ETH zürich

Mechanical and Process Engineering

Research

D MAVT

Content

Welcome

The Department of Mechanical and Process Engineering (D-MAVT) is one of the sixteen Departments of the ETH Zurich. It traces its history back to its establishment in 1855. The Department is an undisputed leader in mechanical and process engineering research and education. It has contributed significantly to technological development in Switzerland and worldwide. Two Nobel Laureates in Physics have been directly associated with the Department and its faculty strives to maintain a strong international reputation in research and teaching. It continually renews its research and teaching portfolio ahead of changes expected in the world.

In response to its dynamic attitude and international attractiveness, the Department has become a magnet for students and scientists, now having the largest student population at ETH Zurich. D-MAVT is a key link between ETH Zurich and Swiss and international industry. In this manner, the Department plays an important role in making ETH Zurich a leading engineering university worldwide.

This brochure provides an overview of the current research at the Department, with presentations of each professor’s research activities.

Laboratory for Energy Conversion

The activities of the Laboratory for Energy Conversion (LEC) span a broad range of multi-disciplinary fields, including turbomachinery (power generation and mobility), instrumentation (sensors and actuators, mechatronics, and controls), plasma science (extreme ultraviolet light source for lithography and metrology), wind energy (measurements on full-scale and dynamically-scaled wind turbines, computational modelling, and social acceptance), and energy economics and policy (modelling of power generation technologies, analysis of power transmission networks and electricity markets, management of energy portfolios, and assessment of policy and design of policy options).

Figure 1: Multi-stage axial turbine research facility with automated robotic arm

LEC's activities span turbomachinery, instrumentation, plasma science, wind energy and energy economics and policy.

Experiments in LEC's axial turbine, radial compressor and film cooling facilities have resulted in the development of advanced designs that improve efficiency, and consequently lower the emissions of turbomachinery that is used for power generation and mobility. These experiments are complemented with LEC's in-house Computational Fluid Dynamics (CFD) tool, MULTI3, that is used to simulate the complex, three-dimensional unsteady flows in turbomachinery. A Graphics Processing Unit (GPU)-version of MULTI3

Figure 2: High-speed radial compressor

provides approximately two orders of magnitude speed-up compared to its CPU predecessor.

Advancement of LEC's Fast Response Aerodynamic Probe (FRAP) technology has continued. A high-temperature FRAP probe has been developed. A fast response entropy probe that provides measurements of unsteady entropy generation in harsh turbomachinery environments has been developed. The FRAP technology has been transitioned to applications in wind energy and plasma science. A low dynamic pressure design is used both on autonomous drones to measure around full-scale wind turbines and is nacelle-mounted on multi-MW wind turbines for measurements of atmospheric flow and wakes. A high-temperature FRAP is used in liquid metals in order to provide real-time monitoring in LEC's fully operational, continuous-running, multi-kHz, high brightness, EUV light source.

The laser-produced-plasma light source is comprised of a number of sub-systems including a droplet dispenser, a high-energy laser with focusing optics, a debris mitigation system, triggering and droplet tracking systems, in-situ plasma diagnostics, and a control system. Different multi-layer, coated collector optics are used to either run the source in a high power, high-volume manufacturing mode or as a metrology source with high brightness. A multi-scale suite of computational tools that cover the large range of time and length scales relevant to Laser Produced Plasma (LPP) sources has been developed in LEC.

A mobile laboratory, with working and living quarters for two persons, is equipped with 3D scanning LIDAR for measurements of the wind flow in wind farms. Autonomous drones and kites, equipped with FRAP, are also used to complement the LIDAR measurements. Geometrically-scaled wind turbine models are tested under controlled conditions in LEC's wind turbine test (WEST) facility. The measurements from the field and from the WEST Facility are used to support the development and validation of LEC's CFD tool, MULTI3, that has been adapted for the micrositing of wind turbines in wind farms. MULTI3 is also linked to a mesoscale weather model, visual impact model, and life cycle cost model, such that the integration of wind power plants can be assessed.

Energy policy is analysed using LEC's integrated framework for the analysis of energy, economics and policy. The impact of policy on the development of infrastructure for power capacity and energy delivery is assessed from more than 200 variables related to infrastructure, geography, climate, regulations and financial parameters. Scenarios are simulated to determine the role of varying policy framework on the optimum power generation mix, the operation of electricity transmission infrastructure, and the financial performance of power plants and energy systems.

Prof. Reza S. Abhari

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Institute of Energy Technology

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Reza S. Abhari has been Full Professor of Aerothermodynamics at the Swiss Federal Institute of Technology since October 1, 1999. He is the head of the Laboratory for Energy Conversion at ETH Zurich, a multi-disciplinary research center. He is or has been: (2005–2009) Delegate of the Rektor, Head of department of Mechanical and Process Engineering (2003–2005), Founder and Head of Academic and Career Advisory Program (2005–2009), and Head of Institute for Energy Technologies (2001–2003, 2011–present).
Prof. Abhari received his BA degree in Engineering Science from Oxford University in 1984 and his Ph.D. from the Aeronautical and Astronautical Engineering Department of MIT in 1991. Following his Ph.D., he held various senior research positions in industry. In 1995, he joined the faculty of the Ohio State University (OSU) with a joint appointment in the Aerospace Engineering and Mechanical Engineering.

Figure 3: Mobile laboratory equipped with 3D scanning LIDAR system

Figure 4: End-of-year presentation for New Enterprise for Engineers course

Highlights and achievements

Prof. Abhari is the author/co-author of over 220 articles and journal publications. He is currently or has been in the past a member of a number of editorial boards, including for the Journal of Power and Energy.

He is a member of the Swiss National Academy of Engineering Sciences (SATW). He is also a Fellow of American Society of Mechanical Engineers (ASME), as well as the recipient of many awards, including election as the Christensen Fellow of St Catherine's College, Oxford University in 2010.

He has given a number of major keynote speeches in the US, Europe and Asia on topics related to energy supply and conversion, climate change mitigation, technology management, and innovation management. He was a speaker and Chairman of the Forum on Innovation in energy systems in the 2010 World Future Energy Summit in Abu Dhabi.

Organization of the professorship

The Laboratory for Energy Conversion is in 2012 staffed with:

- 1 Professor
- 1 Administrative Assistant
- 3 Support staff
- 2 Workshop technicians
- 3 Senior Researchers (Oberassistenten)
- 3 Postdoctoral students
- 1 Researcher
- 1 Conference assistant
- 21 Doctoral students
- 4 Interns

A total of 40 people work here.

Teaching activity

The courses offered through LEC range from the study of fundamental principles, through the application of engineering principles, up to the process of entrepreneurship. These courses provide a balanced approach to covering the fundamental knowledge important to energy systems, as well as the practical application.

Teaching is offered in a series of courses, excursions, and a broad selection of semester and diploma projects.

- Aerospace Propulsion (with Dr. Chokani)
- Energy Systems and Power Engineering (with Prof. Abhari, Prof. Steinfeld)
- Gas Turbine Mechanics and Design (with Dr. Wettstein)
- Wind Energy (with Prof. Abhari, Dr. Chokani)
- Anatomy of a Turbocharger (with Dr. Chokani)
- Thermodynamics III (with Prof. Abhari, Prof. Steinfeld)
- Turbomachinery Design (with Prof. Abhari, Dr. Chokani, Dr. Ribi)
- New Enterprise for Engineers (with Prof. Abhari)

Fostering young academics

Six recent doctoral students (three of whom are women) are/were on LEC's staff as postdoctoral researchers. Dr. Sarah Barber (Ph.D. 2007), 2007–2011 in LEC; Dr. Nadia Gambino, (Ph.D. 2011) 2011–present; Dr. Anna Gawlikowska (Ph.D. 2011), 2011–present; Dr. Michel Mansour (Ph.D. 2008), 2008–present (now Senior Researcher); Dr. Oran Morris (Ph.D. 2009), 2010–2012; and Dr. Bob Rollinger (Ph.D. 2013), 2013–present.

Figure 5: ALPS II, laser produced plasma light source

Collaborations

Industrial

- ABB
- BKW
- EOS Holding
- Hitachi
- MAN TURBO AG
- Mitsubishi Heavy Industries
- MTU
- Siemens
- Toshiba

Government

- Swiss Federal Office of Energy: SCCER - Grids and their Components
- Swiss Federal Office of Energy: SCCER – Economy – Environment – Law-Behaviour
- Government of Poland
- Swiss National Science Foundation (SNSF)
- Commission for Technology and Innovation (CTI)

Key publications

- Abhari R.S., Rollinger B., Giovannini A., Morris O., Henderson I., Ellwi S.S., Laser-produced plasma light source for extreme-ultraviolet lithography applications, 2012, Journal of Micro/Nanolithography, MEMS, and MOEMS, Vol. 11, No. 2, 021114.
- Basol A.M., Jenny P., Ibrahim M., Kalfas A.I., Abhari R.S., Hot Streak Migration in a Turbine Stage: Integrated Design to Improve Aero-Thermal Performance, 2011, J. Engr. Gas Turbines Power, Vol. 133, 019011.
- Behr T., Kalfas A.I., Abhari R.S., Unsteady Flow Physics and Performance of a One-and-1/2-Stage Unshrouded High Work Turbine, 2007, J. Turbomachinery, Vol. 129, pp. 348–359.
- Burdet A., Abhari R.S., Influence of Near Hole Pressure Fluctuation on the Thermal Protection of a Film-Cooled Flat Plate, 2009, Journal of Heat Transfer, Vol. 131, 022202
- Kammerer A., Abhari R.S., Experimental Study on Impeller Blade Vibration During Resonance–Part II: Blade Damping, 2009, J. Engr. Gas Turbines Power, Vol. 131, 022509.
- Kocer G., Mansour M., Chokani N., Abhari R.S., Müller M., Full-Scale Wind Turbine Near-Wake Measurements Using an Instrumented Uninhabited Aerial Vehicle, 2011, J. Solar Energy Engr., Vol. 133, 041011.
- Mansour M., Chokani N., Kalfas A.I., Abhari R.S., Time-Resolved Entropy Measurements using a Fast Response Entropy Probe, 2008, Measurement Science Technology, Vol. 19, 115401.
- Mansour M., Kocer G., Lenherr C., Chokani N., Abhari R.S., Seven-Sensor Fast-Response Probe for Full-Scale Wind Turbine Flowfield Measurements, 2011, J. Engr. Gas Turbines Power, Vol. 133, 017102.
- Mischo B., Behr T., Abhari R.S., Flow Physics and Profiling of Recessed Blade Tips: Impact on Performance and Heat Load, 2008, J. Turbomachinery, Vol. 130, 021008.
- Schuepbach P., Abhari R.S., Rose M.G., Germain, T., Raab, I., Gier J., Improving Efficiency of a High Work Turbine Using Nonaxisymmetric Endwalls - Part II: Time-Resolved Flow Physics, 2010, Journal of Turbomachinery, Vol. 132, 021008.

Aerothermochemistry and Combustion Systems Laboratory

Our work is focused on experimental and simulation-based research into the fundamentals of reactive thermofluidics, with an emphasis on unsteady turbulent combustion. In collaboration with industry, we transfer research insights to the development of technologies for minimal CO_2, "zero"-emission engine combustion systems including biogenic energy carriers for transportation and decentralized co-generation. We also employ systems assessment in transportation and energy conversion, while a group led by Prof. I. Karlin pursues the advancement of the entropic lattice Boltzmann method for mesoscale flow problems.

Figure 1: Direct numerical simulation (DNS) of turbulent flow fields in engine-like-geometries

Research in the area of combustion systems is driven by industry needs as well as public legislation aimed at minimizing pollutant emissions, including, recently, the dominant greenhouse gas CO_2. Biogenic fuels are increasingly used to power combustion engines in an industrial context. Some of these are more complex in their chemical composition than traditional fossil fuels, and therefore involve correspondingly complex reaction kinetics. The research focus of the laboratory lies in unsteady turbulent combustion as it applies particularly to internal combustion engines. In this context we consider an in-depth understanding of the mechanisms for turbulence-thermochemistry interactions in such systems to be absolutely essential for the further advancement of technology in this area.

We carry out research using both experiments and numerical simulation. Experiments deal with optically accessible model test rigs (spray combustion chambers and a rapid compression/expansion machine) using laser-based optical diagnostics on the one hand and single- and multi-cylinder engines for industry-oriented research projects on the other. These engines are equipped with state-of-the-art measurement devices that enable fast spectroscopy at the exhaust and miniaturized endoscopic techniques for combustion and emission analysis.

We develop and apply advanced simulation methods for combustion processes, employing the full spectrum of Reynolds-averaged Navier-Stokes (RANS), Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS) methods. For the first two categories our main contribution relates to accurate modeling of non-premixed turbulent combustion on the basis of the conditional moment closure (CMC) method. Our DNS work employs a powerful code, co-developed by researchers within our group that is the first one of its kind worldwide that is capable of dealing with real engine geometries including detailed chemistry and transport properties for involved species.

Two other smaller groups within LAV work in the areas of a) very fast model development for engine optimization and control purposes and b) system assessment of energy converters in transportation. A third group works on further development of the entropic lattice Boltzmann method (see separate report by Prof. Ilya Karlin).

Highlights and achievements

> Attainment of accurate DNS results for complex flows, which have provided new insights concerning turbulence-thermochemistry interactions in reactive flows in microchannels, flame kernel evolution, autoignition of turbulent jets and, more recently, engine flows.
> Demonstration of CMC-method potential for prediction of combustion and emissions in diesel engines.
> Identification of mechanisms for stable combustion of dilute/lean mixtures in IC engines and gas turbines with H_2 containing fuel.
> On-line detection of soot formation/oxidation in steady and transient operation of diesel engines and development of virtual soot sensors.
> Development and validation of global reaction mechanisms for autoignition in homogeneous charge compression ignition (HCCI) combustion.

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Dipl.-Ing. Mechanical Engineering, National Techn. University of Athens, 1978; Ph.D., Mechanical Engineering, ETH Zurich, 1984; Postdoctoral Researcher, Mechanical and Aerospace Engineering Department, Princeton University, 1987–1988; Group Leader (1998) and Senior Scientist (1994), ETH Zurich; Head of the Combustion Research Lab, Paul Scherrer Institute (PSI), 1995–2004; and Joint Combustion Research Program Director, ETH/PSI (1995–2005); Full Professor and Head of Aerothermochemistry and Combustion Systems Laboratory, ETH Zurich, 2002–present; Founding Chairman of the interdisciplinary Energy Science Center, ETH Zurich, 2005–2011.
Member of editorial board of the International Journal of Engine Research; Steering Committee Swiss Competence Center Energy and Mobility (CCEM); Advisory Board of the Institute Vehicle Technology of the German Aerospace Center (DLR); Advisory Council of Federal Chancellor D. Leuthard on Energy Issues; permanent position at the Energy Commission, Swiss Academies of Arts and Sciences; Science Advisory Board of Swiss Academy of Engineering Sciences.

- Distinguished Paper Award in the colloquium New Technology Concepts from the Combustion Institute Pittsburgh, 2006.
- Innovation Prize from the German Natural Gas Association, 2007.
- BP Award on Health, Safety & Environment by the International Council on Combustion Engines (CIMAC), 2007.
- Georg Fischer Prize for Excellent Dissertation, 2007.
- ETH Medal for outstanding Ph.D. thesis, 2009.
- Kamm-Jante Medals for best dissertation on combustion engines (2011, 2012).

Goals and future priorities

Challenges in our area of research are numerous and will offer ample space for high-level research in the years to come.

On the numerical simulation side, we intend to take full advantage of our DNS code and of the (mid-term) emergence of exa-scale computing capabilities that can address real-life combustion problems. Such accurate numerical experiments shall also serve as a validation platform for advanced turbulent combustion models in the RANS and particularly the LES frameworks.

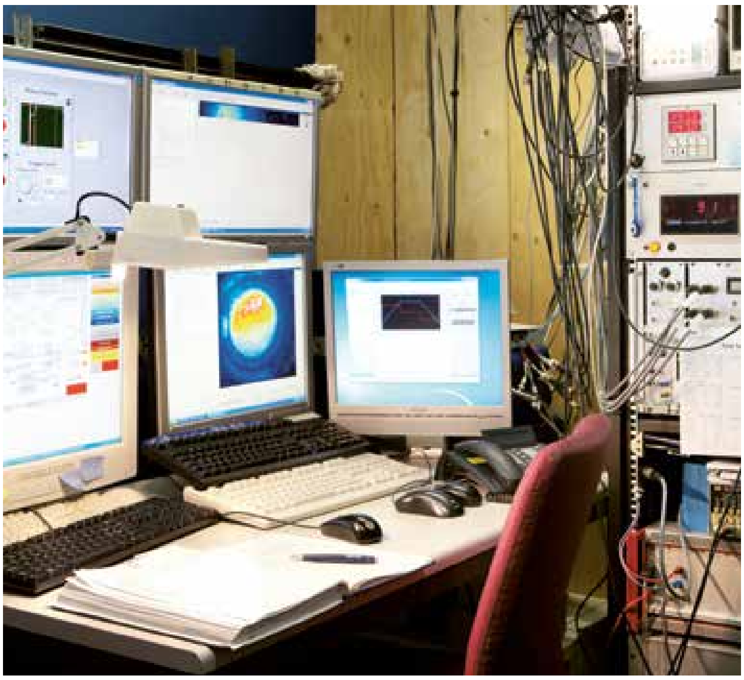

Figure 2: Flame structure autoignition in homogenous charge of synthetic fuels

On the experimental side we aim at synergetically using optical methods in model test rigs and research engine experiments to validate and further develop premixed and two-phase, non-premixed combustion models. Here we see the potential for a very interesting area of expansion in the investigation of autoignition and the combustion behavior of new synthetic renewable fuels.

We also see excellent future prospects in the integration of combustion models along the continuum from the fundamental (and very expensive) to the fast, specifically applicable (and affordable) level, to serve a wide spectrum of fundamental and industrial research needs. The laboratory is currently equipped with the full arsenal of experimental techniques required to address all of these research questions.

Organization of the professorship

The professorship employs around 30 people. Of these, almost half are doctoral candidates, four or five are postdocs, five are technical personnel, two are administrative staff, one is a laboratory manager, and five are senior scientists who lead individual groups (including titular Professor Ilya Karlin). The Head of the Laboratory is also currently academically responsible for another six doctoral candidates (two in industry R&D departments and four at the Swiss National Research Labs PSI and EMPA).

The five research groups within LAV are headed by Prof. I. Karlin (Entropic Lattice Boltzmann/Kinetic Theory), Dr. C. Frouzakis (DNS in Combustion), Dr. Y. Wright (Reactive RANS/LES), Dr. B. Schneider (Optical Diagnostics/Experiments) and Dr. F. Noembrini (Systems Assessment). The laboratory technical personnel are led by P. Obrecht.

LAV enjoys funding from the Swiss National Science Foundation, the Swiss Office of Energy, EU-Research programs, the Commission for Technology and Innovation (KTI), the FVV (pre-competitive research organization of the German IC engines industry) as well as direct industry funding at an amount of more than 2 Mio CHF per year on average and in total.

Teaching activity

In agreement with its research strategy, our laboratory is responsible for the major part of teaching at D-MAVT in the area of combustion at both the Bachelor and Master levels.

At the undergraduate level LAV is engaged in the course Thermodynamics II, where we are responsible for teaching chemical thermodynamics (50 % of the course with about 400 students). In addition, LAV teaches 70 % of the course Combustion and Reactive Processes in Energy and Manufacturing with about 80 students. We also participate in a Diagnostics Laboratory with approximately 80 students.

At the Master level LAV is responsible for the courses IC Engines I and IC Engines II, Theory and Modeling of Reactive Flows, Gas Turbine Combustion, Fluid Dynamics and the Lattice Boltzmann Method, Diagnostics in Experimental Combustion and, to a small degree, for the course Energy Systems Analysis.

We also supervise yearly on average more than 10 Bachelor theses as well as around 10 Semester projects at the Master level and 10 Master theses. In addition to D-MAVT students, LAV is also heavily engaged in tutoring Master students within the interdisciplinary Master in Energy Science and Technology Program at ETH Zurich.

Energy engineers for the future

Growing the next generation of engineers calls for an approach that combines natural-science-based, in-depth analysis with systems-orientated synthesis capabilities. In the field of energy technologies and specifically in combustion systems, this means that we aim at equipping young professionals with the fundamentals of chemistry, thermodynamics, fluid mechanics, materials, etc., while at the same time ensuring they are capable of integrating such knowledge into the design of complex systems that satisfy multi-parameter optimization requirements.

Figure 3: Assembling the optically accessible Rapid-Compression-Expansion Machine

Fostering young academics

We encourage young academics to engage regularly in conferences, publishing, reviewing of paper submissions and to participate in project management and leadership in international collaborative tasks with such organizations as the Engine Combustion Network and the IEA Implementing Agreement in Combustion (where we lead the collaborative Task on Gas Engine Combustion). Within the last six years, three of our former doctoral students/postdoctoral scientists have been appointed as professors in Germany, Canada and India.

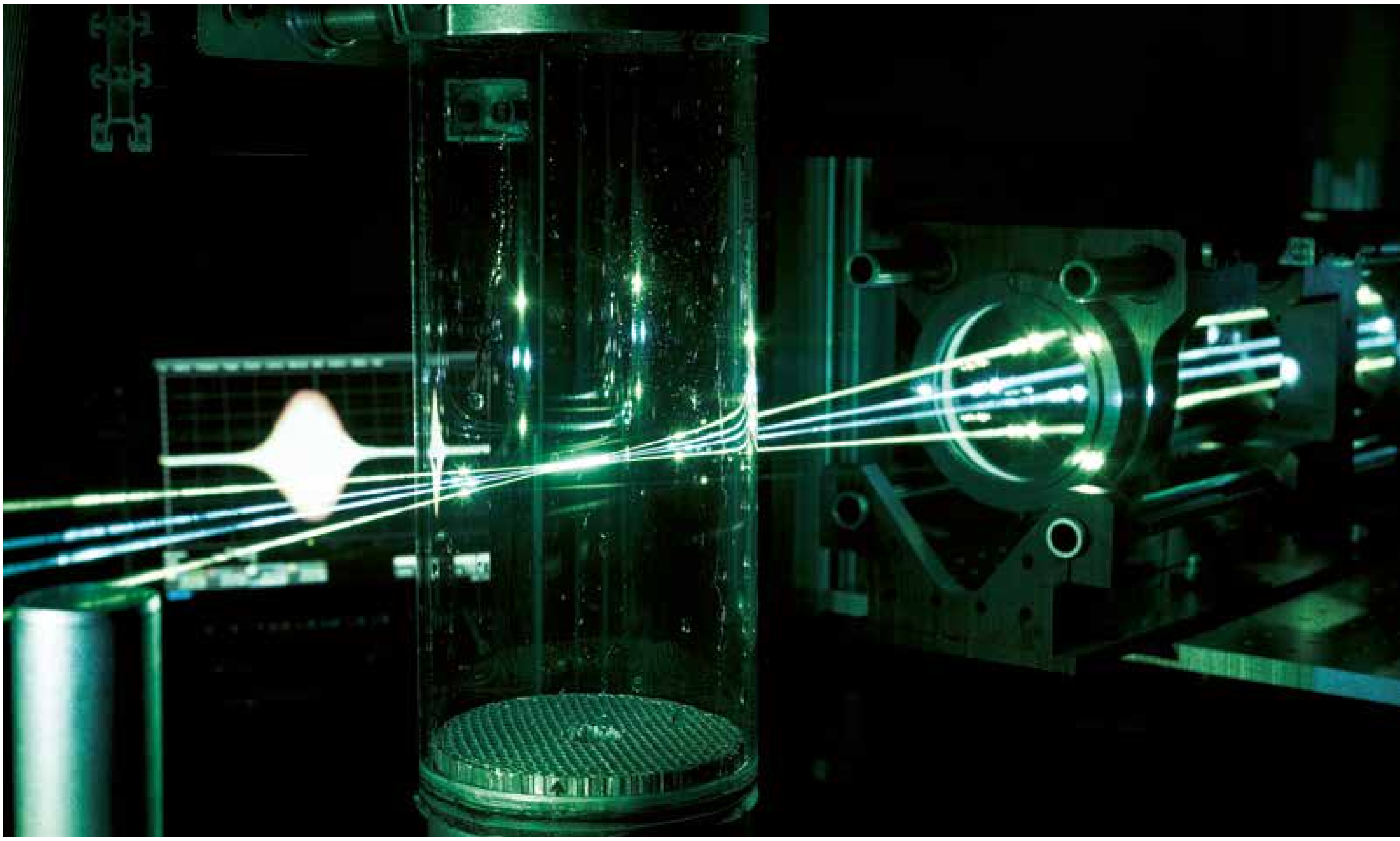

Figure 4: Phase Doppler Anemometry (PDA) measurements in a large spray combustion chamber

Collaborations

Industrial

Part of our mission at LAV is to transfer fundamental knowledge to applications in industry. We therefore engage in several collaborations with leading companies in the field. These include, among others:

> ABB Turbosystems
> Wärtsilä CH
> Liebherr Machines
> Kistler
> Wenko and Motorex
> Bosch
> Volkswagen
> Daimler
> BMW
> MAN
> MTU
> Continental

Most importantly, we receive significant competitive funding from the German Engine Combustion Industry Research Association (FVV).

Academic

> Combustion Research Laboratory at PSI
> Engine Group at EMPA
> Cambridge University (Prof. E. Mastorakos)
> Argonne National Lab (Dr. P. Fischer)
> University of Illinois (Prof. M. Matalon)
> Stuttgart University (Prof. M. Bargende)
> TU Munich (Prof. G. Wachtmeister)
> Karlsruhe Institute of Technology (Proff. Spicher/Koch)
> Politecnico di Milano (Prof. A. Onorati)

Key publications

> Vandersickel A., Wright Y.M., Boulouchos K., Combustion, Theory and Modeling, 2013 (accepted for publication)
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> Gerke U., Boulouchos K., Int. Journal of Engine Research, Volume 13, Issue 5, October 2012, p. 464-481
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> Pizza G., Frouzakis C.E., Mantzaras J., Tomboulides A.G., Boulouchos K., Journal of Fluid Mechanics, vol. 658, pp. 463-491, 2010
> De Paola G., Mastorakos E., Wright Y.M., Boulouchos K., Combustion Science and Technology, 180, pp. 883-899, Taylor & Francis, 2008.
> Pizza G., Frouzakis C.E., Mantzaras J., Tomboulides A.G., Boulouchos K., Combustion and Flame, 155, no. 1-2, pp. 2-20, October 2008.
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> Wright, Y.M., de Paola, G., Boulouchos, K., Mastorakos, E., Combustion and Flame 143, 402-419, 2005.

Agile and Dexterous Robotics Laboratory

At the Agile and Dexterous Robotics Laboratory (ADRL) we develop model-based and model-free control and machine learning methods that enable robots with arms and legs to roam and manipulate dynamic and complex environments robustly and with agility. These environments require generalized approaches to impedance and whole body control. To achieve robust performance we complement robots with adaptive and learning methods. We develop reinforcement learning algorithms, whereby a robot improves its performance in much the same way humans learn highly developed skills from experience. Our research has applications in mobile manipulation, grasping, legged locomotion, prosthetics, field/space robotics, bio-mechanics and bio-inspired robotics.

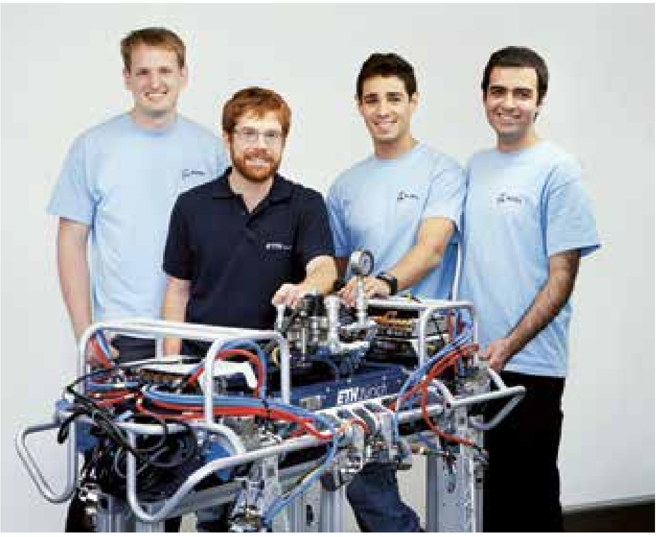

Figure 1: ADRL's founding members: M. Neunert, J. Buchli, T. Boaventura, F. Farshidian

In order to achieve our goal of understanding how robots, humans and animals can control dynamic motion in unstructured environments, we are taking robots with arms and legs outside the lab, where they can encounter environments that are dynamic, stochastic and (in general) not 'known ahead of time'. Characteristics such as these make environments outside the lab difficult to model, and yet for a robot to function well in these circumstances, it must be able to cope with the unforeseen. Our goal is to develop robots capable of *legged mobile manipulation* that are *actors* (not just observers), and which can autonomously manipulate their environment with only high-level guidance from a human operator. By focusing on versatility, agility and dexterity, this research will lay the groundwork for the service robots of the future.

Three primary challenges must be addressed if we are to meet this goal: contact, uncertainty and context. Dynamic locomotion (such as running and jumping) and skillful manipulation (such as handling tools) require a robot to come into contact with its environment. These kinds of rapidly changing contact situations are challenging, and require us to extend previous approaches to force, impedance and whole-body control. We therefore focus our research on generalizing these techniques so that they can be applied to hard-to-model dynamic situations, or to robots with arms and legs with many degrees of freedom. One important extension is to include adaptive and learning methods. We develop state-of-the-art reinforcement learning algorithms, whereby a robot or a virtual agent can learn to improve its performance from simple, unspecific feedback on the quality of task performance; that is, just like how humans learn complex skills. In order to account for dynamic motion, which requires fast feedback loops at many levels, our approach to robotics spans challenges that are currently treated as separate problems in planning or control. We therefore must develop control methods that can scale to include low-level actuator commands all the way up to planning tasks on longer time and spatial scales, such as how to get from the current position to a given geolocation. Uncertainties related to taking robots into unstructured environments present another significant challenge. This requires approaches that embrace stochasticity and probabilistic analysis. We develop methods based on stochastic optimal control. The resulting control policies and machine learning techniques can cope with stochasticity and are robust in uncertain situations. For example, a robot can learn to grasp an item with uncertainty in its pose by properly exploiting its kinematics and tuning the hand impedance.

Last but not least, we work on giving robots the required context knowledge for them to be able to act adequately and quickly in their environment. We enable robots to use their previous experiences to infer models and predictions of the world, their bodies, and their sensor system, and therefore develop context models for future use. We achieve this by mining the rich data streams that robots collect through their many sensors and combining this with machine learning algorithms. These models are inherently probabilistic to reflect the uncertain knowledge and relationships that can be inferred from the (sometimes) sparse events in the data.

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Jonas Buchli has been a Swiss National Science Foundation (SNF) Assistant Professor for Agile and Dexterous Robotics at ETH Zurich since September 2012. He holds a Diploma in Electrical Engineering from ETH Zurich (2003) and a Ph.D. from EPF Lausanne (2007). In his thesis work he developed adaptive frequency oscillators and applied them to the modeling and design of robotic locomotion pattern generators. At EPFL he organized the 2006 Latsis Conference on 'Dynamical principles for neuroscience and intelligent biomimetic devices'. From 2007 to 2010 he was Postdoctoral Fellow at the Computational Learning and Motor Control Lab at the University of Southern California, where he was the team leader of the USC Team for the DARPA Learning Locomotion challenge. From 2010-2012 he was a team leader at the Advanced Robotics Department of the Italian Institute of Technology in Genova. Jonas Buchli has received a Prospective and an Advanced Researcher Fellowship from the SNF. In 2012 he received an SNF Professorship Award. He has contributed to research in diverse fields such dynamical systems approaches to motion generation and control, the theory of coupled oscillators, planning and control of dynamic locomotion, machine learning, whole body control, whole body force and impedance control and modeling of human motor control. He was involved in the development of robotic platforms as well as software engineering projects for robotic control software. His current research interests include model-based control of legged robotic and human locomotion and manipulation, machine learning and adaptive control, and dynamic and versatile service and field robots.

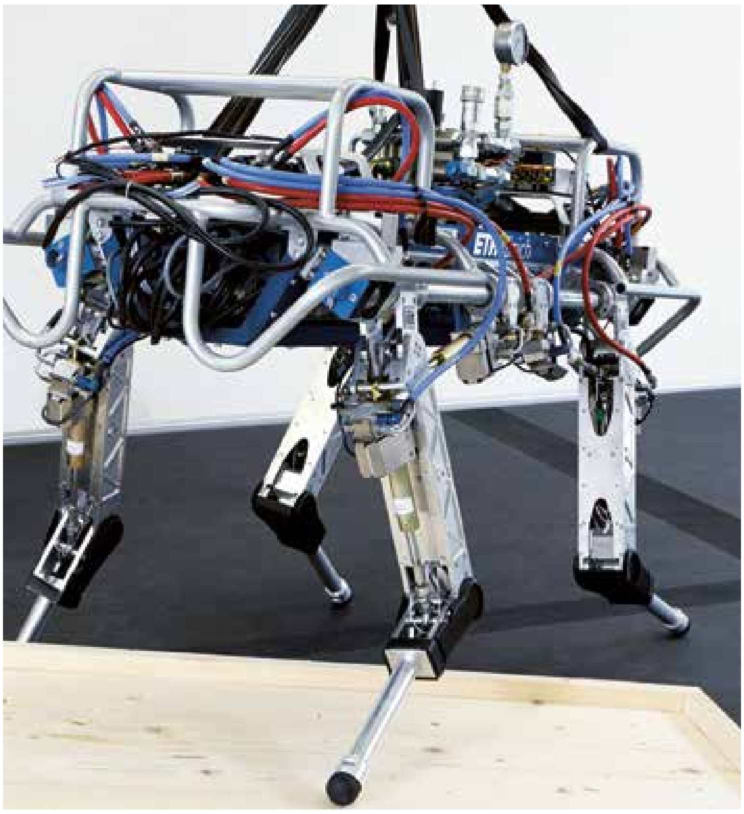

Figure 2: HyQ Blue - ETH's hydraulic torque controlled quadruped, built by IIT Genova, funded by the SNFS and IIT

Highlights and achievements

> Best overall performance in the DARPA Learning Locomotion challenge (with Mrinal Kalakrishnan, Peter Pastor, Michael Mistry and Stefan Schaal). In this challenge a small quadruped robot was required to walk completely autonomously over very rough, previously unseen terrain. Competitive project setting involving major US universities.

> Development of PI^2 (with Evangelos Theodorou and Stefan Schaal), one of the fastest Reinforcement Learning algorithms. With PI^2, robots can learn full body skills robustly under arbitrary and stochastic cost functions.

> Development of adaptive frequency oscillators (with Ludovic Righetti and Auke Ijspeert). Adaptive frequency oscillators are model systems that can 'learn' the frequency of any periodic or quasi periodic signal. They are used in models in physics, biology and in the control of robots for observer and pattern generation.

> Development of software and control for Hydraulic Quadruped HyQ (with Claudio Semini and Darwin Caldwell). Hydraulic Quadruped (HyQ) is the only fully torque-controlled hydraulic quadruped that has been published in academic journals and conferences. It is also the only legged robot that is able to run and walk robustly in rough terrain using only active impedance control (i.e. without using any passive elements like springs).

Goals and future priorities

At ADRL we will continue to develop machines that can reason with their own dynamics, the dynamics of their environment and its unknowns. The three big challenges of contacts, uncertainty and context are problems we have only just begun to approach. We will thus focus on addressing these problems by integrating with the fields of control, state estimation and machine learning in order to meet our broader goal of developing useful, versatile, dexterous and agile service robots. This challenge requires us to derive new algorithmic approaches, develop new theoretical concepts, and to work on solid software engineering principles. We work with colleagues in academia and partners in industry to transfer insights gained by our research into applications that address societal needs, be that in the realm of biomedical technology, construction, or architecture. We also aim to support fundamental research in the fields of biomedicine and biomechanics.

Our long term vision is to come up with complete and robust robotic actors by integrating multi-modal perception, motion planning, and control to allow a fluent and seamless coordination of sensing and action. We envision systems that can perform fast and efficient manipulation while walking and running, and that can greatly extend their standard workspace by using whole body motions.

We aim to develop robots that have similar or better agility and dexterity than humans and animals in the face of a spectrum of tasks that require roaming or manipulating the environment. With these features, general purpose autonomous robots could revolutionize how we manipulate the real world, much in the same way as the general purpose computer has lead to a revolution in how we process abstract information.

Organization of the professorship

ADRL has currently a staff of eight: four doctoral students, one postdoc, one technician, one administrative assistant and the lab director. It is funded through the Swiss National Science Foundation, the European Commission (FP7) and ETH Zurich.

Due to its small size ADRL has a flat organizational structure. Every scientific member is involved in more than one scientific project. This overlap serves to foster exchange of ideas, and many of our approaches naturally apply to different projects. The doctoral and postdoctoral researchers also support ADRL's student project supervision, either by being directly responsible supervisors or co-supervisors.

ADRL makes extensive use of computer simulations to develop and prepare algorithms and controllers, but always with the goal of transfering these to a real machine. ADRL has a robot lab space with a high-speed custom treadmill (3.5x5m, 4m/s) for robot and human locomotion experiments. ADRL has the only copy of IIT's Hydraulic Quadruped (HyQ) robot, a fully torque-controlled versatile legged robot built for outdoor operation.

Teaching activity

ADRL has taken up lecturing activities in 2013 with a course on optimal control and learning for autonomous robots. In this lecture the students learn the fundamentals of optimal and learning control. The students learn how these fundamental ideas can be applied to real world problems encountered in autonomous and articulated robots. This lecture gives the students the understanding and tools to apply learning and optimal control to problems encountered in robotics and other fields.

Since its start in September 2012, ADRL has supervised more than 20 Master, Semester and Bachelor students in their project work, some of which resulted in award-winning performance and with results that have been submitted for peer review.

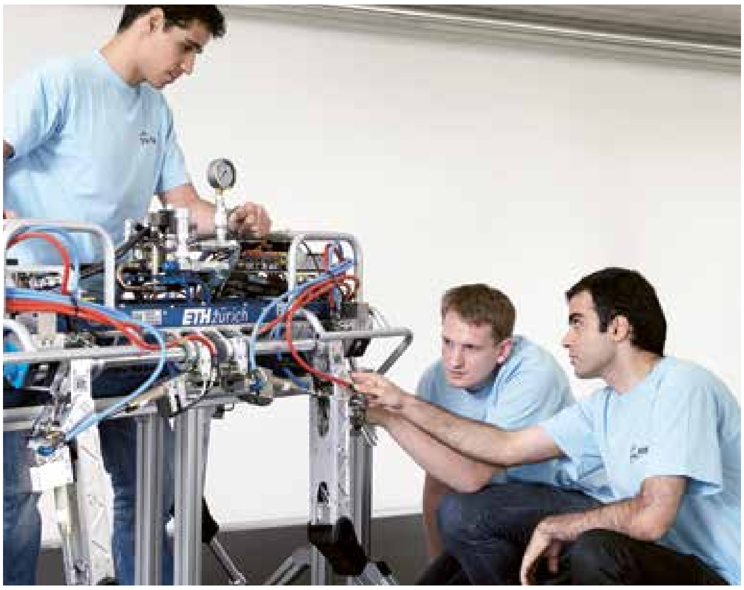

Figure 3: The team discusses the actuator control of the HyQ Robot

Fostering young academics

Prof. Buchli is or has been mentor to five doctoral students (two at USC, graduating in September 2013; three as supervisor at IIT, graduated in April 2013) and three postdocs (two at IIT and one at ETH).

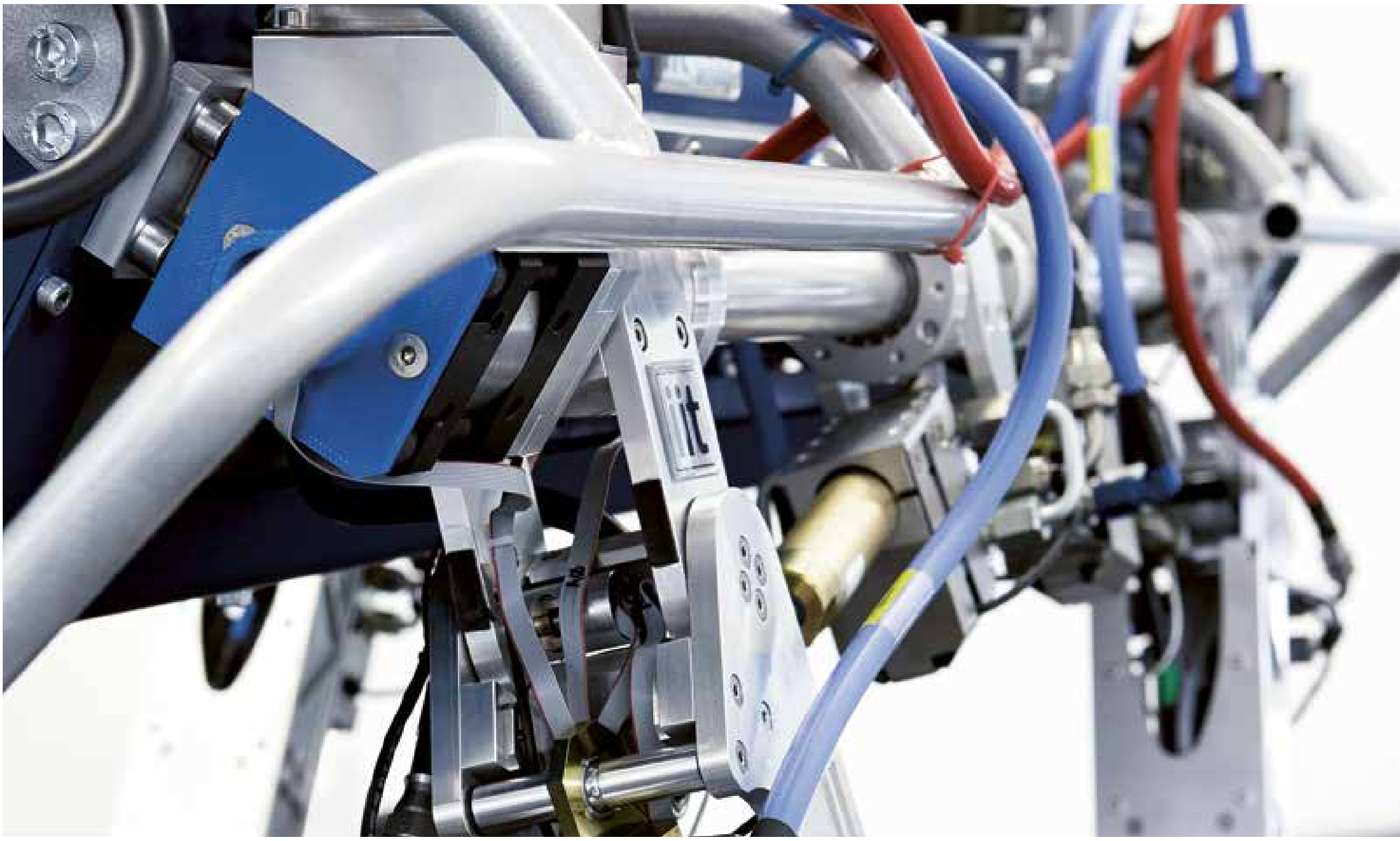

Figure 4: Details of HyQ blue's hydraulic actuation system

Collaborations

Industrial

> Hocoma, Volketswil Switzerland

Academic

> ETH Zurich, D-MAVT, Autonomous Systems Lab, Prof. Dr. Roland Siegwart
> University of Southern California and Max Planck Institute for Intelligent Systems, Prof. Dr. Stefan Schaal
> University of Southern California, Prof. Dr. Francisco Valero-Cuevas
> Italian Institute of Technology, Dept. of Advanced Robotics, Prof. Dr. Darwin Caldwell/Dynamic Legged Systems Group, Dr. Claudio Semini
> Disney Research Zurich
> ETH Zurich, D-ARCH, Chair for Digital Fabrication, Gramazio & Kohler
> George Washington University, Prof. Dr. Evan Drumwright

Key publications

> V. Barasuol, J. Buchli, C. Semini, M. Frigerio, E.R. De Pieri, and D.G. Caldwell, "A Reactive Controller Framework for Quadrupedal Locomotion on Challenging Terrain", IEEE International Conference on Robotics and Automation (ICRA), 2013.
> L. Righetti, J. Buchli, M. Mistry, and S. Schaal, "Inverse dynamics control of legged robot s with optimal distribution of ground reaction forces", Intl. Journal of Robotics Research, 2013, 32(3), pp 280–298.
> J. Buchli, F. Stulp, E. Theodorou, and S. Schaal, "Learning Variable impedance control", Int. J. Robotics Research, 2011, 30(7), pp 820–833.*
> M. Kalakrishnan, J. Buchli, P. Pastor, M. Mistry, and S. Schaal, "Learning, planning, and control for quadruped locomotion over challenging terrain", Int. J. Robotics Research, 2011, 30(2), pp 236–258.*
> E. Theodorou, J. Buchli, and S. Schaal, "A Generalized Path Integral Control Approach to Reinforcement Learning", Journal of Machine Learning Research, 11 (2010), pp 3137–3181.*
> M. Mistry, J. Buchli, and S. Schaal, "Inverse dynamics control of floating base systems", IEEE Int. Conference on Robotics and Automation (ICRA), pp 3406–3412, 2010.*
> J. Buchli, A.J. Ijspeert, "Self-organized adaptive legged locomotion in a compliant quadrupedrobot", Autonomous Robots, Vol. 25(4), pp 331–347, 2009.*
> J. Buchli, L. Righetti, A.J. Ijspeert, "Frequency Analysis with Coupled Nonlinear Oscillators", Physica D, 237(13), pp 1705–1718, 2008.*
> J. Buchli, L. Righetti, and A.J. Ijspeert, "Entrainment and Adaptation in Limit Cycle Systems", Biological Cybernetics, Vol. 95, No. 6, 2006.*
> L. Righetti, J. Buchli, and A.J. Ijspeert, "Dynamic Hebbian learning in adaptive frequencyoscillators", Physica D, 216(2), pp 269–281, 2006.*

* Published before joining the ETH Zurich

Dynamic Systems and Control

Work in Prof. D'Andrea's group is focused on the creation of systems that leverage technological innovations, scientific principles, advanced mathematics, algorithms, and the art of design in unprecedented ways, with an emphasis on advanced motion control. Testbeds include dynamic sculptures, juggling machines, industrial robot arms, and the Flying Machine Arena. Main research areas are the control of distributed systems, control of autonomous systems, and machine learning.

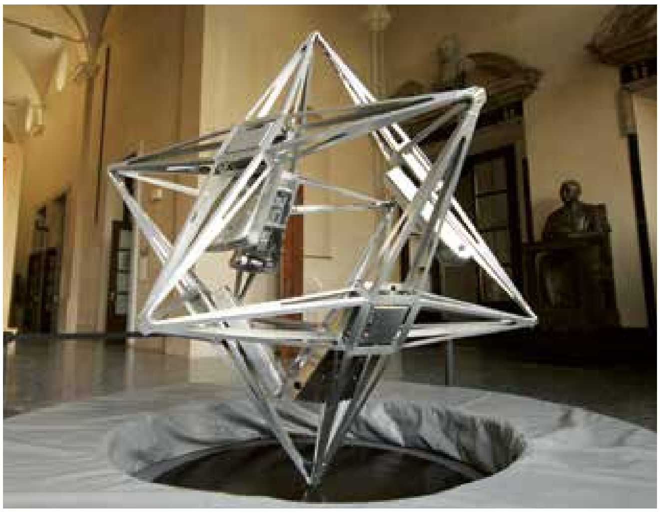

Figure 1: The Balancing Cube is a research testbed used for the development and testing of distributed control algorithms.

Our research relies on the following testbeds:

The **Balancing Cube** (Fig. 1) can balance on any of its edges or corners thanks to a series of six rotating mechanisms located on each face of the cube. The cube is an example of a distributed control system: the problem of balancing the cube is distributed across six independent balancing mechanisms, which coordinate their actions by exchanging data over a shared communication network. One focus of our research is the cost of network communication: since the network is a shared resource across the system and can only be accessed by one balancing unit at a time, the cost of communication must be managed for the system design's overall efficiency. For general distributed and networked control systems, we have developed methods that address the design of a network access strategy ("who talks to whom and when") in tandem with the design of estimation and control algorithms that use network data. With the developed algorithms, data is exchanged between the control units only when required, and the average network load can be reduced significantly as compared to loads in traditional systems that use periodic data transmission.

The **Flying Machine Arena** (Fig. 4) is an experimental platform for research in aerial robotics and autonomous control. Equipped with a state-of-the-art motion capture system, this 10 x 10 x 10 meter airspace can track objects such as flying vehicles at several hundred frames per second with millimeter accuracy. The fleet of quadrocopters used for our research is equipped with custom electronics and onboard sensors to allow for precise vehicle control. The research carried out using this platform aims to develop computationally efficient control algorithms for precise maneuvering during high performance flight. Research topics include fast trajectory generation algorithms, the use of iterative learning methods to improve performance over time, multi-vehicle coordination problems, methods for mid-air failure mitigation, and the interaction of quadrocopters with humans as well as the environment. Furthermore, the testbed is used to evaluate novel aerial robot concepts that aim to reduce mechanical complexity, provide additional degrees of freedom and faster flight dynamics, and reduce the reliance on external localization methods.

The **Juggling Machines**, including the Blind Juggler, the Cloverleaf Blind Juggler (Fig. 2), the Swinging Blind Juggler, and others are robotic devices that keep balls bouncing on one or multiple paddles without using cameras, microphones, or other sensors to determine ball location. Instead, they rely on mathematics-driven design to stabilize ball trajectories. One main topic of research is the use of chaos to control systems that are composed of various subsystems with identical nonlinear dynamics, and which have a shared, common control input. The Cloverleaf Blind Juggler, which juggles multiple balls, is an example of this kind of system.

The **Distributed Flight Array** (Fig. 3) is a flying platform consisting of multiple autonomous single propeller vehicles that are able to drive, dock with their peers, and then fly in a coordinated fashion. Once in flight, the Array hovers for a defined amount of time and then falls back to the ground, only to repeat the cycle in a new configuration. The Distributed Flight Array has rich dynamics and numerous sensing, communication, and processing modalities. One main current research direction is the development of algorithms that exploit information sharing among agents to achieve tasks such as tilt estimation, self-reconfiguration or coordinated flight for vehicles.

The **"Cubli"** (after the Swiss-German diminutive for "cube") is a small cube with a side length of 15 cm that can jump up and balance on its corner using momentum wheels mounted on the inside of three of its faces. Research on the Cubli extends our research on the Balancing Cube to multiple dynamically decoupled systems that communicate via an unreliable wireless network.

A **KUKA Lightweight Robot Arm** was one of four demonstrator testbeds that we used in **RoboEarth**, a European-Commission-funded, pioneering effort to create a World Wide Web for robots. A first research focus is on developing and testing a cloud computing platform that allows robots to outsource computationally heavy tasks (e.g., map building, computing 3D models, grasp planning) to the cloud to create lighter, smarter, low-cost robots. A second research focus is the development of online knowledge bases for robots.

Our new research effort in the area of **Wingsuits** aims to connect in spirit and ambition to the man-on-the-moon-type projects that have so successfully fueled human inventiveness and innovation in the past. Existing wingsuits are purely passive designs. The goal of this long-term research project is to achieve unconstrained human flight using an actuated, self-propelled wingsuit.

Figure 2: Cloverleaf Blind Juggler

Prof. Raffaello D'Andrea

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Spanning academics, business and the arts, Raffaello D'Andrea's career is built on his ability to bridge theory and practice. He is professor of Dynamic Systems and Control at ETH Zurich, where his research redefines what autonomous systems are capable of, and co-founder of Kiva Systems (recently acquired by Amazon), a robotics and logistics company that develops and deploys intelligent automated warehouse systems. He was also the faculty advisor and system architect of the Cornell Robot Soccer Team, four time world champions at the international RoboCup competition. In addition, he is an internationally-exhibited new media artist, best known for the Robotic Chair (Ars Electronica, ARCO, London Art Fair, National Gallery of Canada) and Flight Assembled Architecture (FRAC Centre, France). Other creations and projects include the Flying Machine Arena, the Distributed Flight Array, the Blind Juggler, the Balancing Cube, and RoboEarth.

Highlights and achievements

- Prof. D'Andrea was the recipient of a $1,000,000 United States Presidential Early Career Award for Science and Engineering for his work on "Theoretical and Experimental Advances in the Robust Control of Feedback Systems". This award is the highest honor bestowed by the US government on outstanding scientists and engineers beginning their independent careers.
- He was the faculty advisor and system architect for the Cornell Robot Soccer Team, four-time world champion at the international RoboCup competition in Sweden, Australia, Japan, and Italy, where teams from around the world field squads of fully autonomous soccer-playing robots.
- While on leave from Cornell, from 2003 to 2007, he co-founded Kiva Systems, where he led the systems architecture, robot design, robot navigation and coordination, and control algorithms efforts. Kiva has deployed installations worldwide, including a 1,000+ mobile robot system in the United States. By the time Amazon acquired Kiva in May 2012 for 775M dollars, it was a 300-person company with a long customer list that included Walgreens, Staples, and Saks, with more than 30 warehouses deployed across Europe and North America.

> He is an IEEE Fellow; a recipient of best paper awards from the American Automatic Control Council, the Institute of Electrical and Electronics Engineers, and the International Federation of Automatic Control (IFAC); and has received the National Science Foundation Career Award and several teaching awards in the area of project-based learning.

Goals and future priorities

After being appointed professor at ETH Zurich in 2007, Prof. D'Andrea established a research program that combined his broad interests and cemented his hands-on teaching style. His team engages in cutting edge research by designing and building creative experimental platforms that allow them to explore the fundamental principles of robotics, control, and automation. His creations include the Flying Machine Arena, the Distributed Flight Array, the Balancing Cube, and Blind Juggling Machines. In addition, he is collaborating with scientists, engineers, and wingsuit pilots to create an actively controlled suit that will allow humans to take off and land at will, to gain altitude, even to perch, while preserving the intimacy of wingsuit flight. Playful and creative, each of these projects supports his team's natural instincts to be curious, explore and discover. At the same time, they serve as real experimental platforms for developing new practical technologies.

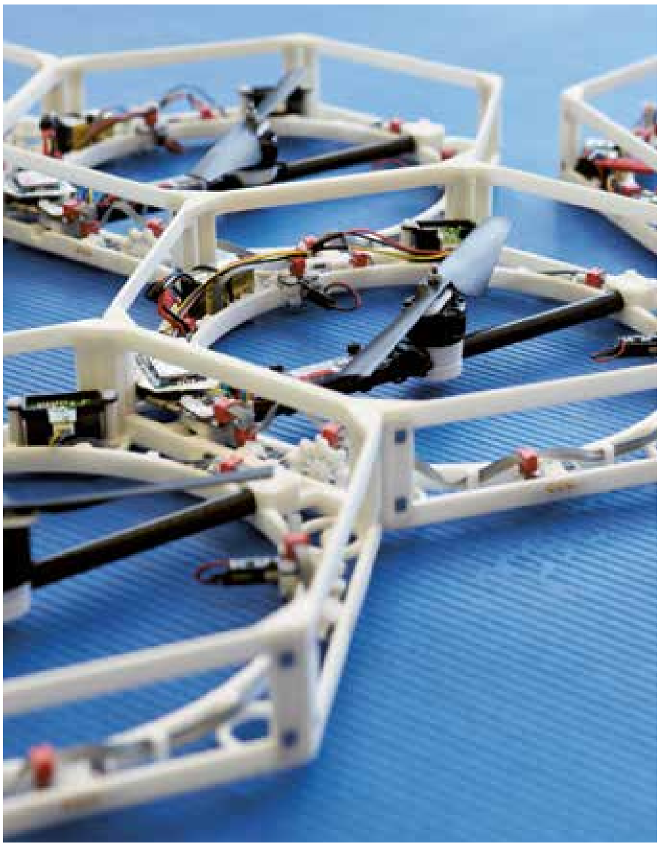

Figure 3: The Distributed Flight Array

Organization of the professorship

Our group is part of the Institute of Dynamic Systems and Control in D-MAVT. We currently have a research staff of ten doctoral students, two postdocs, and one senior researcher. Our research is additionally supported by 20-30 students working on Master, Bachelor, and Semester theses, as well as by 3-4 interns and/or visiting scientists per year. Research activities are further strengthened through focused collaborations such as the installation "Flight Assembled Architecture" (which makes use of current research on flight-enabled construction), or the robotic demonstrations that are part of the RoboEarth project. Dedicated experimental spaces such as the Flying Machine Arena, underpin all our research activities.

The nature of our research, which spans from the development of novel theoretic concepts to their implementation and demonstration on robust hardware testbeds, requires support by trained technical staff. This staff currently includes a mechanical designer, an electrical engineer, a graphic designer, and a mechanical engineer, as well as an administrative assistant, most of whom are engaged part time.

Teaching activity

Next to our research activities, education and teaching are the second main focus of our group. Contributions fall into the following categories:

> Classes: We currently teach three classes at the undergraduate and graduate level, which attract record student numbers (>100) and are highly valued by students (Prof. D'Andrea was awarded the Golden Owl Teaching Prize in 2010).
> Tutoring: Prof. D'Andrea acts as a guide and advisor to more than two dozen Master students per year.
> Master, Bachelor, and Semester theses: Students perform guided research in close, direct collaboration with Ph.D. students as part of 20-30 student projects per year. This model has proven highly successful: many

Fostering young academics

> Angela Schoellig, Ph.D. in 2012, was hired as Assistant Professor at the University of Toronto in 2012 immediately following her Ph.D.
> Sebastian Trimpe, Ph.D. in 2013, was hired as a research scientist in the Autonomous Motion Department at the Max Planck Institute for Intelligent Systems in Tuebingen, Germany.
> Cedric Langbort, Ph.D. in 2005, is currently an associate professor at the University of Illinois at Urbana-Champaign.

Figure 4: Four quadrocopters in the Flying Machine Arena

of the Bachelor and Master students involved in these projects have coauthored papers that have been published in major international conferences and journals. Numerous students have received awards for their Master theses (e.g., ETH-Medaille 2013, Willi Studer Award 2013, Willi Studer Award 2012, Hans-Eggenberger-Prize 2012, Jakob Ackeret Award 2011).

> Ph.D. theses: Ph.D. student education is defined by Prof. D'Andrea's hands-on teaching style. It combines freedom and responsibility to define the students' own educational and research goals and priorities with almost daily interaction with Prof. D'Andrea. Most projects are deeply collaborative and interdisciplinary, an approach that results in opportunities for project-based learning and the creation of strong team players. This style has proven highly successful, resulting in numerous awards (e.g., "Best Interactive Paper Prize", IFAC World Congress 2011, and "Best Paper Award Finalist", IEEE International Conference on Robotics and Automation 2010).

Collaborations

- Technische Universiteit Eindhoven
- Universität Stuttgart
- Universidad de Zaragoza
- Technische Universität München
- ETH Zurich, Profs. Fabio Gramazio and Matthias Kohler

Key publications

- Sergei Lupashin, Angela Schoellig, Michael Sherback, and Raffaello D'Andrea, "A Simple Learning Strategy for High-Speed Quadrocopter Multi-Flips", IEEE International Conference on Robotics and Automation, pp.1642–1648, 2010.
- Raymond Oung and Raffaello D'Andrea, "The Distributed Flight Array", Mechatronics, Volume 21, Issue 6, pp. 908-917, 2011.
- Markus Waibel, Michael Beetz, Javier Civera, Raffaello D'Andrea, et al., "RoboEarth - A World Wide Web for Robots", IEEE Robotics and Automation Magazine, Volume 18, Issue 2, pp. 69–82, 2011.
- Oliver Purwin, and Raffaello D'Andrea, "Performing and Extending Aggressive Maneuvers Using Iterative Learning Control", Robotics and Autonomous Systems, Volume 29, Issue 1, pp. 1–11, 2011.
- Ramu S. Chandra, Cedric Langbort, and Raffaello D'Andrea, "Distributed Control Design with Robustness to Small Time Delays", Systems & Control Letters, Volume 58, Issue 4, pp. 296–303, 2009.
- Peter R. Wurman, Mick Mountz, and Raffaello D'Andrea, "Coordinating Hundreds of Cooperative, Autonomous Vehicles in Warehouses", AI Magazine, Volume 29, Issue 1, pp. 9–19, 2008.
- Matthew G. Earl, and Raffaello D'Andrea, "A Decomposition Approach to Multi-Vehicle Cooperative Control", Robotics and AutonomousSystems, Volume 55, Issue 4, pp. 276–291, 2007
- Oliver Purwin, and Raffaello D'Andrea, "Trajectory Generation and Control for Four Wheeled Omnidirectional Vehicles", Robotics and Autonomous Systems, Volume 54, Issue 1, pp. 13–22, 2006.
- Matthew G. Earl, and Raffaello D'Andrea, "Iterative MILP Methods for Vehicle-Control Problems", Robotics, IEEE Transactions, Volume 21, Issue 6, pp.1158–1167, 2005.
- Cedric Langbort, and Raffaello D'Andrea, "Distributed Control of Spatially Reversible Interconnected Systems with Boundary Conditions", SIAM Journal on Control and Optimization, Volume 44, Issue 1, pp. 1–28, 2005.

Chair of Mechanics and Materials

Our lab is primarily interested in developing a physical understanding of how the constitutive behavior of materials can be controlled in nonlinear, ordered and disordered solid media at length scales ranging from nanometers to meters. We exploit this understanding for the creation of new materials and devices for engineering applications ranging from optomechanics to shock absorption. To achieve these goals, our research takes advantage of the interaction between material properties and structures to create novel systems and new materials with unprecedented global properties.

Wave propagation in granular crystals
We study the dynamic response of materials composed of granular elements (i.e., particles of different shapes) assembled in specific geometrical lattices (i.e., granular crystals). These materials exhibit a highly nonlinear behavior because the contact interaction between the particles is nonlinear. We exploit and manipulate these nonlinearities to control stress waves and shocks as they propagate through the crystals. We research energy trapping, stress redirection and elastic waves dissipation in these systems.

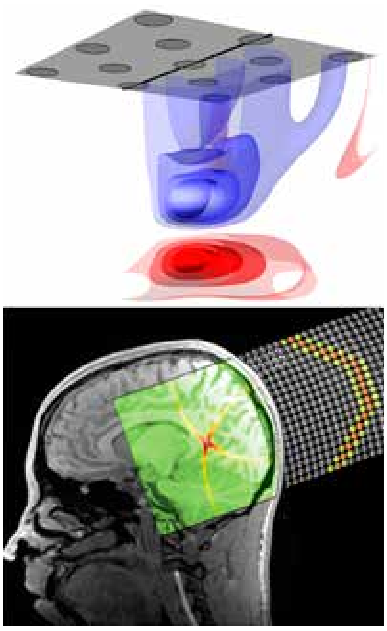

Figure 1: Top: Sound bullet focused in water. Bottom: Potential biomedical application of sound bullets. Image credit: Mike Tyszka, Caltech Imaging Center and MR Physics.

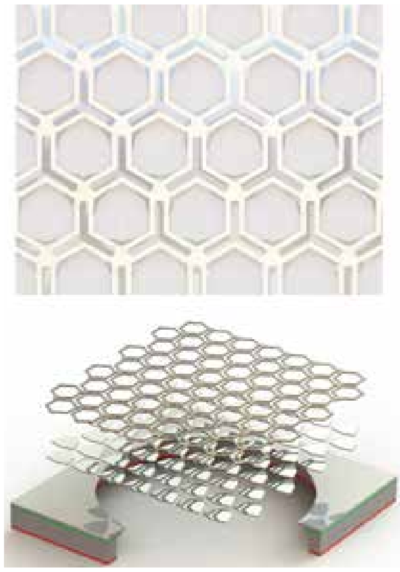

Figure 2: Top: Self-standing thin film with tunable, near-zero coefficient of thermal expansion for application in ultra-stable optical mirrors. Bottom: Schematic of our fabrication approach.

The materials we design, fabricate and test are composite systems in which, typically, basis elements are arranged in well-defined geometries, such that the aggregate system exhibits properties that are not usually found in natural systems and can be exploited in engineering applications. Although our work is primarily experimental, it is informed by numerical and analytical studies, which serve as a guide in the construction of metamaterials and the validation of their properties. Some of our main research activities include:

Micro-/nano-structured materials: high-rate response
We test micro- and nano-structured composites for the design of novel flexible and durable impact protectors, and create materials with unprecedented properties dictated by the choice of individual micro- and nanoscale components. In some of our designs, we take inspiration from hard biological systems. We study these experimentally by testing their dissipation mechanisms, impact absorption, and mechanical properties with quasi-static, impact, and life-cycle fatigue deformation tests. We have also designed

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Professor Daraio received her Laurea degree in Mechanical Engineering from the Universita' di Ancona, (Universita' Politecnica delle Marche), Ancona, Italy (2001). She received her MSc (2003) and Ph.D. degrees (2006) in Materials Science and Engineering from the University of California, San Diego. She joined the Aeronautics and Applied Physics departments at the California Institute of Technology (Caltech) in the fall of 2006, and was promoted to Full Professor in 2010. In January 2013, she joined the Department of Mechanical and Process Engineering at ETH Zurich. She has been a guest researcher at the Lawrence Berkeley National Laboratories (NCEM) and a visiting research physicist at the Scripps Institute of Oceanography in San Diego. She serves on the editorial board of the Journal of Strain Analysis and is a co-founder of two start-up companies.

experimental setups to test the dynamic properties of micro-structured materials, using force measurements coupled with *in-situ* visualization of micro-scale deformations.

Thin films with tunable coefficients of thermal expansion
Motivated by applications in the energy microelectronics and aerospace industries, we develop tunable, thermally stable, mechanically robust, and highly reflective thin film structures. We characterize their mechanical, optical and thermal properties, and compare our findings with theoretical predictions.

Nonlinear acoustics for biological imaging and materials testing
We are developing new systems and acoustic lenses for biological imaging and for evaluating the mechanical properties of hard biological materials. These systems use highly nonlinear acoustic waves as information carriers, and exploit the parameter sensitivity of nonlinear systems. Examples of applications include the evaluation of bone and bone implant material properties, and the detection of defects and stress states in biological materials. We are also designing new actuators and sensors for stress wave generation and detection for use in the monitoring of civil infrastructures and mechanical systems. We expect such sensors to transition to industry as a new spin-off from ETH Zurich in the upcoming months.

Highlights and achievements

Prof. Daraio has established a broad research group that includes experimentalists and theorists who jointly investigate the properties of nonlinear aggregates across scales and use these properties to design nano- and macro-scale metamaterials. Her major accomplishments include the development of novel, tunable acoustic lenses for imaging and diagnostics, the application of which led to the discovery of "sound bullets", and the demonstration of tunable acoustic band-gap materials for vibration insulation, shock mitigation and energy harvesting.
Prof. Daraio's research has been recognized with several awards. She received a Presidential Early Career Award (PECASE) from the White House in 2012, was elected as a Sloan Research Fellow in 2011 and received an ONR (US Office of Naval Research) Young Investigator Award in 2010. She is also a winner of the NSF (US National Science Foundation) CAREER award (2009) and of the Richard Von Mises Prize (2008). Her work is featured in the John F. Kennedy Presidential Library and Museum in Boston and has been highlighted worldwide in scientific news coverage by major channels such as CNN, Scientific American, National Geographic, Discover, Discovery Channel, NPR, London's Telegraph, and Popular Science. She has published over 80 peer-reviewed papers, 2 book chapters and 14 patents.

Figure 3: Granular crystals in 1-D (sphere diameter ~200 microns), 2-D (spheres diameter ~1 cm) and 3-D (spheres diameter ~2 mm).

Goals and future priorities

Bridging the macro- and nanoscale in new materials
One grand challenge in mechanics and material science is the engineering of materials with desired properties from first principles (i.e., obtaining "materials by design"). Our research aims to identify basis units (or "artificial atoms") at different length scales (from nanotubes to the macroscopic granular particles), thereby defining a "potential" of interaction between them that might control, for example, stress propagation. New materials, or devices, can then be assembled from aggregates of these basis units. Extending the analogy with chemical elements, the basis units can be assembled into new materials as "artificial crystals" and "macroscale molecules". This requires an understanding of their properties, constitutive assumptions, and functionalities at different length scales.

The research challenges described above provide our group with a great opportunity to study fundamental physical phenomena and to create new structured materials and improved devices. In the years to come, we plan to continue to contribute to this area of research and hope to have an impact on the engineering of new materials, mechanical structures, and devices for biomedical and acoustic applications.

Teaching activity

Prof. Daraio is committed to teaching and mentoring students. At Caltech, she taught three core graduate and undergraduate courses in the mechanical and aerospace engineering programs: Mechanics of Structures and Solids (graduate course), Mechanics of Materials (junior undergraduate course) and Statics and Dynamics (sophomore undergraduate course). She also introduced two new graduate level courses: Mechanics of Nanomaterials and Linear and Nonlinear Waves in Periodic Media. She has served as a research advisor to more than 40 graduate students and postdoctoral scholars, mentored numerous undergraduate students for short-term research projects and senior theses, and hosted in her laboratories several high-school students as trainees and research assistants. She has served as a judge in science competitions and was active in recruiting and advising women and minority students by participating in activities, panels, and discussions in the Women Mentoring Women program.

At ETH she will teach core undergraduate and Master level courses in mechanics. Prof. Daraio will teach a fundamental mechanics course for civil and mechanical engineering students at ETH (Mechanics II) from spring 2014 with a projected enrollment of ca. 800 students.

Organization of the professorship

Prof. Daraio's group is composed of four post doctoral scholars (one at ETH and three at Caltech), thirteen doctoral students (five at ETH and eight at Caltech), one Master student (at ETH), one visiting student (at ETH), and one undergraduate research assistant (at Caltech). The group is supported by a part-time administrator, a machinist (ETH) and an electronics expert (ETH) supported based on effort. The entire group meets weekly (at ETH and via web-conference with overseas members) to discuss individual research projects and to read relevant literature. Once a year, the group meets for a three-day retreat to discuss academic issues and attend topical workshops. Prof. Daraio meets individually every week with each student and postdoctoral scholar.

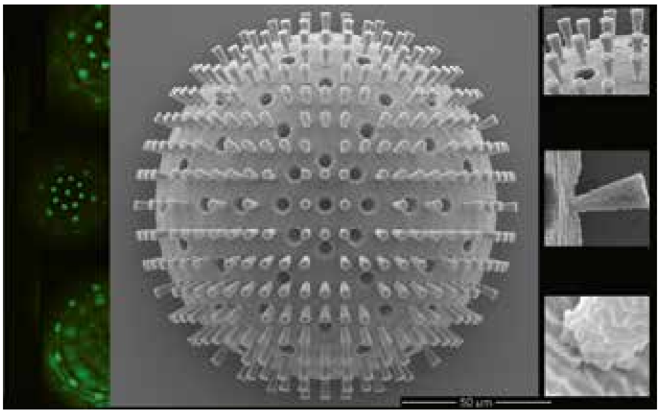

Figure 5: 3D printed antibiotics. (Center) Spherical capsule with guiding pillars and holes to trap bacteria. (Left) Fluorescent microscopy images. (Right) Details of the structure.

Figure 4: The Mechanics and Materials research group at the annual retreat in Rigi

Fostering young academics

Alumni of the Daraio group have moved on to become postdoctoral scholars and assistant professors at renowned universities including: MIT, Oxford University, the University of Washington at Seattle, EPF Lausanne, Penn State University, the University of South Carolina, the French CNRS, the Jet Propulsion Laboratory (NASA), Baylor University (Texas), and the Indian Institute of Science, among others. Several members were awarded competitive prizes and fellowships for their graduate and postdoctoral work.

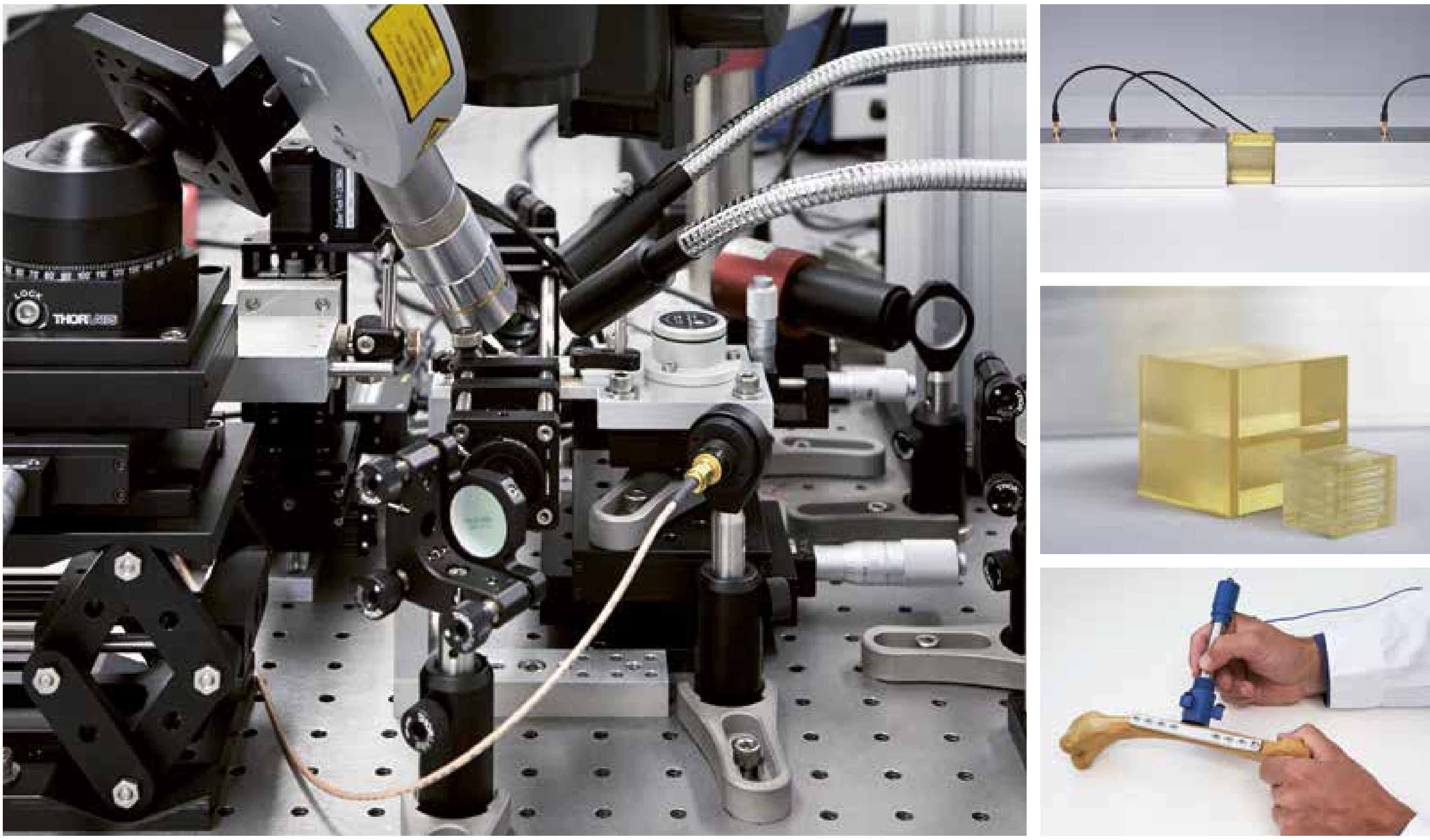

Figure 6: Left: Micro-dynamic experimental setup. Right from top to bottom: Acoustic measurement setup. Material testing device based on nonlinear waves.

She is contributing to the focus specialization in Design, Mechanics and Materials and to the teaching and research activities of the Master specialization in Micro and Nanosystems (MNS). In fall 2013, she teaches a Master level course on Wave Propagation in Solids. She plans to introduce a new course on the Mechanics of Nanomaterials, inspired by her past and current research in the area.

Collaborations

Industrial

Northrop Grumman; Lockheed Martin; United Technology Research Center

In 2008, Prof. Daraio launched a spin-off company emerging from one of her research projects.

Academic

Profs. Y. and P. Kevrekidis (Princeton University and the University of Massachusetts, Amherst); Prof. Porter (Oxford University); Prof. Lambros, Prof. Tortorelli and Prof. Geubelle (UIUC); Prof. Kochmann and Prof. Ravichandran (Caltech); Prof. Yang (University of Washington); Dr. Luigi De Nardo (Politecnico di Milano, Italy).

Her group regularly hosts students for internships and Master theses from the Politecnico di Milano, the Ecole Polytechnique, the University of Salerno and the University of Milan in Italy.

Key publications*

> Bandaru, P.R.; Daraio, C.; Jin, S. and Rao, A.M. "Novel electrical switching behavior and logic in carbon nanotube Y-junctions". Nature Materials, 4, 663–666, 2005.

> Daraio, C.; Nesterenko, V.F.; Herbold, E.; Jin, S. "Tunability of solitary wave properties in one dimensional strongly nonlinear phononic crystals". Physical Review E, 73, 026610, 2006.

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> Spadoni, A.; Daraio, C. "Generation and control of sound bullets with a nonlinear acoustic lens". Proceedings of the National Academy of Sciences, 107, 7230, 2010.

> Fraternali, F.; et al. "Multiphase mass-spring models for carbon nanotubes arrays accounting for strain localization and hysteresis", Journal of the Mechanics and Physics of Solids, 59, 1, 89–102, 2011.

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Laboratory for Mechanics and Experimental Dynamics

Our research focuses on analytical and numerical modeling of mechanical systems and corresponding experiments. We determine the properties (density, viscosity, viscoelasticity) of a fluid by quantifying its interaction with a vibrating system. We also study the vibrational characteristics of water turbines and, at smaller scales and higher frequencies (MHz), we work on modeling and design of devices for ultrasonic particle manipulation. Further areas of research include the study of wave propagation in structures and thin films (nanosonics), as well as time dependent phenomena in snow mechanics.

Figure 1: Large and small viscosity sensors: the vibrational characteristics are changed by a fluid interacting with the vibrating structure

Dynamic viscosity and density sensing

When a vibrating system, such as a tube or rod, is brought in contact with a fluid, the vibrational characteristics of the fluid (resonance frequencies and damping) undergo changes. These changes can be related to the density and viscosity or even viscoelasticity of the fluid by calibration or by modeling. We use resonators that are rod- or tube-shaped (Fig. 1), or, in cases where small quantities of fluid are being investigated, U-shaped (Fig. 2,[1]*). These are excited to a near-resonance state using electromagnetic forces, for example; and are then made part of a gated phase locked loop, such that the vibration is stabilized near the resonance frequency with a resolution of up to 1 in 10'000'000. We then determine damping with a digital measurement, where the resonator is driven at two phase values close to the resonance frequency. Our research can be applied to the measurement of fluid properties in the oil-and-gas and food industries, and also has applications within DNA research.

Ultrasonic particle manipulation

When a high power ultrasound field is generated in a fluid containing particles (bacteria, functionalized beads etc.), these particles experience a force field that is approximately derived from Gorkov's potential. Such fields can be generated in microfluidic systems (Fig. 3, 4, [2]*, [3]*, [5]*, [7]*), which are excited harmonically by piezoelectric transducers at frequencies in the MHz regime. The frequencies are tuned to one of the resonance frequencies of the system, such that a strong standing wave field is obtained. Our research focuses on the modeling of such systems at all scales. The assembly consisting of transducer, fluid cavity etched into a silicon chip, fluid and particles is modeled using COMSOL

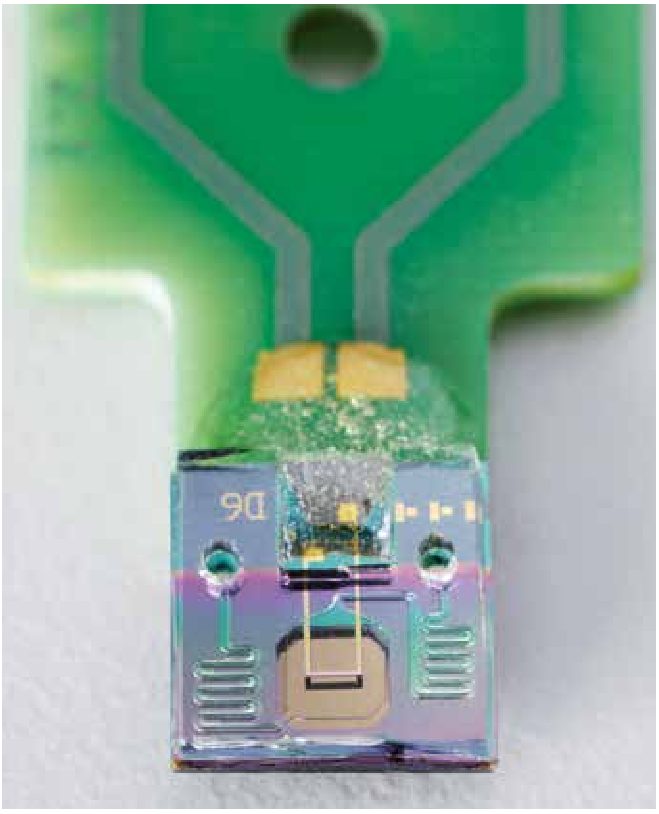

Figure 2: A vibrating U structure is interacting with a fluid in a micro-cavity for very high sensitivity viscosity measurements with small sample volumes

* reference to Key publications

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Jürg Dual (1957) studied mechanical engineering first at ETH Zurich, then with a Fulbright grant at the University of California in Berkeley under Prof. W. Goldsmith. He received his Dr.sc.techn. degree at ETH Zurich with Prof. M. Sayir in Mechanics. In 1989, he was awarded the Latsis Prize at ETH Zurich for his dissertation. After one year as Visiting Assistant Professor at Cornell University in Ithaca, NY, he returned to ETH Zurich as Assistant Professor. Since 1998 he serves as Full Professor of Mechanics and Experimental Dynamics in the Center of Mechanics at ETH. He is a Fellow of the ASME, a member of the Swiss Academy of Technical Sciences, Honorary Member of the German Association for Materials Research and Testing, and a Swiss delegate within International Union of Theoretical and Applied Mechanics. In 2012–2013 he was CEO of the startup Viscoteers GmbH.
He was President of the Planning Commission (2000–2004) and of the University Assembly (2008–2012) at ETH and is President of the Swiss-American Society of Zurich.

multiphysics to obtain the acoustic field. The system's potential landscape can then be computed from the field using Gorkov's potential. Varying frequencies produce time-varying potentials so that patterns of particles in the cavity, such as lines or dots, can be observed. Particles can also be rotated by manipulating the fluid's acoustic radiation torque or viscous torque (Fig. 3). Modeling efforts are underway to determine forces in nonstandard conditions, including systems that involve viscous effects or the effects of nearby boundaries.

Further topics
We investigate time reversal in structural wave propagation to find multiple cracks in structures. Further topics include the experiments and modeling of vibrations in water turbines (Fig. 5) and ultrasonics in the GHz regime using an optical pump probe setup for probing nanostructures and thin films. In collaboration with the Swiss Avalanche Institute, modeling of avalanche release systems is also under way.

Highlights and achievements

> In the area of fluid resonating sensors, we founded a spin-off to develop a sensor for downhole applications for the oil and gas industry. Industry was very enthusiastic of our work and fully supported the project financially.
> Our research contributed to the development of a microscopic viscosity sensor capable of detecting changes in water viscosity of better than 1 %. This research has applications in the area of biomedical analysis.
> In the area of ultrasonic particle manipulation, and in collaboration with our colleagues from USWNet, we contributed to the publication of a series of 23 papers [2]* in the highly-selective Lab on a Chip Journal. We also developed software that allows the computation of acoustic radiation forces and torques for arbitrarily shaped particles. We recently received funding for latest-generation PLD and DRIE systems that will further improve our capabilities in designing ultrasonic particle manipulation systems.
> Using a combination of time reversal and suitable pulse shapes, we were able to detect multiple cracks with high precision in beams by using the dispersive nature of bending waves.
> We are proud that, in teaching basic mechanics, we have kept a high level of teaching quality despite a small number of contributing faculty.

Goals and future priorities

Going forward, we will remain focused on resonating sensors and ultrasonic particle manipulation. These topics both have a strong component of fluid structure interaction, thereby fostering each other.

Most of the fluids that need to be characterized are Nonnewtonian. Therefore viscoelastic properties will be determined using multifrequency control of resonating sensors. We will also investigate the behavior of non-homogeneous fluids (suspensions).

We will continue our modeling efforts in the area of particle manipulation. Gorkov's potential is only valid for ideal compressible fluids, spherical particles and infinite space. We are currently using a newly-acquired high-speed camera and optical trap to investigate methods for calibrating force fields, and are comparing our findings with available theories. We will also pursue quantitative predictions of acoustic streaming. As we take further steps towards applications for our research in the biomedical field, we will expand collaboration with industry and within academia.

* reference to Key publications

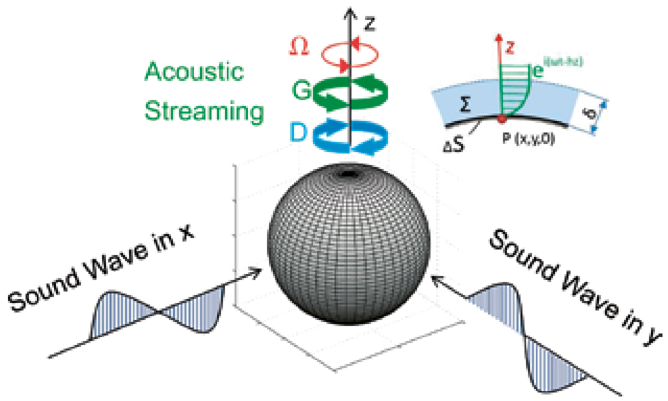

Figure 3: Viscous torque for the rotation of spherical particles

With respect to my teaching responsibilities, I am planning a new course in acoustofluidics, which will be comparable to the summer school course offered on this topic by the International Center for Mechanical Sciences (CISM).

Organization of the professorship

Our group forms part of the Institute of Mechanical Systems. It consists of eleven doctoral students and two postdocs. Experimental work is conducted in dedicated labs, where doctoral students with similar topics work together with common equipment. There are currently six laboratories dedicated to wave propagation, micromanipulation, fluid characterization, nanosonics, biochemistry and water turbines. To facilitate communication and discussion within the major groups, monthly meetings are held with all group members. Wherever possible, infrastructure is also shared with neighboring institutes. Dr. Stefan Blunier runs the CLA part of the Frontiers in Research: Space & Time (FIRST) clean room facility, a shared facility for fabricating microstructures like acoustic manipulation devices. I am also part of the FIRST management team. Within the Institute we share minimal infrastructure consisting of one secretary, one technician and one electronics engineer. Computers are coordinated and administered by Dr. S. Kaufmann, together with a part-time external member of staff. Dr. Kaufmann also helps us to carry the very large load of teaching, along with a group of over 40 student assistants.

Figure 4: A microcavity etched into a silicon wafer is used as a precise chamber for ultrasonic manipulation of particles.

Teaching activity

Over the last eight years, Profs. Glocker, Mazza, and Dual have had a very high teaching load as a result of there being two open positions in mechanics at ETH. My group contributed to the lectures on statics and strength of materials for mechanical and civil engineering, as well as mechanics for electrical engineering and environmental engineering. In these basic lectures, students learn for the first time how to apply mathematical analysis to real physical systems. As there are no entry examinations for new students, their capabilities must first be brought to the high academic standards of ETH. We accomplish this by offering classical lectures and small recitation sections, which are given by excellent senior students.

At the 6th semester Bachelor level, Prof. Dual regularly teaches a class on experimental mechanics for approximately 50 students. Knowledge of basic physics and electrical engineering is applied to the modeling of experiments in mechanics. The students conduct three experiments: phase-locked loop stabilization of resonating structures, nondestructive testing (NDT) using resonant ultrasound transducers, and vibrational analysis using a scanning laser interferometer. At the Master level, Prof. Dual regularly teaches a course on wave propagation in solids, primarily geared toward mechanical and civil engineering students, which covers many aspects of structural and 3D waves.

As an institute, we also offer a tools course in Mathematica, as well as didactic courses for students who are interested in pursuing teaching.

Additionally, together with colleagues at USWNet, we have organized an international summer school at CISM in Udine on the topic of ultrasonic particle manipulation.

Fostering young academics

32 doctoral students and many Bachelor and Master students have graduated from our group.
We have received many prizes, including several R.W.B Stephens Prizes, IUTAM Prizes for Solid Mechanics, Silver Metals at ETH, Georg A. Fischer Prizes, several prizes for Best Paper, as well as the Goldene Schiene. See our website for more detail.
Academic positions for former postdocs and doctoral students include:

> Prof. O. O`Reilly, UC Berkeley; Prof. E. Mazza, ETH; Assoc. Prof. A. Neild, Monash University; Senior Lect. N. Szita, University College of London; Assistant Prof. P. Federolf, University of Calgary.

Figure 5: Test facility for the investigation of fluid structure interaction in water turbines

Collaborations

Industrial

- In the area of macroscopic fluid structure interaction, we collaborate with Andritz Hydro (www.andritz.com), one of the major producers of water turbines, as well as Viscoteers Inc. GmbH, a start up company for the sensing of fluid density and viscosity.

Academic

- In the area of ultrasonic particle manipulation, we actively contribute to the activities of the international USWNet. A yearly workshop in acoustofluidics is held (2008 in Zurich), a summer school was offered to doctoral students in 2010 at CISM and, in 2011–2013, a series of papers on acoustofluidics was published in the high-profile journal Lab on Chip. Our group was responsible for four of the 23 published articles. As members of USWNet, we also act as co-referees for doctoral students of other members, and are currently pursuing a book project. Details can be found at www.uswnet.org.
- On snow and avalanche projects, we collaborate with the Swiss Avalanche Institute (www.slf.ch) located in Davos.
- Further collaborations include projects with IMT Freiburg, Germany, and with various institutes at ETH.

Key publications

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Composite Materials and Adaptive Structures

Our competences span from material science to novel engineering applications, covering (i) design, fabrication and characterization of intelligent material systems, including their integration in active and passive smart structures, (ii) understanding and control of complex impregnation and curing phenomena, and (iii) development of models and more efficient numerical methods to analyze the physical behavior of material and structures and to design optimized composite and adaptive structures.

Figure 1: Semi-active airfoil with variable bending/twist-coupling

Our approach combines experimental techniques with analytical and numerical methods. We are particular interested in problems involving smart handling of vibrations, tunable material properties, aeroelastic morphing, computational structural mechanics and intelligent manufacturing processes.

Smart handling of vibrations: We develop piezoelectric (PZT) transducers for robust damping in the concurrent design of adaptive structures, focusing on adaptive resonant and switching shunt techniques (Delpero et. Al., 2013). More recently, we have introduced a metamaterial that includes tunable stiffness elements. Key elements of this phononic crystal are variable connectivity elements, which are realized by shunted PZT discs, which behave as frequency dependent stiffness links to control wave propagation (Bergamini et. Al., 2014).

Tunable stiffness elements: We have successfully developed and applied Electro-Bonded Laminates (EBLs), which are capacitor-like multilayered devices able to control the shear stress transfer, for damping and morphing purposes (Di Lillo et. Al., 2012). Another successful approach are purely elastic variable stiffness components. Stiffness alteration is obtained by embedding multi-stable composites with integrated PZT actuators in selective compliance structures (Arrieta et. Al., 2013).

Aeroelastic Morphing: Our research in this area exploits compliant elements such as EBL devices for variable bending–twist coupling and multi-stable composites (Raither et. Al., 2013), and concurrently considers design features, actuation, control, fluid-structure interaction and aeroelastic coupling. Our multi-disciplinary optimization tool delivers 3D-wing designs based on measurable physical objective functions (Molinari et. Al. 2011).

Computational structural mechanics: The group is headed by Dr. Kress, who is a senior scientist in my research group. Recent activities include in-depth mechanical modeling and simulation of corrugated laminates (Winkler, Kress, 2013), development of a new design improvement method for complex laminates parts by use of virtual layers (Schläpfer et. Al. 2013), and participation in the second world-wide failure exercise (WWFE-II).

Modeling and Control of composite fabrication processes: We currently focus on modeling bleeding mechanisms in hybrid out-of-autoclave/Liquid Composite Molding (LCM) processes as part of the EU-Project Clean Sky. In cooperation with DOW, we also investigate resin toughening in high Tg-systems, especially particle filtering effects. Recently, we have implemented a fast numerical algorithm that exploits information from a small number of pressure transducers to reconstruct flow front evolution and map spatial permeability distribution (Di Fratta et. Al., 2013).

Highlights and achievements

In the past decade we have continuously increased our international visibility in the synthesis, optimization and fabrication of advanced structures. We have developed and validated multi-disciplinary optimization-based design methodologies

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and successfully applied them to complex problems involving structural design, morphing, and structural damping. We have been particularly successful in developing a number of viable approaches to resolving the conflicting requirements of load-carrying capability and shape adaptation in aeroelastic morphing. We have also taken significant steps towards the implementation of piezoelectric switching shunt techniques in real-world structural applications by introducing robust energy-based design methodologies, improving the efficiency and performance of Synchronized Switching Damping on Inductance shunts (SSDI), and realizing an original encapsulation technique for PZT transducers which enables a significant increase of the design allowables and thus improves the structural efficiency of the whole system.

Over the years we have developed a remarkable network of academic and industry partners. Concerning the latter, 8 doctoral students have been directly financed by industry (Airbus, Alcan, Autoneum, Daimler, Dow) and since 2008, we have participated in four major EU-Projects (Maaximus, Cleansky, Dream, Coalesce) involving European aerospace groups (e.g. Airbus, Dassault, RUAG, Saab, Snecma). Thanks to the Commission for Technology and Innovation (CTI), we have developed successful collaborations with many Swiss Companies (e.g. Acutronic, Busch, EMS-Chemie, Huber & Suhner, Kringlan, SIKA, RUAG, Scobalit, and Suter Racing).

Interaction with industry has been very fruitful, not only in terms of scientific output. We have promoted various initiatives to intensify the exchange between academia and industry, including networks (e.g. SAMPE and the Carbon Composites network), organization of technical workshops, consulting, promotion of industry awards for excellence, and organization/patronage of industry-oriented conferences.

Paolo Ermanni, has been Full Professor of Composite Materials and Adaptive Structures at ETH Zurich since 2003. He studied Mechanical Engineering at ETH Zurich and received his Doctoral degree from ETH in 1990 for his dissertation on novel process technologies for highly-integrated composites in fuselage structures. He spent more than five years at Airbus Germany, Hamburg as a senior engineer and later on, as a project manager. In 1997, he took on a new challenge as Manager in the strategic consulting firm A.T. Kearney, Milan. He was appointed Associate Professor at ETH Zurich in 1998.
Prof. Ermanni has authored 100+ papers in archival journals and supervised hundreds of student theses. He has served on numerous commissions, boards, and review panels including at ETH, DLR, EMPA, TU Munich, Helmholtz-Gemeinschaft, FNR Luxembourg, SCieX, and CCMX. He is currently President of the European Chapter of the Society for Advancement of Material and Process Engineering (SAMPE), Member of the Board of the Network Carbon Composites Schweiz (CC Schweiz), member of the editorial boards of Council of European Aerospace Societies (CEAS) Aeronautical Journal and Composite Science & Technology and member of the International Advisory Board of the Flow Processes in Composite Materials (FPCM) and International Conference on Adaptive Structure and Technologies (ICAST) conferences. Since 2007, he has been Director of the Centro Stefano Franscini and Member of the Admission Commission for the MSc Mechanical Engineering. He is also Member of the Board of Directors at Acutronic Switzerland Ltd. and at Inspire AG.

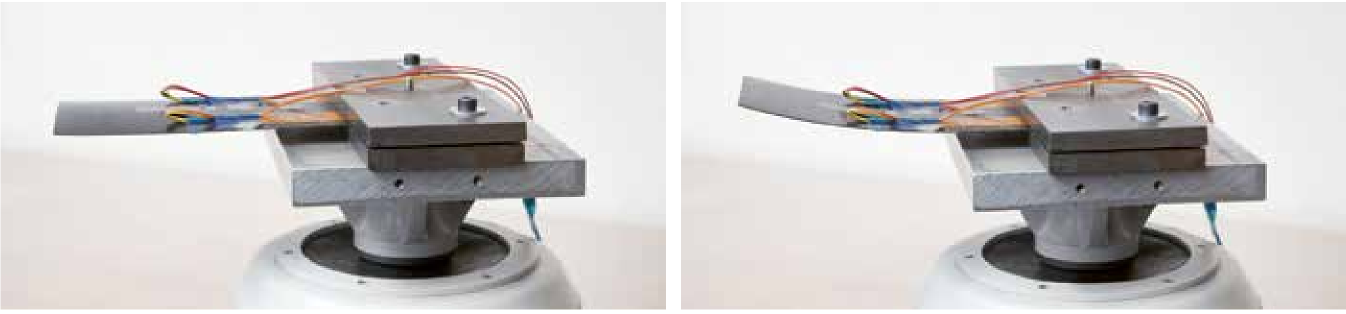


Figure 2: Multi-stable composites with integrate piezo actuators

Goals and future priorities

We have successfully cross-linked our research, teaching, and cooperative activities, establishing a well-balanced portfolio of fundamental and more applied projects in collaboration with industry. We will maintain this in the future. Our research will focus further on passive and semi-active adaptive systems, intelligent fabrication processes and composite mechanics, with the following priorities: (i) integration of variable stiffness in lightweight structures and their use beyond laboratory applications for morphing and vibration control purposes; (ii) multi-stable composites for energy harvesting and aeroelastic morphing; (iii) tunable periodic structures and metamaterials (e.g. for vibration and wave propagation control); (iv) corrugated laminates and other periodic or helical structures; and (v) modeling and control of resin flow in textile structures (e.g. flow front reconstruction, closed-loop control).

One of the institute's main tasks is to coordinate the basic education in engineering design at ETH, ensuring consistency and the flexible pooling of resources between research groups. We will continue to improve our Bachelor and Master programs (focus specialization, focus projects, and Master curricula) by emphasizing both academic education and project-based learning.

Organization of the professorship

Since July 1st, 2013, the Composite Materials and Adaptive Structures Lab has been a member of the newly established Institute of Design, Materials and Fabrication (IDMF). The research group currently comprises: one professor, five senior scientists, 16 research assistants/doctoral students, 39 Master students, one secretary and two technicians.

Teaching activity

Students are strongly integrated in our research activities and industrial collaborations and are closely working together with PhD students. They appreciate our commitment to teaching: In the past 10 years, we have supervised roughly 600 student projects, including more than 120 Bachelor-Theses, 290 Semester-Theses and 190 Master- resp. Diploma Theses.
At Bachelor level we offer 4 courses:

- Dimensionieren (P. Ermanni, B. Weisse)
- Introduction to FEM programs (Tools-course, G. Kress)
- Structural Testing (Tools-course, P. Ermanni)
- Structural Laboratory (P. Ermanni, M. Zogg)

We are involved in the Focus Specialization in Design, Mechanics and Materials, which is a kind of a general Mechanical Engineering Specialization, thus optimally bridging Bachelor and Master Curriculum. Furthermore the Chair is offering exciting focus projects on a regular base: We supervised the successful focus-project CIEO - Human powered vehicle, being also involved in various focus-projects in the past years, such as Suncar and Formula Student.
At Master-level, we provide a comprehensive program on advanced structures and aerospace engineering, which is very popular among the students. Courses combine academic challenges with high application relevance, providing in-depth knowledge and skills in theoretical aspects, computational methods, materials and process technologies to successfully tackle challenging engineering problems. Current offer includes:

- Adaptive Materials for Structural Applications (A. Bergamini)
- Aircraft Structures (P. Ermanni)
- Manufacturing of Polymer Composites (P. Ermanni)
- Mechanics of Composite Materials (G. Kress)
- Polymer Composites Lab (P. Ermanni)
- Structural Analysis with FEM (G. Kress)
- Structural Optimization (G. Kress)

In addition, high-level courses provided by external Lecturers and mentored by Prof. Ermanni have been integrated in the Master curriculum: Engineering Design with Polymers (G. Terrasi), Ropeway Systems (G. Kovacs), fatigue strength of materials, components and structures (R. Koller and M. Guillaume).

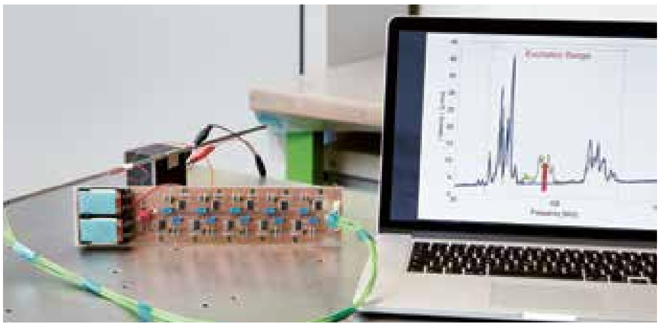


Figure 3: Phononic crystal with adaptive topology

Fostering young academics

Over 190 Diploma and Master students and 36 doctoral students have graduated under my supervision in the past 10 years. We are very proud of the fact that six former doctoral students have successfully transferred innovative concepts developed in our lab to the marketplace. Four spin-off companies have emerged from our research in the past 10 years: Evolutionary Engineering AG (2004), Kringlan Composites (2007), Compliant Concepts (2009) and Monolitix (2012). Some former students have taken up academic positions: one is Professor at HSR Rapperswil, and two have research positions in the UK and France. Andres Arrieta received an ETH-Fellowship and Alexander Hasse an ETH Pioneer Fellowship. The majority of our students go on to take over challenging positions in industry.

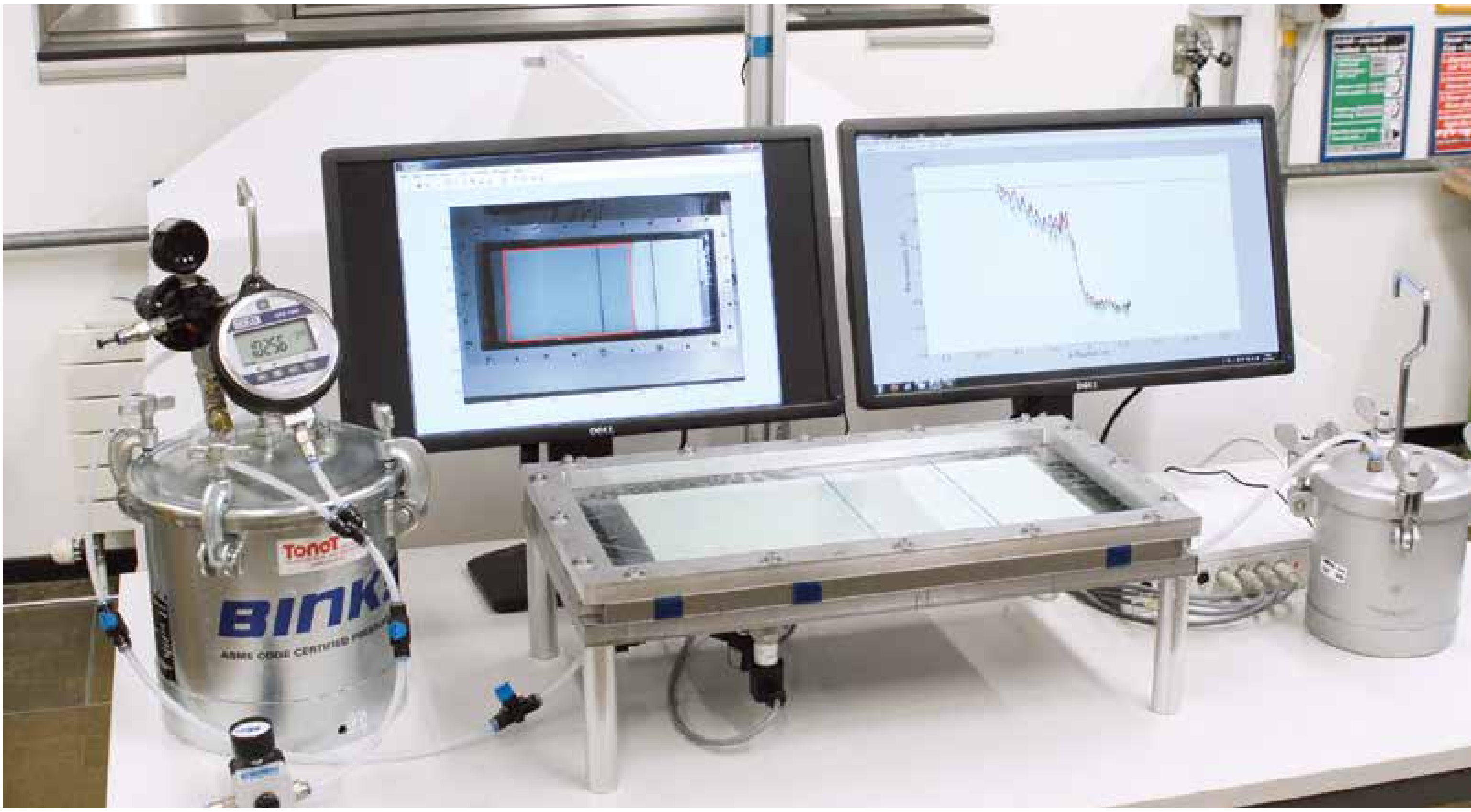
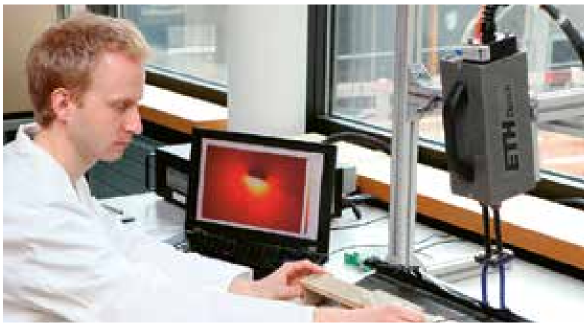


Figure 4: Permeability mapping and flow-front reconstruction experiment

Inspire Innovative Composites Solutions

The group Inspire Innovative Composite Structures (ICS) is bridging our research activities with those of Inspire AG. Inspire AG is a research and development organization at ETH Zurich in the field of production technology. It provides technology and knowledge transfer to industrial partners in close cooperation with various research groups at ETH. In this context, Inspire ICS is the center of competences of Inspire in composite materials, lightweight structures and related fabrication technologies. The group was established in 2008 to foster dissemination of research results and innovation in industry. It currently employs one group leader, one senior scientist and three research co-workers, including one doctoral student. The Inspire team is fully integrated into the teaching program of the Chair.
Actual topics include the design-life enhancement of large load-carrying glass-fiber reinforced structures, the dynamic optimization of high-precision mechatronic systems, innovative damping treatments for stiff structures, novel approached based on the combination of additive manufacturing and continuous fiber reinforced polymers, and original processing routes taking advantage of patched laminates to minimize cut-off in the manufacturing of lightweight structures made of fiber reinforced polymers.



Experimental set-up for adhesive curing by induction heating

Key publications

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Analytical Mechanics and Non-Smooth Dynamics

Analytical mechanics provides both the mathematical and the axiomatic framework for mechanics, while non-smooth dynamics is concerned with time discontinuities in mechanical evolution problems. We combine analytical mechanics and non-smooth dynamics to create a proper environment for non-smooth mechanical theories, which comprise the stages of modeling, mathematical formulation, and numerical schemes. Our key tools are the extended principle of interaction and the principle of virtual work, which naturally lead to the weak equilibrium formulations of the dynamic evolution problems.

Figure 1: Bobsled simulator software in operation

Non-smooth dynamics
Non-smooth modeling elements, their mathematical representation via normal cone inclusions, and their associated inequality solvers are well understood today. Still open is the question of suitable time integration routines, to which we have contributed an extrapolation method with variable step size and order control, and a family of energetically consistent index-2 inequality solvers, both based on normal cone inclusions. The proper formulation of impact laws is another open and still active field of research, which addresses consistent constitutive modeling of frictional collisions and the like. We proposed a general setting for Newton-type and Poisson-type inequality impact laws, by which we were able to resolve a 30-year-old problem, known as Kane's paradox. We also developed a theoretical concept in full generality that addresses the question of energetic consistency for perfect impacts in over-constrained non-autonomous systems.

Continuum mechanics
Over time, our previously rigid bodies became increasingly flexible. The first fundamental example was to formulate the mathematical quaternion constraint as a perfect mechanical constraint. By virtual work principle, this lead to an unconstrained body with seven degrees of freedom that could change its size by scaling up or down. We recognized that, in particular, the concept of constraints is heavily underdeveloped in nonlinear continuum mechanics, but would be needed for a seamless combination with multibody theory. Also, non-smooth mechanics enters this field by the Galerkin approximations through the choice of the spatial shape functions. They might contain discontinuities in some of their derivatives at the connection points and these must be taken into account by (atomic) measures and be represented in the numerical schemes.

Bobsleds
Since the start of the CITIUS project in 2007, we designed an entirely new chassis for the Swiss two-men and four-men sleds from scratch, based on common engineering skills, part-by-part analysis of existing sleds, concept studies, stress and strain analysis via FEM, and tailored numerical studies of the sled dynamics in curved portions of the track. Nine sleds are currently in use by the Swiss team for the World Cup and for the Olympic Games. Most successful in the 2009 World Cup were the two-men CITIUS sleds, which received four out of the eight gold medals, and nearly 50 % of the medals in total. Based on experience gained during the CITIUS project, we developed a bobsled simulator

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Christoph Glocker is currently Full Professor for Mechanics at ETH Zurich. He studied mechanical engineering at the Technische Universität München (TUM). After receiving his diploma in 1989, he worked as a research assistant at the Institute of Mechanics and wrote his doctoral thesis under the guidance of Professor F. Pfeiffer. In 1996 he received a Feodor Lynen Fellowship from the Alexander von Humboldt Foundation and spent one year at the Aristotle University of Thessaloniki working with Professor P.D. Panagiotopoulos on hemivariational inequality problems in dynamics. He then returned in 1997 to the Institute of Mechanics as a senior engineer. In 2001, he obtained the Certificate of Habilitation in Mechanics with his postdoctoral thesis on non-smooth dynamics. In the same year, he became Associate Professor for Mechanics at ETH Zurich, where he was promoted to Full Professor in 2006. Christoph Glocker has been Director of Studies at D-MAVT from 2009 to 2011, during which the revision of the Bachelor Program for Mechanical and Process Engineers took place.

software that in essence consists of an implicit multibody code with non-smooth dynamics elements, such as contact, friction and impact. The code is robust, and is able to process velocities of more than 150 km/h in real-time.

Highlights and achievements

- Variational impact problems: We were able to relate the 1st and 2nd Weierstrass-Erdmann conditions to the weak and strong form of Hamilton's principle for perfect impacts.
- T. Kane's example of an energy increase during a frictional impact: We have explained this 30-year-old paradox by introducing kinematic unilateral constraints to impact theory.
- Poisson impacts: We have proven energetic consistency for one frictional impact contact in a general Lagrangian system.
- Unit quaternions: Through the virtual work approach and the d'Alembert/Lagrange principle, we have formulated the quaternion constraint as a geometric bilateral constraint in order to prevent the body from scaling up or down.
- Nonlinear rod theories: We were able to derive all existing rod theories from the weak form of the virtual work and the d'Alembert/Lagrange principle, and were able to consistently apply any spatial discretization scheme on them.
- For trusses, we have developed a way to directly access the weak continuum formulation by only using the principle of interaction and the virtual work approach.
- We have come to see the stress tensor as a covector-valued 2-form, by which the Cauchy theorem becomes trivial and the symmetry meaningless.
- Bobsleds: We designed, dimensioned and manufactured the new CITIUS bobsled chassis. Nine sleds have been in successful operation since 2009, and are currently being used by the Swiss team for the World Cup and the Olympic Games.
- Bobsled simulator software: We developed a special-purpose non-smooth multibody code that enables real-time simulated piloting on two official tracks at velocities of up to 150 km/h.

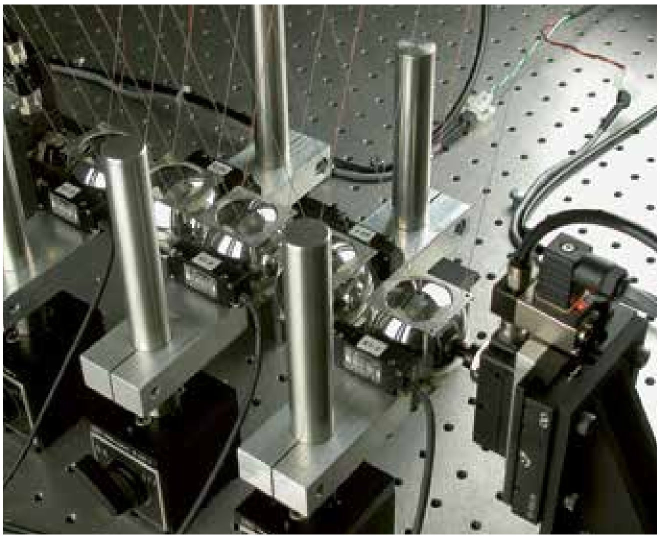

Figure 2: Test setup for Newton's cradle with five balls

Goals and future priorities

Mechanics is the science of forces. A professor has to do research in his area. A professor for mechanics has therefore to do research on forces. No man has ever seen a force. Forces are abstract entities and require as such a proper definition within the field of mechanics. The only way to access forces is to check them out by applying test displacements and to feel the result, which is the virtual work. We are convinced that the virtual work is THE definition of force, at least from the viewpoint of mechanics. We have found several arguments which prove that mechanics can not be done without the concept of virtual work. Maybe, the above is even the main achievement of my academic career.

Our future research will continue to focus on the dynamics of mechanical systems with discontinuities. Going forward, however, this will be done in an extended setting by comprising general combinations of continua together with their discretization in space and time. Beginning with the fundamentals of mechanics, we must develop a method for directly and efficiently accessing the virtual work in its weak form for the entire system; later restrictions caused by the numerical discretization should be accounted for from the very beginning. Most demanding in this context will be the mechanical formulation of plates and shells, and the embedding of non-smooth Galerkin methods in spacetime, which will require the extension of the virtual work to the virtual action.

Organization of the professorship

The Professorship for Analytical Mechanics and Non-Smooth Dynamics is shared with the Titular Professorship of Dr. Remco Leine, and is part of the Center of Mechanics, and its parent, the Institute of Mechanical Systems. Various resources such as office secretary, mechanical and an electrical workshops, lab spaces and computer equipment are shared between the professors of the center, as well as the significant teaching load.

Teaching activity

We are responsible for educating students in dynamics, beginning in the 3rd semester and continuing up to the Master level. Fundamental courses include: “Mechanics 3”, “Technical Dynamics”, “Dynamics of Multibody Systems”, “Dynamics of Structure-Variant Systems”. These lectures are complemented by the courses “Nonlinear Dynamics” and “Rail Vehicle Dynamics”, and a workshop “Simulation in Multibody Dynamics”, in which the students are introduced to commercial software. During their Bachelor and Master theses, students develop their own codes to simulate particular systems from current application problems and research.

We use classical teaching methods. Students must copy the material that is written on the blackboard or on the overhead projector. By intention, no official script is available. Students are thus forced to join the lectures and to concentrate on the material present there. In my opinion, this is still the most efficient way to teach mechanics, as the teaching material is transferred in a condensed and complete form, without overloading the students.

Our philosophy is to offer students an advanced education in classical analytical mechanics, as this continues to be the key to learning multibody dynamics. Particular emphasis is placed on the selection of exercises, many of which are related to practical problems and are designed to make use of standard elements in multibody models. The exercises are intentionally demanding, so that students can feel the limits of analytical approaches. All exercises are complemented by fully documented solutions, sometimes up to 20 pages long. The examples are not solved by special or tricky methods, but always within a well-developed methodical approach. From the start, matrix vector notation is used exclusively, in both the lectures and exercises.

Collaborations

Industrial

- SBB, Bern
- Swiss Sliding, Cham
- Bombardier Transportation, Winterthur
- BMW AG, München
- ThyssenKrupp Presta AG, Eschen
- TRW Automotive, Koblenz
- Siemens VDO Automotive AG, Regensburg
- Suter Racing Technology AG, Turbenthal
- Hilti Entwicklungsgesellschaft, Kaufering
- Hilti Corporation, Schaan
- Porsche AG, Weissach
- TRUMPF Maschinen AG, Baar
- Schindler, Ebikon
- Alstom Power Turbo-Systems, Baden
- Sulzer Pumps, Winterthur
- PROSE AG, Winterthur
- SMR SA, Biel
- maxon motor, Sachseln

Fostering young academics

Promotion of excellent young academics is done on an individual basis by supporting them in every possible way. We feel it is important to provide them with as much academic freedom as possible, and to let them develop their own scientific view within their field.

Figure 3: Assembly of the CITIUS bobsleds in the workshop at ETH Hönggerberg

Academic

> Prof. Bernard Brogliato and Dr. Vincent Acary, INRIA Rhone-Alpes
> Dr. Patrick Ballard, CNRS Marseille
> Prof. John Papastavridis, Georgia Tech
> Prof. Peter Betsch, Karlsruher Institut für Technologie
> Prof. Michael Beitelschmidt, TU Dresden
> Prof. Pierre Alart, Universite Montpellier II
> Prof. Hartmut Bremer, Johannes Kepler Universität Linz

Key publications

> Eugster, S.R.; Glocker, Ch.: Constraints in Structural and Rigid Body Mechanics – A Frictional Contact Problem. Annals of Solid and Structural Mechanics, DOI 10.1007/s12356-013-0032-9, 12 pages, 2013.
> Glocker, Ch.: Energetic Consistency Conditions for Standard Impacts. Part II: Poisson-Type Inequality Impact Laws. Multibody System Dynamics, DOI 10.1007/s11044-013-9387-2, 65 pages, 2013.
> Glocker, Ch.: Energetic Consistency Conditions for Standard Impacts. Part I: Newton-Type Inequality Impact Laws and Kane's Example. Multibody System Dynamics 29 (1), pp. 77–117, 2013.
> Möller, M.; Glocker, Ch.: Rigid Body Dynamics with a Scalable Body, Quaternions and Perfect Constraints. Multibody System Dynamics 27 (4), pp. 437–454, 2012.
> Glocker, Ch.; Cataldi-Spinola, E.; Leine, R.I.: Curve Squealing of Trains: Measurement, Modelling and Simulation. Journal of Sound and Vibration 324 (1–2), pp. 365–386, 2009.
> Studer, Ch.: Numerics of Unilateral Contacts and Friction. Lecture Notes in Applied and Computational Mechanics 47, Springer Verlag, Berlin, Heidelberg 2009, 181 pages.
> Möller, M.; Glocker, Ch.: Non-Smooth Modelling of Electrical Systems using the Flux Approach. Nonlinear Dynamics 50 (1–2), pp. 273–295, 2007.
> Glocker, Ch.: An Introduction to Impacts. In: Nonsmooth Mechanics of Solids. CISM Courses and Lectures Vol. 485 (eds. Haslinger, J.; Stavroulakis, G.), pp. 45–102, Springer Verlag, Wien, New York, 2006.
> Glocker, Ch.; Aeberhard, U.: The Geometry of Newton's Cradle. In: Nonsmooth Mechanics and Analysis: Theoretical and Numerical Advances. AMMA Vol. 12 (eds. Alart, P.; Maisonneuve, O.; Rockafellar, R.T.), pp. 185–194, Springer, 2006.
> Glocker, Ch.: Models of Non-Smooth Switches in Electrical Systems. International Journal of Circuit Theory and Applications 33 (3), pp. 205–234, 2005.

Thermotronics Laboratory

In Prof. Guzzella's lab at the Institute for Dynamic Systems and Control (IDSC), we pursue a model-based approach to the analysis, optimization and control of thermotronic and medical systems. Traditionally, engine systems have been the focus of the majority of our research projects. We are currently working on transfering the methodologies thus derived to building systems and medical devices in order to gain new insights and find opportunities for progress in these areas. Our close contact with academic and industrial partners helps us to remain focused on relevant topics. A well-established testing infrastructure serves to validate our theoretical concepts and methodologies. We also benefit from the inclusion of highly-engaged students in our research process.

Figure 1: High efficiency CNG engine with diesel pilot injection

Our research is focused on model-based control of energy conversion systems, building systems and medical devices. The majority of our doctoral students are working on engine and automotive systems. Topics in this area span from active control of the combustion process over control-oriented modeling of exhaust aftertreatment systems, to energy management for hybrid powertrains. We also pursue the development of new engine systems, such as the pneumatic hybrid engine or the high-efficiency compressed natural gas (CNG) diesel pilot engine.

Research results are published in WoS journals and are specifically optimized and customized to the needs of our industrial partners.

Following the first successful applications of these tools to building systems, we went on to accomplish several interesting projects in this area. Topics ranged from data-mining for efficient solar-system design and the integration of smart-grid systems, to energy management for autarkic buildings. A highlight of our research is the New Monte Rosa Hut, a cabin in the Swiss Alps. Our lab developed the energy management system for this building and contributed to the improvement of its overall design.

Our research on biomedical systems started with a project on the modeling of intracranial and cerebrospinal fluid (CSF) dynamics. A follow-up project called "SmartShunt – The Hydrocephalus Project" was aimed at conducting basic research necessary for the subsequent development of a smart CSF shunt for the treatment of normal pressure hydrocephalus. We extended our engagement with biomedical research with a project aimed at the mechanical support of human blood circulation. With this project, we focused on new control strategies for ventricular assist devices (VADs) and their interaction with the human heart, in collaboration with the University Hospitals of Zurich and Berne. This project has recently received much recognition in connection with the launch of the "Zurich Heart" project, to which IDSC will contribute the control and sensing components. Much of our experience gained working with vehicles, such as our expertise in the area of hardware-in-the-loop simulation, can be transferred to biomedical systems.

Students are a major asset to our lab. Six courses in control are offered at the Bachelor level, which enables students to contribute to our research at this early stage of their studies by way of an internship with a partner company, a Bachelor thesis supervised by one of our doctoral students, or a research assistant position at IDSC.

Highlights and achievements

> 2014 Watt d'Or prize awarded by the Swiss Department of Energy (with Natural Gas Diesel Hybrid Team)

> 2011 1st Prize Regional: Switzerland of the European Satellite Navigation Competition 2011 (with AHEAD team)

> 2011 ETH Medal for Gregor Ochsner's Master thesis "Valve Design and Torque Control of a Hybrid Pneumatic Engine with Camshaft Driven Charge Valves"

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Lino Guzzella has been Full Professor of Thermotronics at ETH Zurich since 1999.
Among other awards, he has received the IEEE-MSC – Industry Award for Excellence in Translational Control Research, the IEEE Control Systems Magazine Outstanding Paper Award, the SAE Arch T. Colwell Merit Award and the Ralph R. Teetor Educational Award, the IMechE Thomas Hawksley Medal and the Crompton Lancaster Medal, the Energy Globe Award and the VSETH Golden Owl 2011 for Excellence in Teaching.
He has published more than 100 research articles in peer refereed journals and conferences as well as one lecture (*Analysis and Synthesis of Single-Input Single-Output Control Systems*, vdf Hochschulverlag AG, 3rd ed., 2011) and two research textbooks (*Introduction to Modeling and Control of IC Engine Systems*, Springer Verlag, 2nd ed. 2010; and *Vehicle Propulsion Systems – Modeling and Optimization*, Springer Verlag, 3rd ed. 2012). He has been a keynote speaker at many conferences worldwide.
Lino Guzzella is a fellow of IFAC and a fellow of IEEE as well as a member of the Swiss Academy of Engineering Sciences (SATW). He is a member of several international and national research committees, e.g. the Swiss CTI Committee on Engineering Sciences and was until recently a member of the Board of Governors of IFAC.
In 2012 Lino Guzzella became Rector of ETH Zurich. Starting on January 1st 2015 Lino Guzzella will be the President of ETH Zurich.

- 2010 Watt d'Or prize awarded by the Swiss Department of Energy (with Phybe team)
- 2010 KPMG Inspiration Grant (with Phybe team)
- 2010 Hans-Eggenberger Prize for Philipp Elbert's Master thesis "Optimal Component Design for Serial Hybrid Electric Buses"
- 2010 ETH Medal for Christian Dönitz's dissertation "Hybrid Pneumatic Engines"
- 2010 Hermann-Appel Prize for Christian Dönitz's dissertation "Hybrid Pneumatic Engines"
- 2010 ETH-Medal for Tobias Ott's Master thesis "Hybrid Pneumatic Engine using Camshaft driven Charge Valves"
- 2009 Premio Pro Ticino di Zurigo for Raffaele Bornatico's Master thesis "Investigation on the Fuel Path Dynamics of a Spark Ignited Engine"
- 2009 Diplomandenpreis of the SEW-EURODRIVE Foundation for Stephan Zentner's Master thesis "Supercharging a Pneumatic Hybrid Engine (Phybe) – Design, Identification and Control"
- 2007 Watt d'Or prize awarded by the Swiss Department of Energy (with PAC-Car team)

Figure 2: Ventricular assist device testbench

Goals and future priorities

As of September 20, 2013, Lino Guzzella has been elected as the next president of ETH. He will begin his new office on January 1, 2015. In this position he will not be able to continue his teaching and research activities at MAVT. Most of his doctoral students will graduate by the end of 2014, and the remaining students will be supervised by Christopher Onder, who will also maintain a minimum teaching and research activity in the propulsion system area.

Figure 3: Exhaust aftertreatment system for a heavy duty vehicle

Organization of the professorship

The group run by Prof. Guzzella is part of the IDSC, and shares technical infrastructure and teaching load with Prof. D'Andrea's group.

Senior researchers and postdocs are fundamental to the operation of the group. Senior researchers usually work part-time, bringing in new ideas and applications from outside the lab; postdocs often manage projects that follow from their own doctoral research. Currently, our senior staff consists of four senior researchers and lecturers and five postdocs. Our administrative staff consists of two part-time assistants who deal with financial and personnel issues, organize travel and manage student administration.

Since we rely heavily on our ability to validate simulations on test-benches, highly-trained technicians are essential to the group. One mechanical and two electrical technicians are responsible for building up test-benches and integrating new measurement devices.

Finally, between 10 and 15 doctoral students form the core of our lab. Approximately half of them are working on engine systems projects, one quarter on building technology and the remaining quarter on medical systems.

All of our activities are supported by students who are hired as teaching and research assistants.

Teaching activity

IDSC is responsible for teaching control in the D-MAVT. Within IDSC Prof. Guzzella's lab is responsible for basic education in control systems. In the third and fourth semester of the Bachelor curriculum, two lectures, "Control Systems I and II", systematically guide the students from a basic understanding of single-input single-output systems to systematic model-based control design methodologies. In the fifth semester, this knowledge is complemented by a "Control Laboratory" where the students receive hands-on experience with real control systems and an introduction to Matlab™. Also in the fifth semester, the course "System Modeling" introduces methods for the control-oriented modeling of complex systems. Learning to set up correct cause-and-effect diagrams for large systems is the primary focus of this lecture. In the sixth semester, the students are introduced to "Digital Control Systems". This course contains a lab where the task is to stabilize an inverted pendulum using a standard hardware and software configuration.
At the Master level, courses are offered for various programs within D-MAVT. In accordance with the major research activities of the professorship, we offer the courses "Engine Systems" and "Vehicle Propulsion Systems". The second one is taught together with Dr. Antonio Sciarretta from IFP Energies Nouvelles, Paris, France. The block course "Embedded Control Systems" is taught together with Prof. Jim Freudenberg of the University of Michigan, Ann Arbor, MI, US.

Education for doctoral students is informal and consists of frequent project presentations for our partners in industry and government, complemented by participation in conference talks.

Collaborations

Industrial

Alpiq, BMW, Boesch, Bombardier, Bosch, BPW, Brusa, Bucher Schörling, Daimler, EV/UP Erdöl-Vereinigung, ewz, Ferrari, Ford, Hess, Hilti, Iveco, KPMG, Kissling, Kistler, Liebherr, MTU, Peugeot, Siemens, swissauto, Toyota, Vela Solaris, VW.

Fostering young academics

Due to the translational nature of our research, many of our doctoral students pursue careers in industry rather than academia after graduating. Examples include: Dr. Elena Cortona, Vice President R&D for Global Top Range Applications at Schindler; Dr. Corrado Nizzola, Department Head Hybrid Research at Daimler; Dr. Thomas Böhme, Group Leader at ABB; and Dr. Olle Sundström, Research Staff Member - Smart-Grid at IBM Zurich Research Laboratory.

Figure 4: Formula hybrid vehicle and powertrain

Academic

Beijing Institute of Technology; Chalmers University; Eindhoven University of Technology; EMPA Dübendorf; IFP Energies Nouvelles, Paris, France; Aerothermochemistry and Combustion Systems Laboratory (LAV), ETH Zurich; Linköpings Universitet; Laboratory of Thermodynamics in Emerging Technologies (LTNT), ETH Zurich; Politecnico di Milano; University of Michigan; Universität Karlsruhe; Université d'Orléans; The Ohio State University.

We have also established an excellent cooperative relationship with the Università di Bologna via visiting doctoral students.

Figure 5: New Monte Rosa Hut
© ETH-Studio Monte Rosa/Tonatiuh Ambrosetti, 2009

Key publications

> Tschanz F. et al., "Feedback control of particulate matter and nitrogen oxide emissions in diesel engines", 2012, IFAC J. of CEP, DOI 0.1016/j.conengprac.2012.09.014
> Voser C. et al., "In-Cylinder Boosting of Turbocharged Spark-Ignited Engines. Part 2: Control and Experimental Verification", 2012, IMechE Part D: J. of Automobile Engineering, Vol. 226, No. 11, pp. 1564–1574
> Ott T. et al., "Cycle-averaged efficiency of hybrid electric vehicles", 2012, IMechE Part D: J. of Automobile Engineering, Vol. 227, No. 1, pp. 78–86
> Ebbesen S. et al., "Battery State-of-Health Perceptive Energy Management for Hybrid Electric Vehicles", 2012, IEEE Trans. on Vehicular Technology, Vol. 61, No. 7, pp. 2893–2900
> Schmid Daners M. et al., "Craniospinal Pressure-Volume Dynamics in Phantom Models", 2012, IEEE Trans. on Biomedical Engineering, Vol. 59, No. 12, pp. 3482–3490
> Bornatico R. et al., "Optimal sizing of a solar thermal building installation using particle swarm optimization", 2012, Energy, Vol. 41, No. 1, pp. 31–37
> Sundström O. et al., "Torque-Assist Hybrid Electric Powertrain Sizing", 2010, IEEE Trans. on CST, Vol. 18, No. 4, pp. 837–849
> Schmidt A. P. et al., "Experiment-driven electrochemical modeling and systematic parameterization for a lithium-ion battery cell", 2010, J. of Power Sources, Vol. 195, No. 15, pp. 5071–5080
> Ambühl D. et al., "Predictive Reference Signal Generator for Hybrid Electric Vehicles", 2009, IEEE Trans. on Vehicular Technology, Vol. 58, No. 9, pp. 4730–4740
> Niederberger A. S. P. et al., "Thermoacoustic Instability Suppression by Gain-Delay and H_∞ Controllers Designed for Secondary Fuel Injection", 2009, IEEE Trans. on Control Systems Technology, Vol. 17, No. 5, pp. 1028–1042
> Boehme T. et al., "Dynamic Model of an Auto-Thermal Gasoline Fuel Processor", 2008, International J. of Hydrogen Energy, Vol. 33, No. 21, pp. 6150–6164

Nonlinear Dynamical Systems

We develop nonlinear dynamical systems methods to solve complex problems in applied science and engineering. We specialize in divising analytical and numerical techniques for problems with nonstandard features: high-dimensional, strongly nonlinear, time-dependent or multi-scale. Such problems are also often defined through spatially and temporally limited data sets, not by equations. Examples include the analysis of transport processes and coherence in the ocean and the atmosphere, real-time detection of aerial turbulence near airports, theory and control of unsteady aerodynamic separation, dynamics of inertial particles under memory effects, and dynamic transition state theory in chemical reaction dynamics.

Unsteady moving continua invariably display coherent structures. While these structures are straightforward to observe, their exact mechanical properties and mathematical description have been elusive. Our group's main focus over the past few years has been to understand, model, extract, and forecast large-scale coherence in natural and technological systems. We have shown that the core patterns of observed coherent flow systems can be analyzed in terms of the repulsion, attraction, or shearing of material surfaces as described by Lagrangian Coherent Structures (LCS). LCSs can be uncovered using sophisticated methods from continuum mechanics, nonlinear dynamical systems theory, variational calculus and differential geometry.

In collaboration with a number of groups, we have used LCS theory to solve several problems of societal importance. With a group of oceanographers at the University of Miami, we have developed a scheme to forecast sudden changes in large-scale environmental pollution patterns, such as oil spills and volcanic ash clouds. Working with atmospheric scientists at the Hong Kong Airport, we have used LCSs to develop a real-time wind shear alert system for commercial aircraft that promises to surpass the efficiency of currently operational algorithms. With other geophysicists from Miami, we have developed a mathematical framework and detection method for super-coherent oceanic eddies. This allows us to quantify the impact of mesoscale ocean vortices on global circulation and climate.

At the same time, we have advanced LCS theory itself to develop a broadly applicable analytical and computational platform for general dynamical systems. This has involved the extension of the theory to three-dimensional unsteady flows, to inertial particle motion, and to partially known data sets. These extensions are now being applied in areas of research beyond fluid dynamics, including celestial mechanics, animal locomotion, chemical reaction dynamics and classic rigid body dynamics with temporally aperiodic forcing. A notable recent advance by our group is the establishment of a direct mathematical analogy between black holes in cosmology and coherent material vortices in turbulence. This result opens the way to an automated topological detection algorithm for coherent Lagrangian vortices in experimental and numerical flow data.

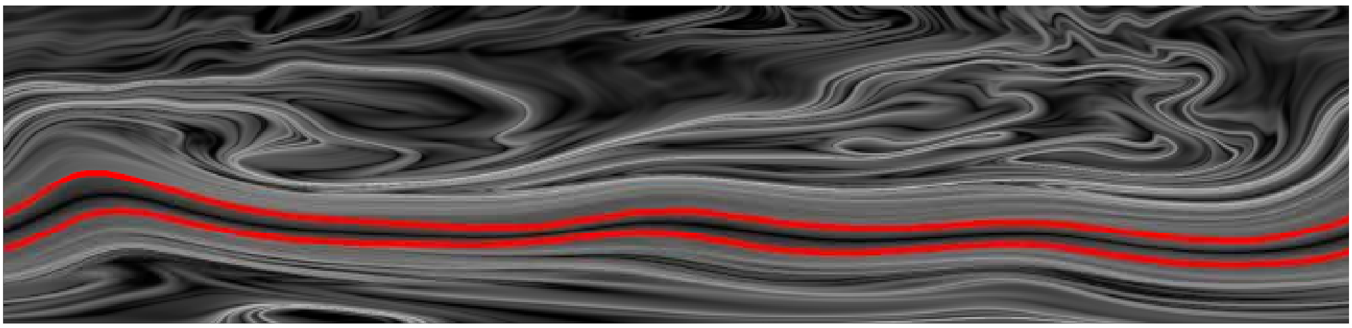

Figure 1: Lagrangian turbulent jet boundaries in the atmosphere (Image: Mohammad Farazmand)

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George Haller received his Ph.D. in Applied Mechanics at the California Institute of Technology in 1993. He then spent a year as postdoc at the Courant Institute of Mathematical Sciences at New York University, prior to joining the Division of Applied Mathematics at Brown University as Assistant Professor in 1994.
In 2001, he left Brown University as Associate Professor to join the Department of Mechanical Engineering at the Massachusetts Institute of Technology, where he became Professor in 2005. While still a professor at MIT, he became the first director of Morgan Stanley's Mathematical Modeling Center in Budapest, which he headed for three years. He then joined the Department of Mechanical Engineering at McGill University in 2009 as Faculty of Engineering Distinguished Professor, serving as Department Chair till 2011. He is currently Professor of Nonlinear Dynamics at ETH Zurich. Professor Haller has served on the editorial boards of the SIAM Journal for Mathematical Analysis, the Journal of Nonlinear Science, and the Journal of Discrete and Continuous Dynamical Systems.

Highlights and achievements

Our group has made the following main contributions over the past two decades:

- We established the field of Lagrangian Coherent Structures (LCS), an active research area currently pursued by a number of groups around the world, which seeks to understand and leverage coherence in unsteady fluid flows.
- We developed and verified the kinematic theory of aerodynamic separation for two- and three-dimensional unsteady flows.
- We developed the Energy-Phase Method, a mathematical technique to detect chaotic behavior caused by resonances in physical systems. We summarized this theory in a monograph entitled Chaos Near Resonance (Springer, 1999).
- Prof. George Haller built up and directed Morgan Stanley's Mathematical Modeling Center in Budapest (2006–2009), heading the development of one of the first dynamic models for mortgage-backed securities following the 2007–2008 credit crunch.

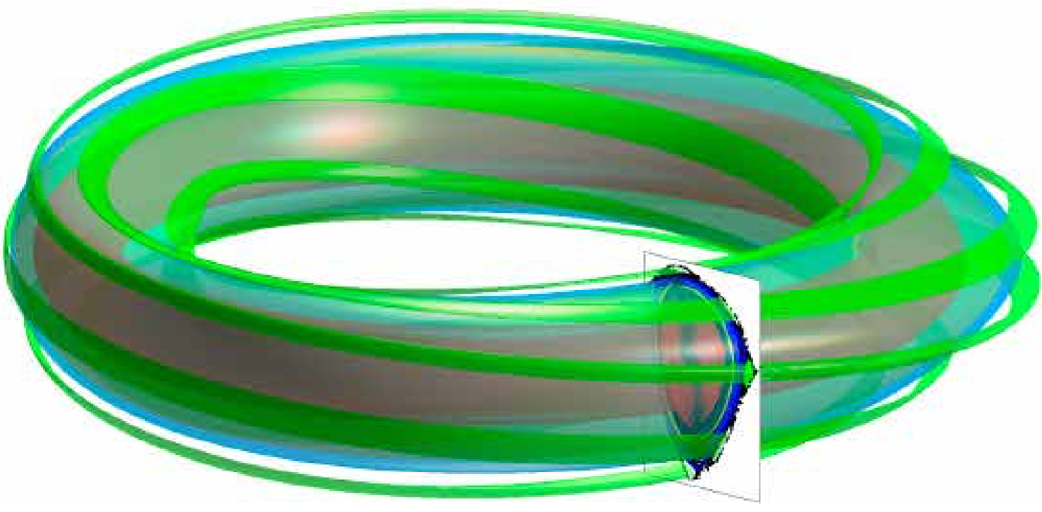

Figure 2: Elliptic Lagrangian transport barriers extracted by LCS methods from a chaotic, three-dimensional flow (Image: Brendan Keith)

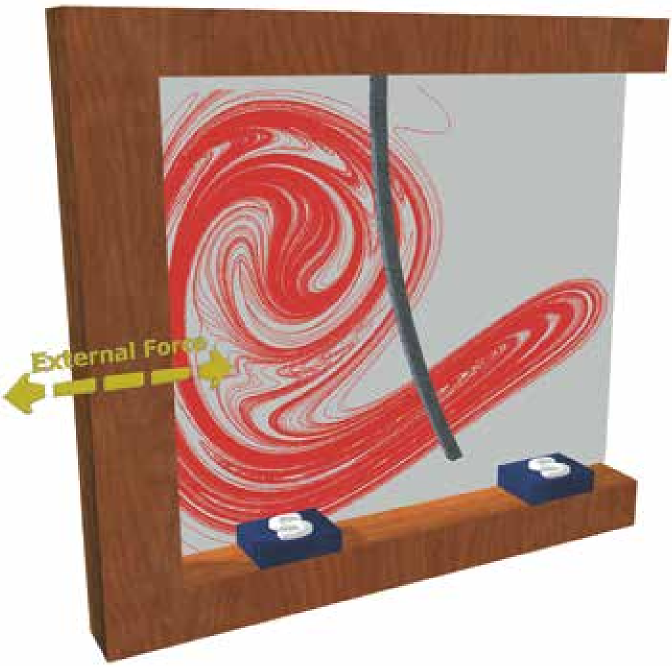

Figure 3: The attractor of a chaotically forced slender beam revealed by coherent structure methods (Image: Alireza Hadjighasem)

Goals and future priorities

Our priorities going forward are to:

> Continue to expand our research group and teaching portfolio at ETH Zurich.
> Actively pursue new research collaborations and funding opportunities in Europe.
> Complete key review articles and monographs on research on coherent structures.

Specific research projects will include:

> Impact of geophysical coherent structures on global circulation and climate change.
> Exploration of planetary turbulence and mixing from available video footage (e.g. footage of Jupiter from the Voyager spacecraft).
> Analysis and forecast of nonlinear dynamics of inertial particles in unsteady fluid flows, with applications to marine-life spread on the ocean surface (e.g., sargassum distribution).
> Development of a time-dependent transition state theory for molecular dynamics applications in physical chemistry.

Organization of the professorship

The Chair in Nonlinear Dynamics currently counts three postdoctoral fellows, five doctoral students, and one administrator among its members.

Teaching activity

The Nonlinear Dynamical Systems Laboratory is committed to education in the general area of Dynamics at all levels.

Core undergraduate courses
We share joint responsibility with Prof. Christoph Glocker's group for teaching Mechanics III (Dynamics) to both mechanical engineering and civil engineering undergraduate students.

Advanced undergraduate courses
We are developing an advanced undergraduate course in the area of Chaotic Dynamics, with an emphasis on applications in mechanical engineering. Prof. Haller has taught a well-received course on Topics in Chaotic Dynamics at Brown University, which will serve as a basis for the development of a similar course at ETH Zurich.

Masters/Ph.D. level courses
We alternate in the teaching of Nonlinear Dynamics I with Prof. Remco Leine. We have also developed a more advanced follow-up course, Nonlinear Dynamics II, offered by our laboratory every other year. Nonlinear Dynamics I introduces graduate students to the modern geometric theory of dynamical systems, with applications selected from various branches of mechanical engineering and applied science. Nonlinear Dynamics II builds on this material and prepares students for Ph.D.-level research specifically in the area of nonlinear dynamical systems.

Fostering young academics

Postdocs and graduate students in the group regularly attend major international conferences and present their work. They perfect their presentation skills in weekly research updates, where they receive detailed and in-depth feedback on their work. All members of the group have powerful computational resources available to them, including one high-end workstation per person, as well as access to the BRUTUS cluster at ETH. This environment ensures that young academics in our group are well-positioned for academic and industrial careers at top institutions, as is demonstrated by the professional achievements of former members of the group. Positions currently held by former group members include tenured faculty positions at Brown University, City University of New York, San Diego State University, University of Central Arkansas, and the University of East Anglia; tenure track faculty positions at Harvard, MIT and UC Berkeley; and a senior research position at United Technologies.

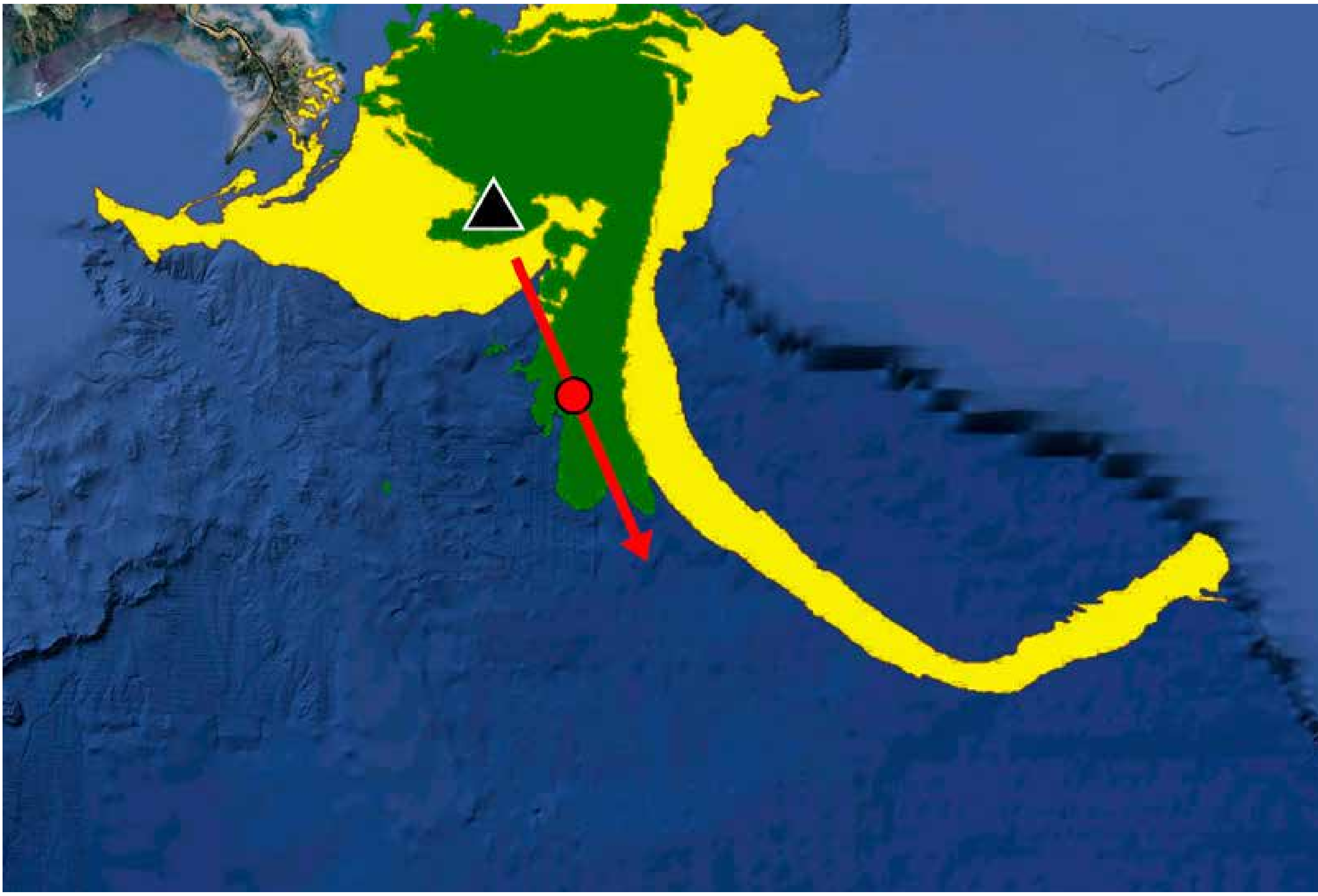

Figure 4: Location and direction of a large-scale instability predicted for the 2010 Gulf of Mexico oil spill (Image: Josefina Olascoaga)

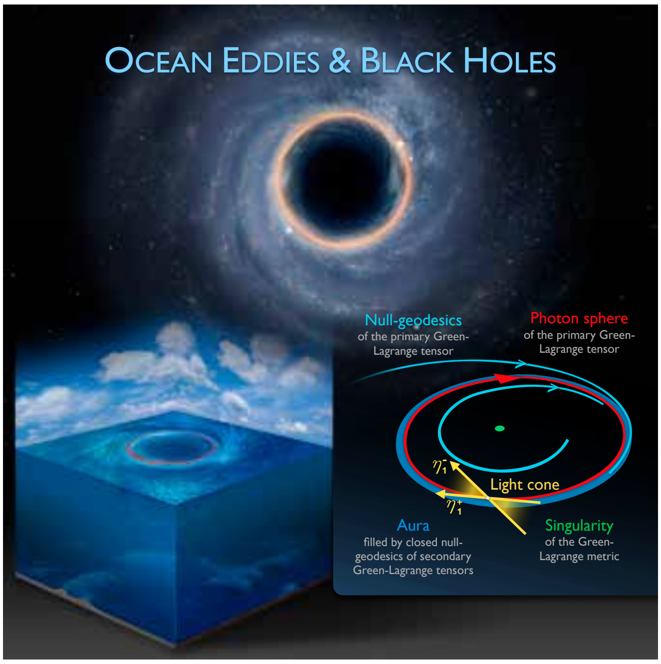

Figure 5: Mathematical analogy between coherent ocean eddies and black holes

Key publications

- F.J. Beron-Vera, Y. Wang, M.J. Olascoaga, J.G. Goni and G. Haller, Objective detection of oceanic eddies and the Agulhas leakage, Journal of Physical Oceanography, 43 (2013) 1426–1438.
- G. Haller & F.J. Beron-Vera, Geodesic theory of transport barriers in two-dimensional flows, Physica D, 241 (2012) 1680–1702.
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Chair of Micro and Nanosystems

Research in the Micro and Nanosystems Group is centered on three related areas: advanced microsystems, new materials for microelectromechanical systems (MEMS), and carbon nanotube sensors. Our projects focus on the exploration of novel fabrication and integration processes for the utilization of specific material properties in functional devices and future products. Our main topics include advanced MEMS and nanoelectricomechanical systems (NEMS) technologies with efforts invested in 3D integration, functional polymers, large-area thermoelectric energy harvesters and carbon nanotube transistors and sensors. In 2009, the ETH spin-off company greenTEG GmbH was founded by former doctoral students from our group.

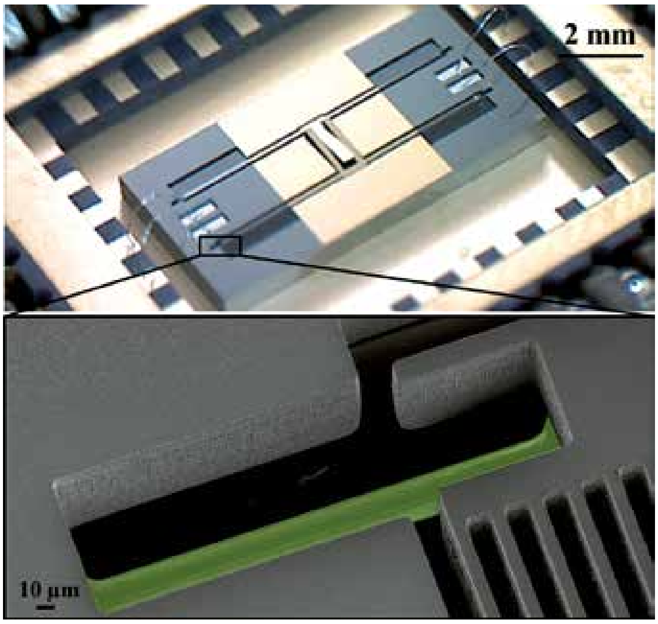

Figure 1: RF MEMS phase shifter (V-, W-band) with soft polymer spring actuator (green false color) DOI 10.1109/JMEMS.2013.2252146

The strategic dimension of the research in the Micro and Nanosystems Group is best described by the phrase "turning material properties into functions". Material integration for new devices with novel and advantageous properties requires integrated process flows, which allow for technology transfer and industrial upscaling for fabrication. In engineering sciences, research related to the exploration of new materials and their respective integration into devices should include aspects of technology transfer and production. For example, reproducibility and cost-efficiency should be factored into the very early stages of research to speed up technology driven innovation cycles.

We apply this approach in our research for the fabrication of thermoelectric materials for energy harvesters (TEG). We started in 2002 with the idea of flexible TEGs based on electroplated thermopiles in polymer molds. Since then, a competitive fabrication process has been developed and commercialized by the ETH spin-off company greenTEG GmbH. Cofounders of the company, who now serve as CEO and COO, are both graduates of ETH Zurich whose doctoral projects were completed within our group. A third doctoral project, soon to be completed, focuses on the optimization of the thermal interfaces for thermoelectric generators (TEGs). Our group includes seven engineers collaborating with greenTEG in funded projects for technology transfer and testing.

Our research on 3D integration of MEMS and drives exploits silicon-based, high aspect ratio MEMS technology for (e.g.) radio frequency (RF) MEMS (Fig. 1). Two doctoral students have already graduated with projects focused in this area, and a third will finish soon. One graduate received an ETH Pioneer Fellow Award to support next steps towards "an active MEMS squeeze-film vacuum gauge".

Five doctoral students have finished their research on functional polymer materials for MEMS. Their projects focused on: material properties, a wireless strain sensor, SU-8 photoresist filled with super-paramagnetic nanoparticles, and conductive biodegradable polymers for resonators. A project in collaboration with the Institute of Robotics and Intelligent Systems on 3D helical structures by planar technology and self-assembly is underway and shows good progress.

Exploratory research on single-wall carbon nanotubes (SWNTs) and novel integration processes (Fig. 2) is the core activity of the group. Our key objectives are the development of ultra-low power sensors for autonomous systems and the further miniaturization of sensors. Six doctoral students successfully graduated with projects on the controlled growth, integration and demonstration of SWNTs and devices for strain, pressure and NO_2 gas sensors. Four of them received ETH awards for outstanding results. Rigorous focus on defect-free tubes and their respective integration is the key to good device performance in our field; this area of research is now the focus of five doctoral projects.

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Christofer Hierold has been Professor of Micro and Nanosystems at ETH Zurich since April 2002. He was Head of the Department of Mechanical and Process Engineering from 2009 until 2011 and now serves as Deputy Head. Furthermore, he has been appointed ETH Zurich's Executive Coordinator of the Binnig and Rohrer Nanotechnology Center (BRNC) at Rüschlikon. Before joining ETH Zurich he worked with Siemens AG, in their Corporate Research branch, and at Infineon Technologies AG, both in Germany. At Siemens, his major areas of research and responsibility were microsystems, advanced CMOS processes and new materials. At Infineon's Wireless Products business group, he was responsible for technology development, intellectual property, and competence management. In 1990 he graduated from Technical University Munich (TUM) with a Dr.-Ing. degree in Engineering Sciences. Prof. Hierold has published more than 190 papers in journals and refereed conference proceedings. He is member of the Swiss Academy of Engineering Sciences (SATW).

Highlights and achievements

Research

- Ultra-clean, SWNT transistors demonstrate the capabilities of SWNTs as functional material for detecting strain and gases. They show excellent performance, repeatability of measurements, ultra-low power capability, and very good sensitivity and resolution with acceptable signal-to-noise ratio.
- The low-cost processing of thermoelectric materials, such as n- and p-type Bi_2Te_3, by electroplating in thin polymer molds allows for the development of efficient energy harvesters and a new generation of heat flux sensors.
- High aspect ratio MEMS and 3D integration prove the feasibility of large-stroke actuators with soft springs for RF MEMS.

Department / ETH Zurich

- Prof. Hierold has been the Head/Deputy Head of the Department of Mechanical and Process Engineering
- Prof. Hierold has been the Founding Coordinator/ Executive Coordinator ETHZ of Binning and Rohrer Nanotechnology Center, Rüschlikon
- greenTEG GmbH was spun off the Micro and Nanosystems Group in 2009

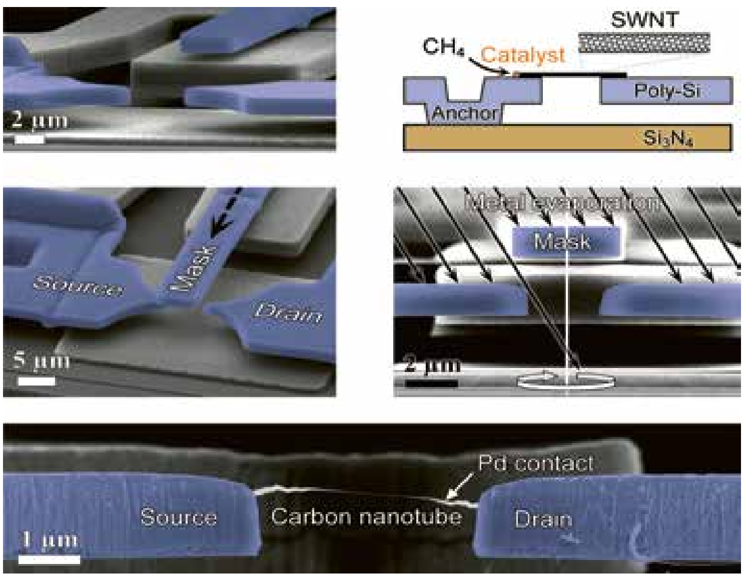

Figure 2: Ultra clean fabrication process for carbon nanotube sensors
DOI 10.1038/NNANO.2010.129-Nature Publishing Group

Academic services

- Editor in Chief of the IEEE Journal of Microelectromechanical Systems
- General Co-Chair of the IEEE International Conference on Micro Electro Mechanical Systems (MEMS 2009)
- Program Chair of
  Transducers 2013 & EUROSENSORS XXVII
- Designated General Chair of Transducers 2019
- Co-Chair of the International Steering Committee of EUROSENSORS

Goals and future priorities

The Micro and Nanosystems Group will continue its strategic focus on the fabrication and integration of new materials for sensors and actuators. Our strategic objective is the early consideration of technology transfer requirements to reduce the transfer cycles for technology driven innovations. This focus is well-aligned with ETH Zurich's and the Department of Mechanical and Process Engineering's (D-MAVT's) strategic initiative, on "Manufacturing across

Scales-from Nano to Macro". Prof. Hierold has been appointed by the president of ETH Zurich to coordinate fund-raising activities for the ETH Foundation to support "Manufacturing across Scales" with donations from industry and private organizations.

We will continue research on the following topics: carbon nanotubes for ultra-low-power sensors, functional polymer materials for microsystems, and the exploitation of MEMS technology for various applications. For example, new collaborative projects will be started on the application of thermoelectric harvesters for portable electroencephalogram (EEG) and electrocardiogram (ECG) systems, and on the development of novel MEMS sensors for the detection of acoustic events in mountain areas, allowing for early warnings of rock avalanches.

Organization of the professorship

The Micro and Nanosystems Group is an independent professorship in D-MAVT. The group structure is centered on doctoral students, who are supported by postdoctoral and senior researchers. The current funds for exploratory research allow the support of 11–12 doctoral students and 4–5 senior researchers. In addition, innovation activities and technology transfer projects in collaboration with greenTEG GmbH support seven engineers and senior scientists. In total, including professor and team assistant, the group counts 25 people. Our research projects are strongly supported by numerous Bachelor and Master students, who pursue projects mainly in collaboration with the doctoral students.

Micro- and nanotechnology research strongly depends on the availability of state-of-the-art processing equipment. ETH Zurich supports our research by way of technology platforms, such as multi-user cleanrooms and laboratories. We use ETH Zurich's cleanroom facilities called FIRST, FIRST-CLA and BRNC (Fig. 3) and the Electron Microscopy Center (EMEZ) for imaging. Prof. Hierold and the group have actively contributed to the definition, operation and management of FIRST, FIRST-CLA and BRNC.

Teaching activity

Undergraduate and graduate student education in micro- and nanosystems is a core activity of the professorship.

We are part of D-MAVT's Bachelor Program (Focus Coordinator Microsystems and Nanotechnology) and Master Program (Micro & Nanosystems and Processes). In addition, Christofer Hierold coordinates the Specialized Master Program in Micro and Nanosystems, which is jointly offered by D-MAVT and the Department of Electrical Engineering (D-ITET). Faculty members for this program, particularly the 16 tutor-professors from mechanical and electrical engineering, physics, physical chemistry and biosystems, are committed to providing a cutting-edge research and teaching environment in which education is linked to their internationally-recognized research. This educational program has been created to address the challenges of an ever-changing industrial and academic environment. The Micro and Nanosystems Group offers or contributes to courses in Microsystems Technology, Devices and Systems (together with Andreas Hierlemann, Department of Biosystems Science and Engineering D-BSSE), Studies on Micro and Nanosystems and a practical course, named Embedded MEMSlab.

Doctoral student education is focused on project work and seminar presentations in the Seminar on Micro and Nanosystems. All doctoral students are encouraged to present their research at highly competitive international conferences: for example, our group had three contributions at MEMS 2013 in Taipei, including one that received an award for outstanding poster paper, and six contributions at Transducers 2013 & EUROSENSORS XXVII in Barcelona.

Collaborations

Industrial

- Siemens, Prof. Max Fleischer[1], Dr. Roland Pohle[1]
- IBM Research
- Colibrys
- greenTEG, Dr. Wulf Glatz[1]
- CSEM

Academic

- Univ. of Cambridge, UK, Profs. John Robertson[1], Stephan Hofmann[1]
- DTU, Denmark, Prof. A. Boisen[1]
- TU Delft, The Netherlands, Prof. Lina Sarro
- Univ. of Colorado, Boulder, US, Profs. Victor Bright[1], Steven George[1]
- Univ. of Michigan, Ann Arbor, US, Prof. Khalil Najafi

Fostering young academics

Four former group members have been appointed as professors: Prof. C. Stampfer, RWTH Aachen; Assoc. Prof. D. Juncker, McGill, Montreal; Assistant Prof. K. Zhang, CU of Hong Kong; Assistant Prof. S. Schmid, DTU Copenhagen.

Six doctoral students have been recognized by ETH awards:

- ETH Silver Medals: C. Stampfer, A. Jungen, S. Schmid, T. Helbling and C. Boutry;
- Georg Fischer Prize: L. Durrer.

Prof. Hierold is Consultant (Vertrauensdozent) of German scholarship students in Switzerland (Studienstiftung der Deutschen Wirtschaft)

[1] Joint publications. The list of collaborations is not exhaustive.

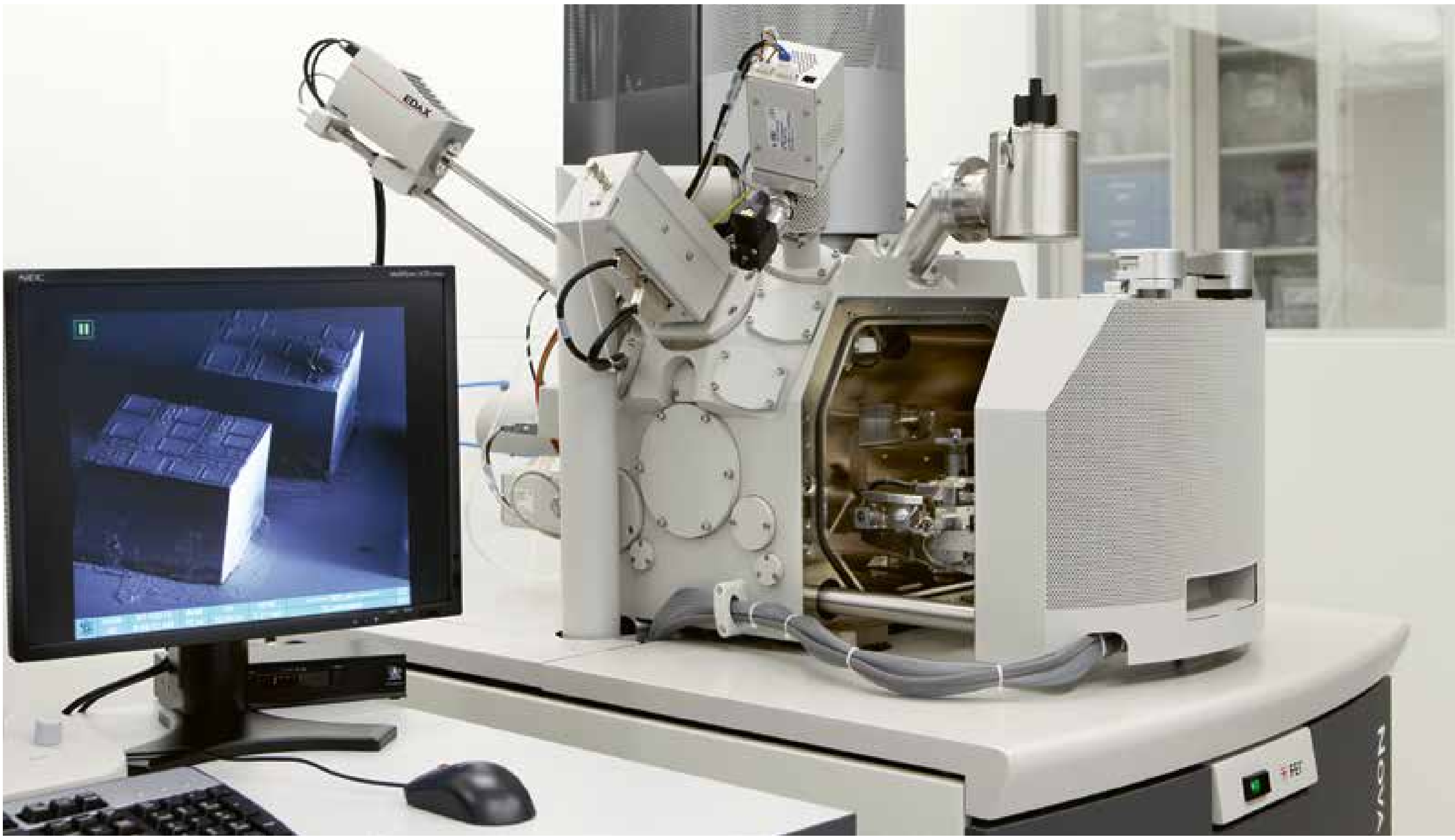

Figure 3: Binnig and Rohrer Nanotechnology Center, Rüschlikon

- Univ. of Kyoto, Japan, Profs. Osamu Tabata, Toshiyuki Tsuchiya
- EMPA, Switzerland, Dr. Urs Sennhauser[1], Dr. Oliver Gröning[1]
- Univ. of Basel, Switzerland, Prof. Marcel Mayor
- EPF Lausanne, Switzerland, Profs. Adrian Ionescu, Nico de Rooij, Laszlo Forro, Maher Kayal
- ETH Zurich, Switzerland, Profs. Klaus Ensslin[1], Elgar Fleisch[1], Christian Hafner[1], Brad Nelson[1], Dimos Poulikakos[1], Sotiris Pratsinis[1], Roland Riek[1], Philipp Rudolf v. Rohr, Wendelin Stark[1], Lothar Thiele, Gerhard Tröster

Figure 4: Binnig and Rohrer Nanotechnology Center, Rüschlikon

Key publications

- C. M. Boutry, et. al., "Towards biodegradable wireless implants", Philosophical Transactions of the Royal Society A-Mathematical Physical and Engineering Sciences, 370, 1967, pp. 2418–2432, May 2012.
- Y. Li, et. al., „A microdevice with large deflection for variable-ratio RF MEMS power divider applications", Journal of Micromechanics and Microengineering, 21, pp. 074013, July 2011.
- M. Muoth, et. al., "Hysteresis-free operation of suspended carbon nanotube transistors", Nature Nanotechnology, July 4, 2010.
- T. Helbling, et. al., "Signal-to-Noise-Ratio in Carbon Nanotube Electromechanical Piezoresistive Sensors", Nano Letters, vol. 10, 9, pp. 3350–3354, September 2010.
- W. Glatz, et. al., "Bi2Te3 Based, Flexible Micro Thermoelectric Generator with Optimized Design", Journal of Microelectromechanical Systems, 18, 3, pp.763–772, 2009.
- M. Mattmann, et. al., "Sub-ppm NO2 Detection by Al2O3 Contact Passivated Carbon Nanotube Field Effect Transistors", Appl. Phys. Lett., Vol.94, Issue 18, pp. 183502, 2009.
- S. Schmid, et. al., "Damping mechanisms of single-clamped and prestressed double-clamped resonant polymer microbeams", Journal of Applied Physics, vol. 104, 9, pp. 093516, 2008.
- L. Durrer, et. al., "SWNT growth by CVD on Ferritin-based iron catalyst nanoparticles towards CNT sensors", Sensors & Actuators B-Chemical, 132, 2, pp. 485–490, 2008.
- C. Hierold et. al., "Nano Electromechanical Sensors based on Carbon Nanotubes", Sensors and Actuators A-Physical, 136, pp. 51–61, 2007.
- C. Stampfer, et. al., "Fabrication of Single-Walled Carbon-Nanotube-Based Pressure Sensors", Nano Letters, Vol. 6, No. 2, pp. 233–237, 2006.

Virtual Manufacturing

The activities of the Institute of Virtual Manufacturing are subdivided into five research areas: Virtual Process Simulation, Digital Material Models, Tribology, Innovative Forming Processes and Adaptive Process Control (Fig. 2). Due to the complexity and diversity of new materials, developments in this area are mainly focused on sophisticated material and failure models, on experiments to determine model parameters, and on numerical simulation tools. Virtual material and process modeling enables the efficient design of materials and forming processes and shortens the time required for product development.

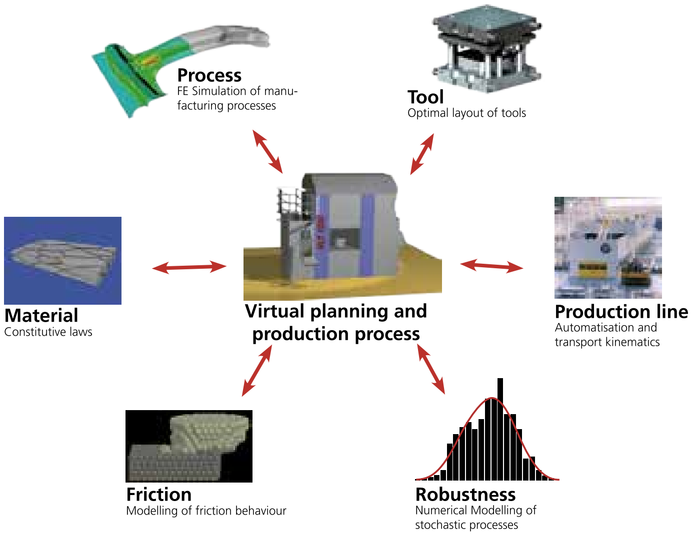

Figure 2: Research areas at the institute

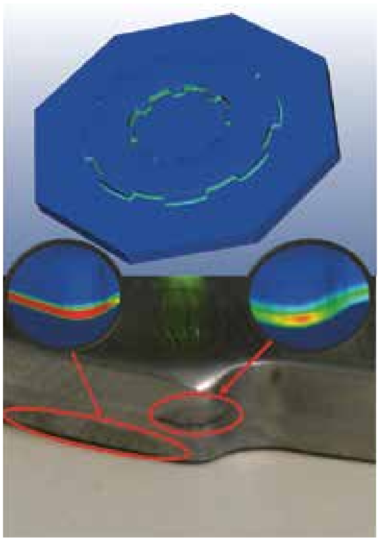

Figure 1: ALE-FE formulation for the accurate failure prediction in fine blanking

The rapid development of numerical models and computer power has enabled the intensive analysis of prominent forming processes, such as deep drawing, as well as of special processes like fine blanking (Figs. 1 and 4), press hardening, forging, and extrusion. Our research, which is supported by industry, the Commission for Technology and Innovation (CTI), and by the EU-Project Manufacturing Error Free Goods at First Time (MEGaFIT), is focused mainly in the following areas:

Failure prediction

The research at IVP is focused on the numerical and experimental determination of failure. Examples of this include the determination of limit diagrams that include strain rate and temperature dependency, failure criteria that depend on hydrostatic stress, and computational damage mechanics (CDM) (CTI-Project: 13082.1 PFIW-IW).

Hardening

IVP's approach to computing stress distribution in multi-step deformation models is to use the finite element method. Examples include springback and residual stress evaluation, description of the cyclic hardening phenomena in bulk and sheet metal forming, and the modeling of temperature-dependent hardening effects like ageing and press hardening. We use material models that are mainly based on the physics of the investigated material, e.g. the evolution of dislocation density and phase transformation phenomena (CTI-Project: 8317.2 PFIW-IW, 8649.1 PFIW-IW).

Anisotropic materials

IVP research includes modeling the anisotropic hardening and anisotropic behavior of material subjected to thermo-mechanical loading, and developing, for example, complex models for the description of the evolution of yield locus and its influence on failure criteria (CTI-Project: 10929.1 PFIW-IW).

Parameter identification

Another area of research for IVP is the development of experimental and numerical methods for determining model parameters such as elasto-plastic material behavior including complex loading histories, and damage and fracture parameters (EU-Project MEGaFIT, CTI-Project: 13082.1 PFIW-IW).

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Pavel Hora has been a Full Professor of Virtual Manufacturing and Forming Technology at ETH Zurich since December 6, 2012. He was an Associate Professor from October 2004 to November 2012. Born on June 6, 1955 in Prague, Prof. Hora studied at the Department of Mechanical Engineering at ETH Zurich, focusing on thermal turbo-machines and fluid dynamics. In 1990 he received his Ph.D. under Prof. J. Reissner in the field of numerical failure modeling. In 1996 he was nominated as a titular professor at ETH Zurich. In 2005, he also became an associate member of the D-MTEC at ETH. While in these positions, Prof. Hora was involved in the development of the Autoform program, which became a leading software product in the field of virtual forming. Before undertaking his Ph.D., Prof. Hora worked with the BBC in the department for technical and scientific computational applications, where he was responsible for furthering the development and application of boundary element methods. He also worked at the MARC Res.Corp. in Palo Alto on different software projects.

Distortion-free measuring techniques
IVP works on the non-destructive measurement of mechanical material properties, and the development of eddy current measurement systems for controlling fluctuations in the mechanical properties of sheet metals. Knowledge of property variations is required in order to predict the robustness of these processes by stochastic simulation methods.

Numerical methods
IVP develops special purpose software, e.g. for the numerical description of fine blanking (CTI-Project: 9144.1 PFIW-IW).

Tribology
IVP also develops numerical and experimental methods for the determination of friction behavior for bulk metal forming, especially for extrusion processes (Fig. 3) (CTI-Project: 12232.1 PFIW-IW).

Highlights and achievements

> 2012: Development and patenting of a method for personal protection from tram accidents, in collaboration with Bombardier.
> 2012: Introduction of localized-level FLD (IDDRG'12)
> 2011: Development of an eddy current system for the non-destructive measurement of mechanical material properties (Diss. Heingärtner J.).
> 2011: Exact description of the stress states around sharp edges based on ALE modeling (Diss. Manopulo N.: ETH-Medal).
> 2008–2011: Virtual modeling of press hardening (Diss. Burkhardt L., Diss. Hochholdinger B.).
> 2011: Development of the so-called "tribo-cone test", a new experimental setup for dealing with friction problems in bulk metal forming.
> 2009: Extension of the Barlat YLD2000 model, which allows the description of anisotropic hardening phenomena.
> 2008: Introduction of a time-dependent FLC evaluation method, which was implemented in ARAMIS, the leading commercial software program in this field (www.gom.com). Furthermore, the G-IDDRG established a working group, which is now in the process of preparing a new ISO-Norm based on the Volk-Hora-Eberle procedure.
> 2005: Active V-Ring was patented by Prof. Hora and the company Feintool Technologie AG.
> 2005: In a procedure proposed and patented by Prof. Hora, a method based on hardness measurements (HV, HB) was extended to enable the evaluation of Rp 0,2.

Goals and future priorities

The goals and priorities of the IVP are to conserve the high quality of our research and education, and to extend the focus of our research into the following areas:

Material and failure modeling
Investigations will be focused especially on multi-scale modeling and on the development of advanced methods for failure modeling in large strains and nonlinear strain paths.

Virtual process control
A new development in forming technology concentrates on the intelligent and adaptive control of manufacturing processes for the MEGaFIT project. Based on virtually identified metamodels, IVP will develop new methodologies for controlling on-line process parameters for this project.

Outstanding international reputation

IVP is one of the best-known institutes for forming technologies worldwide. Our reputation was founded initially on the development of the AutoForm software program and has been maintained since then thanks to a number of innovative breakthroughs. We organize the Forming Technology Forum (FTF) conferences, which are established as high-level meetings where the best researchers in this field can come together and exchange knowledge. We also organized Numisheet '08 and IDDRG '13, leading international conferences on sheet-metal forming. Prof. Hora is also member of scientific and steering committees of various conferences as well as member of the editorial board of the International Journal of Material Forming.

Developing Switzerland's international technology transfer network

Thanks to its international network, the IVP is able to open doors for Swiss small- and medium-size enterprises (SMEs) and assist their development across many fields.

Top education

The IVP has an internationally recognized reputation for educating students in the field of virtual process modeling for forming processes. Our students have been offered positions at leading companies such as AUDI, BMW, and Daimler directly upon graduation.

Organization of the professorship

Our research is focused mainly on virtual process planning and optimization, mathematical material modeling and failure predictions, and processes for the virtual modeling of manufacturing behavior, particularly with regard to the evaluation of process robustness. The staff at the institute is made up primarily of the following:

> One professor, who serves as head of the institute
> Postdoctoral researchers, including senior scientists
> Doctoral students
> Administrative and technical staff

Postdocs are mainly responsible for preparing project proposals, organizing conferences, supervising doctoral students, as well as research and education. Technicians support the research by preparing and performing experiments. The major part of our research work is financed by CTI-Projects. A considerable part of our research and development work is financed by several industrial partners and by the EU-Project, MEGaFIT.

Teaching activity

The aim of the institute is to promote integrated thinking. We enable our students to combine scientific methods with engineering tools in order to synthesize new ideas and innovative solutions. Interdisciplinary knowledge is of crucial importance in current research. Our lectures therefore provide an introduction to machine elements, virtual modeling of complex material behavior, virtual forming processes, numerical methods, optimization and robustness analysis. The numerical modeling of materials and the development of forming processes are multidisciplinary research fields that draw from disciplines such as continuum mechanics, applied mathematics, material sciences and applied computer sciences. Thus, we offer the following lectures and courses:

> Forming Technology I (Basic Knowledge) (BSc)
> Forming Technology II (Introduction Virtual Process Modeling) (BSc)
> Forming Technology III (Forming Processes) (BSc)
> Product Design I - Machine Elements (BSc)
> Engineering Tool IV/V: Digital Automotive Plant Simulation Methods (BSc)
> Chassis and Aerodynamics of a Formula Student Electric Car (BSc)
> Vehicle Simulation and Suspension of a Formula Student Electric Car (BSc)
> Power Train of a Formula Student Electric Car (BSc)
> Virtual Process Control in Forming Manufacturing Systems (MSc)
> Principles of Nonlinear Finite-Element-Methods (MSc and Ph.D.)
> Principles of FEM-Based Optimization and Robustness Analysis (MSc and Ph.D.)
> Computational Methods in Micro- and Nano-Structures (MSc and Ph.D.)

Fostering young academics

After graduating, the majority of IVP`s doctoral students are employed in industry, often taking leading roles at the companies that hire them. Other students seek careers as academics or entrepreneurs.
Graduates employed in industry or industry competence centers include Lukas Burkhardt (2008), Jürg Krauer (2010), Alexandre Mutrux (2011), Jörg Heingärtner (2011), Raphael Hitz (2012), Christoph Annen (2012), and Silke Wagner (2012). In 2012, Bernd Hochholdinger launched an ETH spin-off; graduates aspiring for an academic career include Bekim Berisha (Habilitation at ETH Zurich since 2012) and Niko Manopulo (ETH Medal 2011).

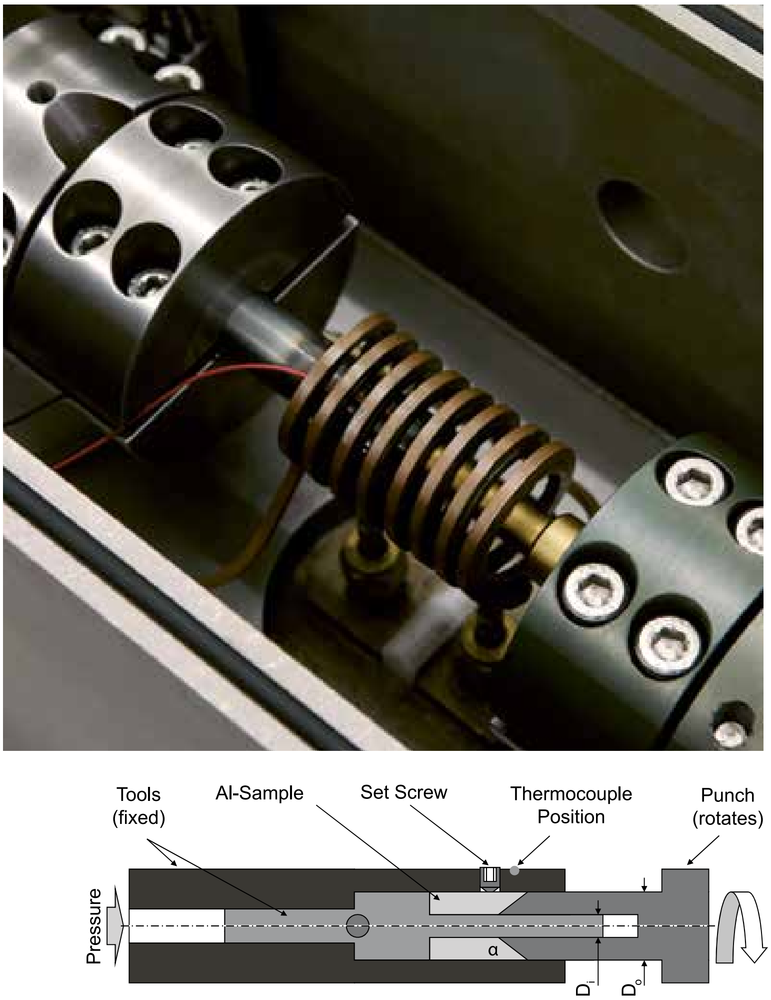

Figure 3: New experimental Tribo-Torsion-Test for the detection of frictional behavior

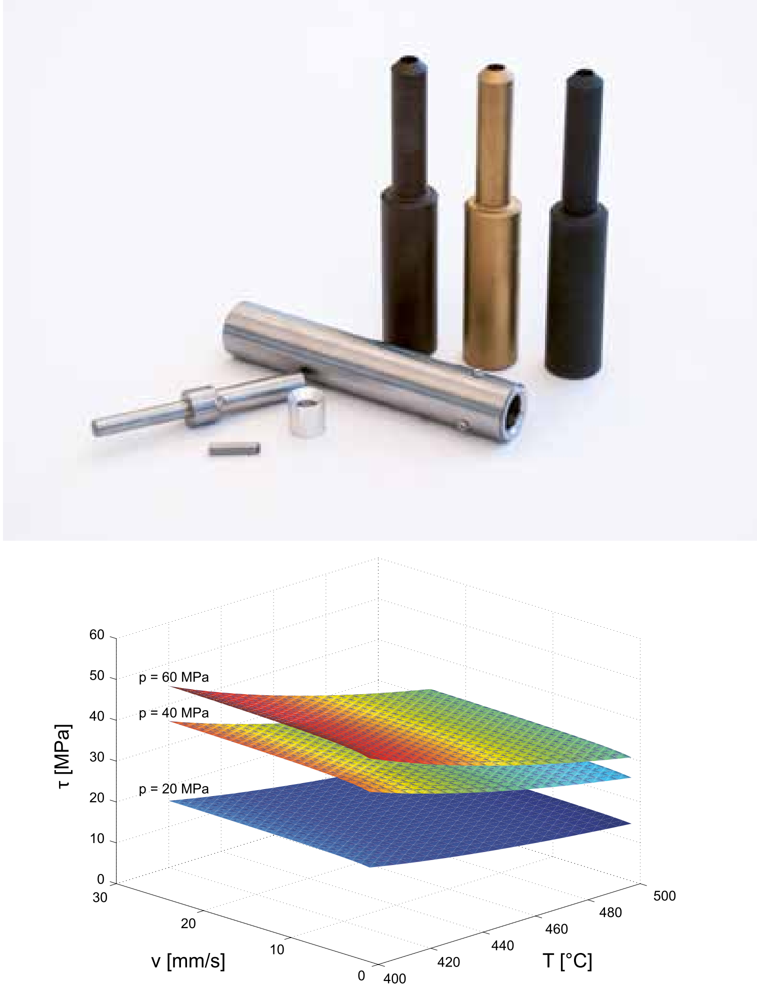

Figure 4: Experimental Tribo-Torsion-Test samples and CVD coated specimen (top); influence of pressure, temperature and velocity on frictional shear stress (aluminum/coating contact)

Collaborations

Industrial

> Audi AG; Daimler AG; BMW AG; AutoForm GmbH; Feintool Technologie AG; Synthes Raron GmbH; Steeltec AG; Suisse Technology Partners; Keiper GmbH; WEFA Swiss AG; Novelis Switzerland SA; GOM International AG; Franke Technology and Trademark Ltd.; Sauber F1 Team, Sauber Motorsport AG; Kistler Instrumente AG; Bombardier Transportation (Switzerland) AG; Voest-Alpine Stahl GmbH; AdvalTech AG; RUAG Schweiz AG; Hilti AG; Hoffmann; Alupack; ESI Group; MSC-MARC; Philips Consumer Lifestyle.

Academic

> University of Twente, Prof. T. van den Boogaard; Universität Stuttgart, Institut für Umformtechnik IFU, Prof. M. Liewald; Technische Universität München, UTG, Prof. W. Volk; TU-Berlin, SPZ-Berlin, Dr. S. Müller; Pohang University of Science and Technology, Prof. F. Barlat; Ohio University, Prof. R. Wagoner; Hiroshima University, Prof. F. Yoshida; Paul Scherrer Institute (PSI), Prof. H. Van Swygenhoven; Ecole des Mines de Paris, Prof. E. Massoni; Shanghai Jiao Tong University, Prof. Xueyu Ruan.

Key publications

> Hora et al. 2012: Numerical and experimental methods for the prediction of failure in sheet metal forming, FTF 2012, 1–10

> Hora et al. 2011: Modified maximum force criterion, a model for the theoretical prediction of forming limit curves, Int J of Mat Form, DOI: 10.1007/s12289-011-1084-1

> Mutrux et al. 2011: Prediction of cyclic softening in a medium carbon steel during cross roll straightening, J of Mat Proc Techn, 211(8):1448–1456

> Han et al. 2011: Numerical studies of flow-induced defects in aluminum ingot die casting process, Adv Mat Res, 239: 825–828

> Krauer and Hora 2011: Enhanced material models for the process design of the temperature dependent forming behavior of metastable steels, Int J of Mat Form, DOI 10.1007/s12289-011-1057-4

> Volk and Hora 2011: New algorithm for a robust user-independent evaluation of beginning instability for the experimental FLC determination, Int J of Mat Form, 4(3): 339–346

> Hora et al. 2010: Damage dependent stress limit model for failure prediction in bulk forming processes, Int J of Mat Form, 4(3): 329–337

> Berisha et al. 2010: A combined isotropic-kinematic hardening model for the simulation of warm forming and subsequent loading at room temperature, Int J of Plast, 26(1): 126–140

> Manopulo et al. 2010: A Dual-Mesh Strategy for the 3D Simulation of Fineblanking Processes, Int J of Mat Form, 2(1): 589–592

> Hora and Vanini 2006: Is the tensile test sufficient? Influence of the yield curve extrapolation on the accuracy of the failure prediction, FLC 2006-Zurich, 64–68

Bio-Inspired Robotics Laboratory

The research interests of the Bio-Inspired Robotics Lab lie at the intersection of robotics and biology. Through abstraction of the design principles of biological systems, we focus on developing the following core competencies: the design and control of dynamic mechatronics systems, bionic sensor technologies, and computational optimization techniques. Our main goals are to contribute to a deeper understanding of the adaptivity and autonomy of animals through the investigation of dynamic robots, and to engineer novel robotic applications which are increasingly adaptive, resilient, and energy efficient.

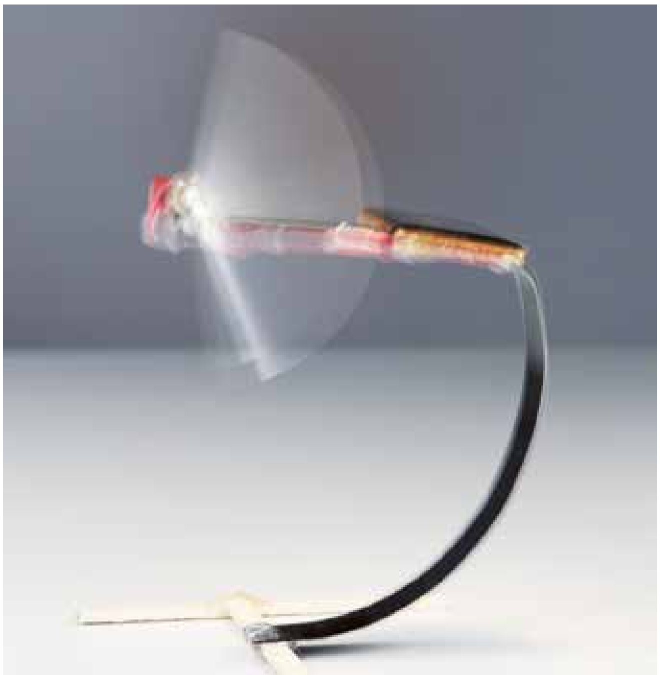

Figure 1: Miniature hopping robot driven by a micro motor and solar panel

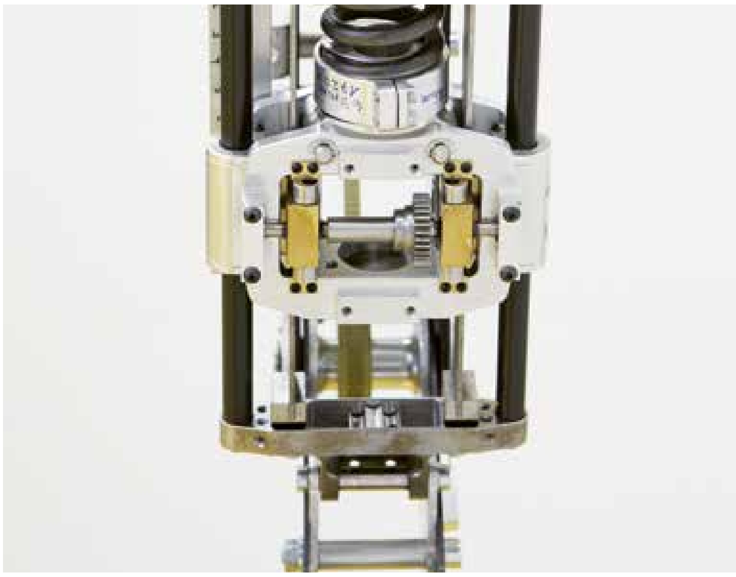

Figure 2: Linear multi modal actuator for flexible mechanical dynamics

While a number of successful applications have been developed based on conventional robotics technologies, the capabilities of current robotic systems are still far behind those of biological systems in terms of autonomy, efficiency, and, in particular, adaptability. These factors considerably restrict robotic systems to niche applications.

In nature, animals' motor control systems most often utilize highly maneuverable and efficient passive dynamics, while being able to flexibly switch to precise and high power actuation when necessary. In animal nervous systems, information is processed in massive parallel networks, and are optimized through both rapid learning and relatively long-term developmental processes. Intelligent behaviors emerge from the interaction between animals' nervous systems and their sensory motor capabilities through activities such as making use of tools, structuring environments, and social interactions such as cooperation. The complexity of these systems and processes creates a challenge for robotics engineers and scientists. We tackle this challenge with an interdisciplinary approach that bridges robotics, computer science and the biological sciences. The vision of the Bio-Inspired Robotics Lab is to create life-like robots and, through systematic investigations, to rapidly and incrementally identify both the fundamental problems in this area of research and their solutions.

Our research program consists of two large areas of investigation: first, we explore novel technologies such as sensory, motor and computational components, which enable us to develop physical robotic systems that more plausibly resemble biological systems; and second, based on our core technological competencies, we make inroads investigating the fundamental factors that distinguish animals from machines by applying an understanding.

The main challenges addressed by our research include the design, fabrication, and control of autonomous robotic

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Fumiya Iida has been an assistant professor of bio-inspired robotics at ETH Zurich since August, 2009. He received his Bachelor and Master degrees in mechanical engineering at Tokyo University of Science (Japan, 1999), and his Dr. sc. nat. in Informatics at University of Zurich (2006). In 2004 and 2005, he was also engaged in biomechanics research related to human locomotion at the Locomotion Laboratory, University of Jena, (Germany). From 2006 to 2009, he worked as a postdoctoral associate at the Computer Science and Artificial Intelligence Laboratory at the Massachusetts Institute of Technology, US. His research interests include biologically inspired robotics, embodied artificial intelligence, and biomechanics. He has been involved in a number of research projects related to dynamic legged locomotion, navigation of autonomous robots, human-machine interactions, and self-reconfigurable soft robots. Based on these research achievements, he has so far published over seventy publications in major robotics journals and conferences, and edited two books. Currently, he serves as an associate editor of the Journal of Soft Robotics, and on the editorial board of the Journal of Intelligent and Robotic Systems, and serves as a program committee member of international conferences and workshops.

systems that are made of unconventional soft materials, such as continuum elastic body, low-density composite materials, and thermoplastic adhesive materials. While soft materials are very common in nature as exemplified by whiskers, octopus tentacles, and mammals' skins, the use of soft and deformable materials has not yet been widely explored in artificial systems. Conventional robots are usually composed of metal and other rigid materials, and there already exist many standard techniques for using these. One of the main challenges of working in the area of soft robotics is developing techniques for exploring and handling unconventional materials, as we do not yet know what types of soft or unconventional materials will become available for use in robotics, or how to design and manufacture robots that make use of these components.

Figure 3: Single leg hopping robot equipped with unconventional actuators

Another fundamental problem of soft robotics is related to the sensing and control of over-redundant and underactuated systems. Conventional control approaches that assume rigid-body dynamics cannot be easily applied. This problem can be addressed through the modeling and analysis of soft body dynamics, and requires the development of more advanced state estimation techniques.

Finally, the effectiveness of our entirely new approach to designing and controlling soft robots needs to be proven in an industrial context. The basic concepts and technologies have to be tested in the context of realistic and practical application scenarios such as bio-medical applications, human-oriented manufacturing processes, home appliances, and systems for extreme environments.

Highlights and achievements

Prof. Iida has served as:
> Member of the editorial board of two international robotics journals
> Author and co-author of 25 journal articles, 8 book chapters, 31 conference publications
> Invited keynote speaker at 14 conferences and workshops worldwide
> Organizational committee member of 28 international conferences and workshops
> Project leader of SNF NCCR[1] Robotics, coordinating 10 research labs in Switzerland
> Founder of IEEE-RAS[2] Technical Committee on Soft Robotics, 10.2012
> General chair of the International Workshop on Soft Robotics, July 15–19, 2013, Ticino Switzerland
> General chair of the International Summer School on Soft Robotics, June 2012, Zurich, Switzerland
> General and program chair of the International Conference on Morphological Computation, March 26–28 2007, Venice Italy

Goals and future priorities

In the future, we expect to obtain a better understanding of adaptive motion control in biological systems, and to extract the basic principles that will allow us to create robust and intelligent robotics applications. To this end, we will conduct both basic research and application-oriented investigations in actuation, sensing, and the (properties and uses of) unconventional materials, ultimately leading to a new generation of robotic systems.

Organization of the professorship

The Bio-Inspired Robotics Lab currently consists of one principal investigator, three post doctoral fellows, six doctoral students, and three other technical staff. The lab is currently running several large projects funded by the Swiss National Science Foundation, ETH Zurich Foundation, and the European Commission's Seventh Framework Programme (FP7).

Teaching activity

The educational activities in the Bio-Inspired Robotics Lab consist of three components.

First, we have been organizing an annual graduate course called "Introduction to Biologically Inspired Robotics". This course gives an overview of the interdisciplinary field of bio-inspired robotics and introduces fundamentals, such as basic skills for modeling and simulating biological systems and technological components for building bio-inspired robots.

Second, a number of Bachelor and Master students participate in semester or thesis projects in which students learn the practical skills for research projects and contribute to scientific progress in the field. Students are closely supervised by senior graduate students as they learn practical skills including modeling, simulation, robot manufacturing, programming, and experimentation. Students also gain important writing experience when their research is published in scientific journals.

The third category of educational activities is focused mainly seminars, summer schools, and workshops. These usually involve invited participants and lecturers from different labs, institutes and universities around the world. For example,

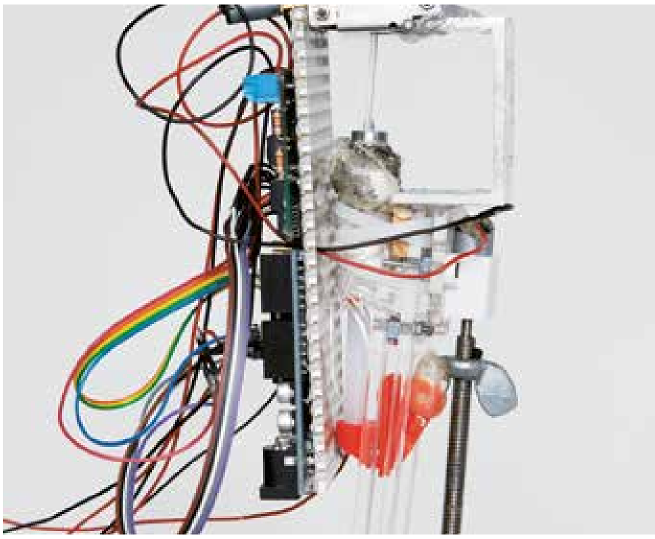

Figure 4: Spider robot that uses thermoplastic adhesives for dragline locomotion

Figure 5: Spider robot that uses thermoplastic adhesives for dragline locomotion (in detail)

[1] Swiss National Science Foundation, National Competence Center of Research (SNF NCCR)
[2] Institute of Electrical and Electronics Engineers, Robotics and Automation Society (IEEE-RAS)

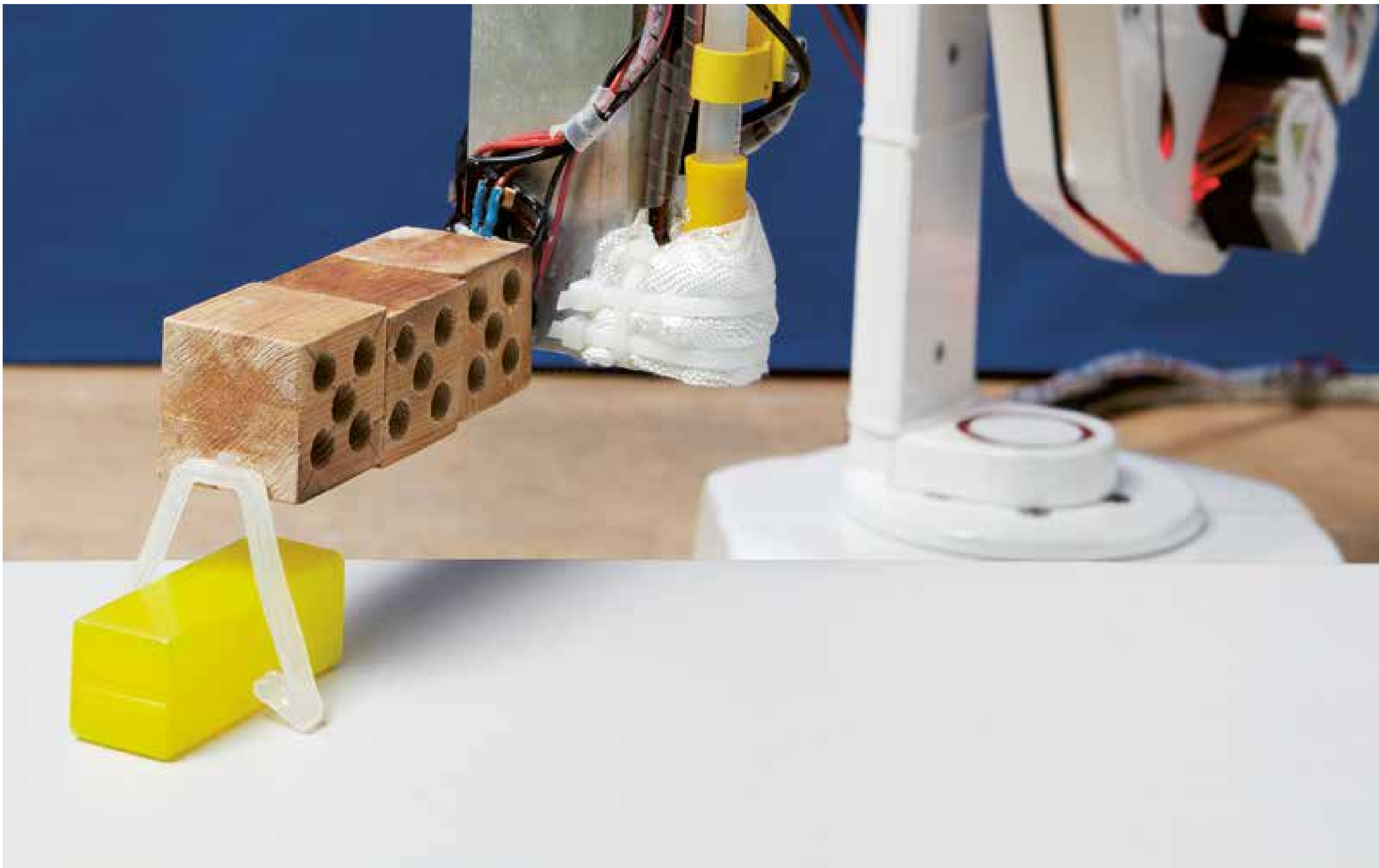

Figure 6: Adaptive 3D printing robot that autonomously extends its own body

every semester for the last three years, we have organized a meeting of the "BioRobotics Network in Zurich" (BiRoNZ) seminar series, where six speakers working in the vicinity of Zurich are invited to discuss biology- or robotics-related issues.

Additionally, we organized the ETH Summer School on Soft Robotics in 2012, and the International Workshop on Soft Robotics and Morphological Computation in 2013. Dozens of leading scientists from around the world were invited to and attended these events.

Collaborations

Academic

> Rolf Pfeifer, Artificial Intelligence Laboratory, University of Zurich
> Dario Floreano, Laboratory of Intelligent Systems, EPFL
> Alois Knoll, Technical University of Munich, Germany
> Martin Haegele, Fraunhoffer Institute, IPA, Germany
> Chris Melhuish, Bristol Robotics Laboratory, University of West England, UK
> Cecilia Laschi, Biorobotics Institute, Scuola Superiore Sant'Anna, Italy
> Frank Clemens, EMPA

Key publications

> Leach, D., Guenther, F., Maheshwari, N., and Iida, F. (2013). Linear multi-modal actuation through discrete coupling, IEEE/ASME Transactions on Mechatronics, (in press).
> Blumberg, M.S., Marques, H.G., and Iida, F. (2013). Twitching in Sensorimotor Development from Sleeping Rats to Robots, Current Biology, 23(12): R532-R537.
> Wang, L., Graber, L., and Iida, F. (2013). Large-payload climbing in complex vertical environments using thermoplastic adhesive bonds, IEEE Transactions on Robotics, 29(4): 863-874.
> Marques, H.G., Imitiaz, F., Iida, F., and Pfeifer, R. (2013). Self-organisation of reflexive behaviour from spontaneous motor activity, Biological Cybernetics, 107(1): 25–37.
> Pfeifer, R., Lungarella, M., and Iida, F. (2012). The challenges ahead for bio-inspired ‹soft› robotics, Communications of the ACM, 55(11): 76–87.
> Wang, L. and Iida, F. (2012). Physical connection and disconnection control based on hot melt adhesives, IEEE/ASME Transactions on Mechatronics, 18(4): 1397-1409.
> Reis, M., and Iida, F. (2013). An energy efficient hopping robot based on free vibration of a curved beam, IEEE/ASME Transactions on Mechatronics, (in press).
> Iida, F., and Tedrake, S., (2010). Minimalistic control of biped walking in rough terrain, Autonomous Robots, 28(3): 355–368.
> Iida, F., Rummel, J., Seyfarth, A. (2008). Bipedal walking and running with spring-like biarticular muscles, Journal of Biomechanics, 41: 656–667.*
> Pfeifer, R., Lungarella, M., and Iida, F. (2007). Self-organization, embodiment, and biologically inspired robotics, Science, 318: 1088–1093.*

* Published before joining the ETH Zurich

Computational Fluid Dynamics and Multi-Scale Modeling

Our group focuses on developing models and numerical algorithms for turbulent and reactive flows, rarefied gas kinetics, flow in porous media and bio-fluid dynamical applications. While mainly concentrating on fundamental research, we are always motivated by practical challenges, many of which are relevant for industrial applications. Application areas include energy (turbulent combustion, oil recovery and enhanced geothermal systems), environment (CO_2 sequestration, NOx emission and contaminant transport), medicine (cerebral blood flow and red blood cell transport), and de-mixing.

Figure 1: Qualitative flow demonstrations with the virtual wind tunnel

Turbulence

While large eddy simulation (LES) is a very powerful approach to modeling turbulent flows, it is not yet widely used in industrial workflows because of the associated computational costs. These can be high, particularly in cases involving wall turbulence, where computational modeling is Reynolds-number dependent. The research community has therefore proposed various hybrid methods that combine LES with methods based on Reynolds-averaged Navier-Stokes equations (RANS). Our group developed a new approach, which is based on simultaneous LES and RANS simulations coupled via forcing terms to ensure internal consistency. This strategy allows us to overcome many of the problems associated with previous methods that use LES/RANS interfaces.

Combustion

More than 80 % of consumed energy is converted by burning fossil fuels, therefore small improvements in combustion technology can have a very large impact on energy efficiency. Achieving such improvements, however, requires the capability to accurately predict the governing physical processes involved in combustion. A modeling approach, which has proved to be both generally applicable and very powerful, is based on solving a joint probability density function (PDF) transport equation. Unlike other approaches, such PDF methods do not require a model for turbulent convection and present no closure issues related to averaging the reaction's source terms. Our group has developed various new PDF solution algorithms and combustion models.

Rarefied gas kinetics

It is well known that the Navier-Stokes equations become invalid in cases that involve large Knudsen numbers. Such scenarios can occur, e.g. in nano-scale devices, at re-entry of a space vehicle, in plasma flows, and in the presence of very strong shocks. The group has devised a new de-mixing concept and, for corresponding numerical investigations, an efficient modeling approach, which is valid and efficient for the whole Knudsen number range.

Porous media

The study of flow and transport in porous media has many applications in earth science, energy science, and in many other areas. We are particularly interested in oil recovery, CO_2 sequestration, enhanced geothermal systems, and uncertainty assessment for contaminant transport. Our group has developed a multi-scale finite-volume method for oil reservoir simulation, stochastic particle methods for multi-phase flow and uncertainty assessment, and various numerical schemes.

Cerebral blood flow

Cerebral blood flow (CBF) can be defined as the arterial blood delivery to the capillary bed in the brain. A graph model for CBF simulations was recently developed, revealing that the dynamics of red blood cells at bifurcations has a much more dramatic impact on blood flows than was expected. We are currently investigating the consequences of this phenomenon for flow regulation and network development.

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In 1997 Patrick Jenny received his Ph.D. in Computational Fluid Dynamics (CFD) at the Swiss Federal Institute of Technology (ETH) and from July 1997 till October 1999 he was a postdoctoral researcher in the Mechanical and Aerospace Engineering Department of Cornell University. Then he joined the reservoir simulation and optimization research group of Chevron in San Ramon, California, before he was appointed SNF Assistant Professor at the Institute of Fluid Dynamics at ETH Zurich. In 2005 he received the National Latsis Prize, and since May 2012 Patrick Jenny has been Full Professor for Computational Fluid Dynamics and Multi-Scale Modeling.

Highlights and achievements

> Parametrized scalar profile mixing model for multiple inert and reactive scalars
> Probability density function model for premixed turbulent combustion
> Model for NOx formation including radiation effects
> Hybrid LES/RANS model for complex turbulent flow
> Fokker-Planck collision operator for efficient simulations of rarefied gas flow
> Demonstration of novel de-mixing concept relying on high Knudsen numbers
> Iterative multi-scale finite-volume method for flow in heterogeneous porous media
> Particle-based transport model with Markovian velocity processes for tracer dispersion in highly heterogeneous porous media
> Stochastic particle method for multi-phase flow in porous media with relevance for CO_2 sequestration
> Multi-level Monte Carlo method for uncertainty quantification of two-phase flow and transport in porous media
> Unconditionally stable scheme for non-linear problems arising in simulations of multi-phase flow in porous media
> Model for computing red blood cell distribution in capillary networks with relevance for cerebral blood flow
> Stencil method for efficient simulations of light scattering in turbid media accounting for polarization, fluorescence and arbitrary phase functions

Goals and future priorities

Turbulence and combustion

> Development of large eddy simulation feasible for a broader range of applications
> Exploitation of the full potential of the probability density function closure for turbulent combustion
> Improved theory and modeling of group phenomena in turbulent dispersed two-phase flows with relevance for spray combustion

Fluid dynamics at the molecular scale

> Improved models and simulation capabilities for rarefied gas flows ranging from very small to very large Knudsen numbers
> A better understanding of thermodynamic non-equilibrium effects in rarefied gas mixtures
> Effective de-mixing concepts

Flow in porous media

> More general multi-scale methods for coupled multi-phase flow and transport
> Improved predictive capabilities for uncertainty quantification of subsurface flow, e.g. of contaminant transport and oil recovery
> Better quantification of the relevant CO_2 capturing mechanisms for sequestration
> Reduction of seismic risks related to the creation of enhanced geothermal systems and CO_2 sequestration

Bio-fluid dynamics

> Improved understanding of cerebral blood flow regulation, oxygen delivery in the cortex and adaptation of vascular networks
> Feasible mechanical concepts to assist blood flow circulation

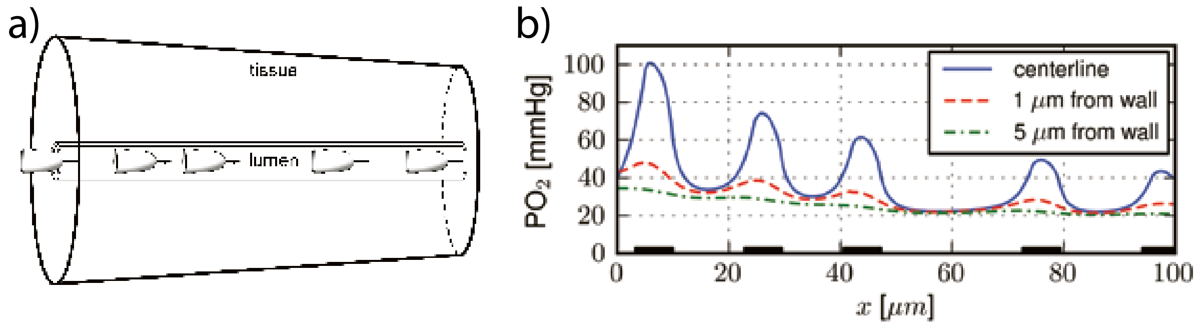

Figure 2: a) Computational domain with a fixed tissue region and red blood cells moving in a capillary. b) Longitudinal partial oxygen pressure profiles at three radial positions. The thick lines indicate the red blood cell locations.

Organization of the professorship

The group is part of the Institute of Fluid Dynamics (IFD) and much of its infrastructure is shared among the three IFD professorships, including computing facilities, office space, student and seminar rooms, as well as our secretary and system administrator. All issues that concern the institute as a whole are discussed during monthly meetings. The teaching load and other obligations are distributed equally among our doctoral students, who serve as assistants.

Dr. Daniel W. Meyer, who is a senior scientist, supports the professorship with the supervision of a doctoral student. He also teaches one course and helps with administrative matters. All group members supervise student projects, i.e. Semester, Bachelor and Master theses.

Teaching activity

The group offers courses both at Master and Bachelor levels. We teach 30 % of the core course Fluid Dynamics II, the engineering tool course on Computational Fluid Dynamics (CFD) with OpenFoam, which runs twice a year, and 70 % of the Bachelor course Turbulent Flows. The latter is also offered in the Master program, along with Turbulence Modeling, Advanced CFD Methods, Stochastic Methods for Fluid Dynamics, and Biofluiddynamics. Together with the other two groups at IFD, we offer the seminars "Thermo- and Fluid Dynamics" and "Research Seminar in Fluid Dynamics".
The group continuously ensures supervision of numerous Semester, Bachelor and Master projects, promotes external projects, and hosts visiting students.

Collaborations

Industrial

- Dr. Seong Lee; Chevron & Schlumberger
- Dr. Djamel Lakehal; ASCOMP GmbH

Academic

- Prof. H. Tchelepi; Stanford University, Department of Energy Resources Engineering
- Profs. B. Weber and A. Buck: University Hospital Zurich, Nuclear Medicine
- Profs. Ch. Schwab and S. Mishra; ETH Zurich, Sem. for Applied Mathematics
- Prof. M. Mazzotti; ETH Zurich, Institute of Process Engineering
- Dr. K. Evans; ETH Zurich, Institute of Geology
- Prof. P. Ermanni; ETH Zurich, Centre of Structure Technology
- Prof. E. Mazza; ETH Zurich, Institute of Mechanical Systems
- Dr. D. Obrist; ETH Zurich, Institute of Fluid Dynamics
- Dr. I. Mantzaras; Paul Scherrer Institute, Combustion Research Laboratory
- Prof. L. Kleiser; ETH Zurich, Institute of Fluid Dynamics
- Prof B. Müller; NTNU, Fluids Engineering Laboratory

Fostering young academics

Since 2008, twelve doctoral students have graduated from the group and one of them won the ETH medal for his thesis. All graduates immediately found very good positions; five of them in academic research labs. One former doctoral student is now a professor at TU Delft, two former postocs are professors at the University of Lausanne and at Virginia Tech, respectively, and one former doctoral student returned to ETH as a research associate, after two years at Stanford University, with the goal of writing a habilitation thesis.

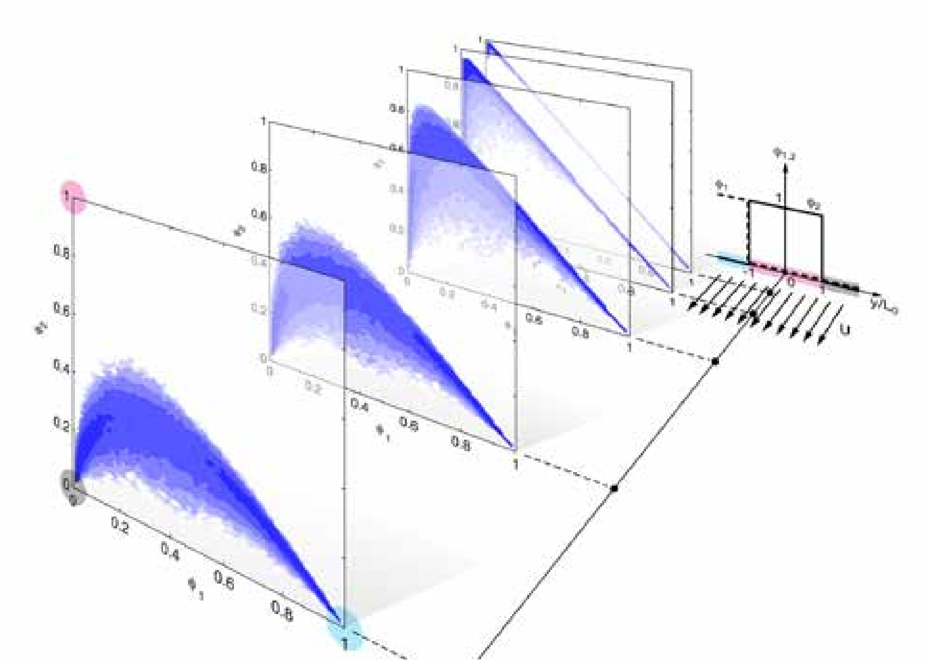

Figure 3: Simulation results of a spatially inhomogeneous three-stream mixing configuration resulting from a PSP-based velocity-conditional mixing model. PDF evolutions (logarithmic contour plots) are depicted.

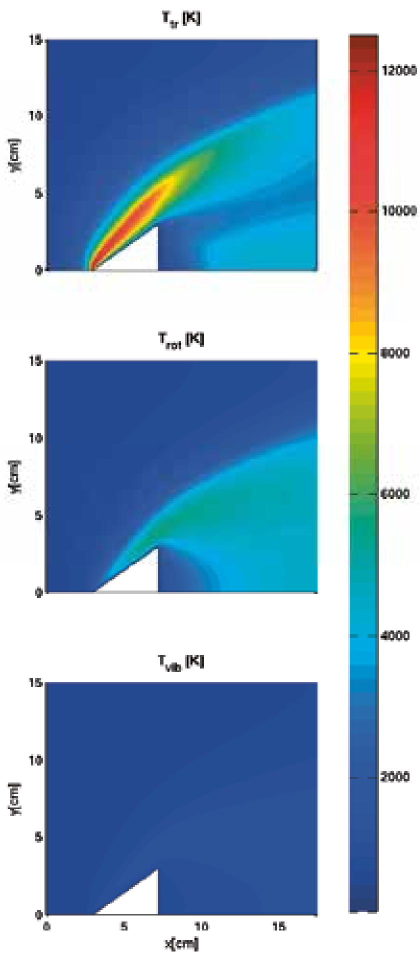

Figure 4: Hypersonic nitrogen flow over a wedge using the Fokker-Planck collision operator. Translational temperature at top, rotational temperature at middle, and vibrational temperature at bottom.

Key publications*

- P. Jenny, D. Roekaerts, N. Beishuizen. Modeling of turbulent dilute spray combustion. Progress in Energy and Combustion Science, 38, 2012.
- D.W. Meyer, P. Jenny. A mixing model for turbulent flows based on parameterized scalar profiles. Phys. of Fluids, 18(3), 2006.
- P. Jenny, M. Torrilhon, S. Heinz. A solution algorithm for the fluid dynamic equations based on a stochastic model for molecular motion. J. of Comp. Physics, 229, 2010.
- P. Jenny, S.H. Lee, H. Tchelepi. Adaptive multiscale finite-volume method for multi-phase flow and transport in porous media. SIAM J. for Multiscale Modeling and Simulation, 3(1), 2005.
- I. Lunati, P. Jenny. Multiscale finite-volume method for compressible multiphase flow in porous media. J. of Comp. Physics, 216(2), 2006.
- P. Jenny, H. Tchelepi, S. Lee. Unconditionally convergent nonlinear solver for hyperbolic conservation laws with s-shaped flux functions. J. of Comp. Physics, 2009.
- P. Jenny, S. Mourad, T. Stamm, M. Voege, K. Simon. Computing light statistics in heterogeneous media based on a mass weighted probability density function method. J. of Optical Society of America, 24(8), 2007.
- D. Obrist, B. Weber, A. Buck, P. Jenny. Red blood cell distribution in simplified capillary networks. Philosophical Transactions of the Royal Society, 368(1921), 2010.
- D.W. Meyer, H.A. Tchelepi, P. Jenny. A fast simulation method for uncertainty quantification of subsurface flow and transport. Water Resources Research, 2013.
- H. Xiao, P. Jenny. A consistent dual-mesh framework for hybrid LES/RANS modeling. J. of Comp. Physics, 231(4), 2012.

* since 2005

Aerothermochemistry and Combustion Systems Laboratory

Fluid motions and their varied consequences have an undeniable impact on human activity. Their simulation is key to predicting a wide variety of phenomena, from the turbulent motion of boiling water, to next week's weather, to future directions in energy technology. The entropic lattice Boltzmann method (ELBM) is a paradigm-changing innovation in computational fluid dynamics that opens the door to the direct simulation of turbulence. With its roots in statistical mechanics, and underpinned by the Second Law of Thermodynamics, it is based on an incredibly simple "free flight + collision" model that uses fictitious particles engineered to retain only the microscopic details strictly necessary to recover their fluid flow.

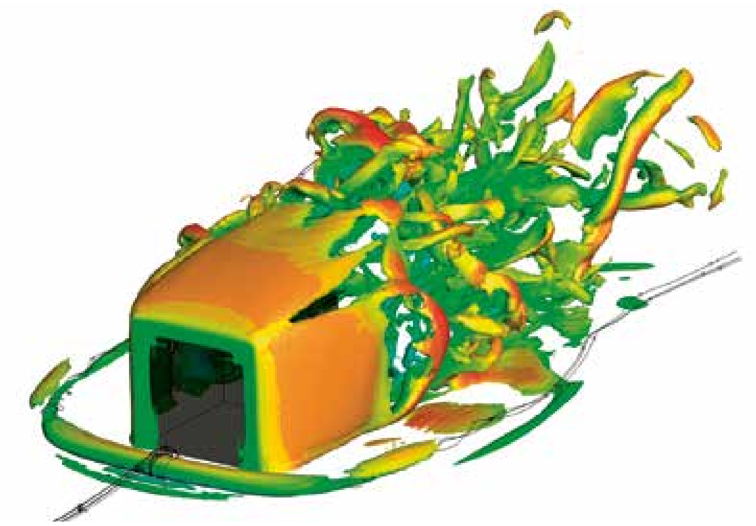

Figure 1: ELBM simulation of turbulent flow past a surface-mounted cube

Our group invented ELBM, and we actively promote this method across three areas of research: simulation of turbulent flows in complex geometries, compressible flows, and flows at a micro-scale where the laws of classical continuous mechanics break down. In the latter area, the Ansumali-Karlin kinetic boundary conditions developed by our group, as well as our exact solutions, have become universal references for researchers in the field.

Our research responds to a thirst for new LBM models that go beyond incompressible hydrodynamics to represent compressible, multi-phase, and reactive flows. Our discovery of a hierarchy of higher-order lattices consistent with the Second Law of Thermodynamics resolved the last remaining obstacle to lattice-Boltzmann modeling. This enabled us to model all remaining admissable lattices, which in turn, has opened the door to designing novel LBMs with improved properties.

ELBM is a shining example of model reduction, where a microscopic physics is reduced to the minimum required to create efficient simulations. We pioneered a general approach to reduction, the Method of Invariant Manifold (MIM) based on the key idea that, broadly understood, solving the problem of model reduction lies in finding slow invariant sub-manifolds in the phase space of the system. The principle of extracting slow invariant manifolds in MIM for dissipative systems is analogous to the celebrated Kolmogorov-Arnold-Moser theory of classical mechanics. Selected applications of MIM included exact hydrodynamics at all Knudsen numbers and efficient model reduction of polymer dynamics. The computational realization of MIM – the method of invariant grids - opened up the way to combustion simulations with realistic chemistry.

Highlights and achievements

- Fully resolved simulations of turbulent flows revealed that ELBM is at least an order of magnitude more efficient than state-of-the-art computational fluid dynamics (CFD) solvers.
- Full characterization of admissible lattices for ELBM was achieved.
- ELBM was characterized as a built-in sub-grid model for coarse grid simulations.
- Lattice Boltzmann models for compressible flow, realistic multi-component mixtures and surface reactions were developed and validated.
- New boundary conditions for ELBM simulations in complex geometries were found.
- Reduced reaction mechanisms, starting with hydrogen-air mixture and currently extended to n-heptane were obtained.
- Coupling of the reduced chemical kinetics to the ELBM fluid solver was achieved.
- Exact hydrodynamics were derived from the Boltzmann equation; the result sheds new light on the celebrated Hilbert's 6th problem.

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Prof. Karlin's scientific path began with a Ph.D. in theoretical physics and research at the Russian Academy of Sciences in Krasnoyarsk. He was Alexander von Humboldt Fellow at the University of Ulm, and later CNR[1] Fellow at the University of Rome. He joined ETH Zurich in 1998 as a Senior Scientist and became a faculty member in 2012.
His research is devoted to advanced and novel methods in computational fluid dynamics. His expertise covers methods of model reduction (Method of Invariant Manifold) and has applications in kinetic theory and the Boltzmann equation, polymer dynamics, and complex chemical kinetics. He was a key developer of the lattice Boltzmann method for fluid dynamics and micro-flow of rarefied gas. He is the inventor of the unconditionally stable ELBM, which opened the door to the high-performance computation of turbulent flows. In 2011, the significance of his research was recognized when he was awarded a European Research Council Advanced Grant. He heads a highly active research group at ETH Zurich; two of his recent Ph.D. students received ETH Medals for their theses. He has authored over 100 scientific papers in peer-reviewed journals and a book "Invariant Manifolds for Physical and Chemical Kinetics" in the Lecture Notes in Physics Springer series.

Goals and future priorities

ELBM is focused on achieving major breakthroughs in the three directions: direct numerical simulation of turbulence, compressible reactive flows, and micro-flows. The established success of ELBM in these three domains will boost our research in other areas such as biological, relativistic and multiphase flows. This work will impact a wide range of contemporary problems, from the design of fuel cells and vacuum valves to aircraft design. Our approach is inherently physical in its use of a kinetics framework translated onto a lattice in position, momentum, time and space. This physical component is coupled with new computational ideas that enable us to study fluid flows in extremely complex geometries more efficiently, accurately, and with more robustness than was heretofore possible.

Teaching activity

Ph.D.s supervised:
> E. Chiavazzo, Method of invariant grids and lattice Boltzmann simulation of combustion, ETH Zurich (2009)
> S. Chikatamarla, Lattice Boltzmann hierarchy for fluid mechanics, ETH Medal (2008)
> N. Prasianakis, Lattice Boltzmann method for thermal compressible flows, ETH Zurich (2008)
> S. Ansumali, Minimal kinetic modelling of hydrodynamics, ETH Medal (2005)

Annually, we offer the Master course Fluid Dynamics With The Lattice Boltzmann Method.

Collaborations

Industrial
> Co-founded of the ETH spin-off company Frontier Lattices GmbH (2010).

Academic
> Sauro Succi (IAC Rome), Pietro Asinari (Politecnico di Torino), Bruce Boghosian (Tufts University), Hudong Chen (Exa Corp., Burlington MA), Alexander Gorban (University of Leicester), Miroslav Grmela (Politechnique, Montreal), Yannis Kevrekidis (Princeton University), Kai Luo (University of Southampton), John Mantzaras (Paul Scherrer Institute), Ananias Tomboulides (University of Western Macedonia).

Key publications

> A.N. Gorban and I.V. Karlin, Invariant Manifolds for Physical and Chemical Kinetics (Lecture Notes in Physics 660), (Springer, Heidelberg, 2005). 495 pp.
> S.S. Chikatamarla, S. Ansumali, I.V. Karlin, Entropic lattice Boltzmann models for hydrodynamics in three dimensions, Physical Review Letters 97, 010201 (2006).
> S.S. Chikatamarla, I.V. Karlin, Entropy and Galilean invariance of the lattice Boltzmann theories, Physical Review Letters 97, 190601 (2006).
> I.V. Karlin, M. Colangeli, M. Kroger, Exact linear hydrodynamics from the Boltzmann equation, Physical Review Letters 100(21), 214503 (2008).
> S. Arcidiacono, J. Mantzaras, I.V. Karlin, Lattice Boltzmann method for the simulation of catalytic reactions, Phys. Rev. E 78, 046771 (2008).
> E. Chiavazzo, I.V. Karlin, C. Frouzakis, K. Boulouchos, Method of invariant grid for model reduction of hydrogen combustion, Proc. Combustion Institute 32, 519–526 (2009).
> S.S. Chikatamarla, I.V. Karlin, Lattices for the lattice Boltzmann method, Phys. Rev. E 79(4), 046701 (2009).
> S.S. Chikatamarla, C.E. Frouzakis, I.V. Karlin, A. Tomboulides, K.B. Boulouchos, Lattice Boltzmann method for direct numerical simulation of turbulent flows, J. Fluid Mech. 656, 298–308 (2010).
> E. Chiavazzo, I. Karlin, Adaptive simplification of complex multiscale systems, Phys. Rev. E 83, 036706 (2011).

[1] National Research Council (CNR)

Fluid Dynamics

Main research areas of the group are fundamental problems of fluid dynamics and the development of advanced flow simulation methods for incompressible and subsonic compressible flows. Laminar-turbulent transition, turbulent and particle-laden flows are investigated, as well as the origin and propagation of aeroacoustic noise. The selection of problems is motivated by their physical complexity and high practical relevance. New accurate and efficient simulation methods are developed to tackle these problems with the aid of massively parallel supercomputers. Another major, interdisciplinary research area is biomedical flows, which are studied in close cooperation with clinical medical researchers using computational, theoretical and experimental methods.

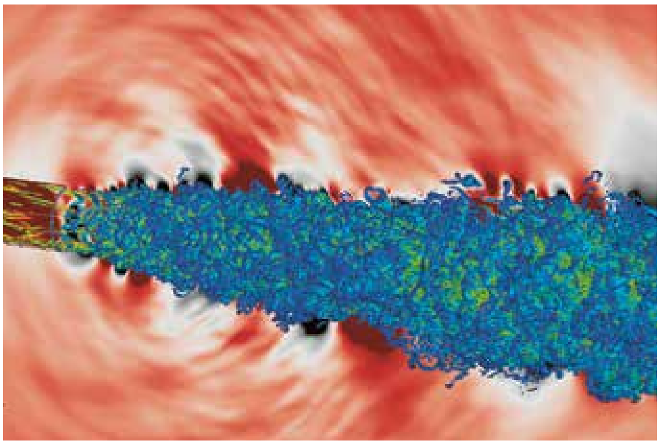

Figure 1: Noise emission from turbulent nozzle-jet flow

Turbulent and transitional flows: The numerical simulation of turbulent flows and of laminar-turbulent transition is a central field of the group's research. The flows are investigated by fully resolved Direct Numerical Simulations (DNS), and by Large-Eddy Simulations (LES) which require models for unresolved scales. The group has developed two such LES subgrid-scale models and has demonstrated their success for a number of increasingly complex flows. Furthermore, the models were successfully implemented into the computational fluid dynamics (CFD) code NSMB, which is capable of handling complex industrial configurations.

Simulation of particle-laden flows: Disperse particle-laden two-phase flows are studied in which the mutual particle interaction can be neglected. Either the fluid equations are solved in an Eulerian framework only while the particles are tracked individually along their trajectories, or both the clear and the particle-laden phase are computed in an Eulerian manner. These numerical approaches have been applied to particle-laden flow in a channel and over a backward-facing step, to particle-driven gravity currents, and to particle transport, mixing and settling mechanisms in estuaries.

Computational aeroacoustics and vortex breakdown: Noise emission of aircraft at take-off is a serious problem. Our projects in this area aim at the analysis and prediction of jet noise with a direct noise computation approach for the acoustic near-field. Single and heated coaxial round subsonic jets are investigated using stability theory and numerical simulations. Major progress has been achieved by developing a computational simulation setup in which laminar, transitional or turbulent nozzle flows develop in a physically realistic manner. The acoustic data from direct noise computations is extrapolated to the far-field with a solver that is based on Lighthill's acoustic analogy. Using the same simulation code, we study vortex breakdown in swirling nozzle-jet flows. Significant differences are observed between cases with non-rotating and rotating nozzle walls.

Biomedical fluid dynamics: The study of flow systems in the human body is the focus of our bio-fluid dynamics activities. In several interdisciplinary projects we bring together clinical medical research, fluid dynamics, applied mathematics and modern numerical simulation methods. Most projects address flows at low Reynolds numbers as found, e.g., in the inner ear which includes the sense of balance (and its pathologies) as well as the cochlea, our hearing organ. Further projects address cerebral blood flow, lung ventilation, the gastric system, and sonic toothbrushes. Results from these projects are exploited jointly with our collaborative partners.

Advanced computational methods for complex flows: In the context of our research projects, we develop the necessary high-fidelity flow simulation codes with a strong focus on their performance on massively parallel supercomputers. In recent years, we developed a high-performance solver for incompressible flows and a parallel version of a compressible flow solver with cylindrical grids. For a range of problems in biofluid dynamics, we designed a meshless solver for Stokes flow with finite-size particles.

Prof. Leonhard Kleiser
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Leonhard Kleiser has been a full professor of Fluid Dynamics at ETH Zurich since 1994 and will retire in 2014. He is an elected Fellow of the American Physical Society (APS), Division of Fluid Dynamics. Education: Diploma in mathematics (with minor in physics) from the University of Freiburg (DE), 1976; Dr.-Ing. in Mechanical Engineering from the University of Karlsruhe (TH) (DE), 1982. Employment: Staff member at Forschungszentrum Karlsruhe, 1976; Transition and Turbulence group leader at German Aerospace Research Establishment (DLR) in Göttingen (DE), 1982. Research visits at UC Santa Barbara, Caltech (US) and the Universities of Uppsala (SE) and Trondheim (NO).
His main research interests lie in the elucidation of fundamental flow phenomena by advanced theoretical and numerical methods. Transitional, turbulent and particle-laden multiphase flows, biomedical flows and aeroacoustic noise are of particular interest. New accurate and efficient simulation methods are developed simultaneously for this purpose. Their transfer into industrial codes and practical applications is a special concern.

External evaluation and funding: Typically, our research projects are evaluated externally and funded partially through grants from the Swiss National Science Foundation (SNF), an internal funding scheme of ETH Zurich, the national Commission for Technology and Innovation (CTI), and directly by industrial research partners. Substantial amounts of supercomputer resources have been awarded through competitive funding by the Swiss National Supercomputing Centre (CSCS) and programs of the European Union.

Highlights and achievements

- LES: Subgrid-scale models developed by the group produce excellent results for complex (transitional/turbulent/swirling/compressible) flows. The LES approach was transferred into an industrial CFD code and applied, e.g., to film cooling with great success.
- Particle-laden flows: Demonstration of unprecedented high-resolution estuary flow simulations with particle-laden river. Received Ph.D. award from ETH Zurich.
- Jet aeroacoustics and vortex breakdown: Development and successful application of a parallelized code for physically realistic nozzle-jet flow simulations.
- Biomedical flows: Computational models developed for the inner ear and for a common disease of the balance sense called benign paroxysmal positional vertigo (BPPV). Discovery of new flow phenomena in balance sense and cochlea. Joint interdisciplinary projects with researchers from the University Hospitals in Zurich and Bern. Proposal and organization of a EUROMECH Colloquium, Biomedical Flows at Low Reynolds Numbers.
- Parallel CFD code IMPACT developed from scratch. This is one of the fastest high-fidelity, incompressible Navier-Stokes solvers (test simulations with more than 100 billion grid points on 20,000 processors).

Goals

The goals of the group are clear as Prof. Kleiser approaches the date of his regular retirement in mid-2014. Most of the group's remaining doctoral projects and related publications are expected to be completed before the end of that year. Four assistants hired recently by mutual agreement (to support the teaching of large classes with more than 400 students) will be transferred to Prof. Jenny and Prof. Rösgen, along with the two permanent staff members. Key courses are being handed over to Prof. Jenny. The course on Stability and Transition will be discontinued.

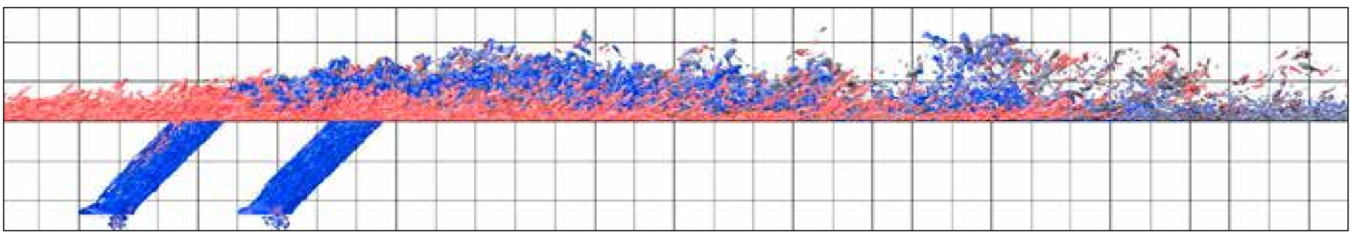

Figure 2: Hot (red) and cold air (blue) in anti-kidney vortex film cooling along a flat plate

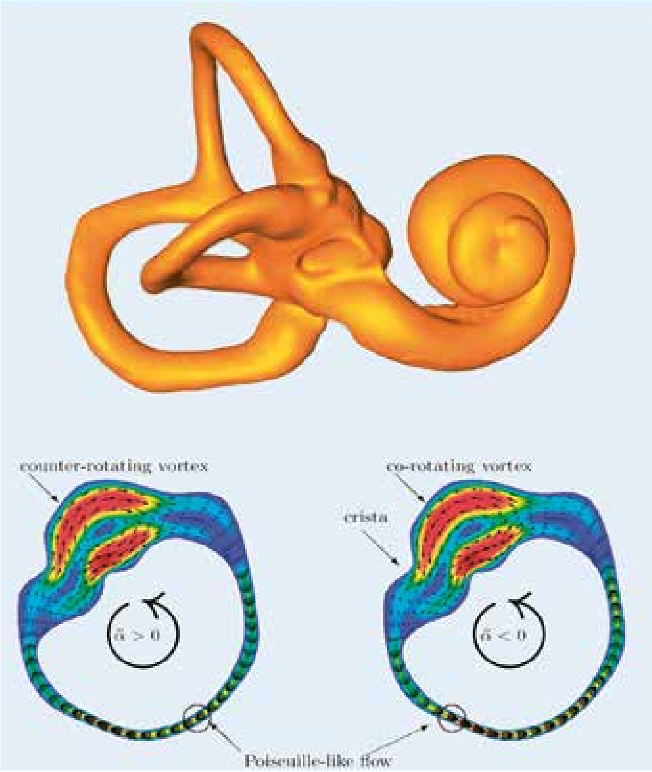

Figure 3: Inner-ear labyrinth (top) and newly detected vortical flows

Organization of the professorship

Professor Kleiser's group consists of one (non-permanent) senior research associate, PD Dr. D. Obrist, and nine doctoral students. Dr. Obrist acts as key advisor for the research projects in the biomedical area.

Regular supervision and exchange between research projects is fostered by weekly meetings (individually or in small subgroups) and by monthly meetings of the whole group.

At least once a year, each doctoral student gives a detailed update of his/her project during IFD's[1] weekly Research Seminar (organized jointly with Profs. Jenny and Rösgen). Research results are disseminated through participation in international conferences and publications in leading peer-reviewed journals. In addition to their research activities, doctoral students support teaching activities of the three IFD[1] professorships as teaching assistants.

The professorship also employs the Institute's secretary and the IT specialist who are shared among all Institute members. Matters of IFD[1]-wide interest are discussed and coordinated in regular monthly meetings of the three professors and key staff.

Teaching activity

The teaching activities of the professorships at IFD[1] are closely coordinated, as explained in the corresponding description of Prof. Rösgen. Prof. Kleiser contributes to the basic education in fluid dynamics primarily through the mandatory course "Fluid Dynamics 2" in the 5th semester and a basic course on CFD methods in the 6th semester. At the Master level, the professorship offers courses in the three study profiles: Fluid Science and Engineering, Aerospace Engineering, and Biological Fluid Science. In addition, we provide the mandatory education in fluid dynamics and an eligible specialization within the interdisciplinary Bachelor/Master program in Computational Science and Engineering (CSE) at ETH Zurich.
Courses offered by the professorship in the Bachelor curriculum are:

- Fluid Dynamics 2 (in recent years with Prof. Jenny), mandatory course, 350 students
- Computational Methods for Flow, Heat and Mass Transfer Problems
- Engineering Tools: Computational Fluid Dynamics (CFD) with OpenFoam (supporting Prof. Jenny)

Courses offered in the Master curriculum are:

- Hydrodynamic Stability and Transition
- Turbulent Flows (with Prof. Jenny)
- Biofluiddynamics (with contributions by Prof. Jenny)

Doctoral students attend the following seminars:

- Research Seminar in Fluid Dynamics
- Colloquium Thermo- and Fluid Dynamics

The latter comprizes a dozen professors from D-MAVT and has been organized by IFD since 1999.

In addition to the courses, we offer a large number of research projects for Bachelor and Master theses, semester projects, as well as seminar projects for CSE students.

Fostering young academics

Six doctoral theses have been completed since 2008 (after 15 in the ten years before). Three of these won a prestigious ETH award. Under suitable circumstances, doctoral students are offered to spend part of their research time with cooperating partners abroad. Dr. Obrist completed his habilitation in 2012 (following two habilitations in 2000). Beginning December 2013, he will be a tenured Professor of Cardiovascular Engineering at the University of Bern.
Former coworkers regularly found very good new positions. Four of them made distinguished academic careers (winning professorships or equivalent positions at TU Munich, KTH Stockholm, University of Bern and ZHW Winterthur), others made prominent careers in the private sector (e.g. as Director of GE Global Research-Europe, or within Swiss industry).

[1] Institute of Fluid Dynamics

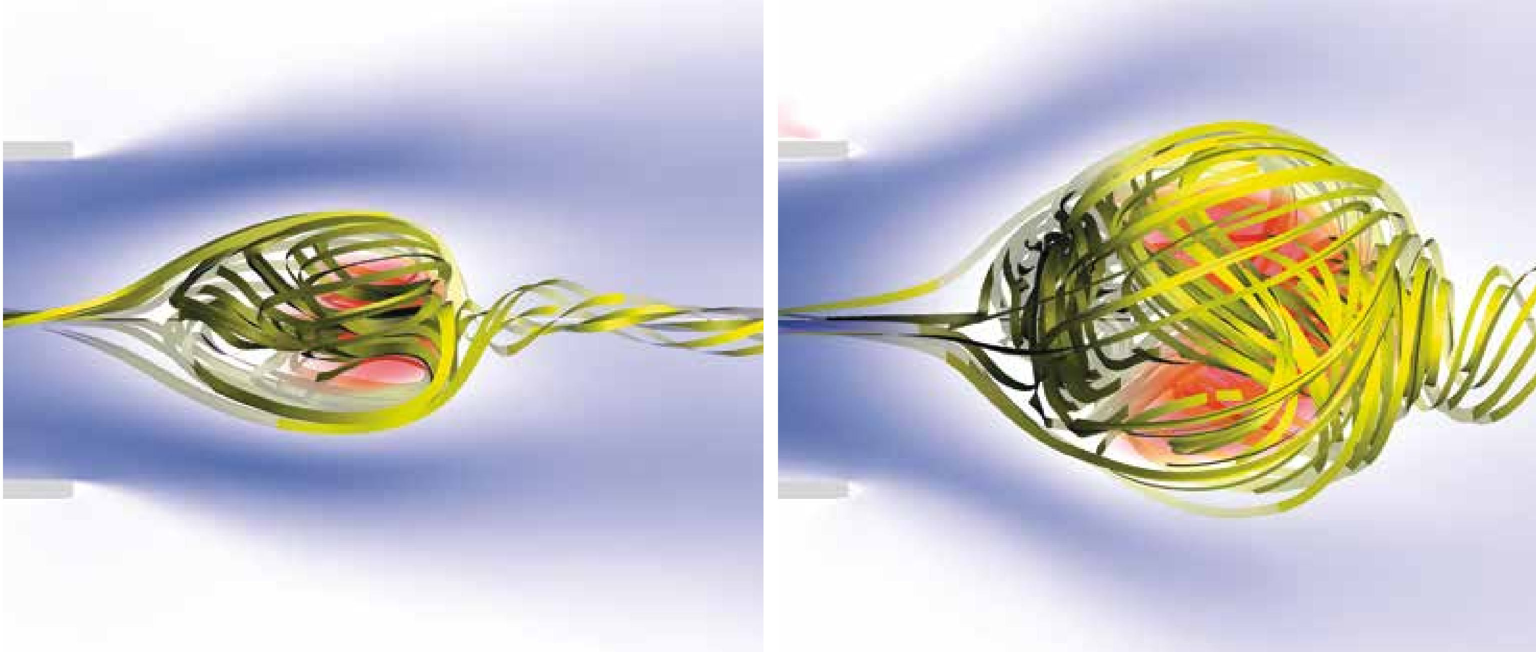

Figure 4: Vortex breakdown in swirling nozzle-jet flow. Left: nozzle at rest, right: rotating nozzle. Red color indicates backflow regions.

Collaborations

Prof. Kleiser's group collaborates and maintains contacts at various levels with academic and industrial partners. These collaborations range from short-term student projects with industrial partners and technology-transfer projects for simulation tools, to long-term scientific partnerships with peers from other academic institutions. The research code IMPACT has been shared with collaborating groups within and outside of ETH Zurich.

Academic collaborators and contacts in specific areas:

> Hydrodynamic stability, transition and turbulence: Prof. U. Rist, University of Stuttgart (DE); Prof. P. J. Schmid, Ecole Polytechnique, Palaiseaux (FR); Prof. F. Gallaire, EPF Lausanne

> Particulate flows: Prof. E. Meiburg, UC Santa Barbara (US)

> Aeroacoustics: Prof. C. Bogey, Ecole Centrale Lyon (FR)

> Biomedical fluid dynamics: Profs. R. Probst, A. Huber, A. Weber, F. Buck, T. Imfeld, T. Attin, W. Schwizer, PD Dr. S. Hegemann, PD Dr. A. Steingötter, University Hospital Zurich; Profs. P. Latzin, R. Vogel, University of Bern

> Computational methods: Prof. B. Müller, NTNU Trondheim (NO); Prof. M. Deville, EPF Lausanne; Profs. P. Arbenz, C. Schwab, ETH Zurich.

Industrial collaborations:

> Joint research projects: Cochlear Ltd. (AU); Dassault SA (FR); Eco Medics AG (CH)

> Student projects: AFC, ABB Turbo Systems, Glas Trösch (CH); Hilti AG (LI); Porsche AG (DE)

> CFD technology transfer: CFS Engineering (CH)

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> Henniger R., Obrist D., Kleiser L., High-order accurate solution of the incompressible Navier-Stokes equations on massively parallel computers, J Comp Phys 229(10): 3543-3572, 2010

Chair of Computational Science

Advances in information technology and mathematics present us with an unprecedented potential for scientific discovery and engineering innovation. Computational science integrates and enhances these advances with the goal of developing models with quantifiable uncertainties for the analysis, optimization and prediction of scientific and engineering problems. Research in the Professorship of Computational Science is focused in the areas of multi-scale modeling and simulation, high performance computing, optimization, and uncertainty quantification. Applications range from aerodynamics to nanofluidics, and from cell migration and cancer-induced angiogenesis to the modeling of artificial schools of fish.

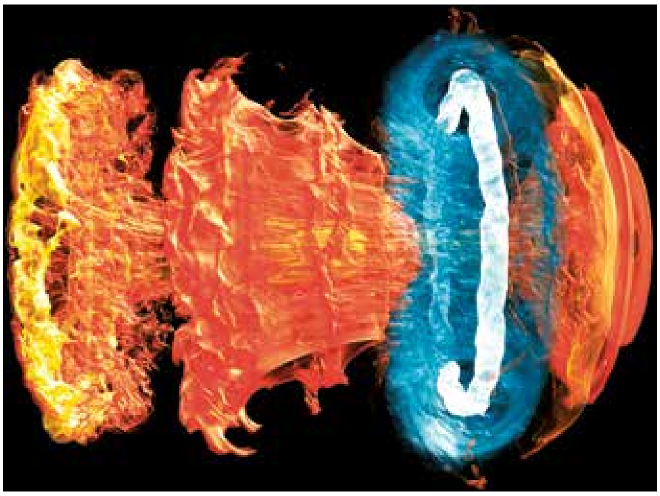

Figure 1: 3D simulations of shock-bubble interaction (density volume rendering)

"We shall not cease from exploration, and the end of all our exploring will be to arrive where we started and know the place for the first time." Thomas S. Eliot

Our research interfaces between information technology and numerical mathematics as we seek to understand fundamental phenomena pertaining to applications in science and engineering. We recognize that several challenging scientific problems have a multi-scale and multiphysical character. We seek to address these problems by developing suitable models and related numerical methods and emphasizing their effective implementation in modern computer architectures. We appreciate the availability of an ever-increasing amount of data from related real-world systems and experimental studies. We develop algorithms that are capable of integrating large quantities of data into models with predictive capabilities.

We consider the application of fluid mechanics to be a core competence of our group, as these emerge across a number of scales and disciplines. We actively seek out collaborations with domain scientists in biology and nanotechnology to elucidate the role of fluid mechanics in these disciplines. Some of the questions we ask are: How do drug-bearing nanoparticles and cancer cells get transported through the body's vasculature? What can we learn about engineering applications from schooling fish? Besides application-oriented questions, we also consider fundamental aspects of computational science. How can we better interface models and data, by taking advantage of learning and evolutionary processes observed in nature? How can we achieve the best performance for our codes with currently available computing hardware?

In order to achieve these goals, we develop original imaging, simulation, optimization and uncertainty quantification software that is made openly available to the scientific community. We emphasize the concurrent development and application of computational methods and pursue an integrative ("learning by discovery") approach in the education of our lab members. We seek to maintain the highest standards on all components of our interdisciplinary research and strive for an open, inclusive, inquisitive and free-thinking environment in all aspects of our research and educational activities.

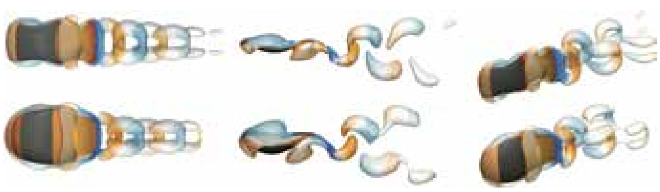

Figure 2: Vortex structures in the wake of optimal fast (top) and efficient (bottom) self-propelled swimmers

Prof. Petros Koumoutsakos
Chair of Computational Science

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Professor Koumoutsakos is a Greek/Swiss citizen, born in 1963. He received his Diploma (1986, National Technical University of Athens, Greece) and a Master degree (1987, University of Michigan, Ann Arbor, USA) in Naval Architecture. He received a Master (1988) and doctoral degree in Aeronautics and Applied Mathematics (1993, California Institute of Technology, US). He was a US National Science Foundation (NSF) fellow in parallel computing (1993–1994, Caltech Center for Research on Parallel Computation, US) and a research associate with the Center for Turbulence Research (1994–1997, NASA Ames/Stanford University, US). He first joined ETH Zurich as Assistant Professor of Computational Fluid Dynamics (1997–2000). He became Full Professor of Computational Science in 2000 in the Department of Computer Science at ETH Zurich and was the Director of the Institute of Computational Science (2001–2005). He was the founding director of the ETH Zurich Computational Laboratory (2000–2007). Prof. Koumoutsakos joined the D-MAVT in 2012.
He serves as an associate editor for several journals in the field of computational science. In 2013 he received an Advanced Investigator Award from the European Research Council. He is an elected Fellow of the American Physical Society and Fellow of the American Society of Mechanical Engineers.

Highlights and achievements

Our main contributions are in the areas of computing, fluid mechanics, nanotechnolgy, biology and in particular the interfaces between these disciplines. Specifically, our achievements include:

Computing: Extensive development of open source, algorithms and software for imaging, simulation and optimization on scalable computer architectures. We achieved the largest-ever peak performance in computational fluid dynamics, with over 14.4 PFLOPS and using 13 trillion elements in simulations of two-phase flows (2013 Gordon Bell winner).

Fluid Mechanic: Benchmark simulations of bluff body flows and high Re number vortex reconnection. The simulation and optimisation of swimmers demonstrated that the escape patterns of fish are natural examples of optimal fluid dynamics.

Nanotechnology: State-of-the-art simulation of water interactions with graphene and carbon nanotubes. We elucidated and quantified the transport of water in carbon nanotubes by way of unprecedented molecular dynamics simulations.

Biology: The first-ever simulations of diffusion inside a realistic image of reconstructed cell organelles has led to a reevaluation of the diffusion constants of several molecules in biology. We presented the first 3D simulations of angiogenesis inside an extracellular matrix and developed open-source, highly-used image and video analysis software.

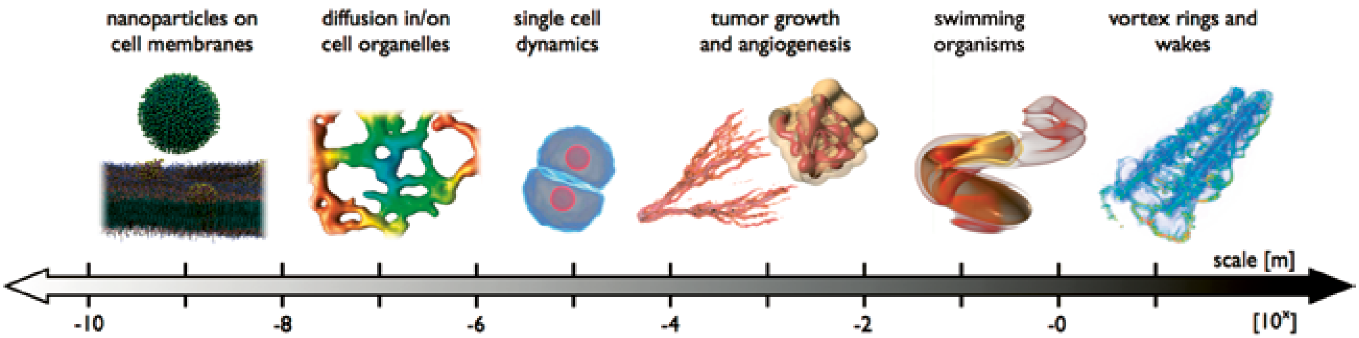

Figure 3: Simulations in the CSE Lab in Life Sciences, Nanotechnology and Fluid Mechanics spanning over 10 orders of magnitude

Goals and future priorities

We wish to respond to some of the world's most pressing challenges such as energy and environmental sustainability, and cancer. Motivated by these challenges, we pursue solutions to fundamental scientific problems as we seek to understand natural and engineered systems. We believe that modeling, simulation and optimization are enabling technologies that can address these challenges and we seek to enhance their capabilities through an active process of discovery and experimentation. We seek to close the gap between the capabilities of modern computer architectures and their effective utilization. We value an environment of active learning and free thinking as we aim to educate a new generation of scientists who understand, develop and use computing to advance science and to solve challenging engineering problems for the benefit of society.

Organization of the professorship

The Professorship employs one professor, one 20 % permanent staff member, one administrator, and on average four postdoctoral fellows and ten doctoral students. We have on average two external visitors in our lab. We work in an open, non-hierachical, collaborative environment.

Teaching activity

Our goal is to teach the fundamental concepts of computing to engineering students. We believe that engineers should have intimate knowledge of programming, be fluent in the use of scientific visualization, and be well educated in the fundamentals of information technology.

Figure 4: Molecular dynamics simulations of water being transported via micrometer-long carbon nanotube membranes.

We have initiated the development of a new joint ETH Zurich/University of Zurich doctoral program in Computational Science.
Our classes are fundamentally interdisciplinary. The course High Performance Computing is attended by 100 students from the departments of Computer Science, Mechanical Engineering, Physics and Mathematics. The course Computational Engineering is attended by 200 engineers and aims to provide principles of simulation and software engineering practices for object-oriented programming. Our course in Uncertainty Quantification for Engineering and Life Sciences is attended by biologists, computer scientsist and engineers.
Special courses are organized in technologies such as graphic processing unit (GPU) and multicore computing. Over the last 15 years this professorship has offered more than 20 different courses ranging from Machine Learning, to Numerics of Partial Differential Equations and Computational Fluid Dynamics.

Collaborations

Industrial
We have a long standing collaboration with IBM Zurich. Collaborations with industrial partners such as ABB and RUAG occur on a per project basis. We have initiated the development of Academia-Industry Modeling (AIM) weeks to promote active exchange on the topic of Modeling and Simulation.

Academic
We have an extensive network of collaborators, having published together with 12 different professorships at ETH Zurich and Swiss universities, as well as with ten different groups from the US, Europe and Japan. We participate in an active exchange program with the California Institute of Technology, the Danish Technical University and the University Joseph Fourier in Grenoble.

Fostering young academics

We recognize the challenges specific to being educated in an interdisciplinary domain and we actively pursue the promotion of young scientists through collaborations, conference organisation and extensive networking. The professorship has awarded 15 doctoral theses, with eight having received an ETH Medal (top 5 % of all ETH Zurich theses). Three doctoral students and five postdoctoral fellows have received offers of assistant professorships Europe, the US, and Japan. All doctoral students have received job offers within three months of their graduation while several lab members have received offers from various research institutions. Ph.D. graduates of the CSE-Lab have conducted postdoctoral work at Caltech, Harvard and Stanford University. Industrial employers of our graduates include ABB, MAN Turbo, Microsoft Research, IBM, Intellectual Ventures, DE Shaw Research.

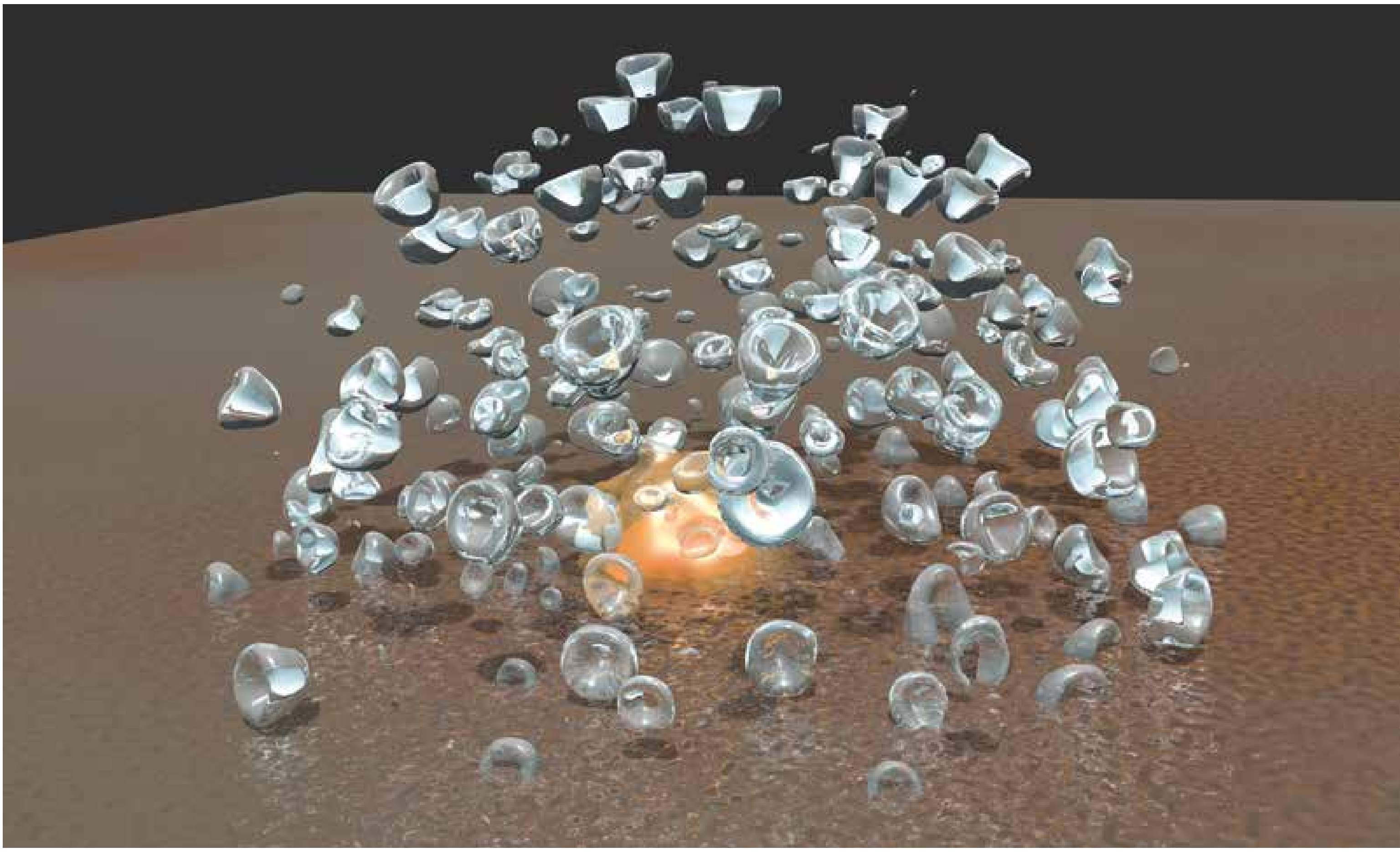

Figure 5: 14.4 PFLOPs simulations of Cloud Cavitation Collapse (2013 Gordon Bell Award in Supercomputing)

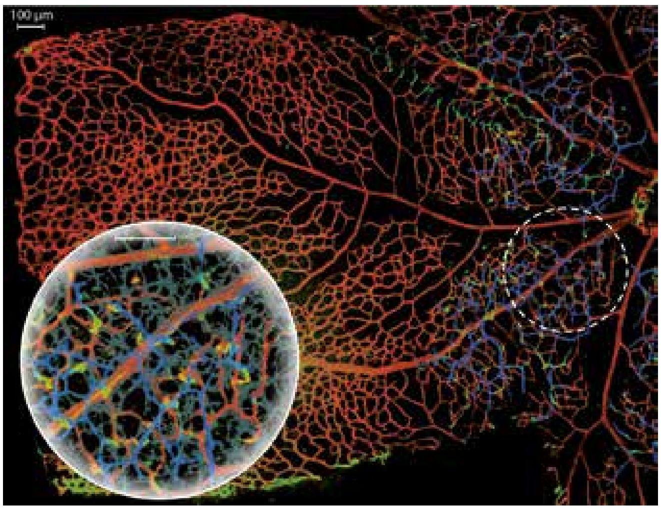

Figure 6: Developing vasculature in the mouse retina.
Depth dependent color map (red to blue).

Key publications

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Nonlinear Dynamics and Stability Theory

The research group Nonlinear Dynamics and Stability Theory investigates the nonlinear dynamic behavior of machines, devices and physical processes through the use of stability and bifurcation theory. A major focus of our research is the nonlinear dynamics of non-smooth systems; we therefore bridge the fields of nonlinear dynamics and non-smooth dynamics. In close cooperation with industry and experts from other fields, we investigate problems in robotics, machine dynamics, control theory, thermo-acoustics, mechatronics and geotechnics. Our mission is to explain nonlinear phenomena in various scientific fields through qualitative analysis, while both using and developing methods in nonlinear dynamics.

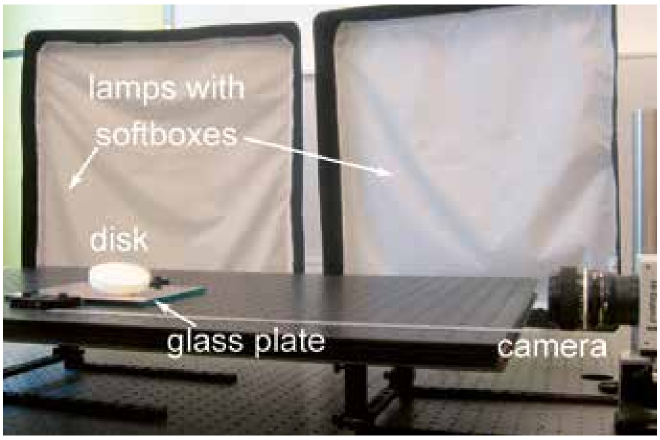

Figure 1: Experimental analysis of the Euler disk's finite-time singularity

The stability of non-smooth dynamical systems is a novel research field that has received increasing attention due to the rising use of non-smooth models in many engineering applications. Theorems for the stability properties of non-smooth systems are useful for both design and control purposes. The ongoing SNF Project "Synchronization of Dynamical Systems with Impulsive Motion" studies synchronization phenomena in mechanical systems that involve impact and friction. Synchronization for these types of non-smooth systems will be used to design state observers for impulsive systems.

The SNF project "Multibody Dynamics of Polygonized 3D Objects with Unilateral Frictional Contact: Application to Rockfall" is a collaboration with the WSL Institute for Snow and Avalanche Research SLF. As part of this project, we develop numerical methods as well as a simulation code for the simulation of the three-dimensional motion of polygonized objects with frictional unilateral contacts. These methods are tailored for the simulation of rockfall trajectories in hazardous areas in Switzerland. The simulation code has been integrated into the commercial natural hazards software developed and distributed by the SLF.

We study the nonlinear dynamics of thermo-acoustic instabilities in gas turbines as part of a joint project with ALSTOM Power Systems. In gas turbine combustion chambers, thermo-acoustic self-induced vibrations lead to high-amplitude pressure oscillations, which reduce the lifetime of the turbine and limit its capability for energy-efficient, low-emission operation. Thermo acoustic instabilities, which are mitigated with Helmholtz dampers, are usually analyzed with linear stability theory, which gives, at most, a local analysis of the dynamics involved. The aim of the project is to conduct a nonlinear stability analysis, thereby giving a global analysis of thermo-acoustic coupling in a damper-equipped combustion chamber.

We are conducting a combined experimental and theoretical analysis of Euler's Disk, a scientific toy that exhibits a finite-time singularity, and which has attracted much attention from the research community. Our high-speed camera measurements of the Euler Disk's motion, being the most accurate to date, clearly indicate that a type of rolling friction is responsible for the finite-time singularity. This insight runs contrary to the more commonly accepted viscous air dissipation hypothesis. Future work will study the stability of a tall cylinder, driven by a flexible shaft, which is in frictional contact with a supporting hyperplane.

Highlights and achievements

Stability theory
We have extended Lyapunov stability techniques to non-smooth dynamical systems. Our theoretical results are of direct use for tracking and position control. These are summarized in the book ***Stability and Convergence of Mechanical Systems with Unilateral Constraints***, which has been translated into Russian.

Multibody dynamics
We developed a 3D simulation software program for the prediction of rockfall trajectories. The simulation software, which uses state-of-the-art techniques from multibody dynamics and non-smooth dynamics, is currently being tested and will be commercially distributed in the near future.

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Since 2012, I have been Titular Professor with the Institute of Mechanical Systems and lead the research group Nonlinear Dynamics and Stability Theory, which is affiliated with the group Non-smooth Mechanical Systems run by Prof. Ch. Glocker. I received the Master degree from Delft University of Technology in 1996 and the Doctoral degree from Eindhoven University of Technology in 2000, both in mechanical engineering. In 2007 I obtained the Habilitation degree from the ETH Zurich and was appointed as a Privatdozent for Mechanics. I have been a postdoctoral researcher with the Technical University Munich, the Institut National de Recherche en Informatique et Automatique Rhône-Alpes (INRIA Grenoble), and the ETH Zurich. I received a fellowship from the Royal Dutch Academy of Sciences and have been with the Institute of Mechanical Systems at the ETH Zurich since 2003.

Analytical dynamics

We have formulated a generalized version of Hamilton's principle as variational inequality, which holds for systems with perfect unilateral constraints. This generalized variational principle will be of key importance in furthering the progress of stability theory and will be instrumental for the rigorous development of dedicated numerical methods for unilaterally constrained systems.

Teaching activity

I am currently responsible for the courses Nonlinear Dynamics and Technical Dynamics and, from 2010–2012, was responsible for the course Mechanics III for Civil Engineers.

Furthermore, I regularly lecture at international summer schools and workshops. I have been awarded the Golden Owl, the ETH prize for excellent teaching.

Nonlinear dynamics

The elective Master course Nonlinear Dynamics attracted over 90 students in the spring of 2013, making it one of the largest courses on this topic worldwide.

Technical dynamics

This course on Lagrangian dynamics has a solid foundation in the calculus of variations and the principle of virtual work. Each lecture is interwoven with accounts from the history of mechanics.

Collaborations

Industrial

- BOMBARDIER Transportation: condition monitoring of railway bogies
- KISTLER Instrumente AG: nonlinear phenomena in piezoresistive sensors
- ALSTOM Power Systems: thermo-acoustic instabilities of gas turbines

Academic

- WSL Institute for Snow and Avalanche Research SLF
- Eindhoven University of Technology
- NTNU Trondheim
- ETH (IRIS, BIRlab)

Key publications

Books:

- Leine, R.I. and van de Wouw, N.: ***Stability and Convergence of Mechanical Systems with Unilateral Constraints***, LNACM, 36, Berlin, Springer, 2008 (Russian translation 2011).
- Leine, R.I. and Nijmeijer, H.: ***Dynamics and Bifurcations of Non-Smooth Mechanical Systems***, LNACM, 18, Berlin, Springer, 2004 (second edition 2006).

Journal papers:

- Leine, R.I. et al.: "Simulation of rockfall trajectories with consideration of rock shape", Multibody System Dynamics, accepted, 2013.
- van de Wouw, N. and Leine, R.I.: "Robust impulsive control of motion systems with uncertain friction", International Journal of Robust and Nonlinear Control, 22(4), 369–397, 2012.
- Leine, R.I. and Heimsch, T.F.: "Global uniform symptotic attractive stability of the non-autonomous bouncing ball system", Physica D, 241, 2029–2041, 2012.
- Leine, R.I., Aeberhard, U. and Glocker, Ch.: "Hamilton's principle as variational inequality for mechanical systems with impact", Journal of Nonlinear Science, 19, 633–664, 2009.
- Leine, R.I.: "Experimental and theoretical investigation of the energy dissipation of a rolling disk during its final stage of motion", Archive of Applied Mechanics, 79(11), 1063–1082, 2009.
- Transeth, A.A., Leine, R.I., Glocker, Ch. and Pettersen, K.Y.: "3D Snake robot motion: Non-smooth modeling, simulations, and experiments", IEEE Transactions on Robotics, 24(2), 361–376, 2008.
- Leine, R.I. and van de Wouw, N.: "Uniform convergence of monotone measure differential inclusions: with application to the control of mechanical systems with unilateral constraints", International Journal of Bifurcation and Chaos, 15(5), 1435–1457, 2008.

Experimental Continuum Mechanics

We perform advanced experiments for understanding and modeling the mechanical behavior of novel engineering materials (e.g. dielectric elastomers) and soft biological tissue (e.g. liver, fetal membranes). We develop mathematical models and computational tools for simulation of materials and material systems. Our experiments investigate the mechanical response to large and non-homogeneous deformations related to multi-axial and time dependent mechanical loads. Our research aims to link continuum mechanics and material physics, and to bridge the gap between these scientific disciplines and their application in engineering and medicine.

Figure 1: Mechanical engineering students at the Mechanics 2 lecture

Our work relies on competencies and expertise in a variety of areas, including: conception and realization of novel experimental procedures; implementation of sensors, actuators and control algorithms; quantitative analysis of materials microstructures; modeling the whole experimental system; solving the inverse problem; and, formulating and implementing constitutive model equations into algorithms used in numerical calculations.

Our aspiration device for *in vivo* experiments on human organs is one example of how we have successfully applied these competencies. We developed dedicated hardware and software, implemented constitutive equations and optimization procedures into numerical codes for solving the inverse problem, and analyzed histological data for the physical interpretation of our mechanical models. We also designed and realized dedicated versions of the aspiration device, and successfully applied these to clinical studies in Switzerland and abroad.

Another example is our work on the mechanical behavior of human fetal membranes: characterizing and understanding the deformation behavior of the amnio-chorion layers is important for predicting and preventing their spontaneous or iatrogenic (in the case of fetal surgery) premature rupture. We developed protocols for measuring the response in multi-axial stress states, correlated mechanical parameters with biochemical data on collagen and elastin content, performed *in-situ* measurements in a multi-photon microscope, and developed constitutive model equations based on all observations. In collaboration with gynecologists, we apply the model to identify fetal membranes at risk of premature failure, to simulate medical procedures in order to minimize the risk of iatrogenic rupture, and to develop repair strategies.

Surgery planning based on finite element simulation of human organs is another important application of our models. We have developed anatomically detailed models of the human pelvic floor and of the face based on organ segmentations from medical images. Simulations are used to understand physiological and pathological deformations, thus providing new evidence for surgery planning and for assessing the *mechanical biocompatibility* of implants.

In collaboration with surgeons and implant manufacturer we evaluate the mechanical behavior of mesh implants, tissue engineered vascular grafts, and stents with the aim to optimize their integration and interaction with host tissues.

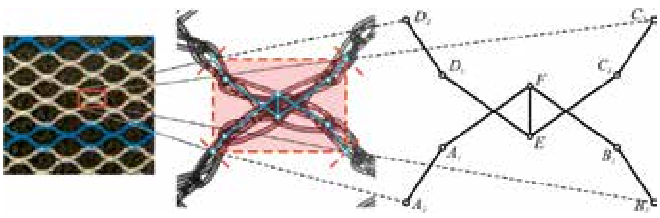

Figure 2: Multiscale model of medical mesh implants

Prof. Edoardo Mazza

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Institute of Mechanical Systems

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E. Mazza is 44 years old and has been Full Professor of Mechanics at ETH Zurich since 2010. He studied mechanical engineering and received his doctoral degree at ETH. He worked in industry until 2001, and was appointed as Assistant Professor at ETH in 2002; in 2006 he was appointed Associate Professor. He also leads the Mechanical Integrity of Energy Systems at EMPA, the Federal Laboratories for Material Science and Technology. 20 doctoral students have graduated from his group in the past eight years. He is author of more than 75 peer reviewed journal papers, has been lecturer of 35 courses at ETH, and has supervised more than 90 student projects. He has also served in various search committees at ETH, evaluation panels for academic institutions, organizing and scientific committees for international conferences, and has reviewed more than 150 journal papers. Noteworthy awards include the ETH Medal, the Golden Owl (Goldene Eule), and the ETH President's Award for merits in teaching (2010, 2011). He has been head of the Adaptive Materials program at EMPA, is board member of Inspire AG, head of the Institute of Mechanical Systems (since 2009), and head of the Teaching Commission (since 2011).

Highlights and achievements

During the past ten years we have performed a very large number of intra-operative experiments on abdominal and pelvic organs. Our aspiration measurements during laparoscopic intervention (Hollenstein et al., 2013, Medical Image Analysis) are a highlight of these experiments. Another is the successful execution of more than 1000 measurements on the uterine cervix of non-pregnant and pregnant women (Badir et al., 2013, Prenatal Diagnosis). An ongoing international clinical study aims to evaluate the relevance of this approach in the prediction of preterm delivery.
Our multiaxial characterization of the non-linear and time-dependent mechanical behavior of dielectric elastomers and soft biomembranes has received significant attention in the scientific community. We recently showed that amnion possesses highly remarkable mechanical properties, and we rationalized these based on the characteristics of amnion's microstructure (Bürzle et al., 2013, J. Biomech.).
In teaching, we have developed a comprehensive and effective program for education in mechanics (three Bachelor and two Master/Ph.D. courses).

Goals and future priorities

Our focus in the future will remain on biomedical applications. Priorities will be on (i) *in-vivo* mechanical characterization for diagnostic purposes; (ii) fetal membrane models for reducing risk of premature rupture; (iii) fundamental understanding of the deformation behavior of biological membranes (continuum and fiber network models); (iv) modeling of muscles in face and pelvic floor; (v) application of the paradigm of "mechanical biocompatibility" for the optimization of medical meshes, tissue engineered grafts, and stents; (vi) tissue engineered hyperelastic biomembranes (e.g. for fetal membrane repair, artificial heart).

We will further develop collaborations with hospitals and biomedical companies in Switzerland, Europe and the US. External support for research will be maintained at a high level, based on grants from ETH, SNF, EU and from industry.

Figure 3: Cyclic inflation experiment on human fetal membrane (diameter 50 mm)

Figure 4: Tissue aspirator for mechanical characterization of the ecto-cervix in pregnancy

In teaching, I plan to continue supporting undergraduate mechanics courses. In the near future I will set-up a new course on the mechanics of soft biological tissue (micro-structural mechanisms of deformation, tools for analysis, experiments, models and their implementation for simulations, and medical applications).

Organization of the professorship

My group at ETH currently includes: eleven Ph.D. students, one senior scientist, one postdoc, 15 Master students, one part-time secretary (20%), two part-time technicians (30%). The group is part of the Institute of Mechanical Systems (IMES). With our colleagues at the IMES we share responsibility for a large number of undergraduate courses, we organize regular Ph.D. seminars (where students present their research), and a seminar in mechanics (with external speakers). We also share common research infrastructure, including computer systems, a workshop and an electronics lab.

I have also the responsibility for a laboratory at EMPA. The group includes two senior scientists, eight Ph.D. students, two engineers, one technician, one part-time secretary (20%), and a few undergraduate students. The activities of this group are described in www.empa.ch (Mechanical Integrity of Energy Systems). See also next page.

Teaching activity

In the past five years I have been lecturer of 25 courses at ETH, including ten basic lectures (14x3 hours + tutorials/exercises) and fifteen advanced lectures (14x2 hours+ tutorials/exercises). The content of each course is summarized hereafter. I have also supervised more than 70 Bachelor and Master student projects.

Mechanics 1 (mechanical and civil engineers, up to 800 students, in German): Position of a material point, velocity, kinematics of rigid bodies, forces, mechanical power. Statics: groups of forces, moments, equilibrium, statics of systems, principle of virtual power, trusses, frames, forces in beams, friction.

Mechanics 2 (mechanical and civil engineers, up to 800 students, in German): Strength of materials: stress tensor, strain tensor, linear elastic stress strain relation, tension, bending and torsion of beams, numerical methods, elastic strain energy, energy methods.

Procedures for structural analysis (3rd year course, 30–40 students, in German): Basic theories for structure integrity calculations with focus on strength, stability, fatigue and elasto-plastic structural analysis. Theories for one dimensional and planar structures are derived based on energy theorems.

Continuum mechanics for engineers (final year course, 30-40 students/Ph.D., in English): Constitutive models including anisotropic linear elasticity, linear viscoelasticity, plasticity, viscoplasticity. Homogenization theories and laminate theory. Engineering applications and experiments.

Non-linear continuum mechanics (final year course, 30–40 students/Ph.D., in English): An introduction to finite deformations and nonlinear material behavior. Basic tensor manipulations and calculus, kinematics and balance laws. Discussion of invariance principles and elastic mechanical response.

Together with Prof. Dual and Prof. Glocker we shared the responsibility for two additional undergraduate courses in electrical (200 students) and geomatic engineering (90), lecturer: Dr. S. Kaufmann.

Fostering young academics

Former postdoc M. Jabareen is now a senior lecturer at Technion, and A. Ehret received an ETH-Fellowship (promotion of excellent postdoctoral researchers). Of the 20 Ph.D. students who have graduated from the lab in the past eight years, one has an ETH pioneer fellowship (program for realization of highly innovative products), two are entrepreneurs in spin-off companies, one is professor at the University of Applied Science, four have held postdoc positions, and all others are working for industry in Switzerland or abroad.

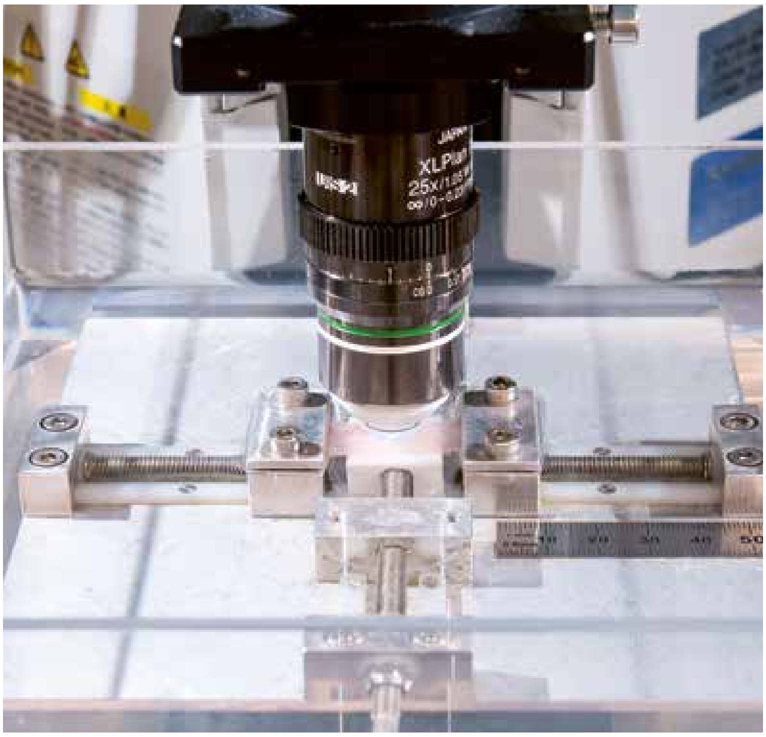

Figure 5: Set-up for *in-situ* measurements in the multiphoton microscope

Figure 6: Mounting a mesh implant testpiece in the biaxial machine

EMPA's laboratory: Mechanical Integrity of Energy Systems

Mechanical models are essential for the development of modern and highly efficient energy systems, in that they provide the means to optimize design, to understand and predict failure of mechanical parts, and to thus ensure the integrity and reliability of mechanical components. Classical, but for many applications still unresolved questions reside in the definition of equations that describe the non-linear, time and history dependent force-deformation behavior of materials (constitutive modeling, continuum mechanics) as well as the service history dependent deterioration of materials (damage mechanics). Advanced high temperature testing (see figure), and material structure damage condition assessment are performed for a variety of applications ranging from diesel engines, to steam and gas turbine components, and high voltage power line conductors.

Set-up for service-like thermomechanical fatigue experiments

Key publications

- Mazza E., Parra-Saavedra M., Bajka M., Gratacos E., Nicolaides K., Deprest J., 2014, In vivo assessment of the biomechanical properties of the uterine cervix in pregnancy, Prenatal Diagnosis, 34, 33-41
- Röhrnbauer B., Mazza E., 2014, Uniaxial and biaxial mechanical characterization of a prosthetic mesh at different length scales, Journal of the Mechanical Behavior of Biomedical Materials, 29, 7-19
- Mauri A., Perrini M., Mateos J.M., Maake C., Ochsenbein-Koelble N., Zimmermann R., Ehrbar M., Mazza E., 2013, Second Harmonic Generation Microscopy of Fetal Membranes under Deformation: Normal and Altered Morphology, Placenta, 34, 1020-1026
- Bürzle W., Mazza E., 2013, On the deformation behavior of human amnion, J. Biomech., 46
- Hollenstein M., Ehret A. E., Itskov M., Mazza E., 2011, A novel experimental procedure based on pure shear testing of dermatome-cut samples applied to porcine skin. Biomech. Mod. Mechanobiol., 10
- Barbarino G., Jabareen M., Trzewik J., Nkengne A., Stamatas G., Mazza E., 2009, Development and validation of a 3D finite element model of the face, J. Biomech. Eng., 131 - ***cover***
- Jabareen M., Mallik A.S., Bilic G., Zisch A.H., Mazza E., 2009, Relation between mechanical properties and microstructure of human fetal membranes: an attempt towards a quantitative analysis, Europ. J.Obst. and Gyn. and Repr. Biol., 144
- Mazza E., Nava A., Hahnloser D., Jochum W., Bajka M., 2007, The mechanical response of human liver and its relation to histology: an in vivo study, Medical Image Analysis, 11
- Mazza E., Nava A., Bauer M., Winter R., Bajka M., Holzapfel G.A., 2006, Mechanical properties of the human uterine cervix: an in vivo study, Medical Image Analysis, 10
- Wissler M., Mazza E., 2005, Modeling and simulation of dielectric elastomer actuators, Smart mat. struct., 14

Separation Processes Laboratory

"To develop efficient, safe, and sustainable processes for high quality products and environmentally responsible systems" is the vision of the Separation Processes Laboratory (SLP). Its mission is to educate future engineers and scientists, trained in the science and engineering of economically optimized and environmentally beneficial separation processes, by carrying out cutting edge research in the areas below.

SPL research deals with adsorption-based separations and chromatography, and with crystallization processes. Applications are in the purification of biopharmaceuticals and in carbon dioxide capture and storage systems.

Figure 1: «Prima di essere ingegneri, voi siete uomini» (F. De Sanctis, 1860)

Crystallization and precipitation

Our ultimate goal is that of controlling product quality in terms of purity and particle size and shape distribution (PSSD), by using first-principles process modeling. Constitutive equations for all the relevant mechanisms are obtained through characterization protocols that exploit state-of-the-art monitoring tools (Fig. 3).

Highlights: the development of a fully predictive model of precipitation, growth and agglomeration of L-glutamic acid [1]*; the optimization of the combined cooling and anti-solvent crystallization of acetyl-salicylic acid [3]*; the elucidation through PBE modeling of the highly debated mechanism of the Viedma ripening process [7]*; the realization of a unique instrument for the on-line measurement of PSSD of particles [8]*; the molecular modeling of face-selective growth of urea crystals in the presence of additives [9]*.

Adsorption and chromatography

Besides multi-column continuous chromatographic processes (SMB), where SPL has a worldwide leadership particularly for chiral separations, also cyclic gas phase separation processes for CO_2 capture (PSA/TSA) have become a core activity; in both areas the focus is on model-based design, optimization and control.

Highlights: the development of an array of new Simulated Moving Bed processes (EE-SMB, I-SMB, 3C-ISMB), see review [2]*; the theoretical discovery of the delta-shock [5]*, a brand new phenomenon in nonlinear chromatography, then demonstrated experimentally [6]* (see also Mazzotti M., Rajendran A., Equilibrium Theory–Based Analysis of Nonlinear Waves in Separation Processes, Annu. Rev. Chem. Biomol. Eng. 4 (2013) 119-141)."

CO_2 capture and storage

There are two main thrusts, namely researching second and third generation technologies (adsorption-based capture, storage in coal seams, mineral carbonation) and promoting system-level integrating activities in both Switzerland and Europe, with the ultimate goal of setting up pilot tests.

Highlights: experimental and modeling characterization of CO_2 injection in coal [4]*; the design and validation of a lab-pilot PSA unit for pre-combustion CO_2 capture [10]*; co-authorship of two monographs for the American Physical Society ("Direct air capture of CO_2 with chemicals – A technology assessment for the APS POPA", 1–100, 2011), and of the European Academies Science Advisory Council ("Carbon capture and storage in Europe – EASAC policy report 20, 1–86, 2013).

Highlights and achievements

- Marco Mazzotti has published more than 220 peer-reviewed articles (100 from 2007 until now), 2 monographs, and about 30 articles in books. He has an h-factor of 38 (20 years after promotion), corresponding to about 5000 citations (w/o self-citations).
- 28 doctoral students have graduated with him and 12 are currently advised by him. 18 promotions were in

* reference to Key Publications

Prof. Marco Mazzotti

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Marco Mazzotti, an Italian and Swiss citizen born in 1960, married, with two children, has been professor of process engineering at ETH Zurich since May 1997 (associate until March 2001 and Full Professor thereafter). He holds a Laurea (MSc, 1984) and a Ph.D. (1993), both in Chemical Engineering and from the Politecnico di Milano, Italy. Before joining ETH Zurich, he had worked five years in industry (1985-1990), and had been Assistant Professor at the Politecnico di Milano (1994–1997). He was coordinating lead author of the IPCC Special Report on CCS (2002-2005). He was President of the International Adsorption Society (2010–2013) and is an active member of the Working Party on Crystallization of the EFCE. He is chairman of the Board of the Energy Science Center of the ETH Zurich (since 1.11.2011) and one of the six Executive Editors of Chemical Engineering Science (since 1.1.2012). He was a contributor to the Nobel Peace Prize for 2007 awarded to the Intergovernmental Panel on Climate Change (IPCC).

2007–12, awarded with 4 ETH Medals and 1 ABB Prize. No doctoral student has ever quit SPL after starting their doctoral program.

> He was the chair of the 9th International Conference on Fundamentals of Adsorption FOA9 (Taormina, I, May 20–25, 2007), and of the 18th International Symposium on Industrial Crystallization (Zurich, CH, September 15–16, 2011).

> He has been coordinator of the project CARMA (Carbon Management in Swiss Power Generation, 2009–12), of the project "Roadmap for a Carbon Dioxide Capture and Storage pilot project in Switzerland" (funded by the UVEK, 2012–13), of the Swiss participation in the EU/ESFRI program ECCSEL (European Carbon dioxide Capture and Storage Laboratory Infrastructure).

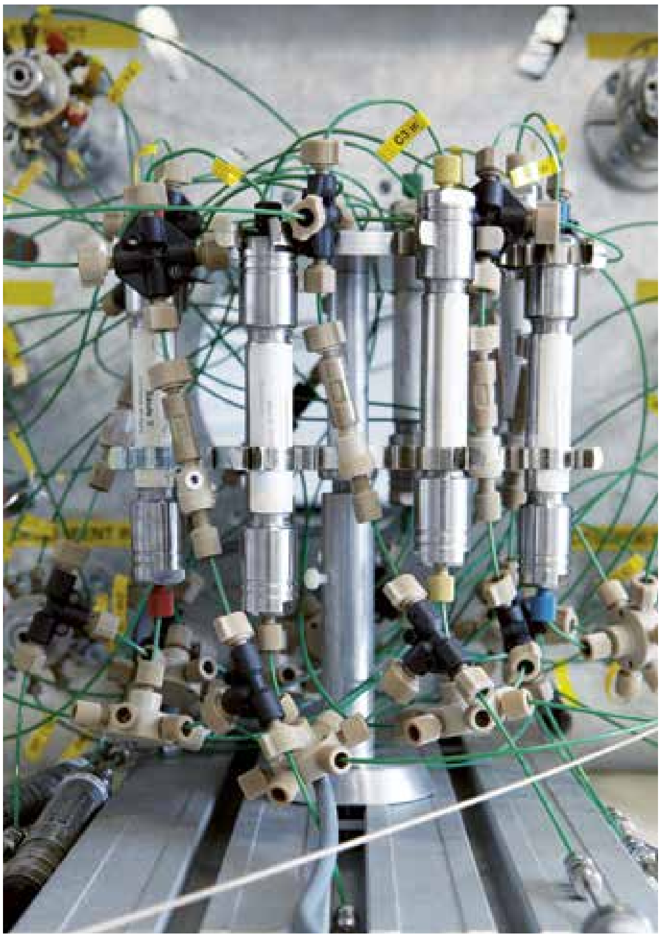

Figure 2: «Parlare oscuramente lo sa fare ognuno, ma chiaro pochissimi» (G. Galilei, 1590)

Goals and future priorities

People
Further enhance scientific quality and professional potential of graduate students, for their own sake and for the benefit of the society and scientific community.

Crystallization and precipitation
Further strengthen our scientific impact in the fundamentals (nucleation, molecular modeling, ripening), the monitoring and characterization (particle size and shape distribution), the process optimization and control, while addressing new applications (deracemization via Viedma ripening, heat storage using phase change materials, functionalization of implants).

Chromatography
Consolidate our leadership position in the theory and optimization of nonlinear multi-column continuous chromatography, while increasing its penetration into applications.

CO_2 capture and storage
Continue the development of second and third generation CO_2 capture technologies (adsorption-, absorption- or precipitation-based), and lead the process towards pilot-testing CO_2 capture and, above all, CO_2 geological storage in Switzerland.

Separation processes
To make a targeted effort to enhance our technology portfolio (e.g. membranes) and our application range (e.g. water treatment).

Figure 3: «...fatti non foste a viver come bruti, ma per seguir virtute e canoscenza» (Dante, 1321) [Inferno XXVI]

Organization of the professorship

SPL personnel consists of Prof. Marco Mazzotti, a part-time administrative assistant, a chemical lab technician, a workshop technician, two scientists shared with the Swiss Seismic Service (affiliated to ETH/ERDW) and with the lab of Prof. Parrinello (ETH/CHAB, located in Lugano), a couple of postdoc research associates and ten to twelve doctoral students. A varying number of Master, Bachelor and visiting students are present too. IT support is provided by ETH/MAVT.

Group structure is horizontal. Cooperation among Ph.D. students is strongly encouraged, to guarantee knowledge transfer, development of team work attitudes, and mutual support. Doctoral students support teaching activities by supervising student projects, running lab Practica, and managing home assignments.

Experimental research can be conducted in cutting edge facilities featuring automated lab-pilot units for PSA/TSA processes, mineral carbonation (Fig. 1), supercritical fluid assisted precipitation, SMB processes (with online controller, Fig. 2). Characterization techniques are available for particle size and shape distributions, adsorption isotherms, as well as spectroscopic instruments for online process monitoring. Funding is from ETH, SNF, KTI, EU, and industry.

Teaching activity

Teaching approach
Lectures, using slides and blackboard, with focus on fundamentals, thorough derivations, quantitative aspects. Intensive student interaction and challenging exercises.

Mechanical Engineering Bachelor:
> Introduction to Chemical Engineering (4^{th} sem., elective): bridging chemistry to engineering, by teaching phase equilibria, kinetic theory of gases, particle formation and chemical reactors.
> Focus Project on Energy (5^{th} and 6^{th} sem., elective): a team of 5 students in HS2011–FS2012: "Geological storage of carbon dioxide", with the goal to design, build and operate a show-case that demonstrates visually but rigorously how CO_2 stored in deep saline aquifers migrates and is permanently trapped (in Fig. 4 a typical injection demonstration).

Process Engineering Master (8^{th} sem., core course) and Chemical Engineering Bachelor (6^{th} sem., compulsory):
> Separation Process Technology: non-empirical design of gas-liquid and liquid-liquid unit operations.
> Modeling and Mathematical Methods in Chemical and Process Engineering: non-numerical solution of systems of ODEs and first order PDEs, with application to chemical kinetics, batch distillation, chromatography.
> Practica in Process Engineering: hands-on in the unit operations laboratory.

Process Engineering Master and Chemical and Bioengineering Master (7^{th} sem., elective):
> Rate Controlled Separations in Fine Chemistry: crystallization, membrane processes, adsorption separation processes (including preparative chromatography).

Various Masters (including Energy Science and Technology Master):
> Carbon Dioxide Capture and Storage (CCS): introduction to CCS systems and related technologies, with internal and external lecturers.

Fostering young academics

Doctoral students attend 2–3 scientific conferences per year to present their work, to make experience, to gain visibility, to build a network. After doctoral studies, those interested and gifted are encouraged and supported in seeking positions in academia outside ETH. Former SPL associates are faculty at University of Alberta, Colorado School of Mines, University of Qatar, Royal Institute of Technology Stockholm, and in Universities of Applied Sciences in Switzerland; others are postdocs in various institutions abroad.

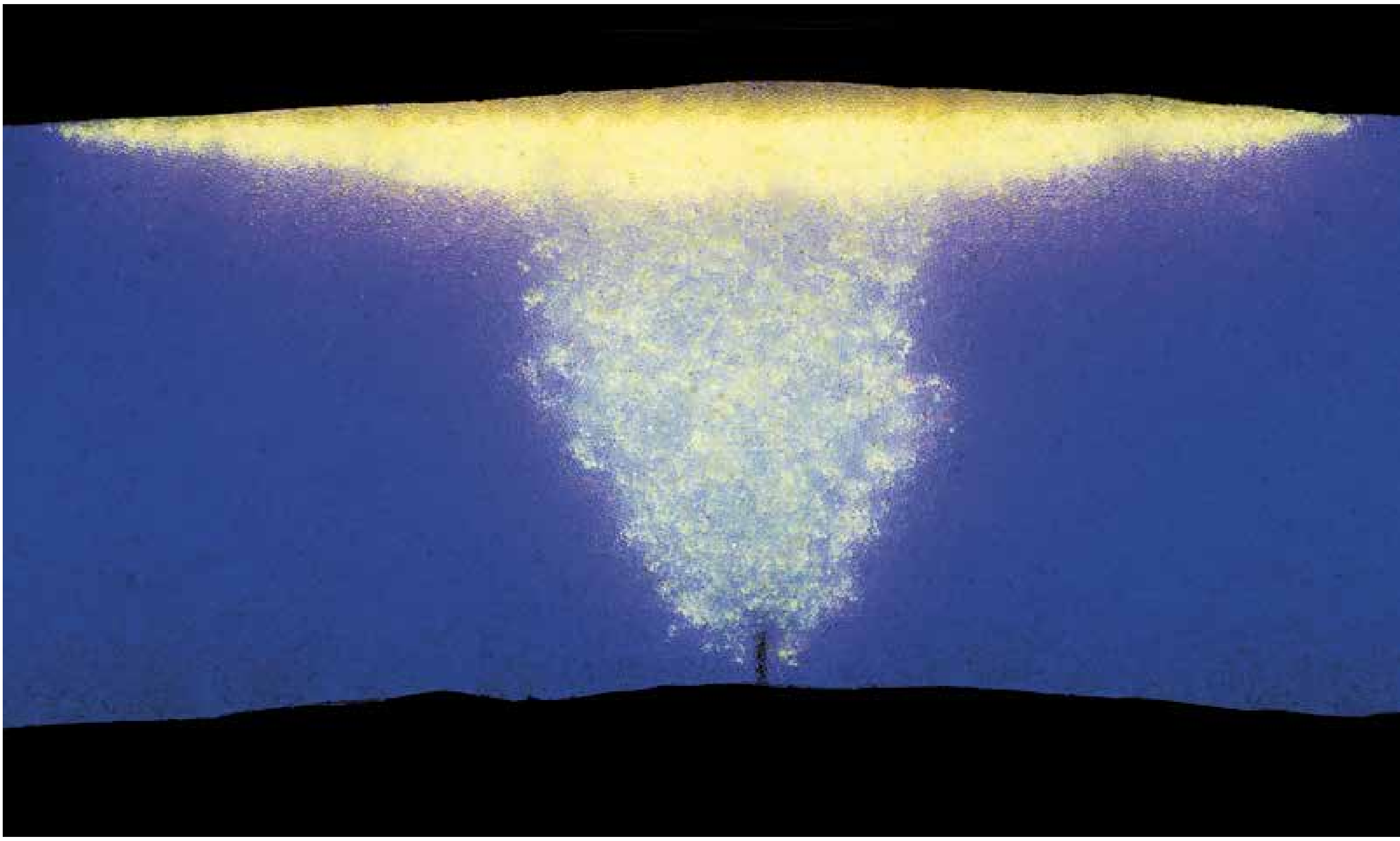

Figure 4: «...ad ora ad ora m'insegnavate come l'uom s'etterna» (Dante, 1321) [Inferno XV]

Collaborations

Industrial

> Crystallization and precipitation: Actelion (CH), Astra Zeneca (SE), BASF (DE), Lonza (CH), Mettler Toledo (CH), Novartis Pharma (CH), Roche (CH).

> CO_2 capture and storage: ABB (CH), Alstom (CH), Casale (CH), Shell (NL).

> Preparative chromatography: BASF (CH), Bayer (DE), Carbogen Amcis (CH), GE Healthcare (DE and SE), SK Innovation (ROK), Unilever (NL).

Academic

> Crystallization and precipitation: J. Baldyga, Warsaw (PL), B. Gander, ETH/CHAB; D. Marchisio, Torino (I); M. Morari, ETH/ITET; M. Parrinello, ETH/CHAB.

> CO_2 capture and storage: R. Baciocchi, Rome (I); R. Blom, Sintef (N); L. Burlini, ETH/ERDW (deceased); S. Hirschberg, PSI (CH); K.S. Lackner, Columbia (US); F. Marechal, EPFL (CH); R.H. Socolow, Princeton (US); G. Storti, ETH/CHAB; S. Wiemer, ETH/ERDW.

> Preparative chromatography (all completed): G. Guiochon, Univ. Tennessee (US); M. Morari, ETH/ITET; M. Morbidelli, ETH/CHAB; H.-K. Rhee, SNU (ROK).

Key publications

> [1] Lindenberg C., J. Schöll, L. Vicum et al., L-glutamic acid precipitation: agglomeration effects, Cryst. Growth Des. 8 (2008) 224–237.

> [2] Rajendran A., G. Paredes, M. Mazzotti, SMB chromatography for the separation of enantiomers, J. Chrom. A 1216 (2009) 709–739.

> [3] Lindenberg C., M. Krättli, J. Cornel et al., Design and optimization of a combined cooling/antisolvent crystallization process, Crys. Growth Des. 9 (2009) 1124–1136.

> [4] Pini R., S. Ottiger, L. Burlini et al., Role of adsorption and swelling on the dynamics of gas injection in coal, J. Geophys. Res. 114 (B04203) (2009) 1–14.

> [5] Mazzotti M., Nonclassical composition fronts in nonlinear chromatography: Delta-shock, Ind. Eng. Chem. Res. 48 (2009) 7733–7752.

> [6] Mazzotti M., A. Tarafder, J. Cornel et al., Experimental evidence of a delta-shock in nonlinear chromatography, J. Chrom. A 1217 (2010) 2002–2012.

> [7] Iggland M., M. Mazzotti, A Population Balance Model for Chiral Resolution via Viedma Ripening, Cryst. Growth Des. 11 (2011) 4611–4622.

> [8] Schorsch S., T. Vetter, M. Mazzotti, Measuring multidimensional particle size distributions during crystallization, Chem. Eng. Sci. 77 (2012) 130–142.

> [9] Salvalaglio M., T. Vetter, F. Giberti et al., Uncovering Molecular Details of Urea Crystal Growth in the Presence of Additives, J. Amer. Chem. Soc. 134 (2012) 17221–17233.

> [10] Schell J., N. Casas, D. Marx.et al., Precombustion CO_2 Capture by Pressure Swing Adsorption (PSA): Comparison of Laboratory PSA Experiments and Simulations, Ind. Eng. Chem. Res. 52 (2013) 8311–8322.

Product Development and Engineering Design

Product development and engineering design are in regard to research and education, an important field for academia and industry. The research focus of the Product Development Group Zurich (pd|z) is related to industry oriented product development methods, processes and complex engineering systems. Engineering products are today characterized by the integration of different domains and technologies – this interdisciplinarity is a major challenge. The group has three main research areas: human behavior, focusing on customer needs and engineering decisions, design for new technologies, fostering new technologies for new engineering solutions and validation of complex bio mechatronic systems.

Figure 1: 2nd semester Bachelor students working on an Innovation Project for engineering design

People – human behavior

Relevance: Human behavior is a central aspect of engineering design. Design methods and processes are developed to support the stakeholders in product development. Until recently, human-centered design methodologies have not been widely accepted and our research responds to a strong need for improvement in this area. In addition to supporting stakeholders, our methods also take into account the users/customers for a given product. As a result of new research methods in cognitive science, completely new opportunities have opened up for design research in this area.
Main activities: Setting up of an eye tracking lab; developing an eye tracking study with engineers to analyze technical product representations; developing an eye tracking study with customer/users to analyze behavior in real applications; founding the Eye Tracking Interest Group Zurich (involving 12 institutes from across ETH Zurich, UZH[1] and University Hospitals); initializing an international conference in this field (that will take place in October, 2014 and funded by ETH Centro Stefano Franscini (CFS); and serving as Co-Chair of the international special interest group Human Behavior in Engineering Design of the Design Society.

Technologies – design for new technologies

Relevance: Applying new technologies in product development is important to be competitive. The challenge is that there are only rare or even no existing design expertise, methods or guidelines for these new technologies. It is essential to provide engineers with design knowledge in order to apply these technologies. Our particular focus in this area is on developing applications and training engineers in AM[2] and machine elements for medical devices.

Main activities: Developing a research project on additive manufacturing (Design Patterns and Strategies for AM); founding the Design for AM Group in collaboration with Inspire AG; founding the special interest group Additive Manufacturing and 3D Printing in collaboration with seven other institutes; working on a joint research proposal for the Zurich Heart initiative; developing the Programmable Mechanical Cylinder Lock project, which is funded by the CTI[3].

Validation – prototyping and iterations

Relevance: Validation is about assuring that a product/system meets the needs of the user/customer. In classical design approaches, validation is understood as a stage at the end of the development process. With the opportunities provided by rapid prototyping hardware/software-in-the-loop approaches, validation becomes an activity integrated into all stages of the product development process.
Main activities: Conducting research for a project on validation (Adjustable Impedance Element); working on a prototyping project funded by Mobiliar Forum Thun (Ideation and Innovation for SME); collaborating with Stanford University in the field of prototyping.

[1] University of Zurich (UZH)
[2] additive manufacturing (AM)
[3] Commission for Technology and Innovation (CTI)

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Mirko Meboldt (*1975) has been Full Professor of Product Development and Engineering Design at ETH Zurich since June 1st, 2012.
Prof. Meboldt studied mechanical engineering at the University of Karlsruhe (KIT) and graduated with a Dipl.-Ing. degree in the area of product development and engineering design in 2002.
He continued as a research associate at the Institute of Product Engineering Karlsruhe (IPEK) Institute. After receiving his doctoral degree in 2008, Prof. Mirko Meboldt started his industrial career at Hilti AG in Liechtenstein where he was globally responsible for CAD/PDM[4] systems, standardization, and development methods. In his last position at Hilti he was responsible for global technology and product development processes.

Highlights and achievements

International research community
- Co-Chair of the special interest group Human Behavior in Design (The Design Society)
- Initiation of the international conference Human Behavior in Design: Elaborating Possibilities with New Research Methods (14–17.10.2014)

Initialization of local research communities
- Eye Tracking Interest Group Zurich (six seminars p.a.)
- Additive Manufacturing and 3D Printing Interest Group Zurich (four seminars p.a.)

Academic collaboration
- Hosted visiting postdoctoral researcher for three months from Stanford Engineering Design Center

Research and industry
- Funded CTI-Project with KABA AG
- Member of the Zurich Heart project
- Three-year funded project with Mobiliar Forum Thun
- Lead Professor and group of Inspire AG
- Lead the Customer Integration working group within the Innovation Network

Education
- Redesign of the first year engineering design education: introduced problem-based learning in a design project with 500 students including production and testing
- New educational framework for student focus projects: established basecamp and practice courses
- Taught at Erasmus Summer School on Embodiment Design at TU Delft
- ETH Program Director of the European Program Unitech

Goals and future priorities

Best-in-class engineering design education
- Increase team- and problem-based learning in education at the Bachelor level (approximately 500 students) and build up a design workshop to incorporate production and testing into engineering design education
- Implementation of the Coach the Coaches framework for teaching assistants to increase teaching quality
- Foster interdisciplinary education with other departments and other universities

Human-centered design methods
- Develop evidence-based research methods in the field of engineering design
- Conduct studies with engineers in order to develop human-centered design methods

Figure 2: Design for additive manufacturing

[4] computer-aided design/product data management (CAD/PDM)

- Innovate new methods for customer integration into product development processes

Prototyping and validation in design processes
- Design systematic prototyping and validation methods for all development stages in order to provoke early iterations

Design for additive manufacturing (AM)
- Create methods for identifying AM potential and support design for AM
- Establish AM as common design practice for serial products

Machine elements with additional features
- Create mechatronic machine elements with variable passive stiffness and damping behavior
- Design machine elements for biomedical applications

Organization of the professorship

To increase the visibility of ETH Zurich in the field of engineering design, a new institute was founded involving three design-related chairs: Kristina Shea (Chair in Engineering Design and Computing), Paolo Ermanni (Institute of Mechanical Systems, Chair of Composite Materials and Adaptive Structures) and Mirko Meboldt (Chair in Product Development and Engineering Design). The new group, named the Institute of Design, Materials and Fabrication (IDMF), began its activities on July 1st, 2013.
IDMF will foster high-level education at the Bachelor level, and will be responsible for coordinating basic education in engineering design at ETH. The Bachelor and Master curricula are clearly focused on combining academic education and project-based learning.
The Product Development Group Zurich has a flat structure that includes: one postdoc; four doctoral students; one external doctoral student; one technician; one industrial designer; one visiting postdoc; one administrative assistant; and one team leader from the Inspire AG Group (Design for Additive Manufacturing), an Industrial Committee for research exchange.

Teaching activity

Redesign of the engineering design education
For the last seven years, there has not been a chair in engineering design at ETH Zurich. Related lectures were split amongst different chairs. To ensure a consistent syllabus in Bachelor education, a redesign of the curriculum in this area is currently envisaged.

Road map redesign Engineering Design Education
1st and 2nd semester 2012–2014;
3rd to 6th semester 2013–2015;
Master level 2014.

2nd Semester innovation process/project
This project focuses on team- and project-based learning with a group of 500 students. The full proof of a design can only be experienced by testing the manufactured and assembled system. To give students this experience, we have incorporated manufacturing and testing directly into their education by implementing a learning infrastructure that includes CNC[5] laser cutters and test environments. With this infrastructure in place, students experience the complete development cycle of a product while receiving a parallel theoretical foundation in engineering design by way of lectures. Starting from an idea, and following through with a concept digital model, design freeze, CAD/CAM[4] production, assembly and testing, the students develop a deep understanding of the challenges involved in real design projects.

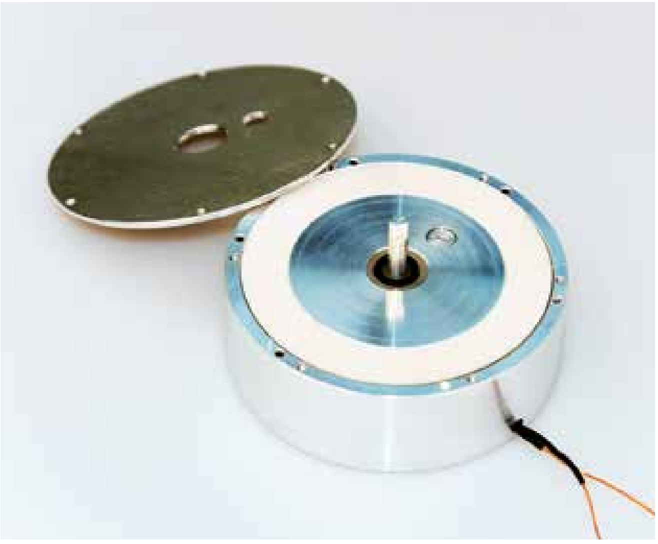

Figure 3: Prototype for an adjustable damping element, based on MR fluid

Fostering young academics

Young academics need access to both a scientific network to discuss their research and an industrial network to reflect their results in a practical context. Every doctoral student is responsible for a special interest group and/or an industrial working group.
In addition to their professional competencies they need to learn how to coach people in development and research projects. Every doctoral student is encouraged to coach a Focus Project with support from the Coach the Coaches framework.

[5] computer-numerical-control (CNC)

Figure 4: Analysis of human behavior by eye tracking

Main Courses: Innovation Process; Innovation Project; Machine Elements; Focus Projects; Base Camp for Focus Projects.

Tool Courses: Selecting and Dimensioning Mechanical Machine Elements.

Co-taught Courses: Cross-Disciplinary Research and Development in Medicine and Engineering (ETH & UZH[1]); Practice for Focus Projects on Product Development; Practice for focus projects on CAD and CAE.

Collaborations

Industrial

> Kaba; Mobiliar; Baxter; Geberit; E-plan; Bühler AG; Bystronic; Brusa; Inspire AG; Innovation Network CH.

Academic

> University of Zurich (Institute for Physiology); University Hospital (Clinic for Cardiac and Vascular Surgery); Stanford University (Center for Design Research); Norwegian University of Science and Technology Trondheim (Department of Engineering Design and Materials); Delft University of Technology (Design Methodology Group); Karlsruhe Institute of Technology (Institute of Product Engineering); Zurich University of the Arts (Industrial Design).

Key publications

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- Stücheli, M.; Meboldt, M. (2013): Mechatronic Machine Elements: On Their Relevance in Cyber-Physical Systems. In: CIRP Design Conference 2013. Bochum, Germany.
- Matthiesen, S.; Meboldt, M.; Ruckpaul, A.; Mussgnug, M. (2013): Eye Tracking, a Method for Engineering design Research on Engineers' Behavior while Analyzing Technical Systems. In: International Conference on Engineering Design ICED'13. Seoul, Korea.
- Leutenecker, B.; Meboldt, M.; Lohmeyer, Q. (2013): Impart ‹Design for Production' Knowledge by Application of Functional Prototyping. In: Engineering and Product Design Education E&PDE 2013. Dublin, Ireland.
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- Leutenecker, B.; Lohmeyer, Q.; Meboldt, M. (2013): Konstruieren mit generativen Fertigungsverfahren – Gestalterische Lösungen für die Substitution von Serienbauteilen. In: Design for X Symposium 2013. Hamburg.
- Stücheli, M.; Leutenecker, B.; Meboldt, M. (2013): Anthropomorphic and Linear Arm Models for Mechanical Power Tool testing. In: ASME IMECE 2013. San Diego, CA, US.

Laboratory of Energy Science and Engineering

Research in the Laboratory of Energy Science and Engineering (LESE) is aimed at applying fundamental insights obtained from experiments performed in well-controlled laboratory-scale systems to the industrial challenge of sustainable energy conversion. Such research requires a multidisciplinary approach that engages not only with aspects of chemical engineering, but with challenges related to material science, catalysis and the physics of particulate systems. The LESE's three main research areas are introduced below.

CO_2 capture

One possible mid-term strategy for mitigating climate change involves the capture and storage of CO_2; however, the current technology available for the CO_2 capture process, i.e. amine scrubbing, has very high and potentially prohibitive costs. Our laboratory is thus concerned with new schemes that could substantially reduce CO_2 capture costs. One of the CO_2 capture processes we are intensively studying is calcium looping, in which CO_2 is captured and subsequently released as a pure stream via the carbonation and calcination reactions of, respectively, CaO and $CaCO_3$. In particular, our laboratory develops new, highly efficient CaO-based CO_2 sorbents which possess a cyclically stable CO_2 capture capacity. These new materials are manufactured using advanced synthesis methods, such as sol-gel techniques, which allow a careful adjustment of the morphological and structural characteristics of the materials.

Hydrogen production

Currently, the dominant industrial process for producing hydrogen is steam-methane reforming (SMR). However, the SMR process requires a series of reactors and emits large quantities of CO_2. In our laboratory we are working, in collaboration with Prof. Christophe Copéret (Department of Chemistry and Applied Biosciences, ETH Zurich), on new materials for the so-called "sorbent enhanced" SMR process that would produce high-purity hydrogen while simultaneously capturing CO_2. In this single-step process, SMR reactions are run simultaneously with a CO_2 abstraction reaction, such as the carbonation of CaO. An important factor in making this process viable for use in industrial applications is the development of bi-functional materials that contain (i) a large weight fraction of the CO_2 sorbent, CaO and (ii) a reforming catalyst, such as Ni, that is highly dispersed and has a small particle size.

Figure 1: Equipment for studying the fast catalytic pyrolysis of biomass

Single- and two-phase granular systems

Single and two-phase granular systems are ubiquitous in industry with applications ranging from the production of cement in rotating kilns to the production of gasoline in fluid catalytic crackers. However, granular systems are poorly understood on a fundamental level owing to, amongst other factors, their highly non-linear characteristics and their opacity. Indeed, we do not currently have a set of governing equations, akin to the Navier-Stokes equations for fluids, that would allow us to describe granular systems accurately. To gain a better understanding of granular systems and to allow for the prediction of their behaviour on a large scale, our laboratory is developing a multi-scale numerical modelling strategy. Our models range from direct-numerical simulations of the fluid flow around individual particles, to Euler-Lagrangian and Euler-Eulerian approaches. Additionally, in collaboration with Prof. Klaas Prüssmann (Department of Electrical Engineering and Information Technology, ETH Zurich), we are aiming to apply Magnetic Resonance Imaging (MRI) as a non-intrusive means of imaging the dynamics of granular systems. Compared to

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Christoph Müller studied mechanical and process engineering at the TU München, Germany, supported by a scholarship from the Studienstiftung des deutschen Volkes (German National Academic Foundation). In 2004, he obtained his Diploma degree and commenced his doctoral studies at the University of Cambridge, UK in the Department of Chemical Engineering and Biotechnology. His doctoral studies were supported by scholarships from the Deutscher Akademischer Austauschdienst (DAAD) and the Cambridge European Trust. His doctoral thesis was entitled "Fundamental aspects of fluidised bed reactors" and he obtained his Ph.D. in 2008. In 2007, on the basis of work performed during his doctoral studies, he was awarded a Junior Research Fellowship at Queens' College, University of Cambridge. In 2009 he received the Danckwerts-Pergamon Prize for his doctoral thesis. He was Director of Studies in Chemical Engineering, Queens' College, University of Cambridge from 2008–2009. In January 2010, Christoph Müller became an assistant professor (tenure-track) at ETH Zurich and established the Laboratory of Energy Science and Engineering. To date, he has (co-)authored 58 peer-reviewed journal publications.

other imaging techniques, MRI has the important advantage of being able to measure the solid fraction and the velocity of particles. However, the acquisition of ultra-fast MRI measurements is very challenging as it requires the implementation of advanced pulse programs and novel hardware developments, such as parallel imaging.

Highlights and achievements

CO_2 capture
We have successfully developed Al_2O_3-stabilized, carbon-gel templated, CaO-based CO_2 sorbents that possess a hierarchical, but also thermally stable pore structure. The CO_2 uptake of the new material was 0.56 g CO_2 g^{-1} sorbent after 30 cycles, exceeding the performance of the reference limestone by 180 %.

H_2 production
Using a hydrotalcite based synthesis approach we were able to synthesize a bi-functional CaO-based CO_2 sorbent that also contains the reforming catalyst Ni. We demonstrated that an $MgAl_2O_4$ matrix effectively stabilizes Ni and CaO particles. Using this new material, we were able to obtain hydrogen of 99 % purity in a single step.

Figure 2: Material characterisation: High-pressure thermo-gravimetric analyser

Single- and two-phase granular flows
Based on the lattice-Boltzmann approach, we successfully developed and implemented a direct numerical simulation (DNS) model for gas-particle systems. This numerical model is currently being employed to develop drag force correlations for agglomerates of non-spherical particles, which are not currently available in the literature.

Having already demonstrated numerically that particle shape is a critical factor in the dynamics of granular systems (as in particle dispersion, for example), we extended our Lagrangian modelling capabilities to the simulation of smooth non-spherical particles.

Additionally we imaged the formation, interaction and stability of jets in packed beds using MRI. These measurements allowed us to address open questions regarding jet formation, such as the influence of walls, and to demonstrate the existence of a hysteresis in the relationship between orifice velocity and jet length.

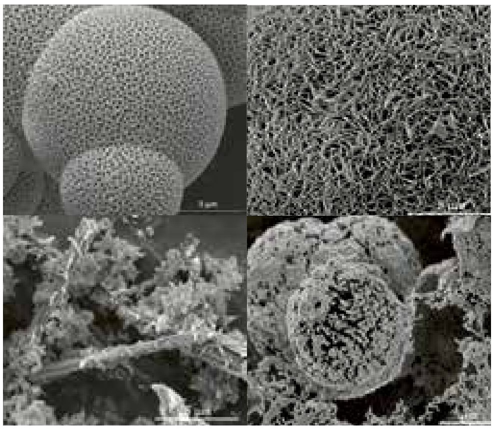

Figure 3: Scanning electron microscope images of novel CaO-based CO_2 sorbents synthesized in our laboratory

Goals and future priorities

Over the last three and a half years, the laboratory has established a solid research foundation that will support our goals and future priorities over the next six years. These include:

CO_2 capture and conversion
We would like to study fundamental aspects of the carbonation reaction including the reaction mechanism, product layer formation and the effect of dopants. This research will require the development and utilization of advanced characterization techniques including nuclear magnetic resonance (NMR), tomographic electron microscopy, and X-ray absorption techniques. An important priority for the next six years will be to increase substantially our research activities in the field of catalysis. The catalytic conversion of CO_2 into fuels or other valuable chemicals will be one of our first projects.

Biomass conversion
In collaboration with Prof. Pérez Ramírez (Department of Chemistry and Applied Biosciences, ETH Zurich) we have recently started research activity in the area of the fast catalytic pyrolysis of biomass. This research forms an important step in our strategy to increase our activities in the area of catalysis. An important aspect of this joint project is the development of new catalysts that minimize coke formation and possess high yields and selectivities for fuels and chemicals that are desirable for industrial applications.

Granular systems
We would like to incorporate heat and mass transfer into our models, which would enable us to study reactive systems. However, this will require research into additional closure relationships with respect to heat and mass transfer in the assembly of particles. Furthermore, in collaboration with Prof. Prüssmann, we will put substantial effort into the development of MRI strategies for the rapid imaging of gas-solid granular systems. This will allow us to probe their dynamics with unprecedented temporal and spatial resolution.

Teaching activity

LESE actively contributes to the teaching activity in our department. We offer the following courses:

Single- and two-phase particulate flows
This course is offered to MSc students and provides students with a fundamental understanding of single- and two-phase particulate systems. An important aspect of this lecture is the derivation of analytical expressions to explain various phenomena occurring in those systems. The complex phenomena covered in the lecture course are typically introduced by experiments in the lecture room.

Carbon dioxide capture and storage (CCS)
This lecture course provides an introduction to the concepts and technologies used to capture carbon dioxide in

Figure 4: Wet-chemical synthesis of CO_2 sorbents and catalysts

Figure 5: Granular systems: Formation of surface waves in vibrated beds

fossil-fired power stations. CO_2 capture technologies are discussed together with CO_2 transportation issues and different options for CO_2 storage and utilization. Besides technical details, the course also addresses economic, juridical, and social aspects of CCS.

In addition to teaching the lecture courses, we also participate in the "Kolloquium Thermo- and Fluid Dynamics" organized by the Institute of Fluid Mechanics at ETH Zurich.

Collaborations

Industrial

> We have an intensive and fruitful collaboration with Alstom in the area of carbon dioxide capture and storage (CCS).

Academic

Our main international and national collaborators are:

> Dr. David Scott (University of Cambridge, United Kingdom): granular materials; Prof. Calin Cormos (Babes–Bolyai University, Romania): carbon dioxide capture; Prof. Antonio Acosta Iborra (Carlos III University, Madrid): numerical modelling of gas-solid systems; Prof. Klaas Prüssmann (ETH Zurich, D-ITET): magnetic resonance imaging of granular materials; Prof. Christophe Copéret (ETH Zurich, D-CHAB): catalysis and material synthesis; Prof. Pérez Ramírez (ETH Zurich, D-CHAB): fast catalytic pyrolysis of biomass.

Key publications

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> G. Lu, J.R. Third and C.R. Müller, Critical assessment of two approaches for evaluating contacts between super-quadric shaped particles in DEM simulations, Chemical Engineering Science, 78, 226–235, 2012.

> M. Broda and C.R. Müller, Synthesis of highly efficient, Ca-based, Al_2O_3 stabilized, carbon gel templated CO_2 sorbents, Advanced Materials, 24, 3059–3064, 2012.

> Q. Imtiaz, A.M. Kierzkowska and C.R. Müller, The development of copper-rich, alumina stabilized materials for CO_2 capture via chemical looping combustion, ChemSusChem, 5, 1610–1618, 2012.

> M. Broda, A.M. Kierzkowska and C.R. Müller, Application of the sol-gel technique to develop novel, synthetic Ca-based sorbents that possess excellent CO_2 capture characteristics, ChemSusChem, 5, 411–418, 2012.

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Multi-Scale Robotics Laboratory

The Multi-Scale Robotics Lab (MSRL) pursues a dynamic research program that maintains a strong robotics research focus on several emerging areas of science and technology. A major component of the MSRL research leverages advanced robotics for creating intelligent machines that operate at micron and nanometer scales. MSRL research develops the tools and processes required to fabricate and assemble micron sized robots and nanometer scale robotic components. Many of these systems are used for robotic exploration within biomedical and biological domains.

Figure 1: The Nanomag on an inverted microscope for cell manipulation studies

Microrobotics is a field that combines the established theory and techniques of robotics with the exciting new tools provided by MEMS technology in order to create intelligent machines that operate at micron scales. MSRL research develops the tools and processes required to fabricate and assemble micron sized robots. Many of these systems are used for robotic exploration within biological domains, such as in the investigation of molecular structures, cellular systems, and complex organism behavior.

Nanorobotics is the study of robotics at the nanometer scale, and includes robots that are nanoscale in size and large robots capable of manipulating objects that have dimensions in the nanoscale range with nanometer resolution. Nanorobotic manipulation is an enabling technology for nanoelectromechanical systems (NEMS) and promising for nanorobots. NEMS with novel nanoscale materials and structures will enable many new nanosensors and nanoactuators.

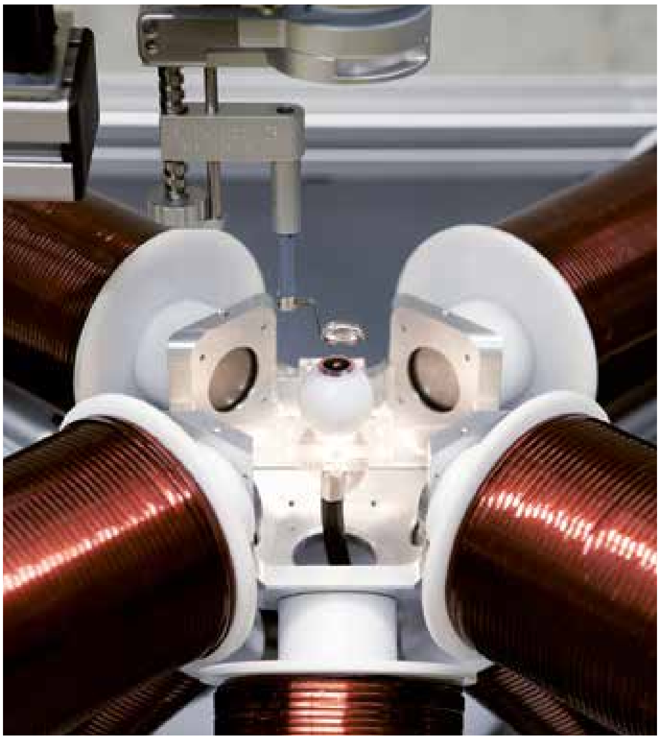

Figure 2: The OctoMag with ophthalmoscope for microrobotic retinal surgery

Projects at the MSRL are highly integrated, multidisciplinary collaborations that aim to push the boundaries of current knowledge and broaden the scope of micro and nanoscale engineering. Our research examines topical problems in such diverse fields as microrobotically assisted surgery, magnetic actuation and manipulation, micro and nanofabrication, low Reynolds number locomotion, wireless delivery of power, electrostimulation of biological materials and micro and nanostructure characterization.

In the past few years we have begun to interact more closely with medical doctors as our microrobotic systems move toward clinical trials. We have performed animal experiments with the guidance of electrophysiologists and ophthalmic surgeons. We also work with urologists, pediatric surgeons, and neuro surgeons.

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Brad Nelson is the Professor of Robotics and Intelligent Systems at ETH Zurich. His primary research focus is on microrobotics and nanorobotics with an emphasis on applications in biology and medicine. He received a B.S.M.E. from the University of Illinois at Urbana-Champaign and an M.S.M.E. from the University of Minnesota. He has worked as an engineer at Honeywell and Motorola and served as a United States Peace Corps Volunteer in Botswana, Africa, before obtaining a Ph.D. in Robotics from Carnegie Mellon University in 1995. He was an Assistant Professor at the University of Illinois at Chicago (1995-1998) and an Associate Professor at the University of Minnesota (1998-2002). He became a Full Professor at ETH Zurich in 2002. Prof. Nelson has served as the head of the ETH Department of Mechanical and Process Engineering, the Chairman of the ETH Electron Microscopy Center (EMEZ), and is a member of the Research Council of the Swiss National Science Foundation.

Highlights and achievements

Prof. Nelson has received a number of awards including more than a dozen Best Paper Awards and Award Finalists at major robotics conferences and journals. He was named to the 2005 "Scientific American 50," Scientific American magazine's annual list recognizing fifty outstanding acts of leadership in science and technology from the past year for his efforts in nanotube manufacturing. His laboratory won the 2007 and 2009 RoboCup Nanogram Competition, both times the event has been held. In 2010 he was elected to the IEEE Robotics and Automation Society Advisory Committee as a member-at-large (top two of 17 candidates). In 2011 he was awarded an ERC Advanced Grant. His lab appears in the 2012 Guinness Book of World Records for the "Most Advanced Mini Robot for Medical Use," and he joined the ISI Thomson-Reuters list of Highly Cited Researchers in 2013.

Prof. Nelson serves on the editorial boards of several journals and is a Senior Editor of the IEEE Transactions of NanoTechnology and the IEEE Transactions on Robotics. He has chaired several international workshops and conferences, is a fellow of the IEEE and ASME, and has been invited to give more than two dozen keynote lectures at major conferences.

Figure 3: Human-sized magnetic manipulation system with integrated fluoroscope

The lab has achieved a number of firsts in research, which is evidenced by the publication of several highly cited papers on a range of topics and more than a dozen journal-covers featuring the lab's work. Their early MEMS work on multi-axis force sensing led to the formation of a startup company in 2007 that now commercially distributes MEMS-based force sensors and grippers around the world. Their first work on the magnetic manipulation of microrobots is considered a seminal paper in the field, which was later extended to full six degree-of-freedom control. This technique was patented by ETH and is licensed for biomedical applications. This was followed by the experimental realization of bacteria-sized microrobots whose swimming strategy was inspired by E. coli, and the group built the first micron-sized swimming microrobots using two-photon photopolymerization. Fluidic trapping was also pioneered by the lab. More recently the group has moved much of their research from *in-vitro* laboratory bench work to *in-vivo* animal experiments in which they use mice, rats, rabbits and pigs as test subjects.

Goals and future priorities

The MSRL will continue to pursue its balance between fundamental and applied research. The lab consistently publishes highly cited papers in top journals while also driving significant industrial interactions. The ground breaking technologies developed at the MSRL have led to the formation of two startup companies with convincing business plans, FemtoTools AG and Aeon Scientific AG. FemtoTools designs and manufactures ultra high precision instruments for testing and handling in the micro and nanoscale domains and has a worldwide distribution network. Aeon Scientific is developing next generation medical technologies based on electromagnetic manipulation and enjoys strong financial backing from Swiss leaders in biomedical technology.

Organization of the professorship

The Multi-Scale Robotics Laboratory is a highly multidisciplinary group that integrates three distinct sub-groups individually focused on robotics and systems, materials and fabrication, and cellular biology. Over the past several years the group has numbered between thirty and forty individuals and averages funding from sources external to ETH well in excess of 2 Mio CHF per year.

Figure 4: Electrochemical setup to synthesize magnetic patterns of microrobots

Teaching activity

The MSRL is strongly committed to supporting undergraduate and graduate education and offers a variety of courses that educate students in the fundamentals of experimental and theoretical robotics. The institute also offers advanced courses in robotic systems design and micro and nanorobotics. The following cources are offered by the lab:

- Introduction to Robotics & Mechatronics (151-0641-00)
- Theory of Robotics & Mechatronics (151-0601-00)
- Microrobotics (151-0604-00)
- Nanorobotics (151-0630-00)
- Studies on Mechatronics (151-0640-00)
- Studies on Micro and Nano Systems (151-0643-00)
- ETH Zurich Distinguished Seminar in Robotics, Systems, and Controls (151-0623-00)

Our courses are highly subscribed with IRM, TRM, Microrobotics, and the ETH Seminar in RSC all attracting in excess of 100 students per semester. We receive no departmental support for teaching assistants for any of these courses.

Collaborations

Industrial

- CSEM SA
- EMPA
- IBM-Zurich
- Novartis
- Alcon
- Oertli
- Seagate
- Happy Plating
- Femtotools AG
- AEON Scientific AG

Academic

- ETH Zurich
- University of Zurich
- University of Bern

Fostering young academics

A number of researchers trained under Prof. Nelson have gone on to careers in academia: Prof. Yu Sun (Univ of Toronto), Prof. Jake Abbott (Univ of Utah), Prof. Lixin Dong (Michigan State Univ), Prof. Li Zhang (Chinese Univ of Hong Kong), Prof. Arunkumar Subramanian (Virginia Commonwealth Univ), Prof. Ge Yang (Carnegie Mellon Univ), Prof. Eniko Enikov (Univ of Arizona), Prof. Michael Greminger (Univ of Minnesota at Duluth), Prof. Serdar Sezen (St. Cloud State Univ), Dr. Salvador Pane is a 2013 ERC Grantee.

Figure 5: A microrobot docked in a retinal vein model

- EPF Lausanne
- The Wyss Institute
- Autonomous University of Barcelona
- University of Grenada
- Scuola Superiori Santa Anna
- Medizinische Hochschule Hannover
- University of Oldenburg
- INRIA-Sophia Antipolis
- ENSI Bourges
- IRCAD-Strasbourg
- Zhejang University
- Daegu Gyeongbuk Institute of Science and Technology
- Korea Advanced Institute of Science and Technology
- Stanford University
- Massachusetts Institute of Technology
- Harvard University

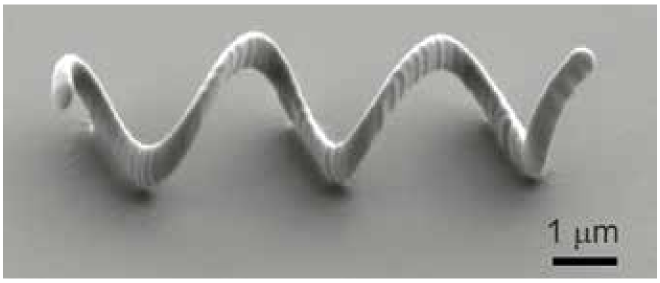

Figure 6: The microrobotic platform called the Artificial Bacterial Flagellum (ABF) was inspired by the swimming technique exhibited by flagellated *E. coli.*

Key publications

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- K.B. Yeşin, K. Vollmers, B.J. Nelson, "Modeling and Control of Untethered Biomicrorobots in a Fluidic Environment Using Electromagnetic Fields", Int J Rob Res, 5(5–6) 2006, 527–536.

Optical Materials Engineering Laboratory

Research in the Optical Materials Engineering Laboratory (OMEL) aims to create materials that have interesting and useful interactions with light. By changing the size, shape, or periodicity of a solid, new phenomena can arise. Current efforts in OMEL are focused on two materials: nanoscale semiconductor particles (known as nanocrystals) to investigate the influence of size, and thin patterned metals (known as plasmonic films) to investigate shape and periodicity. In addition to fabrication and characterization of these materials, OMEL is exploring applications in solar energy conversion.

Figure 1: Deposition of metals for the fabrication of plasmonic films

OMEL has focused primarily on two main classes of optical materials. First, nanoscale semiconductor particles (also known as nanocrystals or quantum dots) can exhibit size-dependent optical properties that are useful for many applications, including light-emitting diodes, solar cells, and bio-imaging. This has motivated advances over the last two decades in the liquid-phase chemical synthesis of nanocrystals. The particles, which are highly crystalline, strongly fluorescent, and uniform in size, can be easily manipulated and processed in solution. However, despite their advantages, nanocrystals are typically extremely poor conductors when deposited as films.

This is problematic, since many targeted devices, such as solar cells, require electrical charge to be transported efficiently to contacts. A major thrust of OMEL is to address this issue by incorporating intentional impurities (or dopants) into the nanocrystals. This problem has been studied for 25 years, with little success until recently. In particular, we have made progress in understanding how electronically active impurities (similar to those used in silicon to obtain transistors) can be added to and exploited in nanocrystals. Second, OMEL has focused on structures made from metals, which can exploit electromagnetic waves known as surface plasmons. Because these waves allow light to be concentrated in nanometer-scale volumes (or "hot spots"), they can lead to enhanced light-matter interactions (e.g. absorption, fluorescence, etc.). Consequently, patterned metallic films have been studied for various applications including sensing, solid-state lighting, and solar cells. OMEL has recently developed a simple, general approach to fabricate high-quality metallic structures. We then extended this method to create patterned films from refractory metals (e.g. tungsten) for applications in solar thermophotovoltaics. In these devices energy from the sun is absorbed and used to heat the structure. It then re-emits this energy as infrared light, which can be converted by a photocell into electricity.

In principle, this approach can lead to high efficiency but has been limited by the broad thermal emission spectrum of typical metals. Patterned plasmonic metals provide new opportunities to tailor these spectra and obtain efficient thermophotovoltaic devices. Indeed, OMEL has recently demonstrated a structure (the metallic bull's eye in Fig. 3) that can produce a directional "heat ray" due to the pattern in the metal.

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David J. Norris was elected Professor of Materials Engineering at ETH Zurich in March 2010. Born in 1968, he received his BSc in Chemistry from the University of Chicago in 1990. He then pursued a Ph.D. in Physical Chemistry at MIT, graduating in 1995. After a National Science Foundation post-doctoral fellowship at the University of California, San Diego, he joined the NEC Research Institute in 1997, where he led a research group working on optical materials. In 2001, he moved to the University of Minnesota as an Associate Professor of Chemical Engineering and Materials Science. He was promoted to Professor in 2006 and served as the Director of Graduate Studies in Chemical Engineering from 2004 to 2010. He is a Fellow of the American Physical Society and the American Association for the Advancement of Science. He received the Golden Owl award at ETH in 2012 for excellence in teaching. He has published over 90 peer-reviewed papers, which have been cited more than 14,000 times by other researchers.

Highlights and achievements

Research

- Demonstrated the "template-stripping" approach to smooth patterned metals for plasmonic applications [*Science* 325, 594 (2009).]
- Predicted "thermal beaming" from bull's eye patterns on thin metallic foils [*Optics Express* 18, 4829 (2010).]
- Demonstrated "hot-electron" transfer from semiconductor nanocrystals to a substrate [*Science* 328, 1543 (2010).]
- Demonstrated the ability to image individual impurities (dopants) in semiconductor nanocrystals [*Nano Letters* 11, 5553 (2011).]
- Demonstrated electronic impurity doping in semiconductor nanocrystals [*Nano Letters* 12, 2587 (2012).]

Teaching

- Initiated two new courses in D-MAVT: "Introduction to Quantum Mechanics for Engineers" and "Introduction to Plasmonics."
- Presented the Debye Lecture at the University of Utrecht in 2011.
- Received the Golden Owl Award for excellence in teaching in 2012.

Professional service

- Chair of the Gordon Research Conference on Clusters, Nanocrystals, and Nanostructures in 2009.
- International Jury Member, Francqui Prize, Francqui Foundation (Belgium) in 2012.
- Editorial Board Member of Advanced Functional Materials (2000–2012).

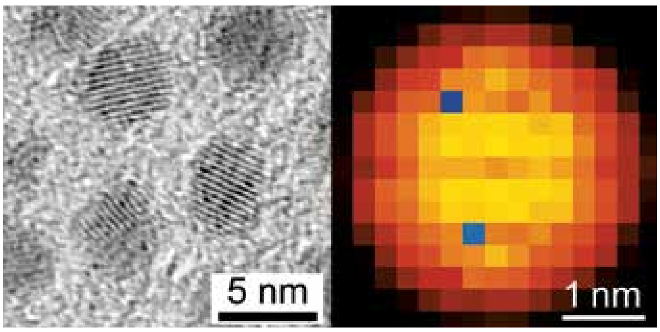

Figure 2: Electron micrograph of doped nanocrystals (left) and simulated imaging of individual embedded dopants (right)

Goals and future priorities

In addition to the areas above, two future priorities will be pursued. First, we will fabricate and study inorganic colloidal particles that have a chiral shape. In general, an object is chiral if it cannot be superimposed on its mirror image. Colloids involve solid particles that are dispersed in a solvent. Despite the importance of colloids in many commercial products, it remains a fundamental challenge to prepare colloids that exhibit a chiral shape. If available, they could present many new and interesting chemical, transport, and optical properties. In particular, if made from plasmonic metals such as gold, they should exhibit strong optical phenomena, including large circular dichroism. Consequently, they can have uses in many applications, such as catalysis, optics, sensing, and separations.

Second, we will combine the two classes of materials studied in OMEL (fluorescent semiconductor nanocrystals and patterned metallic films) to fabricate and study devices known as spasers, which are the plasmonic analog of conventional lasers. Spasers can provide an extremely versatile nanoscale source of surface plasmons, photons, and/or intense electromagnetic fields, depending on the design.

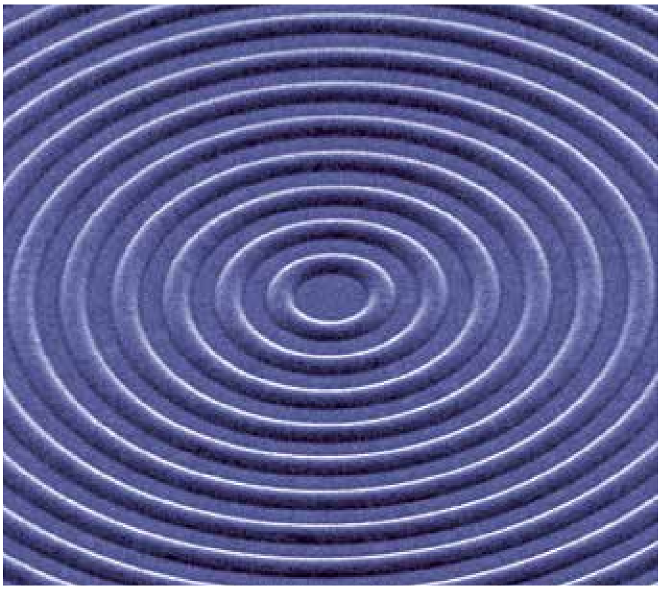

Figure 3: Metallic bull's eye pattern for thermal beaming of a heat ray

Organization of the professorship

The Optical Materials Engineering Laboratory is part of the Institute of Process Engineering. As it was established only recently in June 2010, with its core facilities opening in February 2011, it is still emerging from a start-up phase. At the end of 2012, OMEL included three postdoctoral researchers, seven Ph.D. students, eight Master students, five Bachelor students, and three support staff. These researchers pursue projects that include the simulation, fabrication, and characterization of optical materials. In addition to in-house facilities for the chemical synthesis and physical deposition of semiconductor and metallic nanostructures, OMEL researchers utilize the central facilities at ETH, including the electron microscopy facility (EMEZ) and its three clean rooms (FIRST, FIRST-CLA, and BRNC).

The emphasis in all of its activities is on the training of students and postdoctoral researchers. Lab members are involved with the mentoring of younger students. Participation in classroom teaching is also encouraged. Weekly group meetings are used to train students in presentation skills. Students are encouraged to present their results at external conferences.

Teaching activity

The primary purpose of OMEL is to train Bachelor, Master, and doctoral students. This includes activities both in the classroom and the laboratory.
In the classroom, two new courses have been initiated since the establishment of OMEL. The first, "Introduction to Quantum Mechanics for Engineers", is an elective course taught in the fourth semester of the Bachelor program in D-MAVT. It has attracted 240 students each year, and Prof. Norris was selected by the students to receive the Golden Owl award for these lectures in 2012. The second course, "Introduction to Plasmonics," is offered to Master students in D-MAVT, D-ITET, and D-PHYS. It was taught for the first time in the fall semester of 2012. Both of these courses have exercise periods that are taught by OMEL group members with interest in teaching. OMEL has also participated in the course, "Introduction to Nanoscale Engineering", in collaboration with Prof. Pratsinis. Here, students learn about a variety of methods, phenomena, and applications in nanoscale materials. It also requires a research project for each student in one of the laboratories at ETH.

In addition to these courses, OMEL also supports students in their semester and thesis projects. For Bachelor and Master students, the goal is to assign each with his/her own research problem, rather than an incremental aspect of a larger project. Each student is also mentored on a one-to-one basis by a doctoral student or postdoctoral researcher.

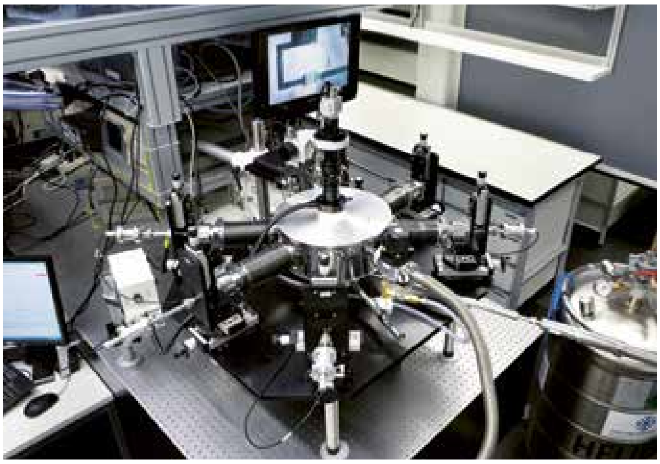

Figure 4: Apparatus for electrical and optical characterization of solar cells

Fostering young academics

Since 2008, 5 former members of OMEL have accepted assistant professorship positions, including:

- Prof. Benjamin Wiley, Department of Chemistry, Duke University (2009).
- Prof. William Tisdale, Department of Chemical Engineering, MIT (2011).
- Prof. Moon Sung Kang, Department of Chemical Engineering, Soongsil Univeristy (2012).
- Prof. Sang Eon Han, Department of Chemical and Nuclear Engineering, Univ. of New Mexico (2012).
- Prof. Prashant Nagpal, Department of Chemical and Biological Engineering, Univ. of Colorado (2012).

Figure 5: Synthesis of colloidal semiconductor nanocrystals

Collaborations

Industrial

- PNL Innotech on thermophotovoltaics
- DLR on thermophotovoltaics
- JCMwave on plasmonics
- Intellisense on plasmonics

National laboratories

- US Naval Research Laboratory on nanocrystal doping
- CEA Grenoble on thermophotovoltaics
- PSI on thermophotovoltaics

Academic international

- Univ. Minnesota on plasmonics, nanocrystal doping, and solar cells
- TU Munich on nanocrystal doping
- Univ. Duisburg-Essen on nanocrystal doping
- Univ. Rome on thermophotovoltaics

Academic ETH

- Prof. Poulikakos on plasmonics
- Prof. Wood on nanocrystal devices

Key publications

- D. J. Norris, A. L. Efros, S. C. Erwin, "Review: Doped Nanocrystals", Science 319, 1776–1779 (2008).
- P. Nagpal, S. E. Han, A. Stein, D. J. Norris, "Efficient Low-Temperature Thermophotovoltaic Emitters from Metallic Photonic Crystals", Nano Lett. 8, 3238–3243 (2008).
- P. Nagpal, N. C. Lindquist, S.-H. Oh, D. J. Norris, "Ultra-Smooth Patterned Metals for Plasmonics and Metamaterials", Science 325, 594–597 (2009).
- K. S. Leschkies, T. J. Beatty, M. S. Kang, D. J. Norris, E. S. Aydil, "Solar Cells Based on Junctions between Colloidal PbSe Nanocrystals and Thin ZnO Films", ACS Nano 3, 3638–3648 (2009).
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Nanoscience for Energy Technology and Sustainability

The Professorship of Energy Technology, led by Prof. Hyung Gyu Park since 2009, runs a research program focused on nanoscientific solutions for energy and clean technology applications. By using various nanofluidic, optoelectric and electrochemical platforms comprised of graphene and CNTs[1], the group studies unique mass transport phenomena in the graphitic nanoenvironment, chemical detection by SERS[2], and post-lithium-ion-battery energy storage, all of which are oriented toward addressing the future of global energy sustainability.

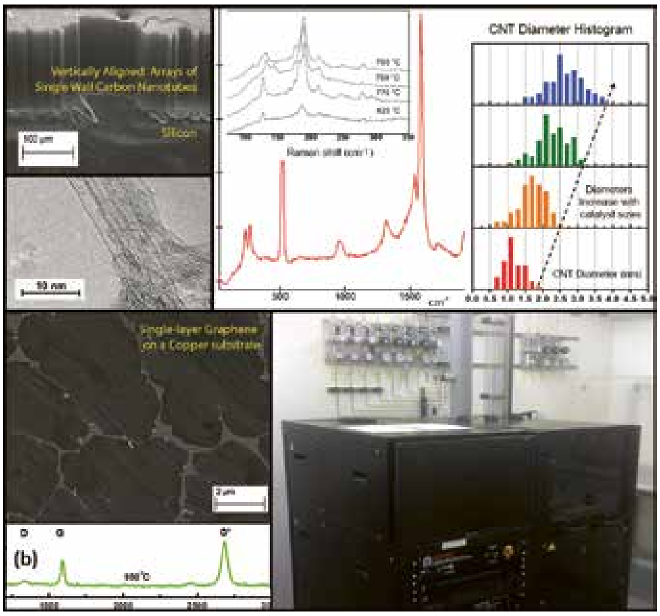

Figure 1: Size-tailored synthesis of graphene and carbon nanotubes for energy and clean technologies

From its beginnings, carbon nanoscience research has been motivated in part by the urgent energy- and water-related sustainability challenges facing humanity. Late Nobel laureate Dr. R. Smalley and others in the field have carefully traced a vision of nanoscience's potential contribution to the search for solutions. Prof. Park's group is interested in fundamental nanoscience centered around graphene and CNTs[1] for energy and clean technology applications. CNTs[1] are seamlessly rolled tubules of graphene with a diameter of a few nanometers. CNTs[1] exhibit many unique properties, including the fast mass transport of molecules under extreme confinement, commensurable with the molecules' size. Such mass transport may have applications in cost-efficient filters in which CNTs[1] serve as pores that selectively filter out ions. Graphene, if perforated with tiny holes, can produce a very intriguing filter-membrane of nearly atomic thickness, that effectively acts a a filtration system. The transport phenomena of such a system are only marginally understood. Prof. Park's group sieves through these efficient mass transport phenomena by means systematically developed nanofluidic platforms. A deeper understanding of the molecular transport behavior should support the development of smart techniques and devices for energy and clean technology applications such as carbon capture, gas separation, water purification/desalination, and post-lithium-ion-battery energy storage.

Vertically aligned CNTs[1] contain other structural and electrical properties that are useful for constructing functional nanowire arrays for applications in sensors, and energy harvesting and storage. When CNTs[1] are vertically aligned their exterior graphitic surfaces run parallel from a common ground, facilitating ballistic electron transfer at a massive scale. Rendered from the synthesis stage to have a density in the billions of tubes per square centimeter, this nanotube array can be imparted with a variety of electrical and chemical functionalities via concentric layers of coatings. In contrast with nanowires made of homogenous materials, the resultant nanowire array based on a CNT[1] template has the potential to act as an interface that can easily be pumped full or stripped of mobile electrons. Prof. Park's group is particularly interested in this potential and is building up their competence in the nanomanufacturing of semiconductor-CNT[1] and dielectric-CNT[1] nanowires. Using this CNT[1]-based nanowire platform, the group is developing and investigating a photoelectrochemical energy harvester, an electrical double layer capacitor (supercapacitor), and SERS[2] chem-bio agent sensors.

Highlights and achievements

Scientific and scholarly contributions

- Establishment of a protocol for manufacturing a nanofilter from sub-5-nm, VA[3] CNT[1] arrays
- First measurements of fast mass transport through such a narrow CNT[1] interior
- First demonstration of ion rejection (> 90 %) at high water fluxes, with the implication of potential breakthrough applications in seawater desalination and water purification

[1] carbon nanotubes (CNT)
[2] surface enhanced Raman spectroscopy (SERS)
[3] vertically-aligned (VA)

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Hyung Gyu Park is a tenure-track assistant professor in the Department of Mechanical and Process Engineering, ETH Zurich. Prior to joining ETH in April 2009, he worked as a postdoctoral research staff member at Lawrence Livermore National Laboratory, US, where he participated in the nano-manufacturing of diverse engineering platforms for surface enhanced Raman spectroscopy (SERS), field ionization, and carbon nanotube membranes. In 2007, he received his Ph.D. in Mechanical Engineering from the University of California, Berkeley, US, based on his pioneering experimental study of unique nanoscale mass transport phenomena in carbon nanotubes. He received his BSc and MSc from the Department of Mechanical Engineering, Seoul National University, Korea, in 1998 and 2000, respectively, and, trained as a computational fluid dynamicist. His current faculty research interest lies in nanomanufacturing, nanofluidics, plasmonics, and electrochemical systems around the use of carbon nanomaterials for energy and clean technologies.

> Facile diameter selective synthesis of VA[3] CNTs[1] via invention of temperature-gradient chemical vapor deposition
> First demonstration of the Gompertzian kinetics in graphene synthesis on copper
> First demonstration of a plasmonic energy barrier for surface enhanced Raman spectroscopy, enabling a femtomolar sensitivity in chemical detection
> Cultivation of a new scientific discipline, Carbon Nanofluidics, which studies the thermodynamics and transport of materials in the graphitic nanoenvironment

Recognition and citations

> Cover articles in Science (2006), Nano Today (2007), PNAS[4] (2008), Advanced Functional Materials (2012), and Advanced Materials (2013)
> 1000 times of citation received (Science, 2006)
> Patents licensed and an R&D100 award received for the invention of a CNT[1] nanofilter
> Public recognition of our VA-CNT filter as the preferred future technology for seawater desalination (source: National Geographic, 2010)

Goals and future priorities

As a scholar, Prof. Park will contribute to establishing the newly emerging field he has named "Carbon Nanofluidics". Carbon nanofluidics pertains to the study of unique nanoscale mass transport phenomena in the graphitic nanoenvironment. He plans to organize the knowledge built up in this field for the last 12 years in a monograph format. Another equally important goal is to establish concrete measurements via platforms incorporating graphene and carbon nanotubes.

From a technological point of view, he will continue to build upon current successes and strengthen the competencies his group attained through earlier research activities. Prioritized topics will include: (1) tailored syntheses of graphene, carbon nanotube, and other 2D materials; (2) on-demand water purification by combining pollutant detection (SERS) and membrane gating techniques; (3) carbon capture and gas separation via nanocarbon membranes; and (4) post-lithium-ion batteries for energy storage.

These topics are all linked to the broader study of nanoscience for energy technology and sustainability.

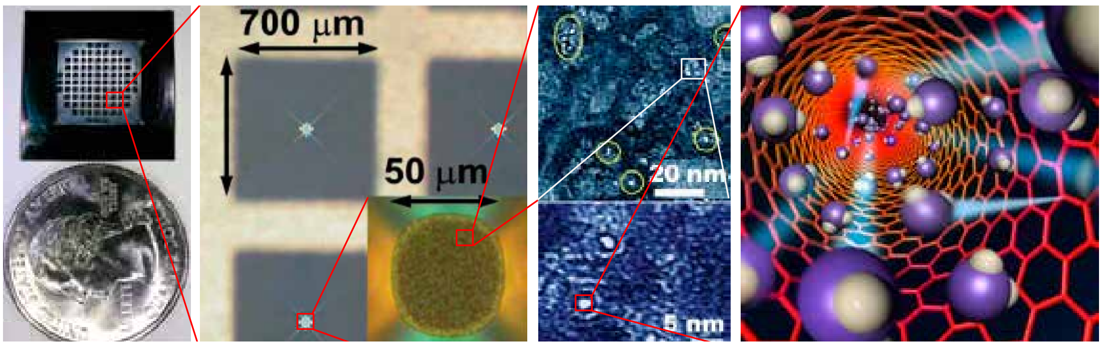

Figure 2: Membrane that the interior of carbon nanotubes serves as pores

[4] Proceedings of the National Academy of Sciences (PNAS)

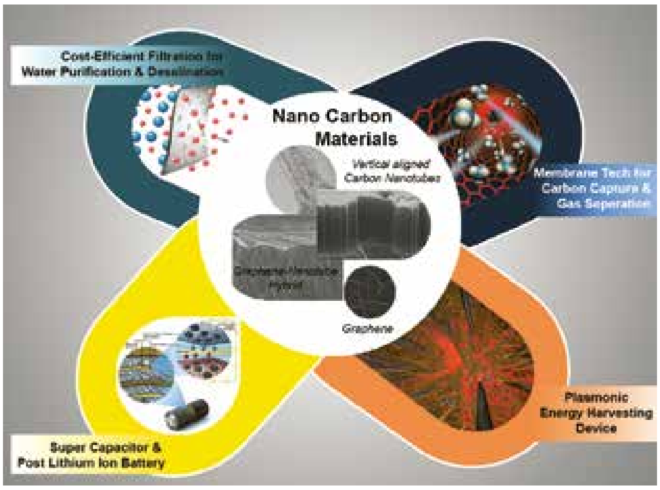

Figure 3: The Park group`s research portfolio at D-MAVT, ETH Zurich

Organization of the professorship

The Professorship of Energy Technology consists of one faculty (Prof. H.G. Park) and a part-time (80 %) secretary. The faculty currently supervises seven Ph.D. students directly, which will become nine in 2014, including weekly meetings and tight supervision combined in a flexible way. Hence, flexibility and fast decision making are the advantage of the group. Ph.D. students with similar topics team up to work and discuss together, and Master students are distributed to the subgroup of their interest. These topic-wise subgroups are chemical vapor deposition of carbon nanomaterials, graphene nanofluidics, CNT nanofluidics, gas separators, supercapacitor, and SERS sensing. Since all the research projects are geared toward nanoscientific application to energy and clean technologies, they have a very high demand for high-quality nanomanufacturing and characterization facilities. Therefore, the professorship is conducting their experimental work at Binnig Rohrer Nanotechnology Center, in the IBM Zurich campus of Rüschlikon. This nanotechnology center was cofounded by ETH Zurich and IBM Zurich in 2011. At the Rüschlikon site, the group has a wet chemistry laboratory, a dry characterization laboratory, two offices, and full access to the micro-nano-fabrication equipments in the multiuser clean room facility. The group has three offices and one laboratory at the ETH Zentrum campus.

Teaching activity

The Professorship of Energy Technology offers courses at graduate school level. Prof. Park regularly teaches two courses per year and, in 2010, participated for one year in the multi-lecturer course Devices and Systems.

In the autumn semester, he teaches Energy Conversion (151-1633-00, 4 credits) for students enrolled in the Master of Energy Science and Technology program at the Energy Science Center, ETH Zurich. The objective of Energy Conversion is to provide students with the necessary engineering thermodynamics knowledge they will need to proceed in the multidisciplinary field of energy technology. In order to achieve this goal, the course covers a comprehensive review of basic thermodynamics for students coming from backgrounds other than mechanical or process engineering.

In the spring semester, Prof. Park lectures on the course Convective Heat Transport (151-0211-00, 5 credits). This course teaches advanced convection heat transfer in close connection with fluid mechanics and engineering mathematics, covering rigorous derivation of governing equations for fluid flow and heat transfer, laminar and turbulent heat transfer processes for internal and external flows, natural convection, and related practical topics.

During his participation in the Devices and Systems course in the spring semester of 2010, he offered three weeks of lectures about general nanofluidic aspects of gases and liquids in the graphitic nanoenvironment of the carbon nanotube interiors.

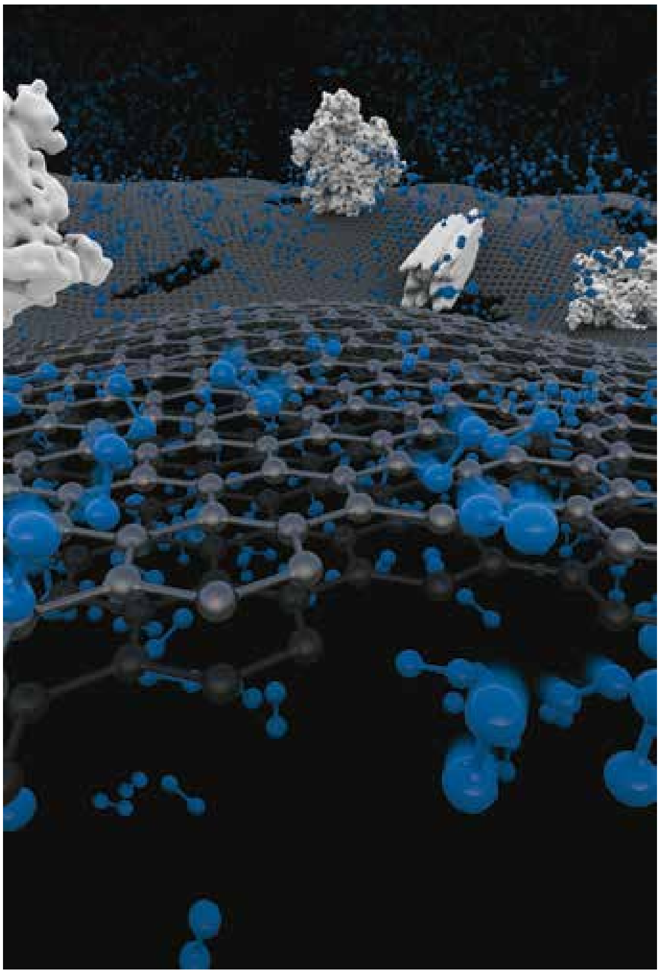

Figure 4: Two-layered graphene membrane

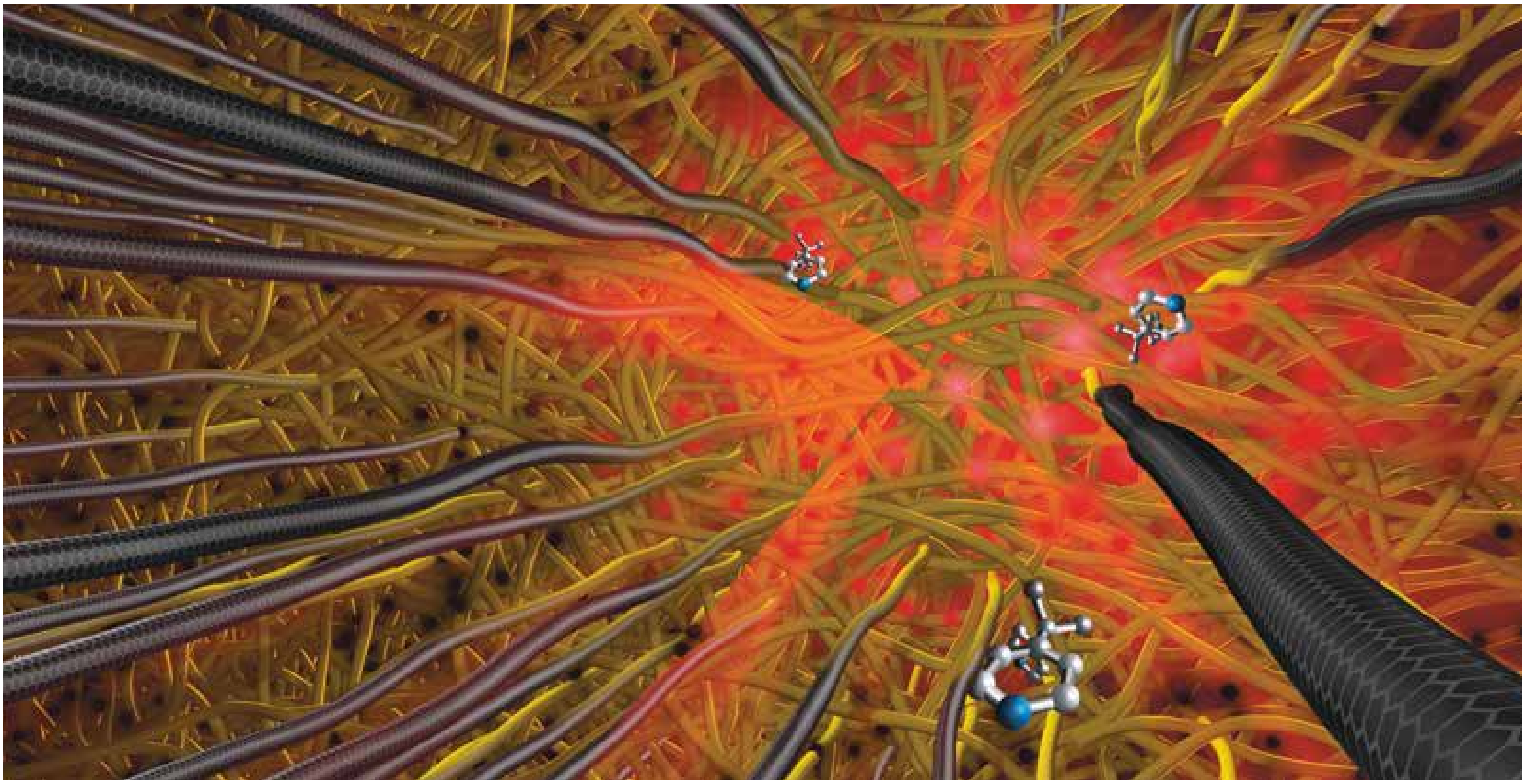

Figure 5: High-sensitivity plasmonic (SERS[2]) sensor shown alongside gold-dielectric-CNT[1] nanowires

Collaborations

Industrial

- Alstom, Switzerland: Nanomaterials Platform for CO_2 Capture and Release (funded since 2012)
- SABIC[5], Saudi Arabia: Nanotechnology Solution for Natural Gas Separation (funded since 2012)
- LG Electronics, Korea: Graphitic Nanofilter for Water Technology Applications (funded since 2013)
- Porifera, CA, US: Synthesis of Carbon Nanotubes and Membranes (collaboration without funding, 2012–present)
- Aixtron, UK: Synthesis of Carbon Nanotubes and Graphene (collaboration without funding, 2011–present)

Academic

- T. Bond, LLNL[6], US: Surface Enhanced Raman Spectroscopy Sensor Development (2011–present)
- W. Pronk, Eawag[7], Switzerland: Evaluation of Nano Carbon Membranes for Micropollutant Removal (2012–present)
- J. Patscheider, B. Keller, EMPA[8], Switzerland: XPS[9] & TOF-SIMS[10] of carbon nanomaterials (2011–present)
- I. Utke, EMPA[8], Switzerland: Metal Oxides Conformal Coating of Carbon Nanotubes (2012–present)
- V. Wood, ETH, Switzerland: Nanoelectrodes for Solar Cells (2011–present)
- Y. Jung, KAIST[11], Korea: Nanoscale Water Transport (2010–present)
- A. Noy, LLNL[6], US: Nanoscale Mass Transport (2013–present)
- C. Duan, University of Boston, US: Nanoscale Mass Transport (2013–present)

Key publications

- K. Celebi, J. Buchheim, H.G. Park et al., Ultimate Permeation across Atomically Thin Porous Graphene, Science, 344, 289-292, 2014.
- H.G. Park (co-corresponding), Y. Jung, Rapid Water Transport in Graphitic Nanoenvironment for Energy Technology Applications, Chemical Society Reviews (Invited Review), 43, 565-576, 2014.
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- K. Celebi, H.G. Park et al., Evolutionary Kinetics of Graphene Formation on Copper, Nano Letters, 13, 967–974, 2013.
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- F. Fornasiero, H.G. Park, O. Bakajin et al., Ion Exclusion by sub-2-nm Carbon Nanotube Pores, Proceedings of the National Academy of Sciences (COVER), 105, 17250–17255, 2008.
- A. Noy, H.G. Park, O. Bakajin et al., Slippery Nanopipes: Nanofluidics in Nanotubes, Nano Today (Invited Review & COVER), 2, 22–29, 2007.
- J.K. Holt, H.G. Park (equal contribution), O. Bakajin et al., Fast Mass Transport Through Sub-2nm Carbon Nanotubes, Science (COVER), 312, 1034–1037, 2006.
- H.G. Park, C.P. Grigoropoulos et al., Methanol Steam Reformer on a Silicon Wafer, The Journal of Microelectromechanical Systems, 15, 976–985, 2006.

[5] Saudi Basic Industry Corporation (SABIC)
[6] Lawrence Livermore National Laboratory (LLNL)
[7] Swiss Federal Institute of Aquatic Science and Technology (Eawag)
[8] Swiss Federal Laboratories for Materials Science and Technology (EMPA)
[9] X-ray Photoelectron Spectroscopy (XPS)
[10] Time-Of-Flight Secondary Ion Mass Spectrometry (TOF-SIMS)
[11] Korea Advanced Institute of Science and Technology (KAIST)

Laboratory of Thermodynamics in Emerging Technologies

We perform fundamental research in the areas of interfacial transport phenomena and thermodynamics across scales (nano-/meso- to macro-), and on the development of transformative energy technologies.

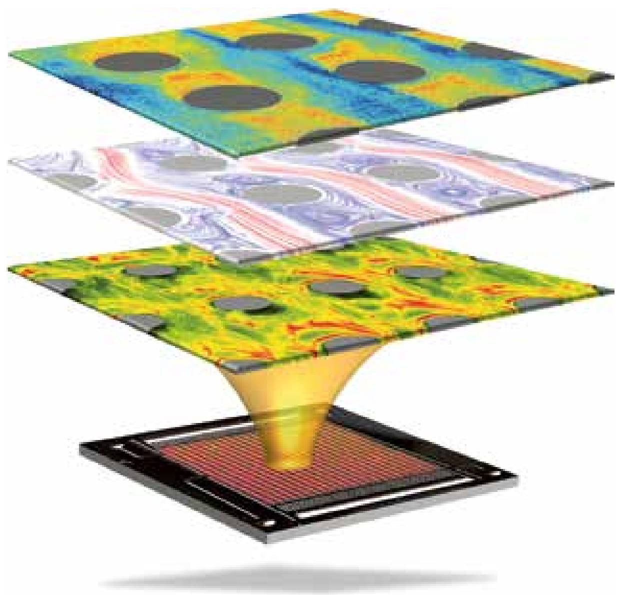

Figure 1: 3D-integrated cooling of electronics: Micro-PIV and Micro-LIF measurements of 3D-integrated electronic chip stacks

Our current research areas include:

Fundamental research on interfacial transport phenomena and thermodynamics across scales:

> We develop novel processes for the facile nanofabrication of functional nanostructures. This research has a broad range of applications including nanoelectronics, plasmonics for energy harvesting, nano-optics, and biomedical microfluidics.
> Our research into contactless acoustophoretic planar motion and handling of matter (liquid drops and solid particles) in air, is paving the way for a broad range of possible applications in the chemical/pharmaceutical industries and in materials processing.
> We are pursuing the science-based design of super-icephobic surfaces. We are also developing superhydrophobic and omniphobic nanoengineered surfaces, focusing on their performance at low temperatures (e.g. for supercooled liquids).

Transformative energy technologies:

> A long-term collaboration with the IBM Lab in Zurich aims at developing energy-efficient supercomputers and data centers. Energy-efficiency is a new performance norm alongside speed of calculation. The research encompasses path-breaking methods for 3D-integrated liquid cooling of electronics at the microprocessor level, as well as a focus on the reuse of recovered thermal energy from data centers.
> The lab's research activity in the area of nanoscale materials for thermoelectrics is focused on the design of materials (nanowires) leading to high-ZT coefficients. This is achieved through the reduction of the nanowires' thermal conductivity by way of atomic-level engineering of their crystal lattices as a means of severely limiting phonon transport.
> We are members of a research consortium working on a visionary concept of a solid oxide fuel cell (SOFC)-based micro-power plant for portable device power generation.

Specific examples of our activities in the two general areas described above include:

3D-integrated electronics cooling and energy-efficient supercomputers and data centers (Figs. 1 and 2)

We are investigating the efficient 3D-integrated cooling of electronic microprocessors using water as a coolant, in collaboration with IBM. Water has vastly superior thermal properties when compared with air. These can be used to enable the efficient cooling of supercomputers by way of compact chip-stack-integrated heat transfer concepts, and the reuse of the energy of hot water extracted from the data centers. These techniques improve the overall energy efficiency of data centers as measured according to a new norm, based on computation performed per unit of power expended (FLOPS/Watt).

In-plane and 3D printing of true nanostructures of colloids and liquids (Figs. 5 and 6)

We have developed a unique process for the in- and out-of-plane open atmosphere, controlled nanoprinting of liquids and colloids, which opens up a new frontier for printing technologies with features reaching well below 100nm, down to a single nanoparticle. This same process is paving the way for a new generation of microfluidic platforms by allowing attoliter-sized, highly volatile sessile droplets to be sustained in an open atmosphere for a virtually indefinite period of time. We are working on a broad array of novel applications in this area, including solar energy harvesting, touch screen technologies, and biology and chemistry.

The rational, nanostructuring of supericephobic and omniphobic surfaces (Fig. 3)
We are working on designing surfaces with a rational, thermodynamically guided, hierarchical micro-to-nanoscale morphology, which dramatically suppress ice formation as well as reduce the adhesion of ice on surfaces. We have illustrated how the icing process is critically affected by changes in environmental conditions such as humidity variation and the presence of air flow. We are investigating robust anti-icing surfaces that can resist the dynamic impact of droplets in extreme-cold conditions.

Acoustophoretic transport of matter in air
We have realized a path-breaking process for the controlled planar motion of heavy objects (droplets and particles) in air, employing acoustophoresis. We demonstrated the planar transport and handling in air of liquids with high density, of the order of magnitude of water, and solids as heavy as steel. Methods for the controlled motion of matter in air have a wealth of potential applications ranging from materials processing to biochemistry and pharmaceuticals.

Highlights and achievements

> Path-breaking 3D-integrated electronics cooling and energy-efficient supercomputing. AQUASAR is the world's first prototype of a (warm) water-cooled supercomputer that integrates the reuse of waste heat.

Figure 2: AQUASAR; the detail shows a typical board with water cooled chip structures

Prof. Dimos Poulikakos
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Since 1996 , Dimos Poulikakos has been Professor of Thermodynamics at ETH Zurich, where he founded the Laboratory of Thermodynamics in Emerging Technologies. Positions at ETH have included: from 1991-2001, Head of the Institute of Energy Technology; from 2001-2005, Member of the Research Commission at ETH Zurich; from 2002-2005, Vice Chair and Chair of the Leonard Euler Center; from 2005-2007, Vice President of Research at ETH Zurich; from 2008-2011, ETH coordinator of the IBM-ETH Binnig-Rohrer Nanotechnology Center; from 2011-present, Head of the Mechanical and Process Engineering Department.
Current research: Interfacial transport phenomena and thermodynamic in emerging technologies and energy across scales. The focus is on understanding the physics at micro- meso- and nanoscales and using it to develop novel technologies.
Major Awards: White House/NSF Presidential Young Investigator Award in 1985; Pi Tau Sigma Gold Medal in 1986; SAE R. R. Teetor Award in 1986; University of Illinois Scholar Award in 1986; ASME James Harry Potter Gold Medal in 2000; Russell S. Springer Professor UC Berkeley in 2003; Hawkins Memorial Lecturer Purdue University in 2004; ASME Heat Transfer Memorial Award for Science in 2003; Dr.h.c. NTUA Greece in 2006; visiting Fellow at Oxford University and the University of Tokyo in 2008; Nusselt-Reynolds Prize in 2009; Max Jacob Award of ASME/AIChE (highest honor in the field of heat transfer) in 2012; and the Outstanding Alumnus award from UC Boulder in 2012. In 2008 he was elected to the Swiss National Academy of Engineering (SATW), where since 2012 he has been the president of its science board. He is the Editor in Chief and member of the board of editors of several international journals. He is a Fellow of the American Society of Mechanical Engineering (ASME).

> Direct electrohydrodynamic NanoDrip printing of colloids and liquids at the nanoscale, representing a new frontier for the facile fabrication of both planar and 3D structures with a wealth of potential applications in the areas of energy technology, materials science, and biology.

> Rational (thermodynamics-driven) design of nanostructured surfaces with extreme icephobicity and omniphobicity to liquids.

> Nanostructured materials (core/shell and superlattice nanowires) with extremely low thermal conductivity for efficient thermoelectrics (Fig. 3).
> Acoustophoretic transport of liquids and solids in air, paving the way for new materials processing and pharmaceuticals platforms.

Goals and future priorities

In the next several years we will be working very intensively in the fundamental area of interfacial transport phenomena and thermodynamics across scales (nano-/meso- to macro-). We will also continue our efforts on the development of transformative energy technologies, and hope to contribute solutions to the global energy challenges that face us in the 21st century. Most of the research outlined above is in its initial stage and we expect significant groundbreaking activities in years to come.

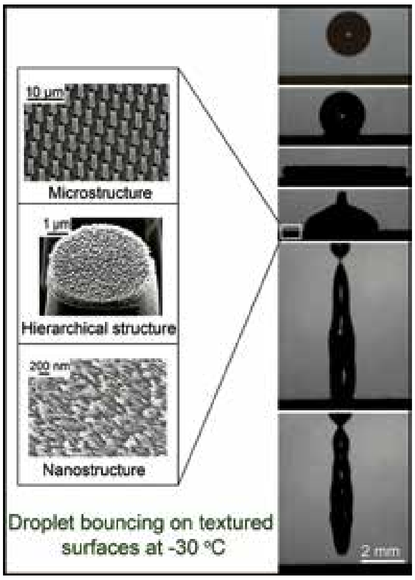


Figure 4: Water droplet rebound from a nanoengineered supericephobic surface at -30 deg C

Organization of the professorship

In addition to the Professor, our group consists of one or two senior scientists who are also responsible for administrative aspects of research projects, as well as several postdocs and doctoral students. The hierarchy of the lab is flat and all members participate in an intense but engaging weekly meeting where researchers may present and discuss their work. Researchers present the progress of their work at maximum on a biweekly basis. The interaction of all scientists in the lab is continuous and straightforward. The group is supported by an administrative assistant (80 %), an electronics technician (full-time) and a machinist (50 %). The lab's computer infrastructure is supported by the Department at the cost of a 50 % equivalent position.

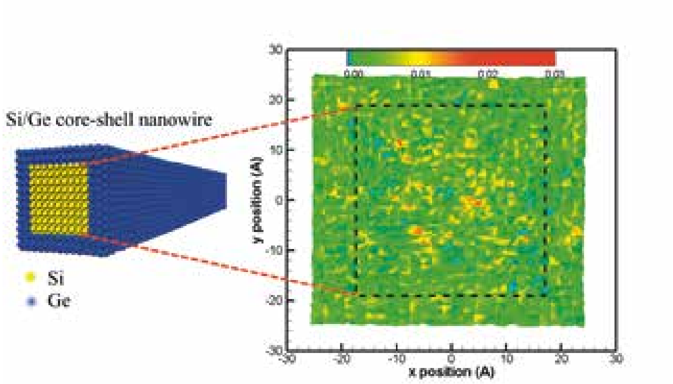


Figure 3: Si/Ge ultrathin core/shell nanowires for high efficiency advanced thermoelectrics.

Teaching activity

The laboratory has significant and heavy teaching responsibilities covering the fundamentals of thermodynamics (3rd and 4th semester undergraduate) plus specialized courses at the Master and advanced BSc levels. The courses taught by LTET are outlined below:

Fostering young academics

The promotion of young academics is an important responsibility of the LTET. In recent years several lab members interested in academic careers have been offered postdoctoral positions at top institutions worldwide. Recent examples include positions at MIT and UC Berkeley in the US. Even more importantly, several former lab members have been appointed to faculty positions worldwide. Our group is equally supportive of graduates who aspire to transfer novel technologies developed during their doctoral research to practical applications through entrepreneurship. Some recent examples of faculty and entrepreneurial positions are:

> Manish Tiwari, Assistant Professor, Department of Mechanical Engineering, University College, London (UCL)
> Vartan Kurtcuoglu, Assistant Professor, University of Zurich
> Ming Hu, Assistant Professor, RWTH Aachen
> Nico Hotz, Assistant Professor, Mechanical and Materials Engineering, Duke University
> Yiannis Ventikos, Full Professor, Engineering Department, Oxford University, UK
> Daniel Attinger, Associate Professor, Mechanical Engineering, University of Iowa
> Partick Galliker, ETH Pioneer Fellow for nanoprinting, planned founding of start-up
> Simone Bottan, ETH Pioneer Fellow for biological materials, planned founding of start-up

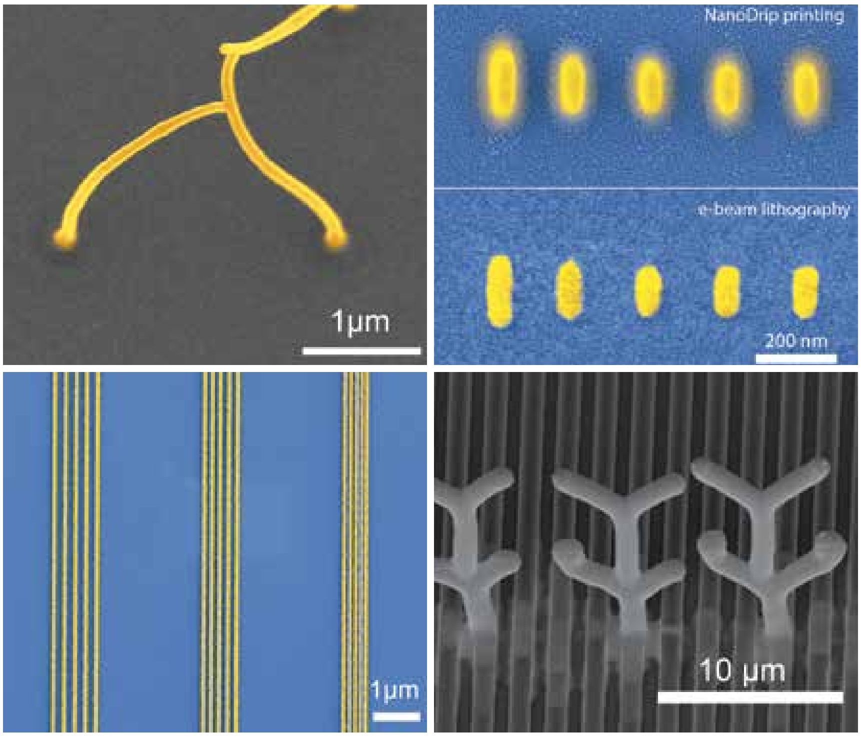


Figure 5: 2D and 3D direct printing at the nanoscale: From plasmonic nano-antennas to nanoscale conductors.

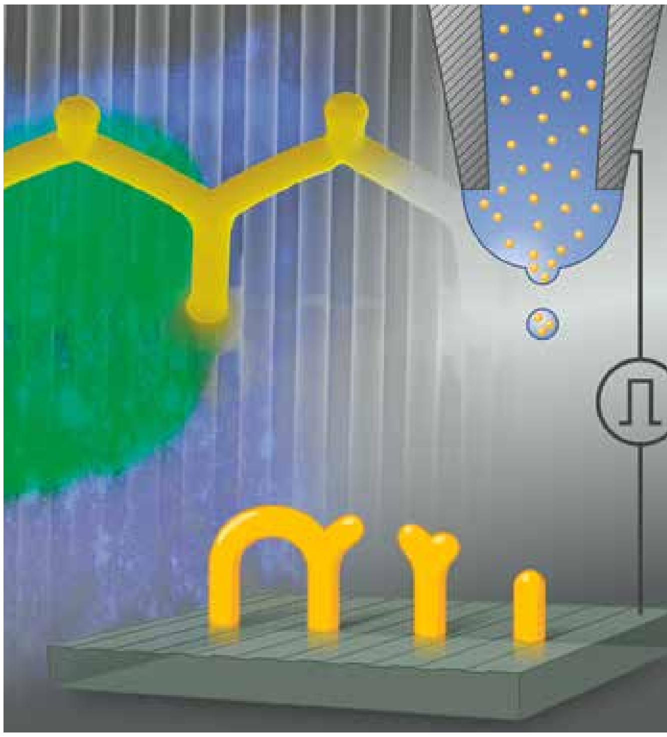


Figure 6: 3D micropores for cell interstitial migration, fabricated by our ultra-high-resolution NanoDrip printing process.

Fall semester

- Thermodynamics I (3rd semester, over 400 students)
- Energy Conversion and Transport in Biological Systems (Master, advanced Bachelor level)
- Thermodynamics of Novel Energy Conversion Technologies (Master, advanced Bachelor level)
- Principles and Engineering Applications of Molecular Dynamics Simulations (Master level)

Spring semester

- Thermodynamics II (4th semester, 50 % responsibility, co-teaching with Prof. Boulouchos, 400 students)
- Thermodynamics and Energy Conversion in Micro- and Nanotechnologies (Master, advanced Bachelor level)

Collaborations

We collaborate on research projects with a broad range of top academic institutions and industries worldwide.

Industrial

- IBM; ABB; Bühler AG; Reishauer AG; Biolab.

Academic

- UC Berkeley; Massachusetts Institute of Technology; University of Illinois; California Institute of Technology; University of Tokyo; École Polytechnique Fédérale de Lausanne; RTWH Aachen.

Key publications

- D. Foresti, M. Nabavi, M. Klingauf, A. Ferrari and D. Poulikakos; Acoustophoretic contactless transport and handling of matter in air, Proceedings of the National Academy of Science of the United Stated of America (PNAS), DOI: 10.1073/pnas.1301860110 (2013).
- P. Galliker, J. Schneider, L. Rüthemann and D. Poulikakos; Open-atmosphere sustenance of highly volatile attoliter-size droplets on surfaces, PNAS, DOI/10.1073/pnas.1305886110 (2013).
- A. Renfer, M.K. Tiwari, R. Tiwari, F. Alfieri, T. Brunschwiler, B. Michel and D. Poulikakos; Microvortex-enhanced heat transfer in 3D-integrated liquid cooling of electronic chip stacks, International Journal of Heat and Mass Transfer, 65, 33–43 (2013).
- P. Galliker, J. Schneider, H. Eghlidi, S. Kress, V. Sandoghdar and D. Poulikakos; Direct printing of nanostructures by electrostatic autofocussing of ink nanodroplets, Nature Communications, (2012), 3, 890.
- S. Jung, M.K. Tiwari and D. Poulikakos; Frost halos from supercooled water droplets. PNAS (2012). DOI: 10.1073/pnas.1206121109.
- S. Jung, M.K. Tiwari, N.V. Doan and D. Poulikakos; Mechanism of supercooled droplet freezing on surfaces Nature Communications 3:615 (2012). DOI: 10.1038/ncomms1630.
- A.J. Santis-Alvarez, M. Nabavi, N. Hild, D. Poulikakos and W.J. Stark; A fast hybrid start-up process for thermally self-sustained catalytic n-butane reforming in micro-SOFC power plants, Energy & Environmental Science, DOI: 10.1039/c1ee01330k (2011).
- S. Jung, M. Dorrestijn, D. Raps, A. Das, C.M. Megaridis and D. Poulikakos; Are superhydrophobic surfaces best for icephobicity?, Langmuir 27, 3059–3066 (2011).
- M. Hu, K.P. Giapis, J.V. Goicochea, X. Zhang and D. Poulikakos; Significant reduction of thermal conductivity in Si/Ge core-shell nanowires, Nano Letters 11, 618–623 (2011).
- M. Hu, J.V. Goicochea, B. Michel and D. Poulikakos; Water nanoconfinement induced thermal enhancement at hydrophilic quartz interfaces, Nano Letters 10, 279–285 (2010).

Laboratory of Nuclear Energy Systems

Our field of research is the thermal fluid dynamics of nuclear power plants and we are specifically focused on the optimization of safety and efficiency of light-water reactors. Our main contribution to current research lies in the development of novel, high-resolution fluid-dynamic instrumentation and its application to processes governed by turbulent mixing and complex two-phase flow structures. Results are used for the development and validation of thermal-hydraulic and CFD[1] models. The lab is lead by Prof. Prasser, who also serves as head of the LTH[2] at the PSI[3]. The two laboratories operate in close collaboration.

Innovative instrumentation is a key component in the development and validation of fluid-dynamic computer models, which are needed for the optimization of safety and efficiency of nuclear power plants.

The Laboratory of Nuclear Energy Systems pursues the development of novel instrumentation mainly geared toward measuring concentration, temperature and velocity fields with a spatial and temporal resolution sufficient to describe three-dimensional phenomena. Current developments in nuclear technology aim to push the limits of safety, efficiency and economy. Our work responds to the growing need for the development of new types of reactors with inherently safe operation principles and reliable, passive systems for reactor shut down and emergency cooling. The main measuring techniques that we study are (1) methods based on electrical impedance measurements, (2) imaging with fast, thermal and cold neutrons, (3) attenuation and emission of infrared light, and (4) ultrasound transmission.

The laboratory applies the developed instrumentation in experiments that target selected components and processes in nuclear power plants. For example, reliable heat removal from a reactor's core is important for safety and efficiency of nuclear plants. To this end, we conduct adiabatic experiments on the structure of the transient annular flow formed in the upper part of the core of boiling water reactors. Specifically, we equipped the surface of a fuel model with our novel liquid film sensor and gained new insights into complex wave structures and droplet deposition. A special focus was put on the effect of so-called "functional spacers", which are used to enhance heat transfer and push dryout limits. We also conduct complementary tomography experiments with cold neutrons, which provide film thickness distributions with a very high resolution.

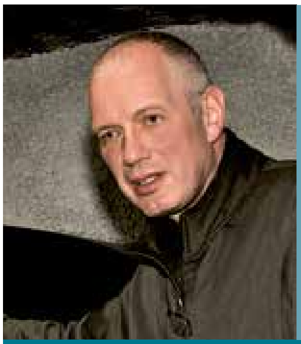
Figure 1: Doctoral student running experiments on coolant cross-mixing and two-phase flow in an adiabatic fuel rod bundle model located at PSI

A test rig installed at PSI[3] is dedicated to cross-mixing and dynamic two-phase flow structures in rod bundles for pressurized water reactors. The phenomena we study are of great practical interest and our results are attracting increasing attention from fuel rod manufacturers.

In close cooperation with the LTH[2] at PSI[3], safety-relevant thermal hydraulic phenomena in the containment of nuclear power plants are studied at the large-scale test facility PANDA, such as hydrogen accumulation, transport and dispersion, phase transition in the containment atmosphere, and the efficiency of passive safety systems. For the testing of special containment instrumentation, a dedicated test facility was erected at ETH Zurich called MiniPanda, which complements the large-scale sister facility PANDA by enabling generic tests applicable to 3D containment code development and validation.

The laboratory has started studies of the fluid dynamics of thermal solar panels, taking advantage of similarities between this field and that of nuclear thermal hydraulics. A test panel was installed, and issues of flow stagnation and degassing are being investigated both experimentally and theoretically. Similar cross-field synergies exist in an industry-financed project being executed at LTH[2] on the the CFD[1] modeling of large-stirred vessel reactors used for the production of base chemicals.

[1] computational fluid dynamic (CFD)
[2] Laboratory of Thermal Hydraulics (LTH)
[3] Paul Scherrer Institute (PSI)



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Horst-Michael Prasser was born in 1955 in Germany, graduated in Nuclear Engineering at the Moscow Institute of Power Engineering in 1980 and obtained his Ph.D. at the Technical University of Zittau in 1984. From 1987 until 2006 he worked at the Research Center Rossendorf (FZR) near Dresden. During the process of the German reunification, Prasser took part in the conversion of the former Central Institute of Nuclear Research Rossendorf into an Institute of the Leipnitz Society, serving as scientific secretary on the board of the research center. Between 1994 and 2006 he was head of the departments of Safety Analysis and Experimental Thermal Fluid Dynamics at the Institute of Safety Research at the FZR. In 2006, Prasser was appointed as Full Professor of Nuclear Energy Systems at the ETH Zurich. Since 2007, he serves a parallel role as head of the Laboratory of Thermal Hydraulics at the Paul Scherrer Institute. From 2008 until 2012, Prasser was a board member of the Swiss Federal Nuclear Safety Inspectorate (ENSI).

Highlights and achievements

Instrumentation

- Novel high-speed sensors for two-dimensional liquid film thickness distributions with high spatial and temporal resolution
- Adaptation of tomographic imaging with cold neutrons to cooling channel models of boiling water reactors
- Novel velocity and gas composition sensors for the hostile reactor containment environment
- Miniaturized temperature and liquid film thickness sensor arrays produced in the clean room

Efficiency of nuclear reactors

- Characterization of the effect of functional spacer grids in reactor fuel rod bundles (e.g. enhancement of turbulent cross-mixing, two-phase flow pattern) with unprecedented spatial and temporal resolution

Safety of nuclear reactors

- Quantification of temperature fluctuations that lead to the ageing of power plant equipment
- Use of MiniPanda test data in an international containment modeling benchmark exercise carried out by the German CFD Alliance under the leadership of the German Society of Reactor Safety (GRS)

Thermal solar panels

- Modeling of flow stagnation and degassing, resulting in a patent on continuous automatic removal of dissolved gases from thermal solar panel circuits

These results are complemented by the achievements of the Laboratory of Thermal Hydraulics at PSI[3] in the fields of containment thermal hydraulics, severe nuclear accidents and multi-phase computational fluid dynamics.

Goals and future priorities

We will continue work on novel instrumentation for turbulent mixing studies and gas-liquid two-phase flows. Our results on the enhancement of turbulent cross-mixing and the influence on the two-phase flow pattern of functional spacer grids in fuel rod bundles is attracting increasing interest from industrial suppliers of fuel elements.

The laboratory will strive to extend its existing collaborations. Following the directives outlined in Switzerland's new national energy strategy, we will gradually shift our research to focus on the issues in thermal fluid dynamics most associated with novel reactor concepts. These new reactor types can potentially offer a new quality in sustainability and safety, which might be interesting in the more distant future. Potential candidates are gas-cooled high temperature reactors, sodium-cooled fast reactors and molten salt reactors. The safety of the existing light water reactors in Switzerland will stay on the agenda.

Furthermore, we plan to extend our activities to address issues arising from the decommissioning of nuclear power plants with the aim of minimizing collective exposure, waste quantities and costs. A teaching block on decommissioning will be developed.

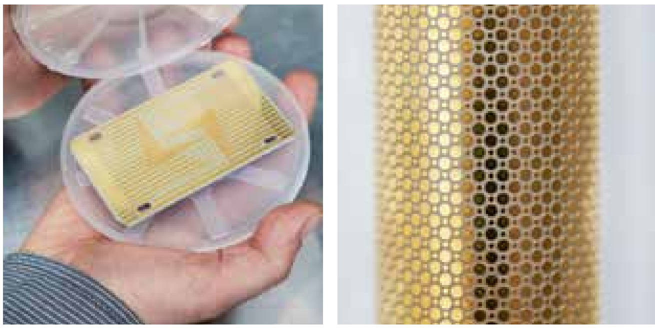

Figure 2: Miniaturized sensors for temperature and liquid film thickness developed by the laboratory.

Figure 3: A spin-off of nuclear thermal hydraulics into solar thermal collector technology.

Organization of the professorship

The professorship of Nuclear Energy Systems was established in April, 2006 based on a contract between the Swiss nuclear utilities, the PSI[3] and the ETH Zurich, which was signed in 2002. In 2012, the lab's funding was reorganized to incorporate a contract with Swisselectric. The research potential of the professorship is strengthened through access to the scientific capacity of the LTH[2] at the Paul Scherrer Institute, where Prof. Prasser has been head since September, 2007. The laboratory belongs to the Department of NES[4]. It operates large experimental laboratories and consists of three groups: (1) Experimental Thermal Hydraulics, (2) Modeling and Simulation, and (3) Severe Accidents.

The LKE[5] at ETH Zurich belongs to the IET[6]. The lab is supported by a part-time secretary and directly employs eleven doctoral students and one postdoctoral student with funds from three SNF[7] projects and an ETH Grant. Three more doctoral students are employed by PSI[3] and financed by third-party funding from industry and nuclear regulators. The lab has two external doctoral students employed by the swiss nuclear industry.

Teaching activity

The laboratory educates academic personnel for industry, research and development in the field of nuclear energy generation, with a focus on nuclear fission. Thus far, our main achievement in teaching has been the launch of a Master program in Nuclear Engineering in cooperation with the EPF Lausanne (EPFL) in 2008. This is the first specialized Master degree to be offered jointly by both federal schools, and it is additionally supported by a third partner, the Paul Scherrer Institute. The program started with three semesters. In 2010, it was extended to a four semester program with 120 credit points under the ECTS[8]. The curriculum is fully compatible with the requirements of the ENEN[9]. The program provides students with in-depth knowledge of the fundamental principles and technology required for harnessing nuclear fission for energy supply, including the fuel cycle. Core courses are complemented by electives on nuclear fusion and nuclear techniques in medicine, research and industry. In order to broaden their scope, students are encouraged to complement their curriculum with courses from the general energetic portfolios at both ETH Zurich and EPFL.

The program, now in its 5th year, has between 12 and 15 new students enrolling each year. It attracts exchange students from all across Europe and a considerable number of students from other Master programs. Compulsory courses for nuclear engineers offered at ETH Zurich include Safety of Nuclear Power Plants, Nuclear Energy Systems, and Radiation Biology and Radiation Protection. Prof. Prasser also teaches the course Reactor Technology at EPFL. Complementary elective courses include: Multi-phase Flows (in cooperation with the professorship of Process Engineering), Computational Multi-phase Thermal Fluid Dynamics, and Beyond Design Basis Safety, a course that includes teaching assignments designed by PSI[3] senior scientists. Exclusively for Master students from outside our lab, we offer a course in Nuclear Energy Conversion at ETH Zurich in the autumn semester. It starts from an introduction to reactor physics and discusses the technology of current light water reactors as well as innovative reactor types.

Fostering young academics

Eight of the best graduates from the Master program of Nuclear Engineering have since been employed as doctoral students in the LKE[4]. Master students are supported in their search for internship positions and jobs in the nuclear industry. Course and Master projects are offered in cooperation with the University of Michigan, the leading institution for nuclear education in the US. The laboratory has exchanged students with the University of Tokyo and the Tokyo Institute of Technology in Japan, the University of Sao Paolo in Brazil, and the University of Pisa, Italy. The postdoctoral student of the laboratory, Dr. Daisuke Ito, has been appointed as Assistant Professor at the Research Reactor Institute of the Kyoto University in 2012.

[4] Nuclear Energy and Safety (NES)
[5] Laboratory of Nuclear Energy Systems (LKE)
[6] Institute of Energy Technology (IET)
[7] Swiss National Science (SNF)
[8] European Credit Transfer System (ECTS)
[9] European Nuclear Education Network (ENEN)

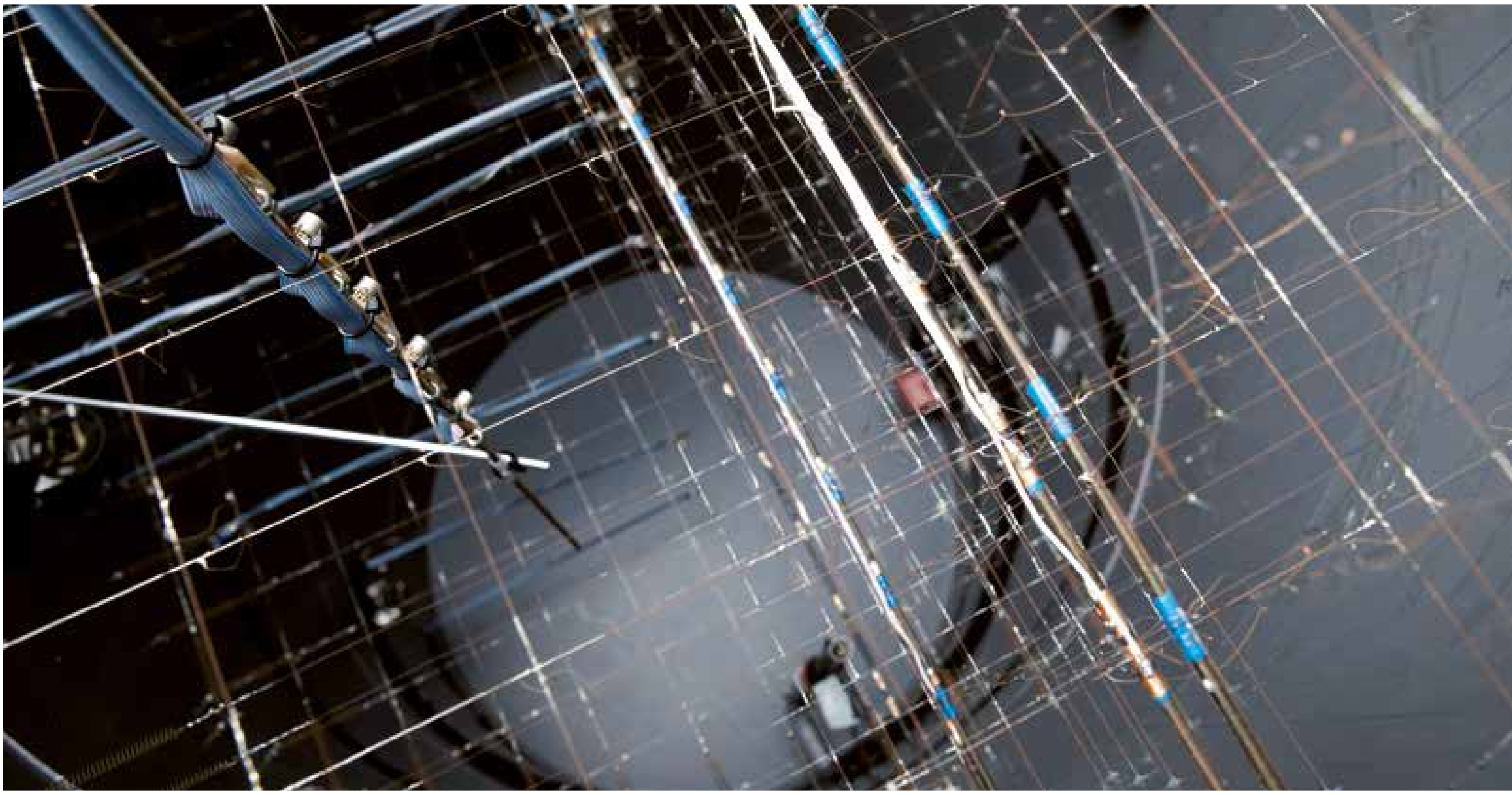

Figure 4: A network of thermoresistive mesh sensors inside the MiniPanda containment facility at ETH Zurich

Collaborations

Industrial

Direct partners of the Laboratory of Nuclear Energy Systems at ETH Zurich include:

AREVA (fluid dynamics of fuel rod bundles, passive safety systems for boiling water reactors); ANSYS Germany (CFD simulation of turbulent mixing and two-phase flows); EdF (pressurized thermal shock, experimental instrumentation); Endress & Hauser Flowtech (flow instrumentation); NAGRA (neutron activation of containment structures); Swissnuclear (temperature fluctuations leading to ageing of power plant components).

We also have numerous international partners through the Laboratory of Thermal Hydraulics at PSI.

Academic

Fachhochschule Nordwestschweiz (FHNW) (two-phase flow instrumentation); Forschungszentrum Jülich (containment thermal hydraulics); Gesellschaft für Reaktor- und Anlagensicherheit (GRS), Garching, Deutschland (thermal hydraulic modeling); Helmholtz-Zentrum Dresden-Rossendorf (former FZR, fluid dynamic instrumentation); Karlsruhe Institute of Technology (nuclear safety); University of Michigan, US (safety of nuclear power plants, nuclear thermal hydraulics, instrumentation); RWTH Aachen (containment thermal hydraulics); Tokyo Institute of Technology, Japan (two-phase flow instrumentation, exchange of students); Universidade de São Paulo, Institute of Petroleum Engineering (multi-phase instrumentation); University of Stuttgart (CFD[1] simulation of two-phase flows, turbulent mixing, instrumentation).

Key publications

> Prasser, H.-M.: Generalized Cross-Correlation Technique for the Measurement of Time-Dependent Velocities, NURETH–15, Pisa, Italy, May 12–17, 2013, paper 409 (best paper award).

> D'Aleo, F. P., Papadopoulos, P., Prasser, H.-M.: Miniaturized liquid film sensor (MLFS) for two phase flow measurements in square microchannels with high spatial resolution, Flow Meas Instr 30 (2013),10–17.

> D'Aleo, F. P., Prasser, H.-M.: Design, calibration and testing of a thin film temperature gauge array for temperature and heat flux measurements in fluid mixing experiments, Flow Meas Instr 24 (2012) 4, 29–35.

> Zboray, R., Kickhofel, J., Damsohn, M., Prasser, H.-M.: Cold-neutron tomography of annular flow and functional spacer performance in a model of a boiling water reactor fuel rod bundle, Nuc Eng Design 241 (2011) 8, 3201–3215.

> Damsohn, M., Prasser, H.-M.: Droplet deposition measurement with high-speed camera and novel high-speed liquid film sensor with high spatial resolution, Nuc Eng Design 241 (2011) 7, 2494–2499.

> Ylönen, A., Bissels, W.-M., Prasser, H.-M.: Single-phase cross-mixing measurements in a 4 × 4 rod bundle, Nuc Eng Design 241 (2011) 7, 2484–2493.

> Ritterath, M., Öztürk, O. C., Prasser, H.-M.: Thermo-resistive mesh sensors (TMS) for temperature field measurements, Flow Meas Instr 22 (2011) 4, 343–349.

> Damsohn, M.; Prasser, H.-M.: Experimental studies of the effect of functional spacers to annular flow in subchannels of a BWR fuel element, Nuc Eng Design, 240 (2010) 10, 3126–3144.

> Walker C., Simiano M., Zboray R., Prasser H.-M.: Investigations on mixing phenomena in single-phase flow in a T-junction geometry, Nuc Eng Design 239 (2009) 1, 116–126.

> Damsohn, M.; Prasser, H.-M.: High-speed liquid film sensor for two-phase flows with high spatial resolution based on electrical conductance, Flow Meas Instr 20 (2009), 1–14.

Particle Technology Laboratory

The focus is on particle science and engineering with emphasis on nanoparticles as their properties are quite different than those of bulk materials creating unprecedented opportunities for the development of new products and processes. Aerosol processes are investigated for their capacity to form high purity particles and films with closely controlled size, morphology and composition. A goal of the lab is to place the design of such processes on a firm scientific basis for systematic scale-up. Synthesis of functional materials and devices are explored in close collaboration with the corresponding world-leading industrial and academic labs.

Figure 1: Manufacturing of up to 5 kg/h of ceramic, nutritional and other nanoparticles

Particles are everywhere: from the air we inhale, to the bread, salt and pepper on the dinner table, in dental fillings, in every medication pill, in automobile tires and diesel exhaust, in the cement, wall or car paint, in every chocolate and in cosmetics, suntan lotions etc.

The mission of our laboratory is to teach the fundamentals of particle science and engineering through basic research. We focus on the smallest particles, nanoparticles, as new challenges emerge for their handling and processing and most importantly in living with them. We specialize on gas-phase (aerosol) processes for their unique capacity to form high purity products (e.g. optical fibers) with closely controlled characteristics (size, morphology, purity and composition) accompanied by few, if any, undesirable liquid by-products. We study one of the most attractive aerosol processes, flame technology, for its potential to make a spectrum of sophisticated materials with its proven scale-up capacity in manufacture of commodities such as carbon blacks, fumed silica and pigmentary titania.

The focus of our program is on understanding particle dynamics during materials synthesis at high concentrations and in particular the formation of aggregates (chemically-bonded particles) and agglomerates (physically-bonded particles) that greatly affect processing and applications of nanostructured materials. We are excited with multi-scale process design. So understanding from the nanoscale level can be incorporated (through molecular and mesoscale dynamics) to the standard design of industrial units by classic computational fluid-particle dynamics for efficient manufacture of novel functional nanomaterials.

Parallel to this we focus on new product discovery as materials with unprecedented properties can be made by flame aerosol technology, taking advantage of the extreme heating/cooling rates that can result in novel material compositions for catalysts, ceramics, sensors, phosphors, and even nutritional materials. We are excited with scaling-up our processes all the way from 0.1 to 10'000 g/h in close collaboration and even partnership with the pertinent industry.

Another focus is the physiological characterization of our new materials. We try to understand any adverse health effects early on in the development of such products in close collaboration with world-leading life science laboratories. That way we incorporate such knowledge into the design of our processes and products as society is quite concerned with the health impact of new technologies.

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Diploma, Chem. Eng, Aristotle Univ. Thessaloniki, 1977; MSc 1982 & Ph.D. Eng., UCLA 1985. He was in the faculty (1985-2000) of Chemical Engineering at the Univ. of Cincinnati until he was elected Professor of Process Engineering (1998) and Materials Science (2003) at ETH Zurich.
He received the 1988 Whitby Award of the American Association of Aerosol Research, a 1989 Presidential Young Investigator Award from the US NSF, the 1995 Smoluchowski Award of the European Association for Aerosol Research, the 2003 Baron Award of AIChE, in 2009 he won an Advanced Investigator Grant from the European Research Council and in 2011 he received a Humboldt Research Award from Germany.
He is Associate Editor of the AIChE Journal and the Chairman of the European Editorial Board of KONA Powder & Particle, and on the editorial boards of: J. Nanoparticle Res., Advanced Powder Technol., Current Opinion in Chem. Eng., J. of Aerosol Sci., Powder Technol. and Ind. & Eng. Chem. Research.
He was Visiting Professor at TU Delft, TU Karlsruhe, Univ. Hiroshima (JSPS Fellow), UC Berkeley (Russell Springer), Harvard Univ. and Univ. Duisburg-Essen.

Highlights and achievements

- Measurement of the oxidation rate of $TiCl_4$ for synthesis of TiO_2, that has been called a "landmark contribution in the pigment industry".
- Development of simulators for optical fiber manufacture by MCVD that have been used widely in the corresponding industry.
- Creation of algorithms for aggregate-agglomerate formation by introducing, for the first time, the two-dimensional (in particle mass and surface area) population balance equations facilitating process design for aerosol manufacture of nanomaterials and commodities (e.g. fumed silica).
- Development of the flame spray pyrolysis process for synthesis of nanostructured films and particles, up to 5 kg/h, a worldwide record for a university. This has led to new sensors and, for the first time, nutritional supplements, battery and dental materials.
- Superior heterogeneous catalysts were made in flames initiating a new field in catalyst manufacturing.
- Filamentary agglomerate particles coalescing to compact spheres follow the same morphology pathway, regardless of composition, sintering mechanism and particle size distribution.
- Ag ions rather than particles dominate Ag toxicity. These ions come from the oxidized surface of small silver particles (<10 nm) resolving a long standing dispute that had special groups petitioning the US EPA to treat nanosilver, one of the largest nanomaterial products, as pesticide.
- A process for rapid and *in-situ* coating of nanoparticles by a nanothin silica film essentially "curing" their toxicity while leaving intact their core properties (e.g. optical, plasmonic, superparamagnetic etc.).
- Flame synthesis and direct deposition of metastable ε-WO_3 creating sensors that selectively detect acetone, a diabetes type-I tracer, in the human breath.
- Scalable synthesis of $FePO_4$ nanoparticles that can cure iron deficiency.

Goals and future priorities

Little is known about how well the unique properties of nanostructured materials are reproduced during their large scale synthesis, and how such manufacturing can be designed and carried out.

Our goal here is to fundamentally understand synthesis of surface-functionalized, nanostructured, multicomponent particles by flame aerosol reactors (a proven scalable technology for simple nanopowders). That way technology for making such sophisticated materials is developed systematically for their efficient manufacture so that active devices containing them can be made economically.

Figure 2: Nanosilver (4 to 16 nm) suspensions with the corresponding plasmonic colors

Figure 3: Phosporescent Eu/Tb-doped Y_2O_3 nanoparticles, about 30 nm in diameter

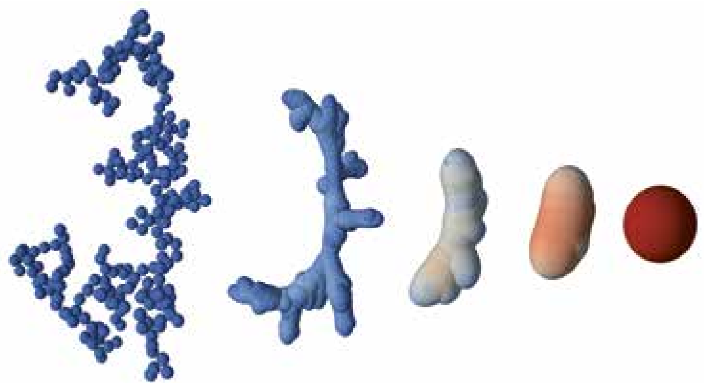

Figure 4: Coalescence of agglomerates of nanoparticles to compact particles by mesoscale simulations

Our focus is on understanding aerosol formation of layered solid or fractal-like nanostructures by developing quantitative process models and systematic comparison to experimental data. This understanding is used to guide synthesis of challenging nanoparticle compositions and process scale-up with close attention to safe product handling and health effects. In fact, curing any deleterious effects of nanoparticles is a goal of our research. The ultimate goal, however, is to address the next frontier of this field, namely the assembling of active devices made with such functionalized or layered nanoparticles.

Organization of the professorship

The professorship is supported by a full time secretary and a technician and part-time microscopy expert, informatics specialist and an electrician on an hourly basis.

A senior Research Associate oversees all laboratory infrastructure and especially the large-scale nanoparticle manufacturing facility (Fig. 1), probably world's largest at an academic institution. He is assisted by a postdoctoral fellow while all lab equipment (5 Mio CHF) is assigned individually to Ph.D. students (0.6 Mio CHF each) for daily control and oversight. Rigorous training and passing of an examination on safety is required for all who work in the lab. Special lectures are given by colleagues from industry Dr. R. Weinekötter (Gericke AG), A. Teleki (DSM Co.) and F. Ernst (Holcim AG) who occasionally host our yearly student excursions.

Each week Ph.D. and MSc students participate at the seminar series of the lab. Once a semester they give a 45 minute lecture on their research progress and plans. These are discussed in detail preparing them for a) job interviews and b) oral or poster presentations at one European and one US scientific conference every year closely related to their research and job interests.

Teaching activity

The fundamentals of particle science are taught with emphasis on its chemical and mechanical engineering applications. In parallel, honesty, ethics, dignity, professionalism, dedication are taught and how to strive for performing excellent research. Essentially the future scientists of the society are "raised".

In autumn, Mass Transfer, Introduction to Nanoscale Engineering (in collaboration with Prof. Norris) and Combustion (in collaboration with Prof. Boulouchos) are taught and in spring, Micro-Nano-Particle Technology & Process Eng. Labs. In addition BSc or MSc projects are supervised throughout the year. Basics (e.g. Mass Transfer & PE Lab) are taught quite rigorously: each semester, we articulate assistant duties to assure a clear understanding that students are our "clients". Student learning is monitored by three tests, 45 minutes each.

Modern BSc (Intro to Nanoscale Eng.) and MSc classes (Micro- and Nano-Particle Technology) are taught more creatively through student projects that are individually supervised by postdoctoral and Ph.D. students. These classes include writing a 2-page proposal (addressing why a topic is important, what has been done and what will be done by the student), giving a 10-minute talk and answering questions for 10 minutes, and finally a 10-page written report.

The Process Engineering laboratory class involves lab work, presentation, questions and written report.

Top BSc and MSc students present research in international conferences and are encouraged to do thesis projects abroad (Harvard, UC Berkeley). Yearly, at least one excursion to industry (Bühler, DSM, Holcim, Cabot, Gericke, BASF etc.) is organized.

Fostering young academics

- Prof. Lutz Mädler, Department of Production Engineering, University of Bremen, Germany
- Assoc. Prof. Wendelin Stark, Department of Chemical and Applied Biosciences, ETH Zurich
- Assoc. Prof. Patrick Spicer, School of Chemical Engineering, University New South Wales, Sydney, Australia
- Dr. Beat Büsser, Department of Chemical Engineering, MIT, Cambridge, US (since 2012)
- Dr. George Sotiriou, Harvard School of Public Health, Boston, US (since 2013)
- Dr. Max Eggersdorfer, Department of Physics, Harvard University, Cambridge, US (since 2013)

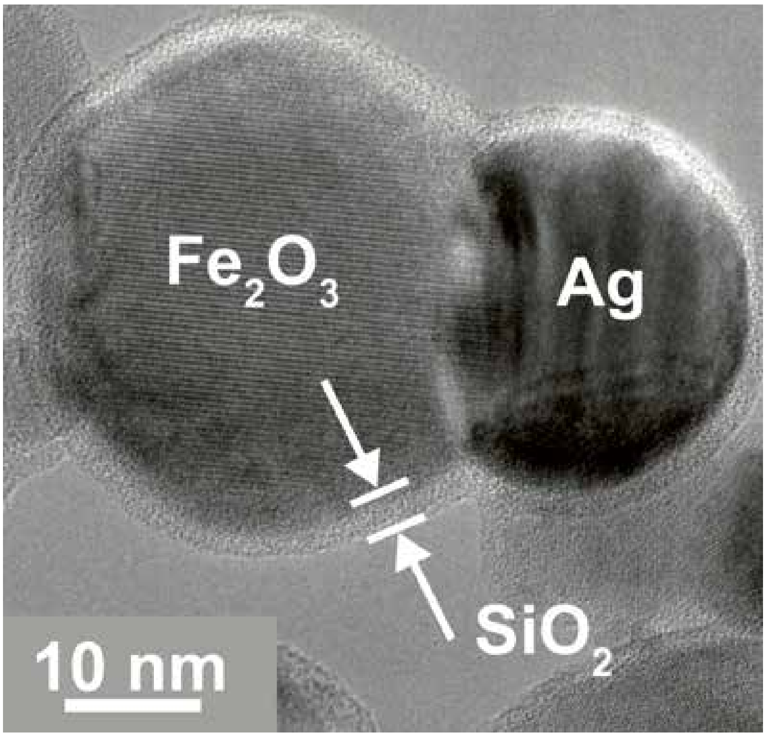

Figure 5: Ag/Fe_2O_3 nanoparticles coated by a nanothin SiO_2 film for cancer cell imaging

Figure 6: Twin-flame synthesis of $Pt/Ba/Al_2O_3$ catalysts for NOx storage-reduction

Collaborations

Industrial

- Bühler AG and Burgerstein AG on development of various nutritional materials
- Sefag AG on nanocomposite dielectrics
- Millennium (Cristal) Co. (US) on silica-coated rutile nanoparticles
- Clariant AG (Germany) on battery and coloristic materials
- Johnson Matthey Ltd. (England) on reactor development for heterogeneous catalysts

Academic international

- Harvard School of Public Health on safe nanomaterials (joint grant from US NSF)
- Univ. Duisburg-Essen on particle synthesis diagnostics
- Innsbruck Medical Univ. on acetone sensors for breath analysis of diabetics

Academic ETH

- Profs Hierold and Nelson on actuators
- Prof. Panke on antibacterial materials
- Profs Zimmermann and Windhab on nutritional materials
- Profs Baiker, Hermans and Poulikakos on catalysts
- Profs Leroux, Vörös and Poulikakos on biocompatible materials
- Prof. Stark on silica-coated particle chains

Key publications

- M.C. Heine, S.E. Pratsinis, "Brownian coagulation at high concentrations", Langmuir, 23, 9882–9890, 2007.
- R. Strobel, S.E. Pratsinis, "Flame aerosol synthesis of smart nanostructured materials", J. Mater. Chem., 17, 4743–4756, 2007.
- A. Teleki, M.K. Akhtar, S.E. Pratsinis, "The Quality of SiO_2 Coatings on flame-made TiO_2-based Nanoparticles" J. Mater. Chem., 18, 3547–3555, 2008.
- M.L. Eggersdorfer, D. Kadau, H.J. Herrmann, S.E. Pratsinis, "Fragmentation and Restructuring of Soft-Agglomerates under Shear", J. Colloid Interface Sci., 342, 261–268, 2010.
- A. Tricoli, S.E. Pratsinis, "Dispersed Nanoelectrode Devices", Nature Nanotechnol., 5, 54–60, 2010.
- M. Righettoni, A. Tricoli, S.E. Pratsinis, "Si:WO_3 sensors for highly selective detection of acetone for easy diagnosis of diabetes by breath analysis", Anal. Chem., 82, 3581–3587, 2010.
- G.A. Sotiriou, S.E. Pratsinis, "Antibacterial activity of nanosilver ions and particles", Environ. Sci. Technol., 44, 5649–5654, 2010.
- B. Buesser, A. Gröhn, S.E. Pratsinis, "Sintering Rate and Mechanism of TiO_2 Nanoparticles by Molecular Dynamics", J. Phys. Chem. C, 115, 11030–11035, 2011.
- B. Buesser, S.E. Pratsinis "Design of Nanomaterial Synthesis by Aerosol Processes", Annual Rev. Chem. Biomol. Eng., 3, 103–27, 2012.
- M.L. Eggersdorfer, S.E. Pratsinis, "Restructuring of Aggregates and their Primary Particle Size Distribution during Sintering", AIChE J. 59, 1118–1126, 2013.

Experimental Fluid Dynamics

The research in the experimental group at the Institute of Fluid Dynamics (IFD) is focused on three primary areas: the development of novel flow diagnostics methods (with special emphasis on imaging techniques); the study of environmental flow phenomena, in particular those related to tunnel fires; and the study of fundamental flow phenomena with applications in industry and medicine. The research group operates a number of dedicated and general purpose facilities (wind and water tunnels), which are used in education, academic research and occasional commercial investigations.

Figure 1: Aerodynamic testing in the large ETH wind tunnel

The imaging activities focus on the evaluation and development of methods suitable for large scale applications such as commercial wind tunnels and open-air field tests. Among the techniques being studied and developed are Doppler global imaging, imaging laser Doppler velocimetry, and laser speckle based digital Schlieren imaging. In addition, specialty devices (e.g. neuronal sensing chips, time-of-flight sensors, motion capture systems, multispectral infrared cameras) are being adapted for efficient use in flow diagnostics such as fluorescence lifetime imaging for pressure sensitive paints, hardware-based motion detection for tracking velocimetry, real-time probe tracking, and sensor fusion.

In the topical area of environmental and safety-related flows, work is concentrated on the development of models for the dynamics and control of tunnel fires. A dedicated sloping hot-gas tunnel is used to study the spreading behavior of smoke in a cross-ventilation scenario, with particular emphasis on the flow structure and evolution of the back-layering zone. Advanced sensing techniques (e.g. fast wire grid temperature sensor, wall-bounded Schlieren, imaging hot-wire) are employed to acquire temperature and velocity fields for subsequent comparison with numerical simulations and semi-analytical models that are being developed at the same time.

Several projects deal with flow phenomena in the biomedical domain. The impact of local flow topology on the accelerated ageing of biological heart valve implants is studied in a dedicated flow loop. Microflows in the alveolar sections of the lung are being investigated to better understand particle deposition mechanisms and to develop novel control and treatment strategies. The investigations rely on both custom-built laboratory models (as for the lung and inner ear studies) and experimental data from *in-vivo* campaigns (e.g. microflows in dental cavities, blood perfusion in the mouse brain). In most cases, state-of-the-art imaging methods are employed (e.g. tomographic and micro PIV, 2-photon microscopy) in alignment with the research group's general competencies and overlapping research objectives.

An additional line of research was opened in the area of fundamental turbulence research. Here the impact of fluid rheology on turbulent microstructure and dissipation is being investigated in a magnetic fluid experiment. Ultrasonic Doppler velocimetry is being developed to acquire the relevant data in these opaque fluids. The sensing technology is at the same time being transferred to other applications in a more applied aerodynamic setting, specifically to the development of a contactless ultrasonic boundary layer probe.

The research group is also increasingly involved in the development of imaging hardware for space flight experiments. Infrared cameras are being used to measure surface temperatures and heat transfer during hypersonic re-entry flight, and at present the designs developed by IFD are integrated into three missions of the European Space Agency ESA (Expert, IXV, ATV) scheduled for launch in the near future. The challenge here is more of a technological nature, as the devices must be accurate and self-calibrating in flight. The knowledge gained from these activities feeds back into the development of new multispectral infrared sensing equipment for aerodynamic measurements (detection of transition and separation) in the IFD wind tunnels.

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Thomas Rösgen has been a Full Professor of Fluid Mechanics at ETH since 1997. Before that, he worked as a senior engineer at the research centre of the European Space Agency (ESA-ESTEC) in Noordwijk (NL). He also held positions as a senior group leader at the Institute of Space Systems, Stuttgart University (DE), and as postdoc/staff engineer at ESA. He holds an engineering diploma from the Technical University in Berlin (DE) and a Ph.D. degree in Aeronautics from the California Institute of Technology (Pasadena, US).
Before his arrival at ETH he worked in a number of different research areas, both fluids-related and others. They include vortex motion in superfluid helium, microgravity fluid dynamics, ferrofluids for levitation, cryo-electronics, digital image processing and restoration of satellite imagery, real-time video motion analysis, and interactive and remote-controlled satellite communications for space experiments.

While most experimental investigations are being conducted as part of doctoral projects, some topics are also being addressed in other constellations, including dedicated research contracts with industry, consultancies by academic staff (including doctoral students) and, in particular, collaborations with the spin-off company streamwise GmbH, which provides an interface to most of the industrial requests received by IFD. An example of this multi-level approach is the ongoing development of an implantable inner ear microphone, which relies on experience gained during a Ph.D. project on surface-mounted MEMS pressure sensors, has led to several student projects and is currently being commercialized by the Institute's spin-off company in collaboration with a leading industrial manufacturer.

Highlights and achievements

The academic highlights for the group in recent years can be listed as:

- Doctoral defense of A. Landolt, J. Sznitman, A. Meier, M. Schäfer, L. Prochazka
- Habilitation defense of Dr. Stefan Schlamp
- Promotion of Dr. J. Sznitman to Assistant Professor at Technion, Haifa following postdoctoral stages at Penn State and Princeton

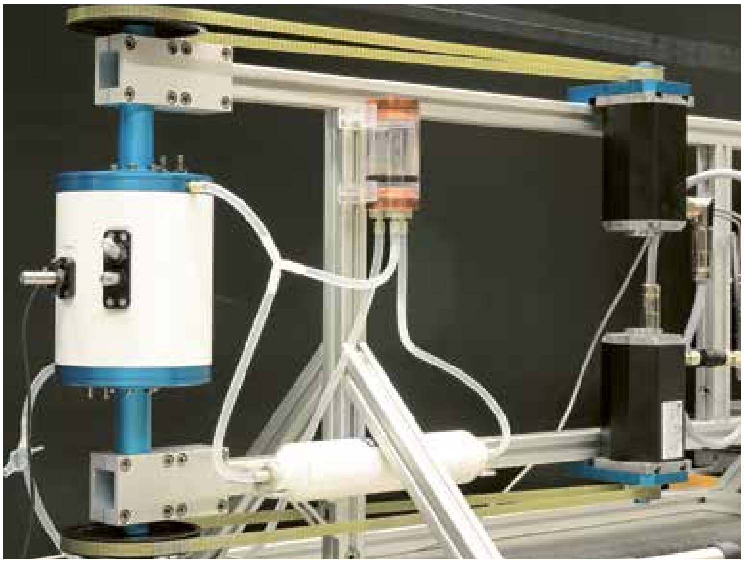

Figure 2: Magnetic fluid flow cell: 3D measurements with ultrasonic Doppler velocimetry

Furthermore, based on the successful industry contacts and collaborations established at the Institute, a spin-off company (streamwise GmbH) was founded in 2010 by a former graduate. The company is active in the development and application of novel flow diagnostics devices for industrial applications.

Goals and future priorities

A gradual shift has evolved in IFD's primary research direction away from the purely technology-driven development of new measurement techniques to more application-oriented projects. It is expected that this trend will intensify, also in connection with the growth of the spin-off company, which has acted several times already as a gateway to new research domains and clients in industry.

In fundamental research, work has started and will increase in several new areas: nonlinear acoustics in flow control and sensing, diagnostics for hypersonic flow experimentation, and fluid flows with variable rheology.

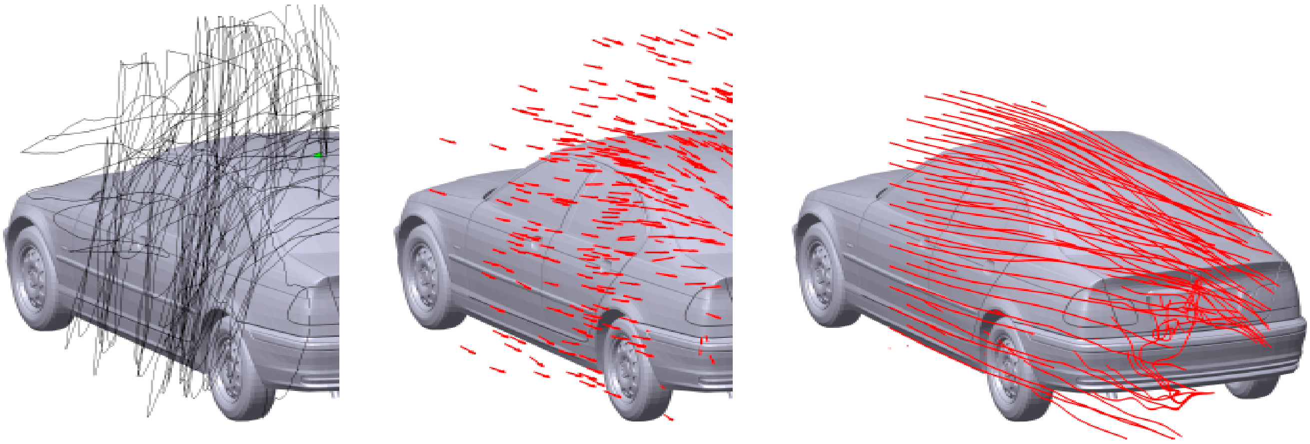

Figure 3: Real-time aerodynamic multi-hole probe tracking: Scan path, vector field, streamline view

Teaching activity

The teaching activities of Prof. Rösgen's group are coordinated with the other faculty of IFD so as to provide a comprehensive curriculum in fluid dynamics both at the fundamental level and in select advanced topics.

Courses are offered to all BSc students (mandatory classes in the 4th and 5th semester), to BSc students selecting the subject major "Energy, Flows & Processes" (5th and 6th semester) and to Master students, in particular those studying according to one of the MSc study profiles offered at IFD ("Fluid Science and Technology", "Aerospace Engineering", "Biological Fluid Science").

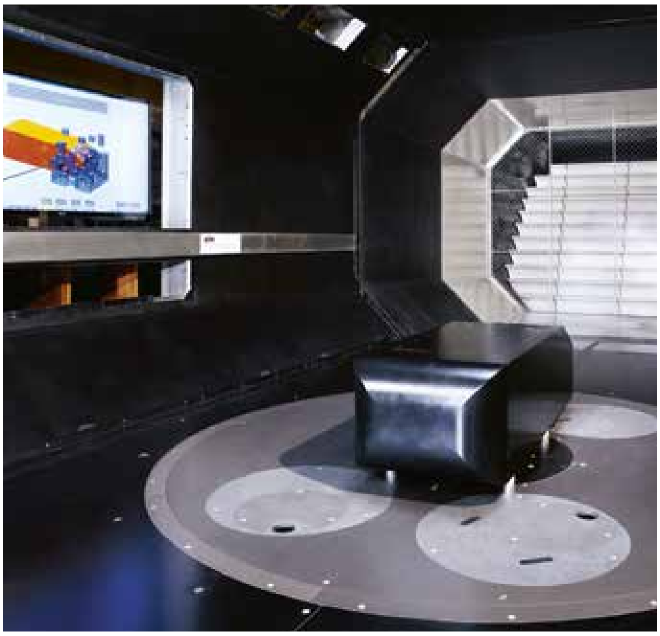

Figure 4: View of the test section in the large IFD wind canal

The classes offered yearly by Prof. Rösgen (and lecturers where indicated) are:

- Fluid Dynamics 1
- Experimental Methods for Engineers
- Engineering "Tools LabView"
- Lab Course Experiments "Wind Tunnel" and "Flow Visualization"
- Quantitative Flow Visualization
- Compressible Flows
- Applied Fluid Dynamics
- Introduction to Vehicle and Aircraft Aerodynamics
- Topics in Flight Mechanics
- Molecular Fluid Mechanics

Besides classes, the experimental group continuously offers and supervises student theses at all levels (BSc thesis, semester project, MSc thesis). Occasionally, one-year projects within the framework of the focus projects are conducted with small groups of students (3-4 participants), for example conducting parabolic flight experiments. Furthermore, group members provide several learning modules in the ETH Zurich postgraduate course "Risk and Safety" and conduct short demonstrations/training experiences to Swiss military pilots.

Fostering young academics

In addition to regularly attending conferences, doctoral students are invited to spend part of their research time abroad (up to 6 months) so as to broaden their professional horizon. Also, doctoral students are permitted to work (and publish) for a limited time on smaller projects not directly related to their thesis topic so as to increase academic exposure. To provide continuity, postdoctoral positions at the Institute are normally available to recent graduates, including the option to work towards a Habilitation degree.

Figure 5: IFD Tunnel Fire Simulation Facility: Study of hot gas propagation using speckle Schlieren imaging and fast temperature grid sensor arrays.

Collaborations

Collaborations exist both on the academic and industrial level. Mostly, students work on individual projects of common interest, be that as part of their thesis (BSc, MSc, Ph.D.) or within the framework of individual research agreements. Collaboration partners include:

Industrial

> Streamwise GmbH (CH); RUAG Aviation (CH); RUAG Space (CH); Oerlikon Textile (CH); Sensirion (CH); Rychiger/Nestlé (CH); EcoMedics (CH); Suter Racing (CH); Alstom (CH); Porsche (DE); BMW (DE).

Institutional research

> Swiss Materials Research Institute EMPA (CH); Swiss Avalanche Research Institute WSL/SLF (CH); German Aerospace Establishment DLR Cologne/Stuttgart/Göttingen (DE); European Space Agency ESA-ESTEC (NL); French-German Research Institute ISL (FR).

Academic institutions

> University of Zurich (CH); University Hospital Zurich (CH); University of Berne (CH); Swiss Fed. Inst. of Technology EPFL (CH); University of Stuttgart (DE); California Institute of Technology (US); University of Michigan (US); Michigan State University (US); University of Washington (US); University of Queensland (AU).

Public outreach

> Swiss Aviation Society (Executive Board Membership); Swiss "Jugend Forscht" (Evaluator and Sponsor, National High School Competition); Zurich High School System (Sponsor of graduation projects).

Key publications

The publications are selected to represent the various research directions followed in the experimental group.

> Improved background oriented schlieren imaging using laser speckle illumination, Meier A.H., Rösgen T., Experiments in fluids 54 (6) (2013)
> Two-photon microscopy with double-circle trajectories for in vivo cerebral blood flow measurements, Landolt A., Obrist D., Wyss M., Barrett M., Langer D., Jolivet R., Soltisynki T., Weber B., Rösgen, T., Experiments in fluids 54 (5) (2013)
> Temperature Mapping of a Re-entry Vehicle Flap in High Enthalpy Flow Test, Rösgen T., Pereira C., Airaghi S., Vuilleumier A., Proc. 12th Quantitative Infrared Thermography Int'l Conf. QIRT 2012 (2012)
> Optically interrogated MEMS pressure sensor array, Prochazka L., Meier A.H., Viggiani A., Rösgen T., Experiments in fluids 52 (4) (2011)
> Probe capture for quantitative flow visualization in large scale wind tunnels, Mueller A., Landolt A., Roesgen, T., AIAA 28th Aerodynamic Measurement Technology, Ground Testing, and Flight Testing Conference (2011)
> Imaging laser Doppler velocimetry, Meier A.H., Rösgen T., Experiments in fluids 52 (4) (2011)
> In vitro model of a semicircular canal, Obrist D., Hegemann S., Kronenberg D., Häuselmann O., Rösgen, T., Journal of biomechanics 43 (6) (2010)
> A novel Infrared Thermography (IRT) based experimental technique for distributed temperature measurements in hot gas flows., Gallo M., Kunsch J.P., Roesgen T., Proc. 10th Quantitative Infrared Thermography Int'l Conf. QIRT 2012, (2010)
> Global Doppler frequency shift detection with near-resonant interferometry, Landolt A., Rösgen T., Experiments in fluids 47 (4-5) (2009)
> Respiratory flow phenomena and gravitational deposition in a three-dimensional space-filling model of the pulmonary acinar tree, Sznitman J., Heimsch T., Wildhaber J., Tsuda A., Rösgen T., ASME J. Biomech. Eng. (2009)

Transport Processes and Reactions Laboratory

The Transport Processes and Reactions Laboratory covers a highly diversified research program that features unique experiments as well as fundamental research relevant to processing. Our novel processes, process-steps and related products find applications across a broad variety of industrial production categories ranging from material processing to traditional chemical processing and manufacturing for the pharmaceutical industry. We focus mainly on the fundamentals of multiphase transport phenomena in connection with processes in the micro - and millimetre scale, on spallation drilling, on volume and surface effects in plasma assisted processes and on green chemical processes.

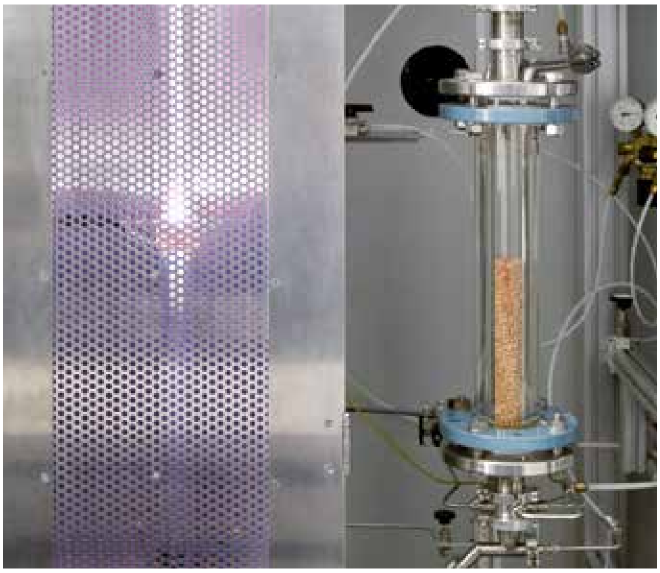

Figure 1: Plasma-circulating fluidized bed reactor for the sterilization of wheat grains

Spallation drilling

Spallation drilling is a promising alternative drilling technology that could prove to be economically advantageous over conventional rotary techniques for drilling deep wells in hard rock formations. The technique has potential applications in future enhanced geothermal systems for the production of electricity. Certain rock types disintegrate into small fragments when rapidly heated to high surface temperatures by a high-energy impinging jet.

The heat flux of the hot impinging jet on rock and its surface temperature are identified as crucial parameters in this process; we investigate this in two pilot facilities.

Plasma process

Non-equilibrium plasmas, observable in nature as the Northern Lights, can also be generated in the laboratory where they are very well-suited for use as a low temperature surface modification tool. Our research in this domain is focused on the functionalization of powders and bulk solids, which enable us to vary the flowability, wettability, or dissolution rate of organic powders, or to sterilize wheat grains without significantly heating them. We additionally modify inorganic bulk solids such as graphite or fluorescent powders to improve the efficiency of lithium-ion batteries and light emitting diodes.

Process intensification and microreactor technology

Increasingly, the chemical and pharmaceutical industries are switching from batch processing to a continuous operation mode of manufacturing. In combination with the miniaturization of units, continuous processing allows for higher selectivity and yield with lower energy input. We design micro-scale reactors and developed a milli-scale reactor with integrated regular porous structure. Turbulent flow can be established at comparably low pressure drops using characteristic diameters in the range of a few millimeters. This approach allows for increased mixing and heat transfer in comparison with methods that use laminar flow reactors.

On the one hand, we investigate these continuous operation processes directly with hydrogenation reactions, and on the other hand, we do experiments in fluid dynamics using particle image velocimetry (PIV) and laser-induced fluorescence (LIF). Measurements achieved by these means allow us to validate our computational fluid dynamics (CFD) simulations.

Green chemistry

Second-generation biofuels produced from lignocellulosic materials like wood show energetic, economic and environmental advantages in comparison with biofuels generated from starch or sugar. However, physical and chemical barriers caused by the entanglement of the main components of lignocellulosic biomass, hinder the enzymatic hydrolysis of cellulose and hemicellulose to fermentable sugars. We are therefore studying pretreatment steps aimed at breaking down the lignin structure and disrupting the crystallinity of cellulose as a means of enhancing enzyme accessibility.

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In 1983 he received a Ph.D. from ETH Zurich. After a two year postdoc at MIT, US he returned to ETH and served as First Assistant in the group of Professor F. Widmer for one year. From 1986 until his start at ETH Zurich as professor in 1992, he worked in an SME (400 employees) close to Basel and became Chief Technical Officer in 1990. At the Institute of Process Engineering at ETH, he served as institute's head and later as its department head. He was a guest professor at UC Santa Barbara in California, US in 1999, and at MIT, US in 2006. In 2013, he took up the role of Invited Professor at the Chinese Academy of Science in Beijing. He is a member of the Swiss Academy of Technical Sciences and active in the European and Swiss Chemical Engineering Associations. In 2006 he received an honorary Ph.D. from the Slovak Technical University in Bratislava. He serves as research council at the Swiss National Science Foundation and as an expert in the Commission of Technology and Innovation. Under his guidance, 45 students have received Ph.D. degrees.

Highlights and achievements

> 2012: Member of the Nuclear Safety Commission in Switzerland (Rudolf von Rohr)
> 2012: Invited to give Schlumberger lecture on spallation drilling at University of Alberta (Rudolf von Rohr)
> 2012: Cover page in Plasma Processes and Polymers on the subject of nanoparticle growth in plasma reactors (Roth et al.)
> 2012: First ever spallation with hot jets in a supercritical water environment (Rothenfluh, Stathopoulos)
> 2012: Patent application (with industry) for Device for processing and conditioning of material transported through device (Rudolf von Rohr et al.)
> 2011 and 2012: Awards for best process engineering students from our group (Haenseler, Edinger), who received overall marks of more than 5.7
> 2011: Invited to lecture on plasma particle processing at the PT15 plasma technology conference in Stuttgart (Rudolf von Rohr)
> 2010: Best poster award at the International Conference on Microreaction Technology (IMRET), (Assmann et al.)
> 2009: Interdisciplinary presentations with University of Zurich on energy; subsequent publication of the book *Energie* (Rudolf von Rohr et al.)
> 2008: ETH medal for a dissertation by S. Kuhn
> 2008: Patent for "Method for attaching nanoparticles to substrate particles" (Spillmann et al.)
> 2006: Doctor *honoris causa*, Bratislava (Rudolf von Rohr)
> 2006: Member of the Swiss Academy of Technical Science (Rudolf von Rohr)

Figure 2: Transparent designed porous structure reactor for the simultaneous investigation by laser induced fluorescence and particle image velocimetry

Goals and future priorities

Objectives in our different fields of research include:

Spallation drilling: Establishing scientific and technological fundamentals for the design of an efficient and cost-effective drilling technology.

Plasma processes: Understanding plasma processes in detail and establishing design rules for applications with particles. Developing an atmospheric pressure process for particle surface treatment.

Process intensification and microreactor technology: Developing our understanding of these processes and technologies with the aim of designing and up-scaling one- and two-phase continuous reaction systems.

Green chemistry: Developing (with other groups) a sustainable process for the treatment of lignocellulosic biomass to improve its yield for useful products.

Organization of the professorship

The organization of our group is simple, and involves no intermediate hierarchical level (except in cases where the professor is on sabbatical, at which point a senior doctoral student takes over all administrative and teaching duties).

> All doctoral students report directly to the professor.
> In brief weekly discussions with the professor, doctoral students discuss new projects, organize workshops, decide on scheduling, submit requests for equipment and other resources, and decide whether project components will be fabricated in-house or outsourced. Project components that are fabricated in-house are designed by technicians using CAD software; the drawings can then easily be transferred to the lab's recently acquired fully-automated milling machine for realization.
> Administrative work is handled by the administrative assistant, who is shared with one other colleague (Professor Mazzotti). Recently, we hired an apprentice in the area of administration who is tutored by our administrative assistant.
> All Bachelor and Master students conducting a project are co-tutored with a doctoral student. A minimum of two open, oral presentations are required. Corrected project reports are discussed and graded together with all tutors.
> For each course, one or two doctoral students are nominated to lead exercises. Additionally, these students assist in developing new examples for written exams.

Teaching activity

We offer lectures and seminars at the Bachelor, Master and Ph.D. levels. In the Bachelor level we offer two classes: Heat Exchange and Design, and Introduction to Process Engineering. The courses Process Design and Safety, and Multiphase Flow are offered at the Master level. At the Ph.D. level, we conduct a seminar on novel process engineering trends.

Our educational activities have a strong basis in student projects; for example, we supervised fourteen Bachelor projects and seven Master projects in the spring of 2013. Our intent is to publish the results of each Master thesis in a refereed scientific journal. Our doctoral students are obliged to present their results in our seminar on the fundamentals of process engineering. We emphasize open discussion as a means of improving scientific and technological approaches and of fostering the transfer of knowledge within our group. The presentations are evaluated anonymously by all other doctoral students attending the seminar and the results of the evaluation are individually discussed. Our first-year doctoral students are heavily involved in tutoring exercises and in laboratory practica.

In addition to our work at the Process Engineering Master program, we are engaged in laboratory practica for all mechanical engineering students and for students in the Master of Energy Science and Technology (MEST).

Figure 3: High-pressure vessel for spallation drilling experiments

Fostering young academics

In spite of the limited number of opportunities at European universities, a number of our former doctoral students have gone on to achieve academic positions.
Professors at universities of applied science in Lucerne (Wellig, 2009), Brugg (Vogel, 2013), Bern (Studer, 2012);
Professors/lecturers at international universities: University College London (Kuhn, Lecturer, 2012), University of Toronto (Günther, associate Professor, 2012).
We send our young academics to conferences and support them with excellent postdoctoral positions.

Figure 4: Test rig for dielectric barrier discharge (DBD)


Figure 5: Surface DBD in Argon

Collaborations

Industrial

- DSM Nutrition, Kaiseraugst, Switzerland: Collaboration on continuous reactions in milli-scale reactors (since 2006), two projects
- Bühler, Uzwil, Switzerland: Sterilization of spores on wheat grains (since 2012)
- Timcal, Bodio, Switzerland and group of Prof. V. Wood, ETH Zurich: Collaboration on graphite particle surface modification (since 2012)
- Sika, Zuerich, Switzerland and group of Prof. W. Stark: Modification of lignin (since 2009)
- Rolic, Allschwil, Switzerland: Continuous processing (2012)
- Leuchtstoffwerk Breitungen, Germany: Plasma surface modification of powders (since 2012)
- Novartis, Basel, Switzerland: Plasma processing (2006–2009)

Academic

- University of Kiel, Germany (Prof. Kersten): Plasma processes
- TU Delft, Netherlands (Prof. Kenjeres): Computational fluid dynamics supported by HPC-Europe2 (2009 and 2007)
- MIT, US and UCL, UK (Dr. S. Kuhn): Flow over complex structures
- EPFL, Switzerland (Dr. Hollenstein): Plasma processing

Key publications

- C. Arpagaus et al., Short-time plasma surface modification of HDPE powder in a plasma downer reactor, Applied Surface Science, 252(5): 1581–1595, 2005.
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- L. Körner et al., Silicon oxide diffusion barrier coatings on polypropylene, Thin Solid Films 518(17): 4840–4846, (2010).
- T. Rothenfluh et al., Penetration length studies of super-critical water jets submerged in a subcritical water environment using a novel optical Schlieren method, Journal of Supercritical Fluids, 57: 175–182, 2011.
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- M. Schuler et al., Simulation of the thermal field of submerged supercritical water jets at near-critical pressures, Journal of Supercritical Fluids, 75: 128–137, 2013.

Reliability and Risk Engineering

Research in the Laboratory of Reliability and Risk Engineering is aimed at the development of innovative techniques and hybrid analytical and computational tools suitable for analyzing and simulating failure behavior of engineered complex systems. We aim to estimate and quantitatively define reliability, vulnerability and risk within these systems. We focus on highly integrated energy supply, energy supply with high penetrations of renewable energy sources, communication, transport, and other physically networked critical infrastructures that provide vital social services.

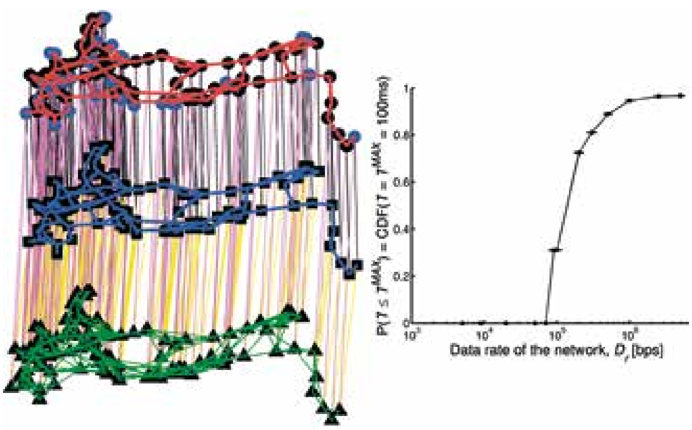

Figure 1: Interdependencies among power, railway and communication infrastructures (left panel); catastrophic transition in power grid reliability as a result of degraded performance of the communication network (right panel).

Critical infrastructures are complex and interdependent. As a result, failure behaviors can emerge from interactions among the topology, physics, and operational procedures that underpin these intricate systems; these pose significant challenges to standard risk-assessment tools, which are insufficient in evaluating the levels of vulnerability, reliability, and risk. These challenges include: the identification of the hazards that threaten these systems, and the adoption of an all-hazard perspective; the identification of critical failures; the identification of critical components and elements at the "system-of-systems" level, including their interdependencies; the evaluation of scenario consequences and probabilities; and the need for effective tools for failure propagation modeling and assessment that can account for topology, physics and operational procedures.

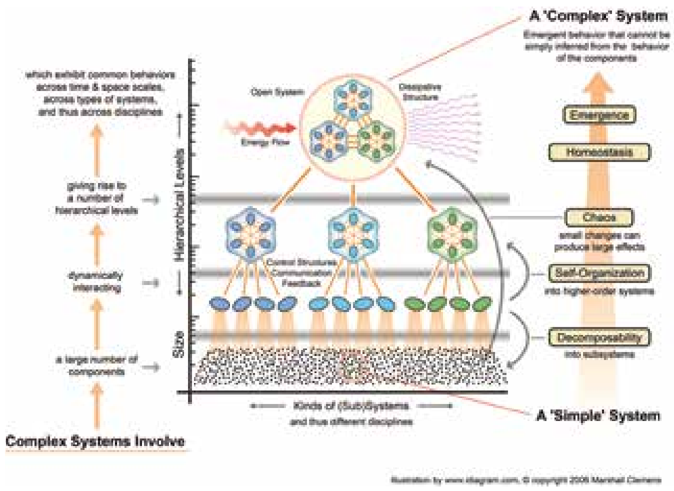

Figure 2: Characteristics of complex systems: emergence and complexity (New England Complex Systems Institute, 2006).

Research in the Laboratory of Reliability and Risk Engineering is aimed at answering these challenges with the development and application of an ensemble of analytical models and computational methods. We use a multidisciplinary, integrated approach to quantify the failure characteristics of complex, interdependent, engineered systems, deploying complex systems theory methods for topological and interdependent systems assessment, hybrid topological and physical models, and a combination of Monte Carlo simulation and advanced machine-learning techniques.

Uncertainty is pervasive within engineered complex systems; thus, its identification and quantification adds a new dimension to the study of these systems. Current research focuses on developing reliable predictions of system behavior in the face of large numbers of uncertain parameters in the modeling of actual complex systems. Indeed, the choice of model parameters is critical to both system response and to the full representation of the variability associated with system response, including variability stemming from the uncertainty in the model parameters themselves. The full quantification of uncertainty therefore adds a further level of confidence to the evaluation of probabilistic safety margins and to the findings of sensitivity analyses.

Our group's specific projects consider: critical infrastructure vulnerability assessment from the standpoint of complex systems theory and network analysis; analysis of the vulnerabilities stemming from interdependencies among critical infrastructures, with reference to the Smart-Grid; and identification and impact of uncertainties in electric infrastructure arising from the high penetration of intermittent energy sources and demand variability.

Highlights and achievements

- We performed vulnerability analysis of interdependent complex networks and referred to the Smart-Grid modeling of electric power grids and communication networks in order to evaluate the impact of the loss of quality in communication on an electric power grid. We detected a catastrophic phase transition point in the frequency of faulty conditions with respect to the data rate of the communication network and suggested the introduction of adequate safety margins.
- Within a distributed generation (DG) penetration assessment, we developed a probabilistic load-flow analysis using Monte Carlo simulations, and quantified the maximum DG power that can be connected to each bus of the distribution network without modifying existing protection, control and automation systems. Using our research, the distribution system operator could decide to connect a quantity of DG greater than the deterministic nodal hosting capacity, thereby accepting a higher risk, for a few hours a year.
- While studying cascading failures in interdependent network systems, we identified the relevant factors affecting the cascade process and detected cascade-safe regions for system operations with respect to the loading level.

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Giovanni Sansavini joined ETH Zurich in June, 2013, as an Assistant Professor of Reliability and Risk Engineering in D-MAVT. He received his B.A. in Energy Engineering in 2003 and his M.A. in Nuclear Engineering in 2005 from Politecnico di Milano (POLIMI). In 2010, as a member of the Atlantis Dual doctoral degree Program, he received his Doctoral Degree in Radiation Science and Technology from POLIMI and his doctoral degree in Mechanical Engineering from Virginia Tech. His doctoral dissertations aimed at developing a methodology for critical infrastructure vulnerability assessment from the standpoint of complex systems theory. As a postdoctoral researcher at Energy Department, POLIMI, he conducted research on the characterization and modeling of the failure behavior of complex systems and critical infrastructures for the study of their reliability, availability, safety, vulnerability, and security, using a computational approach based on advanced Monte Carlo simulation methods, soft computing techniques, and optimization heuristics.

Goals and future priorities

- Evaluation of the effect of functional models on decision-making in the area of protective measures in electric transmission systems: we will assess whether decisions about protection made on the basis of simulations will differ depending on which type of simulation model is

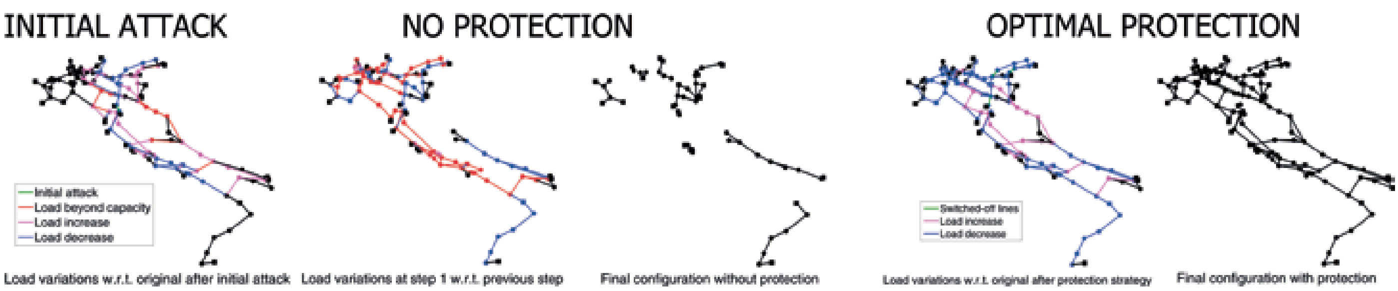

Figure 3: Cascading failure propagation in a high voltage power grid caused by the removal of one line (first panel). The same system with no protection (second and third panels) and with protection (fourth and fifth panels).

used. In cases where abstract and functional models result in the same decision, the former should be preferable because abstract simulations require less time and fewer input data, ultimately allowing for the evaluation of more protection alternatives.

> Assessing the performance of interdependent infrastructures and optimizing investments: we will represent the interdependence of electric and communication networks, using Markov processes to propagate uncertainty found in specific network elements throughout the overall infrastructure. Using this framework, we can formulate an optimization problem geared at finding the investments that maximize performance, subject to a given budget constraint.
> Mitigating performance risk in wind farm projects by engineering asset management: we will account for the stochastic interrelations that link the proactive actions of operation, maintenance and management systems with their effects on production and safety throughout the project life-cycle, with the aim of reducing uncertainties in the return on investment.

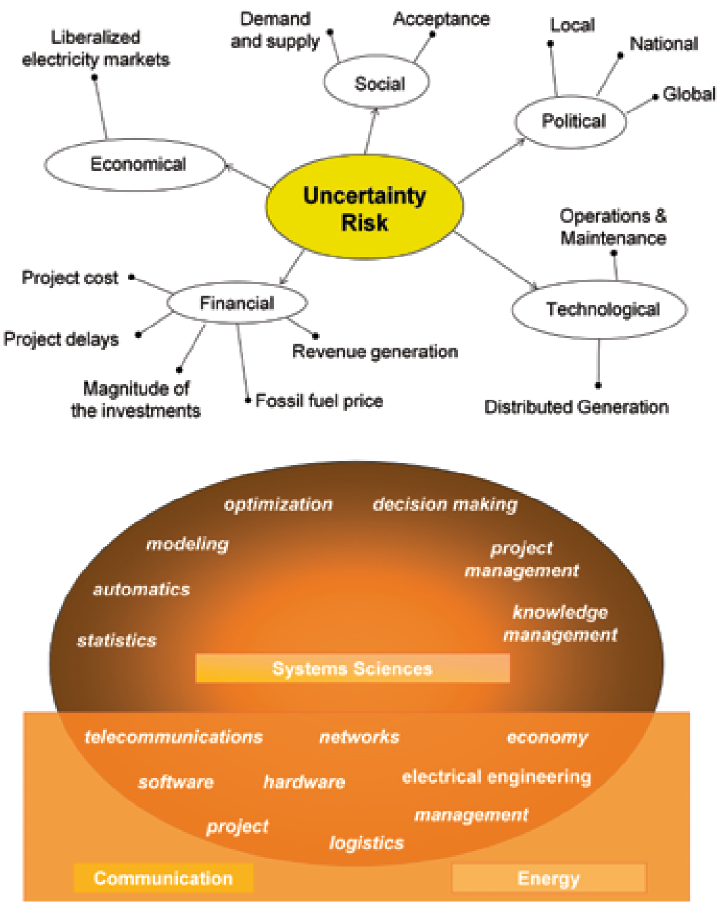

Figure 4: Uncertainties in the future electric power grid (upper panel); modeling the failure behavior of complex systems using a multidisciplinary approach (lower panel).

Organization of the professorship

The Laboratory of Reliability and Risk Engineering started officially on June 1, 2013.

Teaching activity

Teaching responsibilities include contributions to the Department's graduate programs, including the ETHZ/EPFL Master in Nuclear Engineering. Our courses embrace basic concepts and theories used in reliability and risk analysis, proven methods used in systems engineering (such as probabilistic safety assessment), and highly advanced methods and tools for systems modeling and simulation (such as complex systems theory and Monte Carlo method). Emphasis is placed on their application to concrete problems and system integration.

Previous teaching activities at Politecnico di Milano, Italy, include classroom instruction and leading graduate discussion sections as a teaching assistant for the "Reliability, Safety and Risk Analysis" course of the Master in Nuclear Engineering, and being a co-instructor of a doctoral class "Vulnerability Analysis of Critical Infrastructures" on highly advanced methods for complex systems modeling and simulation. Previous teaching activities at Virginia Polytechnic Institute and State University, US, include classroom instruction as a teaching assistant for the "Mathematical Modeling of Biological Dynamics" course of the Master in Engineering Mechanics, and serving as a teaching assistant in the "Computational Methods" and "Statics" undergraduate courses during three academic semesters.

Teaching activity in continuing professional education classes includes lectures on "Event Tree and Fault Tree Techniques" in the class "Reliability, Availability and Maintainability with Application in the Development Phases for Oil & Gas Upstream Projects" for the Italian multinational oil and gas company, Eni.

Fostering young academics

Prof. Sansavini served as co-adviser of one Masters degree dissertation, and of two doctoral theses in the area of identification, quantification and impact of uncertainties in electric infrastructure arising from the high penetration of intermittent energy sources. One of these former students is employed as a postdoc researcher in the area of vulnerability analysis of critical infrastructures at the European Commission, Joint Research Centre, Ispra.

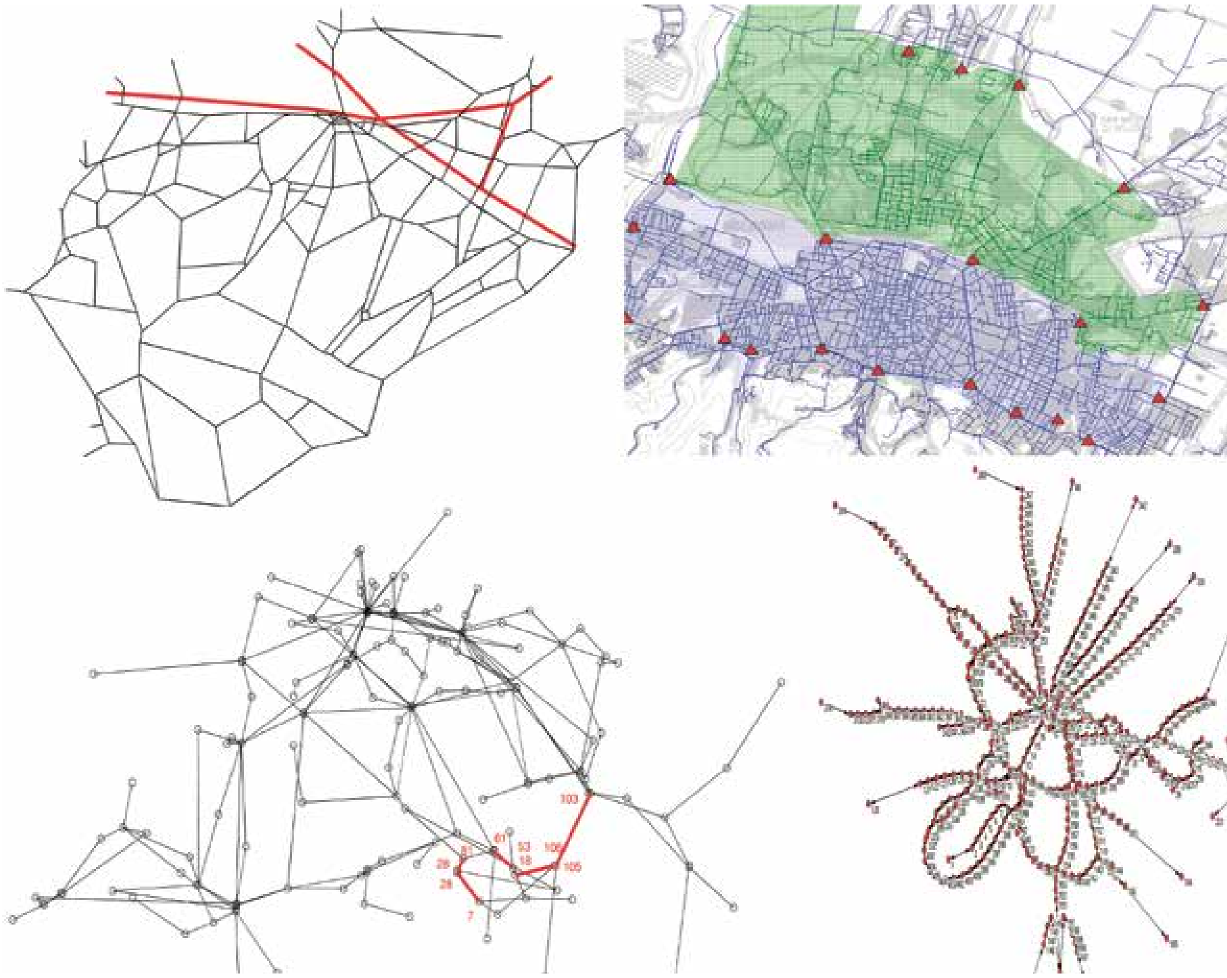

Figure 5: Complex technical systems. From upper left to lower right: road network, water supply network, high-voltage power transmission grid, and streetcar network.

Collaborations

Academic

- Institute of Nuclear Energy Research of the Atomic Energy Council (Taiwan): collaboration in the development of vulnerability analysis of nuclear power transmission networks
- University of Oklahoma (US): collaboration in the quantification of the impact of disruptions in distributed infrastructures on the interdependent industries and infrastructure sectors
- Ecole Centrale Paris (France): collaboration in the area of optimization of cascading failures protection in complex networks
- National University of Defense Technology (China): collaboration in the area of reliability analysis of Smart-Grid communication networks
- Lund University (Sweden): collaboration in the area of functional models for decisions concerning protection measures in electric transmission systems
- Politecnico di Milano (Italy): collaboration in the area of identification, quantification and impact of uncertainties in electric infrastructure arising from the high penetration of intermittent energy sources

Key publications*

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- Zio E. and Sansavini G., Vulnerability of Smart Grids with Variable Generation and Consumption: a System of Systems Perspective, IEEE Transactions on Systems Man and Cybernetics: Systems, 43(3), 477–87, 2013.
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- Zio E., Piccinelli, R. and Sansavini, G., A Framework for Ranking the Attack Susceptibility of Components of Critical Infrastructures, Chemical Engineering Transactions, 26, 309–14, 2012.
- Zio E. and Sansavini G., Component Criticality in Failure Cascade Processes of Network Systems, Risk Analysis, 31(8), 1196–210, 2011.
- Zio E. and Sansavini G., Modeling Interdependent Network Systems for Identifying Cascade-Safe Operating Margins, IEEE Transactions on Reliability, 60(1), 94–101, 2011.
- Sansavini G., Hajj M.R., Puri I.K. and Zio E., A deterministic representation of cascade spreading in complex networks, Europhysics Letters, 87(4), 2009.
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* Published before joining the ETH Zurich

Engineering Design and Computing Laboratory

The Engineering Design and Computing Laboratory (EDAC) focuses on developing cutting-edge computational models, methods and tools that enable the design of innovative and complex engineered systems and products, as well as the automation of design and fabrication processes. Our research is interdisciplinary, combining engineering, design, and computing. It considers early conceptual design phases through to the fabrication of novel solutions. Current topics include computational design synthesis and optimization, model-based design and systems engineering, and design-to-fabrication. We investigate a wide variety of application areas across a number of industries.

Figure 1: Computational design synthesis and optimization: Generating solution spaces

Our research is split into the following three areas:

Computational design synthesis and optimization

This research supports designers in their discovery of new, innovative solutions to engineering tasks, and helps them to gain a better understanding of solution spaces through the interactive and automatic generation of design alternatives. We are currently developing new methods and open-source software platforms for engineering design grammars: one is based on graph grammars for generative concept design including abstraction layers of function, behavior, and structure; the second uses spatial grammars for generative shape design. The graph-based system has been used to generate a variety of powertrain architectures from

Figure 2: Design-to-fabrication: Capitalizing on new fabrication capabilities in design

conventional to hybrid and electric, as well as for automated aircraft cabin configuration. The spatial-grammar-based system has been used to generate vehicle wheel rims, cylinder cooling fins and robot arm concepts. One new area of research investigates the automated integration of constraint solving with the graph-grammar-based platform. We consider both logical constraints that create boolean satisfiability problems and parametric constraints. A second new topic focuses on a systematic method for assisting engineers to develop better generative grammars through automatic rule analysis and feedback.

Model-based design and systems engineering

Our research in this area is focused on creating a formal, model-based approach for the concept design of complex, multi-disciplinary engineered systems. We are developing an integrated, formal product model, along with associated generic model libraries, for mechatronic systems using Systems Modeling Language (SysML). We investigate model libraries at the function, behavior, and structure, also called component, abstraction levels, and formally define valid interconnections between elements. Designers can use model-based libraries in concept stages to rapidly model designs and find alternative, feasible solutions as well as to better understand relationships, e.g. among disciplines. The libraries support customization and extension so that they grow with use.

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Professor Shea graduated in Mechanical Engineering (BSc 1993; MSc 1995) from Carnegie Mellon University (US) where she also earned her Ph.D. in 1997. She then worked as a postdoctoral research assistant until 1999 at the Applied Computing and Mechanics Laboratory in Civil Engineering at EPFL, where she was later a Visiting Professor in 2002 and 2006. Next, she took a position at Cambridge University (UK), Department of Engineering where she worked as a University Lecturer (Assistant Professor) in Engineering Design until 2005. While at Cambridge, from 2002–2005, she also worked as a Senior Engineer in the Arup Foresight, Innovation and Incubation Group in London (UK) where she led the development of expertise in computational design and optimization. From 2005–2012, she was Professor for Virtual Product Development at TU München (Germany) in the Mechanical Engineering Department. In May 2012, she started as Full Professor for Engineering Design and Computing at ETH Zurich. She is a Fellow of the American Society of Mechanical Engineers (ASME).

Design-to-fabrication
Research in this area aims to automate the fabrication of customized parts on computer numerically controlled (CNC) machines through generative fabrication planning and autonomous fixture re-configuration. A new, automatically reconfigurable vise-type fixture was designed for use on a 3–axis milling machine. The customizable vise jaws can be selected automatically from storage using an ontology, or can be designed automatically using a spatial grammar, and then milled directly on the machine for immediate use.

Highlights and achievements

- Successful transition of the research group from TU München to ETH in 2012 and formation of EDAC and Institute of Design, Materials and Fabrication (IDMF).
- Seven completed doctoral dissertations advised: four at TU München; three at University of Cambridge.
- Development of two open-source software platforms for computational design synthesis based on graph and spatial grammars.
- Based on his Ph.D. work, a former doctoral student (TU München) received an EXIST Business Start-Up grant (Germany), 2013.
- One World and one German patent granted for a reconfigurable, vise-type fixture device (Cluster of Excellence, Cognition for Technical Systems, TU München).
- Principle Investigator, SFB 768, Managing Cycles in Innovation Processes, Subproject B2 German Research Foundation (DFG), 2008–2013 (TU München).
- Executive Group and Principle Investigator, Cluster of Excellence, Cognition for Technical Systems, German Research Foundation (DFG), 2006–2012 (three funded subprojects; TU München).
- Co-Chair, Formal Design Synthesis Special Interest Group, Design Society, 2008–present.
- Executive Board of the ETH Women's Professors Forum, 2013 (elected)–present.
- Board of Management of the Design Society, 2011 (elected)–present.
- Associate Editor, Artificial Intelligence for Engineering Design, Analysis and Manufacturing (AIEDAM), 2012–present.
- Editorial Board: Advanced Engineering Informatics [2000-present]; Journal of Engineering Design [2007–2012]; AIEDAM [2011–2012]

Goals and future priorities

Future research priorities include:

Computational design synthesis and optimization
- Automated synthesis of 3D lattice structures, compliant mechanisms and active structures.
- Automated synthesis and optimization of mechatronic systems focusing on robotic applications.
- Multi-objective and multi-disciplinary optimization and exploration methods for computational design synthesis including robust integration of simulation.

Digital Design-to-fabrication
- Structural design optimization methods for digital fabrication focusing on multi-material parts and systems.
- Model-based computational design for digital fabrication to capitalize on new fabrication capabilities in design.

Further potential research topics initiated with student projects include sport equipment design and an interactive 3D printer.

General research priorities include:

- Defining grand challenges for computational design, e.g. considering technological and social advancement.
- Generating human-competitive results including, e.g. patentable mechanical and mechatronic systems or a computational system that could win a design competition.
- Establishing widely adopted benchmarks for computational design synthesis.
- Evaluating research methods and tools in industry.

Organization of the professorship

EDAC currently consists of five (2013) doctoral students, one post-doc and one external doctoral student (TU München). It is supported by an administrative assistant (60%) and a teaching assistant/CAD specialist (25%). Two additional doctoral students and one post-doc will be hired in 2014. The group will then grow based on the acquisition of new research grants and industrial projects. The target group size is 15–20 people. Organizationally, a flat hierarchy is maintained and all people in the group contribute equally to research, teaching, industrial collaboration and the general running of the group. In the future, we plan to have one or two postdocs run their own smaller research groups.

EDAC is part of the Institute of Design, Materials and Fabrication (IDMF) that was founded in July 2013 in collaboration with Prof. Ermanni and Prof. Meboldt. IDMF focuses on Engineering Design as a fundamental discipline within Mechanical Engineering including novel material systems, design methodology, methods and tools, development of innovative technical solutions and novel fabrication processes. IDMF will develop new synergies in education, research and industrial collaboration.

Teaching activity

EDAC is involved in the teaching of Engineering Design as a fundamental part of the Bachelor program. Teaching starts in the first semester and continues through to the fourth semester. Through the foundation of the new Institute of Design, Materials, and Fabrication (IDMF), ETH Zurich aims to build an excellent, consistent, and internationally-leading program in engineering design education. Our lectures focus on theoretical fundamental knowledge and have a strong focus on project-based learning involving open-ended design tasks. Particular attention is given to gender-sensitive education. Development of a state-of-the-art teaching environment for design education is also underway.

EDAC currently teaches the following Bachelor courses:

- Technical Drawing and CAD (1st semester Bachelor lecture and exercise).
- Engineering Tool V: Computer-Aided Design Methods.

In 2013/2014, EDAC will also supervise two Focus Projects in the Bachelor (3rd year):

- Design and Development of an Interactive 3D Printer.
- Design and Development of a Ski Touring Binding.

EDAC contributes to the new Bachelor Focus (3rd year) "Design, Mechanics and Materials". The focus aims to strengthen and broaden fundamentals in Mechanical Engineering and introduce fundamental design methods and state-of-the-art tools for design definition and evaluation of modern mechanical and mechatronic systems.

Within the focus, the following new lectures are planned for the future:

- Computer-Aided Design and Digital Fabrication (Bachelor/Master).
- Engineering Design Optimization (Master).
- Computational Approaches to Engineering Design (Master).

Collaborations

Research collaborations currently exist with TU München, the Chair of Product Development, through the supervision of one doctoral student and University of Texas at Austin through a joint Special Interest Group, Formal Design Synthesis.

Previous research collaborations include Stanford University (US), MIT (US), Texas State University (US), University of Cambridge (UK), EPFL (Switzerland), Technical University of Denmark (Denmark), University of Zagreb (Croatia), TU München (Germany), and TU Kaiserslautern (Germany).

Fostering young academics

The training of doctoral students is supported, e.g., by regular research meetings, participation in international conferences as well as soft skills and language courses. Prof. Shea actively supports young female students and academics at ETH through talks and panels for, e.g., MAVT Girls Day, Fix the Leaky Pipeline and Creating Futures in Science. Prof. Shea is responsible for Young Member activity development in the Design Society and has run a successful international summer school (Institute for Advanced Study, TU München).

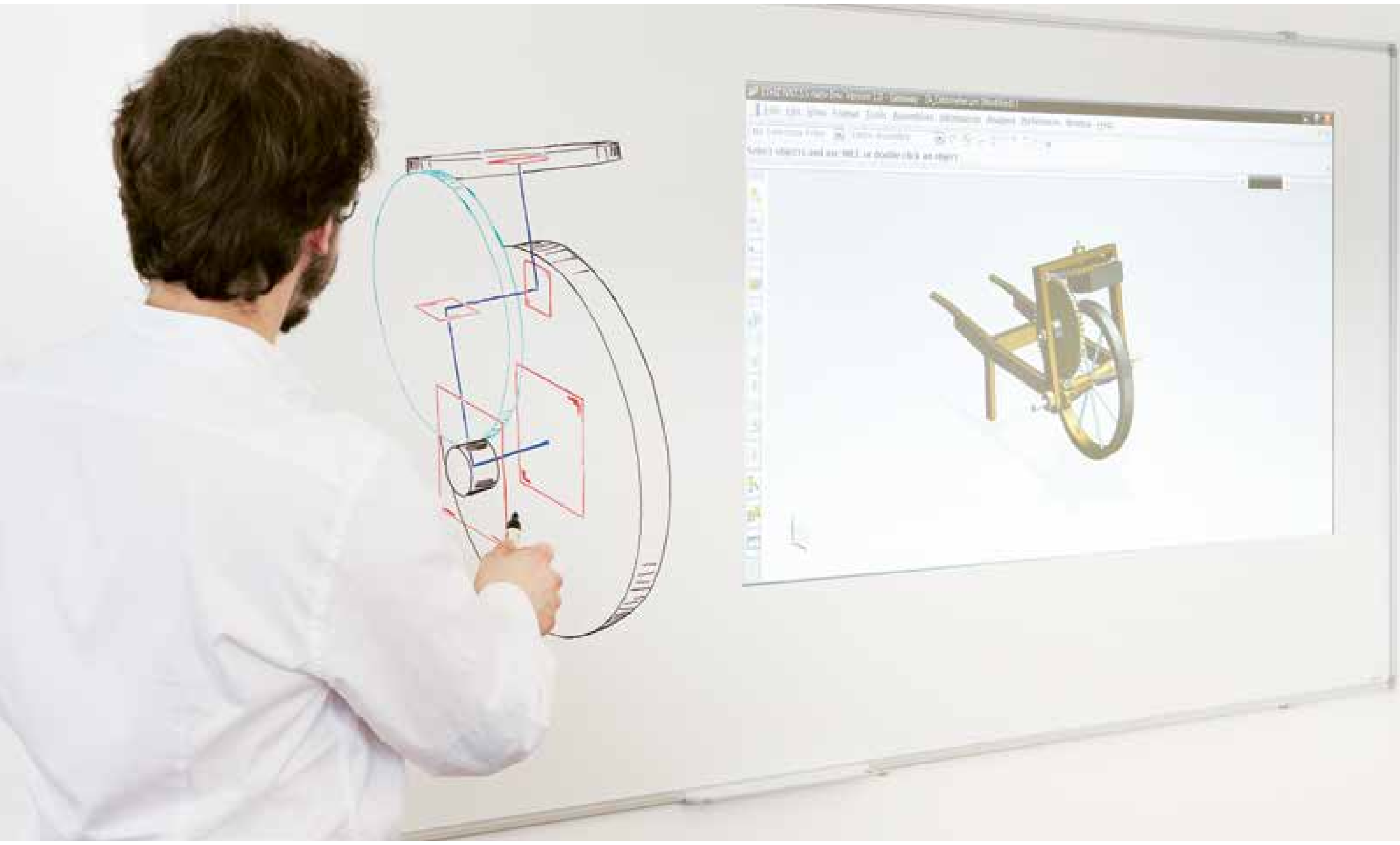

Figure 3: Teaching in Engineering Design: Technical Drawing and CAD

All research topics are ultimately targeted towards improving the competitiveness of product development and manufacturing. Recent industrial collaborations include Siemens (Germany, US), EADS (Germany), Eurocopter (Germany), Bosch-Siemens Hausgeräte (Germany), E.ON (Germany), and the Virtual Vehicle Center (Austria).

Development of new academic and industrial collaborations is underway at ETH Zurich through e.g., participation in Innovation Network events, ETH Industry Day and the Bühler Management Event.

Key publications

- Münzer, C., Helms, B. and Shea, K., "Automatically Transforming Object-Oriented Graph-Based Representations Into Boolean Satisfiability Problems for Computational Design Synthesis", ASME Journal of Mechanical Design, 135(10); 101001 (13 pages), 2013.
- Helms, B., Schultheiss, H. and Shea, K., "Automated Assignment of Physical Effects to Functions Using Abstraction Ports Based on Bond Graphs", ASME Journal of Mechanical Design, 135(5): 051006 (12 pages), 2013.
- Hoisl, F. and Shea, K., "Three-Dimensional Labels: A Unified Approach to Labels for a General Spatial Grammar Interpreter", Artificial Intelligence for Engineering Design, Analysis and Manufacturing, FirstView Article, (18 pages), 2013.
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- Bannat, A., Bautze, T., Beetz, M., Blume, J., Diepold, K., Ertelt, C., Geiger, F., Gmeiner, T., Gyger, T., Knoll, A., Lau, C., Lenz, C., Ostgathe, M., Reinhart, G., Roesel, W., Ruehr, T., Schuboe, A., Shea, K., Stork genannt Wersborg, I., Stork, S., Tekouo, W., Wallhoff, F., Wiesbeck, M., Zaeh, M. F., "Artificial Cognition in Production Systems", IEEE Transactions on Automation Science and Engineering, 8(1):148-174, 2011.*
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* Published before joining the ETH Zurich

Autonomous Systems Laboratory

Our mission and dedication is to create intelligent robots and systems that are able of operating autonomously in complex and diverse environments. We are interested in the mechatronic design and control of machines that adapt to various situations and cope with uncertain and dynamic surroundings. We are fascinated by novel robot concepts that are best adapted for acting on the ground, in the air, or in the water. We are furthermore keen to give them the intelligence to navigate such challenging environments autonomously.

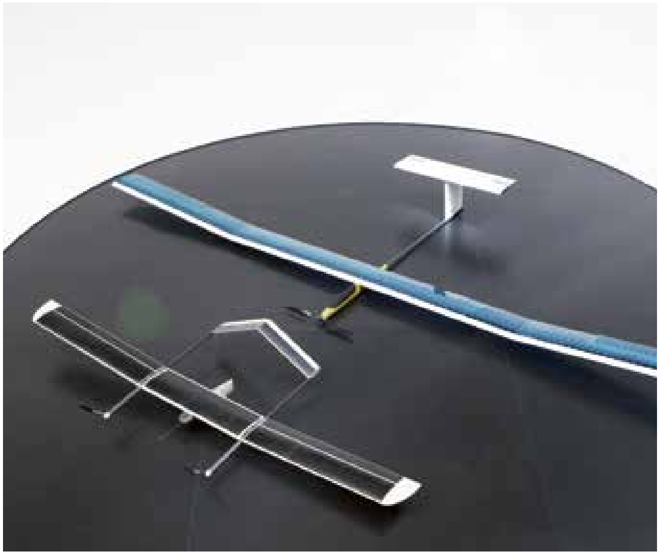

Figure 1: SenseSoar and AtlantikSolar: solar UAVs for long-duration flights

In robotics, the best system designs begin with a careful consideration of the envisioned task and environment. Whereas in our earlier work we had a strong focus on personal-, micro- and all-terrain-robots and quadrotors, our more recent design focus is on bio-inspired walking and swimming robots, and on novel flight concepts.

Our robot StarlETH is an electrically actuated quadruped, capable of static and dynamic gaits including fast walking, trotting, bouncing, and galloping. It exploits the natural dynamics of a given system through an optimal combination of springs and highly dynamic electrical motors. This combination drastically reduces energy consumption while increasing dynamic performance, robustness, and stability. Through various student projects, we have investigated natural swimming concepts that resulted in the robot tuna Naro and the robot turtle Tartaruga.

Our systems-level optimization of small solar-powered unmanned aerial vehicles (UAVs) resulted in our first continuous flight demonstration in 2008. Follow-up designs show promise for long-duration search and rescue operations, and we hope to conduct an Atlantic crossing in 2014. A different approach for long-duration flight is realized with our spherical blimp-robot, Skye, which combines the agility of a quadrotor with the advantages of a lighter-than-air vehicle or a fixed-wing aircraft with vertical takeoff and landing capabilities.

Through our research into robot navigation, we address the scientific questions related to robot state estimation in general, with a focus on localization, map-building, and SLAM[1], as well as fast and dynamic path planning and obstacle avoidance in cluttered environments. Real environments are typically only partially perceivable and perception in these environments intrinsically imprecise. Thus, the actual state of a system must be considered as error prone and inaccurate. With this idea as our basis, we are developing and adapting tools to enable the consideration and modeling of uncertainties for autonomous mobile robot navigation and interaction. Our approach is mainly based on Bayesian mathematics and inspired by recent advances in artificial intelligence and machine learning. All of our theoretical models are verified on real robotic platforms with embedded control, operating in real-world environments and thus producing tangible results. In our recent work, we focus on vision-IMU[2] fusion applied to ground and aerial vehicles, visual SLAM[1] and structure from motion, enhanced applications, and evaluation of ICP[3] algorithms for environment and object recognition and classification.

Highlights and achievements

> The design and evaluation of all-terrain locomotion concepts resulting in the six wheel rover CRAB outperforming existing systems.
> A demonstration of the first continuous flight of a small solar-powered airplane.
> Rezero, a powerful and agile robot capable of dynamic motion on a single ball.
> Skye, a spherical airship with agile omnidirectional motion capability.

[1] Simultaneous Location and Mapping (SLAM)
[2] Inertial-Measuring-Unit (vision-IMU)
[3] Iterative Closest Point (ICP)

- StarlETH, a versatile, electrically-driven running quadruped with series elastic actuation.
- Tartaruga, the first robot-turtle, is taking its first swimming lessons.
- Regional topological segmentation based on mutual information graphs.
- A generic open-source framework for visual-inertial fusion for aerial navigation, adopted by several labs worldwide (e.g. NASA JPL, MIT, TUM).
- The first demonstration of autonomous flight based solely upon monocular vision and IMU[2], including scale estimation.
- BRISK, a fast image keypoint detection, description and matching scheme.
- The development of aerial robotic infrastructure inspection through contact.
- SLAM-In-A-Box solution: a multi-camera and IMU[2] sensor system featuring tightly-coupled SLAM[1].
- Enhancement of data-sets for ICP[3] algorithms.
- Spin-offs: Alstom Inspection Robotics, ElectricFeel Mobility Systems and Distran.

Figure 2: AiRobots: a UAV designed for stereo-camera-based boiler inspection

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Roland Siegwart has been Full Professor for Autonomous Systems since 2006 and Vice President Research and Corporate Relations at ETH since 2010. He holds a Diploma in Mechanical Engineering (1983) and a Ph.D. in Mechatronics (1989) from ETH Zurich. Starting in 1989 he spent one year as a postdoctoral fellow at Stanford University, after which he served as an R&D director for MECOS AG, and worked as a lecturer in Robotics at ETH Zurich. He was Professor of Robotics (1996–2006) and Vice Dean of the School of Engineering (2002–2006) at EPFL. In 2005, he held visiting positions at NASA Ames and Stanford University. Roland Siegwart is member of the Swiss Academy of Engineering Sciences, a fellow of the IEEE[4], officer of the IFRR[5] and was part of the Research Council of the Swiss National Science Foundation. He served as Vice President for Technical Activities (2004–2005) and AdCom Member (2007–2011) of the IEEE[4] Robotics and Automation Society.

Goals and future priorities

The Autonomous Systems Lab will continue with its current research directions, including robot design and navigation. Our main design foci will be to: enhance legged robots for dynamic locomotion in rough terrain, develop novel UAV concepts for long-duration flights close to the ground, and realize swimming robots with biologically inspired propulsion concepts.

Exploiting the expertise on visual navigation that we have built up over the years, we will continue our work on estimation algorithms for easy integration of diverse perception channels available at any time (i.e., continuous-time state estimation); real-time dense local mapping for collision avoidance, using tightly integrated vision-IMU[2] multi-camera systems; path planning in dynamically changing environments that also considers motion constraints; and flying with surface contact.

Application-wise, we will continue to focus on autonomous cars, fixed-wing UAVs that can fly close to the ground (e.g. for the purpose of search and rescue and sustainable farming), multi-copters that handle complex in- and out-door environments (e.g. for inspection), legged robots for search and rescue, and the first Atlantic crossing with a small solar-powered UAV.

[4] Institute for Electrical and Electronics Engineers (IEEE)
[5] International Federation of Robotics Research (IFRR)

Figures 3 and 4: Autonomous sailing boat (left); omnidirectional blimp (right)

Organization of the professorship

The Autonomous Systems Lab is led by Prof. Roland Siegwart and is composed of approximately six postdocs, twenty doctoral students, and some technicians and administrative support staff. Following the departure of Dr. Cedric Pradalier, Dr. Margarita Chli and Dr. Paul Furgale have become the deputies of the lab. In October, Dr. Michael Bosse will join the lab leadership.

The lab's philosophy and operational principle is based on high autonomy and self-responsibility down to the doctoral level. This approach has proven to be very effective and motivating, especially given Prof. Siegwart's very limited availability due to his position as Vice President of ETH.

The research teams of the lab align with our main research areas and larger projects. Currently the main research teams are: the Autonomous Driving team led by Paul Furgale, the Flying Robot team led by Margarita Chli, the Legged Robot team led by Marco Hutter, the Search and Rescue team led by Francis Colas, the Solar Airplane team led by Stefan Leutenegger, the Education Robotics team led by Stephane Magnenat, and the Multi-copter Control team led by Kostas Alexis.

We are also supported by part-time lecturers, and especially by Roland Haas, who is responsible for a project-based lecture called 'Focus Projects'.

Teaching activity

In the Bachelor program, we have been responsible for the first year lectures: Technical Drawings, Machine Elements, Innovation Process, and Innovation Project. These lectures involve approximately 450 students every year. The **Innovation Project** is a mechatronic design competition, where student teams develop a system to fulfill a task such as collecting and sorting colored cubes. Each year we propose three different challenges, that are addressed by approximately 25 teams of 4–6 students each. See www.asl.ethz.ch/education/innovationprojects for more information.

For the last few years, we have offered the **Focus Project** lectures, where student teams design, develop, and build a mechatronic system, from a visionary idea up to functional prototype. Prominent projects have included a Formula Student race car, an autonomous sailing boat, a robot tuna, a ballbot, and a spherical blimp. The Focus Project concept originated in our lab and has since been adopted by many other labs because of its positive reception. Currently we offer our Focus Project teams the possibility of an internship in China, where they have the opportunity to develop their prototype into a product (www.asl.ethz.ch/research/focus). In the Mechanical Engineering and Robotics, Systems and Control Master programs we provide three lectures: Autonomous Mobile Robots, Information Processing for Robotics, and Unmanned Aircraft Design, Modeling and Control. Furthermore we organized three summer schools open to international students: Dynamic Walking, UAVs, and Aerial Service Robotics.

Every year, more than 50 students conduct their Bachelor, Study, or Master theses with our group.


Figures 5 and 6: turtle-bot (left); space rover (right)

Fostering young academics

Most of our doctoral students spend approximately three months in another research lab. Various doctoral students and collaborators have been promoted to professors:
Roland Philippsen, Halmstad University in Sweden; Cedric Pradalier, Georgia Tech Lorraine in France; C. David Remy, University of Michigan in Ann Arbor; Davide Scaramuzza, University of Zurich; Ming Liu, The Hong Kong University of Science and Technology and Margarita Chli University of Edinburgh. Others have continued their careers at top institutions such as EPFL, JPL and IBM Research, or have created their own spin-off company.

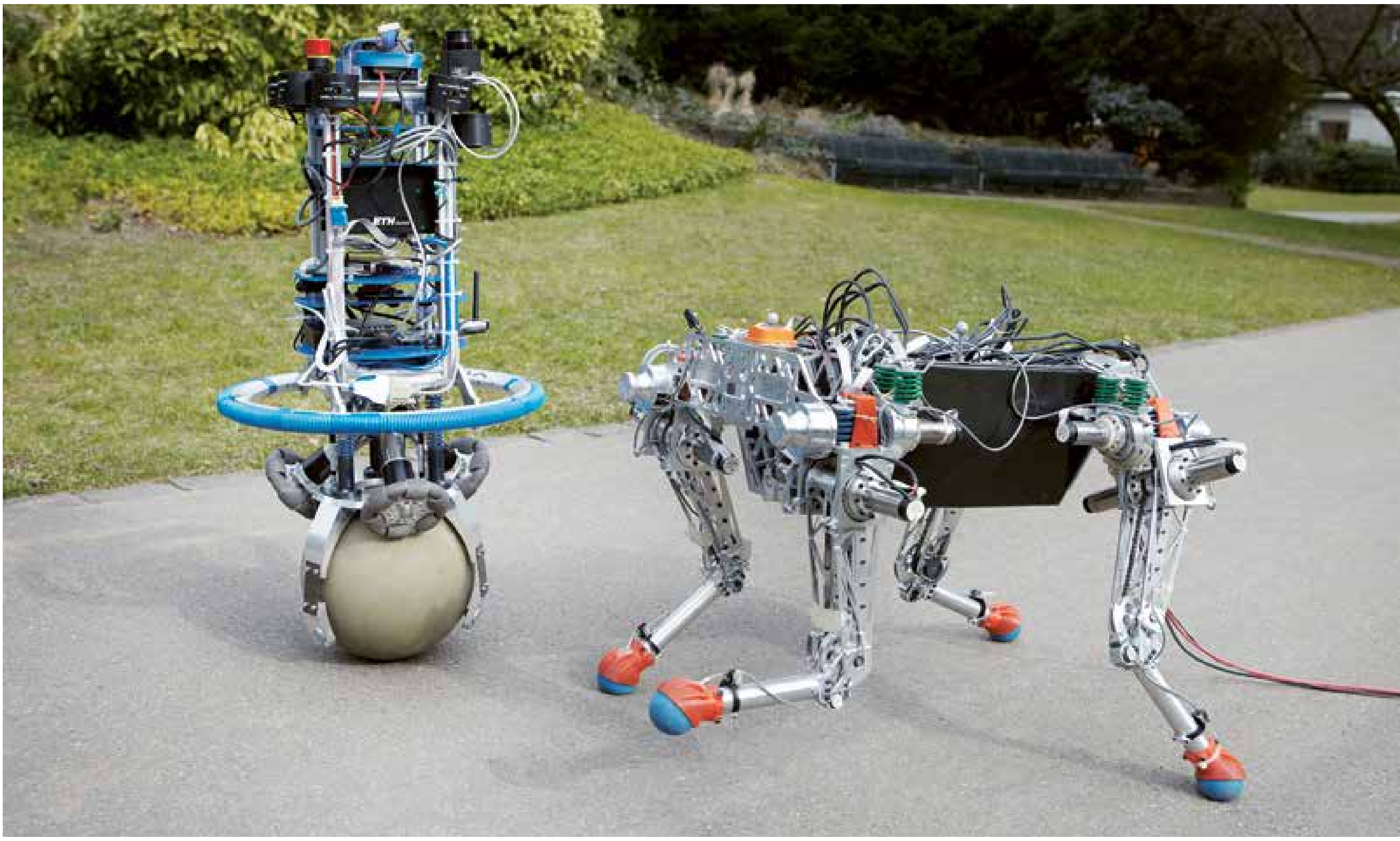

Figure 7: StarlETH and Rezero: a running quadruped and agile ballbot

Collaborations

Industrial

We have very strong and fruitful collaborations with Disney Research Zurich, Ascending Technologies, Leica Geosystems, Super Computing Systems, VW, Bosch, RUAG, Alstom, Dacuda, Maxon and various other companies.

Furthermore, we work with our spin-off companies BlueBotics, Skybotix, GCTronics and Alstom Inspection Robotics.

Academic

Our main European partners include the University of Freiburg (Prof. Burgard), University of Oxford (Prof. Newman), University of Bologna (Prof. Marconi), University of Naples (Prof. Siciliano), University of Twente (Prof. Stramigioli), MPI-Max Plank Institutes (Prof. Schaal), IIT-Italien Institute of Technology (Prof. Caldwell), DFKI-German Research Center for Artificial Intelligence, INRIA-National Institute for Research in Computer Science and Control Grenoble and Sophia-Antipolis, and many more.

Beyond Europe, we have exchange and collaborations with MIT (Profs Rus, Roy), University of Pennsylvania (Prof. Kumar), Stanford University (Prof. Khatib), IHMC-Institute for Human & Machine Cognition Florida (Prof. Pratt), CSIRO Brisbane (Prof. Roberts), University of Toronto (Prof. Barfoot), Tongji University, and many more.

Key publications

- F. Pomerleau, F. Colas, R. Siegwart, S. Magnenat, "Comparing ICP variants on real-world data sets", Autonomous Robots, 2013.
- M. Hutter, C. Remy, M. Hoepflinger, R. Siegwart, "Efficient and Versatile Locomotion with Highly Compliant Legs", IEEE/ASME Transactions on Mechatronics, 2013.
- S. Weiss, M. Achtelik, S. Lynen, M. Chli, R. Siegwart, "Real-time Onboard Visual-Inertial State Estimation and Self-Calibration of MAVs in Unknown Environments", Proc. of IEEE ICRA, 2012.
- L. Kneip, D. Scaramuzza, R. Siegwart, "A Novel Parametrization of the Perspective-Three-Point Problem for a Direct Computation of Absolute Camera Position and Orientation", Proc. of IEEE CVPR, 2011.
- S. Weiss, D. Scaramuzza, R. Siegwart, "Monocular-SLAM–based navigation for autonomous micro helicopters in GPS-denied environments", Journal of Field Robotics, 2011.
- M. Bloesch, S. Weiss, D. Scaramuzza, R. Siegwart, "Vision Based MAV Navigation in Unknown and Unstructured Environments", Proc. of IEEE ICRA, 2010.
- C. Remy, K. Buffinton, R. Siegwart, "Stability Analysis of Passive Dynamic Walking of Quadrupeds", International Journal of Robotics Research, 2009.
- T. Thueer, A. Krebs, P. Lamon, R. Siegwart, "Performance Comparison of Rough-Terrain Robots - Simulation and Hardware", Journal of Field Robotics, 2007.
- S. Bouabdallah, R. Siegwart, "Full Control of a Quadrotor", Proc. of IEEE IROS, 2007.
- A. Noth, W. Engel, R. Siegwart, "Flying Solo and Solar to Mars – Global Design of a Solar Autonomous Airplane for Sustainable Flight", IEEE Robotics and Automation Magazine, 2006.

Renewable Energy Carriers

The research program of the Professorship of Renewable Energy Carriers (PREC, www.prec.ethz.ch) is aimed at the advancement of the thermal and chemical engineering sciences applied to renewable energy technologies. The fundamental research focus comprises high-temperature heat/mass transfer phenomena and multi-phase reacting flows, with applications in solar power and fuels production, decarbonization and metallurgical processes, CO_2 capture and recycling, energy storage and sustainable energy systems. PREC, jointly with the Solar Technology Laboratory at the Paul Scherrer Institute, pioneers the development of solar concentrating technologies for efficiently producing clean power, fuels, and materials.

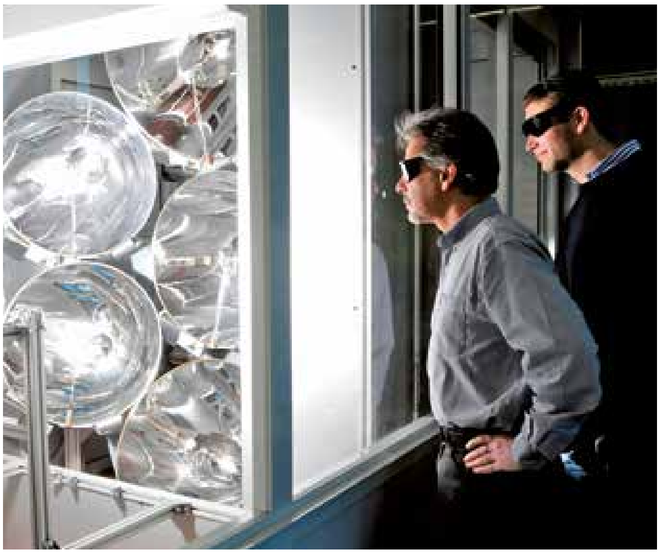

Figure 1: Experimentation at the High-Flux Solar Simulator: solar receivers and reactors are tested at high temperatures (> 1000°C) and high heating rates (> 1000°C/s) under similar radiative heat transfer characteristics of highly concentrating solar systems.

Research main activities and goals

At the fundamental level, the research themes encompass heat/mass transport phenomena and multi-phase reacting flows in high-temperature energy conversion processes. These involve basic thermodynamic and kinetic analyses, CFD and heat transfer modeling, materials development, and the engineering design, fabrication, testing, optimization, and scale-up of efficient thermal converters and chemical reactors. Advanced experimental methodologies, e.g. synchrotron tomography and spectroscopic goniometry, are applied to characterize complex porous materials and determine their effective transport properties. At the applied level, the research themes are grouped in four categories:

1) Solar power generation

Novel and more efficient technologies are being developed for concentrating solar power (CSP) and concentrating photovoltaics (CPV), with the goal to reach significant electricity cost reduction. For CSP, the investigations are centered on innovative solar parabolic trough, dish, and tower systems with better integration of thermal storage and hybridization with fossil-fuel backup. The next generation of solar receiver concepts based on volumetric radiative absorption and alternative thermal fluids operate at high temperatures/high fluxes and promise higher efficiencies, e.g. via Brayton-Rankine combined cycles. For CPV, advanced ray-tracing numerical techniques are applied to optimize optical configurations and reach uniform solar fluxes over 2000 suns at the PV cell.

2) Solar fuels production

Solar thermochemical approaches using concentrating solar energy inherently operate at high temperatures and utilize the entire solar spectrum, and as such provide thermodynamic favorable paths to efficient solar fuel production. The targeted solar fuel is syngas: a mixture of mainly H_2 and CO that can be further processed to liquid hydrocarbon fuels (e.g. diesel, kerosene, gasoline) for the transportation sectors. Solar syngas from H_2O and CO_2 is produced via 2-step thermochemical redox cycles, consisting of the solar endothermic reduction of a metal oxide followed by the exothermic oxidation of the reduced metal oxide with H_2O/CO_2, yielding syngas. Superior redox materials (e.g. zinc, doped ceria, perovskites), structures (e.g. reticulate porous ceramic foams), and solar reactor concepts (e.g. cavity-receiver, volumetric absorption) are developed for enhanced heat/mass transport, fast reaction kinetics, and high specific yields of fuel generation. Solar reactor modeling guides the engineering design and optimization. Solar reactor prototypes experimentally demonstrate the efficient production of solar syngas and their suitability for large-scale industrial implementation. This category also includes projects dealing with decarbonization processes – i.e. reforming, pyrolysis, gasification – with focus on syngas production by the thermochemical conversion of carbonaceous feedstocks such as biomass and C-containing wastes.

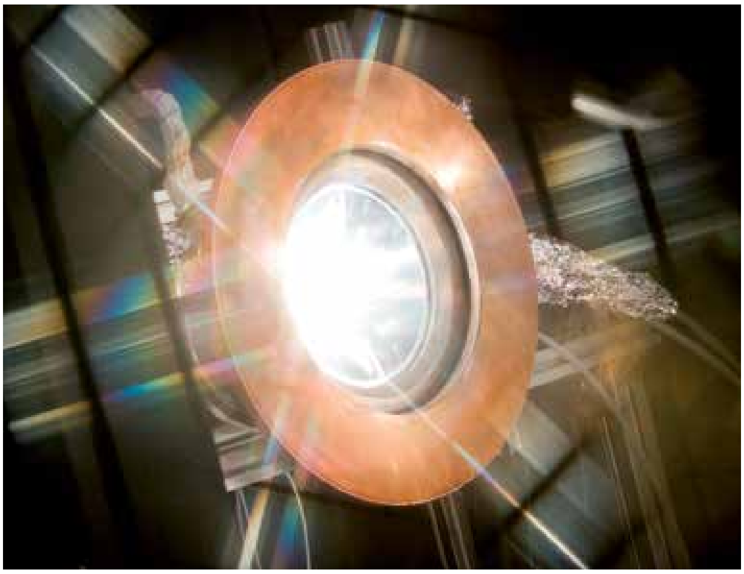

Figure 2: A solar thermochemical reactor prototype for splitting H_2O and CO_2 via redox cycles, exposed to concentrated solar radiation.
©Photo: auto-illustrierte

3) Solar-driven metallurgical processing

The production and recycling of metals (e.g. Al, Si, Zn, Mg, Fe) are energy-intensive processes characterized by their concomitant vast emissions of greenhouse gases and other pollutants. These emissions can be eliminated by the use of concentrated solar thermal energy as the source of high-temperature process heat. R&D involves thermodynamic and kinetic analyses for determining optimal operating conditions and identifying reaction mechanisms, and solar thermochemical reactor engineering for performing the carbothermal reductions with high thermal efficiency and product yield.

4) CO_2 capture from air

The separation of CO_2 directly from atmospheric air, commonly known as "air capture", addresses CO_2 emissions released by the transportation sectors and other distributed sources. Combining air capture with the solar splitting of CO_2 and H_2O offers the production of CO_2-neutral hydrocarbon fuels in a truly sustainable and closed material-cycle. Air capture is accomplished via a temperature-vacuum-swing adsorption/desorption cycle using amine-functionalized biogenic materials. Maximizing CO_2-adsorption capacity and ensuring adsorbent stability, as well as minimizing energy input to the air capture system, are the main objectives of the R&D program.

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Aldo Steinfeld is Full Professor at the Dept. of Mechanical and Process Engineering of ETH Zurich, where he holds the Chair of Renewable Energy Carriers. He further directs the Solar Technology Laboratory at the Paul Scherrer Institute.
He was born 1960 in Montevideo, Uruguay. He earned his BSc in Aeronautical Engineering from the Technion in 1983, his MSc degree in Mechanical Engineering from Tel Aviv University in 1986, and his Ph.D. in Mechanical Engineering from the University of Minnesota in 1989. Prior to joining PSI and ETH, he was a Research Fellow at the Weizmann Institute of Science. At ETH Zurich, he served as the Head of the Institute of Energy Technology from 2005–2007 and Associate Head of the Department of Mechanical and Process Engineering from 2007–2009. He has authored over 250 research articles in refereed scientific journals and filed 25 patents. He served as the Editor-in-Chief of the ASME Journal of Solar Energy Engineering (2005-2009), and is currently serving in several editorial boards. His contributions to science and education have been recognized with the ASME Calvin W. Rice Award (2006), the UOP/Honeywell Lecturer (2006), the University of Minnesota Founders Lecturer (2007), the John I. Yellott Award (2008), the European Research Council Advanced Grant (2012), the ISES Farrington Daniels Award (2013), and the ASME Heat Transfer Memorial Award (2013). Prof. Steinfeld is member of the Swiss Academy of Engineering Sciences.

Highlights and achievements

2010

- Solar H_2O/CO_2-splitting via the ceria-based thermochemical redox cycle (*Science* 330, 1797-1801, 2010).
- Zn-based redox cycle with a 10 kW_{th} solar particle reactor and scale-up to 100 kW_{th}. (*Materials* 3, 4922-4938, 2010).
- Solar aluminum and silicon production by vacuum carbothermal reduction (*Metallurgical and Materials Transactions* 42B, 254-260, 2011).

2011

- A 3 kW_{th} pressurized air receiver for solar-driven gas turbines (*J. Solar Energy Engineering* 134, 021003, 2012).

- Pioneer demonstration of a 150 kW_{th} solar gasification pilot plant in a solar tower, in which carbonaceous waste feedstocks, e.g. agricultural waste, tires, plastics, and fluff, were efficiently converted into high-quality syngas (*Energy & Fuels*, 27, 4770-4776, 2013).

2012

- Record solar-to-fuel energy conversion efficiencies of 3.5 % peak and 1.7 % average for the solar CO_2-splitting with a 3 kW_{th} solar reactor containing reticulated porous ceria (*Energy & Fuels* 26, 7051-7059, 2012).
- Simultaneous splitting of H_2O and CO_2 in consecutive ceria redox cycles, yielding high-quality syngas suitable for the catalytic conversion to liquid hydrocarbons (*Energy & Environmental Science* 5, 6098-6103, 2012).
- Concurrent separation of pure CO_2 and H_2O from ambient air by a temperature-vacuum-swing adsorption/desorption cycle (*Environ. Sci. & Technol.* 46, 9191-98, 2012).
- European Research Council Advanced Grant.

Organization of the professorship

The Professorship of Renewable Energy Carriers (PREC) is committed to excellence in research and education. It performs pioneering R&D projects in emerging fields of energy engineering, maintains state-of-the-art experimental laboratories, offers advanced courses in fundamental/applied thermal sciences, and produces qualified scientists and engineers with expertise in renewable energy technologies. The synergy with PSI's Solar Technology Laboratory, directed as well by Prof. Steinfeld, leads to optimal utilization of resources.
The solar concentrating research facilities include the ETH's high-flux solar simulators and the PSI's solar furnace, which serve as unique experimental platforms for testing optical components under high radiative fluxes (>10,000 kW/m^2) and investigating thermal and chemical processes at high temperatures (up to 3000°C/s) and high heating rates (>1000°C/s).

Figure 3: The solar furnace at the Solar Technology Laboratory of the Paul Scherrer Institute: a sun-tracking heliostat on-axis with a paraboloidal reflector delivers concentrated solar energy at peak radiative fluxes exeeding 5,000 suns (1 sun = 1 kW/m^2).

Teaching activity

Undergraduate courses: Thermodynamics III; Energy System & Power Engineering; Experimental Methods for Engineers.

Graduate courses: Radiation Heat Transfer; Renewable Energy Technologies I; Theoretical and Applied Computational Fluid Dynamics; Fuel Synthesis Engineering.

Other courses: Solar Energy Engineering at Caltech (US), Weizmann Institute of Science (Israel), and Universidad Tecnológica Nacional (Argentina).

Master specialization: The Master program in Mechanical Engineering with specialization in renewable energy technologies is aimed at providing in-depth education and independent research training, with emphasis in the application of the fundamentals of thermal and chemical engineering sciences for the development of clean and efficient energy technologies.

Fostering young academics

Awards to PREC's students: ASME Graduate Student Award to Ph.D. thesis of T. Osinga (2002); ETH Medal to MSc theses of R. Weiss (2004) , H. Ly (2004), F. Meier (2007), J. Wurzbacher (2009), and D. Marxer (2013); ASME Best Paper Award to T. Osinga (2003), A. Z'Graggen (2004), and L. Schunk (2007); Hilti Prize to Ph.D. theses of W. Lipinski (2006) and A. Z'Graggen (2009); Excellent Scholarship and Opportunity Award to M. Kruesi (2008) and Ph. Good (2009); Shell She Study Award to Ph.D. thesis of V. Nikulshina (2009); Swisselectric Research Award to Ph.D. thesis of I. Hischier (2011); Verein Deutscher Ingenieure Prize to MSc thesis of C. Falter (2011); Chorafas Prize to Ph.D. thesis of S. Haussener (2011); TMS Best Paper Award to A. Stamatiou and W. Villasmil (2012); European Talent Award for Innovative Energy Systems to MSc thesis of P. Pozivil (2012); ABB Forschungspreis to Ph.D. thesis of S. Haussener (2012); Solar Energy Journal Best Paper Award to T. Cooper and F. Dähler (2013).

PREC's alumni with faculty positions: Prof. W. Lipinski, University of Minnesota (2009); Prof. J. Petrasch, Fachhochschule Vorarlberg (2012); Prof. P. Loutzenhiser, Georgia Institute of Technology (2012); Prof. S. Haussener, EPFL (2012).

PREC's spin-off companies: Climeworks (2009); Sunbiotec (2011).

Figure 4: The solar-driven thermogravimeter enables the analysis of reaction kinetics during direct exposure to concentrated irradiation. Gas product composition is monitored on-line by gas chromatography and mass spectrometry. Solid products are characterized by X-ray diffractometry and scanning electron micrography.

Figure 5: A spectroscopic goniometry system enables the measurement of directional and spectral radiative properties of semi-transparent media, such as complex porous materials applied in thermal and thermochemical energy conversion processes.

Collaborations

Industrial

Airlight Energy (solar power technologies); Alstom (solar-driven gas turbines); Shell, Bauhaus Luftfahrt (solar jet fuel); Holcim, Sunbiotec (solar gasification of carbonaceous feedstock); Climeworks (CO_2 capture from air); Bühler (thermal energy storage); IBM Research (concentrating PV).

Academic

National: PSI-Paul Scherrer Institute; EMPA-Swiss Federal Laboratories for Materials Science and Technology; EPFL-École Polytechnique Fédérale de Lausanne; SUPSI-Scuola Universitaria della Svizzera Italiana; University of Zurich, SLF-Institut für Schnee- und Lawinenforschung; NTB-Interstaatliche Hochschule für Technik Buchs.
International: University of Colorado; California Institute of Technology; Weizmann Institute of Science; DLR-German Aerospace Center; CNRS-Odeillo; IMDEA-Energy; CIEMAT Plataforma Solar de Almeria; University of Adelaide; Australia National University; CSIRO.

Funding

European Union; Bundesamt für Energie; Kommission für Technologie und Innovation; Schweizerische Nationalfonds; private industry.

Key publications

> Steinfeld A., Palumbo R., "Solar Thermochemical Process Technology", Encyclopedia of Physical Science and Technology, Academic Press, Vol. 15, pp. 237–256, 2001.
> Steinfeld A., "Solar Hydrogen Production via a 2-step Water-Splitting Thermochemical Cycle based on Zn/ZnO Redox Reactions", International Journal of Hydrogen Energy, Vol. 27, pp. 611–619, 2002. (# of citations: 250).
> Hirsch D., Steinfeld A., "Radiative Transfer in a Solar Chemical Reactor for the Co-Production of Hydrogen and Carbon by Thermal Decomposition of Methane", Chemical Engineering Science, Vol. 59, pp 5771–5778, 2004.
> Steinfeld A., "Solar Thermochemical Production of Hydrogen - A Review", Solar Energy, Vol. 78, pp. 603–615, 2005 (# of citations: 350).
> Z'Graggen A., Steinfeld A., "Heat and Mass Transfer Analysis of a Suspension of Reacting Particles subjected to Concentrated Solar Radiation - Application to the Steam-Gasification of Carbonaceous Materials", International Journal of Heat and Mass Transfer, Vol. 52, pp. 385–395, 2009.
> Chueh W.C., Falter C., Abbott M., Scipio D., Furler P., Haile S.M., Steinfeld A., "High-Flux Solar-Driven Thermochemical Dissociation of CO2 and H2O using Nonstoichiometric Ceria", Science, Vol. 330, pp. 1797–1801, 2010 (# of citations: 142).
> Haussener S., Coray P., Lipinski W., Wyss P., Steinfeld A., "Tomography-Based Heat and Mass Transfer Characterization of Reticulate Porous Ceramics for High-Temperature Processing", ASME Journal of Heat Transfer, Vol. 132, pp. 023305 1–9, 2010.
> Wurzbacher J., Gebald C., Piatkowski N., Steinfeld A., "Concurrent Separation of CO2 and H2O from Air by a Temperature-Vacuum Swing Adsorption/Desorption Cycle", Environmental Science & Technology, Vol. 46, pp. 9191–9198, 2012.
> Furler P., Scheffe J.R., Steinfeld A., "Syngas production by simultaneous splitting of H2O and CO2 via ceria redox reactions in a high-temperature solar reactor", Energy & Environmental Science, Vol. 5, pp. 6098–6103, 2012.
> Romero M., Steinfeld A., "Concentrating Solar Thermal Power and Thermochemical Fuels", Energy & Environmental Science, Vol. 5, pp. 9234–9245, 2012 (review article + journal cover).

Nanotechnology Group

The miniaturization of conventional electronic devices into the nanometer range is prone to suffering from fundamental physical limits. To maintain and improve existing performance levels, alternative device concepts, materials, and fabrication methods must be explored and assessed. We focus on bottom-up strategies for assembling and electrically interfacing functional nanoscale components and molecules into device structures, and the development of advanced scanning probe microscopy techniques for analyzing their mechanical, electric and thermal properties locally on the nanometer scale.

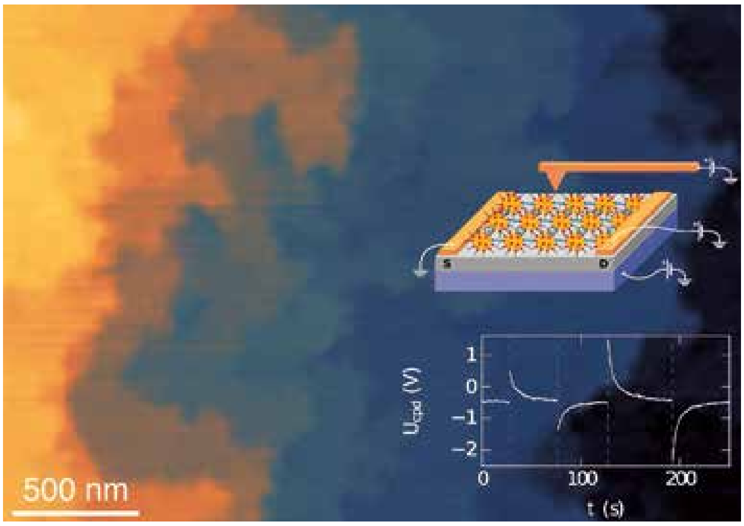

Figure 1: Surface potential and slow transport in disordered nanoparticle film (Image: Tino Wagner)

The Nanotechnology Group pursues a research and education program in nanoscale science and engineering, which projects into the future and anticipates technologies needed ten years from now. We seek to identify, translate and integrate into new technologies basic principles and properties acting on or emerging from nanoscale dimensions.

The Nanotechnology Group has a long track record in developing and applying advanced scanning probe microscopy techniques for surface and materials characterization, in particular in the mapping of local surface potential distributions on passive and active structures. Additionally, we run an active program in directed assembly, bottom-up techniques driven by electrostatic interactions or capillary forces, to deterministically place individual nanoscale objects at desired locations on a substrate. In 2009 we began to focus our research activities towards nanoscale and molecular electronics, as it became evident that technological advances in these areas require both nanometer scale precision in fabrication and assembly, as well as in electric and thermal characterization. In 2011 we further strengthened this focus by moving the entire group to the Binnig and Rohrer Nanotechnology Center (BRNC) on the IBM Research – Zurich campus.

Molecular electronics employs individual molecules or their assemblies as functional electronic building blocks. Designable functionality and precise composition of molecules, coupled with their small size, make this concept a potential candidate to overcome the increasing difficulties current CMOS technology faces upon further downscaling to reach higher performance.

Our current research in the field of molecular electronics targets the assembly of gold nanorods as metallic contacts bridged by few molecules to form functional devices (in collaboration with IBM) and the characterization and visualization of charge transport in nanoparticle structures linked by functional molecules. Our emphasis is on larger molecules and molecular assemblies including biological ones. Towards the advancement of nanoscale electronics, we develop thermal probe techniques to quantify local heat dissipation (in collaboration with IBM) and doping profiles at high resolution, factors that have a crucial influence on the performance of current and future electronic devices. Until 2009 we pursued a competitive research program in high-resolution light microscopy, doubling optical resolution in fluorescence imaging by structured illumination. However, we felt that the field was approaching a very mature level and stopped our activities in this area.

Highlights and achievements

- Fabrication and characterization of sub-5-nm channel length organic field effect transistors from pairs of linked gold nanorods
- Deterministic assembly of gold nanorods into linear, end-to-end aligned chains with 6-nm gaps on solid substrates for applications in molecular electronics and plasmonics
- Mapping of charge transport in two-dimensional arrays of linked gold nanoparticles by Kelvin probe force microscopy

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Andreas Stemmer earned his diploma in Physics at the University of Basel in 1986. He continued his studies in Molecular Biology at the M.E. Müller Institute at the Biocenter, University of Basel, and received certification from the Swiss Commission for Molecular Biology (SKMB). In 1990 he earned his doctorate in Biophysics. After conducting research as Visiting Scientist (1990–1992) at the Medical Research Council Laboratory of Molecular Biology in Cambridge, UK, he was Assistant Scientist (1992–1995) at the Marine Biological Laboratory in Woods Hole, MA, US. In 1995, he was elected Assistant Professor of Nanotechnology at ETH Zurich. He was promoted to Associate Professor in 2001, and Full Professor of Nanotechnology in 2004. He teaches lecture and lab courses in nanoscale science and engineering and in microscopy techniques for the nanometer scale. His current research program focuses on nanoscale and molecular electronics, advanced scanning probe microscopy, and directed assembly.

- Uncoupling of electrostatic and van der Waals forces in atomic force microscopy for accurate height measurements
- Characterization of thermal hotspots in active nanowire junctions and thermal transport across graphene at sub-10-nm lateral resolution
- Characterization of mechanical properties of novel, covalently bonded free-standing two-dimensional polymer monolayers by nanoindentation
- Demonstration of a novel biofuel cell capable of harvesting electric energy from human macrophages and extension of this concept to stress research
- Sub-100-nm lateral resolution in multicolor total internal reflection microscopy using visible light and structured illumination
- Group member Antje Rey received a highly competitive and prestigious IBM Ph.D. Fellowship Award for the academic year 2012–2013

Goals and future priorities

The Nanotechnology Group will continue to focus on nanoscale and molecular electronics, exploring and assessing strategies for assembling nanoscale and molecular building blocks into devices, and characterizing their structure and function at the highest possible resolution by scanning probe microscopy.

In addition to studying bottom-up assembled hybrid metallic-organic complexes and devices, we plan to intensify structural and electric characterization of two-dimensional layered materials by scanning probe microscopy, in particular two-dimensional polymer monolayers in collaboration with Prof. A. Dieter Schlüter, head of the Polymer Chemistry group in the Department of Materials at ETH Zurich. We further plan to expand our research in the direction of plasmonic interactions, which can be excited in assembled nanoscale noble-metal-molecule devices, to analyze their influence on charge transport and device stability, and explore potential applications in the areas of photonics, electronics, and sensing.

Above all, we seek to maintain an attractive and competitive mix of fundamental and application-oriented research projects that mutually benefit one another and foster collaborations among group members.

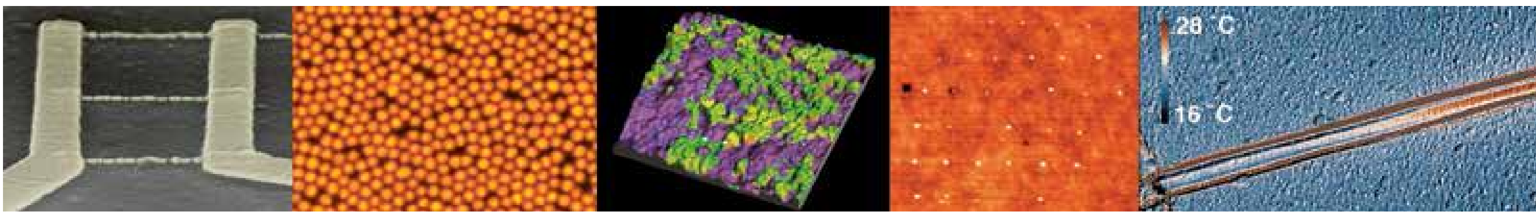

Figure 2: Nanoscale assembly and characterization (Images: Antje Rey*, Jing-Hua Tian, Dominik Ziegler, Livia Seemann, Fabian Menges*)
* in collaboration with IBM Research - Zurich

Organization of the professorship

The Nanotechnology Group is an independent professorship in the D-MAVT. In addition to his role as head of the group, Prof. Stemmer is also associate faculty member of the departments of Materials (MATL) and Information Technology and Electrical Engineering (ITET) and serves as a delegate for professor appointment procedures at ETH Zurich.

In May 2011 the Nanotechnology Group was the first professorship to move to the newly opened Binning and Rohrer Nanotechnology Center in Rüschlikon, where ETH and IBM jointly operate a state-of-the-art cleanroom facility, a result of their partnership in nanoscience formed in 2008. In addition to fruitful collaborations and regular exchanges with colleagues from IBM, at its new location the group benefits from better dry and wetlab infrastructure and in-house processing support, advantages that outweigh limitations imposed by the significantly reduced floor space. The group maintains a small biolab on the main campus of ETH Zurich.

The Nanotechnology Group is focused on people and shaping individual talents. Current staff consists of four to six doctoral students, one or two postdocs, and one electronics engineer. Doctoral students and postdocs envisaging an academic career are encouraged to develop and teach their own lecture modules.

Teaching activity

We teach lecture and laboratory courses in the field of nanoscale science and engineering for advanced undergraduate students, doctoral students, and postdocs. In addition to students from our home department, our courses consistently attract students from other departments including Materials (MATL), Information Technology and Electrical Engineering (ITET), and Health Science and Technology (HEST).

Our lecture course Nanosystems covers fundamental quantum phenomena and interaction forces ruling the nano domain, and places special emphasis on molecular electronics and self assembly. The course Measuring on the Nanometer Scale familiarizes students with the underlying theory and technology of state-of-the-art light, electron, and scanning probe microscopy. Our hands-on Scanning Probe Microscopy Lab covers imaging techniques from basic to the most advanced in this field. We teach this course in our own lab in small groups to maximize microscope time for each student. Until 2009 we pursued an active research and development program in high-resolution light microscopy, accompanied by our lecture and lab course Quantitative and Analytical Light Microscopy, which was geared towards life science imaging.

Bachelor, Semester, and Master theses offered in our own lab or together with colleagues from IBM Research – Zurich provide students with an excellent entry point into challenges in state-of-the-art research and technology. At the same time, the experience of coaching these students through their projects also hones the leadership and science teaching skills of our doctoral students and postdocs, who serve as supervisors.

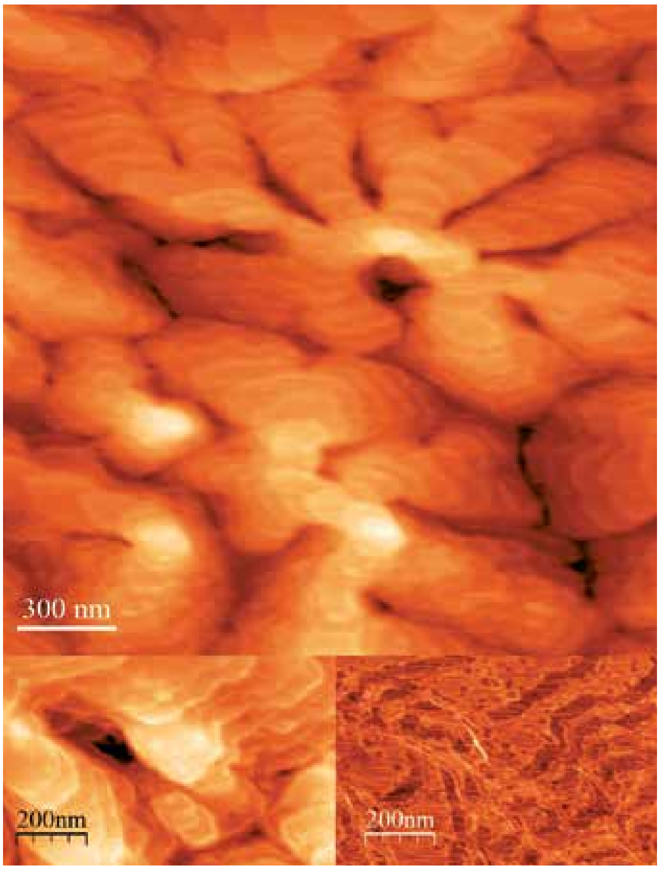

Figure 3: Molecular steps on 15-nm-thick pentacene film (Image: Krithika Venkataramani)

Fostering young academics

Currently, three former doctoral students and two postdoctoral associates are tenured professors at universities in Austria, Germany, United Kingdom, and China.

Recent early-career academic promotions include:

- Jing-Hua Tian (postdoc 2013): Associate Professor, Soochow University, Suzhou, China, 2013.
- Antje Rey (Ph.D. 2013): Lecturer, ETH Zurich, 2010.
- Reto Fiolka (Ph.D. 2009): Lecturer, ETH Zurich, 2008; Instructor in Cell Biology, Director of Microscopy Innovations, University of Texas Southwestern, 2013.

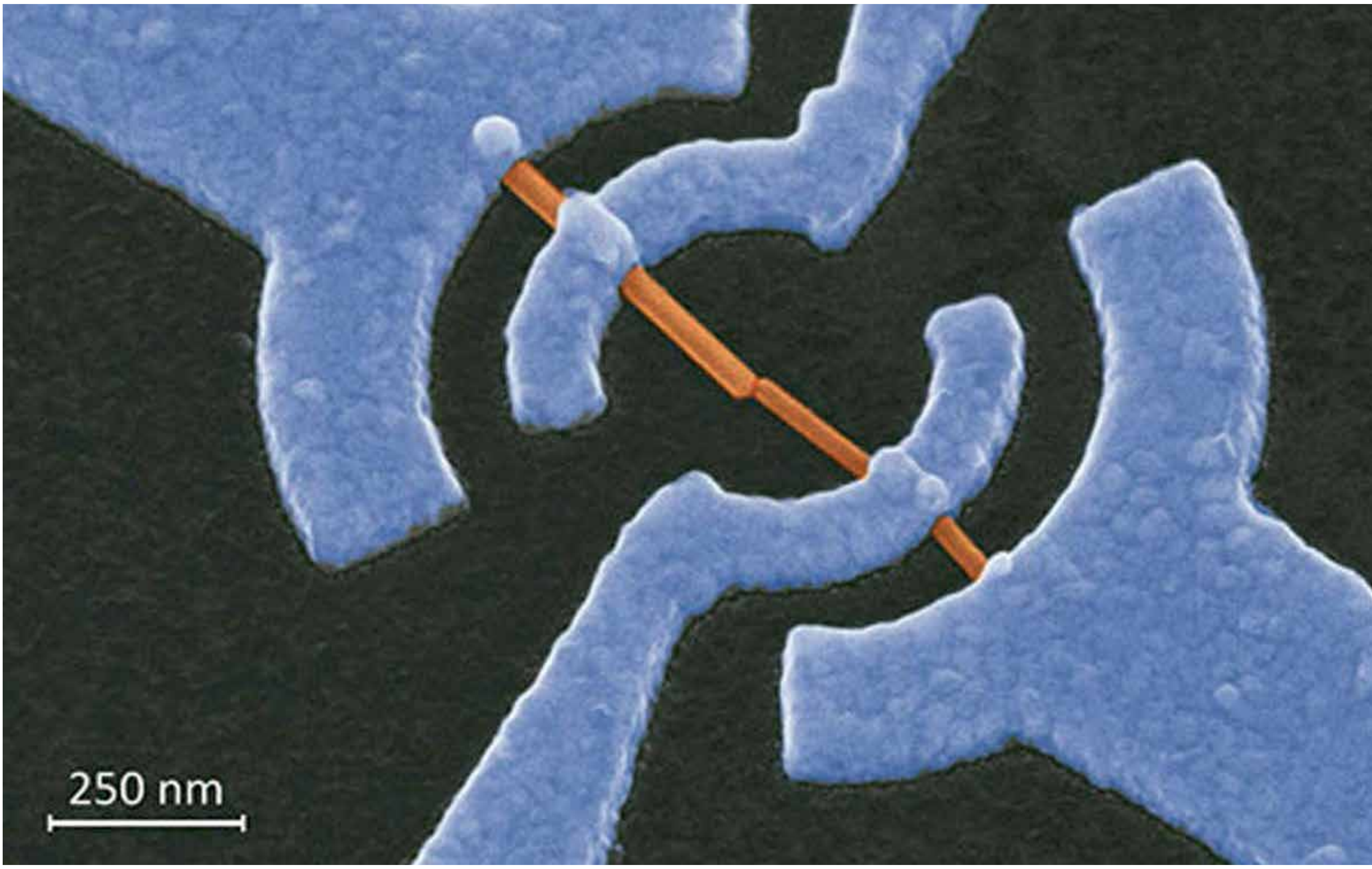

Figure 4: Pentacene transistor made from linked gold nanorods (Image: Antje Rey, in collaboration with IBM Research - Zurich)

Collaborations

Industrial

- IBM Research–Zurich (CH), 2005–present: Joint research on molecular electronics, directed assembly, and scanning probe microscopy[1]
- Zurich Instruments (CH), 2009–present: Scanning probe microscopy applications
- BASF (GER), 2010–2011: Surface functionalizations
- CSEM (CH), 2007–2011: Automated cell sorting and microinjection[1]
- Rolex SA (CH), 2004–2007: Research and service using Kelvin probe force microscopy

Academic

- Prof. A. Dieter Schlüter, ETH, 2008–present: Characterization of two-dimensional polymers
- Profs. Ralph Müller and Jess G. Snedeker, ETH, 2005–2011: Surface morphology of tendon and collagen[1]
- Clinical Psychology and Psychotherapy, Universität Zürich, and Biological Health and Psychology, Universität Bern, 2010–2011: Stress response of macrophages in wound healing[1]
- Prof. Rainer Heintzmann, King's College London (UK), 2008–2009: High-resolution light microscopy[1]
- Institute of Biochemistry, ETH Zurich, 2004–2009: High-resolution light microscopy[1]

[1] Joint publications

Key publications

- Quantitative thermometry of nanoscale hot spots, F. Menges, et al., Nano Letters, 12, 596–601, 2012.
- Variations in the work function of doped single- and few-layer graphene assessed by Kelvin probe force microscopy, D. Ziegler et al., Phys. Rev. B 83, 235434, 2011.
- A novel biofuel cell harvesting energy from activated human macrophages, M. Sakai et al., Biosensors & Bioelectronics 25, 68–75, 2009.
- Simplified approach to diffraction tomography in optical microscopy, R. Fiolka et al., Optics Express 17, 12407–12417, 2009.
- Structured illumination in total internal reflection fluorescence microscopy using a spatial light modulator, R. Fiolka et al., Optics Letters 33, 1629–1631, 2008.
- Sub–100–nanometre resolution in total internal reflection fluorescence microscopy, M. Beck et al., J. Microscopy 232, 99–105, 2008.
- Local surface charges direct the deposition of carbon nanotubes and fullerenes into nanoscale patterns, L. Seemann et al., Nano Letters 7, 3007–3012, 2007.
- Compensating electrostatic forces by single-scan Kelvin probe force microscopy, D. Ziegler et al., Nanotechnology 18, 225505, 2007.
- Multifrequency electrostatic force microscopy in the repulsive regime, R. W. Stark et al., Nanotechnology 18, 065502, 2007.
- Polymeric electrically tunable diffraction grating based on artificial muscles, M. Aschwanden et al., Optics Letters 31, 2610–2612, 2006.

Machine Tools and Manufacturing

The Chair of Machine Tools and Manufacturing (IWF) researches manufacturing technology in close cooperation with industrial partners, from which interesting research topics are distilled. The research results are geared towards applications in industry and are dedicated to the competitiveness of the workplace Switzerland. IWF aims to meet the needs of industry today while anticipating future challenges in manufacturing. IWF is dedicated to developing a profound physical understanding of processes and machine tools and, from this basis, optimizing their performance. The research is focused in six different areas that are linked by strong synergies, selected for their relevance to Swiss industry as well as for their scientific interest.

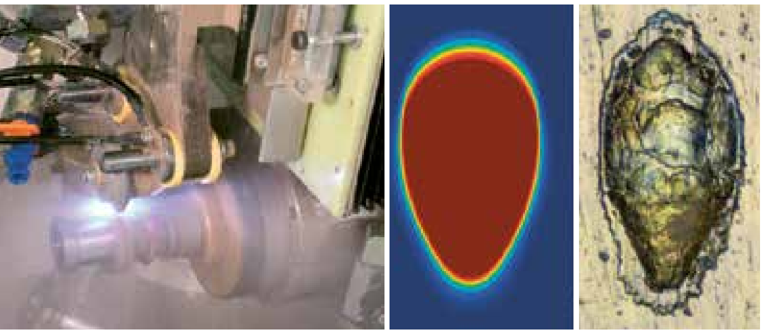

Figure 1: EDD of grinding wheels, crater simulation and real crater

Machine tools

The research of IWF on machine tools is organized around the predictivity of the behavior of highly sophisticated mechatronic systems. Today's performance requirements in manufacturing in terms of accuracy and productivity demand scientific machine tool building. IWF develops methods for a design-accompanying layout procedure and machine tool modeling for kinematic, dynamic, thermal behavior and resource efficiency. The research also covers model-based adaptronics used for set point generation, closed loop control, and dynamic and thermal compensation. These activities are complemented by the development of measuring and calibration strategies together with suitable measuring devices. IWF provides the scientific support for standards like ISO 230 and ISO 14955. IWF develops a new design concept for ultraprecise machine tools, based on combined axes principle. Further research covers the application of new materials, material-dependent design principles and lightweight construction.

Grinding, honing, lapping, wire cutting

These processes with geometrically non-defined cutting edges have a common technological basis, common descriptive models and require similar means for execution. The overall research goals are: the enhancement of the predictability of these processes, the development of conditioning technologies that make use of electroerosion and lasers, the reduction of wear and process forces, and the increase of material removal rate, surface quality, and subsurface integrity. A central research topic is the development of a stochastic kinematic model, which is synthesized from individual interactions between grain and material interactions. This research is supported and extended by single-grain experiments and single-grain interaction modeling by meshless Galerkin methods. For single-grain experiments, a high-frequency dynamometer has been developed. Ultrasonically assisted grinding at 60,000 rpm and 70 kHz, and economical grinding processes for dental implants made of ZrO_2-Y_2O_3-ceramics are explored.

Additive manufacturing

The research in additive manufacturing (AM) is centered around selective laser melting (SLM), selective laser sintering (SLS), and direct metal deposition (DMD) and is dedicated to providing means for the application of these processes in industrial manufacturing. Development of new materials for AM and of suitable process windows is achieved through process modeling, which can predict warp, internal stresses and microstructure. As layering of powder plays a crucial role, powder analysis for AM-processes is developed. To secure the reliability of AM for use in industrial applications, IWF provides measurable testing parameters that serve as a scientific basis for the standardization of these processes for manufacturing.

Laser material processing

IWF's main goal today is the laser manufacturing in ultra materials and follows the idea to substitute for those materials grinding operations by laser ablation to exploit the nearly infinite shape flexibility associated with such fine tool as ps-lasers. Processes for the generation of defined cutting edges and conditioning of grinding tools are developed. For prediction of the foot print of lasers in the pulse width range of 10 ps, a 2-temperature-model is developed. Synergies between the additive manufacturing field and lasers are exploited with a laser cladding research project.

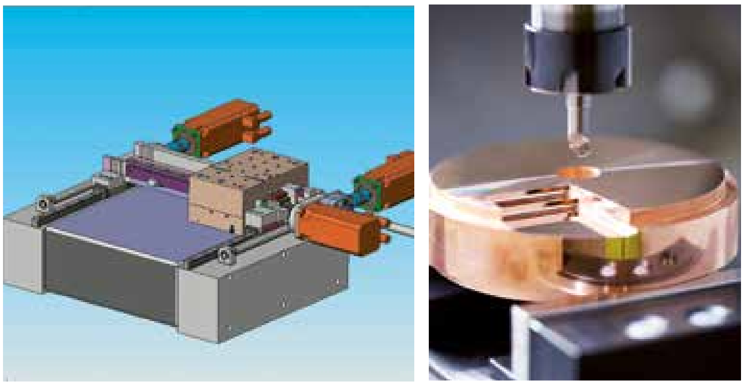

Figure 2: Left: Prazoplan: Ultraprecision machine with planar guiding.
Right: Ultraprecision part

Electroerosion
Electroerosion is a steady growing research field at IWF. Besides synergies to the grinding field for electroerosive conditioning, especially meso-micro-EDM is explored. The utilization of high-speed cameras and spectroscopy allows the exploration of the transient change of a spark's emission fields and the role of dielectrics. Quantitative modeling of material removal is used as a basis for optimizing the process in terms of quality, removal rate, wear and damage. The electrical signals of the process are used to detect and steer the position of sparks. IWF develops a process technology, where a protective and regenerative graphite shield on an electrode can be generated by sequencing different spark durations in oil as a dielectric.

Factory planning and virtual reality
The field of virtual reality pools methods for all research questions pertaining to factory planning organization and process chains. Current research covers the interaction with digital products, particularly production machinery. IWF's lead project on redirected walking allows real walking along a manufacturing line that only exists as a digital model. Further projects include the Virtual Factory Framework and Factory of the Future, which are focused on energy efficiency. Research work on partial observable Markov processes rounds out our activites, contributing to applications in the probabilistic behavior of sensors, actuators and processes, and research into humans operating in virtual environments.

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Konrad Wegener was born in 1958. He studied mechanical engineering at the Technical University of Braunschweig and wrote his doctoral thesis on constitutive equations for plasticity of metals. He began his industrial carreer at Schuler Presses GmbH & Co. KG in 1990. In 1999 he was appointed general manager of a small laser machines company, and developed it into a business with over 50 employees. He has developed and built large welding machines for shipbuilding and the construction of aeroplanes, welding and cutting machines for job shops in the automotive industry, and cutters for fabric. Additionally, he has given lectures on tensor calculus and continuum mechanics at TU Braunschweig and forming technology and machines at TH Darmstadt. He has been the head of IWF since 2003.

Highlights and achievements

- Simulation environment for machine tool dynamics and cross talk compensation
- ISO standardization of measuring and calibration methods and thermal testing (ISO 230) and energetic assessment (ISO 14955)
- Thermal modeling of machine tools with real time compensation of thermal errors
- Präzoplan: a new concept for machine tools with two-dimensional, extremely stiff aerostatic guiding
- Microdyn: a high frequency force measuring platform
- Development of a cutting edge characterization and preparation system
- Laser touch dressing of dressing wheels for gears
- Electro erosive dressing (EDD) for superabrasive metal-bonded grinding wheels
- Zero-wear micro-EDM process
- Development of crack-free and dense SLM with In738
- Smoothed-particle hydrodynamics (SPH) simulation of cutting process
- Ultrasound-supported grinding spindle with 70 kHz at 60,000 rpm
- Stochastic modeling of grinding wheels
- Single-grain experiments
- Active mitigation of chatter

Goals and future priorities

- Complete and sound model for thermal behaviour and thermal compensation in real time
- Concept of 5-axis-machine tool, calibration and compensation to uncertainties below 1µm (500 x 500 x 500 mm)
- Cutting stabilization, strategies for chatter recognition and suppression
- Material-dependent structure and design of machine tools, application of fiber-reinforced plastic (FRP) and polymer concrete, mastering the material mix
- Resource-efficient machine tools and manufacturing
- Modeling of the grinding process, prediction of wear states and work piece properties
- Acoustic dry grinding of railway tracks
- Laser conditioning of grinding tools and their performance
- Surface and subsurface integrity of ground workpieces especially for ceramic parts
- Development of simulation models for AM: SLM, SLS, DMD
- Exploration of new materials for additive manufacturing (including ceramics)
- Further research in micrometric AM
- Development of a scientific test bench for AM
- Utilization of ps lasers for the manufacturing of tool geometries
- Two-temperature model for the prediction of laser ablation of covalent bonded materials
- Development of prediction and planning tool for laser cladding
- Modeling of the electroerosion process, including wear, material removal rate, plasma behavior
- Exploration and comparison of mechanical and physical manufacturing processes concerning their micromanufacturing capabilities
- Development of an Augmented Reality (AR) means for manufacturing and assembly
- Development of a means for immersive interaction between humans and infinitely large virtual worlds

Organization of the professorship

The institute has a hierarchical structure with nine scientific officers covering different topics and a lab engineer who contributes experimental experience. IWF operates the strongest sector of the transfer institution inspire AG. The inspire AG has 30 employees, which accounts for the large number of Ph.D. students associated with IWF.

Teaching activity

Education and training at IWF is oriented toward students seeking careers in industry and academia. About 2000 examinations are conducted each year by IWF. An intense knowledge of materials is essential to manufacturing; IWF therefore covers education in materials for engineers. As basis for the design of production machinery the lecture on dimensioning and as basis for the manufacturing topics the basic course in manufacturing is organized by IWF, all of them as large class courses. An additional twenty higher level courses are offered by IWF. These, together with courses offered by other faculty members, provide students with the full scope of education in manufacturing science and machine tools, covering practical as well as theoretical aspects. For practice-oriented learning, IWF also offers tools courses and exercises on the equipment available at IWF.

At the Bachelor level, IWF is strongly involved in focus projects, where projects on the electrification of mobility, electric racing cars, electric sports cars, and electric family cars are offered. In future IWF will offer a project on electric excavators.

These are ideal projects for students who wish to explore modern technology as they cover topics in mechatronics, project management and energy efficiency. Students acquire and receive training in a full scope of engineering skills over the course of the term.

At the Master level, IWF offers a curriculum that is technology-oriented as well as a separate curriculum that bridges manufacturing sciences and economic sciences, which is operated together with MTEC.

Fostering young academics

IWF educates a large number of docotral students who work, research, and train on industry-related topics. These students thus become acquainted with indsutrial partners over the course of their studies, and are exposed to real industrial situations. Doctoral students at IWF are supervised not only by the professor but by excellent scientific assistants. IWF operates three exchange programs with the Universities of Kyoto, Florianopolis and Stankin. As a matter of principle, younger researchers are named first as authors in papers, and doctoral students are sent to present their results at conferences so that they gain recognition within the international research community. Each doctoral student presents and discusses his results annually with the whole institute.

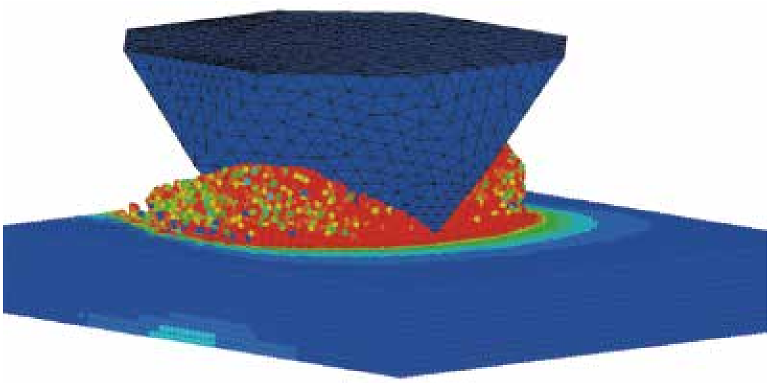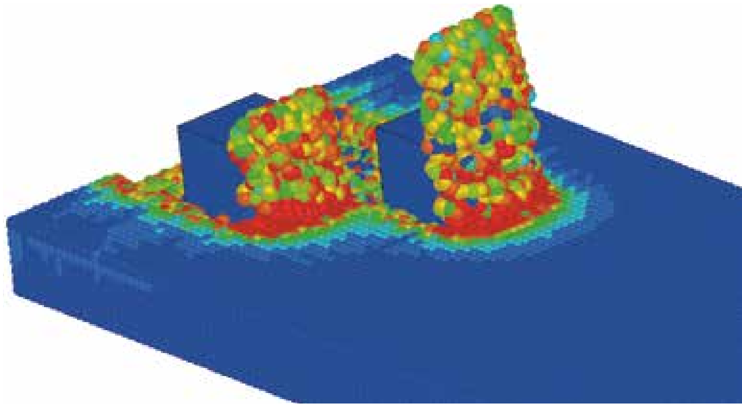

Figure 3: Smoothed-particle hydrodynamic simulation of single grains in grinding

Collaborations

Industrial

To enforce collaborations between ETH and Swiss SMEs, inspire AG was founded and operated mainly by IWF (the head of IWF was CEO of inspire AG until 2011). Inspire has 26 shareholders. The large majority of industrial collaborations are with SMEs, which means that the total income of ca. CHF 7 Mio in industrial research projects is made up of ca. 50 larger projects and numerous smaller projects. The cooperation with industry is extremely fruitful, as it opens up new research topics, helps with the training of doctoral students, and reduces the timeline for transferring research results to industrial applications

Academic

IWF supports 25 local and international research contacts; the most important are listed below:

> D-MAVT, IVP, mainly on the basis of education and simulation; EMPA[1], joint SNF[2] projects, joint doctoral students; NTB Buchs[3], cooperation on electromobility; FhG-IWU, Chemnitz; UFSC[4] Florianopolis, Brasil; University of Kyoto, Japan; Stankin University, Moscow; University of Nottingham, UK; TH Darmstadt; Chalmers Tekniska Högskola, Göteborg; Blekinge Tekniska Högskola, Karlskrona

Key publications

> [1] U. Maradia, M. Scuderi, R. Knaak, M. Boccadoro, I. Beltrami, J. Stirnimann, K. Wegener: Super-finished Surfaces using Meso-micro EDM, Proceedings of the Seventeenth CIRP Conference on Electro Physical and Chemical Machining, Leuven CIRP Procedia 6 (2013) pp 157'–163

> [2] M. Akbari, S. Buhl, C. Leinenbach, R. Spolenak, K. Wegener: Thermomechanical Analysis of Residual Stresses in Brazed Diamond Metal Joints Using Raman Spectroscopy and Finite Element Simulation, Mechanics of Materials, 52 (2012) pp 69'–77

> [3] E. Weingärtner, F. Kuster, K. Wegener: Wire electrical discharge machining applied to high-speed rotating workpieces, Journal of Materials Processing Technology 212 (2012) pp 1298'–1304

> [4] R. Transchel, J. Stirnimann, M. Blattner, B. Bill, R. Thiel, F. Kuster, K. Wegener: Effective Dynamometer for Measuring High Dynamic Process Force Signals in Micro Machining Operations, 5th CIRP Conference on High Performance Cutting, Zurich (2012) pp 575–579

> [5] S. Jaumann, K. Wegener: PRÄZOPLAN - Die aerostatisch flächig geführte Hochpräzisionsfräsmaschine, Wiener Produktionstechnik Kongress, Wien ISBN 978-3-7083-0872-2 (2012) pp 115–124

> [6] M. Ess, J. Mayr, S. Weikert, K. Wegener: An Energy Model for the Calculation of Losses and their Effects on Machining Accuracy, EUSPEN International Conference, Stockholm, ISBN 978-0-0956790-0-0, Vol. 1/2 (2012) pp 515–518

> [7] F. Amado, M. Schmid, G. Levy, K. Wegener: Advances in SLS Powder Characterisation, International Solid Freeform Fabrication Symposium, Austin (2011)

> [8] C. Dold, R. Transchel, M. Rabiey, P. Langenstein, C. Jaeger, F. Pude, F. Kuster, K. Wegener: A study on laser touch dressing of electroplated diamond wheels using pulsed picosecond laser sources, Annals of the CIRP 60/1 (2011) pp 363–366

> [9] N. Rüttimann, S. Buhl, K. Wegener: Simulation of Single Grain Cutting Using SPH Method, Journal of Machine Engineering 10 (2011) pp 17–29

> [10] F. Pinto, G. Vargas Evangelista, K. Wegener: Simulation for Optimizing Grain Pattern on Engineered Grinding Tools, Annals of the CIRP 57/1 (2008) pp. 353-356

[1] EMPA: Eidgenössische Materialprüfanstalt
[2] SNF: Schweizerischer Nationalfonds
[3] NTB Buchs: University of applied sciences Buchs
[4] UFSC: Undiversidade Federal de Santa Catharina

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