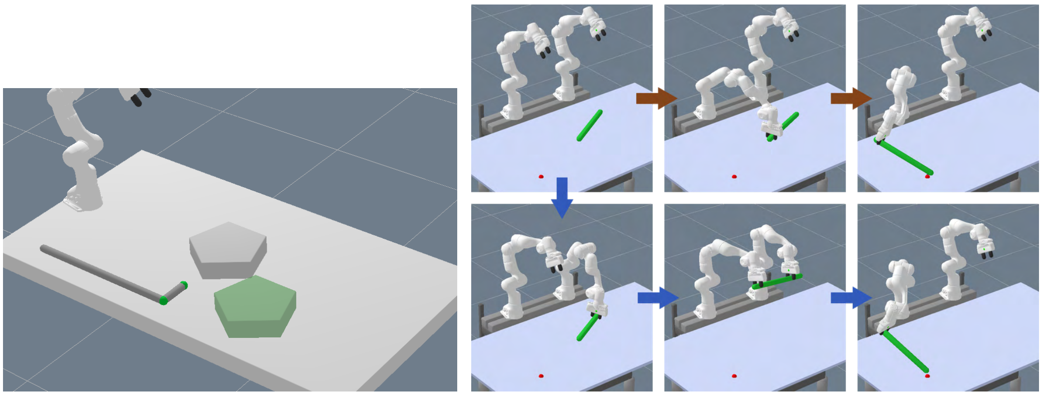


Figure 23.2: Directly predicting solutions to physical problems from perceptual input.

The complexity of solving a general physical reasoning problem – formalized as Logic-Geometric Program – is enormeous. Specifically, the problem is closely related to mixed-integer programming and becomes exponential in the combinatorics of the involved discrete variables, in addition to challenges with local optima.

However, we do not have to solve each physical reasoning problem from scratch – we can leverage the experience of previous solutions. We can *learn to solve* them from previous solution data.

Further, as a "collateral", we can not only learn to solve problems faster, but also learn to solve them on the basis of *perceptual input* only. And thereby get physical reasoning closer to perception.

To this end we developed a novel approach called Deep Visual Reasoning: In [1613], we introduced the concept of predicting the feasibility of a discrete decision for motion planning from an image of the scene. This prediction was trained from previous solution data. We showed that the image-based representation not only leads to better performance when compared to feature-based representations, but that images as input also enable the network to generalize to more objects in the scene than during training.

A limitation of [1613] is that the feasibility for only a single action is predicted, whereas the combinatorial complexity of TAMP especially arises from action sequences. Therefore, in [1614], we developed a convolutional recurrent neural network that predicts action sequences from the initial scene and the goal as input. Both the objects and the goal are encoded in images, enabling the framework to generalize to more objects in the scene than during training (as before), while maintaining high performance. Since the learned reasoning network is goal conditioned, it not only acts as a heuristic to speed up searching over the discrete action sequences, but, most of the time, eliminates the search by directly predicting a feasible one.

Most TAMP approaches focus on kinematic tasks such as pick-and-place. The hybrid nature of manipulation planning, however, is also present in tasks that deal with dynamic models such as pushing. In [1605], we investigated whether the approach of [1614] can be extended to such a broader range of manipulation scenarios by considering not only pick-and-place in more depth, but especially also a pushing scenario where an object has to be pushed to a target location. Since the object can be out of reach for the robot, the robot has to utilize a hook-shaped tool to push or pull the object to the goal location within potentially multiple pushing/pulling phases. Here another advantage of the image-based representation is shown, since it enables generalization to shapes beyond the training distribution.

While [1605, 1613, 1614] have all made significant improvements in solving various challenging TAMP problems more efficiently, the approaches still relied on object models to formulate the trajectory optimization problem. Consequently, in [1610] we explored if this requirement of object models and trajectory optimization can also be removed.

What we proposed is a hierarchical planning and control framework where a high-level reasoning network predicts a sequence of controllers that solve the TAMP problem. The whole framework takes as input only segmented images of the scene and derives the sequence of controllers from them. Although being a fully learned neural network architecture, the framework retains many great properties of classical TAMP frameworks such as the capability of providing multiple solutions to the tasks (if exist) and coordinating the parametrization of the low-level controllers jointly for the whole motion.

Motion Planning and Abstractions

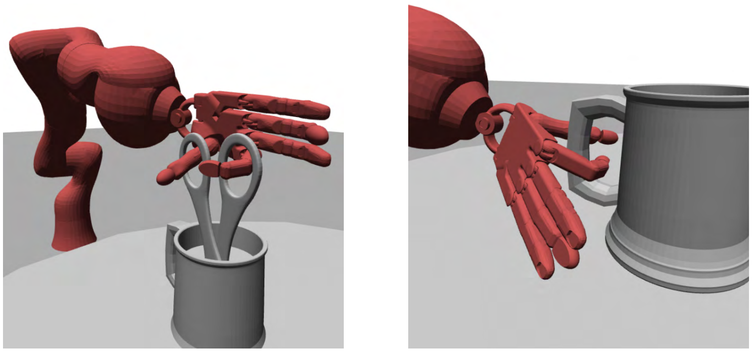


Figure 23.3: Planning of complex manipulation actions using abstract representations.

As human beings, we often solve complex problems by reasoning over multiple levels of abstraction. When animating the motion of a multi-arm robot, we might sequentially coordinate the motion of each arm, while backtracking if the necessity arises. It seems reasonable to utilize similar strategies to let robots autonomously solve these problems.

However, the state spaces involved in these problems are often continuous, high-dimensional and might contain intricate constraints. It is often unclear how we can model multilevel abstractions over those state spaces and how we can develop algorithms to efficiently exploit abstractions while having formal guarantees.

In this project, we concentrate on the problem of multilevel motion planning, the problem of moving robots from start states to goal regions under holonomic or non-holonomic constraints.

In a motion planning problem, we can often abstract or reduce state spaces by removing constraints, by removing robots, by nesting simpler robots, by removing dimensions of the state space, by shrinking links or by shrinking obstacles [1616].

To reason over multilevel abstractions, we formulate them using fiber bundles [1606, 1611], which are mathematical tools useful to develop efficient reasoning algorithms. While most of our research is based solely on quickly finding feasible and optimal solutions, we have also used abstractions to find, enumerate and organize local minima solutions [1608, 1615].

We recently improved upon this by providing an algorithm which provably finds all local optimal solutions to a motion planning problem [1617].

23.3 Research group leader: Marc Toussaint

Biography

Marc Toussaint received his pre-diplomas in Physics and Mathematics from the University of Cologne (1996), his Diploma in Physics (gravity theory) from the same university (1999), and his PhD (evolutionary algorithms and modular learning) from Ruhr-University Bochum (2003). As an Emmy Noether postdoc stipend he spend two years at the University of Edinburgh (2004-2006) where he started his reserach focus in the combination of decision theory, machine learning and robotics. In 2007 he started his independent research group on Machine Learning & Robotics at TU Berlin, and was promoted to an assistent professor (W1) at FU Berlin in 2010, and to a full professor (W3) at University of Stuttgart in 2012.

After a brief appointment as Senior Applied Science Manager at Amazon Research in 2017 and a year as Research Scholar at MIT (2017-2018) he became Max Planck Fellow at the Max Planck Institute for Intelligent Systems in Tübingen, Germany (2018-2021). In 2020 he joint the Technical University Berlin as full professor (W3) to found a new Learning and Intelligent Systems Lab and join the Science of Intelligence Excellence Cluster.

In his view, a key in understanding and creating intelligence is the interplay of learning and reasoning, where learning becomes the enabler for strongly generalizing reasoning and acting in our physical world.

Dr. Toussaint's research interests lie in the intersection of AI and robotics. He believes that a key in understanding and creating strongly generalizing intelligence is the interplay of learning and reasoning, of training and thinking, of data and models. His research therefore bridges between AI planning, machine learning, and robotics, trying to overcome the segregation of data-based AI (ML, Reinforcement Learning) and model-based AI (reasoning, inference).

Concrete research topics include models and algorithms for physical reasoning, task-and-motion planning (logic-geometric programming), learning heuristics, the planning-as-inference paradigm, algorithms and methods for robotic building construction, and learning to transfer model-based strategies to reactive and adaptive real-world behavior. To this end, his research builds on methodologies from optimization, reinforcement learning, machine learning, search, planning, and probabilistic inference. Some of his earlier work was on evolutionary algorithms (esp. evolving genetic representations and compression), relational reinforcement learning, and active learning.

Dr. Toussaint was Program Chair of R:SS 2020, editorial board member of the Journal of AI Research, and Coordinator of the DFG Priority Programme (Schwerpunktprogram) SPP 1527 Autonomous Learning. He published more that 180 peer-reviewed papers broadly in AI, machine learning and robotics. His work was awarded best paper at VINCI'20, R:SS'18, ICMLA'07 and runner up at R:SS'12, UAI'08.

Awards & Fellowships

12/2020	*Best Paper Award* at the Int. Symp. on Visual Information Communication and Interaction (VINCI 2020): D. Hägele et al.: *Visualization of Nonlinear Programming for Robot Motion Planning*
10/2018	Max Planck Fellow at the MPI for Intelligent Systems
10/2018	Keynote Speaker at CoRL 2018 (Conference on Robot Learning)
06/2018	*Best Paper Award* at the Robotics Systems and Science (R:SS 2018) conference: M. Toussaint, K. R. Allen, K. A. Smith, and J. B. Tenenbaum: *Differentiable Physics and Stable Modes for Tool-Use and Manipulation Planning*
06/2012	*Best Paper Runner Up Award* at the Robotics Systems and Science (R:SS 2012) conference: Konrad Rawlik, Marc Toussaint, Sethu Vijayakumar: *On stochastic optimal control and reinforcement learning by approximate inference*
06/2008	*Best Paper Runner Up Award* at the Conference on Uncertainty in Artificial Intelligence (UAI 2008): Marc Toussaint, Laurent Charlin, Pascal Poupart: *Hierarchical POMDP Controller Optimization by Likelihood Maximization*
12/2007	*Best Paper Award* at the Sixth International Conference on Machine Learning and Applications (ICMLA 2007): Volker Willert, Marc Toussaint, Julian Eggert, Edgar Körner: *Uncertainty Optimization for Robust Dynamic Optical Flow Estimation*
04/2007	Emmy Noether fellowship for an independent research group from the German Research Foundation (DFG)
03/2004	Emmy Noether postdoc stipend from the DFG
10/2003	PhD awarded *Summa cum laude*

Employment (appointments) / Academic positions

since 03/2020	Full Professor (W3), head of the Learning and Intelligent Systems Lab, at TU Berlin
11/2018 – 06/2021	Max Planck Fellow at the MPI for Intelligent Systems
07/2017 – 06/2018	Research Scholar, fully funded pure research, at CSAIL, MIT
04/2017 – 06/2017	Senior Applied Science Manager, lead of the Core ML Robotics team at Amazon Core Machine Learning Berlin
since 12/2012	Full Professor (W3), head of the *Machine Learning and Robotics Lab*, at University Stuttgart
10/2010 – 11/2012	Assistant Professor (W1) for *Machine Learning and Robotics* at FU Berlin
4/2007 – 10/2012	Head of the independent research group *Machine Learning and Robotics* (Emmy Noether Programme) before 10/2010 at TU Berlin, later at FU Berlin
08/2006 – 2/2007	Honda Research Institute: Guest scientist at the robotics department of HRI Europe, Offenbach (Dr. Christian Goerick, Prof. Dr. Edgar Körner) Research focus: Learning & behavior organization in robotics

Links

Link to CV on website: https://www.is.mpg.de/person/mtoussai

24 STATISTICAL LEARNING THEORY

24.1 Research Overview

The goal of statistical learning theory is to provide solid theoretical analysis of the behavior of machine learning algorithms. Under the assumption that the data has been sampled from some underlying, but unknown ground truth, we want to assess whether the results achieved by machine learning algorithms are trustworthy, whether the algorithms are well-behaved or erratic, or what is their complexity in terms of data required or computation time needed.

Some branches of statistical learning theory are well-studied and "more or less solved," while others are just beginning to be investigated. We would like to highlight the following two areas:

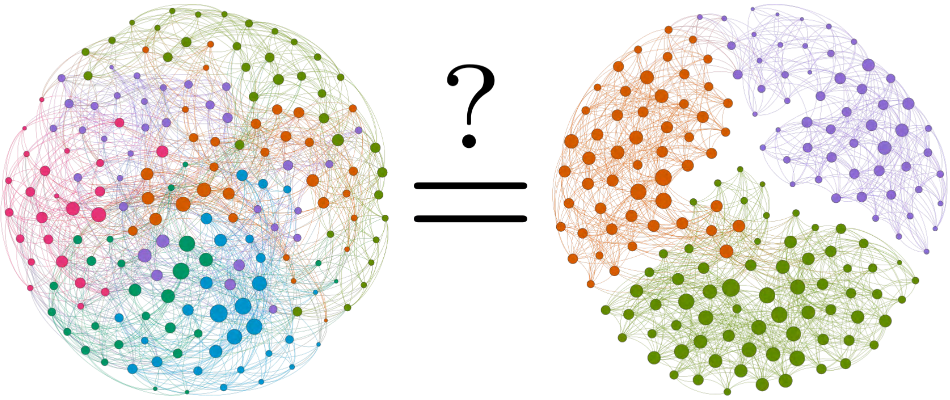
Interactive and interpretable machine learning. Here we ask how a fruitful interaction between machine learning algorithms and human users can be achieved. This is clearly a question of rising importance: machine learning systems get more and more complex and involved, which makes it hard to judge the meaning, implications, and trustworthiness of a machine's inference result. On the other hand, machine learning systems start to have serious impact on every-day life, hence being able to control their results gets more important. The question about interactive and interpretable machine learning clearly has aspects of human-computer interface, but also raises lots of algorithmic and also theoretical issues.

Machine learning for scientific environments. While machine learning methods have been used since more than a decade in some areas of science, for example in bioinformatics or the neurosciences, we currently observe a rising trend to use machine learning methods in many diverse scientific areas, ranging from social sciences over physics to geoscience. When machine learning methods are used in scientific contexts, it is of highest importance to have reliable statistical guarantees. We work towards such guarantees, for example in the field of network science.

24.2 Selected Research Projects

Machine Learning for Scientific Environments

Ulrike von Luxburg, Sebastian Bordt, Damien Garreau



When machine learning is being applied in other scientific disciplines, it is of utmost importance to be able to distinguish "random artifacts" from "true structure". We work on such theoretical guarantees, for example in the field of network analysis.

Two sample tests for random networks. A key question in this field is whether two different networks are likely to have been generated from the same underlying process or not. This question is often formulated in terms of statistical hypothesis testing. Surprisingly, there has been little research on the theoretical aspects of network testing, and it is often not clear whether one can meaningfully test large networks by observing only a few replicates, which is a typical setting in applications of network analysis. In this project, we focus on the problem of two-sample hypothesis testing of networks and provide a clear understanding of the statistical complexity of testing small populations of networks, each defined on a large number of nodes. We formally define a testing problem based on different models and different tests in the small sample, large graph regime, and derive minimax-optimal theoretical hypothesis tests [1666].

We put theory into practice and develop practical two-sample tests based on asymptotic distributions [1674]. We show that these tests are both theoretically consistent in the small sample regime and exhibit good empirical performance for moderate sized networks. We also study the more general problem of comparing two large graphs defined on different vertex sets. Using such testing principles, we provide a formal framework and demonstrate that the testing problem can be ill-posed, and network statistics may not distinguish highly dissimilar networks.

Inductive bias of graph algorithms. In applied scientific domains such as neuroscience or climate science, people often use a network sampling approach to test hypotheses about their networks. While most classical network sampling models are too simplistic to reproduce real-world graphs, a GAN-based approach recently emerged as an attractive alternative: by training a GAN to learn the random walk distribution of the input graph, the algorithm is able to reproduce a large number of important network patterns simultaneously, without explicitly specifying any of them. In one of our recent papers [1669] we investigate the implicit bias of NetGAN. We find that the root of its generalization properties does not lie in the GAN architecture, but in an inconspicuous low-rank approximation of the logits random walk transition matrix. Step by step we can strip NetGAN of all unnecessary parts, including the GAN, and obtain a highly simplified reformulation that achieves comparable generalization results, but is orders of magnitudes faster and easier to adapt. Being much simpler on the conceptual side, we reveal the implicit inductive bias of the algorithm - an important step towards increasing the interpretability, transparency and acceptance of machine learning systems.

More information: https://slt.is.mpg.de/project/machine-learning-for-scientific-environments

Interpretable Machine Learning

Ulrike von Luxburg, Sebastian Bordt, Michael Perrot, Damien Garreau

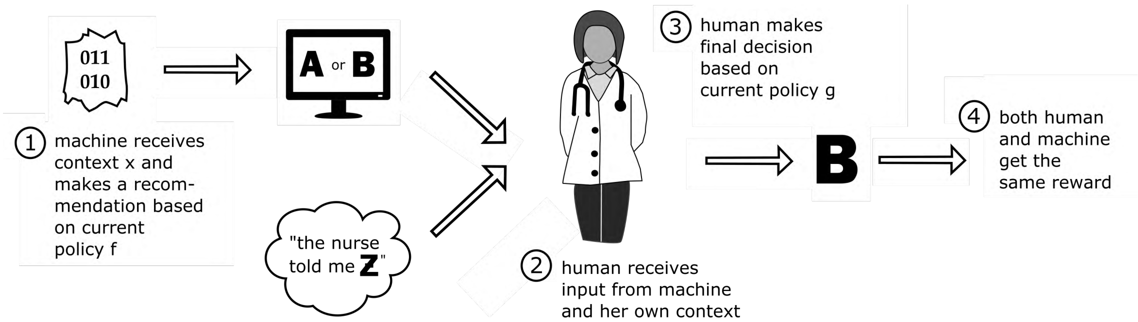


Figure 24.1: A bandit model for human-machine learning

Machine learning is more and more used by non-expert users, in a large variety of different contexts. For this reason it becomes important that (i) machine learning methods are designed for an interactive usage where are humans and machines can jointly improve each other's decisions; (ii) where machine learning results are interpretable, (iii) and where even the input to machine learning algorithms can easily be understood by human users.

Joint Human-Machine Decision Making. In fields like medicine and finance it is becomming increasingly clear that future decisions will be made by humans who are informed by machine learning algorithms. This novel human+algorithm decision making problem poses new challenges for machine learners. It is no longer sufficient to optimize performance on a given task but one also needs to decide how the task of the machine should be given in the first place. As a consequence, and despite an increasing amount of practical work on the topic, human-machine decision making still lacks a systematic understanding. We tried to bridge this gap by providing theoretical perspectives on what can (and cannot!) be expected in human-machine decision making. Our approach is to formally model the most salient aspects of the problem. In our view, these are the presence of unobserved information and limited understanding between the two decision makers (i.e. the human and the algorithm). Our analysis reveals that both of these aspects have important consequences for learning. In particular, we demonstrate the suprising hardness of optimally advising a decision maker who has access to external information. We can prove that in the worst-case, it is impossible to advance beyond a simple learning strategy of trial-and-error. To our current knowledge, more efficient learning is only possible under strong structural assumptions on the problem. A survey of the extant literature on human-machine decision making revealed that most of it (implicitly) makes such assumptions. This work is submitted and can be found on arxiv, but is not published yet.

Analysis of Post-Hoc Explanations. When machine learning algorithms are being used in sensitive applications interpretability becomes a pressing need. Popular post-hoc explainability algorithms such as LIME, SHAP and Integrated Gradients are based on heuristic ideas of how to obtain meaningful explanations. In many sensitive applications a heuristic understanding might not be enough. We would need formal guarantees on how explanations relate to the function that we explain. In [1671], we provide the first theoretical analysis of the popular LIME (Local Interpretable Model-Agnostic Explanation) algorithm for tabular data. We are able to derive closed-form expressions for the coefficients of the interpretable model when the function to explain is linear. In this scenario, LIME indeed discovers meaningful features and the explanations are proportional to the gradient of the function to explain. However, our analysis also reveals that poor choices of parameters can lead LIME to miss important features.

In other machine learning applications, individual features don't have any particular meaning. The most prominent example of this is image classification. These problems and the typically learned deep neural networks are often highly non-linear. Thus, conceptualizing meaningful explanations can become quite challenging. Even in relatively simple examples, it can been shown that

’explaining’ non-linear functions with linear approximations can lead to misleading conclusions. In our most recent project, we attempt to identify neccesary conditions for meaningful explanations in high-dimensional settings. In image classification, a potential candidate to judge the meaningfulness of explanations is the tangent space of the manifold on which high-dimensional image data is often believed to lie. For synthetically constructed problems, we can analytically derive the tangent space of the data manifold and measure empirically how well it aligns with different kinds of explanations. This work can be found on arxiv and is submitted, but not yet published.

Comparison-Based Learning. Machine learning based on easy to generate, human interpretable data. In the typical machine learning setting we are given a data set $\mathcal{D}$ of objects and a distance function δ that quantifies how “close” the objects are to each other. In recent years, a whole new branch of the machine learning literature has emerged that relaxes this scenario. Instead of being able to evaluate the distance function δ itself, we only get to see the results of comparisons such as $\delta(A, B) < \delta(C, D)$, where $A, B, C, D \in \mathcal{D}$. We refer to any collection of answers to such comparisons as ordinal distance information. Our group investigates how machine learning algorithms can work with such data. We can learn a Euclidean representation that respects the comparisons but evaluating the quality of such an embedding is difficult [1675]. As an alternative we proposed several algorithmic solutions that learn directly from the comparisons.

In a series of papers we investigated this learning framework: We developed kernels, allowing us to use kernel methods with ordinal distance comparisons [1678], and derived a series of algorithms for medoid estimation, outlier identification, classification, and clustering based on the lens depth function [1667]. We proposed a method for large scale classification with generalization guarantees in a boosting framework [1673] (IJCAI best paper award). The search for nearest neighbors is another example of a classical machine learning task for which we proposed a comparison-based approach. The comparison tree [1679] is a random tree constructed by recursively splitting the space by choosing random pivots and assigning data points to the nearest pivot. This structure allows for efficient search of the nearest neighbors of a query point, and we proved theoretical guarantees on the performance of this method. In a next step we then aggregate many of these trees to construct a random forest. Albeit having access to very little information, these “comparison-based random forests” perform about as well as methods that have access to the true distances and can be proved to be statistically consistent [1677]. Finally we give theoretical guarantees on hierarchical clustering algorithms based on comparisons Gho[1673].

More information: https://slt.is.mpg.de/project/interpretable-machine-learning

24.3 Awards & Honors

2020

Ulrike von Luxburg got appointed as a member of the German National Academy of Sciences, Leopoldina.

2019

Michel Perrot, Ulrike von Luxburg: Distinguished Paper Award at the International Joint Conference on Artificial Intelligence (IJCAI 2019) for the paper: "Boosting for Comparison-Based Learning"

24.4 Research group leader: Ulrike von Luxburg

Biography

Ulrike von Luxburg studied mathematics at the Universities of Konstanz, Grenoble and Tübingen. She received her PhD in Computer Science in 2004 (MPI for Biological Cybernetics / University of Berlin). After being a research group leader at Fraunhofer IPSI, she became a Minerva Research Group leader at the MPI for Intelligent Systems (2007-2012). From 2012, she was Heisenberg-Professor (W3, full professor) for Machine Learning at the University of Hamburg. In 2015 she got appointed as Full Professor for Machine Learning Theory at the University of Tübingen. In 2017 she also got appointed as a Max Planck Fellow at the MPI for Intelligent Systems.

In the period from 2003 - 2008, she received seven best paper awards at leading machine learning conferences (3 COLT, 2 NIPS, 1 ALT, 1 IJCAI). She has served as Program Chair of COLT (2011) and Program Chair and General Chair of NeurIPS (2016,2017). She has been executive board member for most major machine learning conferences (COLT, ICML, NeurIPS). In 2020 she got appointed as a member of the German Academy of Natural Scientists Leopoldina.

She is one of the two spokespersons of the Cluster of Excellence Machine Learning: New Perspectives for Science at the University of Tübingen.

Ulrike von Luxburg's research focus is on the theory of machine learning, in particular the statistical analysis of unsupervised learning algorithms.

Awards & Fellowships

- **2020:** Appointed as a member of the German National Academy of Sciences Leopoldina.
- **2019:** Co-winner of the Distinguished Paper Award at the International Joint Conference on Artificial Intelligence (IJCAI)
- **2008 – 2013:** Member of the Junge Akademie, the young scientists' branch of the Berlin-Brandenburg Academy of Sciences and Humanities and the German Academy of Natural Scientists Leopoldina
- **Since 2003:** Co-winner of seven best (student) paper awards at leading international conferences (COLT 2003, 2005, 2006; NeurIPS 2004, 2008; ALT 2007; IJCAI 2019)

Education

- 2004: PhD in Computer Science (MPI for Biological Cybernetics / TU Berlin)
- 2001: Diplom ($\approx$ MSc) in Mathematics, University of Tübingen

Employment (appointments) / Academic positions

2017 – 2021	Max Planck Fellow
2015 – present	Full Professor for Computer Science (Theory of Machine Learning) at the Department of Computer Science, University of Tuübingen, Germany
2012 – 2015	Heisenberg-Professor for Computer Science (Machine Learning) at the Department of Computer Science, University of Hamburg
2007 – 2012	Research Group Leader, Max Planck Institute for Intelligent Systems, Tübingen
2005 – 2006	Head of the Data Mining Group at the Fraunhofer Institute for Integrated Publication and Information Systems (IPSI), Darmstadt

Links

Link to CV on website: https://slt.is.mpg.de/~ule

25 CENTRAL SCIENTIFIC FACILITIES

The institute operates several **Central Scientific Facilities** (**CSF**), which are led by scientists and staffed by engineers and technicians. The objective of a CSF is to conduct research and provide high-level scientific and technical support to all departments and research groups in key research areas. Each CSF has a home campus but nevertheless collaborates with scientists at both sites of our institute. The current CSFs in Stuttgart and in Tübingen are as follows:

Materials (Stuttgart) The Materials CSF provides support in fabrication of low-dimensional microstructures by physical vapor deposition, and analysis using X-ray photoelectron spectroscopy, X-ray diffraction, inductively coupled plasma optical emission spectroscopy, and scanning electron microscopy. Current research includes investigating size effects of physical properties.

Medical Systems (Stuttgart) The Medical Systems CSF conducts research and provides scientific services related to preclinical and medical imaging, instrumentation, clinical applications, and related technologies. Furthermore, the CSF runs a state-of-the-art flow cytometer and provides standard cellular and molecular biology technologies to strengthen and enable advanced research in the field of biomedical milli- and nano-robotics.

Optics and Sensing Laboratory (Tübingen) The Optics and Sensing Laboratory provides support for camera-based motion capture, dynamic 3D capturing systems and a variety of optical equipment. Furthermore, this CSF develops custom optical systems for the scientists and introduces machine learning into sensing devices. Current research includes multi-sensor systems technology and computer vision algorithms for psychophysiological signal analysis.

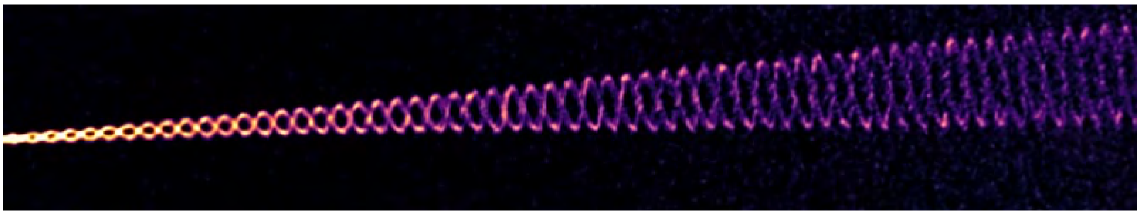
Robotics (Stuttgart) The Robotics CSF works with the researchers of the institute to design and prototype novel robotic and mechatronic systems, including mechanical assemblies, microelectronic layout and fabrication, programming of embedded processors, system integration, control, and validation.

Scientific Computing (Tübingen) The Scientific Computing CSF builds and operates computing and storage infrastructure for the research in the institute while also collaborating with researchers to develop scalable algorithms and applications. It is also envisioned that this CSF will do research at the interface of high-performance computing and machine learning.

Software Workshop (Tübingen) The Software Workshop conducts research and supports the institute in the areas of software engineering and computer science. It operates the software infrastucture of the institute, trains researchers, and helps them to optimize their software development projects, ensuring professional design, development, and distribution. Its general purpose is to improve the overall quality of the software developments of our institute.

The following subsections outline the past and current work of each of these CSFs in greater detail.

25.1 Materials



25.1.1 Mission

Physical properties of materials changes if the dimension of devices decrease. Smaller structures are stronger than bigger ones, magnetic structures change to a superparamagnetic state, colors of nanoparticles are distinct different to bulk, and conductivity in small dimensions increases dramatically. Physical properties have varying thresholds and are typical above the atomic dimension up to the wavelength of light. For quantitative understanding, the entirety of surfaces, defects, dislocations, grains, composition and crystal structure which form the micro- or nanostructure (Gefüge) have to be analyzed.

The mission of the ZWE Materials is so strengthen the knowledge on materials properties and materials science of low dimensional systems in the institute by collaborating within and outside of the institute, and by conducting its own research. The classes of materials utilized are transforming and increasing in scope, a strong future focus will be on new smart systems formed by soft and hybrid materials.

25.1.2 Service

The extensive knowledge of the ZWE Materials employees is shared with the institutes scientists and research groups. Depending on the amount of specimen and the complexity of the fabrication procedures, the fabrication is either carried out by the student/scientist themselves enabling learning-by-doing, or full service is provided by the technicians. The ZWE Materials is accessible to all departments and groups of the institute as a service facility.

Fabrication: Fabrication of devices is based on either condensation or dissociations, the ZWE Materials focuses on the former by physical vapor deposition (PVD): atoms are assembled on a well-defined energy landscape of a substrate, smart nanosystems are formed by agglomeration and self-organization. Seven PVD systems are located, run and maintained in the ZWE Materials and are open for projects of the institute. Considering dissociation, top-down structuring, a plasma induced reactive ion etching (RIE) system is accessible for users.

Analysis: Microstructures analysis is based on either diffraction, imaging or spectroscopy: X-ray diffraction (XRD) is employed for investigating textures, grain sizes, orientation relationships or phase formation. Scanning electron microscope (SEM) with a point-to-point resolution of 2 nm; it is capable to image conducting, non-conducting and biological systems. Inductively coupled plasma optical emission spectroscopy (ICP-OES), X-ray induced photoelectron spectroscopy (XPS) or energy dispersive x-ray spectroscopy (EDXS) provides chemical analysis.

25.1.3 Scientific Projects

The ZWE Materials own research focuses on the relation of physical properties and corresponding microstructure of low-dimensional specimens. They are found in all modern devices, acting as diffusion barriers, interconnects, energy harvesters, sensors or actuators. Apart conventional materials, modern material classes, such as polymers, hydrogels, liquids or composites will be incorporated into the ZWE Materials research direction.

In the reporting period unique one-dimensional metal nanowhiskers (NWs) were in the focus of the research. The ZWE Materials is the only facility to produce such structures, which are defect-scarce, freestanding and prismatic with no taper. The structures are perfect model systems to study the break-down of bulk concepts and the size-effects of physical properties.

Nanomaterials science

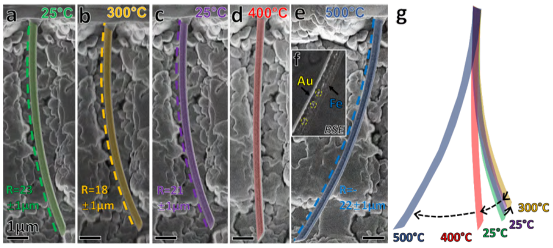


Figure 25.1: Thermal sensor showing irreversible bending due to interface diffusion.

Microstructure formation is determined by thermodynamic and kinetic processes, both having limitations, benefits and disadvantages. Thermodynamics originate from bulk, whereas kinetics process are formulated in the atomistic regime. The path taken by systems to reach thermodynamic equilibrium is determined by atomistic, kinetic processes, forming a complex parameter space. Within this context, nanostructures can never be stable in the sense of thermodynamics.

A simple macroscopic temperature sensor could be the sandwich of two materials with different coefficients of thermal expansion. Changing temperature would lead to a predictable change in curvature. Au-Fe would be suitable materials pair, because these two metals do not form intermetallic compounds. It is expected, that diffusion occurs only on the Au side of the diffusion couple, since Fe exhibits high solubility in Au. In the nanometer regime, the situation is significant different: Diffusion of Au across varying interfaces is distinct different, depending on the coherency of the interfaces. These observations are in stark contrast to bulk predictions, as the Neumann and Curie principles.

Mechanical properties

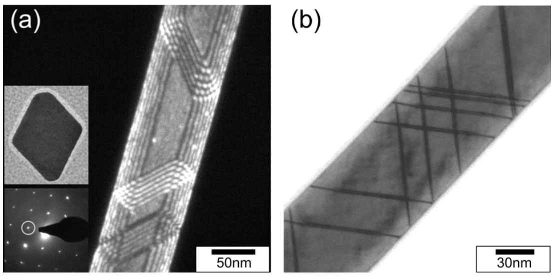


Figure 25.2: TEM micrograph of tensile tested Au NWs showing stacking faults.

Mechanical reliability is dominated in bulk materials by the nucleation and mobility of dislocations. The onset of plasticity is reached when irreversible dislocation interaction occur. In nanostructures, where the volume is not sufficient to accommodate many dislocations, the deformation mechanism has to change; dislocation nucleation on surfaces are the rate limiting processs. The yield stress is at the theoretical limit, independent of testing geometry. Engineering the surface changes the dislocation nucleation probability, no size effect is observed.

Application will have to use structures under dynamic conditions. E.g. *in situ* resonance measurements show a clear influence of the shape is found. This shows that not only size, but also shape is critically for mechanical properties and have to be understood prior future applications.

Magnetic domain structure

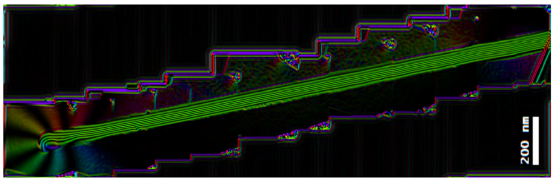


Figure 25.3: False colour electron holography map of individual Fe NW.

Ferromagnetic behavior is determined by the magnetic domain structure. The high magnetic shape anisotropy and high coercivity attributed from the large aspect ratio make NWs unique. The magnetocrystalline easy axis is not always parallel to the whisker axis, e.g. for Co. Changes in defect density did not influence the magnetization direction.

Remarkably all whiskers synthesized were single domain structures with magnetization along the whisker axis. The magnetization direction was dictated by the predominating shape anisotropy rather than the magnetocrystalline anisotropy.

Conductivity Electrical transport properties decreases with decreasing dimensions. Non-zero resistivity is due to the scattering of electrons at phonons, defects, grain boundaries, and at the surface. When the size of the structure is the length of the electron mean free path (MFP), then scattering on the surfaces dominates. I-V curves of NWs exhibit perfect ohmic behavior.

The influence of surface scattering is analyzed by temperature dependent resistivity measurements as described by Bloch and Grüneisen. 4-point measurement gives the room temperature resistivity as ρ_{300K} = 2.27 $\mu\Omega$cm and at 10 K ρ_{10K} = 0.34 $\mu\Omega$cm. The former is exactly, the latter 15 times higher than the corresponding bulk resistivity.

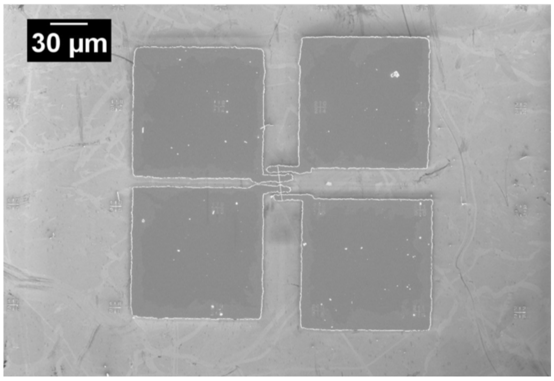


Figure 25.4: Target specific, temperature dependant Kelvin probe resistivity measurement.

The MFP is increasing with decreasing temperature, therefore the probability for surface scattering rises. Assuming a specular scattering probability of 0.95 suffices as explanation for this effect. However, atomistic processes, deviations of the spherical Fermi sphere, Umklapp processes and possible reconstructions on the NWs surface facets are neglected and are interesting projects for the future.

Summary The ZWE Materials provides unique modelstructures to explore physical size effects. They are **freestanding** and prismatic with no taper, have **low energy surface** facets, and are **defect scarce**. Due to the unique microstructure theoretical predicted properties are found experimental.

Collaborations The ZWE Materials collaborated in the reporting period with following research groups: Erik Bitzek (University Erlangen), Thomas Cornelius (University Marseille), Horatio Espinosa (Northwestern University), Joel Eymery (CNRS Grenoble), Dan S. Gianola (University of Santa Barbara), Daniel Kiener (University Leoben), Mark Legros (CEMES-CNRS Toulouse), Sang Ho Oh (POSTECH), Eugen Rabkin (Technion), Etienne Snoeck (CEMES-CNRS Toulouse), Olivier Thomas (University Marseille), Cynthia Volkert (University Göttingen).

Publications From the ZWE's own projects and the collaborations, 52 journal articles were published in the reporting period (see publication list).

25.2 Medical Systems

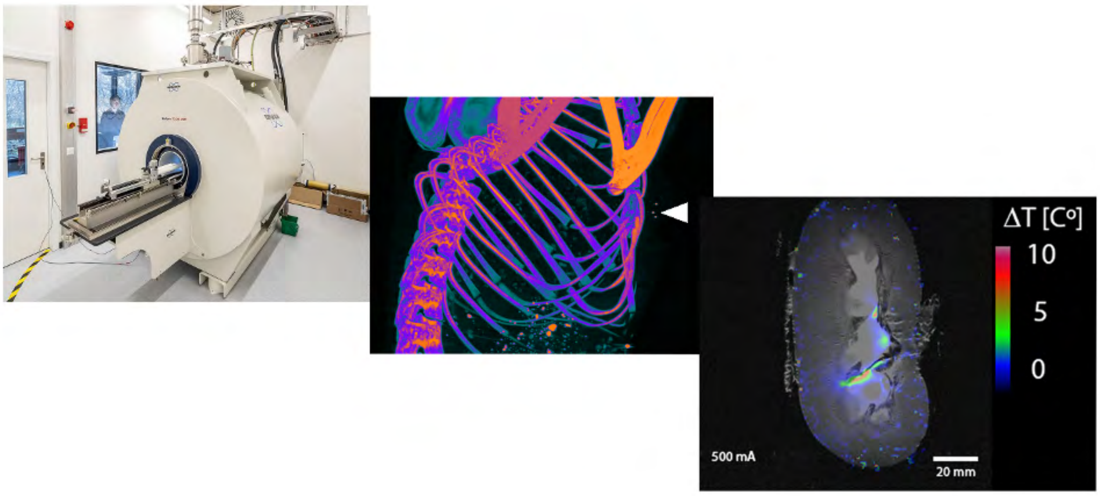


Figure 25.5: The preclinical MRI scanner (7 Tesla) located in the Physics Hall of the MPI-IS campus in Stuttgart. The ex-vivo microCT image (3D rendered) of a mouse thorax showing 50 µm polymer beads (white arrowhead, middle). The temperature increase following an active catheter steering inside a porcine kidney (ex-vivo), measured using magnetic resonance thermometry.

The Medical System CSF was founded in 2016 with vision to support the scientific activities in MPI-IS related to preclinical small-scale medical robotics research. Currently, the facility is equipped with a 7 Tesla (7T) preclinical MRI scanner, high-resolution computed tomography (microCT) scanner, photoacoustic imaging system (MSOT), in-vivo optical imaging system (IVIS), optical coherence tomography (OCT), C-arm X-ray imaging system, and fluorescence activated cell sorting (FACS) system. In the near future, Medical Systems will be located in a small-animal (mice and rats) research facility (MedLab) in our institute's Stuttgart campus, and addition of position emission tomography (PET) insert for simultaneous PET/MRI imaging will become possible. Currently, 7T MRI is located in the Physics Hall, while other instruments are located in 4N15 in the main institute building in Stuttgart and are already used for in-vitro and ex-vivo tests.

Wireless small-scale medical robots have the potential to revolutionize the healthcare systems by enabling minimally invasive and implantable diagnostic and treatment utilities, not possible before in order to improve and enhance the quality of life of the patients. The key to successful biomedical applications will be validation via multimodal medical imaging systems and confirmation of proposed functionalities in-vivo. To achieve this goal, we acquired complementary set of imaging modalities each with unique functions and imaging capabilities. Non-invasive imaging systems are continuously developing, offering new opportunities for diagnosis and treatment interventions. Innovative ways to use them in order to advance robotic design will play a critical role in the future. For example, the combination of MSOT with high-intensity focused ultrasound will enable simultaneous tracking and actuation of microrobots in 3D inside the blood vessels with high speed and precision. The addition of light-sensitive molecules such as indocyanine green, will further extend the functionality of MSOT imaging system to on-demand hyperthermia by utilizing an NIR laser. This way imaging systems can become diagnostic and therapeutic platforms, and at the same time have a direct translational relevance. The use of various imaging modalities will not be limited to visualization, localization and tracking, but on advanced functions such as sensing, actuation and on-demand targeted interventions and drug delivery as well. Using MRI, we have already demonstrated, that wireless milliscale medical robots can be visualized, tracked and utilized for on-demand drug delivery.

25.2.1 Service

The Medical Systems CSF offers standard as well as tailored use of medical and biological imaging systems. The concept of the facility is suited for ex-vivo and in-vivo preclinical studies of the newly developed small-scale medical robots. In the future, a combination of non-invasive imaging technologies would greatly reduce animal numbers necessary for testing, since one animal will be examined using multiple modalities, and the collection of data will be done in the most efficient way.

The high field 7T MRI scanner offers many possibilities for quantitative and functional imaging of micro and millirobots in addition to high-resolution anatomical localization. For example standard quantitative measurements of diffusion, perfusion and blood flow can be performed, in addition to more advanced measurements such as temperature mapping or hypoxia sensing. The custom based software is already implemented to allow magnetic field gradients to have a dual function and allow simultaneous use for steering and localization in real-time. After moving to the MedLab, simultaneous use of PET/MRI will allow very high sensitivity for detection and localization of microrobots labeled with radioactive isotopes.

The IVIS Spectrum in vivo imaging system (Perkin Elmer) offers 2D and 3D fluorescence tomography as well as bioluminescence imaging. The instrument uses leading optical technology to detect bioluminescent and fluorescent reporters across the blue to near infrared wavelength region for non-invasive detection of medical micro-robots, monitoring of disease progression and investigation of gene expression patterns in living animals and biological samples.

The current X-ray based imaging equipment consists of a preclinical in-vivo microCT (Bruker SkyScan 1276) for high-resolution imaging of small animals and biological samples, a compact C-arm (Hologic Fluoroscan InSight FD Flex Mini C-arm) for X-ray fluoroscopy and an X-ray cabinet (Kubtec XPERT 80-L) for the radiography of ex vivo specimens. The X-ray imaging systems are used for example to retrieve anatomical information of the examined specimen in order to localize medical robot systems in organs or to investigate their penetration into tissues.

A state-of-the-art FACS system (BD LSR-Fortessa X-20) and several fluorescence and confocal microscopy systems are available within the Medical Systems CSF to enable and support scientific research in the field of small-scale medical robotics. The technologies are further rounded off by human, murine and bacteria cell culture, cell-based assays to evaluate the toxicity, biocompatibility and immunogenicity of nano-, micro- and millirobots as well as histological analysis.

25.2.2 Technical Support Activities

The Medical Systems CSF team currently consists of two scientific staff with expertise in small-animal imaging systems (MRI, PET, IVIS) and experiments, two technical staff with strong background in cell-based assays, molecular biology, small-animal experiments, and optical microscopy, and one temporary technical staff for the X-ray imaging systems. Below, we highlight two research projects that were completed recently using our scientific services.

MRI-powered wireless medical millirobots [947]: This milliscale robotic system was designed to have versatile functions (on-demand local hyperthermia and drug delivery) and to be simultaneously imaged and navigated using magnetic field gradients, an integral part of the MRI scanner. The major novelty of the design is the ability to change and lock the orientation inside strong magnetic field (7T), providing additional degrees of freedom and enabling the robot to freely rotate around its axis. This way, targeted hyperthermia, tissue ablation and other surgical manipulations can be precisely performed. While the locking mechanism requires minimal remote heating of the robot, the temperature monitoring during hyperthermia is crucial in order to avoid damage to the healthy tissue. Using proton resonance frequency shift technique, the temperature can be non-invasively monitored in almost real time using MRI. The additional advantage of the design is translation potential for a near future human use, since all manipulations are minimally invasive and can be easily performed using clinical MRI scanners.

Interaction dynamics between medical microrobots and the immune system [1733]: This project investigates the interaction between the immune system and medical microrobots depending on their structural design parameters.

Understanding and influencing this interplay is critical for improving parameters such as locomotion and steerability of the microrobot and at the same time preventing an overshooting immune reaction. Three different microrobot designs were demonstrated and tested in this study demonstrating the crucial role of design for the immunogenicity of the microrobot. Moreover, the potential for the development of immunobots was presented, as macrophages (cell type of the immune system) take up synthetic microswimmers and therefore combine the steerable mobility of magnetic microrobots and the immunoregulatory capability of macrophages.

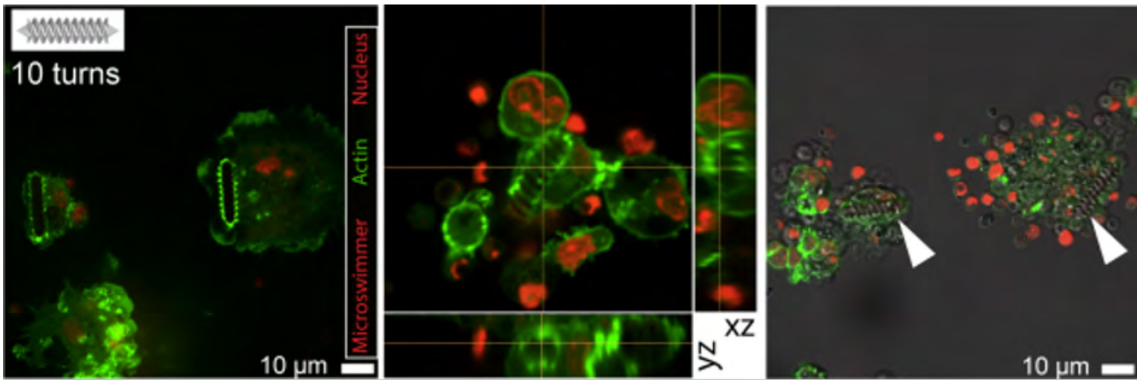


Figure 25.6: Confocal microscopy images of murine splenocytes after co-cultivation with magnetic microswimmers.

25.3 Optics and Sensing Laboratory

Figure 25.7: Left: Horses capture, 64 MoCap and 12 Color cameras setup at veterinary hospital. Right: Stereo-setup on off-road vehicle in Kenya.

The activities of the Optics and Sensing Laboratory (OSLab) include cross-institute technical research support and original research work. OSLab provides design, training and technical support for various motion capturing systems, the institute's (astro) photography equipment and other sensor equipment. The lab members are involved in research work in collaboration with departments and other ZWEs. In particular, the laboratory focuses on original research in the fields of multi-sensor systems technology, wildlife data capturing, and analysis of interpersonal synchrony during psychotherapeutic dyads using computer vision technology. At the same time, OSLab conducts experiments on light-based neural networks and develops novel smart shape-sensors.

25.3.1 Team, Facilities, and Equipment

The OSLab team consists of two research engineers with expertise in multi-sensing technology and optics, two technical assistants, a lab assistant and a varying number of student researchers and interns. Furthermore, OSLab provides close supervision for technical members of the PS department. Master's theses from local universities are supervised by OSLab members on regular basis. OSLab facilities include capturing space focusing on setups with multiple motion capture sensors and AR experiments. This space offers a professional truss system, with black and green screens, high-resolution / high-speed video cameras, optical MoCap system, and controllable light environment.

The sensing equipment of the laboratory consists of a portable biofeedback logger (Mindmedia), Inertial Measurement Unit (IMU) MoCap setup, portable multi-camera setup for outdoor capture, audio recording equipment, array of industrial sensors based on time-of-flight, high-speed and high-resolution cameras, and studio video fixtures and light measurement devices. Furthermore, a high-resolution, high-speed laser scanner for digitization of indoor and outdoor environment, and a middle-IR-band camera to perform remote temperature analysis are available to Institute's scientists.

The OSLab also runs a dedicated optics and laser space, offering stable optical tables, a large collection of lenses, and a variety of specialized devices such as power meters, spectrometers, spatial light modulators. The institute's experimental facilities for computation photography consisting of a photography lab and a telescope dome are also operated by the OSLab.

25.3.2 Scientific Service

One of the OSLab's unique know-how is designing and implementing synchronization, calibration and data capture aspects of multi-sensing systems, relying on 20 years of experience in the field. Using this knowledge we provide continuous research support to various departments and independent groups across our Institute. Another key capacities of the OSLab is the generation and manipulation of light used for research projects across the Institute. In particular, OSLab offers a wide range of services related to operation of lasers. Among other applications, lasers are used for metrology and structured illumination. Thanks to dedicated equipment, OSLab offers extended testing and characterization of optical systems as a service to scientists of the Institute. Design and simulation of new optical systems (using OpticStudio) is another field of expertise of OSLab scientists.

Supported Projects

In the course of the reporting period, OSLab has supported numerous research projects, of which a few are mentioned in the following.

Automatic MTF estimation The OSLab participated in the construction of a test-panel for cameras, allowing to capture the response to point-sources over the entire field in a single shot and thus giving direct access to the modulation transfer function(MTF) of the tested device. The MTF is typically used to characterize the quality of lens objectives. Using a large number of images of the test-panel a neural network was trained to infer the MTF of given lens directly from natural images recorded with the particular lens[1738].

Sky PSF In addition to a test-panel as described above, it is also possible to record the point-source responses of a lens objective by taking pictures of a starry night sky. OSLab has recorded a large database containing images of clear night skies using a wide range of commercial DSLR lenses.

Synthetic image datasets In the context of the NeurIPS 2019 disentanglement challenge, members of OSLab have generated datasets consisting of simplistic and photorealistic rendered images, contributing to the challenge and the resulting publication[1737].

Capture Hall Facility The OSLab is responsible for the establishment of the world leading multi-sensor capturing facility, which allows the institute to acquire unique data to advance computer vision and machine learning research. In particular, the facility consist of 54-camera VICON MoCap system installed on a dedicated truss system, high-resolution 16-color machine vision cameras and in-house designed triggerable studio lights that are synchronized with cameras shutter allows to deliver 12klux of illumination without disturbing human subjects. The uniqueness of the this setup is the 20us accuracy synchronization and the ability of precise geometrical calibration between all cameras. In addition, two a new dynamic 3D scanners were co-designed with 3dMD Ltd, purchased and installed to complete the scanning capabilities. The foot scanner with transparent platform and a new highly-configurable hand scanner that was installed in the Tübingen laboratory of the Haptic Intelligence department.

Multi-Sensor Data Capture Many of institute research projects in the field of computer vision and machine learning are following data-driven approach. The ability to capture unique data became a key aspect for research success. During the last six years the lab was involved in designing and executing large number of this projects. Just to name some of them: Outdoors multi-camera human interaction, Challenging MoCap sessions with 3mm markers and color video cameras of SignLanguage, Yoga, and Object manipulation. In addition, stereo-camera footage of Gravy zebras, elephants and other wild animals at research facility of Mpala in Kenya, Multi-camera recording of Zebras in Stuttgart Zoo, and MoCap + color camera footage of horses at veterinary hospital in Uppsala, Sweden, see Fig.25.7.

25.3.3 Research Projects

The scientists of OSLab conduct diverse research project in collaboration with research group from within and outside the MPIIS. Several of OSLab's projects are funded the Grassroots program for interdisciplinary research spanning across the institute.

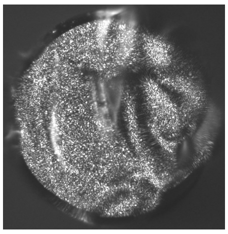


Figure 25.8: Speckle exiting an optical fiber

Smart shape sensor A popular technique to determine the deformation of a particular device is to attach an optical fiber to it and use it as a bend sensor. The motivation behind this is simple: fibers are thin, light-weight, flexible, and inexpensive, allowing them to be integrated as bend sensors into devices easily and at low cost. The OSLab is developing a learning-based method to obtain the geometry of a bent fiber by observing speckle patterns coming out of the fiber, see Fig.25.8. Various physically-motivated architectures of neural networks are trained using supervised learning on previously recorded fiber geometries and speckle patterns. In the first experiments the reconstruction of basic bends showed good agreement with the ground truth. Currently, the experimental setup is being extended to generation of more complex shapes.

Figure 25.9: Heated rubidium vapor cell. Inset: Fluorescence excited by resonant light.

Nonlinear optical layers for light-based neural networks Optical implementations of neural networks show promise as a power-efficient solution for solving machine learning tasks. A major limitation of these networks is the lack of suitable nonlinearities, limiting their overall performance to approximately those of linear systems. The usage of atomic vapors offers rich nonlinear effects, such as saturated absorption, yet is mainly unexplored as potential nonlinear element in optical computing. Together with members of the MNMS-group, we have experimentally implemented a deep diffractive neural network using spatial light modulators as a testbed for versatile optical nonlinear activation functions based on a rubidium vapor cell, see Fig.25.9.

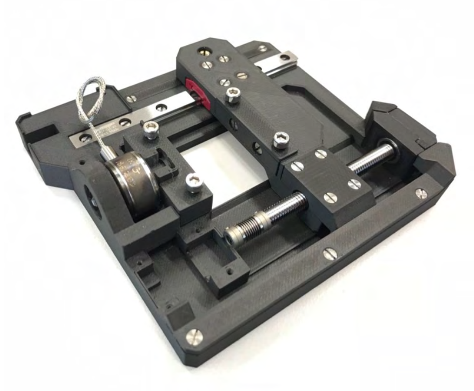
Non-Verbal Interpersonal Synchrony Analysis Tool (nVISA) The aim of this project is an advanced Computer Vision based tool (nVISA) to support healthcare practitioners in automatic detection and analysis of Interpersonal Synchrony (In-Sync) in patient-therapist-dyads. The nVISA tool relies on a state-of-the-art camera setup and carefully adjusted algorithms for body tracking, facial expression detection, and gaze interaction to match psychotherapy settings. Multiple annotated datasets from healthy controls are being collected, during the In-Sync induction procedure, for algorithm development. In the next steps the nVISA tool will be tested in clinical environment. This project is done in collaboration with MPI for Psychiatry.

Portable Capturing Systems Covid-19 pandemic brought a challenge for human data collection effort, restricting the recruitment of participates. We saw an opportunity to develop highly portable motion capture setup that can be delivered to participant's homes. As the first step of this project we established a broad comparison between the variety of available sensors that can be used for this task. We compared the performance of consumer off-the-shelf sensors and industrial sensors, focusing on multi sensor integration to acquire larger capturing volume with high-resolution. Currently, we are finishing the prototype of the system.

25.4 Robotics

The Robotics Central Scientific Facility was established in 2017 to support the institute's research objectives via the design, rapid prototyping, and validation of novel robotic and mechatronic systems. Melding together the complementary disciplines of mechanical design, electrical engineering, embedded programming, and systems integration has made possible the vast majority of the technology that pervades our lives, from modern automobiles to smartphones and surgical robots. The majority of the work within the Robotics CSF takes place in close collaboration with institute researchers. For those with completed designs, the Robotics CSF also offers direct additive manufacturing and electrical circuit prototyping services.

Mechanical Design & Prototyping



The design and rapid prototyping of mechanical structures can be accomplished using a variety of processes and techniques, including additive manufacturing, traditional subtractive techniques, casting, molding, and many more. When thinking about the integration of intelligent components (sensors, actuators, embedded electronics and processing), certain methods may be more or less viable for a given project.

Computer-Aided Design - Capturing geometric constraints, modeling sourced components, design of custom hardware, virtual assembly, motion, stress, and/or interference analysis, bill of materials generation, preparation of files or documents for prototyping and manufacturing

Rapid Prototyping - additive (3D printed) manufacturing of numerous materials, subtractive machining, laser cutting, composite layup, polymer casting

Electronics Design & Fabrication

The majority of embedded electronic systems require the integration of compact surface-mount components on either rigid or flexible substrates. The design of such circuitry often requires numerous iterations, and traditional methods can take weeks to produce. To accelerate the prototyping cycle, the Robotics ZWE has invested in the expertise and equipment to rapidly design and internally prototype fine-pitch, multi-layer, and flexible custom circuitry.

Design - includes the definition of requirements, selection of components, and specification of processes, taking into consideration what tools we have in house as well as our outsourcing vendor capabilities

Capture - schematic design and board layout

Fabrication - production of multi-layer rigid and/or flexible circuits, including fully printed three-dimensional electronics

Assembly - placement and reflow soldering of fine-pitch surface-mount components and hand-soldering of through-hole elements

Test - ensuring that the design and prototyping fit the requirements

Embedded Software Development

Many robotic and mechatronic systems require specific input, output, and computation functionality to be embedded within constrained, mobile, or remote environments. Yet other systems require wired and/or wireless interconnections between existing systems or various other computational elements.

Microcontrollers - experience with all major microcontroller architectures (AVR, ARM, TI, Freescale, Microchip, etc.)

Programming Languages - proficient in a variety of programming languages (C/C++, Java, Python, Matlab, etc.)

Communication Protocols - extensive experience with various communication protocols (I2C, SPI, USB, CAN, etc.)

Additive Manufacturing

The design of complex integrated mechanical systems usually benefits significantly from the ability to rapidly iterate on the design and specific features of mechanical structures. For this reason, the Robotics CSF has established a suite of additive manufacturing tools spanning both the most common techniques as well as some of those on the cutting edge of technology.

Originating in the late 1980s, the field of additive manufacturing (“3D Printing”) continues to evolve and grow at an astonishing rate. The fundamental principle is the layered deposition of material to fabricate given three-dimensional geometry. The most common techniques are:

Fused-Deposition Modeling (FDM) - a thin strand of plastic is heated to near it’s melting point, and laid out by the planar movement of a print head over a flat platter. FDM requires supporting material for overhanging geometry.

Stereolithography (SLA) - lasers are used to selectively cure voxels within the top layer of a vat of UV-sensitive resin. SLA benefits from the uncured resin acting as a supporting material.

Multi-Jet Modeling (MJM) - a print head, similar to an inkjet printer, is used to deposit small droplets of UV-curing polymer that are then cured by a UV lamp. Some MJM systems enable the user to alter the material stiffness and other properties within a single part.

Selective Laser Sintering (SLS) - lasers are used to sinter adjoining particles of material. SLS is self supporting, and can be used for polymers as well as metals.

Choosing a particular process and machine for a given part depends upon the complexity of the geometry, the required bulk mechanical properties, cost, time, and a number of other factors. The Robotics CSF is currently operating eight different 3D printers spanning the range of available technologies described above.

Representative Projects

Over the past five years, the Robotics CSF has worked on projects with researchers from every department and nearly every research group across both sites of the institute. A few representative projects include:

MuscleBot (Empirical Inference) - To design and build a second-generation four-degree-of-freedom pneumatic-muscle-driven ping-pong playing robot.

BLMC Microdriver (Dynamic Locomotion & Control, Autonomous Motion, etc.) - The design, prototyping, refinement, and production of a miniaturized high-current dual brushless-motor controller, which has been used in a range a projects in different groups.

Furuta Pendulums (Intelligent Control Systems - To design and prototype a fleet of rotary inverted pendulums for novel controls experiments.

BL Manipulator (Empirical Inference) - To design and produce as set of eight three-fingered manipulators with cameras, lighting, and enclosures to be used for machine-learning experiments (including remote-team challenges) involving manipulation of a variety of physical objects.

WheelBot (Intelligent Control Systems - To design, prototype, test, and refine a symmetric self-balancing robot with brushless-motor-driven reaction wheels as a testbed for novel control algorithms.

25.5 Scientific Computing

The Central Scientific Facility "Scientific Computing" was established in the year 2013 to plan, build, operate, and maintain computing and storage infrastructure required for the research at the institute, and to help researchers to use these infrastructures effectively. The team of 3 members collaborate with researchers in developing scalable algorithms and applications. It is also envisioned that the group will carry out research in the areas overlapping High Performance Computing and Machine Learning.

25.5.1 Infrastructure and Services

Artificial Intelligence research in general, and especially the research at our institute has been becoming more and more compute and data intensive. Consequently, the computing and storage infrastructure in the institute has become very crucial and it represents the experimental instrument of the research in the institute. Research equipment such as the 4D scanner generate large amount of data and in-house computing resources are necessary to process these data.

The computing cluster belonged to the Department of Empirical Inference in the beginning and was then integrated and rebuilt as part of this Central Scientific Facility in the year 2013. It was expanded in multiple stages in the subsequent years, to be able to support the growing needs from various departments and independent research groups. A major expansion with significant numbers of latest GPUs and larger storage system was under taken in the year 2019. Another major upgrade is currently under way, with more than 200 latest GPUs.

The cluster currently has more than 100 rack-mounted multi-processor nodes, with more than 9000 Intel and AMD 64-bit CPU cores, some of them with 2 terabytes RAM, as well as more than 650 NVIDIA GPUs including the latest Tesla A100s. It also has 1 petabyte of fast, distributed storage space. The nodes are connected via a 100 Gbps network.

A large number of the applications running on the cluster are data intensive, for which I/O performance is crucial. We use the parallel file system *Lustre*[1] to address this requirement. Lustre is an open source software with good community support that is being used by many institutions around the world, and hence the possibility of

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[1] https://www.lustre.org

[2] https://research.cs.wisc.edu/htcondor/

vendor lock-in is avoided. *HTCondor*[2], again an open source software, is being used as the scheduler on the cluster, with a number of in-house improvements and adaptations to tailor it to the specific needs of the researchers. A cluster banking system is used to share the resources fairly among users.

The scientific computing facility has taken active interest in helping the users to use the cluster resources as efficiently as possible. Periodic tutorials were given on how to use the cluster effectively. The scientific computing facility also promotes the use of resources provided by *Max Planck Computing and Data Facility*[3] at Garching, and works together with researchers to identify the best-suited use cases, and helps them port their applications so that they can be run there.

The scientific computing facility coordinated with the building contractors to ensure the successful completion of the new server room in the new building. The cluster was then successfully moved to and set up in the new server room at the beginning of the year 2018. The server room has a capacity of 500 kW as of now. To be able to expand our computing infrastructure to the scale needed for the institute's research requirements in future, the capacity of the server room needs to be expanded to 1 MW soon and to 1.5 MW in the future. The Scientific Computing Facility team worked with the Building Services group and the Scientific Coordination Office in the institute to prepare the plans and obtain necessary approvals. The expansion work is scheduled to happen in the first half of 2022.

The group is continuously working on further expansion of the cluster to address the growing computing needs in the institute, closely working together with the departments, research groups, institute administration, and Max Planck Society administration to identify the needs, secure funding, and procure state of the art hardware in a timely manner. Recently, a plan to expand the cluster has been approved by the Max Planck Society, with a funding of approximately 3.4 Million EUR during the years 2021 and 2022.

In the beginning, the computing cluster was predominantly used by the researchers in the Tübingen campus. However, the user base now includes researchers from the Stuttgart campus of the institute and the Scientific Computing facility supports those users in a regular manner.

25.5.2 Research and Development

A cluster banking system was used on the erstwhile Empirical Inference department cluster to share resources among the users. Based on the experience accumulated from this, a new cluster banking system was designed and developed incorporating the additional features that were needed. In setting up, maintaining and in some cases building these tools, the scientific computing facility has acquired a good amount of in-house expertise that allows it to keep adapting the software systems to the specific needs of the scientists.

The Perceiving Systems department has a 3 petabytes storage system that stores important data that is crucial for the research in the department and needs to be backed up regularly. Scientific Computing facility, in collaboration with colleagues in the department, developed an in-house backup solution that can backup the data in this storage system faster than the alternatives existed. Changes are stored on two different backup tapes, which are placed in two different locations on the campus in Tübingen. With this application, the whole data in the system can be processed within a few days, whereas the alternative backup applications take weeks.

In collaboration with colleagues in Perceiving Systems department and Optics and Sensing Lab, the team analyzed the work flow of the data processing of the capture data in the Capture Hall, tested different configurations, and devised a way to improve the data upload time. A central staging storage server was installed as the primary destination for storing and processing capture data. This system architecture provides faster access to the scanner systems and to the department storage system, resulting in faster data upload.

Members of the group work closely with researchers to promote the effective use of cluster resources and collaborate in building scalable applications. The group also regularly monitors the different components of the cluster and gathers feedback from the researchers in order to identify and address the possible bottlenecks in the architecture of the cluster, such as I/O, GPU memory,

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[3] https://www.mpcdf.mpg.de

etc. This information is used in the successive expansions of the cluster to make sure the resources are used in an efficient way.The group also liaisons with external agencies to support research collaborations that involves significant amount of computing.

We intend to use high performance computing techniques to increase the computational performance of applications and algorithms dealing with large data sets (Big Data) and work in collaboration with departments and research groups. The computing cluster is growing very fast, with addition of very powerful GPU nodes. The energy consumption is also growing in a similar fashion. Hence, it is in our interest to ensure that the cluster is used in an energy efficient manner. Energy aware scheduling of jobs can potentially improve the energy usage by the cluster, and we plan to develop an AI based solution to achieve this.

25.6 Software Workshop

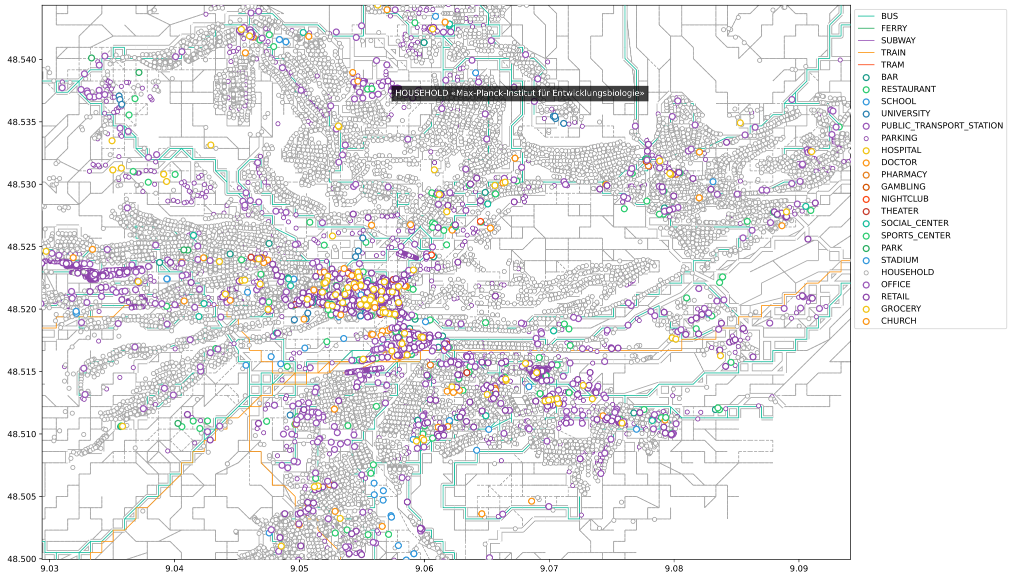


Figure 25.10: representation of Tübingen and its connections using CityGraph.

The **Software Workshop** (**SW**) is a unique central scientific facility at the crossroads between software engineering and research. Our primary responsibility is to increase the quality and impact of the research at the institute, both internally and worldwide.

Research, in particular in the topics of the institute, can only rarely be conducted without computation. Writing code is therefore one of the most critical parts of a research project. It can also be the most challenging component since researchers often lack the time and the specific knowledge in computer science and software engineering to write proper implementations.

The motivation behind the existence of the SW is therefore to help researchers in those topics at the different stages of their projects. We bring together researchers, trained scientists, and engineers to develop innovative software solutions and transform research codes into standardized products. In particular, we focus on the following aspects:

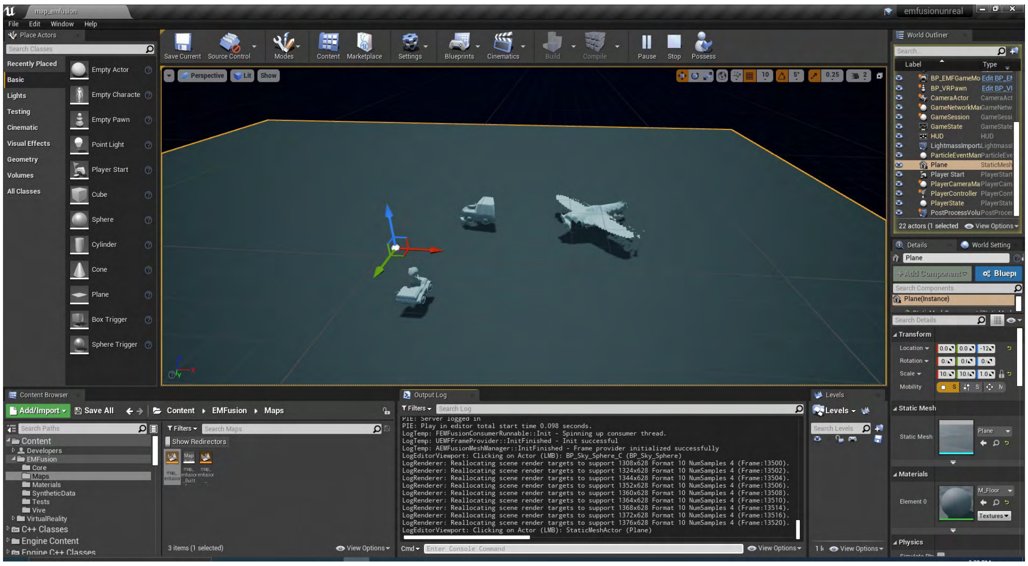
- **Code quality**: we intend to build software with the highest possible quality (e.g. documented, tested, usable, modular, stable, robust). For this purpose we follow industrial standards and processes during the different phases of development of the software, from the needs and requirements analysis to its release.
- **Publication quality**: we encourage making the implementation used in a publication available. Indeed, it contributes to the reproducibility of the results, provides important information that are usually not discussed in the paper, and sustains scientific credibility.
- **Scientific visibility**: additionally, the availability of the code provides a scientific reference that can be used for comparison/benchmark, thus promoting collaborations and contributing to scientific progress.
- **Scientific impact**: we release scientific code, often, and if possible under permissive licenses, thus allowing other communities and industries to integrate scientific work published by the Max Planck Society into their products.

The SW supports all the departments and research groups of the institute. It may also conduct independent research in the area of computer science or in any area of expertise of its members (astrophysics, optics).

25.6.1 Team, Expertise, and Equipment

Between 2016 and 2021, three scientists, two software engineers, one post-doc, one Ph.D. candidate, and twelve students have worked at the SW. As of October 2021, two scientists, one software engineer, and one research assistant are part of the SW team.

The SW collaborates with all researchers and scientists of the institute, regardless whether they belong to departments, research groups, or central scientific facilities. Versatility, adaptability,



```
PIE: Server logged in
PIE: Play in editor total start time 0.098 seconds.
LogTemp: FEMFusionConsumerRunnable::Init - Spinning up consumer thread.
LogTemp: UEMFFrameProvider::InitFinished - Init successful
LogTemp: AEMFusionMeshManager::InitFinished - Frame provider initialized successfully
LogEditorViewport: Clicking on Actor (LMB): BP_Sky_Sphere_C (BP_Sky_Sphere)
LogRenderer: Reallocating scene render targets to support 1308x628 Format 10 NumSamples 4 (Frame:13500).
LogRenderer: Reallocating scene render targets to support 1324x628 Format 10 NumSamples 4 (Frame:13502).
LogRenderer: Reallocating scene render targets to support 1344x628 Format 10 NumSamples 4 (Frame:13504).
LogRenderer: Reallocating scene render targets to support 1352x628 Format 10 NumSamples 4 (Frame:13506).
LogRenderer: Reallocating scene render targets to support 1360x628 Format 10 NumSamples 4 (Frame:13508).
LogRenderer: Reallocating scene render targets to support 1364x628 Format 10 NumSamples 4 (Frame:13510).
LogRenderer: Reallocating scene render targets to support 1368x628 Format 10 NumSamples 4 (Frame:13514).
LogRenderer: Reallocating scene render targets to support 1372x628 Format 10 NumSamples 4 (Frame:13516).
LogRenderer: Reallocating scene render targets to support 1376x628 Format 10 NumSamples 4 (Frame:13520).
LogEditorViewport: Clicking on Actor (LMB): StaticMeshActor (Plane)
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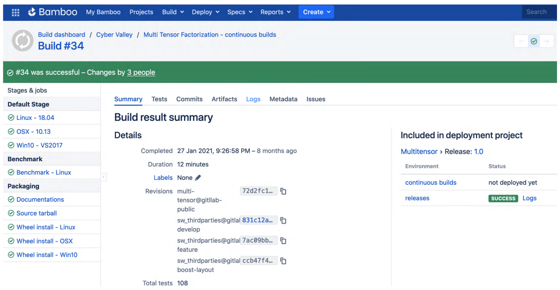
Figure 25.11: development of the Unreal Engine project for EMFusion++.

and a strong scientific background are therefore qualities that the SW team must possess in order to be able to cover such a large diversity of research topics.

The SW expertise includes several programming languages (C++, Python, Matlab, CMake), technologies for software development (Django, Qt, Dash, Ansible, Docker, CUDA, Boost, PostgreSQL, OpenCV, Unreal Engine), workflow management techniques (Agile, Scrum, Atlassian tools), and scientific fields (computer science, algorithmics, numerics, computer vision, physics, for instance).

The SW equipment lies mainly in the several computers needed to perform its tasks. The SW possesses 4 Dell Tower workstations, 3 Mac Pros, 1 iMac, 2 MacBook Pros, 3 mini-PCs, 1 iPhoneX, and 23 *Bamboo agents*. These *agents* usually older machines recycled by the SW and used for processes such as the continuous and automated testing of the entire code base (Figure 25.12).



Build dashboard / Cyber Valley / Multi Tensor Factorization - continuous builds

Build #34

#34 was successful – Changes by 3 people

Stages & jobs

Default Stage
- Linux - 18.04
- OSX - 10.13
- Win10 - VS2017

Benchmark
- Benchmark - Linux

Packaging
- Documentations
- Source tarball
- Wheel install - Linux
- Wheel install - OSX
- Wheel install - Win10

Build result summary

Details

Completed 27 Jan 2021, 9:26:58 PM – 8 months ago
Duration 12 minutes
Labels None
Revisions multi-tensor@gitlab-public 72d2fc1…
sw_thirdparties@gitlal develop 831c12a…
sw_thirdparties@gitlal feature 7ac09bb…
sw_thirdparties@gitlal boost-layout ccb47f4…
Total tests 108

Included in deployment project

Multitensor › Release: 1.0

Environment	Status
continuous builds	not deployed yet
releases	SUCCESS Logs

Figure 25.12: internal Bamboo server used for continuous integration, continuous deployment, and automation.

25.6.2 Service

This section describes the tasks of the SW as a service group.

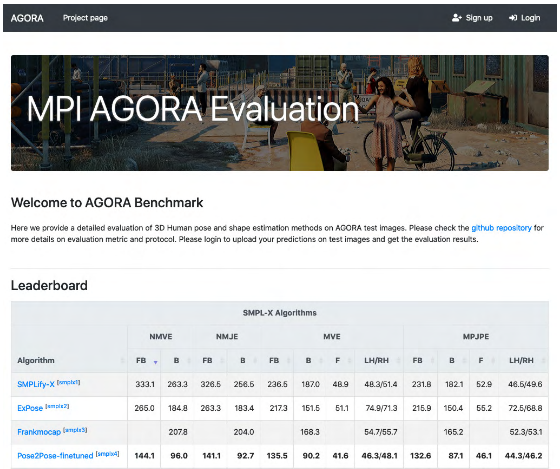
Training The SW regularly organizes events to promote good software development practices and new technologies: general presentations, code reviews, trainings, or individual meetings. In 2021, we have organized two Python workshops in collaboration with the IMPRS-IS.

Infrastructure for Software Development The SW sets up, maintains, and develops the full infrastructure used by the institute for code development. It includes a wiki accessible from both sites (Confluence), servers for hosting codes (GitLab, GitHub), a workflow management tool (Jira), applications to monitor the quality of code developments over time (Bamboo, Fisheye, Crucible), and an internally-developed application for hosting and sharing released codes and their documentation (CodeDoc).

25.6.3 Projects

This section highlights the different types of projects managed by the SW.

Software Engineering Projects The SW has developed an in-depth know-how for building infrastructures to help researchers collecting, organizing, analyzing, and sharing large amounts of scientific data. We implemented several web applications for different purposes, including collecting body scans, organizing robotic data, hosting a database of haptic devices, and comparing human pose estimation algorithms (Figure 25.13). We also built a graphical user interface for analyzing robotic data, a cross-platform application for tracking and training user productivity, and a tool for analyzing coverage in Python codes.



Welcome to AGORA Benchmark

Here we provide a detailed evaluation of 3D Human pose and shape estimation methods on AGORA test images. Please check the github repository for more details on evaluation metric and protocol. Please login to upload your predictions on test images and get the evaluation results.

Leaderboard

SMPL-X Algorithms													
	NMVE		NMJE		MVE				MPJPE			
Algorithm	FB	B	FB	B	FB	B	F	LH/RH	FB	B	F	LH/RH
SMPLify-X [smplx1]	333.1	263.3	326.5	256.5	236.5	187.0	48.9	48.3/51.4	231.8	182.1	52.9	46.5/49.6
ExPose [smplx2]	265.0	184.8	263.3	183.4	217.3	151.5	51.1	74.9/71.3	215.9	150.4	55.2	72.5/68.8
Frankmocap [smplx3]		207.8		204.0		168.3		54.7/55.7		165.2		52.3/53.1
Pose2Pose-finetuned [smplx4]	**144.1**	**96.0**	**141.1**	**92.7**	**135.5**	**90.2**	**41.6**	**46.3/48.1**	**132.6**	**87.1**	**46.1**	**44.3/46.2**

Figure 25.13: server for evaluation human pose estimation algorithms on the Agora dataset.

Research Projects We conducted several research projects, either internally or in collaboration with other researchers of the institute. Among others, we developed a fast and generic k-means algorithm, a cross-platform library for multilayer network tensor factorization, a Python package for representing and moving around a city (Figure 25.10), a demonstrator for an in-house SLAM algorithm integrated with VR hardware (Figure 25.11), and an analysis tool for probing the shape of an optical fiber from intensity profiles.

External Projects SW members are also involved in a few external projects usually connected to their background. As an example, we contributed to the open-source projects Boost and CMake, as well as built a framework for analyzing data produced by stellar astrophysical codes.

Overall, the SW completed more 23 projects since 2016, published four journal articles, and filed one patent. It is part of the Enzo, memmo, and Nugrid scientific collaborations.

26 OUTREACH

26.1 Public Relations

In recent years, the field of artificial intelligence has attracted growing attention, as AI has played an ever-greater role in the world. Accordingly, public interest in the research activities of the Max Planck Institute for Intelligent Systems (MPI-IS) has also seen a strong increase. Especially since the Cyber Valley consortium began gaining momentum in 2017, media coverage of the institute and its research has increased significantly, both in Germany and around the world. As a publicly funded institution, explaining artificial intelligent systems to a broad range of stakeholders, from the general public to policymakers, is our responsibility. We aim to actively contribute our expertise to discussions on the future societal impact of AI. The institute's public relations activities have thus focused on making the research of MPI-IS transparent and accessible to a broad audiencee, highlighting the value that research in machine learning, robotics and related fields may bring to humanity. Since 2016, the institute has further enhanced its press and public relations efforts in response to the growing need for external communication. The current approach is based on the four pillars described in the following subsections.

26.1.1 Press and Media Relations

MPI-IS has steadily increased the frequency of press releases and news items, and the institute has attracted greater media attention as a result. During the global COVID-19 pandemic, when everything appeared to be slowing down, the frequency of press releases picked up substantially, to nearly one per week between January 2020 and July 1, 2021.

Stories about the institute and its activities have appeared in

- regional media such as the Schwäbisches Tagesblatt, SWR, Stuttgarter Zeitung, Reutlinger Generalanzeiger, etc.
- national German newspapers, radio and television broadcasters, among them the Süddeutsche Zeitung, Frankfurter Allgemeine Zeitung, Handelsblatt, Tagesspiegel, Die Welt, ARD, ZDF, MDR, and Deutschlandfunk
- international print and broadcast media outlets such as the Financial Times, Le Monde, BBC, the Guardian, CBC Radio Canada, New York Times, Al Jazeera, etc.
- Youtube science videos, including a new video series that explains machine learning with the popular German Youtube star Doktor Whatson.

26.1.2 Social Media

MPI-IS has increased its presence across all its social media channels since 2016, with the number of followers and subscribers growing steadily. As of July 1, 2021, the institute’s YouTube channel counted 8,170 subscribers (4,500 in 2019). The number of followers on Twitter grew fivefold in only two years to reach 6,963 followers. At the end of the reporting period, there were 3,580 followes on LinkedIn, and more than 775 on Instagram. On Facebook, the MPI-IS following had grown to 3,086 in July 2021.

26.1.3 Visitors' Groups and Delegations

Over the past four years, MPI-IS has welcomed many visitors' groups and delegations – both in person and online – to whom scientists and technicians have presented their research. Prominent visitors from politics, industry, and academia have included: German Chancellor Angela Merkel, the EU Commission's Executive Vice-President Margrethe Vestager, Austria's President Alexander Van der Bellen, Baden-Württemberg's Minister President Winfried Kretschmann, Baden-Württemberg's Science Minister Theresia Bauer, U.S. Consul General Patricia Lacina, and Hungary's Minister of Innovation and Technology László Palkovics. Industry representatives included Robert Bosch GmbH, Porsche SE, Daimler Trucks and Process Engineering, Hyundai Motor Company, IAV automotive engineering, Nvidia Corp., IBM Deutschland Research & Development GmbH, Samsung Electronics GmbH, Schwarz-Gruppe, BASF S. E., and Braun Melsungen AG.

26.1.4 Public Outreach

The institute regularly organizes a broad range of events for the general public, including interested laypeople, youth, and scientists.

Figure 26.1: Kretschmann and Schölkopf during the offical cerenomy for the double anniversary

10/100 Year Institute Anniversary In September 2021, the Max Planck Institute for Intelligent Systems (MPI-IS) celebrated 10 years of MPI for Intelligent Systems and 100 years of MPI for Metals Research (MPI-MF). MPI-IS emerged ten years ago from MPI-MF, which was founded in 1921. At a hybrid event, the MPI-IS directors celebrated the 10- and 100-year double anniversary at Stuttgart's Neues Schloss. Together with the Minister President of Baden-Württemberg, Winfried Kretschmann, and the President of the Max Planck Society, Martin Stratmann, the directors viewed with pride what both institutes have achieved. They reflected on the impressive 100-year history and looked back at the people who have made both institutes world-renowned in their respective fields of research. Meanwhile, staff, alumni and friends of the institute were able to watch the celebrations from their screens. The importance of both institutes for Baden-Württemberg – as well as Germany as a whole – as a center for research was highlighted at the event, in particular the impact generated by recent research results in machine learning, computer vision and robotics. They have made the Stuttgart and Tübingen region and beyond one of the world's leading centers for research into artificial intelligent systems.

The event also included two scientific presentations – one in the field of materials research and one in the field of machine learning. Claudia Felser, Director at the Max Planck Institute for Chemical Physics of Solids, gave a talk titled "From topology to green hydrogen." Joaquin Quinonero-Candela, until recently Distinguished Technical Leader for Responsible AI at Facebook, spoke on the topic of "Responsible AI."

Open House: Open House: MPI-IS opened its labs to the public twice in the period under review. About 1000 visitors attended the open house day in Tübingen in 2016. In 2018, the event was held simultaneously at both the Stuttgart and Tübingen sites, receiving 2500 and 1200 visitors, respectively.

Max Planck Day 2018: Max Planck Day was held on September 14, 2018, as part of a national Max Planck Society campaign that celebrated science across Germany. Both MPI-IS locations took part with the following events:

AI and Society Symposium: The Tübingen campus organized an AI and Society Symposium, which was followed by a panel discussion with Prof. Bernhard Schölkopf of MPI-IS, Prof. Thomas Hofmann of ETH Zürich, Dr. Michael Bolle of Robert Bosch GmbH, Dr. Ralf Herbrich of Amazon Development Center Germany, Prof. Sarah Spiekermann of Vienna University of Economics and Business, Dr. Sandra Wachter of Oxford Internet Institute, and Prof. Andreas L. Paulus of Georg-August-Universität Göttingen (who is also a member of the German Federal Constitutional Court). A total of 450 people attended this symposium.

Science Slams: Science Slams: On the Max Planck campuses in Tübingen and Stuttgart, Science Slams were attended by 250-300 people at each site. At each event, scientists explained their research in an entertaining way that was easy to understand, and the audience chose the winner at the end.

Summer Colloquium in Stuttgart: The Summer Colloquium takes place every year in July and offers four public lectures on current scientific topics. The Günter Petzow Prize is also awarded on the occasion. The last four winners were:

- 2016: Dr. Xing Ma: “Enzyme-Powered Mesoporous Silicia Micro/Nano-Motors: Towards Biocompatibility”
- 2017: Dr. Markus Weigand: “Exploring the Nanoscale with Soft X-rays”
- 2018: Dr. Wenqi Hu: “Smart Magnetic Soft Material and its Application in Miniature Robot”
- 2020: Dr. Hakan Ceylan: “Cell-Size Robots for Minimally Invasive Medical Interventions and Targeted Delivery”

The Max Planck Lecture with top-class speakers and interesting topics on intelligent systems: Scientists and interested laypeople are invited to attend the event, which generally attracts 150-200 participants. The last four lectures were:

- 2016: Prof. Naomi Ehrich Leonard of Princeton University, USA: “On the Nonlinear Dynamics of Collective Decision-Making in Nature and Design”

- 2017: Prof. Amnon Shashua of Hebrew University and Mobileye Vision Technologies Ltd.: “The Three Pillars of Fully Autonomous Driving”
- 2018: Prof. Roland Siegwart of ETH Zürich: “Autonomous Robots that Walk and Fly”
- 2020: Prof. Yoshua Bengio of Université de Montréal and of Mila, the Quebec Institute of Artificial Intelligence: “Machine Learning for COVID-19 Risk Awareness from Contact Tracing”

The inauguration ceremony of the new MPI-IS building in Tübingen on July 12, 2017: 120 guests were invited to the event, among them the Minister-President of Baden-Württemberg Winfried Kretschmann, the state Science Minister Theresia Bauer, the President of the Max Planck Society Martin Stratmann, several members of the state parliament, and Cyber Valley partners.

Girls’ Day: Each year, 40-50 girls are invited to the Girls’ Day event at both MPI-IS sites to gain insights into science and technology professions. Due to the pandemic, Girls’ Day was cancelled in 2020 and 2021.

TÜFFF (Tübinger Fenster für Forschung): The Tübinger Fenster für Forschung (Tübingen Window for Research) takes place every two years at the University of Tübingen and is simi-lar to a Long Night of Science. In 2017 and 2019, MPI-IS took part in the event with an information booth.

AI Monday in Cyber Valley: The popular event series with evenings of talks and knowledge sharing for AI enthusiasts was hosted in Tübingen in November 2019. The event took place in cooperation with Taival and Porsche AG.

26.2 Public Events

26.2.1 Public events (Selection

Date	Description
15-12-21	Igniting the potential of AI - Celebrating 5 years of Cyber Valley
02-12-21	AI GameDev award show
15-10-21	Visit by State legislators from the U.S. and Germany with Assemblymember Cecilia Aguiar-Curry ((D), Califonia State Assembly), Andrea Lindlohr MdL (State Parliament of Baden-Württemberg), Stormy-Annika Mildner, Executive Director (Aspen Institute)
30-09-21	10 and 100 years anniversary
29-04-21	Online Screening of “Picture a Scientist” & MPI-IS discussion
17-12-20	Kickoff AI Breakthrough Hub with Chancellor Angela Merkel, EU-Commissioner Margrethe Vestager, MP Kretschmann, and Science Minister Theresia Bauer
16-10-20	Visit by Anna Christmann MdB
13-09-20	Visit by German Chancellor Angela Merkel
29-07-20	Cyber Valley Research Forum
May 20 until October 2021	Cyber Valley Entrepreneurship Series (12 events with different discussion topics aroun entrepreneurship on AI; to obe continued)

May 2019 until September 2019	Exhibition ’Artificial Intelligence’ on board the MS Wissenschaft 2019: Artistic mirror on board, an exhibit from Cyber Valley startup DeepArt
20-02-20	Visit by EU-Commissioner Margrethe Vestager and Baden-Württemberg’s Minister-President Winfried Kretschmann
05-02-20	Panel discussion with the Chairwoman of the Enquete Commission on AI in the Bundestag, Daniela Kolbe MdB, and Machine Learning Professor Ulrike von Luxburg.
21-01-20	Zeitung in der Schule
24-05-19	TÜFFF (Tübinger Fenster für Forschung)
15-04-19	Visit by Baden Württemberg’s Minister of Economy Dr. Hoffmeister-Kraut
28-03-19	Girls’ Day
28-03-19	Visit by State Minister Schopper, State Secretary Dr. Stegmann
March 2019 until October 2019	Das Gehirn der Zukunft (Four panel discussions; organized in cooperation with the Hertie Foundation)
11.03.19	Besuch der CDU Landtagsfraktion with Frau Gentges
27-02-19	Besuch Anna Christmann MdB & Dieter Janecek MdB (Bundestagsfraktion Bündnis 90/Die Grünen)
29-11-18	Visit by the President of Austria Dr. Alexander Van der Bellen and Baden- Württemberg’s Minister-President Win- fried Kretschmann
26-11-18	Visit of members of Baden-Württemberg’s state parliament, Nico Weinmann and Daniel Karreis
26-10-18	Visit by Baden-Württemberg’s Science Minister Theresia Bauer
23-10-18	Visit of members of the German Bun- destag, Andreas Steier and Mario Brandenburg
22-10-18	Max Planck Lecture: “Autonomous Robots that Walk and Fly”, Prof. Roland Siegwart, ETH Zurich
15-09-18	Open House in Stuttgart: Erleben Sie Grundlagenforschung hautnah!
15-09-18	Open House in Tübingen: Come and visit our labs and learn about our research!
14-09-18	Science Slam for Max Planck Day in Stuttgart
14-09-18	Max Planck Day in Tübingen: Symposium on Artificial Intelligence and Society
14-09-18	Max Planck Day in Tübingen (evening): Science Slam - Light Installation
13-07-18	2018 Intelligent Systems Summer Collo- quium with the 2018 Günter Petzow Prize award ceremony and a celebration in honor of Prof. Manfred Rühle

28-06-18	Visit of members of Baden-Württemberg's state parliament, Andreas Stoch and Gabi Rolland
06-06-18	Visits of students from the Königin-Olga-Stift
28-04-18	Girls' Day in Stuttgart and Tübingen
27-04-18	Visit of students from Stiftung Kinderland Baden-Württemberg
29-09-17	"Hausbesuch bei den Robotern" – Lab tour as part of of the "Robots" exhibition
18-09-17	Max Planck Lecture: "The Three Pillars of Fully Autonomous Driving", Prof. Amnon Shashua, Hebrew University and MobilEye
12-07-17	Opening ceremony of the new institute building in Tübingen
07-07-17	2017 Intelligent Systems Summer Collo- quium with the 2017 Günter Petzow Prize award ceremony
08-02-17	Visit of students from the Königin-Olga- Stift
09-07-16	2016 Günter Petzow Colloquium with the 2016 Günter Petzow Prize award ceremony
18-06-16	Tübingen Open House
06-06-16	Max Planck Lecture: "On the Nonlinear Dynamics of Collective Decision-Making in Nature and Design", Prof. Naomi Ehrich Leonard, Princeton University
28-04-16	Girls' Day
28-04-17	Information booth at TÜFFF – Tübinger Fenster für Forschung
15-12-16	Cyber Valley Kick-off Meeting

26.3 Scientific Events

In addition to the selection of scientific events listed below, the institute frequently hosts talks by scientists from all over the world. A complete list of talks can be found at https://is.mpg.de/talks.

Date	Organizers (MPI-IS)	Description	Location
01-12-22 until 01-13-22	Florian Mayer	Syientific Symposium 2022	Virtual
01-09-21 until 01-10-21	Bernhard Schölkopf	ELLIS PhD Meetup	Virtual
01-04-21 until 20-05-20	Bernhard Schölkopf, Daniele Diaconu	ELLIS against COVID (five sessions)	Virtual
15-09-21	Bernhard Schölkopf, Daniela Diaconu	ELLIS Units: Official Launch	Virtual
14-09-21	Florian Mayer, Oliwia Gust, Cäcilia Heinisch, Melina Danieli	Cyber Valley Research Forum	Virtual
13-04-21	Katherine J. Kuchenbecker, Metin Setti	Meeting with Koç University AI center	Virtual

27-01-21	Leila Masri, Sara Sorce, Katherine J. Kuchenbecker	IMPRS-IS 2021 Symposium	Virtual
06-12-20 until 12-12-20	Valérie Callaghan, Oliwia Gust	NeurIPS 2020: Cyber Valley Coffee Talks	Virtual
03-09-20 until 05-09-20	Bernhard Schölkopf	DALI Meeting 2020	Virtual
31-07-20	Florian Mayer	Scientific Symposium 2020	Virtual
24-07-20	Katherine J. Kuchenbecker, Metin Setti	Summer colloquium 2020	Virtual
28-06-20 until 27-07-20	Bernhard Schölkopf, Georgios Arvanitidis, Mijung Park, Wittawat Jitkrittum	The Machine Learning Summer School	Virtual
23-06-20	Michael J. Black, Bernhard Schölkopf, Julia Braun, Oliwia Gust	Machine Learning for Covid-19 Risk Awareness from Contact Tracing - Max Planck Lecture Yoshua Bengio	Virtual
21-02-20	Katherine J. Kuchenbecker, Barbara Kettemann	IntCDC Spring Conference 2020	MPI-IS Stuttgart
14-10-19	Katherine J. Kuchenbecker, Leila Masri, Sara Sorce	Wallenberg AI, Autonomous Systems and Software Program (WASP) Intelligent Systems Colloquium (WISC)	Both MPI-IS sites
05-07-19	Katherine J. Kuchenbecker, Metin Sitti	Intelligent Systems Summer colloquium (Günter Petzow Prize, Ph.D. graduation ceremony)	MPI-IS Stuttgart
06-12-18	Bernhard Schölkopf	Founding event of the European Laboratory for Learning and Intelligent Systems (ELLIS) at NeurIPS 2018	Montreal, Canada
14-11-18	Hasti Seifi, Farimah Fazlollahi, Gunhyuk Park, Katherine J. Kuchenbecker	AsiaHaptics Workshop: “Haptipedia: An Interactive Database for Selecting, Ideating, and Learning About Grounded Force-Feedback Devices”	Songdo, South Korea

18-09-18 until 20-09-18	Michael Black, Katherine J. Kuchenbecker, Metin Sitti, Bernhard Schölkopf	Special Symposium on Intelligent Systems	Both MPI-IS sites
13-06-18	David Gueorguiev	EuroHaptics Workshop: "From Fingertip Mechanics to Tactile Sensation"	Pisa, Italy
03-04-18 until 05-04-18	Bernhard Schölkopf, Diana Rebmann	DALI 2018 - Data, Learning, and Inference	Lanzarote, Spain
08-02-18	Sebastian Trimpe, Georg Martius, Melanie Zeilinger	Second Max Planck ETH Workshop on Learning Control	ETH Zürich, Switzerland
12-12-17 until 15-12-17	Co-Organizer: Sebastiam Trimpe	Invited Session Series on Learning-based Control at CDC	Melbourne, Australia
29-10-17 until 01-11-17	Michael Black, Julia Braun	Scenes from Video III	Lago di Garda, Italy
20-09-17 until 22-09-17	Michael Black, Tamara Almeyda	Cyber Valley Symposium	both MPI-Sites
16-07-17	Co-Organizer: Jeannette Bohg	Articulated Model Tracking - Workshop at RSS (Robotics: Science and Systems Conference)	Cambridge, USA
15-07-17	Co-Organizer: Jeannette Bohg	Women in Robotics III - Workshop at RSS (Robotics: Science and Systems Conference)	Cambridge, USA
15-07-17	Co-Organizer: Jeannette Bohg	Revisiting Contact - Turning a Problem into a Solution - Workshop at RSS (Robotics: Science and Systems Conference)	Cambridge, USA
10-06-17 until 30-06-17	Bernhard Schölkopf, Ruth Urner, Julia Braun, Diana Rebmann	Machine Learning Summer School	Tübingen
05-06-17	Philipp Hennig	ICERM Seminar on Probabilistic Scientific	Brown University, USA
01-06-17	Philipp Hennig	Summer School on Probabilistic Numerics	Dobbiaco, Italy

18-04-17 until 20-04-17	Bernhard Schölkopf	DALI 2017 - Data, Learning, and Inference	Sestri Tenerife, Tenerife, Spain
27-03-17	Jeannette Bohg	Interactive Multisensory Object Perception for Embodied Agents Symposium at the AAAI Spring Symposium Series in 2017	Stanford University, USA
13-12-16 until 16-12-16	Michael Black, Katherine J. Kuchenbecker, Metin Sitti, Bernhard Schölkopf	Special Symposium on Intelligent Systems	Both MPI-IS Sites
01-11-16	Co-Organizers: Philipp Hennig, Bernhard Schölkopf	Dagstuhl Seminar on the Future of Learning with Kernels and Gaussian Processes	Schloss Dagstuhl
25-09-16 until 28-09-16	Peer Fischer, Samuel Sanchez, Metin Sitti	Max Planck ETH Center for Learning Systems: "Biomedical Micro-/Nanosystems Engineering" workshop	Schloss Ringberg
26-08-16	Philipp Hennig Maren Mahsereci	NeurIPS: "Optimizing the Optimizer" workshop	Barcelona, Spain
11-07-16	Peter Gehler	Max Planck ETH Center for Learning Systems: "Deep Learning" workshop	Donau-eschingen
09-06-16 until 10-06-16	Hakan Ceylan, Kirstin Petersen, Alexander Spröwitz	Max Planck ETH Center for Learning Systems: "Design and Coordination of Micro-to Macro-Scale Swarms" workshop	Radolfzell
01-06-16	Peer Fischer, Samuel Sanchez	International Symposium on Micro- and Nanomachines	Hannover
30-03-16 until 01-04-16	Bernhard Schölkopf	DALI 2016 - Data, Learning, and Inference	Sestri Levante, Italy
15-03-16 until 16-03-16	Michael Black, Bernhard Schölkopf, Metin Sitti	Special Symposium on Intelligent Systems	Both MPI-IS sites

27 PUBLICATIONS

27.1 Autonomous Motion Department

27.1.1 Journal Articles

2021

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2020

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2019

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2018

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2016

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2020

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27.4 Perceiving Systems Department

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27.9 Locomotion in Biorobotic and Somatic Systems Group

27.9.1 Journal Articles

2021

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27.9.2 Conference Papers

2021

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27.10 Dynamic Locomotion Group

27.10.1 Journal Articles

2021

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2021

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27.10.3 Book Chapters

2019

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27.10.4 Theses

Master's Theses

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27.11 Embodied Vision Group

27.11.1 Journal Articles

2021

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2020

[140] J. Vinogradska, B. Bischoff, J. Achterhold, T. Koller, J. Peters. Numerical Quadrature for Probabilistic Policy Search. *IEEE Transactions on Pattern Analysis and Machine Intelligence* **42** (1): 164–175, 2020.

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27.11.2 Conference Papers

2021

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2019

[1355] D. Zhu, M. Munderloh, B. Rosenhahn, J. Stückler. Learning to Disentangle Latent Physical Factors for Video Prediction. In *Pattern Recognition - Proceedings German Conference on Pattern Recognition (GCPR)*, 2019 (cited on page 258).

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2020

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27.12 Intelligent Control Systems Group

27.12.1 Journal Articles

2021

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27.13 Organizational Leadership and Diversity Group

27.13.1 Journal Articles

2021

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27.13.2 Conference Papers

2021

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27.14 Learning and Dynamical Systems Group

27.14.1 Journal Articles

2018

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27.15 Movement Generation and Control Group

27.15.1 Journal Articles

2021

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2021

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27.15.3 Book Chapters

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27.16 Neural Capture and Synthesis Group

27.16.1 Conference Papers

2021

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27.17 Micro, Nano, and Molecular Systems Group

27.17.1 Journal Articles

2021

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27.18 Physics for Interference and Optimization Group

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2021

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27.20 Probabilistic Numerics Group

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27.21 Physical Reasoning and Manipulation Group

27.21.1 Journal Articles

2021

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2020

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2021

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2019

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2021

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27.22 Rationality Enhancement Group

27.22.1 Journal Articles

2021

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2022

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27.22.3 Book Chapters

2021

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27.23 Statistical Learning Theory Group

27.23.1 Journal Articles

2021

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27.24 Materials CSF

27.24.1 Journal Articles

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27.25 Medical Systems CSF

27.25.1 Journal Articles

2021

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27.26.1 Journal Articles

2019

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27.26.3 Journal Articles

2020

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27.26.4 Patents

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27.27.1 Journal Articles

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27.28.1 Journal Articles

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27.28.2 Conference Papers

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