Annual Report 2019
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Dear reader,

Re-thinking engineering – this is the challenge which TUM strives to master in the proposal for excellence strategy in 2019. Engineering in Germany is widely considered as a success story, which is deeply rooted in the educational, sociological and economic culture and history of Germany’s industrial economy. However, it can be fatal to rest on one’s laurels and be passive while competitors adjust to and face the upcoming challenges.

Engineers develop complex machines with great perfection. Important examples are automobiles – highly efficient, very reliable complex machines, affordable to almost everyone. Yet, there is room for improvement and TUM Mechanical Engineering will contribute to discover new technologies – through research in our laboratories and through our graduates and researchers.

Nonetheless, a sustainable engineering strategy requires reflection about its purpose. Do we anticipate early enough the needs of society and humanity? Can we help to shape these needs and purposes to further prosperity and security of society?

Re-thinking engineering implies positioning the human being with his or her needs at the center of planning and thinking. For instance, we may ask ourselves:

- What is the solutions space onto which these needs can be mapped? Current imagination implies air taxis, autonomous cars, or even an exoskeleton allowing us to walk at triple speed. Is something missing? We need a taxonomy to evaluate and expand solution spaces.\n
- Assuming that we chose an autonomous road vehicle. It will be called in on demand and not be parked 22 hours a day in garages or on the road. This increases utilization and thus efficiency. Lifetime and innovation cycles of the specific devices will be dramatically shorter. The actual OEM car producer of today may become a mere supplier of a component of the engineering solution to satisfy the need for mobility.

Currently, a large amount of engineering research at universities is devoted to solve engineering problems of such a mere component, coming up with sophisticated (and potentially expensive) technologies, which may not be needed in the same way much further into the future. Should we not spend more effort on comprehending the system of components and how it addresses the more abstract societal and human needs?

A positive answer of this question implies a gradual change of paradigm in the strategic positioning of engineering as a purpose-driven science: future engineering serves society and humanity by discovery of purpose and innovation through interaction and involvement of the human being throughout all its actions.

Prof. Dr.-Ing. Nikolaus Adams, Dean
Selected Highlights
2018
Pragmatic, Innovative, Successful – 150 Years Department of Mechanical Engineering

‘It began pragmatically – and has remained pragmatic to the present day’ was the way Prof. Dr. Dr. h.c. mult. Wolfgang A. Herrmann, President of the Technical University of Munich, summarised the development of the Department of Mechanical Engineering over the last 150 years in his speech opening the exhibition ‘150 years TUM Mechanical Engineering’. Prof. Dr.-Ing. Nikolaus Adams, Dean of TUM Mechanical Engineering, referred to the department’s stimulating innovative capacity. Even in the founding principle of the Mechanical-Technical Department it was laid down that the department should combine the advantages of independent research with the development of technical solutions and practical applicability. This aim was put into practice early on with the appointment of Carl von Linde to the Chair of Theoretical Machine Science, Johann Bauschinger to the Chair of Technical Mechanics and Graphical Statics, Heinrich Carl Adolph Ludewig to the Chair of Mechanical Engineering, and Friedrich Klingenfeld to the Chair of Descriptive Geometry. After a video message from the President of the three speakers at the opening of the exhibition: President of TUM, Prof. Wolfgang A. Herrmann, CTO of OC oerlikon, Dr. Helmut Rudigier and Dean of TUM Mechanical Engineering, Prof. Nikolaus Adams

Opening of the exhibition on May 3, 2018
Exhibition

From left: History of the department, exhibits from the MMed gear mechanism collection and a tailor-made patient hand robot (PIH robot)

Oerlikon’s administrative board, Prof. Dr. Michael Süß, the CTO of Oerlikon, Dr. Helmut Rudigier, gave an outlook on future development in production technology with a talk on ‘Perspectives in Additive Manufacture’. The department started out with the still well-known teachers Carl von Linde and Johann Bauschinger. In these early years, the paradigm of mechanical engineering evolved; even back then, engineers and scientists developed basic mechanisms, such as the diesel engine and the refrigeration engine. Thermodynamics and fluid mechanics were perfected as scientific disciplines essential to mechanical engineering. Later, in the first half of the 20th century, the paradigm of mechanical engineering drastically improved. Machines working on established principles became smaller and more efficient. As one example amongst many others, Gustav Niemann systematically studied lubricants, new materials and the shapes of toothed wheels in gears. With the availability of microprocessors in the 1970s, new perspectives opened up for mechanical engineers. Processor-controlled machines became much more precise and computer calculations and simulations sped up research tremendously. The field of robots emerged and automation of even complex production steps was made possible. Around 2000, digitization reached a new level: networks allowed sensors and other cyberphysical systems, as well as decisions, to be distributed. Only these technologies enable us to use additive manufacturing technologies today. The exhibition gave an overview on these developments with numerous examples and showpieces from the department. In addition the exhibition highlighted topics which have been under discussion from the very beginning until now: one example is the role of the department in the triangle between science, politics and industry. Clearly, the establishment of the university was a strong political sign to promote Bavaria as a hub for science and industry – as now the decision to establish a Department of Aerospace and Geodesy is a strong investment in this field. Another example is the interplay between contract research and free research, fundamental research and applied research. Already in 1895, shortly after the world exhibition in Chicago, where the US presented itself as the forerunner in technical science, there was a grave dispute between professors in mechanical engineering on how theoretical classes should be taught, most prominently between Egbert von Hoyer and Walther von Dyck.
Three-time Winner – The TUM Hyperloop Team Won the SpaceX Hyperloop Pod Competition for the Third Time in a Row

After winning the first two SpaceX Hyperloop Pod competitions, the competition took place again in Los Angeles in July 2018. The objective was the same: the fastest pod wins. With a new propulsion concept of eight smaller motors, the team managed to increase the power-to-weight ratio of the pod. This improved design led to a new speed record of 467 km/h and secured the first prize among many other teams from all over the world.

In order to achieve better results in the competition and to push the idea of the Hyperloop transportation system further, a research division was founded. The goal is to build a demonstrator of a working Hyperloop system in small scale, using a concrete tube with an implemented propulsion system as well as a levitating pod. By doing this, TUM Hyperloop will come closer to a real-life application of the project. For a first prototype which was displayed at the Hyperloop Pod Competition the team won the special Innovation Award next to the Main Award for high speed.

Shortly after, a separate organization was created. TUM Hyperloop, formerly known as WARR Hyperloop, became part of the newly created student initiative NEXT Prototypes. The team is still run by TUM students from a wide range of academic disciplines and nationalities whose specific goal is the development of various prototypes in the field of transportation, aerospace and robotics.

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The collaborative research center TRR40 was installed in 2008 under the lead of the Institute of Aerodynamics and Fluid Mechanics. In 25 interdisciplinary experimental and numerical teams from TUM, RWTH Aachen, TU Braunschweig and the University of Stuttgart, together with the German Aerospace Center (DLR) and Ariane Group (Ottobrunn), investigate new concepts for next-generation space transportation systems. The focus of the groups is on the liquid rocket propulsion system. Alternative propellants like methane, innovative cooling concepts for the combustion chamber and the nozzle as well as fundamental investigation into multi-physics, multi-scale numerical simulation tools in the light of decreasing production cost and increasing performance define the challenges of the CRC TRR40. Together with state-of-the-art experimental facilities at DLR Lampoldshausen and at various institutes at universities in sub-scale, the next-generation propulsion systems will be more effective and more reliable.

The CRC TRR40 not only develops new concepts and numerical tools for future space-launch systems but also focuses on the education of ‘rocket scientists’. The Ph.D. students undergo special training in graduate courses on all aspects of rocket propulsion design and modelling. The summer research program of the CRC TRR40 is an outstanding feature inviting about 15 international research groups with up to 35 scientists worldwide to

**Temperature field in the thrust chamber.**
*The black line corresponds to the stoichiometric mixture fraction. Axial scaling 50%*

**CRC TRR 40: Technological Foundations for the Design of Thermally and Mechanically Highly Loaded Components of Future Space Transportation Systems**

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challenge and enhance numerical and experimental methods using test cases brought forth from CRCTR40 projects.

The methods and knowledge will be integrated into and tested against three different generic combustion systems of typical Ariane size to prove their applicability and the elevated capabilities for efficient and reliable predictive simulation tools for future design challenges.

NANOSHOCK* – Manufacturing Shock Interactions for Innovative Nanoscale Processes

The ‘Nanoshock’ group at the Institute of Aerodynamics and Fluid Mechanics (Prof. Adams) investigates the highly complex flow physics of shock interactions with interfaces. With the use of numerical simulations, we want to improve the understanding of the relevant physical phenomena of applications ranging from kidney-stone lithotripsy to needleless injections.

A highlight in 2018 was the publication of a paper on bubble-collapse-driven penetration of biomaterial-surrogate liquid-liquid interfaces in the Journal Physical Review Fluids, which became an ‘Editors’ Suggestion’ (Phys. Rev. Fluids 3, 114005, 2018). In this work, we investigated the penetration dynamics of a collapsing gas bubble near a surrogate fluidic cell model. We found two scaling regimes for the penetration depth as a function of post-collapse time in inertia-dominated configurations. Interestingly, for strong shocks and low-viscous gel material the penetration diameter reaches an almost constant size. Weak overpressures, however, result in a continuous widening of the radial pore size. In further investigations we want to focus on this pore size effect to explore its connection to the resealing capability of viable cells after sonoporation.

Interestingly, the numerical methods for simulations of cavitation effects in medical applications are at the same time applicable to other engineering problems such as the shock-driven jet formation in a test tube. We are comparing our simulations to water hammer experiments of a dropped liquid cylinder, where the interaction of shock-waves with a curved liquid-air interface considering contact-angle dynamics generates complex interface deformation with a highly energetic thin liquid jet. The jetting of highly viscous fluids is, e.g. very interesting for ink printing or needleless injection applications. Using a sharp interface model within our compressible multiphase solver, we have qualitatively reproduced the complex interface deformation and can predict the liquid jetting behavior.

The highly complex dynamics of shock-driven multiphase flows require best-in-class numerical methods with unprecedented accuracy and stability. We are continuously improving the numerical schemes beyond the state of the art to capture smallest flow structures with high-resolutions at vanishing numerical dissipation. Recently, we proposed a very simple modification to the classical Roe solver. The original scheme is known to suffer from the so-called carbuncle phenomenon (see Fig. 3 above). With our surprisingly simple fix, the

* This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No 667483).
The carbuncle phenomenon is suppressed and very accurate simulations are possible.

All simulations are performed with our framework ALPACA (open source), that uses multiresolution techniques to compress the numerical grid without loss of accuracy. For more information please also see http://www.nanoshock.org.

Figure 2: Numerical simulation of the liquid jet development from a shocked interface in a dropped test cylinder.

Figure 3: Helium bubble collapse at Ma=6. Above: Original scheme with carbuncle phenomenon. Below: Corrected scheme.
Truck2030 – The Truck of the Future

Truck2030 is a research project, conducted in collaboration with OTH Regensburg (Ostbayerische Technische Hochschule) as well as five industry partners. The project receives support from the Bavarian Research Foundation. The Technical University of Munich units participating are the Chair of Automotive Technology, the Chair for Internal Combustion Engines and the Chair for Industrial Design.

Trucks will remain essential to cargo transport in the upcoming decades. Scientists, students and industry partners have developed a concept for the truck of the future, including Europe-wide approval for the use of LHV trucks (Longer Heavier Vehicles), diesel hybrid drives and multifunctional drivers’ cabs.

According to a forecast by the German Federal Ministry of Transport and Digital Infrastructure, by 2030 the volume of truck cargo transport will have risen by 39% compared to 2010. This means efficient and environmentally friendly transport concepts are of continuing importance when it comes to reducing road traffic and emissions such as carbon dioxide, soot particles and nitrogen oxides.

In the project Truck2030, the team investigated all aspects of the truck of the future and presented their results at the IAA Commercial Vehicles trade show in Hanover. Here are the most important results in the areas of People, Transport and Logistics, Environment and Politics:
Automotive

People
The researchers’ concept is based on the assumption that the truck of the future will drive on the highway automatically. Drivers would then be able to invest the time saved in their own health. The driver’s cabin presented by the team is equipped among other things with cables and pulleys which can be used for exercise, already familiar from health clubs. A game-oriented aspect will be added in order to increase motivation, based for example on a virtual reward system.

Transport and Logistics
Long trucks with a length of 25.25 meters are ideal for efficient cargo transport. Here two LHV trucks can replace three normal-length trucks. This makes it possible to save fuel, resulting in benefits to the environment and the economy. And the total number of trucks on the road will also be reduced.

Environment
The use of LHV trucks alone could cut CO₂ emissions by 20% due to lower fuel consumption with the same cargo loads.

Using diesel plug-in hybrid drives could reduce CO₂ emissions by another 12%, the best solution from both the environmental and economic points of view. Based on the current state of the art, a solely electric drive train would not be feasible, since a battery capable of providing sufficient energy for the necessary range would be too large and too heavy.

Tires with optimized road resistance and improved truck aerodynamics could reduce CO₂ emissions by 7%.

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Politics
The most important prerequisite for realization of the concept is the approval of the use of LHV trucks in all of Europe. In their investigations the scientists successfully refuted counterarguments such as lower driving safety and increased road wear.

Another important point is infrastructure: Use of the diesel plug-in hybrid will require additional charging stations on highways. Electric cars will also be able to use these charging stations.
Autonomous Driving for an Electrically Powered Racing Series

Autonomous driving is considered to become one of the key technological advances in the coming years. The research at the chair of Automatic control is oriented to vehicle dynamics and motion control of the full vehicle. The challenges in this field arise mainly from the highly nonlinear tire behavior at the friction limits and high motion speeds. It is desirable to include model information as well as measured data in the design of such control systems, to achieve near human performance even in the most difficult scenarios, e.g. changes in road conditions. In cooperation with the Chair of Automotive Technology, we are continuously evaluating the real-world performance of our approaches within an autonomous driving racing series named 'Roborace'.

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In a new wind tunnel experiment of unprecedented complexity, TUM researchers demonstrated wake-steering wind farm control in the presence of wind direction changes. Wakes are regions of low speed and high turbulence that form behind wind turbines. When they impinge on downstream turbines, wakes cause power losses and increased fatigue, affecting the economic revenue of a wind plant and its lifetime. TUM is working with a large international consortium on the EU-funded ‘CL-WIND-CON – Closed Loop Wind Farm Control’ project to develop new control techniques to mitigate the effects of wakes.

In a new sophisticated experiment, TUM-developed scaled turbines and their cooperative control logic were tested in the large boundary layer wind tunnel at Politecnico di Milano. For the first time, dynamic wind direction changes were simulated by rotating the wind tunnel turntable, according to pre-defined time series derived from field measurements.

By wake steering, each turbine is pointed slightly away from the incoming wind, which has the effect of moving the turbine wake sideways. The control logic developed by TUM researchers first detects the flow conditions and
then computes the optimal way of steering the wakes of the various turbines in the wind farm. The challenge is to react to changes in wind speed and direction, in the presence of disturbances and uncertainties caused by turbulent wind fluctuations. Through these experiments performed in the controlled and repeatable environment of the wind tunnel, TUM researchers can understand and optimize the way cooperative controllers for wind farms operate, paving the way for testing in the field of this new control technology.

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Publications

Additive Manufacturing of Dental Restorations

Additive manufacturing (AM) has multiple advantages over conventional fabrication techniques, such as the geometrical freedom and, to a great extent, the omission of tooling equipment. These features render it extremely appealing for fabrication of dental restorations, which are patient-specific in their designs, inhabiting complex shapes and serve multi-functional purposes. Despite these advantages, additively manufactured metals display mechanical anisotropy and the material characteristics are highly dependent on manufacturing conditions. In studies on biocompatible ternary Cobalt-based alloys fabricated with selective laser melting (SLM) it was proven that material characteristics, albeit the presence of directional fluctuations, superseded the dental requirements (ISO 22674), with the limitation on their elastic stiffness in the non-heat-treated condition. Due to the rapid cooling rates in SLM, a fine microstructure favoring the face centered cubic lattice results, opposed to the hexagonal crystal lattice prevalent in cast samples. For dental applications, especially in view of the ceramic veneering and the risk of bonding failures caused by greatly differing Young’s moduli, a subsequent heat treatment is inevitable to meet the required stiffness safely. The heat treatments performed raised the Young’s modulus up to 38% compared to the as-fabricated condition. Apart from the increased stiffness, performing a heat treatment is recommended due to its additional benefits on the ductility and the reduction of the anisotropy.
Continuous Casting and Subsequent Forming of Metallically Bonded Copper Compounds

Copper bimetal sheets are mostly produced by roll bonding. The bonding mechanism of these solid-state joining technique is based on a cold welding process to establish an adhesive bonding. Therefore extensive chemical and mechanical preparation of the bonding partners are normally required. Horizontal continuous compound casting could be an adequate alternative to energy- and resource-consuming processes. Using this method of bonding, two different copper materials are continuously cast in a single process. The formation of a cohesive bond is facilitated by the casting warmth, which means significant energy-saving potential when producing hybrid components based on copper. In addition to the production development work relating to casting technology, the feasibility of subsequent working and forming of these compound strips, by means of cold rolling followed by shear cutting, was successfully proven.

An independent jury from industry and research awarded this year’s innovation prize for work on new applications for copper and copper alloys to the doctoral candidates Tim Mittler and Thomas Greß for their research under the supervision of Prof. Dr.-Ing. Wolfram Volk. This project is funded by the Deutsche Bundesstiftung Umwelt (DBU, grant no. 32334/01).
The humanoid biped walking machine LOLA was developed to achieve fast, human-like and autonomous walking. The first version of the robot was built in 2010 and has since been used as a research platform for humanoid walking. The main focus has been on robust walking in unknown environments. Recently, a novel walking pattern generation framework has been developed. The new design combines enhanced safety, robustness, modularity and efficiency. Special focus lies on easy parallelization and thread-safety to exploit the increasing multi-core performance of today’s compute units. Furthermore, new techniques for planning and controlling robot locomotion in the multi-contact setting, i.e. when using additional arm-environment contacts, are investigated. Recently, bio-inspired, dynamic bipedal gait has become a research focus. In collaboration with kinesiologists human gait and control strategies for walking and running are investigated in order to identify fundamental principles of legged locomotion and assess their applicability to bipedal robots.

Moving Forward: LOLA Navigates Rough Terrain

The multi-body simulation of LOLA displaying the contact forces, as well as foot, arm and center of mass trajectories.

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CRC 768: Managing Cycles in Innovation Processes – Integrated Development of Product-Service Systems Based on Technical Products

‘Agile use of knowledge’, ‘Smart integration of customers’, ‘Successfully manage inconsistencies and changes’ – This is offered by the Collaborative Research Centre 768 (CRC 768) in the form of tutorials, tools and scientific results. The CRC 768 enables companies to successfully persist on the market by providing support through the introduction of ‘Product-Service Systems’ (PSS).

How can companies be empowered and supported to successfully design innovation processes, taking into account the cyclic factors influencing them?

Innovations are an essential competitive advantage for German and European companies, which enable companies to evolve their position in a more and more competitive worldwide market. However, companies are facing the challenge of acting and reacting successfully throughout the innovation process under the influence of interlaced innovation cycles. To cope with this challenge, the CRC 768 focuses especially on the market offers from companies that combine products and services in product-service systems (PSS).

This year’s Science Colloquium on August 20, 2018 focused on ‘Model-coupling, Inconsistency Management and Optimization across Models’. International guests from science and industry discussed topics such as inconsistency management, interdisciplinary engineering and knowledge management. Inconsistencies in technical

Interconnected network grid of approaches for successful innovation management. Each node represents one of our 47 models and approaches showing their interaction and dependencies. Explore them interactively on our online platform: www.innovationen-gestalten.sfb768.de
systems or databases are usually regarded being negative, leading to a loss of time and money. However, they can also have positive influences such as helping people to better understand the different aspects of a system and to enhance creativity.

When comparing artificial intelligence like knowledge representation (ontology) and data processing (big data), fruitful findings are derived: Ontologies and big data approaches can complement each other. Ontologies may be constructed from empirical data. On the other hand, ontologies can be applied to structure data and increase the efficiency of data processing. Depending on the use case, each of the two approaches can serve as a starting point for the development of PSS.

What is the real innovation in Industrie 4.0? Is Industrie 4.0 just new technologies or what are the challenges? In the era of Industrie 4.0, the production system is not only referred to as an automated technical system, but becomes a more complex, interconnected, intelligent and innovative PSS.

To answer these questions, education and training is essential. This is exactly where the CRC 768 comes in, engages and plays an active role. Interdisciplinary and transdisciplinary education of teams plays a fundamental role not only including a system engineering approach but also workflow, team aspects as well as supply chains under organizational aspects and users of such PSS. Such teaching concepts are available and well accepted in weekly classroom courses, a block seminar and in international courses, like the two Summer Schools in Singapore that were organized successfully by TUMAsia. The concept is based on case studies that build subsequently on each other and include more and more aspects in interdisciplinary team work sessions using different PSS for demonstration. The interactive sessions are enriched with impulse talks providing the necessary theoretical framework and facts. Educational courses as a training concept enable companies to operate successfully in the dynamic innovation environments of Industrie 4.0.

The CRC 768 transfers knowledge from academia to society and industrial practice. On the one hand, by offering tutorials that demonstrate the agile use of knowledge and tools that show how to integrate customers into innovation management. On the other hand, design and practical approaches make it possible for engineers and other stakeholders to manage inconsistencies and changes effectively. These tutorials, tools and approaches of the CRC 768 are available on our online platform:

www.innovationen-gestalten.sfb768.de
Selected Publications
www.sfb768.tum.de/en/publications/publications
- Reif, Julia; Koltun, Gennadiy D.; Drewlani, Tobias; Zaggl, Michael; Kattner, Niklas; Dengler, Christian; Basirati, Mohammad; Bauer, Harald; Krcmar, Helmut; Kugler, Katharina; Lohmann, Boris; Meyer, Uli; Reinhart, Gunther; Vogel-Heuser, Birgit: Modeling as the Basis for Innovation Cycle Management of PSS: Making Use of Interdisciplinary Models. IEEE International Symposium on Systems Engineering (ISSE) 2017, 2017. https://mediatum.ub.tum.de/node?id=1368449
- Wilberg, Julian; Preißner, Stephanie; Dengler, Christian; Füller, Kathrin; Gammel, Josef; Kernschmidt, Konstantin; Kugler, Katharina; Vogel-Heuser, Birgit: Performance measurement in interdisciplinary innovation processes – Transparency through structural complexity management. 18th International Dependency and Structure Modelling Conference, DSM, 2016. https://mediatum.ub.tum.de/node?id=1328618
- Basirati, Mohammad; Zou, Minjie; Bauer, Harald; Kattner, Niklas; Reinhart, Gunther; Lindemann, Udo; Krcmar, Helmut; Vogel-Heuser, Birgit: Towards systematic inconsistency identification for product service systems. 15th International Design Conference (DESIGN2018), 2018. https://mediatum.ub.tum.de/node?id=1437519

Next event
- September 17-18, 2019: congress, tutorials and exhibit ‘Innovations 360°’ in Sindelfingen near Stuttgart (www.innovation360grad.de)

Further Information
- Tutorials, tools and news at www.innovationen-gestalten.sfb768.de
Handheld Flexible Manipulator System for Frontal Sinus Surgery

Draf drainage is the standard treatment procedure for frontal sinus diseases. In this procedure, rigid angled endoscopes and rigid curved instruments are used. However, laterally located pathologies in the frontal sinus cannot be reached with rigid instrumentation. In order to assist surgeons with such complicated cases, we have developed a handheld flexible manipulator system with 4 mm x 6 mm cross section which enables the use of a standard flexible endoscope with up to 2.9 mm diameter and a standard flexible surgical instrument with up to 1.8 mm diameter. The system consists of a manipulator arm made of nitinol manufactured by electrical discharge machining (EDM) and a mechanical control unit made of PEEK manufactured by milling and turning. Upward and left-right bending of the manipulator arm is enabled by the control unit. Moreover, the control unit allows translation, rolling, activation and also quick exchange of the surgical instrument.
Simulation of Pure Substance Condensation on Structured Tubes for Improved Heat Exchanger Efficiencies

Measurements carried out by the Institute of Plant and Process Technology show that surface structures on tubes can enhance the outer heat transfer coefficient up to 900%. Besides the increased area, this enhancement is also attributed to improved flow characteristics of the condensate. Employing surface structured tubes in tube bundle heat exchangers, therefore, has a high potential for significantly increasing the efficiency of large-scale chemical plants.

For further investigation of the flow characteristics of the condensate during condensation on structured tubes, a CFD solver for pure substance condensation without the dependence on model parameters was developed. The performance of the solver was first validated by investigating pure substance condensation on horizontal smooth tubes, showing a high simulation stability with a very high accuracy of the simulation results. This combination is additionally pleasing, since the simulations are numerically challenging due to high temperature gradients in the thin condensate layer. 2D simulations of the condensation on smooth tubes further revealed that it is not necessary to consider the droplet constriction in axial direction. This allows for detailed simulations on the tube’s surface structure itself rather than a whole Taylor instability.

Simulations of annular low-finned tubes are carried out on a single fin. Integral outer heat transfer coefficients can be obtained from the simulations and stand in very good agreement to the before mentioned measurements. The high accuracy of the simulations and the independence of the model from empirical parameters confirms that the developed phase change model is useful even beyond the scope of structured tubes. The detailed insight in the temperature profiles and the flow characteristics of the condensate enables us to find a design approach for the optimization of the surface structures rather than depending on structure screening. This allows us to customize the fin structure of the tubes depending on the condensation process and even optimize their efficiency beyond the before mentioned 900% increase.
Today additive manufacturing (AM) is an integral part of state-of-the-art production technology. Recent developments mainly focused on the industrial production of metal parts by AM methods. Laser and powder based methods like selective laser melting are already industrialized to a high degree; nevertheless their application in volume production is limited by the elevated cost of raw materials and low build rates. To increase build rates of those machines, designers add more and more lasers to one machine, but laser sources and optics are costly parts, so this also increases the machine cost significantly. Material jetting processes (MJT), on the other hand, print material directly onto a build platform, without the need for powders and lasers. Another advantage of MJT in terms of cost and speed is that individual printing nozzles are comparatively cheap and therefore build rates can be multiplied, by using print heads with a large number of nozzles, without dramatically increasing machine cost. Today, these methods are only commercialized for polymers, while the developments for metals are just starting.

A DFG-funded project (LU 604/42-1), in cooperation between the Chair of Metal Forming and Casting and the Chair of Micro Technology and Medical Device Technology, focuses on the MJT process for aluminium alloys. The aim of this project is to analyze systematically the correlations between thermal conditions, alloy composition and resulting macroscopic part properties like mechanical strength and relative density. In this AM process the resulting part properties and geometry of the part are controlled mainly by the behavior of a single droplet at deposition: How far does it spread, how does it bond to adjacent material and which microstructure develops? All this is dominated by solidification close to the interface and therefore by local thermal conditions. If the system is too ‘cold’, droplets will not fuse properly. However, if it is too ‘hot’ droplets will spread excessively and the desired geometry will be lost. Therefore, a challenge for designers of an industrially relevant manufacturing process will be to define the process in a way that homogeneous and high-quality parts are built at a maximum rate. Ideal process parameters will be dependent on the layer currently being printed.

To gain more insight into this complex manufacturing process, a prototype printing machine was developed and installed at the Chair of Micro Technology and Medical Device Technology laboratory. In an experimental study the described correlations between process parameters and part properties were analyzed quantitatively. Additionally, a novel method to simulate the thermal field in MJT was developed. It allows us not only to obtain a deeper understanding of the experiments but also to simulate a notional industrial process with higher build rates as the prototype.
Production Technology Research on Battery Cells

At TUM’s Institute for Machine Tools and Industrial Management (iwb), research is being carried out on both optimizing the production of conventional battery cells and investigating the production of future-oriented cell types. This is in cooperation with TUM’s Chair of Technical Electrochemistry and the Chair on Energy Storage Technology, as well as the FRM II.

The iwb research production line in Garching near Munich comprises all manufacturing, assembly steps and quality inspection as well as the formation of battery cells on industrial plants with a high degree of automation. Right now a mixing laboratory is being built and will complete the process chain at iwb, where cells with capacities ranging from mAh to several Ah can be manufactured.

The research focus is on the upscaling of materials from laboratory to pilot plant or industrial scale. Two different mixers for the production of conductive pastes as well as extensive measurement technology for their characterization are available for this purpose. Cross-process analyses, big data and Industrie 4.0 tools make it possible to assess the effects of production parameters on subsequent processes and cell quality.

The electrode production systems are integrated into iwb’s clean room (ISO 6). Process parameters and interactions between production steps on the industrial coating plant (various coating processes available) with infrared drying section and calender are researched here on about 100 sq. m. The knowledge base is supported by a self-made system for coating adhesion measurement as well as a table doctor blade for coating on a laboratory scale.

The cell assembly processes as well as filling and forming take place in a dry room of about 100 sq. m. in order to minimize the input of moisture into the hydrophilic materials. The cell assembly is carried out by Z-folding of single electrodes, whereby high flexibility is provided by an automated as well as a manual Z-folding system. For this purpose the electrodes are manufactured with high precision using a laser cutting process. After contacting the electrode stacks by ultrasonic welding, the stacks are...
Production and Logistics

packed either as a pouch cell or in a hardcase housing. Laser welding is used to seal the hardcase housing. The electrolyte is dosed into the cell fully automatically under vacuum subsequently. For tests under special ambient and filling conditions an in-house mobile filling system is also available. A climate chamber and various cell test devices form the infrastructure for forming and testing the battery cells which are produced. Even button cells can be manufactured and tested.

Cooperation within TUM
TUM is one of four WING centres (Material innovations for industry and society – WING) of the ‘ExcellentBattery’ funding measure of the Federal Ministry of Education and Research (BMBF). In close cooperation, the entire process chain from material and electrode development through cell design to the production of large-format cells is being investigated at four research institutes in order to investigate new materials and concepts from the basic principles through to application.

Research on the next generation of battery cells
In addition to research on novel materials and their combination in conventional battery cells, the iwb is also setting the course for the production of solid state cells, which battery research expects to increase volumetric energy density by up to 70% compared to today’s batteries. However, the properties of the various battery components present production technology with enormous challenges. For example, the reactivity of cathode composites and lithium metal requires their processing in a protective gas atmosphere. Scientists at iwb are already addressing these and other production challenges arising from the properties and components of current and future battery technologies.

For more information see: www.iwb.mw.tum.de

PreCoM – Predictive Cognitive Maintenance Decision Support System

The Internet of things not only fundamentally changes the way we manufacture products, but also comes with vast opportunities in the field of maintenance. By applying intelligent algorithms to machine condition data, predictive maintenance enables companies to predict and avoid machine failures and thus significantly increasing OEE. A machine breakdown is one of the most disruptive events that can occur on the production floor and causes high costs. In order to prevent such breakdowns, the iwb is involved in the EU Horizon 2020 research project ‘PreCoM’, which investigates the concept of predictive maintenance in conjunction with production planning, in order to increase machine availability.

‘PreCoM’ is supported by the EU Commission under Grant No. 768575. For further information, please see the precom-project.eu website.

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Intuitive Load Control – Development of an Intuitive, Goal-oriented Control Concept for Load Lifting Machines

Load lifting equipment is frequently operated by radio control systems which allow the user to position himself freely relative to the lifting equipment and thus control the movement of the load from an optimum position. Current control systems require the operator to mentally convert the desired movement of the load to the necessary movements of the individual robotic joints (joint control). The resulting additional mental load complicates operation and is not intuitive for the operator. Therefore, it is desirable to provide a control solution that combines high flexibility through the use of a radio control with intuitive and target-oriented control of the load from the user’s point of view (cartesian control).

The project is being funded by Allianz Industrie Forschung (AiF) in the period 08/2017 to 05/2019 and is managed by the Chair of Ergonomics and the Chair of Materials Handling, Material Flow and Logistics of the Technical University of Munich.

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Prof. Dr.-Ing. Klaus Drechsler, Carbon Composites
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Prof. Dr.-Ing. Johannes Fottner, Materials Handling, Material Flow, Logistics
www.fml.mw.tum.de
Prof. Dr.-Ing. Birgit Vogel-Heuser, Automation and Information Systems
www.ais.mw.tum.de

Prof. Dr.-Ing. Wolfram Volk, Metal Forming and Casting
www.utg.mw.tum.de
Prof. Dr.-Ing. Michael F. Zäh, Machine Tools and Industrial Management
www.iwb.mw.tum.de
The Department of Mechanical Engineering
Governance

The TUM Department of Mechanical Engineering pursues the principles of strategic governance. As one of the very first universities in Germany, TUM began in 2011 to evaluate its units on the departmental and administrative levels – the first department subject to peer review was the Department of Mechanical Engineering. As a consequence, the department decided (i) to strengthen its scientific focus as the basis for sustaining its leading technological competence, (ii) to further enhance its international standing, and (iii) to revise its faculty appointment procedures employing the full TUM career spectrum. Last but not least, the graduate and undergraduate education program is being modernized and restructured in order to prepare students for future engineering challenges.

Strengthening of Engineering Science

The department has decided to focus on three key measures to strengthen its scientific focus:

Significance of High-quality Publications

Peer-reviewed publications are key indicators of scientific accomplishment and visibility. While international university rankings are commonly based on publication databases such as Scopus or ISI Web of Science, among German universities, criteria for relevance of scientific publications often are less strict. The department relies on the external metrics from Scopus and ISI for qualification of a relevant scientific publication in order to follow international practice. Publications listed in at least one of these indices are rewarded with a budget bonus, which currently accounts for about 30% of the tangible means of the department. Doctoral researchers are offered courses on scientific paper writing, conducting literature surveys and bibliometry.

Comparing figures from before the evaluation (2006-2008) and after implementation of the measures (2013-2016), the number of high-quality publications almost doubled from 300 to 500 per year – citation of TUM Mechanical Engineering publications more than tripled from 2000 to 6000 per year.
Strengthened Positioning of Scientific Theses

Theses from undergraduate, graduate and doctoral students are essential parts of the scientific output of the department. Protection of scientific property and quality control prompted the department to enforce the following rules:

- Companies, not the candidates themselves, may propose topics for an external thesis jointly with an academic lecturer at the department.
- As a thesis is part of an examination process the department cannot accept access restrictions to thesis content.
- It is expected that theses are or will be published as scientific papers. The MediaTUM platform provides a good support environment for this purpose.
- Doctoral candidates without a full contract as a scientific assistant are expected to immerse themselves into the research and educational environment at the department for at least 20% of regular working hours.
- The department has licenses a plagiarism check software program.
- The department has implemented a compulsory seminar on good scientific practice for doctoral candidates, as suggested by the standard curriculum developed for the DFG.

To our current knowledge, only few other departments in Germany have implemented similar measures.

Targeted Support for DFG-funded Projects

DFG funding is more competitive than funding through research contracts, but offers more room for scientific creativity. Success in DFG funding lines, especially SFs, is regarded as a key indicator for research strength. Activities for promoting DFG activities are two-fold:

- Whenever third-party funding is used as a parameter for budgeting measures, DFG funding enters with a factor of two as compared to other non-public funding lines. Other public funding lines (e.g. European Commission or Federal/State Ministries) are counted with a factor of 1.5.
- Parallel to support by the university, coordination of SFB is directly supported by the Dean through increasing the personnel budget of the respective unit by an additional research assistant position.

Through these measures, the Department of Mechanical Engineering is currently the second most important department at TUM with respect to total DFG funding.

International Profile

Over recent years international visibility of the Department of Mechanical Engineering has grown significantly as a consequence of the evaluation in 2011:

- Since 2011, out of the 13 newly appointed professors, four have an exclusively international background and three more very significant international experience in non-German speaking countries. In total, more than half of the current faculty have significant international experience.
- 28% of all students are international, not including exchange students such as Erasmus students. This compares to 13% in 2011.

Appointment Process

The department evaluation pointed out the need for a mid- and long-term appointment strategy utilizing the full range of appointment schemes at TUM. The department pursues a three-time-level strategy for structuring its appointment processes, extending from the near future to a time horizon of 12 years into the future. The three-level strategy enables the different time-ranges of tenure-track and tenured appointments to be intertwined. Appointments are derived from the long-term research and teaching positioning strategy of the department.
## Facts and Figures

### Staff

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<thead>
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<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
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<td>1,065</td>
<td>1,019</td>
<td>1,066</td>
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<td>Full Professors</td>
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<td>29</td>
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<td>Associate Professors</td>
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<td>Scientific Staff</td>
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<td>759</td>
<td>763</td>
<td>784</td>
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<td>201</td>
<td>206</td>
<td>187</td>
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<td>Apprentices</td>
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### Students

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<tr>
<td>Total</td>
<td>5,620</td>
<td>5,447</td>
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<td>2,176</td>
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<td>Master</td>
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<td>2,592</td>
<td>2,702</td>
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<td>Total Students</td>
<td>4,776</td>
<td>4,668</td>
<td>4,597</td>
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<td>Freshmen per year</td>
<td>684</td>
<td>652</td>
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<td>Graduations per year</td>
<td>802</td>
<td>542</td>
<td>481</td>
<td>414</td>
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<td>Freshmen per year</td>
<td>1,090</td>
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<td>Graduations per year</td>
<td>1,320</td>
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Additional categories include doctoral and exchange students and others

### Doctoral Programme

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<tr>
<td>Defenses</td>
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### Funding

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<td>1,625,670</td>
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<td>State Positions</td>
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<td>498</td>
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<td>Acquired Research Funding</td>
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<td>53,930,633</td>
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<td>27,592,955</td>
<td>30,019,344</td>
<td>29,702,802</td>
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<tr>
<td>2017</td>
<td>28,889,972</td>
<td>26,337,678</td>
<td>22,661,187</td>
<td>19,967,297</td>
</tr>
<tr>
<td>2016</td>
<td>26,412,923</td>
<td>27,592,955</td>
<td>30,019,344</td>
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<td>26,337,678</td>
<td>22,661,187</td>
<td>19,967,297</td>
</tr>
</tbody>
</table>

Euros total

Euros public sources

Euros private sources
The Department of Mechanical Engineering is headed by the Dean, two Vice Deans and the Dean of Studies, elected by the faculty of the department every three years. In order to facilitate communication and to put decisions onto a broader base a Department Board of Management was established in 2014. It comprises the deans and representatives of groups of professors. The Department Board of Management acts as an advisor to the Dean; the responsibility of the Departmental Board ('Fakultätsrat') regarding formal academic matters remains untouched.

Department Board of Management

Dean

Prof. Dr.-Ing. Nikolaus A. Adams

Prof. Dr. Klaus Bengler

Prof. Dr.-Ing. Hartmut Spliethoff

Vice Dean

Prof. Dr. Ir. Daniel Rixen

Prof. Dr.-Ing. Michael W. Gee

Prof. Dr.-Ing. Wolfram Volk

Vice Dean

Prof. Dr. Tim C. Lüth

Prof. Dr.-Ing. Mirko Hornung

Prof. Dr.-Ing. Ewald Werner

Dean of Studies

Prof. Dr.-Ing. Manfred Hajek

Prof. Dr.-Ing. Boris Lohmann

Prof. Dr.-Ing. Michael Zaeh
The Department Council is the central decision-making body of the department and is headed by the Dean. Here fundamental decisions are made, which effect the department but which are not the responsibility of the Dean, Dean of Studies or other decision-making bodies of the department, such as the Examination Board. Furthermore, the Department Council acts as a central communication platform, where representatives from the department’s various different membership groups can exchange information and voice opinions.

In the current legislative period (01.10.2018-30.09.2019), the following people are members of the Department Council of the TUM Department of Mechanical Engineering. They represent professors, scientific employees, non-scientific employees, students and female staff. In addition, there are permanent guests (without voting rights), who may take part in meetings of the Department Council.

### Professors

<table>
<thead>
<tr>
<th>Name</th>
<th>Role</th>
<th>Email</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prof. Dr.-Ing. Nikolaus A. Adams</td>
<td>Dean</td>
<td><a href="mailto:dekan@tum-mw.de">dekan@tum-mw.de</a></td>
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<td>Prof. Dr. Ir. Daniel Rixen</td>
<td>Vice Dean</td>
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<tr>
<td>Prof. Dr. Tim C. Lüth</td>
<td>Vice Dean</td>
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<tr>
<td>Prof. Dr.-Ing. Manfred Hajek</td>
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<tr>
<td>Prof. Dr. Klaus Bengler</td>
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<td><a href="mailto:bengler@ife.mw.tum.de">bengler@ife.mw.tum.de</a></td>
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<tr>
<td>Prof. Dr. Sonja Berensmeier</td>
<td></td>
<td><a href="mailto:S.Berensmeier@lrz.tu-muenchen.de">S.Berensmeier@lrz.tu-muenchen.de</a></td>
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<td>Prof. Dr.-Ing. Michael W. Gee</td>
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<tr>
<td>Prof. Dr.-Ing. Mirko Hornung</td>
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<td>Prof. Dr.-Ing. Markus Lienkamp</td>
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<td>Prof. Dr.-Ing. Wolfgang Polifke, Ph.D.</td>
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<td>Prof. Dr.-Ing. Veit Senner</td>
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<td>Prof. Dr.-Ing. Wolfram Volk</td>
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<td><a href="mailto:wolfram.volk@utg.de">wolfram.volk@utg.de</a></td>
</tr>
<tr>
<td>Prof. Dr. mont. habil. Dr. rer. nat. h. c. Ewald Werner</td>
<td></td>
<td><a href="mailto:werner@wkm.mw.tum.de">werner@wkm.mw.tum.de</a></td>
</tr>
</tbody>
</table>
With about 5000 students, over 40 professors and well over 1000 employees, the Department of Mechanical Engineering is of a size comparable to many universities. Even though most administrative tasks, including project management and accounting, are handled by the institutes, many responsibilities are allocated to the Dean of the department. This includes responsibility for the resources allocated to the department as well as student services.

**Department Management**
assists the Dean in academic self-administration and the coordination of administrative processes in the department.

**Dr. Till von Felitzsch**
**Dr. Thomas Wagner**

The following units are assigned to the Department Management:

**Assistance to the Dean**
assists the Dean in daily matters, coordinates inquiries in various areas and takes responsibility for administrative duties relating to the department and its administration.

**Melanie Hügel**
**Rella Recsetar**

**Marketing and Media Design**
coordinates marketing activities of the department

**Susanne Höcht**

**Hochbrück Branch**
acts as a contact point regarding administrative issues of the Hochbrück branch of the department, such as room assignments or access control.

**Cornelia Kirsten**

**Quality Management and Controlling**
coordinates the implementation and further development of a quality management system in the Central Services department. A further major responsibility of this section is to maintain a comprehensive reporting system for the department and to carry out budget planning based on the reports.

**Sandra Greil**, Section Head
**Catalina Lala**, Finances and Controlling,
**Room Administration**
**Cornelia Härtling**, Accounting
**Lisa Metz**, Database

**Infrastructure**
coordinates IT and building infrastructure of the department and its central services. In addition, this section assists the Dean with academic procedures such as honorary doctorates and professorships, lectureships, awards and prizes as well as departmental events.

**Dieter Grimm**, Section Head
**Robert Klopp**, IT Administration

**Central Services**
Central Teaching Unit

Central Teaching Unit deals with central trainings for doctoral candidates, as well as trainings on key competencies for Bachelor and Master students of the department. Please also c.f. p. 56 f.

Dr. Birgit Spielmann, Section Head
Franziska Glasi, Deputy
Tamaris Pohl, Center of Key Competencies
Susanne Lösel, Center of Key Competencies
Luise Poetzsch, Center of Key Competencies
Amelie Zauner, Center of Key Competencies
Julia Leicht, Graduate Center
Stefanija Stiebre, Graduate Center
Dilara Turan, apprentice

Student Services

Student Services is the central information office for full-time, international exchange as well as for potential students regarding degrees and degree course organization. It also administers and organizes degree courses, exchange options like ERASMUS+ and double degrees, and administers tuition funds. In addition, it is the contact for the Head of the Department, professors and other bodies of the university regarding degree course development, planning, organization and quality assurance.

Dr. Ingrid Mayershofer, Section Head
Dr.-Ing. Anna Reif, Deputy
Saskia Ammon, Student Exchange
Julia Liebl, Administration

Examination Affairs

Examination Affairs is the central contact point for students regarding all questions concerning examinations; from admissions procedure, through internships in industry before and during the Bachelor program to the complete administration of marking and examinations.

Dr. Edda Wenzig, Section Head

Bachelor’s Degree Examination Board

Arno Buchner, Deputy Section Head, Secretary to the Examination Board
Raffaella Ulfers
Daniela Bösl, TUMonline Examination Administration

Master’s Degree Examination Board

Lisa Lauterbach, Secretary to the Examination Board
Sarah Jean Reiner
Maria Schottenheim

Internships in Industry

Nina Schaumberger
Always held on the second Friday in July, the Department Day Mechanical Engineering is traditionally the ceremonial event which concludes the academic year. The most important items on the program are the ceremonies in which graduates of the previous year are honored and take their leave in the presence of family members and numerous guests of honor from the university and industry. There are addresses from the Dean, Dean of Studies, representatives of the students and TUM. The ceremonies are followed by sparkling wine receptions and then, to round off the day, the department ball with a buffet, dance music and entertainment.

Impressions of the Department Day Mechanical Engineering 2018

340 Master's degree graduates accepted this year's invitation. According to this gratifying interest, the ceremony took place in two lecture halls simultaneously. In their addresses, Dean Adams and Dean of Studies Hajek, congratulated the graduates and wished them a successful future. Furthermore they pointed out to the guests and family members some facts and figures about the department.

Two representatives of the students took a hilarious look back at life as a student. As a special item on the program two former students were invited: Dr. Isabell Franck, co-founder of Insight Perspective Technologies, and Patrick Nathen, co-founder of Lilium. After briefly presenting their startup, they talked about what is necessary to be a successful founder, and what they have learnt at TUM that enabled them to follow this career. They both gave the graduates an idea of what it is like to work in a startup, and to even own it.

After that, while reading out the names of the graduates, four professors, who all wore the traditional academic gown, said farewell to each graduate: with the department’s bronze medal of honor, a handshake und a photo taken on the spot.

In the afternoon, accompanied by a jazz band, the dignitaries from the department and from TUM entered the lecture hall where the ceremony for the doctoral graduates and guests of honor took place. In his address Dean Adams spoke about the implementation of the strategy ‘MW 2030’ covering three areas: teaching, research and personnel. As one step successfully made, the dean welcomed six new professors who had started at the department in the previous 12 months. As a special highlight Prof. Petros Koumoutsakos from ETH Zurich was awarded the TUM Distinguished Affiliated Professorship (see photo).

Seventy of the invited doctoral graduates attended the ceremony. Each one was presented to the guests and received the department’s silver medal of honor, handed over by the Vice Dean Lüth. Furthermore, seven prizes for outstanding dissertations and nine for exceptional academic achievements in the Master’s degree programs were awarded. The prize winners are listed on the following page.
Department Day

**Doctorate Prizes Awarded**

**Rudolf Schmidt-Burkhardt Memorial Prize**
Dr.-Ing. Christian Roth  
Dissertation ‘Multi-dimensional Coupled Computational Modeling in Respiratory Biomechanics’

**Department Prize**
Dr.-Ing. Felix Schranner  
Dissertation ‘Weakly Compressible Models for Complex Flows’

**WITTENSTEIN Prize**
Dr.-Ing. Claas Olthoff  
Dissertation ‘Dynamic Simulation of Extravehicular Activities’

**ARBURG Prize**
Dr.-Ing. Sebastian Kehl  
Dissertation ‘Bayesian Calibration of Nonlinear Cardiovascular Models for the Predictive Simulation of Arterial Growth’

**RENK Propulsion Technology Prize**
Dr.-Ing. Theo Kiesel  
Dissertation ‘Flexible Multi-Body Simulation of a Complex Rotor System Using 3D Solid Finite Elements’

**Willy Messerschmitt Prize**
Dr.-Ing. Vera Hoferichter  
Dissertation ‘Boundary Layer Flashback in Premixed Combustion Systems’

**Manfred Hirschvogel Prize**
Dr.-Ing. Eva Klenk  
Dissertation ‘Ein analytisches Modell zur Bewertung der Leistung von Routenzugsystemen bei schwankenden Transportbedarfen’

**Study Prizes Awarded**

**Department Prize – Best Degree**
Kristina Geyer, M.Sc.  
Best overall grade of all Master’s degrees

**Department Prizes – Excellent Degrees**
Victor Martín Palacios, M.Sc.  
Second-best overall grade  
Joachim Siegel, M.Sc.  
Third-best overall grade  
Markus Schödel, M.Sc.  
Fourth-best overall grade  
Christina Insam, M.Sc.  
Fifth-best overall grade

**WITTENSTEIN Prize**
Fabian Himpsl, M.Sc.  
Master’s thesis ‘Simulation-Free Model Order Reduction of Non-Linear State-Space Models by Means of Basis Vector Derivatives’

**ARBURG Prize**
Agnes Bußmann, M.Sc.  
Master’s thesis ‘Optimizing the Bulk Composition of a Cell-Free Cartilage Replacement Material’

**RENK Propulsion Technology Prize**
Michael Geitner, M.Sc.  
Master’s thesis ‘Erweiterte Zuverlässigkeitsbetrachtung für Zahnradschäden’

**SGL Group Award**
Helena Canet Tarrés, M.Sc.  
Master’s thesis ‘Design of Aerodynamically Scaled Very Large Wind Turbines’
The Department of Mechanical Engineering is one of the most successful faculties of its kind worldwide and has occupied top places in the main research rankings for the past several years. The basis of this success is both very good conditions for teaching and an excellent research record based on a balanced mix of publicly- and industry-funded projects and demonstrated by quality publications and citations.

**QS World University Ranking by Subject**

The QS World University Ranking by Subject evaluates universities according to the academic reputation, employer reputation, number of citations per publication and h-index. In past years the Department of Mechanical Engineering has been placed among the top ones in Europe (currently at position 9 in Europe) and in second position within Germany.

**Placement Worldwide for Mechanical Engineering: TUM**


**CHE**

The CHE – Center for Higher Education provides a study-oriented ranking for the ZEIT Study Guide. Several indicators are allocated to categories ‘top performing group’, ‘medium performing group’ and ‘low performing group’. Most interesting is a survey amongst students, conducted every third year. The latest survey amongst Bachelor students 2016 places the TUM Department of Mechanical Engineering in the top group for 7 out of 13 indicators.

**THE World University Ranking**

The Times Higher Education Ranking evaluates universities in their specialist groups according to their teaching and research performance, based primarily on citations, teaching indicators and research volume. According to this ranking, TUM’s Engineering again occupies the top place among German universities again, with a particular strength being citations.


**Taiwan Ranking**

The National Taiwan University Ranking is based exclusively on the number of publications, citations and h-indexes – primarily from the past decade. It therefore reacts very slowly to a process of change. Evaluation is subject specific meaning parts of the Department of Mechanical Engineering are not assessed (e.g. process technology and materials science). The Department of Mechanical Engineering of the TUM demonstrates particularly strong performance with regard to highly cited publications (‘HiCi’ rank 26) and now holds the top position in Germany.

**Placement Mechanical Engineering worldwide:**


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http://ranking.zeit.de
Research

At TUM Mechanical Engineering, research addresses the whole value chain from scientific foundations up to application scenarios. The competitiveness of research is hard to quantify. Typical indicators are third-party funds and the number of publications.

Third-party Funds

Third-party funds indicate that public bodies, such as the European Commission, ministries and the DFG, and private entities such as industry and foundations trust in the competence and competitiveness of research performed at the department. While in the decade between 1995 and 2004, third-party funds were almost constant at 20 m Euros, in the following decade, third-party funds at the department almost tripled. This compares to a 52% increase of all research funding at German universities from 9.2 bil. (Mrd) Euros to 14.0 bil. (Mrd) Euros between 2005 and 2012 (most recent data available).

In recent years since 2012, direct project funding from public bodies such as state and federal ministries, the European Commission and the German Research Foundation continued to increase. Industry funding, however, has decreased by about 10% every year since 2014.

Publications

Publications accepted in international journals through a peer review process are a key parameter for scientific output. They are referred to in most international research rankings. Contributions listed in Scopus with about 600 peer-reviewed articles and contributions to conferences are now almost twice as many as 10 years ago.

Even more impressive is the increase in citations: while in 2006 publications of faculty at the Department were cited 1800 times, since then this number increased by more than a factor of six. This indicates that research at the department is of tremendous interest to fellow scientists all over the world.
Teaching at the Department of Mechanical Engineering
Studying at the Department of Mechanical Engineering

With about 4200 enrolled students (in winter semester 2018/19), the Department of Mechanical Engineering is one of the largest departments of the Technical University of Munich (TUM). In terms of teaching, the curricula which are offered combine the classical, profound education of mechanical engineering with new aspects such as cutting-edge technology, interdisciplinary research and the development of ‘soft skills’ in order to prepare students for their future professions in research, development and/or production.

A Bachelor’s degree program and ten Master’s degree programs (see table below) will be offered by the Department of Mechanical Engineering up to summer semester 2019.

From the beginning of the winter semester 2019/20, the Department of Mechanical Engineering will offer seven redesigned Master’s degree programs fostering interdisciplinary aspects, internationality and flexibility.

In addition, the Department of Mechanical Engineering collaborates with other TUM departments and takes part in the Bachelor’s and Master’s degree programs ‘Teaching at Vocational Schools – Metal Engineering’ (primary responsibility: TUM School of Education) and ‘Chemical Engineering’ (Department of Chemistry), the Master’s programs ‘Power Engineering’ (Department of Electrical and Computer Engineering) and ‘Robotics, Cognition, Intelligence’ (Department of Informatics), the Bachelor’s program ‘Engineering Sciences’ as well as the Master’s programs ‘Industrial Biotechnology’ and ‘Human Factors Engineering’ (Munich School of Engineering).

On the international level, the Department of Mechanical Engineering participates in the joint Bachelor’s program ‘Engineering Sciences’ with Paris-Lodron University Salzburg. The joint Master’s program ‘Aerospace Engineering’ previously offered by the Nanyang Technological University (NTU) and the German Institute of Science and Technology (GIST) in Singapore will be offered exclusively by the Department of Mechanical Engineering from the beginning of the winter semester 2019/20. Furthermore, the department has signed more than 70 ERASMUS+ agreements in 23 countries and offers 14 double degree programs with renowned universities, such as École Centrale Paris, EPFL Lausanne and the KTH Royal Institute of Technology, Stockholm.

<table>
<thead>
<tr>
<th>BACHELOR’S DEGREE PROGRAM</th>
<th>MASTER’S DEGREE PROGRAMS</th>
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<tbody>
<tr>
<td>Aerospace</td>
<td>Mechanical Engineering</td>
</tr>
<tr>
<td>Automotive and Combustion Engine Technology</td>
<td>Mechanical Engineering and Management</td>
</tr>
<tr>
<td>Energy and Process Engineering</td>
<td>Mechatronics and Information Technology</td>
</tr>
<tr>
<td>Mechanical Engineering</td>
<td>Nuclear Technology</td>
</tr>
<tr>
<td>Mechanical Engineering and Management</td>
<td>Product Development and Engineering Design</td>
</tr>
<tr>
<td>Mechatronics and Information Technology</td>
<td>Production and Logistics</td>
</tr>
</tbody>
</table>

Degree programs TUM Mechanical Engineering is offering up to summer semester 2019. Source: www.mw.tum.de/studium/studierende/dokumente-zu-studiengaengen, accessed 01/21/2019
Bachelor's Degree Program
‘Mechanical Engineering’

The Bachelor's degree program ‘Mechanical Engineering’ addresses students interested in sciences and technology. Within the three-year program (six semesters), students acquire fundamental knowledge, basic methodological skills as well as the soft skills required by a mechanical engineer. The program has a total of 180 credits in the European Credit Transfer and Accumulation System (ECTS).

Admission
To maintain the high quality standards of TUM all applicants have to undergo an aptitude assessment procedure evaluating their overall performance in the university entrance examinations, knowledge in mathematics and sciences (e.g. physics, chemistry), language skills, and general motivation. Excellent applicants are admitted directly to the Bachelor's degree program. Good applicants can be admitted to the Bachelor's degree program after demonstrating their skills and motivation in interviews.

Profile
During the first four semesters of the program, students acquire profound knowledge of mathematics, sciences and several fundamental fields of engineering. These challenging modules are compulsory and prepare the students for more specific and advanced subjects.

In the 5th and 6th semester, students have to pass one more compulsory module (Mathematical Tools). By choosing five out of 41 specialized Bachelor modules from a broad range of options (including two modules offered by the Department of Chemistry, two by the Department of Electrical and Computer Engineering and three by the TUM School of Management) they get prepared for different Master’s Programs. These modules as well as the Bachelor’s thesis enable students either to work as an engineer or to continue their studies in one of the specialized Master’s degree programs. Moreover students do an internship in industry or alternatively a team project at the department. The curriculum of the Bachelor’s degree program is illustrated in the figure below.

Master's Degree Programs

In 2018, the Department of Mechanical Engineering redesigned its Master’s degree programs in order to foster interdisciplinary aspects, internationality and flexibility. Hence, from the beginning of the winter semester 2019/20 seven new Master’s degree programs can be offered that cover a broad range of cutting-edge technical issues and topics. The modified portfolio is illustrated in the figure on the following page.

Admission
All applicants have to undergo an aptitude assessment procedure consisting of two stages: In the first stage, the applicants’ grades, knowledge of advanced mathematics, engineering mechanics, engineering materials and machine elements (for some programs also thermodynamics, fluid mechanics, heat transfer phenomena, automatic control and/or information technology), and motivation are evaluated. Applicants who are not admitted directly after the first stage have to pass a written test, which is the second stage of the aptitude assessment procedure.
### Facts and Figures

Since winter semester (WS) 2010/11, the total number of students has varied between 4000 and 5200. About 15% of the student body is female. As shown in the figure on the following page, the number of Bachelor’s and Master’s degree students decreased in winter semester 2017/18 for the first time since the old ‘Diplom’ degree program was replaced by B.Sc. and M.Sc. programs in WS 2008/09. The following figure illustrates the number of first semester students who started the B.Sc. program and M.Sc. programs at the Department of Mechanical Engineering during the last nine years. The number of B.Sc. freshmen varies between 480 and 900, the exception being 2011 when two age groups of Bavarian high school pupils started studying simultaneously.

The following figure shows the number of graduates in each of the degree programs. The large number of graduates in the Bachelor's degree program in 2015 results from the extraordinarily large number of admissions in 2011: 792 undergraduates graduated after seven or eight semesters of study, the standard duration of study being six semesters for the B.Sc. (four semesters for the M.Sc. and ten semesters for the ‘Diplom’ degree).

### Up to Summer Semester 2019

| Nuclear Technology            | Nuclear Technology            |
| Product Development and Engineering Design | Development, Production and Management in Mechanical Engineering |
| Mechanical Engineering and Management | Mechanical Engineering and Management |
| Production and Logistics      | Production and Logistics      |
| Aerospace                     | Aerospace                     |
| Automotive and Combustion Engine Technology | Automotive Engineering |
| Mechatronics and Information Technology | Mechatronics und Robotics |
| Medical Technology and Engineering | Mechanical Engineering and Assistance Systems |
| Mechanical Engineering        | Mechanical Engineering        |

Modified Master's degree portfolio of the Department of Mechanical Engineering to be offered from the beginning of the winter semester 2019/20

### Profile

Each of the two-year programs has a total of 120 credits. During the first three semesters, students choose master modules in the amount of up to 60 credits. Master modules are specialized courses consisting of at least three 45 minute units per week. Additionally, students have to take two (out of about 130) lab courses (8 credits) in which they work individually or in small groups on practical tasks such as programming or carrying out experiments. Furthermore, students choose three supplementary courses (9 credits) and workshops in key competences from a broad variety of options.

Opportunities to gain insight into research are offered within the research internship (semester project, team project or practical research course) and the Master’s thesis, which are supervised by professors and scientific assistants. The curriculum of the seven new Master's degree programs is illustrated in the figure below.

<table>
<thead>
<tr>
<th>Semester</th>
<th>5</th>
<th>5</th>
<th>5</th>
<th>4</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Master Module I</td>
<td>Master Module II</td>
<td>Master Module III</td>
<td>Lab Course I</td>
<td>Semester Project</td>
</tr>
<tr>
<td>2</td>
<td>Master Module IV</td>
<td>Master Module V</td>
<td>Master Module VI</td>
<td>Master Module VII</td>
<td>Lab Course II</td>
</tr>
<tr>
<td>3</td>
<td>Master Module VIII</td>
<td>Master Module IX</td>
<td>Master Module X</td>
<td>Master Module XI</td>
<td>Lab Course III</td>
</tr>
<tr>
<td>4</td>
<td>27</td>
<td>Master's Thesis</td>
<td>3 Soft Skills I</td>
<td>3 Scientific Writing</td>
<td></td>
</tr>
<tr>
<td>ECTs (total: 120)</td>
<td></td>
<td></td>
<td></td>
<td>30 per semester</td>
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</tbody>
</table>

Curriculum of the Master's degree programs at the TUM Department of Mechanical Engineering from the beginning of the winter semester 2019/20.
Studying at the Department of Mechanical Engineering

Number of full time students (cases) enrolled in degree programs offered by the TUM Department of Mechanical Engineering (by the beginning of each winter semester).
Source: [http://portal.mytum.de/iuk/bw/studenten/tum_std_html](http://portal.mytum.de/iuk/bw/studenten/tum_std_html), accessed on 01/21/2019

Number of students starting their studies (cases) in the degree programs offered by the TUM Department of Mechanical Engineering. (The number for e.g. 2014 is the sum of students starting in the summer semester 2014 and winter semester 2014/15.)
Source: [http://portal.mytum.de/iuk/bw/studenten/tum_std_html](http://portal.mytum.de/iuk/bw/studenten/tum_std_html), retrieved 02/20/2019

Number of graduates at the TUM Department of Mechanical Engineering. (The number for e.g. 2014 is the sum of students graduating in the winter semester 2013/14 and summer semester 2014/15.)
Source: [http://portal.mytum.de/iuk/bw/studenten/tum_std_html](http://portal.mytum.de/iuk/bw/studenten/tum_std_html), accessed on 02/20/2019
As one of the leading departments in mechanical engineering worldwide, the TUM Department of Mechanical Engineering is dedicated to attracting international students, both as full-time students and through exchange programs, as well as to enable TUM students to spend parts of their studies at partner institutions worldwide.

**Full-Time Students**

Almost 28\%\(^1\) of the department’s student body are international students. During the past six years the number of international students enrolled in the B.Sc. and M.Sc. programs almost doubled.\(^2\)

Students from about 80 nations study at the department – the biggest groups being Chinese, followed by Austrian and Spanish students.\(^1\)

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\(^1\) International Students and Student Exchange

\(^2\) International Students and Student Exchange
Student Exchange

TUM students are offered several possibilities to spend some part of their studies abroad – varying in region, duration and educational goal. Within the framework of the European ERASMUS+ program and TUM’s worldwide TUMexchange program, students have the possibility to study one or two semesters at one of TUM’s more than 450 partner universities. Moreover TUM has signed about 35 double degree agreements worldwide, targeting students with excellent academic performance who are interested in doing an additional degree. Tuition fees are waived for double degree students as well as for students going abroad for an exchange. Help regarding administrative issues and housing is usually provided by the department and/or the partner institution. ERASMUS+ and double degree students at EU-partner universities automatically get the ERASMUS+ grant whereas TUMexchange and double degree students studying overseas may apply for scholarships. Apart from offering the exchange options mentioned, self-organized internships within Europe and research projects overseas can be financially supported by TUM. Information about suitable scholarships is provided by TUM and the department. ERASMUS+ student mobility as well as the double degree program is by and large organized on departmental level whereas TUM’s International Center is in charge of the TUMexchange program. A recently issued brochure aims promoting at double degree programs among the department’s students.

Incoming Exchange Students

In addition to recruiting an increasing number of international full-time students, the department successfully attracts an increasing number of international exchange students – both from within Europe and worldwide. In winter 2018/19, 145 exchange students from 27 nations are studying at the Department of Mechanical Engineering. In addition, the centrally organized TUMexchange program enables selected students of the department to study overseas at one of more than 120 partner universities. Moreover a joint B.Sc. degree program ‘Engineering Science’ and a joint M.Sc. program ‘Material Science’ with Paris Lodron Universität Salzburg have been signed and 14 TIME double degree agreements in Brazil, France, Italy, Sweden, Switzerland and Spain have been concluded with renowned associate universities such as Institut Supérieur de l’Aéronautique et de l’Espace (ISAE, Toulouse), Universidade de São Paulo, Università di Trento or Universitat Politècnica de Catalunya ( UPC, Barcelona).

Outgoing Exchange Students

The Department of Mechanical Engineering is not only aiming at increasing its international student body, but also pursues the goal to raise the mobility of its own students. With the objective of being able to offer every student the opportunity to spend at least one semester abroad, the department has signed more than 70 ERASMUS+ agreements in 23 European countries. Most of the department’s partner institutions are in France (12), Spain (12), Italy (8) and Sweden (6). In 2018/19 the number of outgoing students is comparable to the number last year.

Development of the number of international exchange and double degree students (*winter term 2017/18 only)

During the winter term 2018/19 more than 15% of the incoming exchange students of TUM have been enrolled at the Department of Mechanical Engineering and another 44 students have been registered as full-time M.Sc. students within the framework of the TIME double degree programs.  

Development of the number of mechanical engineering students going abroad

1 Source: https://www.tum.de/nc/die-tum/die-universitaet/die-tum-in-zahlen/studium/ (TUM Corporate Communications Center, accessed 29.10.2018)
2 Source: Registrar’s office (TUM), 09/2018
3 Sources: International Center (TUM); Online database “Moveon”; Students’ Services Department of Mechanical Engineering (TUM)
Public Funds to Improve Conditions of Study at the Department of Mechanical Engineering

Since winter semester 2013/14 Bavarian universities and colleges receive state funding grants to replace course fees which were abolished at the end of summer semester 2013. The level of this funding is based on the number of students enrolled at the university in question. The funds may only be used to improve conditions for students and teaching staff.

At TUM funding may be used in two areas:

1. **Common Areas of Responsibility**
   Common areas of responsibility are those that concern several or all departments, one or more campuses, in particular effective priority teaching programmes and university-wide structural programmes to improve conditions of study.

2. **Department Areas of Responsibility**
   Departmental areas of responsibility involve in particular the improvement of matters which relate specifically to degree courses on offer, such as the amount, quality and organisation of tuition (e.g. courses, course-related measures, internationalisation, infrastructure, e-learning), and in some special cases also new degree courses.

The legal basis for the use of tuition funding is laid down in the TUM statute on the use of state funding grants. Based on the tuition funding statute, the Department of Mechanical Engineering has drawn up a tuition funding concept. Projects in the following areas are funded:

- subject and method competence, e.g. through setting up or building up tutorials, practical experience sessions and consultation sessions,
- social competence, e.g. through financing of job positions at the Center of Key Competences,
- personality-related competence, e.g. through extension of the opening hours of the Department of Mechanical Engineering Library, and
- general conditions, e.g. through financing a job position at the Student Services.

Depending on the number of students at the Department of Mechanical Engineering, the department receives c. 1.7 million euros annually in the form of tuition funding. This funding is generally employed as follows:

Use of public funding at the Department of Mechanical Engineering

A detailed list of projects funded can be downloaded from the website www.mw.tum.de/en/for-department-staff/tuition-funding.
Diversity

The Department of Mechanical Engineering is dedicated to increasing diversity, especially with respect to gender and international background. This process was formalized in a target agreement with the university board in 2012, defining 2011 as a point of reference.

Since 2011, the share of female students has increased by a quarter from 12% to 15%. At the same time, the share of female researchers with a time-limited contract (i.e. Ph.D. candidates) increased from 11% to 17% and the share of female researchers in a leading position (i.e. with a permanent contract or at higher pay grades) also by almost three quarters from a mere 6% in 2011 to 8% in 2018. Especially the increase in senior scientific staff gives rise to hope that it will also be possible to gain more female professors in the future.

Since 2011, the department has not only become more female but also much more international. Now 28% of all students are international, more than twice the number in 2011, and 17% of all professors are international – more than half of them have gained significant expertise abroad during their career.
Central Teaching Unit

The Central Teaching Unit trains doctoral candidates as part of the Graduate Center Mechanical Engineering programme, as well as training Bachelor and Master students of the department in key competencies at the Center of Key Competencies.

Center of Key Competencies

The Center of Key Competencies (ZSK) is responsible for the central training aspects of all Bachelor and Master students at the Department of Mechanical Engineering with the aim to expand their soft skills. Through developing their social, methodological and personal competencies, young engineers get trained to complement their technical knowledge. The Center of Key Competencies focuses on the development of skills such as effective teamwork, constructive solution of conflicts or convincing presentations.

2018 – Diverse range of training

During 2018 the Center of Key Competencies was able to significantly broaden the range of training possibilities on offer. Besides the variety of topics ranging from classical soft skills topics to scientific practice, we started to widen our target group. The Center of Key Competencies mainly focuses on students but also integrates highly gifted pupils taking part in the program TUMKolleg, as well as doctoral candidates and other members of the chairs at the Department of Mechanical Engineering.

Highly gifted pupils – Teaching scientific practice within TUMKolleg

As a part of the TUMKolleg network we share our competency within the field of scientific practice and coordinate the program at the Department of Mechanical Engineering. TUMKolleg, headed by the TUM School of Education, promotes talented, high-performing students who are interested in the natural sciences. While studying for their university entrance qualification (Abitur), students visit TUM once a week and write their first research work. Here they are involved in various departments and chairs. In addition to providing help in the search for suitable chairs for their research work, the ZSK offers a research colloquium to support students in writing their scientific papers. Here the students have the opportunity to present their research work in order to get feedback on the process of their scientific writing. In addition, each research colloquium deals with aspects of scientific writing, such as the design of a structure, literature research or the structure of a scientific paper. The ZSK also supports the TUM School of Education in two workshops on scientific work and scientific writing, which are conducted for all students of TUMKolleg.

In February 2019 we were pleased to welcome a new class at the Department of Mechanical Engineering and are looking forward to the upcoming cooperation with the students and the supervising chairs.
Mechanical Engineering Students –
Fusing professional expertise and soft skills
One of the major challenges in training soft skills lies in creating the perfect mix of theory and practice, simulation and reality. As in our regular workshops the concept focuses on experiencing soft skills within simulations and discussions, different collaborations allow us to experience and discuss reality. This happens when soft skills and real teamwork, technical content or a professional background within a company meet. As part of the exclusive training offered by us we collaborate with various different chairs at the Faculty of Mechanical Engineering as well as with TUM organizations, such as FSMB or ASTA, and companies from the engineering and consulting field. We design courses and programs for our partners and support them in extending existing formats by incorporating soft skills workshops. We are proud to support the BME, iwb, FTM, HT, lvk, ZFP and TFD within university internships and lectures. These courses are highly recommended by our students and receive above-average evaluations.

Doctoral candidates and chairs –
Demand-oriented workshops
When it comes to training doctoral candidates and faculty members, the major advantage lies in our close relationship to the field of mechanical engineering and the issues at the department. We cooperate with chairs of Mechanical Engineering in the form of half-day workshops and training sessions lasting several days. We design tailored courses meeting the needs and expectations of the faculty members. In the past we offered topics like effective presentations, leadership, time management or meeting management for teams at different chairs, such as ZFP or FML. For doctoral candidates an accreditation via the Faculty Graduate Center is possible and might be discussed individually. Besides professional competence in training and running workshops, doctoral candidates are welcome to take part in individual coaching within the 360° feedback processes at the department. Analytical sessions facilitate a deep understand of the feedback received and to define further steps to incorporate this feedback into daily practice. We are very much looking forward to broaden the training on offer in the coming year and our collaboration with the Faculty Graduate Center Mechanical Engineering.

2019 – Even more variety to come
We look back on the diverse year 2018, working together with our students and partners to further incorporate soft skills in the field of engineering. We can only agree with the message, that all our partners within industry and ther university convey: Soft Skills are the key to employability, projects in science and business, as well as scientific practice. If your are interested in collaborating with us, please contact the Center of Key Competencies.

Faculty Graduate Center
As part of the TUM Graduate School, the Faculty Graduate Center Mechanical Engineering is a professional organization set up in to foster the advancement of doctoral candidates at the Department of Mechanical Engineering.

The Faculty Graduate Center supports the department’s institutes in creating the very best environment for doctoral candidates during their promotional period. It offers advanced professional training and services which are specifically tailored to the needs of engineers and helps promote networking for doctoral candidates both within and outside the department.

The Faculty Graduate Center assists doctoral candidates in variety of ways, e.g. by organizing subject-specific, interdisciplinary courses, informational and networking events, advising the candidates about the best way to proceed with the fulfillment of their qualification program, enabling financial support for international and/or interdisciplinary advancement and supporting the Doctoral Candidate Representatives in fulfilling their vision.

In 2018 the center strengthened its successful cooperation with ProLehre by not only continuing to organize the joint event ‘Fit in Teaching’ (Fit in die Lehre) at the Department of Mechanical Engineering, but also joining forces in two new events; the interdisciplinary course ‘Supervising Study Work – key to good supervision’, and inviting
ProLehre to give a short introductory presentation during the first ever networking event, Info-Lunch.

The Faculty Graduate Center also supported the Doctoral Candidate Representatives in organizing their networking events as well as organizing the Supervisor Award 2018 at the Department of Mechanical Engineering.

**Strengthening cooperation with ProLehre**

The Faculty Graduate Center, together with Svenja Freund from ProLehre as well as several doctoral candidates, organized the event ‘Fit in die Lehre’ (FidL @MW) twice. It is a half-day event aimed at new doctoral candidates, who are going to be involved in teaching at TUM during their promotion. Around 70 participants took part in both events.

Extending the cooperation with ProLehre, Svenja Freund (ProLehre representative for the Department of Mechanical Engineering), together with Dr. Birgit Spielmann (Managing Director of FGC ME), held an interdisciplinary course ‘Supervising Study Work – key to good supervision’ during the 90th Kick-Off at Raitenhaslach. The course was well received by the participants from various different TUM faculties and encouraged contact between doctoral candidates.

In addition, Svenja Freund was invited to give a short presentation about ProLehre’s Media & Didactics training course during the first ever Info-Lunch.

**Broadening networking during the Info-Lunch**

To offer Ph.D. candidates different networking opportunities and give important information in a new and more available format the Graduate Center has come up with a new event – Info-Lunch.

The concept of Info-Lunch is to cover interesting, important topics for doctoral candidates during an extended lunch break, thus enabling more doctoral candidates to participate, because they do not have to take a day or half-day off from their research. The event lasts between 1.5-2 hours. The informative part of the event takes place for between 30-45 minutes and there is then an opportunity to continue the dialogue in a more relaxed atmosphere over a small lunch snack.

**Supervisory Award 2018**

For the first time this year, doctoral candidates had the opportunity to nominate their outstanding supervisors for the TUM Supervisory Award. This award was introduced by the Graduate Council and is endowed with a prize of 5,000 euros. The Department of Mechanical Engineering also received a number of nominations. The TUM-wide award went to the Faculty of Electrical Engineering and Information Technology this year. Nevertheless, in honor of our outstanding supervisors, the Doctoral Candidate Representatives at Mechanical Engineering and the Faculty Graduate Center decided to award a Supervisory Award to the Department of Mechanical Engineering.

We would like to congratulate Dr.-Ing. Stefan Adami on his third place, Prof. Dr. Daniel J. Rixen for second place and Prof. Dr.-Ing. Harald Klein on achieving first place. The first prize comes with 250 euros for the doctoral training of Prof. Klein.

**Looking back and forward**

Looking back at the new cooperation and networking options for doctoral candidates in 2018, the Faculty Graduate Center is inspired to continue strengthening its support of the doctoral candidates and improve what is offered by the Graduate Center. The Center wishes to make its support services better known through further Info-Lunches, as well as a variety of informative events, intended for doctoral candidates at every stage of their promotion.

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**Contact**

**Center of Key Competencies**

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**Graduate Center Mechanical Engineering**

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The task of the ‘FSMB’, the Student Council for Mechanical Engineering, is to represent all students of the department. It is one of the largest student councils in Germany with more than 150 active members. During yearly elections, held according to the Bavarian Higher Education Law, the students elect a specified number of student representatives, depending on the current count of students enrolled at the department.

Due to the vast number of members, the council is organised in individual departments, which work in close collaboration to improve and ensure the academic conditions at our faculty.

**Event Department**

The summer semester started with the student council’s workshop weekend, dedicated to various topics ranging from improvements in study conditions to the range of courses. Throughout the whole year, regular blood donation events were organised in cooperation with the Bayerische Rote Kreuz and the initiative ‘Talente Spenden’. A more formal event took place in the form of a ballroom dance evening, giving the students an opportunity to dress up and dance in a festive atmosphere. As the university celebrated its 150 year anniversary, students and employees from all campuses came together in Garching for two days in early May for the maiTUM, our very own version of the traditional Bavarian May festival. In the warm days of June, the week-long GARNIX Open Air followed, featuring beer, barbecues and live music. These two events were organized by the TUM general student council (AStA) and supported by us. During the GARNIX various tournaments, such as beach volleyball, basketball and football were held on campus. Moreover, the faculty was supported by the student council at the ‘Tag der Fakultät’, the graduation day, where we offered freshly mixed drinks to our graduates to enjoy at the council’s cocktail bar. For some fun after a long day, the student councils of Mechanical Engineering and Chemistry joined to organise dance nights throughout the semester. To welcome all the newly enrolled students in the winter months, we had a big party in the faculty building with over 3000 of our fellow students in November. After a second workshop weekend in early December, it was time for some more solemn days which were highlighted by the festive Christmas tree in the foyer of the department and our cozy little Christmas fair in front of the faculty building. Many other small events like a pub crawl or a poker competition were organized to delight the students over the year.

**Magazine of the Student Council**

The student council has published six issues of its magazine ‘Reisswolf’. The topics of the individual issues ranged from news about the new Master’s program to reports on voluntary work or car reviews. This year, we
Student Council

started to enrich our topics with informative articles on the latest technical achievements and critical enquiries into current topics. The traditional ‘chair series (Lehrstuhlserie)’ continued to introduce the various chairs of the department. In addition, articles from university groups contribute to every issue. Less serious topics were published on the ‘Klopapier’, the humorous, entertaining poster in the restrooms of the department.

Print Shop

As in previous years, the printery of the student council printed all kinds of lecture notes, collections of past exams and the free student magazine ‘Reisswolf’ in high unit numbers. The lecture notes and collections of past exams are available at student-friendly prices in the lecture script store, open every working day. Thanks to the great cooperation with numerous institutes, the Print Shop was able to offer a wide range of documents for lectures, seminars and lab courses. The amount of scripts on offer was also increased. Furthermore, many special sales were organised, such as package sales for the first four semesters, or extended shop opening hours at key times during the year.

International Department

In order to increase intercultural communication, improve language skills and achieve a better integration of our exchange students, the International Department is in charge of the buddy program. In an online sign-up process, international and local students are brought together according to their preferred language, country or university. At the beginning of each semester, the International Department organises the Welcome Events and a ‘Speed-friending’ for all new exchange students. Furthermore, the buddies can spend time together and meet other international and domestic students in the pub evening program. Last but not least, the International Department holds an Erasmus Christmas Party a week before the Christmas break. With a buffet and culinary delights from the international student’s home countries, an occasion is provided to foster intercultural experience.

Department for Higher Education Policy

Together with the TUM Department of Mechanical Engineering, the Student Council worked on a few major projects to improve teaching and the learning environment. In the course of the ‘Studienzuschusskommission’ (committee for study allowances), more than 300 applications were granted to advance the quality of teaching. We are also very proud of our contribution to the new Master regulations and the improvements already achieved, soon to be enjoyed by our master-freshmen. The most important topic for next year is the founding of the new Department for Aerospace and Geodesy. So far, we have managed to build an interdisciplinary group of students from the departments of mechanical engineering, geodesy and the Munich School of Engineering to accompany the process. Furthermore, we worked on the reformation of a few important statutes and are very satisfied with the results. On the student side, we managed to maintain our broad national and international relationships by attending the ‘Fachschaftentagung Maschinenbau’.

Freshman Department

The job of the Freshman Department is to care for all the freshmen who begin their studies at the department. During the preparation course in mathematics, the POWER (the orientation week) was organised which included a city rally through Munich, a traditional Bavarian breakfast with ‘Weißbier’ and ‘Weißwurst’ and a sport event. All the important information regarding the course of studies and university life were given to the students in a two-day information event at the start of the winter term. Moreover, the Freshman Department informs potential students during numerous events throughout the year.

Public Relations Department

As the first address for questions and information, the Public Relations Department is in charge of e-mail conversation, notice board for jobs and requests, and other information sources. www.fsmb.de
Appointments

In 2018, one new full professor, one distinguished affiliated professor and two honorary professors were appointed to the TUM Department of Mechanical Engineering

Prof. Dr. Marco Caccamo

The professorship ‘Cyber-Physical Systems in Production Engineering’ has been established within the programme ‘Zentrum Digitalisierung Bayern’, funded by the Bavarian State Government. TUM Mechanical Engineering is proud to be host to Marco Caccamo as the first Humboldt Professor in mechanical engineering. Prof. Marco Caccamo is an internationally recognized expert working at the cutting edge of research into safety-critical cyber-physical systems. His focus is on both fundamental research into real-time computing and embedded systems and working with industrial partners in the development of applications. Marco Caccamo was trained as a computer engineer at the University of Pisa and earned his Ph.D. in computer engineering from the Scuola Superiore Sant’ Anna (Italy) in 2002. He joined the University of Illinois at Urbana-Champaign as an assistant professor and was promoted to associate professor at the age of 36, then became a full professor in 2015. He has also served as a visiting professor at ETH Zurich (Switzerland) and with TUM. In addition Caccamo has chaired several IEEE flagship conferences on real-time systems and cyber-physical systems, serves as a board member of leading scientific organizations, including many technical program committees (TPC) and with the IEEE publication, ‘Transactions on Computers.’

The ‘Cyber-physical Systems in Production Engineering’ professorship specialises in designing safe, predictable, and high-performance embedded platforms for next generation cyber-physical systems. Currently, the focus is on: predictable high-performance computing with heterogeneous SoC multicore platforms, a strategy for the physical safety of a cyber-physical system (CPS) under cyber attacks, secure and safe integration of machine learning algorithms with digital controllers for CPS and the development of flexible resource management policies for a broad range of CPS systems.

Prof. Dr. Petros Koumoutsakos

Petros Koumoutsakos has been appointed as only the third Distinguished Affiliated Professor at TUM Mechanical Engineering. He holds the Chair for Computational Science at ETH Zurich and serves as Fellow of the Collegium Helveticum. He studied Naval Architecture at NTU in Athens and the University of Michigan and earned his Ph.D. in Aeronautics and Applied Mathematics at Caltech. Later, he conducted post-doctoral studies at the Center for Parallel Computing at Caltech and at the Center for Turbulent Research at Stanford University and NASA Ames. Petros Koumoutsakos is known for his computational tools for the study of complex scientific and engineering problems. Currently, his focus is on multiscale particle methods and derandomized optimization algorithms applied to areas of life sciences, fluid mechanics, nanotechnology and their interfaces. He emphasizes the parallel development of algorithms, software, hardware and applications.

Hon.-Prof. Dr.-Ing. Johann Dambeck

Johann Dambeck (b. 1967) has been appointed to the department as Honorary Professor for Flight Navigation and Data Fusion at the Chair of Flight System Dynamics. He studied mathematics and technomathematics in Regensburg and Kaiserslautern and earned his doctorate in geodesy and navigation at Stuttgart University. Later, he worked with manufacturers of aircraft and navigation systems. He is known for establishing the field of sensors, navigation and data fusion in Germany. This field, however, is also of fundamental interest to aerospace technology. Johann Dambeck has been teaching Navigation and Data Fusion since 2008 at TUM Mechanical Engineering.

Hon.-Prof. Peter Göttel

Peter Göttel (b. 1957) has been appointed to the department as Honorary Professor for Project Management in Mechanical Engineering at the Chair of Industrial Management and Assembly Technologies. He studied aerospace engineering at the University of the Armed Forces in Neubiberg and later Business Administration as well as Energy and Environment Management in Hagen and Berlin. Later, he worked in project management with several enterprises and has been running his own business for project management for more than a decade. Peter Göttel has been teaching Project Management since 2007.
Department Members

Prof. Dr.-Ing. Nikolaus Adams
Aerodynamics and Fluid Mechanics
www.aer.mw.tum.de
- Numerical modeling and simulation of complex flows
- Low-speed aerodynamics
- Multiphase flows, microfluidics
- Gasdynamics, cavitating flows
- Aircraft, spacecraft and automotive aerodynamics
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Prof. Dr. phil. Klaus Bengler
Ergonomics
www.lfe.mw.tum.de
- Micro ergonomics
- Human-machine interaction
- Digital human modeling
- Cooperative systems and automation
► Page 81

Prof. Dr. rer. nat. Sonja Berensmeier
Bioseparation Engineering
www.mw.tum.de/en/stt/bioseparation-engineering
- Selective separation of biomolecules
- Downstream processing
- Magnetic separation
► Page 88

Prof. Dr. Carlo L. Bottasso
Wind Energy
www.wind.mw.tum.de
- Wind energy system design, modeling and control
- Computational mechanics and simulation technology
- Numerical and experimental aeroelasticity
► Page 91

Prof. Dr. Marco Caccamo
Cyber-Physical Systems in Production Engineering
www.mw.tum.de/cps
- Safety-critical cyber-physical systems
- Real-time systems
- Scheduling and schedulability analysis
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Prof. Dr. phil. Klaus Drechsler
Carbon Composites
www.lcc.mw.tum.de
- Composite materials and process technology
- Textile technology
- Lightweight design
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Prof. Dr.-Ing. Johannes Fottner
Materials Handling, Material Flow, Logistics
www.fml.mw.tum.de
- Innovative conveyor technology
- Sustainable logistics systems
- Planning and control of material flow systems
- Industry 4.0
- Humans in logistics
- Crane engineering and design of load-supporting structures
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Prof. Dr.-Ing. Michael W. Gee
Mechanics and High Performance Computing
www.mhpc.mw.tum.de
- High performance parallel computing
- Fluid-structure interaction
- Cardiovascular biomechanics
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Prof. Dr.-Ing. habil. Dipl.-Geophys. Christian Große
Non-destructive Testing
www.zfp.tum.de
- Quality control during construction
- Inspection of structures and components in civil and mechanical engineering
- Structural health monitoring
Joint Appointment with the TUM Department of Civil, Geo and Environmental Engineering
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Prof. Dr.-Ing. Volker Gümmer
Turbomachinery and Flight Propulsion
www.ltf.mw.tum.de
- Aerodynamics of turbomachinery
- Propulsion technology
- Design concepts for gas turbine components
- Gas turbine systems and cycles
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Prof. Dr.-Ing. Oskar J. Haidn
Space Propulsion
www.lfa.mw.tum.de
- Thrust chamber technologies
- High pressure combustion
- In-space propulsion
- Green propellants
- Combustion dynamics
- Turbopump technologies
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Prof. Dr.-Ing. Manfred Hajek
Helicopter Technology
www.ht.mw.tum.de
- Aeromechanical modeling and test of rotors
- Modelling and simulation of rotocraft flight
- Multi-rotor configurations
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Prof. Dr.-Ing. Florian Holzapfel
Flight System Dynamics
www.fsd.mw.tum.de
- Modeling, simulation and parameter estimation
- Flight guidance and flight control
- Sensors, data fusion and navigation
- Trajectory optimization
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Prof. Dr.-Ing. Mirko Hornung
Aircraft Design
www.lls.mw.tum.de
- Scenario analysis, future trends and technologies
- Aircraft design (civil and military)
- Analysis and evaluation of aircraft concepts
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Prof. Dr.-Ing. Hans-Jakob Kaltenbach
Flow Control and Aeroacoustics
www.aer.mw.tum.de
- Active and passive flow control
- Prediction and mitigation of flow noise
- Aircraft, automotive and railway aerodynamics
► Page 147

Prof. Dr.-Ing. Harald Klein
Plant and Process Technology
www.apt.mw.tum.de
- Process design
- Equipment design methods
- Modeling and thermodynamic property data
► Page 150
Department Members

Prof. Phaedon-Stelios Koutsourelakis, Ph.D.
Continuum Mechanics
www.contmech.mw.tum.de
- Uncertainty quantification in computational science and engineering
- Bayesian formulations for inverse problems
- Atomistic simulation of materials
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Prof. Dr.-Ing. Andreas Kremling
Systems Biotechnology
www.biovt.mw.tum.de/de/weitere-einrichtungen/fg-systembiotechnologie
- Mathematical modeling of cellular systems
- Model analysis and parameter identification
- Model-based experimental design
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Prof. Dr. rer. nat. Oliver Lieleg
Biomechanics
www.mw.tum.de/de/bme/startseite
- Mechanics of biomaterials
- Biological hydrogels
- Biomedical/biophysical engineering
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Prof. Dr.-Ing. Markus Lienkamp
Automotive Technology
www.ftm.mw.tum.de
- Vehicle concepts
- Electric mobility
- Vehicle control and dynamics
- Driver assistance systems
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Prof. Dr.-Ing. habil. Boris Lohmann
Automatic Control
www.rt.mw.tum.de
- Methods and application of non-linear and predictive control
- Modeling, reduction, and control of distributed parameter systems
- Automotive, multicopter, and robot control application
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Prof. Dr. rer. nat. Tim C. Lüth
Micro Technology and Medical Device Technology
www.mimed.mw.tum.de
- Medical navigation, robotics, and control architectures
- Rapid prototyping
- Technology for an aging society
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Prof. Dr. rer. nat. Tim C. Lüth (interim)
Medical Materials and Medical Implant Design
www.medtech.mw.tum.de
- Hemocompatible and -active surfaces and systems
- Functionalized polymeric implants
- Improved polymers, process tooling and analysis tools
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Prof. Rafael Macián-Juan, Ph.D.
Nuclear Technology
www.ntech.mw.tum.de
- Nuclear reactor safety
- Thermal-hydraulic and neutronic analysis of nuclear systems
- Radiation transport
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Department Members

Prof. Dr.-Ing. Steffen Marburg
Vibroacoustics of Vehicles and Machines
www.vib.mw.tum.de
- Experimental and computational acoustics
- Vibroacoustic optimization
- Uncertainty quantification of vibroacoustic systems
- Material data identification
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Prof. Dr. Rudolf Neu
Plasma Material Interaction
www.pmw.mw.tum.de
- Erosion and hydrogen retention in plasma facing materials
- Tungsten alloys and composite structures for heat removal
- Heatflow tests for and development of plasma facing materials
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Prof. Wolfgang Polifke, Ph.D.
Thermo-Fluid Dynamics
www.tfd.mw.tum.de
- Aero- and thermoacoustics
- Mixing and reaction in turbulent flows
- Two-phase flows
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Prof. Dr. Julien Provost
Safe Embedded Systems
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- Fault-tolerant systems
- Formal verification and validation
- Distributed control systems
- Diagnosis of automated systems
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Prof. Dr.-Ing. Gunther Reinhart
Industrial Management and Assembly Technologies
www.iwb.mw.tum.de
- Production management and logistics
- Automation and robotics
- Assembly technology
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Prof. Dr. Dr.-Ing. Thomas Sattelmayer
Thermodynamics
www.td.mw.tum.de
- Combustion and reactive flows, noise and instabilities
- Transport phenomena in single-and two-phase flows
- Energy systems and technologies
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Prof. Dr.-Ing. Veit Senner
Sport Equipment and Materials
www.spgm.tum.de
- New materials (esp. carbon composites) in sports
- Improved interaction between athletes and sports equipment
- Equipment for reduced injury risk in sports
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Prof. Dr.-Ing. Hartmut Spliethoff
Energy Systems
www.es.mw.tum.de
■ Systems studies
■ Combustion and gasification of solid fuels
■ Steam cycles
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Prof. Dr.-Ing. Georg Wachtmeister
Internal Combustion Engines
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■ Gas and diesel engines
■ Injection processes
■ Exhaust gas aftertreatment
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Prof. Dr.-Ing. Karsten Stahl
Machine Elements
www.fzg.mw.tum.de
■ Gears and transmission components
■ Fatigue life, efficiency, NVH behavior
■ Testing, methods, simulation
■ Analysis, computer applications
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Prof. Dr.-Ing. Wolfgang A. Wall
Computational Mechanics
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■ Multifield problems
■ Multiscale problems
■ Computational biomechanics and biophysics
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Prof. Dr.-Ing. Birgit Vogel-Heuser
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■ Model-based and integrated engineering
■ Distributed control systems
■ Quality management and human factors
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Prof. Dr. Prof. h.c. Dr. rer. nat. Ulrich Walter
Astronautics
www.lrt.mw.tum.de
■ Spacecraft and satellite technologies
■ Systems engineering
■ Human exploration technologies
■ Hypervelocity laboratory
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Prof. Dr.-Ing. Wolfram Volk
Metal Forming and Casting
www.utg.mw.tum.de
■ Manufacturing, tooling and measurement technology
■ Development, heat treatment and processing of new materials
■ Virtual manufacturing processes
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Prof. Dr. mont. habil. Dr. rer. nat. h.c. Ewald Werner
Materials Science and Mechanics of Materials
www.wkm.mw.tum.de
■ Materials science of metals and mechanics of materials
■ Phase transformations
■ Alloy and process development
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Prof. Dr.-Ing. Dirk Weuster-Botz
Biochemical Engineering
www.biovt.mw.tum.de
- Microbial bioprocess engineering and industrial biotechnology
- Biocatalysis and fermentation
- Bioprocess integration
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Prof. Dr.-Ing. Michael F. Zaeh
Machine Tools and Manufacturing Technology
www.iwb.mw.tum.de
- Machine tools
- Manufacturing processes
- Joining and cutting technologies
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Prof. Dr. Markus Zimmermann
Product Development and Lightweight Design
www.mw.tum.de/lpl
- Multi-disciplinary design
- Modelling and simulation of complex systems
- Design methods and tools and processes
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Other Academics with Professorial Rights

Hon.-Prof. Nikolaus Bauer
Material Handling, Material Flow, Logistics

Hon.-Prof. Dr. Dr. Hans-Harald Bolt
Thermodynamics

apl. Prof. Dr.-Ing. habil. Christian Breitsamter
Aerodynamics and Fluid Mechanics

Hon.-Prof. Dott. Antonino Cardella
Nuclear Technology

Hon.-Prof. Dr.-Ing. Johann Dambeck
Flight System Dynamics

Hon.-Prof. Dr.-Ing. Marco Einhaus
Machine Tools and Manufacturing Technology

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Applied Mechanics

Prof. Dr.-Ing. Matthias Gaderer
Renewable Energy Systems (TUM Campus Straubing)

Hon.-Prof. Peter Göttel
Industrial Management and Assembly Technologies

Hon.-Prof. Dr.-Ing. Harald Großmann
Plant and Process Technology

Hon.-Prof. Dr.-Ing. Ulrich Heiden
Automotive Technology

Hon.-Prof. Dr.-Ing. Matthias Heller
Flight System Dynamics

Prof. Dr.-Ing. Hans-Georg Herzog
Energy Conversion Technology (TUM Department of Electrical and Computer Engineering)

PD Dr.-Ing. habil. Xiangyu Hu
Aerodynamics and Fluid Mechanics

PD Dr.-Ing. habil. Thomas Indinger
Aerodynamics and Fluid Mechanics
Department Members

**Hon.-Prof. Dr.-Ing. Alexander Kolb**
Thermodynamics

**PD Dr.-Ing. habil. Christian Krempaszky**
Materials Science and Mechanics of Materials

**Hon.-Prof. Dr.-Ing. Christian Lammel**
Industrial Management and Assembly Technologies

**Prof. Dr. Gerhard Rigoll**
Human-Machine Communication
(TUM Department of Electrical and Computer Engineering)

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Automotive Technology

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Aerodynamics and Fluid Mechanics

**PD Dr.-Ing. habil. Thomas Thümmel**
Applied Mechanics

**Hon.-Prof. Dr.-Ing. Peter Tropschuh**
Automotive Technology

**Hon.-Prof. Josef Vilsmeier**
Automation and Information Systems

**Prof. Dr.-Ing. Ulrich Wagner**
Energy Economy and Application Technology
(TUM Department of Electrical and Computer Engineering)

**Hon.-Prof. Dr.-Ing. Walter Wohnig**
Metal Forming and Casting

**Distinguished Affiliated Professors**

**Prof. Dr.-Ing. Wan Gang**
Minister of Science and Technology of the Peoples Republic of China

**Prof. Dr. Petros Koumoutsakos**
ETH Zurich, Switzerland

**Prof. Dr.-Ing. Wolfgang Kröger**
ETH Zurich, Switzerland
Department Members

Retired Professors

Prof. Dr.-Ing. Horst Baier
Lightweight Structures

Prof. Dr.-Ing. Klaus Bender
Information Technology

Prof. Dr.-Ing. habil. Günther Brandenburg
Special Applications of Electrical Drives

Prof. Dr. rer. nat. Heiner Bubb
Ergonomics

Prof. Dr.-Ing. Klaus Ehrlenspiel
Design in Mechanical Engineering

Prof. Dr.-Ing. habil. Rainer Friedrich
Fluid Mechanics

Prof. Dr.-Ing. Willibald A. Günthner
Materials Handling, Material Flow, Logostics

Prof. Dr.-Ing. Dr. rer. nat. Gerd Habenicht
Joining Technology

Prof. Dr.-Ing. Dietmar Hein
Thermal Power Plants

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Automotive Technology

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Prof. Dr.-Ing. Bernd-Robert Höhn
Machine Elements

Prof. Dr.-Ing. Eduard Igenbergs
Astronautics

Prof. Dr.-Ing. Boris Laschka
Fluid Mechanics

Prof. Dr.-Ing. Udo Lindemann
Product Development

Prof. Dr.-Ing. Dr.-Ing. E. h. mult. Franz Mayinger
Thermodynamics

Prof. Dr.-Ing. Alfons Mersmann
Process Engineering

Prof. Dr.-Ing. Reimer J. Meyer-Jens
Lightweight Structures

Prof. Dr.-Ing. Dr.-Ing. E. h. mult. Friedrich Pfeiffer
Mechanics

Prof. Dr.-Ing. Dr.-Ing. h. c. Karl Theodor Renius
Agricultural Machines

Prof. Dr.-Ing. habil. Heinzpeter Rühmann
Ergonomics

Prof. Dr.-Ing. Gottfried Sachs
Flight Mechanics

Prof. Dr.-Ing. habil. Dr. h. c. Rudolf Schilling
Hydraulic Machines and Plants

Prof. Dr.-Ing. Karlheinz G. Schmitt-Thomas
Materials in Mechanical Engineering

Prof. Dr.-Ing. habil. Günter H. Schnerr
Gas Dynamics

Prof. Dr.-Ing. habil. Johann Stichlmaier
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Reports of the Institutes
Aerodynamics and Fluid Mechanics

Numerical modeling, simulation and experimental analysis of fluids and fluid flows

The focus of the Institute of Aerodynamics and Fluid Mechanics in 2017-18 continued on further development of a multi-resolution parallel simulation environment for the NANOSHOCK project, on reduced-order modeling of fluid-structure interaction, on the analysis of advanced aerodynamic configurations for helicopter, aircraft and automobiles, and on advanced simulation and gridding technologies for exterior and interior aerodynamics. A new focus has been placed on learning effective evolution equations from data and physical knowledge, in cooperation with George Karniadakis who received the Humboldt research award in 2018.

A highlight in 2017-18 was the publication of a paper on bubble-collapse-driven penetration of biomaterial-surrogate liquid-liquid interfaces by Shucheng Pan, Stefan Adami, Xiangyu Hu and Nikolaus Adams, which was made the ‘editor’s choice’ of Phys. Rev. Fluids. Nikolaus Adams was appointed as consultant professor and faculty member of the Northwestern Polytechnical University in Xi’an. Updates on the NANOSHOCK open-source code development are available for the scientific community: www.aer.mw.tum.de/abteilungen/nanoshock/news

Experimental Investigation of Shock-induced Droplet Break-up and Numerical Simulation of Collapsing Clouds of Vapor Bubbles

Motivation and Objectives

1) Shock-induced droplet break-up
The break-up of liquid droplets and fluid ligaments in a gaseous ambience is a key element of atomization processes. In combustion engines, the quality of the spray inside the combustion chamber has a large impact on the combustion efficiency and also on size and composition of particles in the exhaust gas. Furthermore, droplet break-up can play an important role in the production of metal powders as used for additive manufacturing. In this case, liquid metal atomization needs to be controlled in order to optimize the quality of the resulting powder. Our objective is to gain insight into break-up mechanisms by investigation of Newtonian and non-Newtonian liquid drops exposed to shock waves generated by a shock tube.

2) Collapsing clouds of vapor bubbles
It is well known that the collapse of vapor bubbles in a pressurized liquid can lead to intense pressure waves with amplitudes of several GPa. The formation of those bubbles can be on purpose, such as in biomedical applications and food engineering, or inevitable, such as in control valves of injection systems [1], rocket engines and in the vicinity of ship propellers. Since the release of potential energy during the collapse of a bubble can be highly focused, it may be used to destroy cancer cells. On the other hand, if clusters of bubbles collapse close to a material surface, severe damage of mechanical devices can be a consequence [2]. Our objectives are to develop and improve numerical techniques for prediction of vapor bubble collapses and to improve understanding of bubble-bubble interaction in collapsing vapor bubble clouds. Furthermore, experimental investigations are performed by exposing bubbles trapped in gelatin to shock waves generated by a shock tube [3-4].

Approach to Solution
We develop and improve mathematical models and highly efficient numerical approaches for simulation of compressible multi-phase flows, especially physically consistent LES (large eddy simulation) codes. The codes are capable of high performance computations on supercomputers, such as SuperMUC at the Leibniz-Rechenzentrum München. The figure above shows collapsed and partially rebounded bubbles, together with a vapor pattern located at a solid surface. The colors indicate shock waves due to prior collapse processes. In this investigation [5], the effects of bubble interaction on intensification of material loads were characterized. It was possible to demonstrate that rebounding vapor patterns can be as erosive as the primary collapse of a bubble cloud.

The shock tube at the institute was recently equipped with a droplet generator in order to investigate shock-induced droplet break-up processes. State-of-the-art high speed cameras/sensors allow for high-quality data acquisition. The following figure shows two time series of break-up processes. In both cases, the bubble is hit by a planar shock wave from left.
Our research is funded by the European Union (project ‘CaFE’ and project ‘UCOM’), the European Space Agency, the German Research Foundation (DFG), and by partners from the automotive industry.

**Key Results**


**NANOSHOCK* – Manufacturing Shock Interactions for Innovative Nanoscale Processes**

We want to investigate the potential of shockwaves for in-situ control of fluid processes with surgical precision. Shockwaves are discontinuities in the macroscopic fluid state that can lead to extreme temperatures, pressures and concentrations of energy. Applications of such shock interactions range from kidney-stone lithotripsy and drug delivery, to advanced aircraft design. With the use of properly focused shockwaves on tissue material, e.g. lesions with unprecedented surgical precision can be generated. Alternatively, improving combustion by enhanced mixing of fuels, shockwave interactions can help to further destabilize and atomize spray droplets.

* This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No 667463).
Our overall objective is to understand and predict the formation and control of shocks in complex environments, such as living organisms, using computational methods.

**Approach to Solution**

We develop best-in-class numerical methods with unprecedented accuracy and stability. The highly complex dynamics of shock-driven multiphase flows require very efficient numerical algorithms to handle the required mesh resolution. We have developed the simulation framework ALPACA that uses multiresolution techniques to compress the numerical grid without loss of accuracy. We use MPI-parallelization to perform efficient simulations on modern HPC architectures using large resolutions to capture all details at phase interfaces and flow discontinuities. With the new level-of-detail available in numerical simulations, we can better understand the underlying physics of complex multi-scale interactions. As a new feature, we now also support 3D visualization at the 5-sided projection installation at LRZ. ALPACA is open-source and available to the public on request, see http://nanoshock.org or more information.

**Key results**

- Droplet breakup as multi-scale computing challenge, S. Adami, N.A. Adams, invited talk at IUTAM Symposium on Dynamics and Stability of Fluid Interfaces, 2018
- Open-source version of ALPACA available to interested users

**Aircraft and Helicopter Aerodynamics**

**Motivation and Objectives**

The long-term research agenda is dedicated to the continued improvement of flow simulation and analysis capabilities enhancing the efficiency of aircraft and helicopter configurations with respect to the Flightpath 2050 objectives. Aircraft aerodynamics research is aimed at detailing flow physics understanding of leading-edge vortex evolution (DFG) and vortex interaction effects (DFG) along with diamond wing aerodynamics and turbulence model conditioning (VitAM, LuFo V-3). Analysis of fluid-structure-interaction effects and aeroelasticity is linked to elasto-flexible lifting surface characteristics (DFG), flutter suppression techniques (FLEXOP, EU) and neuro-fuzzy based reduced order models addressing buffeting and buzz (DFG). Investigations on transport aircraft wings is dedicated to wake vortex alleviation and dynamic lift increase (BIMOD, LuFo V-3). The research work in the field of propeller and helicopter aerodynamics is related to propeller flow analysis at strong inhomogeneous inflow conditions (HyProp, BFS), propeller optimization strategies (AURAIS, Bay. LuFo) and full fairing rotor head design optimization of the RACER configuration (FURADO, CSky2). Further, 3D-printed advanced pressure probes including novel unsteady pressure sensors are under development (ZIM).

**Approach to Solution**

The investigations are conducted using both wind tunnel experiments and state-of-the art numerical simulations. In-house codes are continuously further elaborated in the context of aeroelasticity analysis with respect to time-accurate, fully-coupled simulations as well as the application of novel neuro-fuzzy based reduced order models.
Aerodynamics and Fluid Mechanics

Key Results


Reduced Order Modeling for Automotive Aerodynamics

The recent improvement of high-performance computing hardware has enabled the utilization of unsteady computational fluid dynamics (CFD) for industrial product development. Unsteady CFD can accurately simulate the transient phenomena of the flow field, moreover, highly accurate steady-state results can also be obtained through appropriate averaging. Especially in the field of automotive aerodynamics, the transient flow phenomena around the vehicle can strongly affect driving stability and ride comfort. A difficulty in the analysis of the transient flow field by CFD is that the time series of flow field data typically needs to be saved to disk during and after a simulation. This often requires massive storage space, as the transient flow field data around a vehicle is spatially highly resolved to capture complex flow structures consisting of various time and length scales. One possible solution to reduce the total amount of data is to approximate a transient flow field in reduced order. Proper orthogonal decomposition (POD) is a well-known data-driven modal analysis method that is often used for reduced-order modeling of the flow field. Especially the on-the-fly algorithm of POD, such as incremental proper orthogonal decomposition.
Aerodynamics and Fluid Mechanics

(IPOD) or incremental singular value decomposition, requires much less RAM and disk space, since it updates modes incrementally when new snapshot data is available. As an example, the IPOD modes are computed from the simulated transient flow field around the DrivAer notchback model. The numerical simulation is validated with the wind tunnel experiment (figure above). The computed IPOD modes successfully approximate the complex transient flow field around the vehicle with respect to both transient characteristics and instantaneous flow structures (figure below). Furthermore, this unsteady flow field data approximated in reduced order can be processed by dynamic mode decomposition (DMD) to extract the dominant transient flow structures. Consequently, the amount of transient flow field data is reduced to 11% of the original size with the setups presented. This IPOD computation occupies roughly 80% less memory than the conventional POD algorithm.

A snapshot of the instantaneous vertical velocity on the x-z-plane at y=0.2m from the reconstructed field (above) and the original field (below).

Publications


Numerical Investigation of Homogeneous Cavitation Nucleation in a Microchannel

Motivation and Objectives

Liquid and gas (or vapor) two-phase flows are widely encountered in many chemical, biological, and engineering applications; here bubble cloud dynamics are of fundamental importance. Examples reach from ultrasonic cleaning through medical therapy applications to bacteria disinfection processes. In such flows, bubble nucleation, initializing liquid-to-vapor transition, can be categorized into heterogeneous and homogeneous nucleation. These differ with respect to where nucleation occurs. The former emerges from surfaces in contact with two liquids, the latter relies on impurities in the bulk liquid and thus is more difficult to localize and detect in experiments.

Numerical simulation of homogeneous nucleation in comparison with the experimental results.
Aerodynamics and Fluid Mechanics

Approach to Solution
We investigate numerically homogeneous nucleation in a microchannel induced by shock reflection to gain a better understanding of the mechanism of homogeneous nucleation. The liquid expands due to the reflected shock and homogeneous cavitation nuclei are generated. An Eulerian-Lagrangian approach is employed for modeling this process in a micro-channel.

Motivation
Blunt bodies returning from space are subject to immense heat loads leading to ablation. Roughness on these ablating surfaces can induce laminar-turbulent transition in an otherwise laminar flow. Laminar-turbulent transition increases the heat load on the surface. Roughness is an enhancing effect on laminar-turbulent transition and the effect of roughness including dissociation and non-equilibrium effects is the focal point of the studies.

Approach to Solution
Direct numerical simulations (DNS) including hundreds of millions of points are conducted on national HPC facilities such as SuperMUC and HLRS. The results are compared in international cooperation with theoretical and experimental results from universities and research establishments worldwide.

Key Results

Laminar-turbulent Transition with Chemical (Non-)Equilibrium in Hypersonic Boundary-Layer Flows

Integration domain on a re-entry capsule

Vortical structures and breakdown downstream of a roughness patch for re-entry condition

Key Results
The Institute of Aerodynamics and Fluidmechanics has the speaker role within the DFG-SFB TRR40. Next-generation space transportation systems will be based on rocket propulsion systems which deliver the best compromise between development and production cost and performance. The TRR40 focuses on liquid rocket propulsion systems and their integration into the space transportation system.

Critical, thermally and mechanically highly loaded components of such space transportation systems are the combustion chamber, the nozzle, the aft body and the cooling of the structure. These components offer the highest potential for the efficiency increase of the entire system. However, all components are in close and direct interaction with each other. Optimization or the fundamentally new design of a single component directly affects all other components.

The 25 projects from TUM, RWTH Aachen, TU Braunschweig and the University of Stuttgart, as well as partners from DLR and AIRBUS D&S, investigate in interdisciplinary experimental and numerical teams. The concepts developed will be tested on sub-scale combustion chambers and will be developed to a stage of applicability. In addition, principal experiments are going to be conducted to demonstrate new technologies developed in the TRR40. The scientific focus of all five research areas within the TRR40 is the analysis and the modeling of coupled systems. Based on reference experiments detailed numerical models are developed which serve as the basis for efficient and reliable predictive simulation tools for design.

Instantaneous snapshots of a nitrogen jet in hydrogen: (a) temperature, (b) vapor fraction on a molar basis, (c) hydrogen density and (d) relative difference in density.
SPH Modeling of Fluid-Structure Interaction

The sequence of results (ordered left to right and top to bottom) shows an SPH simulation of a tethered fish flapping in a stream with a Reynolds number of 1,000. An inextensible rope is connected to the left boundary. The color presents velocity magnitude of the fish body and vorticity in flow.

Motivation and Objectives
Fluid-structure interaction (FSI) can be found in many natural phenomena, such as birds flying and fish swimming. Meanwhile, it also plays a very important role in a wide range of engineering areas, e.g. aeronautical engineering, coastal engineering and biomedical engineering. The essential of FSI is the interaction between movable or deformable structures with internal or surrounding fluid flows.

Approach to Solution
We propose a numerical modeling of FSI (fluid-structure interaction) problems in a unified SPH (smoothed particle hydrodynamics) framework. Rather than being strictly monolithic, the present modeling is the combination of a conventional SPH formulation for fluid motions and a total Lagrangian SPH formulation dealing with the structure dynamics. Since both fluid and solid governing equations are still solved with SPH algorithms, fluid-structure coupling is straightforward and the momentum conservation of an FSI system is strictly satisfied. Furthermore, the application of a Lagrangian kernel eliminates the particle-distribution artifact which exhibits in previous SPH simulation of structure dynamics using the incremental constitutive model. Several tests including pure structure oscillation and FSI benchmark cases have been carried out to validate the present modeling and demonstrate its potential.

Key Results
Aerodynamics and Fluid Mechanics

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- Numerical fluid and flow modeling and simulation
- Complex fluids
- Turbulent and transitional flows
- Aerodynamics of aircraft and automobiles
- Environmental aerodynamics

Competences
- Multi-physics code and particle-based model development
- DrivAer car geometry
- Experimental aerodynamics

Infrastructure
- 3 low-speed wind tunnels and moving belt system
- 2 shock tubes

Courses
- Grundlagen der Fluidmechanik I
- Fluidmechanik II
- Computational Solid and Fluid Dynamics
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- Aerodynamik der Raumfahrzeuge – Wiedereintrittsaerodynamik
- Particle-Simulation Methods for Fluid Dynamics
- Biofluid Mechanics
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- Praktikum Simulation turbulenter Strömungen auf HPC-Systemen
- Praktikum Experimentelle Strömungsmechanik

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Ergonomics

Definition and evaluation of human-machine interaction and anthropometric layout of technical systems. Safety, efficiency of use and user satisfaction.

The focus of the Chair of Ergonomics in 2018 was to further increase the activities in the area of cooperative interaction between human and vehicle or human and robots on a global level. Nationally- and internationally-funded project proposals were successful in continuing the fundamental research at the institute.

The second focus was to intensify the development and research activities on digital human modeling and automated driving. Regarding this, the research in digital human modeling examined research questions about future vehicle concepts. In addition, further funded projects investigated automated driving and its impacts on humans. The driving simulators at the Chair of Ergonomics helped to answer these questions. Within the scope of national and international projects, the interaction of vehicles and pedestrians was examined.

Automated Driving

Fully automated vehicles, which no longer require human input and treat the driver as a passenger, promise to make road traffic safer, more comfortable and simultaneously more flexible. At this highest level of driving automation there is still a need for research from the human factor perspective. The Chair of Ergonomics addresses, for instance, the question of how to design the interior of such autonomous vehicles for the different use cases: ‘people movers’ in public transportation, moving office or relaxing/sleeping area. Factors like motion sickness or workplace layout need to be examined. On the technological roadmap to this highest level of driving automation, we have to pass lower levels of automation. At these levels the driver still has a safety-critical role since he or she must supervise the system (Level 2 according to SAE taxonomy) or must intervene at system limits (SAE level 3). Research at the Chair of Ergonomics focuses here on the design of the human-machine-interface in order to ensure safe and comfortable vehicle guidance taking into account the quickly changing responsibilities between driver and system. At level 2, how the driver can be supported in her or his supervising task needs to be examined. At level 3, research focus on determining factors of a safe transition from automated driving to manual driving. For a holistic human-centered view of automated vehicles the Chair of Ergonomics also addresses the design of external human-machine interfaces. In this context, questions of how automated vehicles should communicate with other road users need to be answered.
Corporate Robot Motion Identity

Mobile robotic systems are increasingly merging into human-dominated areas and therefore will interact and coordinate with pedestrians in private and public spaces. To ease intuitive coordination in human-robot interaction, robots should be able to express intent via motion. This will enable an observer to quickly and confidently infer the robot’s goal to establish productive encounters. For long-term interaction, trajectories in straight drive or curvature have been optimized for this purpose. In addition, short-term movement cues are perceivable changes in motion parameters and direction of movement that can be utilized to express intent in a non-verbal manner. For example, yielding priority to a person via a short back-off movement cue, as opposed to merely a stop, provides the possibility of legible and agreeable robot navigation. In the service design domain, the front-line personnel’s behavior is a crucial quality factor of how an organization is perceived by customers and society. Recent developments show that mobile robotic systems are increasingly supplementing a service company’s front line personnel. Companies such as Starship Technologies™ or Deutsche Post apply service robots for transportation purposes. Integrating robot motion into an organization’s visual identity to communicate the visual cues of what the organization wants to express could contribute to the customer experience. In order to provide movement cues that are not only legible but also convey the inherent personality of the robot carrying out the task and therefore reflect on the organization’s public image, we investigate the aforementioned factors for consideration when developing a corporate robot motion identity. Specifically, in the scenario when a robot should yield priority to humans in front of narrow or unclear sections, such as doors or corners without visibility, back-off movements are able to express intention and allow fluent encounters between participants and robots. Via quantitative (e.g., motion tracking) and qualitative (e.g. co-creation) metrics we infer whether humans understand and learn a robot’s behavior.

Education of Future Teachers

Teacher education at the Chair of Ergonomics includes the following three fields:

The Chair of Ergonomics educates students of teaching for secondary schools who are enrolled in ‘Arbeitslehre’ which represents the school subject ‘Economy and Profession’, former ‘Work, Economy, Technology’. The programme comprises, among other subjects, work-related modules like work science, statistics, occupational and production ergonomics. As career guidance is an integral element of secondary schools, it is also part of the students’ work-related studies and has a high priority in the teacher training. By attending the lecture ‘Introduction to career studies’ and related excursions to different companies, the students gain insights into various professions and their specific requirements. They learn how to assess work-related requirements scientifically and discuss how
Investigating Driving with Visual Impairments – A Collaboration with the Schepens Eye Research Institute in Boston

Individual mobility, especially driving, is a crucial part of everyday activities for most of people and plays a significant role when looking at quality of life. It enables individuals to work, participate in social activities and leisure time events and forms as such, accumulated over all road users, the traffic system itself.

To obtain a driving license, everyone needs to meet the special legal requirements regarding motor, cognitive and visual skills in addition to the mandatory driving lessons in some countries. Especially visual capabilities and their impairment affect driving in a decisive way, as nearly 80 percent of driving-relevant information is provided by the visual system.

Together with Harvard Medical School’s Schepens Eye Research Institute in Boston, the Chair of Ergonomics investigates the influence of different visual disabilities as a major side effect of an aging society on driving safety in urban areas. Under the umbrella of the TUM Global Incentive Fund, PhD students and master students built a mobile driving simulator, which can be linked to a pedestrian simulator. Using this setting, the gaze behavior, driving safety and social interaction between both road users can be analyzed in pedestrian crossing situations.

In two studies, conducted in 2017 and 2018, the researchers focused on the effect of central field loss (study 1) and hemianopia (study 2) on driving performance. Additionally, in study 2 a prototype of a tactile hazard warning system was tested, which was especially developed at TUM for that investigation. First analysis and feedback of the participants’ data show a significant positive effect of the device in terms of reducing the amount of critical situation and collisions.

In addition to the scientific activities, the education of young scientists and students at a high interdisciplinary level was promoted as well as building and establishing their international academic network.

Based on this successful collaboration between the two institutions, a memorandum of understanding was signed which constitutes the formal basis for future joint research activities.
Creativity at Work – a Major Business Factor for Future Work?

The generation of creative ideas and the processes involved were already of interest to ancient poets like Aristotle and great scientific minds like Helmholtz (1821-1894) and Poincaré (1854-1912) (Wallas, 1926). Despite a lack of common understanding of ‘humankind’s ultimate resource’ (Toynbee, 1964) and a definition that remains unsatisfactory (Batey, 2012), the topic is probably more of interest today than ever before. Over the last century work has changed. So much for the obvious. Traditional manual work has seen a rise in productivity throughout the 20th century following the principles of Frederick Winslow Taylor and has been proposed as being responsible for all gains (economical as well as social) of that century. In recent years however, with faster product development cycles, the internet as a motor of change and the increased necessity for companies to foster innovation, a new type of worker has become the focus of scientific attention: the knowledge worker, creative worker, or gold-collar worker. These terms refer to a specific type of worker whose main asset for the company is the acquisition, processing, generation, as well as communication of knowledge (Drucker, 1959).

In light of digitization, Industry 4.0 and artificial intelligence it is reasonable to assume that machines will advance even further and cover additional areas of human expertise, leaving the human worker obsolete but for his/her ability to think creatively and generate novel ideas and knowledge (Prasch & Bengler, 2018). Companies already show an increasing focus on the work environment and new forms of work, including agile frameworks and mobile work. Ergonomic principles and guidelines however have not yet been updated and demand an increasing focus of research to provide a sustainable foundation for optimal system performance and well-being in the context of creative work (Dul et al., 2006).

- A. Toynbee, ‘Is America neglecting her creative minority?’, Widening Horizons Creat., pp. 3-9, 1964

New projects

@City – Automated Cars and Intelligent Traffic in the City

The project @City funded by the Federal Ministry for Economic Affairs and Energy started in September 2017 and will run for four years. The project consortium consists of nine German partners. The Technical University of Munich, represented by the Chair of Ergonomics and the Chair of Transport Technology, is the only research institute alongside numerous automobile manufacturers and suppliers. Since in the recent past a research focus has been on automated driving on motorways, the focus of the project @City is now on automated driving in urban areas. Due to the complexity of urban traffic areas, cities set some special challenges for use cases in the automated driving context. Various roundabouts and crossings, the diversity of road users like pedestrians or cyclists and hidden traffic signs complicate the situation understanding compared with a well-structured environment like motorways. As automated vehicles and intelligent traffic are the key elements for safe, efficient and stress-free future traffic, the overall goal of the project @City is to enable automated driving in urban areas. The Chair of Ergonomics aims to enhance the interaction between vehicle and driver or rather between vehicle and vulnerable road users like pedestrians and cyclists. To achieve these goals, the @City consortium developed a specification methodology in the first year of operation. This specification methodology represents an exchange format, which can describe possible automated driving scenarios and relevant information for the stakeholders concerned. Parallel to this, two driving simulators have been linked, which will allow future investigations on the interaction strategies and the design of human-machine interfaces in mixed traffic between automated and non-automated vehicles.
@City-AF – Automated Cars and Intelligent Traffic in the City – Automated Driving Functions

In July 2018, the project @City-AF started with a runtime of four years based on the project @City. @City-AF is funded by the Federal Ministry for Economic Affairs and Energy, consists of five additional partners (compared with @City) and represents an extension of the functional development in @City.

While @City examines HMI concepts and interaction strategies in pilot applications, @City-AF focuses on designing an optimal interaction of an automated vehicle with its drivers/passengers and other road users. Automated vehicles should enable drivers and passengers to drive reliably, safely and comfortably in all situations. The interaction between vehicle and driver, but also between vehicle and pedestrians or cyclists, e.g. at intersections and roundabouts, is fundamental for a safe journey and requires a solid understanding of the situation. The developed concepts should be improved iteratively in driving simulators and a pedestrian simulator. Finally, design and standardization recommendations will be derived.

UNICARagil – A Collaborative Research Project Concerning the Mobility of the Future

The UNICARagil project, carried out by a consortium of seven German universities and six industrial partners (duration: 02/2018 -01/2022), aims to make a significant contribution how electric, agile, automated vehicles can be designed, developed and used on the road. Disruptive architectures in hardware and software, as well as disruptive concepts in safety, security and verification determine the traffic situation and give the information to a modular and scalable vehicle platform, which will act automatically in it. Four prototypes representing different use cases (in UNICARagil: taxi, private vehicle, bus shuttle and delivery vehicle) will demonstrate these disruptive concept ideas and will be used for validation (see figure above).

The Chair of Ergonomics (LfE) is responsible for various tasks in the project. On the one hand, it will investigate the human-machine interaction around the vehicle. Solutions will be suggested how a legible and communicative driving trajectory should be implemented, but also which means of communication the user and the vehicles should have. Together with the Institute of Automotive Technology (FTM), the LfE is responsible for the development and construction of the taxi vehicle and has the possibility to design the interior taxi workplace according to ergonomic suggestions. TUM FTM is responsible for the concept and design of the control room, with the Chair of Ergonomics defining ergonomic requirements for this workplace.
Ergonomics

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Research Focus
- Digital human modeling for ergonomic anthropometric workplace layout, products and cars
- Biomechanics modeling of forces and motions
- Investigation and design of human-machine-interaction
- Investigation of concepts for interaction in cooperative systems
- Development of measurement metrics
- Research on motivational aspects of user behavior

Competence
- Interdisciplinary research approach
- Development of evaluation methods, models and implementation of interaction concepts in the areas anthropometry/biomechanics as well as cognitive ergonomics

Infrastructure
- Static driving simulator mockup
- Dynamic driving simulator mockup
- Static driving simulator (360° fov)
- Modular ergonomic mockup (MEPS)
- Remote and head-mounted eye trackers
- Pupil dilation measurement equipment
- VICON motion capturing system
- CAPTIV motion analysis system
- Seating lab
- Seat test dummy
- Driver distraction usability lab
- Climate chamber
- Biomechanical laboratory
- Cardiopulmonary exercise testing
- Pedestrian simulator

Courses
- Ergonomics
- Product Ergonomics
- Production Ergonomics
- Software Ergonomics
- Human reliability
- Ergonomics Practical Course
- RAMIS Practical Course
- Design of Experiments and Statistics
- Motivational User Interfaces and User Experience
- Human Factors of Automated and Cooperative Driving
- Interaction Programming and Protoyping
- Human Factors in Aviation
- Design Thinking Experience
- Cardiopulmonary Exercise Testing in Human Factors
Selected Publications 2018

Bioseparation Engineering

Process development and intensification, particle technology, biofunctional surfaces, adsorption, filtration, and extraction

The Bioseparation Engineering Group deals with different aspects of the isolation and purification of biomolecules for the pharmaceutical or chemical industry. We are focused on adsorption, filtration and extraction as separation methods as well as their integration into the production process. In addition to the experimental approaches we use different simulation tools for process intensification.

We had a very successful year and were pleased to start three new third-party-funded projects. Firstly, the project ‘Rational design of new surface binding peptides’ will be funded by BMBF for another three years in order to demonstrate the transferability of the model system to industrially relevant applications. In addition, we started a new DFG project in which we are developing new materials for antibody purification that can set new standards in production. Another new project deals with the recovery of a valuable product from whey by magnetic separation. The group was involved in the organization of two international conferences. In March, the Industrial Biotechnology Forum took place in Garching, covering topics of the complete process chain in biotechnological production. The 38th International Symposium on the Purification of Proteins, Peptides and Polynucleotides (ISPPP) in Berlin was also organized as a conference chair, bringing together worldwide researchers in this field.

Process Development

In addition to the optimization of classical downstream processes new innovative separation techniques as well as integrated process concepts are subjects being researched. A focus area is the research on high-gradient magnetic separation, potential-controlled chromatography, and membrane assisted extraction.

Projects

- HOBBIT – Development of a sustainable separation process for purifying small protective solutes (BMBF)
- LactoMag – Magnetic separation for purifying target molecules from whey (BMEL)
- SysBioTerp – Innovative strategies for sustainable production of bioactive molecules (BMBF e:Bio initiative)
- S3kapel – Multiscale simulation for electrochemical separation processes (BMBF)

Description of a particle bed using LIGGGHTS (S3kapel; Bernhard Schmid)
Functional Interfaces

In separation sciences the interaction of particulate carriers among each other and to target molecules is essential for process development. Selective interactions as well as high binding capacities of target molecules to solid phases determine the final purity and yield and therefore the quality of the whole separation step. In contrast, uncontrolled aggregation of particles decreases process performance with regard to robustness, reproducibility, and scalability. All these aspects are main focus topics of our projects.

Projects
- Rational design of peptide-surface interactions (BMBF Biotechnology 2020+ initiative)
- Design of new affinity tags for the purification of recombinant proteins

New Stationary Phases

New stationary phases are essential in bioseparation sciences; classical phases are already well developed and are reaching their limits. The Bioseparation Engineering Group is specialized in synthesis and functionalization of magnetic particles and conductive materials as well as their process implementation. Making use of magnetism or conductivity allows for an additional degree of freedom for state-of-the-art process development.

Projects
- Synthesis, functionalization, and characterization of magnetic nanoparticles (BMBF)
- New conductive materials for potential-controlled chromatography (BMBF)
- New non-chromatographic materials for the separation of antibodies (DFG)

Crystallization

Crystallization or recrystallization is one of the major and oldest purification methods in industries and quiet common for small molecules. Thereby, temperature, pH and concentration of components mainly influence the progress of crystallization and at the same time are the parameters to be controlled in industrial processes. The focus of our work is particularly on the direct crystallization from high-salinity fermentation broths and the influence of other media components.

Projects
- HOBBIT – Development of a sustainable separation process for purifying small protective solutes (BMBF)
Bioseparation Engineering

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Research Focus
- Downstream processing
- Bioprocess integration
- High-gradient magnetic separation
- New magnetic or conductive particles
- Optimization of chromatographic processes
- Biomolecule surface interaction
- Extraction
- Crystallization

Competence
- Synthesis and characterization of nano- and microparticles
- Surface functionalization
- Magnetic separation and automation
- Fermentation
- Molecular biology, microbiology, biochemistry
- Simulation with COSMO-RS, COMSOL Multiphysics, Chrom X, OpenFoam, LIGGGHTS and SuperPro Designer

Infrastructure
- S1 labs (working with genetically modified microorganisms – safety level 1)
- Parallel bioreactor system
- High-gradient magnetic separator (HGMS)
- Diverse chromatography- and filtration systems
- Particle-/surface analytics (DLS, BET, RAMAN, TGA-MS, DSC, contact angle, tensiometry, FT-IR)
- Interaction studies (Quartz microbalance, microscale thermophoresis, peptide array scanner)
- Fluorescent microscope
- HPLC systems

Courses
- Bioseparation Engineering I + II
- Biotechnology for Engineers
- Practical Training on Bioprocess Engineering
- Practical Training on Particular Nanotechnology
- Practical Training on Preparative Chromatography
- Simulation Training by ChromX

Peer-reviewed Publications 2018
- Schwaminger SP, Begovic B, Schick L, Jumani NA, Brammen MW, Fraga Garcia P, Berensmeier S: Potential-controlled tensiometry – a tool for understanding wetting and surface properties of conductive powders by electroimbibition, Analytical Chemistry, DOI: 10.1021/acs.analchem.8b03475
- Schwaminger SP, Blank-Shim SA, Scheifele I, Pipich V, Fraga Garcia P, Berensmeier S: Design of interactions between nanomaterials and proteins: A highly affine peptide tag to bare iron oxide nanoparticles for magnetic protein separation, Biotechnology Journal, to be printed, 2018
- Kaveh-Baghbaderani Y, Blank-Shim SA, Koch T, Berensmeier S: Selective release of overexpressed recombinant proteins from E. coli cells facilitates one-step chromatographic purification of peptide-tagged green fluorescent protein variants, Protein Expression and Purification, 152, 155, 2018
- Fraga Garcia P, Kubitut P, Brammen M, Schwaminger S, Berensmeier S: Bare iron oxide nanoparticles for magnetic harvesting of microalgae: from interaction behavior to process realization, Nanomaterials, 8(5), 292, 2018
- Janoschek L, Grozdev L, Berensmeier S: Membrane-assisted extraction of monoterpene: from silico solvent screening towards biotechnological process application, Royal Society Open Science, 5. 172004, 2018
- Schwaminger SP, Blank-Shim SA, Borkowska-Paneik M, Anand P, Fraga Garcia P, Fink K, Wenzel W, Berensmeier S: Experimental characterization and simulation of amino acid and peptide interactions with inorganic materials, Engineering in Life Sciences, 18,84-100, 2018
Wind Energy

Wind energy technology

Mission of TUM Wind Energy Institute (WEI): ‘to educate students and to advance wind energy science and technology towards a fully renewable future energy mix’.

Wind energy is playing a crucial role in the transition away from fossil fuels. The success of wind energy is primarily due to the great progress made in the last decades in understanding the complex physical phenomena that underlie the process of energy conversion from wind, and translating this knowledge into sound technical solutions. Notwithstanding the recent advances, there are still many scientific and technological challenges that need to be overcome, in order to increase the penetration of wind, reduce its cost and mitigate its impacts. To contribute to the achievement of these goals, the Wind Energy Institute at TUM works on basic scientific and application-oriented problems, often in close collaboration with industry. Areas of specific expertise of the institute embrace all main wind-energy-relevant scientific disciplines, including aerodynamics, structures, dynamics, materials, controls, with a strong focus on multi-disciplinarity and a system-engineering point of view. Some of the most exciting on-going projects at the institute are briefly described in the following sections.

Control of Wind Turbines and Wind Farms

Control technology holds much promise for improving the way wind turbines and wind farms are operated, and may contribute significantly to reducing the cost of energy from wind. In fact, as sensors become cheaper and more capable, digital controls can make existing and future assets ‘smarter’, optimizing the way turbine and farms respond to complex inputs and behave in challenging operational scenarios. These are some of the most interesting and pressing scientific questions we are working on:

- How can we improve the way wind turbines are controlled, to increase power capture and/or decrease loading to extend life?
- Can we move away from the greedy control approach used today on board wind turbines, where each turbine is operated individually with little or no consideration of what neighboring machines are doing?
- What can be gained by using cooperative control strategies of wind turbines within a farm? By using

Demonstration of closed-loop wind farm control in a boundary layer wind tunnel. On the left: three TUM-designed G1 wind turbines; on the right: LiDAR visualization of the flow at hub height. Notice how the wakes of the two front wind turbines are deflected laterally, ‘cleaning’ the flow on the two downstream rotor disks.

Study on the potential of control by wake steering for 12 wind turbines in the north of Germany. The front turbines yaw slightly away from the wind, and ‘clean’ the downstream machines by laterally deflecting their wakes. The implementation is based on standard SCADA data and does not necessitate any additional sensors or equipment, therefore also being potentially implementable on existing wind turbines.
cooperative control, can we mitigate wake losses or reduces loading? Does the use of smart cooperative control lead to new ways of designing future wind farms? And, with cooperative control, can we also improve the way existing wind farms operate today?

■ Can we operate wind farms more similarly to what is done for other conventional energy sources, and can this help in the integration of a higher share of wind in the energy grid?

■ What knowledge on wind and the system response is necessary to enable smart control approaches for turbines and farms? And what sensors can provide such information at a low cost, high availability and moderate complexity?

**Current or Recently Completed Projects**

■ EU H2020 project ‘CL-WINDCON – Closed Loop Wind Farm Control’
■ BMWi project CompactWind I ‘Erhöhung des Flächenenergieertrags in Windparks durch avancierte Anlagenauf- und Parkregelung’
■ BMWi project CompactWind II ‘Nachlaufregelung von Offshore-Windparks bei instationären meteorologischen Bedingungen auf Basis von Standardsensorik’
■ Industrial project ‘Wind Farm Control’
■ Industrial project ‘Development and Testing of Scaled Offshore Wind Turbine Models’
■ Industrial Ph.D. ‘LiDAR-Assisted Control of Wind Turbines’

**Wind Sensing Technology**

At present, wind turbines are largely unaware of the wind blowing on their rotor: they are equipped with anemometers and wind vanes installed on the nacelle, which only measure wind speed and direction at that point in space. Therefore, wind turbines are essentially operating in the dark: they have only a very primitive knowledge of the atmospheric conditions, and they ignore whether or not they are shaded by other machines. This lack of awareness clearly hinders the way they are operated.

We are working on changing this situation, developing new technology that can measure the wind conditions at the rotor disk. This is achieved in a radically new way: turning the whole rotor in a large wind sensor, a novel approach that we have termed ‘wind sensing’. By the use of wind turbine response data, as provided by strain gages or accelerometers installed on the blades or the nacelle, wind sensing technology computes in real-time the wind conditions at each machine. In turn, better knowledge of the wind is used for improved operation of each wind turbine or the whole wind farm with smart control strategies.

These are some of the key scientific questions we are working on:

■ What wind characteristics can we measure and with what precision?
■ What is the minimum set of sensors that are necessary for measuring the wind inflow?
■ What use can be made of detailed wind information at the rotor disk?
■ What new control approaches can be developed based on wind sensing technology? How can wind sensing improve the way a wind turbine is controlled? And how does wind sensing enable smart wind farm control methods?

**Current or Recently Completed Projects**

■ BMWi project CompactWind II ‘Nachlaufregelung von Offshore-Windparks bei instationären meteorologischen Bedingungen auf Basis von Standardsensorik’
■ Industrial project ‘Wind Estimation from Rotor Loads’
■ Industrial project ‘Vertical Wind Shear Estimation from Rotor Loads’
■ H2020 ETN Project AWESOME ‘Wind Energy Operation and Maintenance’
■ EU H2020 project ‘CL-WINDCON – Closed Loop Wind Farm Control’

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*Wind sensing technology in action in the field: experimental verification on a wind turbine in the USA, equipped with a met-mast in front of the rotor. The wind direction estimated by wind sensing (red line) is well correlated with the ‘true’ one measured by the instrumented met-mast (black line). The direction measured by the nacelle-mounted wind vane (blue line) is noisier and often in error of several degrees.*
Design of Wind Turbines

The design of wind turbines is an extremely complex multidisciplinary activity. In the design process, one must be able to find the best possible compromises from different and often contrasting requirements. In addition, multiple aspects of the problem have profound and complex couplings, including the aerodynamic and structural designs, the control laws used to govern the machine, and the performance and characteristics of all on-board sub-systems. To address these challenges, we develop automated design procedures implemented in sophisticated software tools, which are capable of performing the integrated aerostructural design of a complete wind turbine. Using these tools, WEI researchers work on answering the following and many other fascinating questions:

■ What are the optimal machine sizes and configurations for a given application?
■ What are the impacts and possible benefits of new technologies, as for example passive and active load alleviation methods? And what are their costs and drawbacks?
■ Are new wind turbine configurations competitive with standard designs and, if so, for which applications? Is there any advantage in downwind, free-yawing machines, pre-aligned rotors, active flaps or in the use of unconventional techniques such as active coning and morphing rotors?

Current or Recently Completed Projects

■ International collaborative project IEA Wind Task 37 ‘Systems Engineering’
■ Industrial Ph.D. project ‘Design of Very Large Lightweight Rotors’
■ Industrial project ‘Uncertainty Quantification for Large Offshore Wind Turbines’
■ TUM-Nanyang Technological University (Singapore) Ph.D. project ‘Bio-Inspired Wind Turbines for Monsoonal Climates’

A novel way of reducing loads on wind turbines: passive flaps installed on the blades move automatically in response to vibrations, without the need for sensors or actuators. Simplicity and robustness is key for demanding applications in the field.
Experimental testing is crucial for verifying and validating the results of all our research efforts, including mathematical models, simulation tools, control strategies or new technologies. Testing in the field on production machines is however very challenging, possibly expensive and often altogether impossible. To address some of the limits of full-scale testing, WEI has developed new technology for scaled model testing in boundary layer wind tunnels. These are some of the most important research questions that WEI researchers are trying to answer:

- Can we replicate in the controlled environment of a wind tunnel some of the key physical aspects of the energy conversion process from wind? How should scaled models be designed in order to match as many of the relevant physical parameters as possible?
- Can we faithfully replicate wake behavior, wake interactions, and complex terrain effects?
- Can we go beyond the matching of purely aerodynamic effects, replicating at scale also the aeroservoelastic behavior of wind turbines?
- Can closed-loop control methods for wind turbines and farms be tested at scale? If so, what do we capture with good precision, and what are the limits of these scaled models with respect to full-scale reality?

Our scaled models are miniaturized wind turbines and, exactly as full-scale machines, they are governed by closed-loop pitch, torque and yaw controllers. Optionally, a super-controller can be used for the collective control of clusters of wind turbine models, enabling the study of wind farm control techniques. Our family of wind turbines includes at present three different sizes: the largest models (termed G2, with a 2 meter rotor diameter) can be optionally equipped with aeroelastically scaled blades, while the smaller ones (G1 and G0.6, of 1 and 0.6 meters of diameter, respectively) are used for modeling wind turbines clusters, studying wake interactions and complex terrain effects. A high-fidelity digital copy of the models and the wind tunnel has been developed by WEI researchers, using state-of-the-art CFD techniques coupled with aeroelastic wind turbine models. The exper-
Experimental results are used to validate the digital models, which in turn are used for studying wakes, turbulent flows within wind farms and wind plant control, as well as for the planning of future experiments.

Experimental activities at WEI are not limited to scaled testing. In fact, within a joint project with the research cluster WindForS (Windenergie-Forschungscluster), we are working on the development of an experimental test site in complex terrain. The test facility, funded by the Federal Ministry for Economic Affairs and located in Baden-Württemberg, will include two highly-instrumented 750 kW wind turbines, as well as extensive instrumentation for the measurement of wind conditions. Once operational, the test site will enable new exciting and unique testing capabilities, paving the way for an improved understanding of wind conditions and the optimization of wind turbines for complex terrain applications.

Current or Recently Completed Projects
- BMWi project ‘WINSENT – Wind Science and Engineering in Complex Terrains’
- EU H2020 project ‘CL-WINDCON – Closed Loop Wind Farm Control’
- BMWi project CompactWind II ‘Nachlaufregelung von Onshore-Windparks bei instationären meteorologischen Bedingungen auf Basis von Standardsensorik’
- Industrial project ‘Wind Farm Control’
- Industrial project ‘Development and Testing of Scaled Offshore Wind Turbine Models’
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Research Foci
■ Modeling and simulation of wind energy systems
■ Multidisciplinary design
■ Aeroservoelasticity, loads and stability
■ Control of wind turbines and wind farms
■ Wind tunnel testing
■ Operation and maintenance

Competence
■ Multibody dynamics, computational mechanics, non-linear finite element methods
■ Model reduction and system identification
■ Design and synthesis of model-based controllers
■ Design and manufacturing of aeroelastically-scaled and actively controlled wind turbine models for wind tunnel testing
■ Data analytics

Infrastructure
■ Scaled wind turbine and farm models
■ Model building lab
■ Computational lab

Courses
■ Introduction to Wind Energy
■ Modeling, Control and Design of Wind Energy Systems
■ Wind Turbine Simulation
■ Wind Turbine Design
■ Wind Tunnel Testing of Wind Turbines
■ Aeroelasticity

Selected Publications
Cyber-Physical Systems in Production Engineering

Designing safe, predictable, and embedded platforms for next generation cyber-physical systems

The Chair of Cyber-Physical Systems in Production Engineering was founded recently in September 2018. Its research activities in 2018 focused on two main topics: predictable high-performance computing with heterogeneous SoC multicore platforms, and design of “real-time software revival” techniques to guarantee the physical safety of a cyber-physical system (CPS) in the presence of cyber attacks. Other research activities are focusing on the secure and safe integration of machine-learning algorithms with digital controllers for CPS and the development of flexible resource management policies for a broad range of CPS systems.

As a new chair, the first few months were dedicated to setting up office spaces, a laboratory, and starting recruitment of scientific researchers. However, this did not slow down the prompt start of our research, teaching, and service activities. In 2018, we have set up one MSc degree course and one PhD seminar on cyber-physical systems.

Prof. Caccamo is on the editorial board of IEEE Transactions on Computers. Members of the chair were involved in the program committees of several international academic conferences in automation and CPS, including ICCPS 2019, RTAS 2019, and DATE 2019.

On the Predictability of Heterogeneous SoC Multicore Platforms

Modern cyber-physical systems (CPS) are composed of several sensors, actuators, and microcontrollers or processors. Usually, they are designed to control and interact with a specific environment, integrating physical dynamics with software and networks. Applications include system automation, the Internet of Things (IoT), smart buildings, smart manufacturing, smart cities, agriculture, robotics, and autonomous vehicles.

For many emerging CPS domains, such as autonomous vehicles, computing platforms have to deal with diverse, often conflicting requirements, as demonstrated in the figure above. Some tasks, such as autonomous steering, fuel injection, and brakes control, are mission-critical and pose hard real-time requirements on the system. Conversely, multimedia infotainment systems demand high performance and are programmed to tolerate large variations in the quality of service (QoS) provided by best-effort operating systems such as Linux. In addition, a third rapidly growing class of time-sensitive applications requires both predictability and performance at the same time. Thus, modeling, designing, and implementing resource-efficient, predictable and safe CPS is not a straightforward task.

In this project, we study how it is possible to leverage latest-generation, partially reconfigurable system-on-
chip (SoC) embedded platforms for a system design that combines high performance and strict real-time requirements. In our approach, we define multiple criticality domains to be intended as sub-shells of the computing system. Each criticality domain is designed with a different trade-off between high performance and strict temporal determinism. For instance, a high-performance domain may run a general-purpose OS with a complex I/O infrastructure. Conversely, a high-criticality domain is comprised of a real-time operating system (RTOS) supporting time-sensitive applications. The figure above demonstrates the proposed hardware architecture to support mixed-criticality applications using the Xilinx ZCU102 Ultrascale+ platform.

In our design, we assign one high-performance core (A53) to Linux to take care of best-effort tasks and reserve the other three cores to execute critical/sensitive tasks on top of an RTOS. Jailhouse hypervisor provides isolation among the cores. Several low-level resource management techniques, such as page coloring and code relocation, are implemented within Jailhouse to enhance the temporal predictability of running applications and avoid contention at several shared hardware components. We use a three-phase task execution model, in which a DMA engine transfers data from the main memory (DRAM) to the scratchpad (SPM) before a task is executed by the RTOS. The SPM avoids memory contention in the shared DRAM.

Finally, we propose a new schedulability test for event-based real-time tasks using variable TDMA slot sizes for the DMA transfers. We compare the proposed test against an ideal test and existing related work on schedulability tests. The proposed test together with the hardware/software architecture is able to deliver better CPU utilization, while meeting real-time guarantees of time-critical CPS applications.

**Schedulability Tests Comparison – CPU 2**

Comparison of the proposed schedulability test.
Preserving Physical Safety under Cyber Attacks

Some of the recent attacks on cyber-physical systems (CPS) were focused on causing physical damage to the plant. Such intruders make their way into the system using cyber exploits but then initiate actions that can destabilize and even damage the underlying (physical) systems. The trend towards the adoption of remote monitoring and control (often via the internet) of modern cyber-physical systems only further aggravates the safety-related security problems in current and next generation CPS. Many techniques to enhance system security focus on preventing the software platform from being compromised at all times or detecting the malicious behavior as soon as possible and taking recovery actions. Unfortunately, there are often unforeseen vulnerabilities that enable intruders to bypass the security mechanisms and gain administrative access to the controllers.

In this project, we leverage physical properties of the controlled plant (e.g., like inertia in mechanical systems) to guarantee the safety of a controlled plant despite the fact that the control software might be subject to external cyber attacks; in fact, an adversary cannot destabilize or compromise a plant instantaneously (even with complete control over the software). It often takes finite, even considerable time to do that. Hence, we aim to develop analytical methods that can formally guarantee the safety of the physical plant even when the controller unit’s software has been partially (or even entirely) compromised. A key idea is to carry out consecutive evaluations of physical safety conditions inside secure execution intervals. Those intervals should be separated in time such that an attacker with full control will not have enough time to destabilize or crash the physical plant in between two consecutive secure intervals. We refer to these intervals as secure execution intervals (SEIs). In this research work, the time between consecutive SEIs is calculated dynamically in real time, based on the mathematical model of the physical plant and its current state. The key insight for providing formal safety guarantees is to make sure that each SEI takes place before an attacker can cause any physical damage.

We utilize two different approaches to create a trusted execution environment for SEIs where the integrity of the executed code can be trusted. Those approaches are based on 1) restart-based implementation which utilizes full system restarts with software reloads and 2) TEE-based implementation which utilizes trusted execution environment (TEE), such as ARM TrustZone or Intel Trusted Execution Technology (TXT) that are available on some hardware platforms.

The software architecture implements two digital controllers: 1) the base controller (called also safety controller), and 2) the mission controller. The safety (base) controller guarantees safety and it is periodically executed within each SEI, but the mission controller is required to run the controlled system and make progress toward a certain mission goal.
In practice, the proposed software framework implements a good trade-off between safety and performance, i.e. providing guaranteed protection and good performance at the same time. Some experimental results on a 3 degree-of-freedom helicopter and a simulated warehouse temperature management unit show that the proposed techniques are robust against multiple emulated attacks – essentially the attackers are not able to compromise the safety of the CPS. Under extreme attack, e.g. abnormal full control input with maximal capacity or sudden shut down of the controller, the system did not make any progress towards its designated goal, but still remained safe which is the primary goal in this situation. Meanwhile, when attacks did not exist, the high availability of the mission controller ensured significant progress toward the control goal. In our experiments, the average availability of the mission controller for the 3 degree-of-freedom helicopter reached 85.1% while for the simulated warehouse temperature management unit, the average availability was 99.1%.
Cyber-Physical Systems in Production Engineering

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Research Focus
- Safety-critical cyber-physical systems
- Real-time systems
- Scheduling and schedulability analysis
- Secure and safe integration of machine learning with CPS

Competences
- System-level programming
- Embedded system software design
- Hardware and software integration on FPGAs
- Real-time operating systems
- Real-time reachability analysis

Infrastructure
- 3 DOF Helicopter
- Embedded and FPGAs multicore development platforms

Lectures
- Advanced Seminar on Safe Cyber-Physical Systems
- PhD Seminar on Real-Time Cyber-Physical Systems

Selected Publications 2018
- F. Abdi, C.-Y. Chen, M. Hasan, S. Liu, S. Mohan and M. Caccamo, “Preserving Physical Safety Under Cyber Attacks”, IEEE Internet of Things Journal, Accepted, 2018
The focus of the Chair of Carbon Composites in 2018-19 was to establish and strengthen its research program within the three research groups. The main goal was to explore new ways and possibilities to reduce process cycle time and raw material costs to be able to implement high-performance composite structures. At the beginning of the year, we presented our ultrasonic mixing technology with live demonstrations at the JEC exhibition. The opening of our additive technology lab in 2018 will provide the foundation for future development within composite processing. It summarizes our activities in fiber placement and 3D printing. We are proud to contribute to the cluster of additive technologies at TUM.

The biggest change in 2018 is that Dr. Ladstätter, long-term right hand of Prof. Drechsler, moved on back to her home country. The successes of the institute in the past years did strongly depend on her. We wish her all the best for her future way and hope for many joint projects.

Process Technology

SAMPE Innovation Prize 2018
The innovation prizes of the Germany Section of the Society for the Advancement of Material and Process Engineering (SAMPE Deutschland e.V.) were awarded at the 23rd national SAMPE symposium at TU Kaiserslautern from 28.2.-01.03.2018. Both of this year’s prestigious awards went to students from the Chair of Carbon Composites (LCC): Dominik Boos and Stephan Maidl.

Dominik Boos was honored for his Master’s thesis which he conducted at LCC on the topic of ‘Conception, design and experimental investigation of integral fiber composite joints for the application in shape-adaptive wing structures’. In his thesis, a production process for EPDM-prepreg, which enables the production of shape-adaptive aerospace components, was developed. His work on integral fiber composite joints contributed significantly to the success of the FlexMat project funded by the German Federal Ministry for Economic Affairs and Energy. The project was carried out at LCC in cooperation with Invent GmbH and the German Aerospace Center in Braunschweig (DLR).

Stephan Maidl was awarded the prize for his Master’s thesis, which he conducted within the framework of an ERASMUS+ exchange program between the TUM Department of Mechanical Engineering and the Department of Aeronautics at Imperial College London (ICL). He carried out the research under the joint supervision of Professor Paul Robinson (ICL) and LCC. In his work ‘Investigating the use of friction to achieve ductility in composites’, Mr. Maidl transferred the internal structure of the biomaterial nacre (German: Perlmutt) to carbon fiber reinforced plastics. Nacre consists mainly of brittle but – in the world of biomaterials – strong mineral aragonite. Due to its internal structure, nacre is highly ductile without sacrificing much of the strength of aragonite. Hence, this innovative development represents a major contribution to the future realization of composite materials, which are strong and ductile at the same time.

It is a great pleasure for the chair that both of the students will continue their academic career at LCC as research associates.

Additive Manufacturing Lab
The Chair of Carbon Composites further expanded its capacities for additive manufacturing – also known as 3D printing – last year. In addition to high-temperature printers from Apium, printers from Markforged and Anisoprint are now also available. Not only can all thermoplastic polymers available on the market be processed, but they can also be reinforced with continuous or short glass and carbon fibers. The new process capabilities are complemented by new testing equipment, including a new differential calorimeter that can represent the temperature...
gradients in the process, a polarizing microscope to show
the induced interlayer crystal structure, and 3D profilers
and scanners for macro- and microscopic dimensional
stability studies.
In addition to the new capacity, new projects will be
added, such as the Clean Sky 2 project COMBO3D, which
will complement the competencies of the chair in addition
to the process technology in the simulation. The project
will produce additive tools for composite manufacturing
in aviation. Thus, well-established functional integration
improves established processes with regard to their cycle
time, energy consumption and running costs.

In order to print tools for aircraft parts, the chair
will continue to develop its capabilities next year.
On the one hand, six-axis industrial robots push
ahead into new component dimensions, and on
the other hand, the new degrees of freedom in 3D
printing can be used to design and manufacture
load path-compliant systems, as the chair has
already shown in previous EU projects with its auto-
mated fiber placement systems.
Through the combination of local, continuous fiber
reinforcement and classic 3D printing, rigidities can be set
within a component and weak points compensated.
These state-of-the-art manufacturing processes not only
enable more efficient and lighter components, but also
tool and waste-free manufacturing for the aerospace
industry. In order to further increase the cost-efficiency
of these technologies, work is also under way to reduce
the tolerance requirements for semi-finished products by
active regulations or to completely avoid the semi-finished
products.
With the newly built capacities in 3D printing and auto-
mated fiber placement, the chair has laid a solid founda-
tion to support the industry as a development partner for
the most innovative lightweight construction technologies
and to strengthen German development sites.

In Situ Consolidation for Complex Parts
Since 2012 the TUM Chair of Carbon Composites (LCC)
has been researching the thermoplastic automated fiber
placement (TP-AFP) process with the focus on in situ
consolidation. The chair is using a laser-assisted AFP
system from AFPT GmbH. It enables out-of-autoclave
manufacture which saves process time and costs.
However, requiring all process parameters to stay exactly
within their tolerance during lay-up.
The main process parameters are compaction pressure as
well as heating and cooling of the tapes. These param-
eters are mostly constant during tape winding of tubes
and during lay-up of 2D surfaces and can be adjusted by
the machines closed-loop control for these steady-state
processes. However,
most automotive or
aerospace parts are
three dimensional and
show sections with
convex and concave
curvature. The process
boundary conditions are
changing at these sec-
tions (see figure). As the
tool geometry changes
the laser characteristics
on the tape are also
changing. Therefore, the resulting process temperature needs to be adjusted online during lay-up of 3D parts. Only then, overheating and thus material degradation or insufficient heating and thus insufficient consolidation can be avoided.

LCC and AFPT have been investigating the lay-up on strongly convex part geometries in the publicly-funded project ‘Accurat3’ within the AIF ZIM funding scheme. Using a process simulation developed in house, the thermal behavior of the material due to laser heating was examined. A finite-difference simulation was established considering the exact heat transfer of the laser including the first order reflection as well as heat conduction within the laminate and tooling and heat convection to the ambience with respect to the movement of the AFP placement head. Experiments to validate the simulation were conducted on the chair’s TP-AFP machine. Mechanical peel tests of specimens proved that a 3D lay-up of complex geometries with in situ consolidation by laser assisted TP-AFP is possible.

Thermal simulation of the 3D lay-up

Thermoplastic CFRP-Module for a Sounding Rocket with Integrated Fiber Optic Sensors

The Chair of Carbon Composites (LCC) has developed and implemented a manufacturing concept for a carbon fiber reinforced module of a sounding rocket in cooperation with the German Aerospace Center (DLR). The CFRP-module was qualified for flight as part of a REXUS sounding rocket mission and is now ready for the postponed launch in March 2019.

To increase the performance of the rockets LCC has developed and implemented a manufacturing concept for a thermoplastic CFRP-module with integrated fiber optic sensors as an alternative to the existing aluminum modules.

A module consists of a thin cylindrical shell with bulky load input rings on both ends as bolting interface to the neighboring structures. The rings were manufactured by press-forming of long fiber thermoplastic material (LFT), the shell structure by thermoplastic automated fiber placement (TP-AFP). TP-AFP allows an in situ consolidation of the shell on the previously manufactured rings without additional adhesive, mechanical fasteners or a subsequent autoclave consolidation. Polyetheretherketone (PEEK) was used as matrix polymer due to the high mechanical and thermal loads. Mechanical tests were performed on coupon-, subcomponent- and full-scale-level at room- and service-temperature. Capsuled fiber Bragg grating (FBG) sensors were integrated in the TP-AFP laminate during manufacturing at different positions. A measurement system was installed inside the module to operate the sensors and handle the data. This will allow temperature measurements within the laminate during flight.

The CFRP-module with integrated sensors and measurement system is part of REXUS mission 23 with a scheduled launch window mid-March 2019 in Kiruna, Sweden.

The project was funded by the Federal Ministry for Economic Affairs and Energy and partly funded by the REXUS mission. REXUS is realized as a bilateral agreement between DLR and the Swedish National Space Board and gives universities all over Europe the opportunity to perform experiments on sounding rockets.

Simulation

The ‘Simulation’ research group is dedicated to the integration of a virtual composites simulation platform from preforming, infiltration and cure up to structural analysis. One of the numerous achievements in 2018 was the finalization of a virtual simulation platform to address the effect of out-of-plane ply undulations on the load bearing behavior of laminated composites. It establishes a work bench to sample knock-down factors for stiffness and strength of laminates featuring relevant manufacturing effects.

Forming and Flow Process Simulation

This team deals with the simulation of composite manufacturing processes in terms of forming technologies like draping, braiding and automated fiber placement as well as infiltration methods.

Over the last year, the team focused on draping simulation activities in the field of material characterization, simulation and validation. Material models have been developed and calibrated for various materials and process conditions. For example, models of the stamping process of dry textiles have been developed in ABAQUS (Dassault Simulia) to study defect formation during the preforming.
step. The simulation results are compared to experimental trials on a hemisphere subcomponent in order to validate the distribution of fiber orientation and the out-of-plane wrinkling deformation. The forming simulation is a helpful tool to improve the process quality. Since the whole forming process is modeled, it is possible to adapt process parameters to reduce the forming-induced defects, increasing the quality of the final component. A dedicated testing rig with sequential blankholder was developed at the institute to study the improvement of local and variable resistant force on the overall deformation in the preforming process. The blankholder is divided into 23 sections with a force adjustable between 5N and 60N. Due to the high amount of parameters, experimental optimization is hardly possible. In our team, we developed optimization algorithms to deal with this amount of variables. Compared to blankholder forces homogeneously distributed, it is possible to improve the forming results significantly: the wrinkles are reduced and the overall shear deformation is kept below critical values. In our team, we developed optimization algorithms to deal with this amount of variables. Compared to blankholder forces homogeneously distributed, it is possible to improve the forming results significantly: the wrinkles are reduced and the overall shear deformation is kept below critical values. Modelling effort is also put on the understanding of textile deformation mechanisms. Numerical models of dry textiles have been developed to study their mechanical behavior virtually. To that end, the simulation reproduces the fibrous mat at the scale of filaments. The production process of the textile is modeled to generate a virtual ‘as-manufactured’ geometry. This can be subsequently used in a virtual characterization procedure to investigate the mechanical behavior. For example, it is possible to study the influence of production parameters on the deformability of warp-knitted fabrics. With a better understanding of the textile deformation, it is possible to select the most suitable textile for a given component geometry.

**Compaction, Curing and Consolidation Simulation**

The Focus of activities within the ‘Compaction, Curing and Consolidation Simulation’ research team is the development, characterization and industrialization of process models for all cure-related phenomena in order to predict the laminate’s final quality in terms of e.g. degree of cure, porosity or residual stress and deformation. In the EU Project TRANSITION, the goal is to predict the laminate quality of parts produced with modern autoclave prepreg systems. Laminate quality is predicted by a process simulation of compaction and curing during the autoclave cycle. The applied hyper-viscoelastic material model is able to calculate the compaction response of the prepreg material. It allows for an analysis of the squeezing and bleeding flow during compaction and also the cure kinetics of the resin is implemented in the model. Porosity of manufactured prepreg parts is analyzed via CT-scans and micro sections. The distribution and size of the voids is correlated with the processing conditions in the autoclave to validate previously developed models and finally be able to predict the porosity content in the component.

In the EU Project ProTHiC a process simulation and tool compensation methodology for high temperature composites processes is planned to be developed. Within this project, LCC is responsible for the compaction simulation of dry fiber material in the RTM tool and for developing a concurrent tool-design process which includes process simulation in the early design phase. Preliminary material tests disclose that dry carbon fiber fabrics show viscoelastic behavior under compaction. A first implementation of a compaction model has been conducted in the finite element analysis (FEA) software platform ANSYS.

**Material Modeling and Structural Analysis**

The Material Modeling and Structural Analysis research team focuses on the structural analysis and modelling of the deformation and damage mechanisms in fiber-reinforced plastics at different length scales. The research focus of this team in the last year was on the development of a virtual test bench to characterize the load bearing behavior of laminates with the out-of-plane ply waviness and localized wrinkles. In this study, initially the methodologies were developed for the fabrication of
Carbon Composites

Composite plates with controlled out-of-plane waviness and localized wrinkling or folding of a ply. Coupons extracted from these plates have been mechanically tested under static tension and compression loading scenarios and the results will be used for the validation of the virtual test bench. The fabrication methods have proven to be robust and results were reproducible. In the example shown above the wrinkle is introduced in a ply in the center of the laminate. After laying up the dry fabrics as an L-shaped profile and activating the binder, the through-thickness progression of a ply waviness has been realized by bending back the dry laminate into a flat configuration. For this kind of defect configuration the amplitude of ply waviness increases from the bottommost to the topmost ply. Currently the virtual test bench is capable of quick and automatic creation of finite element models of coupons featuring a graded waviness. The test bench is implemented using the Python-based application programming interface (API) in the FEA software platform ABAQUS (Dassault Systèmes). In the undisturbed laminate initially the 90° crack due to inter fiber failure, whereas in the laminate with waviness, there is an earlier occurrence of damage onset driven by mode I (opening) delamination between the topmost plies. In the laminate with waviness, damage of the bottommost plies initiates the final failure, as these plies feature the least waviness.

Material Behavior and Testing

The project CraCpit (acronym for Crash Cockpit) was initiated in 2018. It is a Federal Aviation Research Programme (LuFo) project funded by the Federal Ministry for Economic Affairs and Energy (BMWi) and will be carried out in close cooperation with the Academic Flight Group Munich (Akaflieg) over a four-year period. Besides that it will contain a loose exchange of project relevant information with a similar project in Hanover, that is also taking place in the scope of LuFo. CraCpit will aim at enhancing the safety of light-weight planes: LCC’s main role in the project will be to characterize fibre materials that are going to be used in the manufacture of a sailplane fuselage. After evaluating those material values the simultaneous development of a numerical LS-Dyna Finite Element model will follow in order to enable the project partners to validate a fuselage crash test in a loadcase derived from sailplane accident analyses.

Furthermore the Group for Material Behaviour and Testing was able to purchase an Atos system from GOM GmbH for the investigation of additive manufacturing processes via digital image correlation. This optical system will provide yet another innovative approach to unify the characterization of additive manufactured material systems within the framework of the TUM Cluster for Additive Manufacturing.
Research Focus
- Process technology for fibers and textiles
- Process technology for matrix systems
- Simulation
- Material behavior and testing

Competence
LCC takes an interdisciplinary approach to research, extending from raw materials through implementation of manufacturing technologies to complete composite components. With specially developed simulation methods, the composite manufacturing process chain can be represented virtually.

Infrastructure
- Composite technical lab ‘Preforming and Thermoset Injection Technology’
- Composite technical lab ‘Thermoplastic Technology’
- Composite test lab
- Computing cluster
- Additive manufacturing lab

Courses
- Materials and Process Technologies for Carbon Composites
- Composite Materials and Structure-property Relationship
- Analysis and Design of Composite Structures
- Production Technologies for Composite Parts
- Process Simulation and Material Modeling of Composites
- Multifunctional Polymer-based Composites
- Carbon and Graphite – High Performance Materials for Key Industries
- Supply Chain and Value Creation Composites

Selected Publications 2018
Materials Handling, Material Flow, Logistics

Basic and applied research in logistics engineering

The Chair for Materials Handling, Material Flow and Logistics (fml) perceives itself as an open research institution aiming to contribute to scientific progress in the areas of material flow technology and logistics engineering.

Rapid changes in information technology and increasing computing power offer new possibilities for automation. Today’s highly automated manufacturing requires agile material flow systems. Within logistics, which is characterized by increasingly complex structures and processes as well as shorter reaction times, self-controlling, intelligent systems are therefore becoming more and more important. The main challenges for these intelligent vehicles are the ability to drive in- and outdoors, face different weather conditions, understand the environment, generate data, information and knowledge from it and be able to communicate with the environment and other vehicles. Therefore, the institute develops approaches, methods and models to point out how to implement autonomous transport systems in existing structures in- and outdoors as well as how these systems can understand their environment and link the data and information received in a logistics setting.

Innovative Conveyor Technology

The increasing level of automation and autonomy in many logistic processes includes handling pallets, trolleys and other containers in both storage and production environments. As tugger trains play an important role in supplying production lines with all kinds of containers, the development of automation strategies for tugger trains is a major part of present research. Within this context, an innovative trailer concept has been developed. The trailer is able to automatically load and unload all kinds of common large load carriers by using a telescopic fork and an integrated hoisting mechanism. All processes are automatically controlled by the trailer’s control unit. Hence, no manual action is required. Sensors account for correct load carrier position and for monitoring all drives, with makes the new trailer both flexible and efficient. A first trailer prototype is in use in the institute’s research area and is also the subject of further research and development, e.g. within the areas of automation and human machine interaction.

Projects

- Autonome Transportsysteme auf dem Werksgelände (BMW.TUM)
- Autonomer Routenzug mit verschiedenen Anhängerkonzepten
- Entwicklung von Energieeffizienzklassen für Regalbediengeräte (IGF)
- PräVISION – Methodenentwicklung zur präventiven Steigerung der Arbeitssicherheit an Flurförderzeugen mit Umsetzung eines Assistenzsystems durch Fusion und Analyse von 2D- und 3D-Bilddaten (DGUV)
- Semantische Umgebungsmodelle für autonome Transportsysteme (BMW.TUM)
- Teilautomatische Palettenaufnahme als Fahrerassistenzsystem für Flurförderzeuge (Jungheinrich)
Humans in Logistics

Technologies, such as robotics, big data, artificial intelligence and the Internet of Things are changing today’s logistics processes. These technologies contribute to the digitalization in logistics and drive the transition towards smart factories. However, not only technical challenges have to be met for this change, also humans are decisive for a successful transformation. Workers and their skills are still of great relevance for the effective use of new technologies. Despite increasing automation, experts agree that humans will continue to play a central role in logistics, but their activities will change fundamentally. Therefore, qualification strategies including systematic competence management will become significant. For this reason, the research project ‘Employment Profile for Future Logistics’ develops a procedure for the qualitative and quantitative determination of employee competences. With the help of the project, necessary competences for the digital transformation are identified and purposeful personnel development is supported.

Projects
- Employment Profile for Future Logistics (MAN.TUM)
- ValidKomm – Kommissionierarmband zur Validierung von Picking-Prozessen (IGF)

Innovative Supply Chain

Intralogistics systems are the basis for internal material flows and value creation in production and distribution companies. Therefore, a high availability of these systems is crucial. Intelligent strategies are needed to reduce the severe capital commitment for warehousing of necessary spare parts.

The research project ETKoop designs an innovative supply chain through spare parts management across corporate boundaries. In the project a digital cooperation platform based on dynamic pooling is developed and implemented. It is the linkage between spare part suppliers, consuming companies and intralogistics systems. Decentralized spare part inventories of cooperating companies are combined to form one virtual inventory. The reduced inventory level necessary and where to store which spare part are identified with analytical and simulation-based methods to ensure the availability of spare parts, reduce downtimes and thus increase system readiness. The development of an economical concept and process design enhances the efficiency of cooperating companies in spare parts management.
The growing demand for increased flexibility and throughput capacity of automated warehouses is driving the implementation of automated vehicle storage and retrieval system (AVSRS). In these systems, shuttle- and lift-vehicles are used to store small unit loads in order to supply picking or production areas based on the goods-to-person principle. However, throughput capacity of AVSRS can be further increased by using multiple shuttle-vehicles on each level of an aisle and multiple lift-vehicles in each shaft (AVSRS with multiple servers).

As part of the research project 'Optimal Configuration of Multi-Server Shuttle-Systems (OptiMUSS)' at the chair fml, operating strategies are designed to enable robust and efficient control of AVSRS with multiple servers. A subsequent integration of these strategies into a parametrizable simulation tool allows the analysis and evaluation of different configurations of this high-performance version of AVSRS in the planning phase.
Crane Engineering and Design of Load-supporting Structures

Research in the fields of crane engineering and design of load-supporting structures has a long tradition at the chair fml. Important topics of research are both the realization of user-oriented control systems to simplify crane operation and the development of new calculation methods for lattice boom mobile cranes and loader cranes. These cranes are tall, slender structures with acute-angled suspensions. In industrial practice the stress calculation of lattice boom mobile cranes and loader cranes follows quasi-static calculations according to the valid European standards. Investigation of the cranes using dynamic finite element calculations has shown that their dynamic behaviour is described only approximately by the current calculation standards. In order to avoid time consuming dynamic finite element calculations and to overcome the lacks of the quasi-static approach according to the standards, new vibration models are developed. They enable the generation of quasi-static loads, which characterize the dynamic effects with a very high accuracy. Further research activities are concerned with the integration of the crane drives (hydraulic system) into the dynamic models. These developments are expected to increase the accuracy of calculation significantly.

Projects

- Abbildung der dynamischen Beanspruchungen von Fahrzeugkranen und Lkw-Ladekranen in quasistatischen Berechnungen (DFG)
- Dynamic Structure-preserving Analysis and Control of Flexible Long Boom Manipulator Based on Port-Hamiltonian System (DFG-NSFC)
- Intuitives Laststeuerungskonzept – Entwicklung eines intuitiven Steuerungskonzept für Lasthebemaschinen (IGF)
- MARS – Methodik zur praxisgerechten Auslegung des Rad-Schiene-Systems von Regalbediengeräten
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Courses
- CAD and Machine Drawing I+II
- Materials Handling and Material Flow Technology
- Planning of Technical Logistics Systems
- Machine System Technology
- Material Flow and Logistics
- Logistics in the Automotive Industry
- Ropeway Technology
- Conveying of Bulk Goods
- Planning of Intralogistics Systems in an International Context

Publications 2018

Research Focus
- Innovative conveyor technology
- Sustainable logistics systems
- Planning and control of material flow systems
- Industry 4.0
- Humans in logistics
- Construction logistics
- Crane engineering and design of load-supporting structures

Competence
- Logistics planning
- RFID systems
- Virtual and augmented reality
- Real-time location systems
- FEM and MKS
- Simulation of logistics systems

Infrastracture
- Augmented reality picking zone
- Automatic small parts storage system
- Electric monorail
- Industrial robot
- Kardex shuttle XP 700
- Mechanic workshop
- RFID testing equipment
- Testing facility for high-performance screw conveyors
- Virtual reality laboratory

Materials Handling, Material Flow, Logistics

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Mechanics and High Performance Computing

Parallel algorithms and high performance computing in computational continuum mechanics

Research activities of the Mechanics and High Performance Computing Group in 2018 covered a range of topics in computational modeling and algorithm development in the area of multifield phenomena, highly efficient parallel solution methods, model reduction, inverse analysis and uncertainty quantification. Applications focused on mechanical models of the heart and the circulatory system, the mechanobiology of atherosclerosis and abdominal aortic aneurysms and lately on the integration and optimization of control algorithms with large-scale nonlinear computational models.

Parametric Model Order Reduction with Application to Problems in Biomechanics

Model Order Reduction (MOR) is a technique under current research, which aims at a decrease in computational effort in large scale problems. We apply MOR techniques to finite element mechanical analysis of patient specific models of abdominal aortic aneurysms. The goal is to enable large numbers of model evaluations at different parametric configurations.

The framework under development shall be able to perform dimensional reduction as well as a so-called hyper-reduction of the abdominal aortic aneurysm models. While dimensional reduction aims at a decrease in the number of degrees of freedom, hyper-reduction aims at an efficient evaluation of the model nonlinearity.

Parameter Identification and Uncertainty Quantification in Cardiovascular Mechanics

Personalized computational models in cardiovascular mechanics as a predictive simulation tool represent a promising approach for diagnosis and decision making in clinical practice. Such models, however, require precise knowledge about the individual geometry, boundary conditions and material parameters, making it practically impossible to specify a deterministic simulation model on a patient-specific basis. Thus, our approach is to incorporate the available information into the model in a probabilistic manner, i.e. by taking into account the uncertainties in the model specification. This knowledge often stems from noisy measurements on input parameters or is based on statistics from a parameter identification problem.

We are working on the development and application of efficient UQ strategies for large-scale forward and inverse problems that are able to represent uncertainties in personalized simulations and quantify their effects on the quantities of interest.
In Silico Endovascular Repair of Abdominal Aortic Aneurysms

Endovascular aneurysm repair (EVAR) is a well-established technique to prevent rupture of abdominal aortic aneurysms (AAA). In this technology, a stent-graft (SG) is deployed inside the AAA to exclude the aneurysm sac from the main blood flow. However, EVAR involves some unfavorable complications such as endoleaks or SG migration. Such complications, resulting from incorrect placement of the SG or incompatibility of SG design and AAA geometry, are difficult to predict.

We aim at developing a predictive tool for the selection and sizing process of SGs depending on the patient-specific AAA geometry. A further objective of the predictive tool is a better risk assessment of the intervention indicating potential SG-related complications already in the preoperative planning phase. The predictive, numerical tool based on finite element analysis requires the combination of various complex simulation components, such as contact mechanics between AAA and SG, mechano-

In silico assessment of the quality of seal after endovascular aneurysm repair

Stenteplasty biology of AAA, morphing strategies for the positioning of the SG and material modeling of the superelastic behavior of nitinol.

Functional Modeling of the Heart

Due to the decreasing number of transplantable hearts and deficiencies in current heart assist device technologies, novel concepts of extravascular heart assistance are developed in close collaboration between AdjuCor GmbH and MHPC.

The collaboration aims at minimizing vulnerable impact to the heart and optimizing design and functionality of a novel device by use of computational models. Therefore, computational models of the heart, the vascular system and a novel epicardial augmentation device are developed and their interplay computed on patient-specific cardiovascular conditions in order to predict the increase in heart work required to maintain vascular perfusion. Furthermore, models of oxygen transport and ventricular disease progression after myocardial infarction should help to gain further insights into the specific device operating parameters required to sustain cardiac regeneration.
**Solid Mechanics Modeling using Peridynamics Discretizations**

The aim of this project is to tackle the challenges of large and potentially discontinuous deformations as well as complex, evolving geometries in solid mechanics problems. Peridynamics, a non-local continuum theory introduced by S. Silling in 2000, has been identified as a promising strategy to achieve said objectives. In contrast to classical continuum theories, in which infinitesimal material points interact exclusively with their immediate neighbours, non-local continuum theories admit interactions of material points over finite distances. In this sense, the theory of peridynamics can be viewed as a generalisation of the classical model. Discontinuities in solution fields of a peridynamic model may arise naturally since its governing equations are derivative-free integral equations. Moreover, the governing equations’ integral structure allows for the construction of a mesh-free, Lagrangian discretization scheme which is expected to function well, particularly in large deformation scenarios.

**Fully Automatic Segmentation of Large Vessel Geometries using Machine Learning Methods**

Image segmentation is the process of subdividing a digital image into its constituent components or regions. In the context of medical imaging, this process is used to extract and delineate the boundaries of specific anatomical features (e.g. organs, cancerous lesions, etc.) from various scan types, including MRIs and CT scans. The manual, human-guided segmentation of abdominal aortic aneurysms (AAAs) from CT scans suffers from two key limitations: (1) it is a subjective process whose outcome depends on the person performing the segmentation, and (2) it is very laborious, with a single AAA segmentation demanding 2 to 6 hours, depending on experience level. To address these shortcomings, we are applying convolutional neural networks (CNNs) as a means of automating the segmentation task. Automated CNN-based segmentation of AAAs obviates the exertion and imperfect discretion plaguing manual segmentation. Moreover, CNNs, a form of deep neural network, have been applied very successfully to other medical segmentation tasks, e.g. detection of cancerous lesions and identification of internal organs.

**Analysis of Shape Variability of Abdominal Aortic Aneurysms**

An abdominal aortic aneurysm (AAA) is a local dilation of the abdominal aorta, leading to shapes often threatened by rupture. In clinical practice, the classification between stable and rupture-prone AAAs is done according to one geometrical feature, i.e. the maximum diameter, a criterion that is well established, but proven to be not sufficiently accurate for rupture risk prediction. This project aims therefore at evaluating the rupture risk based on the whole patient-specific AAA abluminal surface.
A Multiscale Model of Atherosclerosis

A multidisciplinary approach to the mechanobiology of atherosclerosis is taken that is based on computational techniques and experimental calibration and verification as well as in- and ex-vivo molecular imaging. The biological processes involved take place at the (sub-)cellular length scale and will be assessed experimentally by histology by our project partners from Klinikum rechts der Isar. Based on the imaged 3D geometries, macroscopic computational fluid-solid interaction models with transport, diffusion and interaction of species and cells supply an understanding of the local mechanical conditions which can then be correlated to the biological findings. A computational mesoscopic biological model will be implemented which will be coupled to the macroscopic continuum representation of the region of interest in a multiscale in time and space framework. Imaging of several stenoses in mice as well as carefully designed in vitro experiments are applied to test the hypotheses of the model, calibrate its behavior and evaluate its predictive capabilities.

Multi Objective/Field Optimization of an Extravascular Assist Device (VAD)

Faster rescue chains and especially improved clinical diagnostics and therapies have reduced the number of lethal heart infarcts. More patients survive but suffer from resulting heart insufficiency. At the same time, heart transplantations are limited to the amount of donor organs, which declined during the past decade. A promising technology are efficient cardiac assist devices. However, the wide range of patient individual requirements makes it challenging to design an appropriate device. Together with AdjuCor GmbH, we are developing a 0D model of the driving unit of a novel VAD and couple it to a 3D patient-specific heart model. This allows us to iteratively optimize device and implant in order to meet the individual patient needs.
Mechanics and High Performance Computing

Selected Publications 2018

Peer-Reviewed

Non-Peer Reviewed
- Hemmler, A.; Franz T.; Bezuidenhout, D.; Gee, M.W.: In Silico Endovascular Repair of Patient-Specific Abdominal Aortic Aneurysms, University of Pretoria, South Africa, November 15, 2018
- Hemmler, A.; Lutz, B.; Reeps, C.; Kalender, G.; Gee, M.W.: In Silico Endovascular Repair of Patient-Specific Abdominal Aortic Aneurysms, Biomedical Engineering Seminar, University of Cape Town, South Africa, October, 9 2018
- Hemmler, A.; Lutz, B.; Reeps, C.; Kalender, G.; Gee, M.W.: In Silico Endovascular Repair of Patient-Specific Abdominal Aortic Aneurysms, 7th Conference on Systems Biology of Mammalian Cells, Bremen Germany, July 4-6, 2018
- Gee, M.W.; Hemmler, A., Lutz, B., Reeps, C.: The Potential of Computational Simulating EVAR, Seminar, Cardiovascular Medicine & Engineering, Odense Hospital, 2.2.2018
Non-Destructive Testing

Quality control, non-destructive testing and structural health monitoring

The focus of the Chair of Non-Destructive Testing in the field of mechanical engineering in 2018 was to establish NDT methods for the inspection of fiber reinforced materials (CFRP and GFRP) together with partners in the automotive and aeronautic industry.

Further research is being conducted in the field of wind energy: structural-health-monitoring of tower and basement and non-destructive testing of rotor blades. In civil engineering, the focus was on inspection techniques for infrastructure constructions and for the detection of vertical cracks in concrete pavements of highways (solving the blow-up problem). In addition, several projects in the field of cultural heritage have been conducted in close cooperation with the Deutsches Museum.

Multiscale Modeling of the Degradation Progress in the Localised Fracture Zone of Carbon Fiber Reinforced High-performance Concrete Subjected to High-cycle Tension and Flexural Tension Fatigue Loading

As a part of the DFG priority program ‘Cyclic deterioration of High-Performance Concrete in an experimental virtual lab’, the study will address the degradation process in carbon fiber reinforced concrete. Part of this work is non-destructive damage detection and deterioration monitoring during laboratory experiments. Ultrasound measurements revealed the precise p- and s-wave velocity of the material and therefore the elastic parameters could be determined. The corresponding wavefield is given in fig. a) above. In addition, three-point bending tests were conducted on specimens with the dimensions 60 x 13 x 3 mm. Acoustic emission measurements monitor the experiments and therefore crack evolution within the specimen. The acoustic emission pattern is given in fig. b) above.

Fast Impact Echo Scanner

Aging infrastructure is a major topic of interest that also applies to road networks. For targeted maintenance and repair measures NDT tools to characterize the current state of structural elements are highly desirable. Concrete pavements approaching the end of their service life can suffer from damage not visible on the surface but potentially affecting safety and serviceability. Such damage includes horizontal cracks or delaminations within the pavement structure due to heat induced stress or detrimental chemical influences for example. Although several non-destructive testing methods can be applied to concrete pavements most of the conventional techniques like ultrasound or ground penetrating radar have drawbacks in imaging the above mentioned defects. On the other hand, testing methods based on the propagation of elastic waves have high sensitivity to flaws like delaminations and have potential to
be applied to concrete pavements in an automated manner. This project focuses on developing an acoustic scanning method to image relevant damage inside concrete pavements. The approach aims to develop a new acquisition strategy for the so-called impact-echo method. Primary goals are the development of sensing systems based on microphone arrays specifically tailored to the demands of concrete pavement testing. Further, acquisition strategies and hardware aspects for testing entire road sections will be examined. The project was financed by the Federal Highway Research Institute (BAST) under the authority of the Federal Ministry of Transport and Digital Infrastructure (BMVI). Subsequent funding is being provided by the German Federation of Industrial Research Associations (AiF) within the framework of a ZIM project.

Non-Destructive Testing of Adhesive Joints in Electric Motors

To optimize the manufacturing process and increase the efficiency of permanent synchronous motors, a new adhesive for fixing permanent magnets is developed. This project aims at supporting the development of the adhesive. Therefore, various non-destructive testing methods, e.g., computed tomography, ultrasonic testing, and thermography are used to observe the microstructural behavior of the adhesive under realistic thermal, mechanical, and chemical loads. Furthermore, the experimental results are used to set up a non-destructive test bench to evaluate the quality of the adhesive joints inside the electric motor. This project is funded by AiF in the framework of a ZIM project.

Non-Destructive Testing of Fiber Reinforced Composites

Fiber-reinforced polymeric materials are used for lightweight constructions and are an integral part of cars, airplanes, or rotor blades of wind turbines. Nondestructive testing (NDT) methods play an increasing role concerning the manufacturing process and the inspection during lifetime. The selection of the best NDT technique for a certain application depends—of course—on many factors including the type, position, and size of the defect to be detected but also on secondary issues like accessibility, automation, testing costs, reliability, and resolution to mention only some. For this reason, the Chair of Non-Destructive Testing is working on the development of numerous NDT techniques, including full matrix capture of ultrasound in reflection (phased-array), optical lock-in thermography, air-coupled ultrasound, Lamb wave propagation, and local acoustic resonance spectroscopy. Novel sensing techniques, e.g., using an ‘optical microphone’ based on the Fabry-Perot interferometer technique (see figure above) are qualified for industrial air-coupled ultrasound inspections. In order to complete the picture of the processes during testing, numerical simulations using the finite element method are conducted alongside experimental work.
Non-Destructive Testing

Structural Health Monitoring of Wind Turbines: MISTRALWIND-Project

Within the next few years, many established wind turbines are going to reach the end of their nominal service life, which is 20 years. Maintaining and operating structural parts of wind turbines beyond their nominal service life makes sense from an economical and technical point of view. To reach this goal, a concept for inspection and monitoring of structural parts of wind turbines was developed in cooperation with IABG, Siemens, Max Bögl Wind AG, as well as the Chair of Structural Analysis and the Chair of Materials Science and Testing of the Technical University of Munich. The work of the Institute of Non-Destructive Testing was focused on developing a long-term monitoring system and short-term non-destructive testing techniques for tower and foundation of onshore wind turbines. Both techniques were successfully applied to a full size 3 MW wind turbine. The results were combined and serve to evaluate loads and the actual state of the structure. With the aid of the acquired data, maintenance and servicing costs shall be optimized. Beyond that evaluated data was employed as a basis for an extension of the service life of wind turbines and for the development of a control strategy that considers the remaining service life. The project was funded by the Federal Ministry for Economic Affairs and Energy (BMWi).

Data from Robot-supported Computed Tomography Evaluated by Neural Networks

Non-destructive inspection based on computed tomography is traditionally applicable to smaller parts and sections only. Newly developed techniques in the automotive industry are qualifying CT scanning techniques using autonomous robot-based scanners in through-transmission. The terabyte of CT data per car and many terabyte per year for such inspections demand automated evaluation approaches. One of the applications that are developed together with an industrial partner is the detection and characterization of possible defects and/or anomalies, which formed during common joining processes. A standard riveting process was investigated with respect to the resulting final head height of steel self-piercing half-hollow rivets. In order to automatically evaluate the reconstructed volumes, which contained several of the aforementioned rivets, the performance of different, publicly available, convolutional neural network (CNN) architectures was compared. The results obtained suggest that an automated evaluation of the generated computed tomography scans, with regard to a rivet's final head height, is feasible.
Non-Destructive Testing

Research Focus
- Material testing using non-destructive techniques in mechanical and civil engineering, automotive, aeronautics, bio engineering
- Development and improvement of NDT techniques
- Structural health monitoring
- Sensor characterization and sensor combinations

Competence
- Inspection techniques: ultrasound, RADAR, infrared thermography, micro waves, eddy current; video endoscopy, radiography, high speed camera
- Monitoring techniques: acoustic-emission, vibration techniques (laser vibrometry), modal analysis, wired and wireless monitoring
- Simulation of non-destructive testing methods

Infrastructure
- NDT laboratory with contemporary NDT equipment, sensors and cameras
- Calibration facilities, modeling tools
- 14 different mechanical testing machines, microscopes

Courses
- Material Science II (Munich School of Engineering)
- Non-destructive Testing in Civil Engineering
- Applications in Non-destructive Testing in Mechanical Engineering
- Measurement and Sensor Technologies (Munich School of Engineering)
- University Internship: Non-Destructive Testing for Engineers
- NDT Seminar

Selected Publications 2018
Turbomachinery and Flight Propulsion

Aerodynamic and structural development, simulation and experimental investigation of innovative and novel turbomachinery systems and components

Research activities at the Institute of Turbomachinery and Flight Propulsion (Lehrstuhl für Turbomaschinen und Flugantriebe, LTF) cover topics in the fields of flight propulsion, gas turbines and thermal turbomachinery. The institute focuses on advanced enhancements of turbomachinery components applied in the field of flight propulsion and energy systems. As a centre of excellence for compression system aerodynamic and structural innovation the institute owns world-class compressor test facilities used along with extensive numerical modelling to take technology to the next level.

Since its re-structuring and re-establishment in June 2016 the institute has been re-inforced and built up, with respect to both human resources and research work in national/european funding programmes and in industry partnerships. The former Institute of Flight Propulsion (LFA) was established back in 1964, when Prof. Münzberg was appointed head of the chair in downtown Munich. Since its foundation the institute has been dedicated to research and teaching in the field of jet propulsion and gas turbines. The institute is an active member of national research associations, participant in European research projects and long-term partner of leading aero-engine and component manufacturers. A cooperation with GE initiated the development of one of the world’s most advanced high-speed research radial and axial compressor laboratories focused on developing tomorrow’s aircraft engines and gas turbines. As a centre of excellence, the institute collaborates with a number of global-player industry partners, such as General Electric, MTU Aero Engines, Rolls Royce, Airbus Helicopters and Siemens. In accordance with the research strategy of the institute four main areas of research are pursued: Turbomachinery Aerodynamics, Propulsor Technologies, Advanced Engine Component Design-and-Make Concepts, and Gas Turbine Systems and Cycles. These are addressed from both the experimental as well as the numerical perspective, directed towards the analysis of the time-resolved aerodynamic and structural behavior of turbomachinery components in flying and stationary gas turbines environments.

Turbomachinery Aerodynamics

Research is carried out in the field of axial as well as centrifugal turbomachinery in order to explore new areas of the design space, targeted at improvements in compressor stability, the reduction of secondary losses in turbomachinery and the optimisation of loading parameters with respect to a further rise in component efficiencies. Both fundamental as well as applied research is pursued in order to derive novel aerofoil configurations which would allow significant reduction in stage count, weight and cost of turbomachinery. An important role in this respect is taken by innovative flow control concepts, which in the mid-term may eventually involve active control. For the purpose of fundamental experimental flow investigation it is planned to develop and build a new large-scale low-speed compressor rig, which allows detailed flow measurements in a wide range of Reynolds numbers, in particular on high-lift aerofoil configurations and new stage concepts. The envisaged date for commissioning of this FRANCC (Fundamental Research and New Concepts Compressor) facility is
2021. This year, in 2018, a novel facility for axi-centrifugal compressor testing was successfully taken into service and valuable measurements have been taken on this rig. Stability enhancement of compressors is an area of research, which the institute has been pursuing since 2000 with great success and recognition. More than one concept has been developed and matured to be ready for application in tomorrow's turbomachinery.

**Projects**
- Experimental Investigation of Variable Geometry on a Axi-Centrif Compressor (2015-2018, IA)
- Erhöhung der Leistungsdichte zur Reduzierung der Stufenzahl durch Impulsausblasung und Einsaugen (2015-2018, AG Turbo, Cooreflex, Vorhaben 1.1.6)
- Conceptual Design and Build of a Large-Scale Low-Speed Research Compressor Rig (2015-2018, LTF PV)
- Flexible Compressor Off-Design Operability (2017-2020, EU, TurboReflex, WP1)

**Propulsor Technologies**

Driven by the multi-disciplinary nature of designs for future gas turbine-driven as well as electrically-driven propulsors (fans or front rotors of stationary systems), research in this field is focused on novel blade design, which is needed for to further improve propulsive efficiency and reduce noise in ducted and open rotor configurations. Also, the aerodynamic integration with an intake, which in the case of integrated engines also requires consideration of boundary layer ingestion, is a key research topic. In particular in flying turbomachinery applications there is significant and increasingly strong inlet flow distortion present when it comes to novel highly-integrated aircraft-engine designs. Therefore, the response of compression components and whole gas turbine systems to severe flow-field distortion and boundary-layer ingestion is subject to current and future research, carried out on a whole helicopter engine, individual compressor components, or most simply in a wind-tunnel arrangement. In the field of numerical prediction, capability is strongly built up to carry out large-size high-fidelity simulation of the time-dependent unsteady flow in advanced blade row configurations, aimed at future propulsor applications. In the future, research will be also carried out in the associated fields of engine/airframe.
Integration, and novel distributed propulsion concepts. In an ongoing project the nature and impact of pressure and temperature inlet distortion on the performance of a helicopter propulsion system is investigated experimentally. Measurements are taken on a scaled wind tunnel model of the real intake geometry for a matrix of pressure and temperature distortion patterns in order to determine distortion transmission and performance characteristics of the intake. Once these are completed the project can proceed carrying out full engine system distortion tests on one of the LTF helicopter engine test beds.

**Design-and-Make Concepts**

In this main research area of the institute emphasis is put on the use of new enabling technologies in the materials and manufacturing sector, as a measure to enlarge the design space for turbomachinery and to come up with novel solutions in terms of turbomachinery parts or turbomachinery components integration, targeted at savings in weight, cost and build complexity. The availability and further maturing of additive layer manufacturing methods brings along a variety of options for basically unlimited shaping of geometries, which can be exploited when optimising turbomachinery parts with respect to their structural stiffness, vibrational behavior and weight. Associated with these structural conceptual changes an improvement in the aerodynamic behavior may be identified – again, research is required to develop multi-disciplinary approaches and simulations, which allow one to take the opportunities given in this field. An enabler for a step change in aero engine efficiency is the use of heat exchangers for the purpose of inter-cooling and recuperative processes. Research at the institute in this area focuses on the quantification of the benefits and the conceptual design of novel heat exchanger geometries, which allow the required engine architecture to be matched better and the desired reductions in weight and size. In this context, additive manufacturing methods are expected to enable a geometrical optimisation of the aero-thermal design features of heat exchangers. Also, integration of heat exchangers with adjacent components such as compressor stages is being addressed within the scope of the advanced design-and-make concepts research. An evaluation system is being built up, applicable for heat exchanger integration in helicopter gas turbines. In a different area, in the field of advanced seals and air bearings for turbomachinery, detailed investigations have been carried out on a fundamental research rig in order to validate new dynamically working air seals.

**Projects**

- **Contoured Endwall Design in High-Lift Propulsor Blade Row Configurations (2017–2020, LTF PV)**
- **Rotorabwindinteraktionen am Triebwerkseinbau (2016–2019, Lufo V2, CHARME, AP 2.3)**
- **Conceptual Design and Numerical Investigation of Novel Inter-Cooling Heat Exchangers (2017–2020, LTF PV)**
This main area of research at the institute is dedicated to future advanced performance cycles as well as novel overall architectures of gas turbines and aero engines. In this field investigations are carried out with respect to potential improvements of overall engine characteristic parameters, such as fuel burn, weight-to-power ratio, propulsive efficiency and thermal efficiency. As engine architecture and performance are increasingly complex, ‘smart systems’ as well as variable geometries will be essential to allow the high degree of control, which is necessary to operate future engines in a stable and efficient way across the entire flight envelope. Part of current research is concerned with improving the starting time of helicopter engines in order to allow a significant increase in single-engine operation. The quick start system is based on the concept of injecting high momentum air under supersonic conditions into the outer portion of the radial compressor of the engine. It is experimentally investigated and developed on the institute’s Allison 250 testbed. The novel system allowed a reduction in the starting time of the engine from approximately 25 seconds to 2 seconds. With this, a much more advantageous management of the two engines in a helicopter has become available. Currently functionality is improved and the quick start system modules are being further developed with respect to their reliability and future use in the real helicopter environment.

Projects
- Konzeption und Erprobung eines Schnellstartsystems für Hubschraubergasturbinen am Beispiel der Allison 250, Phase 2 (2018-2021, Lufo V-3, Ökoeffizientes Fliegen, Quick Start)
- Flexible kombinierte Optimierung von Leitschaufel, Abdichtung und Rotor (2017-2018, AG Turbo, Flex-Verdi)
**Research Focus**
- Turbomachinery aerodynamics
- Propulsor technologies
- Advanced engine component design-and-make concepts
- Gas turbine systems and cycles

**Competence**
- Fluiddynamic simulation of turbomachinery
- Structural simulation of gas turbine components
- Thermo-structural simulation of gas turbine components
- Axial and centrifugal compressor aerodynamic design
- Unsteady multidisciplinary simulations
- Performance cycle modelling
- Axial and radial compressors testing
- Helicopter engine testing

**Infrastructure**
- Multi-stage axial high-speed research compressor test facility
- Centrifugal high-speed compressor test facility
- Axial blower test facility
- Allison 250 and PW206 helicopter engine test facilities
- Multi-stage axial low-speed research compressor rig (under development)
- 2-stage medium-speed research turbine rig (to be re-built)
- Internal compute cluster
- Shop floor (machining, assembly, purpose-built items)

**Courses**
- Basics of Turbomachinery
- Flight Propulsion 1
- Flight Propulsion 2
- Aerodynamic Design of Turbomachinery
- Fluid Machinery
- Turbomachinery
- Design Aspects on Aero Engines
- Numerical Methods in Turbomachinery
- Measurement and Experimental Techniques
- CFD Hands-on Block Course
- FEM Hands-on Block Course
- Fluid Machinery and Flight Propulsion Laboratory

**Selected Publications 2018**
Space Propulsion

Liquid propellant rocket engine technologies

In 2018 the focus of the Space Propulsion Group was on resonance ignition within the project ‘Technologies for Green In-Space Propulsion’ sponsored by Munich Aerospace, on experimental and numerical investigation of combustion and heat transfer in rocket engines with partial funding from DFG, ARIANE.group, Bayrische Forschungsstiftung, Chinese CSC and TUM.

Technologies for Green In-Space Propulsion

Resonance ignition is a major topic in the project concerning the development of green in-space propulsion technologies. The main advantage of this type of ignition technique is the fact that it does not require any electronic parts to generate the activation energy. In principle it requires a small nozzle to generate a sonic flow which is directed towards a cavity inside which shock waves heat up the gas, see figure 1 which shows a sketch of the working principle.

Experiments have shown that, using helium as driving gas, temperatures up to 1600 K can be achieved. Currently, we are working on an injection system which replaces costly helium with a mixture of the propellants methane and oxygen, see figure 2, and first experimental data show that reliable ignition can be achieved in less than 50 ms.

Combustion Modeling

One of the key challenges in methane/oxygen combustion for rocket engine applications is the need for a reduced chemical kinetic mechanism which is small enough to be included in classical CFD tools but still describes with sufficient precision the progress of the reactions. The major problem is a result of the fuel-rich combustion which is standard for space propulsion and which leads to incomplete combustion and the formation of longer hydrocarbons in low temperature regions in the combustion chamber, i.e. near the injectors and along the combustor walls. Such a mechanism becomes even more important for film cooling applications where, due to low temperatures and mixture ratios, the formation of longer, cyclic and poly-aromatic hydrocarbons and finally soot are the main reactions.

In a first phase we developed a mechanism for typical mixture ratios in a rocket engine omitting the film cooling case. Starting with the classical GRI 3.0 mechanism, which includes 53 species and 325 reactions, a skeletal mechanism was developed using standard sensitivity and reaction path analysis techniques which contains only 22 species and 58 reactions, see figure 3 which shows exemplarily the reaction pathways for a temperature of 1700 K and fuel-rich conditions. As can be clearly seen, from methane methyl radicals are formed which go through ethene or ethyl radicals to form ethylene and ethylene radicals and finally ethyne, a classical precursor of poly-aromatic hydrocarbon and later soot formation. This skeletal mechanism has been validated against experimental data for ignition delay times and
Green Propellant Combination LOX/CH4

The propellant combination of liquid oxygen and gaseous methane is the main focus of a research and technology project combining numerical and experimental investigations funded by BFS and ARIANE.group. During the experimental research work, the existing single and multi-injector setups were redesigned to provide the combustors with liquid oxygen (LOX), see figures 5a, 5b and 5c which show a sketch of the 7-injector combustor and the single injector head reworked for LOX applications. For the experimental part of the project, the test facility at the research campus, see figure 6, will be upgraded with new cryogenic storage tanks, valves and fluid lines for liquid oxygen and in addition some with liquid nitrogen supply will be installed to provide cryogenic fluid for chill-down processes. The ordering process is almost complete, manufacturing and assembly for the first cold-flow tests is currently ongoing. This will allow us to identify and quantify phenomena unique for this propellant combination.

In a further step, various modeling methods are being investigated to improve the predictive capability and reliability of a CFD solver adapted for the specific boundary and operating conditions of rocket thrust chamber simulations.
This solver has been extended with an adiabatic modeling approach incorporating the required complex hydrocarbon chemical kinetic scheme, also taking into account non-equilibrium effects. Together with a new framework to perform conjugate heat transfer simulations as depicted in Figure 7a and b, it enabled new insights into the characteristic operating conditions of the experimentally investigated thrust chamber.

As the operating conditions of rocket thrust chambers are characterized by large temperature gradients at the combustion chamber walls, further efforts are underway to develop a numerical simulation model taking into account these non-adiabatic effects. A new numerical-empirical algorithm has been developed to compute flame solutions for a broad range of enthalpy levels. Based on this new approach, the fluid composition and therefore the heat transfer characteristics can be investigated in more detail in the relevant thermal boundary layer region.

Inverse Heat Transfer for Evaluation of Experimental Data

Within the framework of DFG Transregio 40, an existing inverse method utilized for the evaluation of test data from combustion chambers without an active cooling system was extended to allow for heat flux measurements in regenerative cooled engines. Using the information provided by the thermocouples installed in the hardware and a 1-D model for the heat transfer coefficient in the cooling channels, an inverse optimization was developed, which is able to provide spatially and temporally resolved heat flux profiles. The method has been successfully applied for the evaluation of experimental data of a 7-injector combustor (figure 5a) operated with GOX/GCH4, over a wide operational range. The method allowed for the estimation of heat loads along the azimuthal direction, showing the interaction between the individual injectors. The expected differences between the different operational points, which were also shown in CFD simulations, were measured for the first time. Specifically, it was found that load points with higher oxygen momentum (higher O/F) showed a larger stratification of the azimuthal heat flux profile, see figure 8, as the larger oxygen inertia renders the individual flames more cylindrical and suppresses interaction. On the other hand, low O/Fs have a higher methane velocity, thereby leading to a radial expansion of the shear layer in the coaxial element and a stronger homogeneity in the heat flux solutions. Finally, the higher O/Fs, being closer to stoichiometry, also demonstrated a higher heat flux towards the end of the segment (after 128 mm in figure 8), which is attributed to the higher combustion temperature.

Finally, as figure 9 demonstrates, a satisfying agreement between the CFD and the inverse method is achieved, showing that both the numerical evaluation of the heat flux using the inverse method as well as the CFD prediction capabilities are in accordance with each other.
Figure 8: Azimuthal heat flux for different load points (O/F = 2.6, solid line; O/F = 3.0, dash-dotted line; O/F = 3.4, dashed line)

Figure 9: Axial heat flux profile in the first chamber segment.
Space Propulsion

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Research Focus
Prof. Haidn’s research focuses on rocket propulsion with the main emphasis on technologies for liquid propellant rocket engines: propellant injection, ignition technologies, combustion stability, heat transfer, cooling and life cycle analysis, nozzle flow phenomena, turbopump seals, bearings and lifting and environmentally benign propellants and in particular on dynamic processes. The group aims to establish a strong modeling and simulation group parallel to its experimental activities.

Competence
The publications of the Space Propulsion Group clearly demonstrate the competence of the group in the field of rocket engine technology.

Infrastructure
- High pressure combustion facility (- 100 bar, 1.5 kg/s; O₂/CH₄/kerosene)
- Low pressure combustion facility (- 20 bar, 0.5 kg/s; O₂/CH₄/H₂/kerosene)
- N₂O hybrid rocket engine test facility (- 20 bar, ~1 kg/s; LOX, HTPB)
- Multi-fluid cryogenic flashing test facility (-LOX, LCH₄, LN₂)
- Cryogenic combustion facility (- 20 bar, ~0.5 kg/s; LOX/LCH₄)

Courses
- Raumfahrtantriebe 1 (Grundlagen, SS)
- ZÜ Raumfahrtantriebe 1 (SS)
- Space Propulsion 1 (Fundamentals, WS)
- Exercises (SP 1, WS)
- Selected Topics on Launcher Propulsion (WS, SS)
- Heat Transfer (MSE, SS)
- ZÜ Heat Transfer (MSE, SS)
- Practical Training Raumfahrtantriebe (WS, SS)

Selected Publications 2018
Book Chapters

Journals
- Fuchs, A. Haidn, O.J., Effects of uncertainty and quasi-chaotic geometry on the leakage of brush seals, Journal of Turbomachinery, doi:10.1115/1.4041081, 2018

Invitations to Conferences
Helicopter Technology

Performance, efficiency and safety for rotorcraft

Rotating blades are still worth research efforts – whether for a large helicopter or for an electric VTOL (Vertical Take Off and Landing) aircraft carrying one or two persons. The lack of detailed information about the blades’ aeroelastic behavior in arbitrary flow conditions motivated us to build a rotor test rig, which will allow precise measurements of loads and deformations along the blade radius. eVTOL aircraft are meanwhile attracting increasing public interest – and investor funds – without yet being part of public air transport. But are they eco-efficient, silent, and safe? A federal research fund is supporting a project at the Institute of Helicopter Technology to develop metrics for the ecological footprint of eVTOL configurations.

AREA – Autonomous Rotorcraft for Extreme Altitudes – Update

The joint project of DLR and TUM has the aim to develop an all-electric, autonomous rotorcraft for scientific missions up to altitudes of 9000m. The in-house developed and custom-made prototype is able to vary its rotor speed from 85 to 115% to save power. Important requirements for this prototype were good controllability in gusty winds, a very robust but lightweight structure, as well as a very high overall system efficiency. Since the first flight took place in August 2016, more than 300 test flights have been made, accumulating more than 10 flight hours. During the test flights, the system demonstrated lifting 2.3 times its empty weight, cruising with a minimum system power of 63 W/kg and climbing vertically with 8m/s. A recent important milestone was reached in November 2018 with the first altitude test flights at 2800m above sea level in the Austrian Alps. Forty-one different test flights were performed and confirmed promising high altitude performance, among other things a stable and easy controllable hover with a power-to-weight ratio of only 90 W/kg for the whole system was demonstrated. Next milestones are to demonstrate fully automatic waypoint navigation and automatic, nearly autorotative descend. As soon as technically ready, it is planned to do a high altitude test flight campaign at 5000m in Argentina.
Modelling and Testing of Counter-rotating Coaxial Rotor Systems

Counter-rotating coaxial rotorcraft are still a rare species compared to conventional helicopters that in general use single main and tail rotors. But there are some undisputable advantages like symmetry and its associated ease of flying or high speed potential which make them increasingly attractive. Modelling such rotors is particularly challenging due to the obvious interactions between the adjacent rotor disks. Therefore, model validation based on experimental data is a pre-requisite. For the Institute of Helicopter Technology, two different data sources are accessible. The CoAX 2D, an ultralight (max. 450 kg) two-seater helicopter, was flight tested, modelled and evaluated with a grant from the German Federal Ministry for Economic Affairs and Energy with the aim to better understand the limits of the flight envelope of this type of rotorcraft. Coaxial-rotor configurations are also viable candidates when aiming at high-speed flight regimes. Therefore, the existing cooperation with the University of Texas has been continued under the umbrella of VLRCOE.

A Tailplane Made of Flax, Balsa and Carbon

A tailplane – originally used in an ultralight helicopter – was redesigned with the goal of using bio-based materials in a high proportion. Structural requirements were set to match the performance of the original design made of carbon prepreg material and a foam core. Here, pre-impregnated flax fiber composites in combination with a balsa wood core and a small proportion of carbon fiber reinforcements, were used to design a new tailplane. A finite element model was fed with material data from tensile tests, evolving iteratively from coupon and sub-component bending tests. Finally a 450mm section was built and a biobased mass content of approx. 55% could be achieved.

Benefits of the new design are:
- 2-8 times higher damping ratio
- 65% less embodied energy
- reduced carbon footprint

Besides advantages in structural damping, benefits in crash behavior can be expected. First specimen tests showed promising results. The project is funded by LUFO V2; the associated partners are the Department of Lightweight Structures and Polymer Technology at Chemnitz University of Technology and the Institute for Bioplastics and Biocomposites at the University of Applied Sciences and Arts in Hannover.
Competence
- CFD and free wake simulations of rotor wake and vortex flows
- Dynamic stall modeling
- Coupled rotor-fuselage simulation
- Real-time flight simulation
- Hardware in the loop simulation
- Design and manufacture of composite rotor blades
- Sensor integration in lightweight structures

Infrastructure
- Research helicopter simulator with 6 channels, image, terrain and image databases and head tracking system
- Test rig for blade root structures (lead-lag and flap)
- Optical strain measurement system (fiber Bragg gratings)
- Cluster with 500 cores

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Research Focus
- Interacational aerodynamics
- Aeromechanic rotor modeling
- Nonlinear controls
- Pilot assistance and situational awareness
- Rotorcraft design and sizing

Lectures
- Introduction to Aeronautical Engineering (Rotorcraft)
- Helicopter Flight Physics
- Helicopter Design and Architecture I/II
- Helicopter Systems
- Helicopter Safety and Certification
- Helicopter Flight Dynamics and Control
- Fundamentals of Helicopter Aerodynamics
- Helicopter Aerodynamics – Advanced Topics
- Lightweight Structures
- Smart Structures
- Practical Course IFR Helicopter Flight
- Practical Course Lightweight Structures
- Soft-Skill Seminar Helicopter Engineering: Leadership

Selected Publications 2018
Flight System Dynamics

Making innovations fly in certified products of small and medium-sized aerospace companies

As part of the Technical University of Munich Department of Mechanical Engineering, we are devoted to analyzing and modifying the dynamic characteristics of aerial platforms. Our passionate team is committed to mature cutting-edge technologies that are required to initiate the flight system behavior of tomorrow.

During the last years we have acquired all the experience which is needed along the whole process of making control ideas fly. This includes modeling and system identification, controller design and implementation in real aircraft. Our research areas are presented in the following sections. The research infrastructure includes several flight simulators, test rigs, and manned and unmanned aircraft.

We have established important partnerships and synergies with top research institutions and leading industrial players in the field of aerospace. Our ultimate goal is the development and the application of innovative approaches tailored to real world applications and products, as well as to the demanding challenges of tomorrow.

Flight Guidance and Flight Control

In 2018 the Institute of Flight System Dynamics was able to draw upon and continuously expand its successes from previous years in the area of flight guidance and control. For several years the institute has been operating a Diamond DA42M-NG general aviation aircraft as a demonstrator platform for research purposes.

With the personal commitment of several research assistants of the institute the aircraft was modified according to the special demands for flying and testing modern flight control algorithms. In particular a full fly-by-wire system was design and installed.

In November 2016, an automatic flight was demonstrated successfully, ranging from automatic take-off via waypoint en-route flight to automatic landing. In 2017, an active stick was installed into the DA42 to perform manned flight experiments, including angle of attack limitation and stall protection. Based on this success, additional flight hours were gathered and experience was gained in 2018. Furthermore, the DA42 served as a flying testbed for an innovative navigation system that uses an infrared and visible-light camera to improve navigation accuracy and integrity during automatic landing.

Besides the Diamond DA42 the Institute of Flight System Dynamics has also been involved in the development of flight control systems for additional different types of aircraft. Together with industry partners, an experimental autopilot was developed and integrated into a larger CS-23 aircraft (Do 228). In 2018, the performance of the experimental autopilot was successfully demonstrated during an extensive flight test campaign. The same core auto-flight system was also adopted, integrated and flight-tested for the electrically powered UL-class aircraft ELIAS.
Projects

- Total capability approach to highly accurate and safe guidance applied to an automatic landing system (Phase B, BMWi)
- Development of an autopilot for RPAS with fixed-wing, rotary-wing or hybrid configuration (BMWi)
- Development of the flight control system for an unstable tailless jet (industry)
- Development of innovative adaptive flight control algorithms for non-minimum phase systems (industry)
- Model-based development of a certifiable avionics system for unmanned aerial vehicles of 5kg to 2000kg (industry)
- Development and integration of an autopilot system for a Class IV CS-23 aircraft (industry)
- Development of a full envelope autopilot system for a long-endurance, high-altitude aircraft (LuFo) started in 2016
- Development of a fuel-optimal autothrottle and flight guidance system for CS-23 aircraft (LuFo) started in 2016
- All-electric unmanned reconnaissance and aerial imaging airborne system (BMWi) started in 2017

Sensors, Navigation and Data Fusion

Navigation sensors and systems provide crucial information on aircraft flight states, such as position, velocity and orientation, required for flight state control and flight path guidance. Consequently, the performance of flight state control and hence safety greatly depend on navigation accuracy and integrity. Furthermore, flight safety and mission success depend strongly upon availability, continuity and robustness of navigation.

The navigation research group at the FSD focused in 2018 on the following key enabling technologies:

- Inertial sensor and navigation system test facility for sensor calibration and integrated navigation system testing
- Multi Global Navigation Satellite Systems (GNSS) signal from space and augmentation signal exploitation under nominal conditions
- Platform-autonomous fault-tolerant AD-AHRS, aerodynamic model aided navigation or surface range-imaging in GNSS-degraded and denied environments

Projects

- Multi-GNSS navigation
- Inertial laboratory
- Surface, image and model-aided navigation
- Fault-tolerant ADAHRS
- Sensor driven trajectories

Navigation system integration architectures with graceful degradation capability and professional data fusion algorithms
Transition aircraft

With the fast-growing market in UAS (unmanned aircraft systems), new requirements on aircraft arise. Especially for small unmanned aircraft (aka. drones, the term used by the media), users desire to have plug and play systems. A new requirement is gaining importance: flying without given infrastructure. Imagine your unmanned aircraft stored in a box in the trunk of your car. You simply drive to the operating site, unbox and set up the system and start it right off the meadow in front of you. To do so, your aircraft needs to be capable of vertical take-off and landing (VTOL).

The requirement of VTOL is accomplished quite easy by multicopters. However, those systems only have a short range and endurance. So why not combine the advantage of a multicopter (VTOL capability) with those of a wing-born plane (range and endurance)? A transition aircraft emerges.

Transition aircraft are capable of VTOL and fly wing-born with high efficiency. This offers them a broad range of applications and market. For UAS VTOL systems, the design can differ a lot from classic manned aircraft VTOLs. Electric propulsion and different requirements on redundancy bring out different concepts. So, VTOL UAS are becoming a large area of research.

A major part of this research is occupied by the development and implementation of control algorithms on the quite new vehicle configurations. Besides classical control objectives, such as performance and robustness, the main focus in modern control techniques includes several further aspects. A main aspect is reflected by developing modular, encapsulated and easy-to-adapt control systems for the diversity of existing and futuristic aircraft configurations and maximizing their robustness against unforeseen disturbances and uncertainties – even the loss of one or more control effectors.

For the development of a VTOL UAS in particular a model-based approach is chosen, which simulates a vehicle model online on the flight control computer, in order to compute the real-time forces and moments, as well as their efficiencies on the commands. This enables an optimal distribution of control effector effort and additionally allows the consideration of secondary objectives as minimizing energy and maximizing safety.

It is a long way from the idea of an aircraft to the first prototype being ready for flight testing. This holds true for manned aircraft as well as for unmanned aircraft if the software and hardware is intended to be designed according to processes and standards from manned aviation. There are many steps within the development process, which are necessary to ensure that the implementation of algorithms and the design of the avionic system is done with the required level of rigor while keeping the objectives in mind which establish the confidence that the aircraft can be operated safely. This means that beside the implementation and design tasks, different verification methods, adapted from manned aviation development processes are also used for unmanned aircraft. Beginning from the lowest level of verification, model-in-the-loop simulation gives results on software functions and modules, up to hardware-in-the-loop simulations which incorporate all software modules running on the target system in a closed loop with a high-fidelity simulation model of the real aircraft.
In recent years, the work of the Flight Safety Team at the institute has caught the attention of several international airlines and agencies. Besides the ongoing projects, bilateral cooperations have been strengthened in 2018. Furthermore, Flight Safety Team members have presented their work at several conferences well renowned in the flight safety community.

The Future Sky Safety project is on its way to developing a prototype for a risk observatory of the total aviation system. The main contribution of TUM is to create models describing the flight operations of airlines including the hazards and their contributing factors. The project is currently entering its final year with many exciting results to come.

Another ongoing project is the European Horizon2020 project SafeClouds.eu (www.safeclouds.eu). The project consortium involves five airlines and three air navigation service providers with the goal of improving flight safety through aviation data mining. The institute is managing the descriptive analytics deliverable, which has been successfully completed this year. This year’s consortium meeting was held in November in Palma de Mallorca.

The European Operators Flight Data Monitoring (EOFDM) Forum is a voluntary framework initiated by the European Aviation Safety Agency (EASA) and allows flight data experts to meet and exchange ideas. FSD Flight Safety Team members are active members of the EOFDM working groups and continued to contribute in 2018.

To allow the analytics developed at the institute to be used in the flight safety community in the future, the cooperation with one of the few flight data monitoring software providers has been further intensified in 2018. This year’s focus was on the actual technical implementation for the algorithms as a third-party library in the FDM tool. The experience in flight data analyses gained at the institute raised attention by several European airlines and agencies. As a result, the research group is part of the consortiums of two European Horizon2020 projects directly related to flight data analyses with respect to flight safety. Furthermore, a cooperation with the TUM Statistics Department exists to incorporate advanced statistical concepts into flight data analysis.

**Projects**
- Future Sky Safety: development of a risk observatory for the total aviation system (EU-H2020)
- SafeClouds.eu: Sharing data to make aviation safer (EU-H2020)
- Copula based dependence analysis of functional data for validation and calibration of dynamic aircraft models (DFG)
Trajectory Optimization

The trajectory optimization research group gladly welcomed respected researchers, among them Associate Professor Sébastien Gros from Chalmers University of Technology, who held a well-attended series of lectures on “Reinforcement Learning in Optimal Control”. Furthermore, Professor Joseph Z. Ben-Asher from Technion University returned for a visit under the IC Visiting Professor Program. As in previous years, his lecture was visited by a large, interdisciplinary audience. This year, he covered most recent advances in the solution of the famous Goddard problem, which lecturers have considered for optimal control courses in its original form for many years. The new results extend the analytical solution in cases of singular arcs, which are difficult to handle with conventional tools and provide insight into the optimal control theory at the same time. Prof. Ben-Asher advised various different employees on theirs projects and agreed to spend another sabbatical at TUM in 2019.

The bilevel optimization algorithm for ATM research was extended to an online capability based on discussions with Prof. Ben-Asher and Prof. Gros, who agreed to continue to cooperate on this topic. Within the VaMEx-CoSMiC project, the goal of the trajectory optimization research group was to develop an online trajectory generation module for path-following including obstacle avoidance. Therefore, a custom online optimal control tool has been developed. The algorithm has been implemented and tested onboard a hexacopter and lays the foundation of a new research proposal in 2019.

The skOPTing project, focusing on determining optimal trajectories for ski jumpers, is ongoing. The current development stage is the system identification using optimal control methods. Data were obtained during measurement campaigns in the summer.

A new research project within the scope of the Munich Aerospace Scholarship Program aims at optimizing the atmospheric reentry trajectory of a capsule to minimize heating on or in the vehicle. All projects employ the optimal control tool Falcon.m (www.falcon-m.com), which was developed in house.

Projects

- Robust Dynamic Programming Approach to Aircraft Control Problems with Disturbances (DFG)
- Optimal Control Methods in Ski Jumping (IGSSE)
- Valles Marineris Explorer (VaMEx) – Cooperative Swarm Navigation, Mission and Control (CoSMiC) (DLR)
- Optimierung des Wiedereintritts zur Minimierung der Aufheizung oder der Infrarotsignatur (Munich Aerospace)
Flight System Dynamics

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Research Focus
- Flight guidance and flight control
- Modeling, simulation, parameter estimation and flight safety
- Trajectory optimization
- Avionics and safety-critical systems
- Sensors, navigation and data fusion

Competence
- Simulation of aerospace systems
- Development of GNC functions in accordance with aerospace standards
- Trajectory optimization under application relevant constraints
- Airline operational safety assessment

Infrastructure
- Multiple fixed and rotary wing UAS/ RPAS
- Three flight simulators (from research to level 6 FTDL)
- Two manned research aircraft serving as flying test bed: one of them with active access to flight controls
- HIL test benches

Courses
- Introduction to Flight System Dynamics and Flight Control
- Flight System Dynamics I/II
- Flight Control I/II
- Flight Guidance I/II
- Safety and Certification of Avionics and Flight Control Systems
- Nonlinear Flight Control
- Model Reference Adaptive Control
- Flight Dynamics Challenges of Highly Augmented Configurations I/II
- Aircraft Trajectory Optimization
- Operational Flight Safety
- Navigation and Data Fusion
- MATLAB/Simulink for Computer Aided Engineering
- Flight System Identification and Parameter Estimation
- Fundamentals of Practical Flight Lab
- Flight Guidance Lab
- Flight Testing Lab
- Optimal Control Lab
- Flight Control Systems Lab
- Navigation and Data Fusion

Selected Publications 2018
Aircraft Design

Applied aircraft design for civil aviation and unmanned aerial systems

- System Integration is one of the most challenging engineering tasks in aircraft design and testing. The safe and reliable operation of multiple systems in an aircraft or drone architecture does pose severe challenges to any engineering team, through interfaces, interoperability and interferences between a heterogeneous set of systems utilized. Early identification of integration challenges are key to fast and successful aircraft development processes. With the newly established system integration lab, methods and tools will be established for small to medium-sized aircraft to support this task.

As part of the System Integration Lab the Institute of Aircraft Design has integrated multiple system simulation and testing capabilities into an iron bird test rig, which is interfaced with the virtual environment for the operational assessment of UAVs.

The new system allows for a stepwise integration of hardware and software solutions in an artificial mission performance assessment, also simulating aerodynamic forces and other loads providing operational conditions as realistic as possible.

UAV Iron Bird Test Facility

As part of the system integration lab, the UAV iron bird test facility is a core element to test and demonstrate system integration for novel unmanned aircraft solutions. The iron bird offers a modular environment for stepwise integration and ground-based testing of systems like actuators, power management and energy storage systems, as well as communication and control systems. Equipped with multi-signal acquisition/generation capabilities and mechanical load generation devices, the iron bird provides a realistic environment for the analysis of UAV system behavior under controlled conditions.

The primary objective of this infrastructure is to interlink aircraft design and ground-testing effectively. Novel propulsion/actuation concepts, modern wiring architectures and complex flight control algorithms can be evaluated at an early stage. Test results are processed into reports before they are forwarded to the design team with the aim of increasing confidence in the functionality of the UAV and shortening deployment processes.
MILAN – Morphing Wings for Sailplanes

A concept for a morphing forward section of a sailplane wing is developed in the national LuFo project MILAN. Preliminary studies showed great potential for total aircraft drag decrease of up to 12% compared to conventional designs by adapting the front part of the wing to high-speed and low-speed conditions, i.e. high lift configuration, through morphing and thus mitigating the design compromise for different speeds of a fixed geometry configuration. The shape change from the original high-speed airfoil to the actuated low-speed/high-lift airfoil is accomplished by deforming the wing shell precisely using several spanwise arranged ribs, designed as compliant mechanisms. Aerodynamic design of airfoils and wing planform optimization are performed using numerical optimization methods. Topology optimization is used to generate the geometry of the compliant mechanism ribs. Currently a new topology optimization software environment is under development including finite strain theory, stress constraints and non-linear material models. Several wing shell concepts with anisotropic bending stiffness for the morphing section are studied and tested.

Integrated Design of Multifunctional Flight Control Systems

Recent flight control systems (FCS) of commercial transport aircraft consist of highly optimized flight control surfaces, which are conventionally classified as primary or secondary – depending on their function and criticality. This mainly knowledge-based design with generally mono-functional allocation is often limited to small and local improvements under high effort. Consequently, various research studies present new technologies and concepts for functional enhancement of the FCS to increase aircraft efficiency or performance during certain flight phases.

Therefore, the aircraft design group developed an integrated design approach for advanced FCS with multifunctional flight control devices in early aircraft design phases. The integrated design approach includes the FCS configuration design, the FCS architecture design and the FCS mass estimation, within the framework of conceptual or preliminary aircraft design. For overall system derivation, the configuration design tool, among others, estimates the low and high speed aerodynamics of the aircraft model. The aerodynamic modeling is implemented in an object-oriented programmed MATLAB® tool, using the Athena Vortex Lattice (AVL) program as a ‘black box’ to derive aerodynamic datasets. The figure shows the exemplary results of a transport aircraft with baseline flap setting (left) and with differential flap setting (right). The inboard (IB)/outboard (OB) flaps are set to 30°/30° (baseline) and to 30°/15° (differential) downward deflections. The result of the 30°/15° differential flap setting shows the expected shift in the lift distribution towards the wing root, resulting in a reduction of the wing root bending moment, and thus enables a reduction of the wing’s structural mass.
Future airliner wings will feature increased aspect ratios of the wing in order to lower drag. At the same time the structural weight needs to be further reduced to improve fuel efficiency. Therefore next generation wings are inherently highly flexible and implicate further challenges in aeroelastic design.

The idea of a virtual aircraft model, which allows virtual flight tests to predict aircraft loads and performance is part of the nationally funded LuFo research project VitAM. The combination of structural and aerodynamic models with an application background on highly flexible wing structures to a unified coupled aeroelastic aircraft model is at the core of the research.

High fidelity coupled CSM-CFD methods are used for highly accurate load and aerodynamic drag prediction. Therefore, staggered fluid-structure-interaction methods in combination with a trim algorithm are developed. In addition, dynamic flight maneuvers on a reduced order model are performed to investigate the dynamic behavior of the new wing designs. Within the investigated methods, the number of degrees of freedoms are typically reduced from millions to some hundreds, without loss of the most important dynamic aircraft properties. Modelling of unsteady aerodynamics based on DLM theory as well as CFD-based approaches to provide higher fidelity results are developed. Both results are compared and used to assemble a linear aeroelastic aircraft model for higher aspect ratio wings. The methods are used to investigate wing instabilities due to gusts or flutter around a given flight stage.

The enhanced UAS simulation and evaluation environment developed at the institute allows the aircraft design, payload, communication and other elements of the system to be brought together into one multi-disciplinary design process. This process consists of a preliminary UAS design utilizing mission simulation in the visualized operational environment for mission assessment and mission-based optimization. Integration of these sub tools represents a closed loop UAS design process. In order to design an effective UAS solution by means of the presented environment an initial set of UAS configurations is defined according to the mission demands and design parameters. Further, all configurations are simulated and assessed in the elevation-based visualized operational environment. Thus, key evaluation criteria such as sensor coverage area, extensions to cover, probabilities of objects detection, time of communication losses, obstacles in line of sight and search pattern limitations are obtained as results from the simulation.

In order to assess and compare different UAS configurations an overall mission performance index (MPI) is introduced in the form of a weighted sum of key mission evaluation criteria. The MPI is implemented as an objective function of the system optimization process, which is based on a genetic algorithm. Thus by varying the
Aircraft Design

Fixed Wing VTOL Research

Fixed-wing VTOL configurations are aircraft designs featuring vertical take-off and landing capabilities like multicopters or helicopters and at the same time provide higher cruise efficiencies at elevated speeds. With increasing power densities of electric propulsion systems and better energy densities the design space opened up on these concepts to be utilized for multiple applications. At the Chair of Aircraft Design (LLS) research has been conducted in the field of unmanned fixed-wing VTOL aircraft since 2016. For the fixed-wing VTOL working group at LLS, the first big milestone was achieved in 2018 with the successful demonstration of the Dragonfish configuration, a 5 kg fixed-wing VTOL aircraft to our industrial partner AUTEL Robotics Europe GmbH. Throughout the year, flight testing of this prototype was performed to verify handling qualities and power consumption. In the course of the year, modifications to the original configuration were conducted and tested on the ground and in flight tests flown in order to extend the performance potential of the aircraft. Pusher rotors mounted under the fuselage, hover rotor retraction systems and different wingtip types were developed and investigated in flight. With the successful demonstration of the baseline architecture scale-up activities were also performed to utilize the technology for bigger payloads and extended performance. Targeting systems with around 25 kg gross weight, multiple aircraft configurations were derived and evaluated together with our industrial partner. Parameter studies and concept trade-offs were performed with the inhouse fixed-wing VTOL aircraft design tool. This design tool has been constantly advanced taking results of testing into consideration. Dedicated features like database enabled powertrain selection, powertrain thermal modelling, combined hover-cruise powertrain analysis and cable harness optimization where implemented in the course of the project. The fixed-wing VTOL aircraft design tool does provide the institute with a powerful design environment to derive and analyse a wide variety of configurations in this domain. At the same time supporting easy prototyping of sub-systems and overall system architectures.

Aircraft geometry as well as sensor parameters and using a genetic optimization algorithm the UAS concept, which optimally fulfills a certain mission task, is obtained. Deriving UAS designs from an integrated mission evaluation approach provides significant improvements in overall system performance, especially for missions in regions where the elevation of the landscape plays a major role, as for example in mountainous areas. In the course of validation several application studies have been conducted. The results showed the importance of taking the terrain data into account during the UAS optimization process.
In 2018, the German Aerospace Center (DLR) in cooperation with the National Aeronautics and Space Administration (NASA) hosted a student aircraft design competition for the second time. The task for the student teams was to develop an efficient and quiet transport aircraft, with the aim to work out an environmentally sustainable solution for the growing demand for commercial aviation. Over a period of several months, two student groups of the TUM eagerly participated in the challenging competition and elaborated technically advanced concepts. One of the two achieved the first place nationwide with the eRay aircraft concept, by utilizing an innovative propulsion architecture and synergistic effects between aerodynamic, structural and propulsive disciplines. The winner team from Munich was invited to a joint symposium at NASA in Langley, where the students exchanged views with US counterparts.

During WS 17/18 the practical course ‘Aircraft Design’ students had the task to design a 3D-printed aerial exploration system for Benin. Benin is a city in Africa, which is often flooded by water. The aircraft had to be designed, manufactured and tested as part of the course; it thus incorporates several teaching aids: in a fictional role-play, depicting a governmental development program, the students are divided into two groups, representing two competing companies. The fictional request for proposals contains requirements for a flight mission, which must be proven by a preliminary and critical design report, concluding with an actual flight test. The winning team is identified by a scoring system, evaluating quality and accuracy of the reports, as well as flight test results. A suite of well-proven computational design and evaluation tools is provided to the students, assisted with tutorials and short introductory lessons. Based on a modular UAV structure, electronics and instrumentation system, which has been specially developed for the course, where most of the relevant aircraft configurations may be represented. This maximizes the design space, while simplifying detail design and manufacturing. The winner was the ‘Red’ team, shown in the picture:
Aircraft Design

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Research Focus
- Scenario and future analysis
- Aircraft design
- Analysis and evaluation of aircraft concepts

Competence
- Szenario technique
- Aircraft design methods and tools
- Propulsion integration, electrical and hybrid propulsion systems
- Aircraft and system integration and verification (UAVs, prototypes)
- Unmanned aircraft (UAV/drones)
- Demonstrator aircraft
- Fixed-wing VTOL drones
- Operational assessment: noise, airport, capacity, cost

Infrastructure
- Integrated aircraft design environment
- Laboratory for demonstrator aircraft
- Experimental UAS (e.g. IMPULLS UAV)
- Demonstrator aircraft (e.g. FLEXOP)
- Propulsion integration lab
- System integration lab (virtual environment, UAV iron bird)
- Mission simulation
- Airport simulation

Courses
- Fundamentals in Aeronautics (jointly with the Institute of Helicopter Technology)
- Aircraft Design
- Aircraft Systems
- Aerospace Structures
- Fundamentals of Aircraft Operations
- Operational Aspects of Aviation

Practical Courses
- Aviation Scenarios, Technology Evaluation
- CAD in Aircraft Design
- Aircraft Design

Publications 2018
Flow Control and Aeroacoustics

Numerical and experimental study of flow and sound fields and their control

The focus of the research group in 2018 was the development, testing and usage of research tools for the numerical prediction of flow and sound fields.

Our research dealt with topics in two focus areas, including the numerical and experimental modeling of the wake evolution and radiation of low-frequency sound from wind turbines and tonal noise prediction for a 2-blade pusher propeller. For the wind-turbine flow simulation the in-house code INCA is used with actuator line treatment of rotating blades and LES modeling of the turbulent inflow and wake development over rough ground. For sound prediction the acoustic prediction tool SPYSI, developed at the Friedrich-Alexander Universität Erlangen in the group of Prof. S. Becker, is used. It is a time-domain implementation of the Flowcs-Williams Hawkings formulation of Lighthills acoustic analogy. For the present studies it has been complemented in order to consider the effect of mean flow advection on the sound propagation. It has also been used to assess the low-frequency noise from wind turbines emerging from the unsteady blade loading due to interaction with atmospheric boundary layer turbulence.

Implementation of the Actuator Line Method

For upcoming studies on the evolution of wind turbine wakes in complex terrain the actuator line method was implemented in ANSYS Fluent. The implementation was compared with results from established codes like EllipSys-3D and INCA. Figure 1 shows the influence of the chosen turbulence model on the normal and tangential forces along the radial extent of the blade. Figure 2 visualizes the axial velocity field. The decay of the tip vortices turns out to be very sensitive with respect to details of the numerical solution scheme and chosen turbulence model.

Figure 1: Tangential (left) and normal (right) component of the blade force along the radial extent of the blade for different turbulence models. From: Andrea Martinez-Garcia, term paper at SBA, TUM, 2018

Figure 2: Isosurfaces of the axial component of the velocity in a wind turbine wake modelled in FLUENT with the ALM method. From: A. Martinez-Garcia, term paper, 2018
Influence of a V-shaped Tail on the Noise Radiation from a Two-bladed Pusher Propeller

The blade loading for a pusher propeller mounted downstream of the V-tail of the UAV IMPULLS has been predicted using ANSYS CFX in URANS mode. Figure 3 shows a side-view of the tail section. The propeller cuts through the wakes of the two stabilizer fins. As a result of the unsteady blade loading the contributions from higher harmonics of the blade passing frequency to the loading noise increases as shown in Figure 3 for an observer located 45 degrees off the rotor axis.

Figure 3: Left: Side-view of instantaneous static pressure in the tail section of the IMPULLS UAV equipped with a V-tail (empennage) and a two-bladed pusher propeller. Right: Magnitude of velocity in a cross-section between tail fins and propeller. Source: Peng Liu, Master's thesis, SBA, TUM 2018

Figure 4: Comparison of loading noise in the far field at an observer position 45 degree off the axis from the pusher propeller with and without the empennage. Source: Peng Liu, Master's thesis, SBA, TUM 2018.
Flow Control and Aeroacoustics

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Research Focus
- Numerical prediction of generation and propagation of flow-induced noise
- Flow control with focus on suppression of flow separation and noise mitigation
- Self-noise of splitter attenuators
- Wake interaction of wind turbines

Competence
- Numerical prediction of flow and sound
- Experimental investigation of flow and sound fields

Infrastructure
- Use of wind tunnel at the Institute of Aerodynamics and Fluid Mechanics
- Test set-up of a microphone array

Courses
- Continuum Mechanics (for BSc Engineering Sciences of MSE), 50%
- Grundlagen der numerischen Strömungsmechanik
- Aeroakustik
- Strömungsbeeinflussung
- Numerische Strömungskubistik
- Praktikum Numerische Strömungssimulation
- Praktikum Numerische Strömungsakustik

Publications 2018
Plant and Process Technology

Modeling and simulation of chemical processes, equipment design, thermodynamic property data

The Institute of Plant and Process Design is a research center in the area of plant and process engineering. In the context of the German initiative “Energiewende” with an increasing portion of renewable energy in 2018 the dynamic behavior of chemical production processes and the unit operations involved were investigated in various projects.

The research is organized in the three focus areas; process design, equipment design methods, modeling and thermodynamic property data. Thereby, modern experimental methods along with state-of-the-art mathematical software tools like dynamic simulation and computational fluid dynamics are widely used in the research activities.

Process Design

In the SynErgie consortium of the long term BMBF project Kopernikus, the energy intensive process for cryogenic air separation units (ASU) was selected as an example to identify the potential of flexible plant operations and the contribution to flexible demand site management. However, as most chemical production processes, air separation units are presently not designed for dynamic operation modes with rapid load and process changes. Therefore, it is required to demonstrate which process and equipment modifications are required in order to operate an ASU under severe...
dynamic conditions. At the Institute of Plant and Process Technology the main heat exchanger and the columns of the double rectification system of an ASU, which consists of the pressure column and low-pressure column, were investigated in 2018 in close cooperation with Linde Engineering. In order to develop a digital twin of an air separation unit the so-called pressure-driven modelling approach can be applied. Thereby, the process flows inside the packed columns are described with a flow-pressure correlation which reflects the real physical phenomena much better than the state-of-the-art mass flow-based approach. Hence, the dynamic warm start-up scenario of an ASU can be simulated as well as different realistic plant shut-down procedures. As a second task, a pilot plant for the investigation of the dynamic load changes of plate fin heat exchangers (PFHX) was designed and commissioned in 2018 at the pilot facilities of Linde Engineering. Here, the target is to validate the thermo-fluiddynamic modelling of PFHXs, which serves as the basis for the thermo-stress distribution with a finite element method (FEM). Thereby, it is possible to establish correlations which predict the expected lifetime of the unit and to develop smart restart concepts which extend the lifetime of a PFHX.

Packed columns are widely used for distillation and absorption in the chemical industry. Columns with structured packing are characterized by high efficiency and low operating cost. Fluid dynamics in structured packings has already been investigated with CFD simulations. The results show an excellent agreement with the X-ray tomography examinations (see figure). For the first time, the Institute of Plant and Process Technology conducted simulations with simultaneous computation of fluid dynamics and mass transfer. To achieve this, capacities of the SuperMUC at Leibniz Supercomputing Centre were used. These simulations give a special insight into the events on the micro scale. These data can be used to specifically enhance the design of those packings. Since distillation processes generally have a high energy requirement, potential energy savings are on a significant scale.

In previous years a cell model for the prediction of liquid distribution in random-packed columns has been developed at the Institute of Plant and Process Technology. After the last adjustments modeling is now finished and the results show a very good agreement with the experimental data. With the model at hand, column design can now be optimized for the exact application. An example is the liquid distributor at the top of the column. The model can be used to optimize the drip point density and the distance between wall and drip points. It takes into account the type of random packing and achieves an ideal result for the specific application. For the future, an integration of the mass transfer calculation into the model is planned.
The efficiency of PEM fuel cells in automotive applications strongly depends on the humidity of the electrolyte. To ensure a high water content, the air supply stream needs to be humidified before entering the cell. External membrane humidification is the preferred method for this task, as no additional energy or water supply is required. The existing membrane test stand at the Institute of Plant and Process Technology was optimized and automated to enable long-term testing and a higher accuracy of the test results. By integrating the crucial components into a heating cabinet, stable test conditions are achieved and the membranes can be tested for their water permeability and longevity under operating conditions typical for PEM fuel cells.

To predict the water transport for different operating conditions, a discretized 1D model was created. While flow conditions are described with Nußelt- and Sherwood correlations, sorption isotherms of the membrane material are based on literature or experimental data. The model calculates the water transport in the membrane module as a function of the local driving force, boundary layers and gas properties. The comparison with experimental values shows good agreement.
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Research Focus
- Process design
- Equipment design methods
- Modeling and thermodynamic property data

Competence
- Process modeling and simulation (MATLAB, Unisim Design, Aspen Plus)
- Experimental measurement of thermodynamic property data
- Predictive computation of thermodynamic property data
- Experimental measurement of heat transfer coefficients
- Experimental measurement of maldistribution
- CFD-modeling and simulation of heat and mass transfer processes
- Pilot-scale investigations of apparatus design methods

Infrastructure
- High pressure phase equilibrium laboratory
- Analytical laboratory
- Distillation columns (pilot scale)
- Condensers & evaporators (pilot scale)
- Workshop
- Computer room

Courses
- Introduction to Process and Plant Engineering
- Thermal Separation Principles I & II
- Heat and Mass Transfer
- Process and Plant Engineering
- Equipment Design
- Process Design
- Modeling of Chemical Engineering Processes
- Similarity and Dimensionless Numbers
- Lab Course in Process Engineering
- Practical Course in Process Simulation
- Principles of Refrigeration and Industrial Low Temperature Systems

Selected Publications 2018
Continuum Mechanics

Predictive computational modeling

The focus of the Continuum Mechanics Group in 2018 was the development of novel models, methodologies and computational tools for quantifying uncertainties and their effect in the simulation of engineering and physical systems. Our work has been directed towards four fronts: a) the development of probabilistic surrogates for uncertainty quantification in random media, b) the discovery of coarse-grained models for atomistic simulations of materials, c) the computational simulation of electromagnetic wave propagation, and d) the extraction of governing equations from data in multiscale systems where effective models (or closures) remain elusive.

The award of the project Physics-Informed LeaRnIng for Multiscale Systems (PILgRIMS) by DARPA, USA in the context of the disruption opportunity (DO) on innovative basic research concepts exploring radically new architectures and approaches in artificial intelligence (AI) that incorporate prior knowledge, such as known physical laws, to augment sparse data and to ensure robust operation. The project aims at addressing many of the limitations of current approaches with interest in high-dimensional parameterizations, representing multi-scale/multi-output data and complex dynamics, all while adhering to a correct specification of the underlying physics in predictions. Collaborators in this project are the University of Notre Dame and the University of Pennsylvania.

Physics-constrained Surrogate Modeling for Problems in Random Heterogeneous Media

The computation of output quantities (forward uncertainty quantification) in the context of random heterogeneous materials poses significant challenges due to the high-dimension of input uncertainties and the cost associated with each forward model evaluation. Surrogates or emulators aim at addressing this problem by replacing the expensive forward simulation by a cheaper, yet inaccurate model based on a small set of full-order evaluations as training data. Off-the-shelf machine learning algorithms exist but are cumbered by both the high dimensionality of random material properties and the limited number of data available (small data).

This project investigates a novel strategy of constructing probabilistic Bayesian surrogates incorporating information from simplified constitutive law assumptions. Instead of solving the expensive full-order model, we apply a three-step encoder-decoder model as depicted schematically in Figure 1. In the first step, the high-dimensional random material inputs are encoded into a low-dimensional set of effective material properties mediated by a linear combination of a small set of microstructural features selected by a sparsity enforcing prior. In the second step, these effective material properties serve as the input to an emulator model based on simplified physical behavior which can be evaluated much faster. Finally, the emulator output is projected back onto the full order solution space with probabilistic decoder mapping. The model is fully Bayesian in the sense that all model parameters are

Figure 1: Visualization of the proposed, physics-aware, coarse-graining framework.
treated as random variables and are averaged over their respective posteriors. Estimates for aleatoric (finite data), as well as epistemic (model inadequacy) uncertainty, are readily provided by the probabilistic surrogate output as shown in Figure 2. The latter depicts results from a multi-physics framework whereby Stokes flow provides the full-order model and Darcy flow the coarse-grained one. In this setting, only a few tens of full order evaluations are needed to yield accurate predictions on several thousands of random inputs.

Figure 2: Predictions for three different microstructures. Colored curve is the reference pressure field obtained by the full-order model (Stokes flow), the blue surface the posterior mean obtained by the calibrated coarse-grained model (Darcy flow) and gray curves correspond to 5% and 95% predictive, credible intervals

Coarse-Graining of Atomistic Systems with Deep Bayesian Models

Continuum thermodynamics offers an effective but phenomenological description of the behavior of materials at the macroscopic scale. First-principles methods, e.g. molecular dynamic simulations, allow for detailed in-silico experiments of materials while the simulated microscopic behavior provides bottom-up information for macroscopic approximations. Atomistic/molecular simulations can advance drug discovery and research on diseases caused by protein misfolding, e.g. Alzheimer's. The gigantic number of degrees of freedom in atomistic simulations and the minute temporal scales involved, limit their wide-spread application. To that end coarse-grained (CG) models are needed to make relevant scales accessible. In collaboration with TUM Ambassador and Director of the Center for Informatics and Computational Science at the University of Notre Dame, Prof. N. Zabaras, a data-driven coarse-graining methodology for overcoming the aforementioned limitations has been introduced. The proposed framework synergistically employs tools from machine learning and approximate Bayesian inference (Figure 3 for ALA-15, an alanine peptide with 15 residues). The probabilistic unsupervised learning task is carried out with the employment of neural networks. The optimization of the networks parameters suffers especially in the small data regime. We address this with sparsity-inducing priors resulting in a robust training process, a physically meaningful CG representation, and improved predictive capabilities. The Bayesian formulation allows us to capture epistemic uncertainties in the form of credible intervals.

Figure 3: Predicted configurations of ALA-15 peptide (originally of dimension 480) when moving along the path indicated with a red, dashed line along the two-dimensional space of collective variables identified from MD simulation data.
The goal of this project is the development of computationally effective methods for the simulation of electromagnetic wave propagation in underground strata formations. This effort is part of a multinational research project for the development of a signal transmission apparatus. The objective is to determine whether electromagnetic signals can be sent through the underground formations at a drilling site. The simulator discretizes in time and space the Maxwell equations, the partial differential equations that describe electromagnetic phenomena, using the discontinuous Galerkin finite element method. The resulting systems of algebraic equations are subsequently solved on high-performance computing systems. The solutions obtained indicate whether the transmission is possible and what noise to expect from the propagation of the field in such heterogeneous domains. The mathematical formulation of the method has been appositely formulated and the simulation software has been developed as a branch of the research code BACI in collaboration with the Institute for Computational Mechanics.

As a first test case, the stationary solution of a resonant wave in a cubic cavity is illustrated in Figure 4a. Figure 4b depicts the convergence rates achieved for this example as a function of the finite-element size $h$.

**Physics-constrained, Data-driven Discovery of Coarse-grained Dynamics**

The process of extracting predictive mathematical and physical models from simulation data represents an exciting challenge in the area of computational physics. We address this challenge from a Bayesian perspective; a physically inspired coarse-grained system, which is maximally predictive for the full system and its dynamics, is postulated and calibrated using limited simulation data from the high-dimensional fine-scale system. This process consists of two components. Firstly, the discovery of a good set of coarse-grained state variables. This step is crucial as the outcome depends a lot on the ability of the CG variables to represent the evolution of the system. The second step consists of prescribing a suitable evolution law for the coarse-grained variables. It is useful to include many different terms in this evolution law and enforce sparsity with the help of a suitable prior. To generate a complete Bayesian framework, we define a probabilistic mapping from the high-dimensional system to the CG model as well as a probabilistic evolution law of the CG model.
variables. The advocated framework is particularly suitable for high-dimensional deterministic or stochastic systems, whose solution is generally dominated by the smaller time scales involved, even though the outputs of interest might pertain to time scales that are greater by several orders of magnitude. We applied the method to a system of 4800 random walkers, following the evolution law of the Burgers equation, and extracted a CG model by only using data of two time steps. In Figure 5 the fine-scale solution is shown as well as three inferred and predicted solutions of the coarse scale including the uncertainty bound. The data points used for generating the coarse model are marked with a red cross. The data-based coarse model learned is even capable of representing a Burgers type shock.

Unsupervised Learning and Probabilistic Reasoning for Physics-constrained Systems

The goal of this project is to employ probabilistic reasoning and machine learning techniques to learn the behavior of complex physics-constrained systems, and to subsequently predict their behavior at a significantly reduced cost. Instead of expensive forward solutions of partial differential equations, we only assess plausibility in terms of compliance with physical laws, such as conservation of momentum or the second law of thermodynamics. In our current research we combine this fundamental idea with an information bottleneck defined by an encoder-decoder architecture (see Figure 6), where structure is endowed to the latent variables by means of a latent coarse physics $L_{cuc} = 0$. The encoder-decoder learns salient features to be encoded in the latent space, given the objective to recover predictions that comply with the underlying physical laws. In the end, probabilistic predictions about the physical system are obtained without ever solving the PDE, nor providing any data to the algorithm.

Figure 6: Schematic of architecture – learning salient features for latent physics and subsequent reconstruction in absence of any data (unsupervised learning).
Continuum Mechanics

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Research Focus
- Uncertainty quantification
- Random media
- Coarse-graining in molecular dynamics
- Bayesian inverse problems
- Design/optimization under uncertainty

Competence
- Computer simulation
- Mathematical modeling of stochastic systems

Infrastructure
- 256core HPC

Courses
B.Sc.
- Continuum Mechanics – MSE (WS)
- Modeling in Structural Mechanics (WS)
- Modeling of Uncertainties and Data in Mechanical Engineering (SS)
- Uncertainty Modeling in Engineering (SS)

M.Sc.
- Probability Theory and Uncertainty Quantification – MSE (WS)
- Multiscale Modeling – MSE (SS)
- Journal Club Uncertainty Quantification (WS-SS)

Selected Peer-reviewed Publications 2018
- C. Grigo, P.S. Koutsourelakis. Bayesian model and dimension reduction for uncertainty propagation: applications in random media. SIAM/ASA Journal on Uncertainty Quantification. Accepted for publication, to be printed. 2018
Systems Biotechnology

Model-based metabolic engineering for bacterial systems

Systems biotechnology combines methods from engineering sciences, microbiology, and computational sciences to improve biotechnological processes.

The Systems Biotechnology Group focuses on the application of methods from systems biology to problems related to biotechnology. Central to our current projects is the understanding of resource allocation during growth and production. Heterologous protein production with microorganisms is becoming an increasingly important pillar in various fields of biotechnology. Combining theoretical methods with experimental studies we systematically analyze the population behavior depending on differing load strength. Here, a new experimental approach that allows the monitoring of mRNA as well as protein dynamics in the same cell are applied and fitted to mathematical models. This opens new perspectives in the understanding of single cell dynamics and in designing new strains in biotechnology. A further focus of our studies is the use of mixed co-cultures for biotechnological production. We use a phototrophic strain that is able to produce carbohydrates only from light and CO₂. With a heterotroph strain, the carbohydrates can then be converted into interesting products.

Fundamentals for Experimental Analysis and Mathematical Modeling of Cellular Networks

The regulation of transcriptional and bio-chemical processes in a bacterial cell is essential for survival in changing environmental conditions. Understanding the events taking place is pivotal for using bacteria in industrially interesting applications. The experimental information derived either in the group’s own laboratory or by collaboration partners gives rise to mathematical models that contribute to a better understanding of cellular processes. Our first focal area is on the analysis of mathematical models that are described in a stochastic framework. To this end, a novel theoretical framework was established, with which noise can be quantified based on the topological and kinetic properties of the reactions in the circuit being examined. For a comprehensive characterization, different measures of noise were considered. Moreover, they were chosen to be applicable to multistable systems by regarding the noise levels of every stable expression state separately. Besides the state-specific means and variances of mRNA and protein copy numbers, the skewness and temporal structure of protein fluctuations could be examined using detailed descriptions of protein burst sizes and frequencies. Simulation-based validation suggested that the novel methods generated estimates of higher accuracy than comparable existing approaches (rate equations and linear noise approximation), since they were better suited to describe mesoscopic genetic circuits. The applicability of the newly developed framework is however restricted to systems in which deterministic multistability is associated with stochastic multimodality, a condition that is not necessarily fulfilled: First of all, deviations may occur due to a deterministic description not suitable for mesoscopic processes. This was mostly prevented through the development of a hybrid-deterministic approach, which also provided the basis for the above-mentioned methods for noise characterization. However, a further systematic analysis also revealed how the number of modes in the protein distribution might change under large translational bursts – a phenomenon that cannot be captured deterministically.
Another research focus lies on the establishment of a co-culture between a photosynthetically active organism extruding sugar molecules and heterotrophic organisms capable of producing industrially interesting compounds. In recent years, new efforts have been made to explore the benefits of defined mixed culture cultivations that excel in their robustness and versatility. These new approaches bear the potential for faster growth, better yields and a lower risk of contamination compared to conventional processes. We present an engineered defined mixed culture, consisting of transgenic Synechococcus elongatus PCC7942 and Pseudomonas putida KT2440 that were specifically modified to show a collaborative, commensalistic lifestyle: We used an S. elongates variant that expresses the sucrose permease CscB to secrete sucrose that is accumulated intracellularly to combat salt stress. This sugar was in turn metabolized by P. putida strains that were modified to be able to use sucrose as a substrate. The work was divided into three general parts: MiniTn5 transposon-based plasmids containing the cscAB genes from Escherichia coli were constructed. These sucrose-splitting transposon plasmids (pSST) were the first genetic vectors to confer the ability to grow on sucrose as the sole carbon source to P. putida. In the second part we established a defined mixed culture with this new P. putida strain and the sucrose secreting S. elongatus cscB in a 1.8 liter airlift photobioreactor. In the last part, we constructed even more superior sucrose-using P. putida strains by genomic insertion of the cscRABY gene cluster from Pseudomonas protegens Pf-5 by means of a Tn7-transposon vector.

Projects
- Engineering and analysis of defined mixed cultures of pseudomonas putida and synechococcus elongatus for bioplastics production
- Model based characterization of intrinsic noise in multistable genetic circuits

Metabolic Engineering of Halophiles:
Towards Halomonas elongata as Industrial Producer

The project focuses on ectoine production by the halophilic bacterium Halomonas elongata. The reasons for that choice were not only the interest of ectoine as a novel product for medicine and cosmetics but also the potential of H. elongata for further biotechnological applications. Ectoine is a highly soluble organic molecule that belongs to the group of compatible solutes and is found as an osmotic agent in a wide range of cell types and has also been shown to stabilize and protect macro-molecules in adverse conditions. The current applications of ectoine cover a wide range of different fields, such as biomedicine, cosmetics, support roles in analytic and industrial processes and bioremediation.

Projects
- HOBBIT – Halophilic bacteria for bio catalysis
Metabolic Engineering of Escherichia coli: Combing Synthetic and Systems Biology

Escherichia coli is the organism of choice for basic research in biotechnology due to the possibility for genetic alterations as well as its simple culture conditions. In two projects, together with experimental partners from different places in Munich and Germany, E. coli is used for the production of chemical bulk components or interesting precursors for medical applications. Based on genome-scale mathematical models, optimal flux distributions and optimal intervention strategies are determined that makes the processes more efficient. However, our studies revealed that theoretical concepts to calculate only flux distributions are not sufficient to predict the growth and production behavior of the strain variants. We analyzed nearly 30 studies published in various international journals and it turns out that the number of experimental studies that applied the theoretical methods is only one. This points to the need to integrate more and different types of measurement into the models. Our group, therefore, has started to develop new theoretical methods. Based on the stoichiometry of the biochemical reactions, kinetic mathematical models are developed in the ensemble-modelling framework. That is, the analysis is not restricted to a single model but an ensemble of models with different sets of parameters is generated and analyzed. The analysis of the model ensemble is then based on the sensitivity of the model parameters to a defined target, for example, the yield of an interesting product with respect to the substrate used.

In order to understand the cellular processes and limitations during foreign protein production from an experimental point of view, we set out to quantitatively describe the distribution of the resources between the intrinsic processes needed for maintenance and the extra load introduced by the heterologous pathway. The cellular behavior was analyzed under a systematic variation of heterologous load. In addition to the process parameters, we are able to record on-line the transcriptional and translational rates of the heterologous load. This is achieved by the introduction of a specially-designed plasmid into the cells that allows us to monitor and quantify the expression of a desired gene in vivo. To assess the cellular fitness, the cellular capacity in terms of resource-distribution was investigated. With this setup, we were able to quantify mRNA and protein production rates, as well as stabilities. Furthermore, resource distributions and cellular capacity were quantified via immuno-quantification and different fluorescent monitor-systems. Besides the availability of ribosomes, the RNA-polymerase can be limited just to name the most important ones. Since productivity is not only affected by the availability of resources but also of the distribution of metabolic fluxes, metabolic activity at different energetic states and process configurations were tracked in addition. Finally, we integrated our experimental findings into the mathematical model.

Projects

- DynOpt – Dynamic process optimization in biotechnology, BMBF, biotechnology 2020+ initiative
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Research Focus
- Mathematical modeling of cellular systems
- Model analysis
- Model-based metabolic engineering
- Experimental design

Competence
- Model library for different model systems (metabolic modules, gene expression modules, signaling modules)
- Design space analysis
- Time hierarchy analysis
- Process design

Infrastructure
- S1 laboratory (allows work with genetically modified strains)
- Photo bio-reactor system
- Standard bio-reactor system
- Tecan reader

Courses
(for M.Sc. ‘Industrial Biotechnology’, MSE)
- Applied Mathematics
- Modeling of Cellular Systems
- Analysis and Design of Cellular Systems
- Optimization in Biotechnology
- Data Analysis and Statistical Models
- Exercises in Simulation Studies in Biotechnology

Publications 2017-18
Biomechanics

Biological (hybrid-)materials and bio-interfaces

The mission of the Biomechanics Group is to:
1. discover new, to-date unknown material properties of biopolymer materials and biological interfaces;
2. identify the microscopic principles that govern those material properties (mechanics, permeability);
3. apply those principles to create biomimetic materials for biomedical or technical applications.

The biomaterials studied range from very soft gels, such as mucus and biofilms, to tissues such as cartilage and hard, artificial materials such as mortar and concrete. Accordingly, a broad variety of characterization methods is used in the Biomechanics Group. Biomedical questions addressed include understanding the wetting resistance of bacterial biofilms and developing surface modifications by biopolymers to reduce friction and wear on biological tissues or to inhibit biofouling.

In our highly interdisciplinary projects, we work together with chemists, physicists, and medical researchers to generate, characterize and optimize existing and novel biopolymer-based materials and to test their applicability for biomedical or industrial purposes.

Highlights in the year 2018 were the development of an oscillatory tribology setup and its application to food science as well as discovering a chemical treatment procedure which reduces the wetting resistance of bacterial biofilms by altering the surface topography of the biomaterial.

Microfluidic Chips for Diffusion Studies

PDMS microchips are a versatile platform to study the behavior of fluids in small dimensions. We aim at generating microchip solutions to quantify diffusive processes at the liquid/gel interface. We also try to mimic complex biological interfaces such as the bloodstream/connective tissue. In collaboration with medical researchers and physicists, we then compare the results obtained from our gel-on-chip assays to in vivo data and theoretical models.

Project

- DFG: Barrier properties of mucin hydrogels

By conducting molecular diffusion experiments, we were able to analyze the influence of mucoadhesion on the penetration behavior of molecules into mucus hydrogels.
Biomechanics

Biotribology and Biolubrication

We study the mechanical and tribological properties of biological tissues. By exploiting loss and gain of function experiments, we aim to understand what molecular components are responsible for the outstanding mechanical properties of cartilage and which lubricants minimize friction and wear. Furthermore, we examine the effectiveness of different biopolymers as lubricants on biological and artificial surfaces. We also develop novel, tailored tribology setups and apply them to questions outside engineering, such as food science.

Project
- Applications of oscillatory tribology

(Bio-)Hybrid-Materials

Many biomolecules offer outstanding properties but cannot be used in medical/technical applications on their own. Thus, we develop hybrid materials where we either mix biological molecules in new combinations or add biological components to inorganic/synthetic materials. Examples for such hybrid-materials are hydrogels with programmable drug release kinetics and nanoparticles created from condensed biomacromolecules.

Material Properties of Bacterial Biofilms

Bacteria secrete a broad range of biopolymers, that form a protective matrix around the prokaryotes. This community of biopolymers and bacteria is referred to as a biofilm. Bacterial biofilms can grow on a broad variety of surfaces and constitute a severe issue in industry and medicine. We aim at quantifying the mechanical and water-repellent properties of bacterial biofilms. We have recently found a way to reduce or even completely abolish the hydrophobic surface properties of biofilms, thus rendering them susceptible to erosion by water and chemical attack, e.g. by antibiotics.

Projects
- SFB 863: Forces in Biomolecular Systems
- Biopolymer-based Materials

The wetting behavior of bacterial biofilms can be altered from hydrophobic (left) to hydrophilic (right) by smoothing the surface texture of the biomaterial.
**Research Focus**
- Biological (hybrid-)materials
- Cartilage and cartilage replacement materials
- Biological hydrogels as selective diffusion barriers
- Material properties of bacterial biofilms
- Medical applications of nanoparticles

**Competence**
- Rheology, tribology
- Microfluidics, diffusion measurements
- Surface characterization
- Purification of antibacterial/antiviral glycoproteins
- Cell culture, microbiology

**Infrastructure**
- Rheometer, tribometer
- Optical microscopes
- Optical profilometer
- Scanning electron microscope
- S1 laboratory (working permission for genetically modified microorganisms of biosafety level 1)
- Laboratory for cell culture
- Equipment for protein purification
- Quartz crystal microbalance

**Courses**
- Microscopic Biomechanics
- Experimental Techniques for the Characterization of Biomaterials
- Design Principles in Biomaterials
- Bio-inspired Material Design
- Lab Course: Characterization of Soft Materials
- Biophysics Lab Course for Biochemistry Students

**Publications 2018**
Automotive Technology

Vehicle concepts – smart mobility – vehicle dynamics and control systems – driver assistance and safety –
electric vehicle components

The research focus of the Institute of Automotive Technology is the emerging field of mobility with a particular emphasis on electric mobility. Therefore, the focus is not only on vehicle concepts but also on infrastructure and market conditions as well as on powertrain technologies and driver assistance systems.

The Institute of Automotive Technology collaborates closely with partners from industry to ensure that the research addresses current needs and provides both undergraduates and Ph.D. students the opportunity to have an easier start into future job. In many research projects Ph.D. students and their undergraduates work in cooperation with industry partners, but there are also some very large research projects with many firms and other universities. This quickly allows (Ph.D.) students to connect with industry and research and also have better entry-level opportunities for jobs.

Vehicle Concepts

The focus of the institute on e-mobility creates a lot of chances and challenges in the field of vehicle concepts. Not only cars offer many opportunities for improvement, but trucks also do. In the project ‘Truck2030’ scientists at TUM investigated all aspects of the truck of the future and will present their results at the IAA Commercial Vehicles trade show in Hanover. Here are the most important results in the following areas:

People: The researchers’ concept is based on the assumption that the truck of the future will drive on the highway automatically. Drivers would then be able to invest the time saved in their own health. The driver’s cabin presented by the team is equipped among other things with cables and pulleys which can be used for exercise, already familiar from health clubs. A game-oriented aspect will be added in order to increase motivation, for example based on a virtual reward system.

Transport and logistics: Long trucks with a length of 25.25 meters are ideal for efficient cargo transport. Here two LHV trucks can replace three normal-length trucks. This makes it possible to save fuel, resulting in benefits for the environment and the economy. And the total number of trucks on the road will also be reduced. Apps that record cargo information using scan codes or NFC could save time and resources during loading and unloading.

Environment: The use of LHV trucks alone could cut CO₂ emissions by 20 percent due to lower fuel consumption with the same cargo loads. Using diesel plug-in hybrid drives could reduce CO₂ emissions by another 10 percent, the best solution from both the environmental and economic points of view. Based on the current state of the art, a solely electric drive train would not be feasible, since a battery capable of providing sufficient energy for the required range would be too large and too heavy. Tires with optimized road resistance and improved truck aerodynamics could reduce CO₂ emissions by 10 percent.

Politics: The most important prerequisite for realization of the concept is the approval of the use of LHV trucks in all of Europe. In their investigations the scientists successfully refuted counterarguments such as lower driving safety and increased road wear.

Another important point is infrastructure: Use of the diesel plug-in hybrid will require additional charging stations on highways. Electric cars will also be able to use these charging stations.
Electromobility and Automated Driving

First prototype designs

There is one really large research project, involving not only the research group’s driver assistance and safety and vehicle concepts, but many German universities. In the project UNICARagil, a consortium of several German universities is working together with their respective research priorities. Fully automated driverless vehicles will be developed based on the research into automated and connected driving and electric mobility. The basis is a modular and scalable vehicle concept including the use and the drive unit. It can be flexibly adapted to various applications in logistics and passenger transport, which can be sensibly developed by driverless, emission-free vehicles. The goal of the project is the demonstration of the four use cases: private car, taxi, delivery and shuttle. The Institute of Automotive Technology (FTM) is responsible for the body of the taxi (AUTOtaxi). The module body of the taxi includes everything from conceptual design to construction and assembling to testing. The special needs of an autonomously driving vehicle should be considered in the vehicle concept and implemented in the construction.

As a supplement to line-based public transport, passengers will be able to use the AUTOtaxi for individual trips in urban environments. The vehicles can be booked by smartphone or opened and used directly on the street. The test field for testing the AUTOtaxi prototype is located on and around TUM’s university campus Garching. Furthermore, the Institute of Automotive Technology is developing the operations center. The operations center personnel monitors the fleet of autonomous vehicles, affects their behavior and controls single vehicles when necessary. On the one hand, the operations center gains the users’ trust since the users can communicate with the operations center personnel if required. On the other hand, the operations center extends the operational design domain of the autonomous vehicles. For example, if an autonomous vehicle reaches the boundaries of its operational design domain, the operations center takes over control and brings the vehicle back in an autonomous mode.

Driving and Driver

The IMAGinE (Intelligent Maneuver Automation – cooperative hazard avoidance in realtime) project is developing innovative driving assistance systems for cooperative driving. Cooperative driving refers to road traffic behaviour in which road users cooperatively plan and execute driving maneuvers. Individual driving behaviour is coordinated with other road users and the overall traffic situation based on automatic information exchange between vehicles and infrastructure. Critical situations can be avoided or mitigated, thereby making driving safer and more efficient.

Communication technologies enable vehicles to exchange information with other vehicles about objects detected by on-board sensors in real time, thus providing the technological basis for collective environmental perception. Intuitive human-machine interaction concepts ensure high user acceptance of these technologies. IMAGinE employs advanced simulation systems to analyse to what extent cooperative driving maneuvers increase traffic efficiency. The IMAGinE project consortium consists of twelve German partners and brings together leading companies from the automotive industry, small- and medium-sized businesses focusing on simulation, an academic institution, and a public road management company. IMAGinE is funded by Germany’s Federal Ministry for Economic Affairs and Energy.
Road users are increasingly supported by technical assistant systems that provide them with safety-related recommendations or even directly execute such actions. However, these recommendations and actions are neither communicated nor coordinated with other vehicles. So far, conflicts between vehicles are addressed individually – either by technical systems or by the drivers themselves. These critical driving situations affect the flow of traffic and may lead to accidents. Active cooperation between vehicles contributes to avoiding these critical driving situations.

The importance of cooperation between vehicles will increase significantly in the coming years and in the future, traffic will be characterized more and more by vehicles with varying degrees of automation. Vehicles with automated driving systems will depend on the cooperative behaviour of other vehicles, for example if environmental perception is only possible to a limited extent for whatever reason.

Other Projects

- Driving simulator
- Tele-operated driving
- Safety assessment of highly automated vehicles
- Safety assessment of autonomous roborace race vehicles
- Sim2Gether – Collaboration platform for interdisciplinary simulation
- aCar – Vehicle concept for Sub-Saharan Africa
- WATE – Web-based analysis tool electromobility
- QOStreet – Classification of road surface quality with big data
Automotive Technology

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Research Focus
Vehicle concepts
Smart mobility
Driving dynamics
Driver assistance
Electric vehicle components

Competence
E-mobility
Safety
Efficiency
Human-vehicle interaction
Tele-operated driving

Infrastructure
3D printer
Dynamic driving simulator
Mechanical and electrical workshop
Dynamometer test rig
Battery testing lab
Hardware in the loop test stands
Measurement of driving dynamics
Mobile data capturing via smartphones
Computing cluster

Courses
Basics of Motor Vehicle Construction
Road Vehicles: Design and Simulation
Dynamic of Passenger Cars
Design of Electric Vehicles
Technology of Motorcycles
Race Car Technology

Selected Publications 2018

Baumann, Michael; Wildfeuer, Leo; Rohr, Stephan; Lienkamp, Markus: Parameter variations within Li-Ion battery packs – Theoretical investigations and experimental quantification. Journal of Energy Storage 18, 2018, 295-307

Büchner, Stefan; Streubel, Patrick; Deixler, Norbert; Stroph, Ralf; Ochner, Udo; Lienkamp, Markus: Potential of elastodynamic analysis for robust suspension design in the early development stage. In: Proceedings. Springer Fachmedien Wiesbaden, 2018

Heilmeier, Alexander; Graf, Michael; Lienkamp, Markus: A Race Simulation for Strategy Decisions in Circuit Motorsports. 21st International Conference on Intelligent Transportation Systems (ITSC), 2018

Koberstaedt, Sascha; Eiba, Maximilian; Huber, Manuel; Kalt, Svenja; Soltes, Martin; Lienkamp, Markus: Development of a process for a customized vehicle testing for new vehicle concepts in new markets – Application example Sub-Saharan Africa. 2018 Thirteenth International Conference on Ecological Vehicles and Renewable Energies (EVER), IEEE, 2018

Wassiliadis, Nikolaos; Adermann, Jörn; Frericks, Alexander; Pak, Mikhail; Reiter, Christoph; Lohmann, Boris; Lienkamp, Markus: Revisiting the dual extended Kalman filter for battery state-of-charge and state-of-health estimation: A use-case life cycle analysis. Journal of Energy Storage 19, 2018, 73-87
Automatic Control
Model-based analysis and design allow for the successful control of complex dynamical systems

The chair is focused on both the development of methods and their practical application. For an efficient control of technical processes, new techniques are devised in nonlinear control, energy-based modeling and design, the control of distributed parameter systems, model order reduction, as well as adaptive and predictive control and methods of optimization and computational and artificial intelligence. Moreover, a Collaborative Research Centre puts a spotlight on the modeling and analysis of nontechnical systems. Cooperations within a DFG Priority Program and within a joint international ANR-DFG funding initiative have been established. Concerning application, highly challenging problems include the treatment of vibrations in mechanical systems and in automobiles, the robust control of unstable robots, and the feedback control of technical and nontechnical industrial processes.

Autonomous Driving
Autonomous driving is considered to be one of the key technologic advances within the next few years. The research within our group is oriented to vehicle dynamics and the motion control of the full vehicle. The challenges in this field mainly arise from the highly nonlinear tire behavior at friction limits and high-motion speeds. It is desirable to include model information as well as data into the design of such control systems to achieve near human performance even in the most difficult scenarios, e.g. changes in road conditions. We are continuously evaluating the real-world performance of our approaches within an autonomous driving racing series named ‘Roborace’ (see picture on the right).

Active and Semi-Active Suspension Control
Active suspension systems can significantly contribute to the comfort and safety of passenger cars by minimizing vibrations acting on passengers and by reducing dynamic wheel load. Recent developments in our research include nonlinear and adaptive disturbance compensators as well as optimal proactive preview control. Thereby, different design objectives can be achieved transparently. To gather and manage the required preview data, we look into approaches including vehicle-based road profile estimation (see figure to far left) combined with vehicle-to-infrastructure (V2I) communication. The so-called hybrid suspension system, developed at our chair, is shown in the figure left; it includes a low-bandwidth actuator and a high-bandwidth variable damper, together with a sophisticated control system.

Experiments are performed at a quarter-car test stand available in the Chair of Automatic Control.
Model Order Reduction

The modeling of dynamic systems frequently leads to large sets of differential equations. The goal of model order reduction is to find a much smaller (reduced) model preserving the most important properties of the original model. Recent research in our group deals with reducing parameter-dependent systems, nonlinear systems, mechanical structures, port-Hamiltonian models and systems of differential algebraic equations. The resulting new methods guarantee high approximation accuracy, while being numerically efficient.

Modeling and Control of Socio-Technical Systems

As part of the collaborative research center 768 ‘Managing Cycles in Innovation Processes’, the Chair of Automatic Control is concerned with the modeling and control of socio-technical and cyber-physical systems. As opposed to physical systems, socio-technical systems often inherit strong uncertainties, complex micro and macro dynamics and are commonly modeled as agent-based models, for which no general control-design method is available. Thus design methods which are valid for a broad class of dynamical systems, like fuzzy control and learning algorithms, are in the focus of this research group. While being primarily developed for socio-technical systems, the algorithms are also transferred to real plants and machinery for validation and comparison.

Distributed Parameter Systems/Energy-based Modeling and Control

We develop new techniques for the discretization and control of distributed parameter systems that preserve or are inspired by an energetic model structure. Examples are all kinds of transport and diffusion phenomena, e.g. the flow of pressurized air through a tube or heat transfer in a catalytic foam. We also work on motion control of flexible mechanical systems using geometric methods. Current research highlights are:
A modular flexible link manipulator in the simplest configuration to validate the fast point-to-point motion control of the flexible beam based on a PH discretized model

Modeling, identification and control of pneumatic systems. The benchmark example of a pneumatic transmission line with nonlinear friction is used to validate different mathematical models, and to develop, in a late lumping approach, feedforward and feedback controllers, based on flatness and backstepping.

Control of flexible mechanical systems based on PH models. Our flexible link lab manipulator serves as a test bench for the experimental validation of numerical control methods based on structure-preserving discretization. The use of an industrial PLC and the communication via real-time Ethernet and CAN bus impose the consideration of communication delays and the use of discrete-time modeling and control.

Energy errors under structure-preserving numerical integration of PH systems: Both approximations of supplied and stored energy are consistent with the order of the symplectic integration scheme (Lobatto IIIA/IIB pairs).

Numerical methods for port-Hamiltonian systems. Preserving the mathematical structure that represents power exchange and energy storage in port-Hamiltonian (PH) system models is a desirable feature of discretization methods. We work on structure-preserving discretization schemes in space and time and exploit the resulting models for nonlinear trajectory planning and feedback control.

Structured modeling and order reduction of coupled phenomena. Within the DFG-ANR funded project INFIDHEM we develop in a first stage structured, high-dimensional numerical models for the heat transfer on dual complexes, as given by the structure of catalytic foams. The structure of the models will be preserved in a second stage of parametric model order reduction.
High-Performance Control of Constrained Fast Systems

There is great interest in modern robots for transportation and service capable of performing fast maneuvers while maintaining stability at all times. As these systems are often inherently nonlinear, unstable and fast, control requirements are increasing rapidly. Our groups pursue two main approaches to high-performance control of such systems: model predictive control (MPC) and Lyapunov-based nonlinear control methods. The main advantage of the MPC paradigm is the possibility of systematically considering constraints on input and state variables. However, the real-world application of nonlinear MPC remains challenging, as non-convex optimization problems have to be solved online with sufficient accuracy in order to obtain desirable closed-loop dynamics. Currently, a novel control concept for multirotor systems using adaptive and predictive components is developed in cooperation with the Institute of Flight System Dynamics.

Lyapunov-based techniques can use a linear representation of the nonlinear system to design a controller that stabilizes an operating point locally. Particularly, low- and high-gain methods require the solution of either a Riccati or a parametric Lyapunov equation providing an optimal control law together with a contractive Lyapunov function which, for systems under input saturation, can be used as an estimate of the domain of attraction. The main advantage of this approach results from the controller structure, which allows the convergence rate of the trajectories to be accelerated by discretely or continuously scheduling a single parameter. Nevertheless, as long as the closed-loop system is not operated in a region sufficiently close to the nominal setpoint, the linearization does not accurately reflect the behavior of the nonlinear system. Therefore, our chair conducts further research focusing on regulation and tracking tasks using different nonlinear approaches, like command governors and extended linearization.
Research Focus
- Automotive and active vibration control
- Model order reduction
- Model predictive and optimal control
- Energy-based modeling and control
- Modeling and control of distributed parameter systems
- Takagi-Sugeno models, agent-based modeling
- Learning control and artificial intelligence

Competence
- Mechatronic systems design and control
- Modeling, analysis and control of technical and non-technical processes
- Control and optimization
- Adaptive, learning and model predictive control

Infrastructure
- Two quarter-car test stands
- Various mechatronic test rigs and (autonomous) robots
- Modular flexible link manipulator
- High-resolution optical tracking system
- Control systems design lab
- Electrical and mechanical workshop

Courses
- Regelungstechnik
- Systemtheorie in der Mechatronik
- Moderne Methoden der Regelungs-technik 1-3
- Zeitdiskrete Systeme und Abtast-regelung
- Künstliche Intelligenz in der Fahrzeug-technik
- Advanced Control
- Nonlinear Control
- Lab Course ‘Computergestützter Regelungsentwurf’
- Lab Course ‘Moderne Methoden der Regelungstechnik’
- Lab Course ‘Reglerimplementierung auf Mikrocontrollern’

Publications 2018
- Dengler, C.; Lohmann, B.: Actor-critic reinforcement learning for the feedback control of a swinging chain. 2nd IFAC Conference on Modelling, Identification and Control of Nonlinear Systems (MICNON), 2018
- Strohm, J. N.; Lohmann, B.: A Fast Convergence FxLMS Algorithm for Vibration Damping of a Quarter Car. 57th IEEE Conference on Decision and Control (CDC), 2018
Micro Technology and Medical Device Technology

Computational design and rapid manufacturing of certified devices, mechanisms and robots

The focus of the Institute of Micro Technology and Medical Device Technology is to accelerate the process of developing ideas into products. In research and science, the time required for implementation is a significant factor for success. Therefore, rapid prototyping and rapid manufacturing technologies are part of our main research interest. We are systematically developing and analyzing new rapid technologies, as well as applying them in the areas of precision engineering, micro technology and medical device technology. We are systematically validating our research devices to achieve reliable scientific results. In the area of medical technology, we develop according to ISO 13485, certify our devices according to MDD/FDA and perform clinical studies according to ISO 14155.

Incremental Casting: Droplet-based Generative Fabrication of Parts from Aluminum-Alloys

Most additive manufacturing processes today are based on polymeric building materials. Despite their superior properties, metals are a far less common building material for three dimensional printing (3DP). Although there are commercial processes for the additive manufacturing of metallic products, the high equipment costs impede their widespread adoption. Therefore a novel 3DP process based on the direct deposition of droplets of molten aluminum was developed in a joint DFG-funded (LU604/42) research project in cooperation with the Chair of Metal Forming and Casting (utg).

In this project, a pneumatically actuated droplet generator is used to generate droplets of molten aluminum alloys at temperatures of up to 750 °C. The droplets are deposited on a heated build platform which is mounted on a computer-controlled translation stage situated in an inert gas atmosphere. This setup enables cost effective 3D printing of aluminum parts without any intermediate steps.

Patient-Specific Heart Valve Replicas for Preoperative Planning

Heart valve regurgitation results in heart valves not closing completely, which impairs the pumping function of the heart. With heart valve repair, heart surgeons restore the normal function of heart valves with regurgitation. Preoperative planning on heart valve repair is done with ultrasound imaging. However, the ultrasound images only provide vague information of the heart valves. The real planning of the repair only takes place during the operation after the heart surgeon has inspected the patient's heart valve. To improve the planning of heart valve repair patient-specific heart valve replicas are developed. Three-dimensional ultrasound images of the patient's heart are taken and a virtual model of the heart valve with the regurgitation is segmented and manufactured. The replicas make the patients' heart valves tangible and they provide heart surgeons with a better understanding of the heart valves preoperatively. Heart surgeons simulate heart valve repair with their hands and instruments on the heart valve replicas as in a real operation. This may be helpful in the planning of complex heart valve repairs.
Droplet-based Additive Manufacturing with Polymers

The claim in additive manufacturing is changing more and more from just generating prototypes for demonstrating issues to producing final functional parts. This increases the requirements concerning the freedom of material, dimensional accuracy and component properties. In 2013, after a collaboration with our institute, Arburg GmbH introduced Arburg Plastic Freeforming (APF) as a novel droplet-based additive manufacturing method. Using conventional thermoplastic polymers, the Arburg Freeformer expands the freedom of manufacturing. In earlier collaborations, our institute took part in designing the droplet generator and the data preprocessing. Present research concentrates on investigating in the achievable component properties and introducing new materials for the manufacturing process. Furthermore, material parameters and dimensional accuracy of the manufactured parts should be optimized systematically. Therefore, new building strategies are developed to influence the temperature distribution during the manufacturing process. In this way unwanted effects like curling can be reduced and dimensional accuracy can be improved.

Machine Learning Based Algorithms for Kinematic Synthesis

Kinematic synthesis of four-bar linkages is solved graphically in the plane using a maximum of five positions of the coupler. For more than five positions, optimization methods are implemented to find the best approximation of the lengths of the mechanism for the desired curve. However, these methods are computationally complex and a mechanism needs to be computed for each new curve. The goal of this research is to optimize the relationship between coupler curves and lengths of the four-bar linkage. Once this relationship is optimized, the dimensions of the mechanism are automatically computed for a specific curve. This process is fast in terms of complexity, once the optimization is made. The results show that a handdrawn path of a foot taken from a walking video, when tested, has a four-bar linkage solution.
SLS-printed Grippers

Individualized monolithic flexure hinge structures with helical end pose manufactured using selective laser sintering (MiMed)

Shape Memory Structures
The particularly compliant and adaptable properties of soft robotic systems offer enormous potential for use in unpredictable environments as well as for safe and interactive work in human environments. The approach examined is an automated design process for monolithic soft robotic structures that can assume pre-defined end poses.

Shape memory structures

Thereby, the idea is to design simple individualizable systems that are 3D-printable and require a minimum number of actuators. Using the automated design process, we can generate soft robotic systems that show flexible characteristics in the undeflected mode and a pre-defined end pose in the stiff deflected mode. Therefore, we call them shape memory structures.

Spine-based Soft Robotic Structures
The research deals with hybrid soft robotic systems consisting of a 3D-printed skeletal framework integrated into a soft material body covering the robot. The extrinsically soft framework structure enables functional structures to be integrated into the otherwise intrinsically soft structure and sensor elements to be positioned precisely. This approach allows reproduction of bionic structures, which typically consist of skeletons for stabilization and force application as well as surrounding soft tissue for force transmission and protection.

Structural Shape Optimization

A design example with structural shape optimization (CAO and SKO) (MiMed)

In the early days, the development of the structural design was always limited by the manufacturing techniques. The reason is that the traditional tools cannot reach the precision of some complicated structures. With the development of additive manufacturing, this limit for structural design can be overcome. It also means that the manufacturing-driven design is gradually shifted to design-driven manufacturing. Against this background, our group is developing some structural optimization algorithms (CAO, SKO, etc.) with the help of a constructing toolbox ‘SG Library’ in Matlab. The basic idea of such optimization algorithms is to allow the design proposal for the desired component to grow into a shape with constant von Mises stress at its surface, which makes the component much stronger under the same load. Our aim is to achieve such a lightweight design with a shorter design period.
Research Focus
- Medical navigation and robotics
- 3D printing of robots and instruments
- Additive production technology
- Micro-technological production
- Synthesis of kinematics
- Assistance systems for the aging society

Competence
- Automatic CAD construction/Matlab
- Synthesis of joint mechanisms
- 3D measurement technology (optical, EM)
- Robotics
- Mechatronic control
- Quality management (ISO 9001/13485)
- Droplet generation

Infrastructure
- Precision mechanics workshop (ISO13485)
- Micro-technology laser treatment
- Additive manufacturing systems (3D printing, FDM, SLS, freeformer)
- Certified OR
- Electronics workshop

Courses
- Microsystem Technology
- Medical Device Technology
- Automation in Medicine
- Admission of Medical Devices
- Kinematics
- Mathematical Tools for Engineers

Publications 2018
Medical Materials and Medical Implant Design

Polymer engineering, additive manufacturing, cell-based medical engineering, IoT and materials, MedTech OneWorld initiative

In 2018 several forward-looking projects were established. The founding of the MedTech OneWorld initiative, in which the internationalization activities of the chair in teaching and research are bundled, was of particular significance. International R&D groups were set up in Singapore and Ethiopia. Another highlight was the successful spin-off of KUMOVIS GmbH, winner of the competition, ‘Münchener Businessplan Wettbewerb 2018’.

In 2018, the chair was again significantly involved in the design of the Master’s programme in Medical Technology and Engineering. In addition, the chair taught the basics of plastics technology in lectures, seminars and internships.

The focus of research & development in 2018 continued to be on medical plastics engineering technology. In addition to working on existing projects, five new projects were acquired in 2018.

IoT and Plastics
Coordinator: Dipl.-Ing. Valerie Werner

SmartMold: Integration of IoT Electronics in Plastic Parts
(Funding: Internal; Leader: Dipl.-Ing. Valerie Werner)
Within the thematic focus ‘Digitale Gesundheit und Medizin’ of the Zentrum Digitalisierung Bayern, the chair coordinates the Community of Practice ‘IoT & Werkstoffe’.
In 2018, the foundations were laid for the creation of a ZIM cooperative network with eight industrial and academic network partners, in which R&D projects for the realization of smart biomedical plastic products are to be carried out from 2019.

Electronic components that are to be integrated into plastic parts using processes suitable for mass production (Photo: Tobias Hase)
**Plastics Engineering**
Coordinator: Dipl.-Ing. Matthias Zeppenfeld

**BioPolFol: Antimicrobial Plastics Based on Electrets**  
(Funding: BMWi; Leader: Markus Ahrens, M.Sc.)

Studies show that around 11 million tons of food are disposed of as waste in Germany every year. The aim is therefore to extend the shelf life of food. Plastic packaging plays a major role in this, with bioplastics becoming the focus of interest. Through certain modifications a charge change on the plastic surface can be achieved, so that electrets are produced. Electrets are materials that can store oriented electrical dipoles or an excessive electrical charge for a certain period of time and can also exert an antimicrobial effect. The aim of the BioPolFol project is to develop electrets with antimicrobial properties on the basis of various bioplastics by means of surface treatment.

**Cell-based Medical Engineering**
Coordinator: Dr. Markus Eblenkamp

**Lab 4.0: Smart Bioreactors for Cell-based Therapies**  
(Funding: StMWi; Leader: Richard Schmid, M.Sc.)

Cell-based methods offer fascinating new therapeutic possibilities ('healing with cells'). The goal of the project is the development of miniaturized, mobile, intelligent systems for the cultivation and transport of therapeutic biological samples. The highly function-integrated plastic systems will be equipped with a wide range of sensors and digital, cloud-enabled interfaces that allow continuous process control and online process monitoring over the entire cultivation time.

**AntiMik2: Antimicrobial Plastics Based on TiO₂**  
(Funding: BMWi; Leader: Theresa Fischer, M.Sc.)

Surfaces in medical facilities are always considered to be contaminated by microbes. These surface pathogens often form biofilms in which microorganisms stabilize each other and thus make decontamination more difficult. The resulting contaminations are further spread through contact between the hands of hospital staff and surfaces which leads to hospital infections. Antimicrobial polymers can be used in order to prevent the transmission of germs via surfaces. This project focuses on the development of a permanently antimicrobial silicone elastomer as an overlay material for relevant contact surfaces in medical areas.
**Additive Plastics Processing**
Coordinator: Stefan Leonhardt, M.Sc.

**filAMent: High Performance Filaments for Additive Manufacturing**
(Funding: Internal; Leader: Fabian Jodeit, M.Sc.)

The quality of the filaments as semi-finished products has a decisive influence on the quality of the FDM 3D printing process and the properties of the resulting parts. In the project filAMent, plastics relevant to medical technology are systematically processed as FDM filaments, evaluated with regard to their printability and further optimized using additives.

**APROV RB: Development of a Realistic Surgical Phantom for Minimally Invasive Surgery**
(Funding: Zeidler-Forschung-Stiftung; Leader: Sebastian Pammer, M.Sc.)

Using additive manufacturing, an abdominal phantom was developed which is characterized by a previously unattained reality of the intraoperative situation. It represents an excellent exercise model for surgeons, which can also be used to simulate patient-specific surgical conditions in preparation for surgery.

**CONNECT: Minimally Invasive Implant for the Connection of Intestinal Ends (Anastomosis)**
(Funding: DFG; Leader: Stefanie Ficht, M.Sc.)
Using additive manufacturing, a degradable implant is developed with which the intestinal ends, after partial intestinal resections, can be surgically connected in a minimally invasive procedure.

**RapidNAM: Automated Production of Palatal Plates for the Treatment of Cleft Lip and Palate**
(Funding: Zeidler-Forschung-Stiftung, Leader: Franz Bauer, M.Sc.)
Using additive manufacturing and digital techniques, a system for generating individualized palatal plates for early childhood therapy of cleft lip palates was developed.
Medical Materials and Medical Implant Design

MedTech OneWorld
Coordinator: Fabian Jodeit, M.Sc.; Dr. Markus Eblenkamp

The MedTech OneWorld initiative was founded to bundle and strategically align the chair’s international projects. Special attention is paid to developing countries. The aim is to implement high-tech medical engineering solutions in emerging regions. In Singapore and Addis Ababa (Ethiopia) the basis for joint research labs was laid. Furthermore, the student research group ‘MedTech OneWorld Students’ has developed from this commitment and currently has around 30 active members.

Events

Symposium on Medical Plastics Engineering, Singapore

The specific aspects of plastics technology for the manufacture of medical products was the focus of the symposium and was elaborated by experts from renowned institutions. In addition, the symposium was to serve as the kick-off event for a permanent joint initiative and formation of international cooperation clusters on medical plastics engineering in Singapore.

New Frontiers in Biomedical Additive Manufacturing, Singapore

As an initiator, the chair, in cooperation with TUM Asia, NUS and NAMIC (National Additive Manufacturing Innovation Center), organized the networking seminar ‘New Frontiers in Biomedical Additive Manufacturing’ in Singapore on 6 February 2018. It was possible to bring together a cross-section of the Singaporean and German players in additive manufacturing (academic institutions, AM companies, clusters and funding organizations) and thus lay the foundations for joint international R&D projects to be implemented in 2019.

Congress Zukunftsrat der Bayerischen Wirtschaft, Munich

On 16 July 2018, this year’s congress of the Zukunftsrat der Bayerischen Wirtschaft on the topic of ‘health and medicine’ took place. The chair presented its teaching and research activities in the field of additive manufacturing, cell-based medical engineering and the internationalization initiative MedTech OneWorld.
Entrepreneurship – From Bench to Market and Bedside

KUMOVIS GmbH
This spin-off of the chair (Miriam Haerst, Stefan Leonardt, Alexander Henhammer, Sebastian Pammer and Stefan Fischer) has won the competition, ‘Münchner Businessplan Wettbewerb 2018’. KUMOVIS is developing a printer technology for processing high-performance polymers such as PEEK for medical applications. The team and the first concepts emerged from a project seminar of our chair. In 2018 the developments and the business concept were driven forward in the context of a successfully acquired EXIST transfer of research grant.

IMPACT Platform for Autologous Cell Therapies
The use of blood derivatives, e.g. platelet-rich plasma (PRP), to support the healing processes of injuries and surgical interventions is becoming increasingly important. Based on the developments of previous years, it was possible to bring a system for the fully automatic production of PRP and other autologous cell therapy derivatives to market maturity in 2018 via Plasmaconcept AG with the support of our chair.

inveox GmbH
Within the framework of an EXIST company founder grant and development cooperation, the chair supported the further development of inveox. The aim of its technology is to automate pathological processes in order to increase the efficiency of the processes and, in particular, to make them safer and the diagnoses more reliable for the benefit of patients.

Vocational Training
In 2018, the chair under the direction of Mr. Uli Ebner continued its intensive commitment to vocational training. Currently, six apprentices are being trained in precision mechanics.
Medical Materials and Medical Implant Design

Research Focus
- Medical materials
- Polymer technology
- Machine and process technology
- Cell-based medical engineering
- Implantology

Competence
- Polymer processing
- Additive manufacturing
- Materials testing, incl. biocompatibility
- Bioreactor designing
- Blood processing

Infrastructure
- Technical lab (CNC milling machine, water jet cutting, etc.)
- Bio lab (biocompatibility and sterility testing)
- Polymer lab (injection molding, extrusion, compounding, testing)
- 3D lab (DLP, FLM, multijet printing)
- Electronic lab (anechoic chamber, micrograph analysis, etc.)

Courses
- Introduction in Medical and Polymer Technology
- Biocompatible Materials
- Plastics and Plastic Processing
- Trends in Medical Engineering
- Vascular Systems

Selected Publications 2018
- Düregger, Katharina; Trik, Sina; Leonhardt, Stefan; Eblenkamp, Markus: Additive-manufactured microporous polymer membranes for biomedical in vitro applications. Journal of Biomaterials Applications 33 (1), 2018, 116-126
- Grill, Florian D; Ritschl, Lucas M; Dikel, Hannes; Rau, Andrea; Roth, Maximilian; Eblenkamp, Markus; Wolff, Klaus-Dietrich; Loeffelbein, Denys J; Bauer, Franz X: Facilitating CAD/CAM nasoalveolar molding therapy with a novel click-in system for nasal stents ensuring a quick and user-friendly chairside nasal stent exchange. Scientific Reports 8 (1), 2018

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Nuclear Engineering

The focus of the Chair of Nuclear Engineering in 2018 was the development of multi-physics nuclear safety methodologies with coupled code systems, with particular emphasis on uncertainty and sensitivity determination; experimental two-phase flow thermal-hydraulics regarding the behavior of droplets entrained in the flow along pipes; the simulation of the behavior of thorium-based nuclear fuel; the further development of advanced molten salt reactor concepts, and the development and testing of numerical methods to simulate the dynamics and the mass and heat transfer of bubbles in two-phase vertical flows. The work has been performed in collaboration with other German and international research institutes (NBJC (PL), KIT (D), ITU (D), GRS (D),) and university departments (Harbin University (CN), UPV (E), UPM (E), KTH(S), and Chalmers (S)). In 2018 Prof. Macian was made a Guest Professor of Nuclear Engineering at the College of Nuclear Engineering at Harbin University in Northern China.

Nuclear Reactor Safety Analysis of Current and Future Reactor Designs

Research on nuclear safety is the main area of the chair’s activities and it is carried out with sophisticated computational methodologies. They integrate the most important physical processes that drive the response of nuclear systems during operation and off-operation conditions. The projects currently ongoing focus on local multi-physics descriptions of the behavior of fuel assemblies to rod displacements and vibrations and to flow oscillations. The changes in the ratios of fuel to moderator resulting from them generate coupled feedbacks between the neutron flux and the moderator and fuel temperatures and densities. Understanding them is fundamental for a series of important phenomena which can impact on the power oscillations in the core, on the appearance of ‘hot spots’ in the fuel rods and on the onset of dangerous rises in heat flux which can damage the rods. For the analyses of these phenomena we have created a detailed ‘numerical test reactor’ based on the computational fluid dynamics (CFD) code ANSYS/CFX coupled in real time with state-of-the-art multi-dimensional time-dependent neutronic codes (PARCS). Dynamic feedback can then be calculated at the level of individual fuel rods. The test reactor consists of nine fuel assemblies fully coupled and driven by the boundary flow and neutronic conditions. A technique has been developed to simulate rod and fuel assembly displacements by modifying moderator to fuel ratios and the cross-section information following the position of the fuel assemblies during simulation time. The result is a very detailed dynamic description of the power distribution inside the core model. Larger cores are methodologically possible, but new approaches will be explored to reduce the need for computational resources.

Related Projects

- Development and assessment of methodologies for the analysis of neutron oscillations in PWR fuel assemblies (BMWi)
- Development of a methodology for local BWR stability analysis (StMWFK)
- Mechanical analysis of bowing in PWR fuel assemblies (E.On Kernkraft)
Experimental Two-Phase Flow Thermal-hydraulics

At the Chair of Nuclear Engineering we operate a two-phase flow experimental laboratory with three facilities: a scaled hot-leg of a PWR reactor with injection of emergency coolant (COLLIDER); a low pressure loop with a vertical test section to study bubble condensation (SCUBA), and a scaled version of a safety coolant tank, in which steam condensation can be studied. Counter-current flow limitation (CCFL) is one of the important two-phase flow phenomena related to the safety of pressurized water reactors (PWRs) during SBLOCA accidents. CCFL is characterized by a complex interfacial topology and scaling effects are still a main issue for the entrainment in downscaled models. In collaboration with the Institute of Nuclear Safety System and Kobe University both in Japan, an in-depth comparative study of CCFL data in a scaled PWR hot-leg pipe geometry obtained at the COLLIDER and at the Kobe University facilities has been carried out. The detailed comparative analysis of the data yielded important insights into the most relevant hydraulic criteria for the CCFL onset, as well as on the effect of the scale of the experimental test sections on the most relevant mechanisms for CCFL in different parts of the pipe mock-up.

Related Projects
■ SCUBA: Experimental investigation of the condensation phenomena in large steam bubbles at atmospheric pressure (E.On Kernkraft)
■ COLLIDER: Experimental investigation of counter current flow in a scaled model of the hot-leg of a Konvoi-PWR (E.On Kernkraft)
■ Experimental studies of condensation in the suppression pool of BWR reactors (with U. Politécnica de Madrid (E))

Development and Design Optimization of the Dual Fluid Reactor (DFR) Concept

The Dual Fluid Reactor (DFR), a new concept of nuclear reactor conceived at the Institute of Solid State and Nuclear Physics (IFK) in Berlin, has been a research topic at the chair for several years. The reactor consists of a molten salt core and a second molten metal (lead) as coolant. With this configuration, the DFR can fission long-lived radioactive isotopes present in spent nuclear fuel, thus removing the need to supervise nuclear waste for very long periods of time. A high efficiency using the available nuclear fuel resources by breeding more fuel than it needs to operate allows for the use of the enormous amount of thorium and uranium on earth for future energy production. The work in 2018 focused on the study of the operational strategies and neutronic characteristics of the DFR core and on the on-line reprocessing of fission products produced during reactor operation. This work, performed in the context of a BMWi-funded project, has been done in collaboration with IFK researchers and has yielded a detailed analysis of the feasibility and fundamental operational characteristics of a series of proposed pyrochemical processes, which can be used during DFR operation for the extraction of
fission products. In addition, a prototype of a machine for the fast processing of conventional fuel assemblies has also been proposed in order to feed the DFR reactor with spent nuclear fuel from conventional nuclear power plants, so that the minor actinides present in this fuel can be efficiently destroyed by the fast neutron flux of the DFR reactor core. A new project is in preparation in collaboration with IFK and the Fachhochschule Darmstadt to continue the developments initiated with this first project. Additionally, work has started in collaboration with the Center for Nuclear Research (NCBJ) in Poland funded by a PhD-student grant program from the polish Government to perform the dynamic analysis of the DFR with state-of-the-art system analysis codes.

Related Projects

- Development of a coupled neutronic and thermal-hydraulic models for the Dual Fluid Reactor concept (molten salt coolant) (E.On Kernkraft)
- NuDest Project: Development of chemical techniques for the pyroprocessing of fission products and minor actinides (BMWi)

Uncertainty and Sensitivity Methodologies Applied to Nuclear Safety

The safety analysis of nuclear systems requires the use of complex programs capable of simulating their behavior. The physical models used in them are the best available at the time, but they cannot describe all the physics involved. Moreover, even if the models are very complete, they are still the result of experimental data fitting procedures and, therefore, their accuracy depends strongly on the quality of the data. For these reasons their predictions are affected by uncertainty, which is then propagated and combined with those of other models used in a given analysis of the final simulation results. Uncertainty affects any description of nuclear system behavior, such as thermal-hydraulics, neutronics and fuel behavior. The development and application of methodologies for its quantification is an important part of the chair’s research work. Two main EU-funded projects are currently under way: SESAME and CORTEX. The first one addresses the issue of uncertainty and sensitivity for molten metal reactors in multi-physics applications with coupled-system and CFD computer codes (ATHLET-ANSYS CFX), and the other one deals with the propagation of uncertainty in neutron noise calculations (CORESIM and PARCS). Both projects are developing integrated computer frameworks to carry out automatic sensitivity determination and surrogate function development and are embedded in a larger effort related to simulations and experimental data evaluation (TALL, CROCUS and AKR-2 facilities) carried out by the other international project partners.
In order to complement the research on experimental two-phase flow, the chair is also involved in the development of detailed models for the simulation of bubble dynamics, interfacial friction and mass and heat transfer across the steam-liquid interface. These models are then implemented in advanced CFD codes, such as OpenFOAM, and tested against our own experimental data and data from a variety of other sources. The work carried out in 2018 in this area extended a newly developed volume of fluid (VoF) method used in OpenFOAM, isoAdvector, to a coupled method (CLSISO) which combines the advantages of both the geometric VoF and the level set (LS) approaches for the simulation of bubble dynamics in still liquid. The isoAdvector method preserves a sharper interface than the algebraic VoF method (MULES). Thus, the CLSISO method can not only considerably reduce the magnitude of the non-physical parasitic currents surrounding the bubbles but also preserve the sharp interface of the bubbles and follow their breakup. Peripheral breakup patterns are thus found and both complex bubble’s radius stretching and central breakup can also be reproduced. The analysis of predicted breakup patterns permitted the identification of a new breakup behavior, already seen in our experiments, for large bubbles: in the central breakup region during the toroidal stage: a pinch of the torus develops at the top and moves downwards leading into a peripheral breakup at the bottom of the bubble (torus).

Related Project
- Development of advanced models for two-phase-flow simulation with computational fluid dynamics (CFD) codes (supported by the China Scholarship Council)
Nuclear Engineering

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Research Focus
- Thermal-hydraulic and neutronic analysis of current and advanced nuclear systems
- Reactor dynamics
- Nuclear fuel behavior
- Experimental two-phase flow
- Radiation transport and radiation protection
- Medical applications of radiation
- The development and application of Uncertainty Analysis methodologies

Competence
- Safety analysis for nuclear systems and fuel behavior
- Two-phase flow experimental measurements
- Monte-Carlo based radiation transport and Radiation dosimetry calculations
- Single and two-phase flow computational fluid dynamics
- Nuclear reactor dynamics
- Molten salt reactor technology

Infrastructure
- Thermal-hydraulic two-phase flow laboratory
- Computer laboratory with state-of-the-art nuclear safety codes

Courses
- Introduction to Nuclear Energy
- Fundamentals of Nuclear Engineering
- Applications of Radiation to Medicine, Research and Industry
- Fundamentals of Thermal-hydraulics in Nuclear Systems
- Advanced and Future Nuclear Reactor Systems
- Radiation and Radiation Protection
- Nuclear Fusion Technology
- Nuclear Safety Seminar
- Praktikum on the Use of System Analysis Codes in Nuclear Safety

Selected Publications 2018
Vibroacoustics of Vehicles and Machines

Vibroacoustics, acoustics of vehicles, experimental acoustics, computational acoustics (FEM/BEM), structural dynamics and structure-borne sound, uncertainty quantification, damage detection, acoustic porous materials

The Chair of Vibroacoustics of Vehicles and Machines deals with various aspects of simulation, experiment and fabrication in acoustics, noise reduction and applications in industry. Research in this group in 2018 covered a wide range of topics in establishing computational and simulation algorithms with the aim of developing novel methods for noise and vibration insulations.

Calm, Smooth and Smart: DFG Priority Program PP1897

Within the framework of a project in the DFG priority program 1897 ‘Calm, Smooth and Smart’, damping of lightweight structures by virtue of sound radiation is studied. A numerical framework for solving the fully coupled structural acoustic interaction problem has been developed in order to predict the extent of acoustic radiation damping. In particular, sandwich panels, consisting of two thin and stiff face sheets enclosing a thick, lightweight and often anisotropic core, were investigated last year (2018). They exhibit high radiation damping in a wide range of frequencies due to the anisotropy of the flexural wave speed and due to the presence of local bending motions of the face sheets that cause sound radiation in addition to the global bending motion. Fig. 1 shows the simulation model of an exemplary panel that is made of a honeycomb sandwich material typically used in aerospace engineering along with its predicted radiation loss factors. Considering that loss factors associated with other dissipative mechanisms (such as material inherent damping) are often well below 10⁻¹, those results clearly demonstrate the significance of radiation damping. Therefore, the results of this project enable other engineers to better estimate the relevance of radiation damping in order to take well-informed action for vibration mitigation in the future.

Innovative Modeling Strategy in Vibroacoustics for Complex Structures

A new methodical approach establishes the relations between the individual components of simulation and experiment. It enables the influence of uncertainties during the developing process to be analyzed. Typically, a computer-aided design (CAD) model is used to manufacture a physical structure. While the CAD model leads to one three-dimensional (3D) finite element (FE) model as usual, a second FE model was compiled from computed tomography (CT)
measurements of the investigated engine assembly components. The advantage of this procedure is an excellent approximation of the uncertainties resulting from manufacturing tolerances with respect to the parts’ geometry. The assembly process of the individual components yields uncertain parameters in connection with bolted joints. The influence of the bolts’ pre-load forces and the interface and contact properties are examples. If the 3D FE model has been established by CT, there are three main categories into which uncertainties: material, discretization, and contact uncertainties, see Fig. 2. The material parameters taken into consideration are Young’s modulus $E$, Poisson’s ratio $\nu$, and the density $\rho$. These are uncertain with respect to their spatial distribution $\vec{x}$ and their value $\psi$. Discretization errors can result from distorted elements, non-converged element sizes, or the approximation with respect to geometry connected to the CAD model. Bolts influence the result significantly, as the system’s stiffness varies with bolt pre-stress and induced interfacial stiffness. After both the total uncertainties resulting from measurement and simulation are determined, they are compared together with the respective spreads. A sensitivity analysis concerning individual uncertainties is possible.

**Squeak Noise Prediction using Nonlinear Calculation Methods**

In a vehicle cabin, a number of sounds reach a passenger’s ear. Some of them are wanted and even especially designed to be heard such as the engine sound. Others are undesired and found to be disturbing; they are referred to as noise. In customer surveys, interior noise is one of the top issues and a reason for warranty claims. In order to avoid related costs and unsatisfied customers, manufacturers put a lot of effort into the development of silent interiors. While hardware tests are conducted at the end of the development process, virtual methods can be used to identify problems at an early stage. In order to predict noise more reliably than with state-of-the-art linear FE calculations, nonlinear calculation methods are applied. Contact and friction are taken into account, facilitating the calculation of the system’s actual response. The results are used to calculate the radiated sound power as a measure for radiated noise, see Fig. 3.

**Vibroacoustic Analysis of Ultrasonic Transducers**

Ultrasonic transducers play an important role in surround sensing for automotive and industrial applications. The development of autonomous driving functions is one of the top challenges for mobility solutions of the 21st century. Key enabler for this are high performance surround sensing systems. In cooperation with Robert Bosch GmbH, the use of acoustic metamaterial is investigated in order to achieve ultrasonic transducers with increased performance. A major design challenge is the achievement of low mechanical cross-coupling between the single transducer elements. Cross-coupling induces a loss of imaging resolution. In this work, the mechanical cross-coupling between acoustic transducers is investigated for a generic model. The model contains a common backing with two bending elements bonded on top. The dimensions of the backing are small; thus, wave reflections on the backing edges have to be considered, cf. Fig. 4.
Sound Design, Structural Optimization and Casting of a Jazz Bell

Within a master thesis project, the Chair of Vibroacoustics of Vehicles and Machines cooperated with the Chair of Metal Forming and Casting. Based on an idea that arose in the practical course ‘Schallabstrahlung’ (sound radiation), the purpose of this project was to choose a sound, create a bell model and optimize this model with respect to the required sound. The final version of the bell was cast. An A9 chord, which is typical for cool jazz, was chosen as a target sound. Though jazz is rather far from traditional central European church bells, for this chord the ratios of the respective frequencies to the fundamental are very close to the ones of a major-third bell. The shape of the latter was used as a starting point for the structural optimization in Comsol Multiphysics, which is a numerical simulation tool to solve various types of physical problems. Using the MatLab LiveLink and a genetic optimization algorithm, as well as a carefully chosen set of parameters together with the appropriate target function, the bell was structurally optimized for the frequencies to match the A9 chord. As the final shape was obtained, the casting was simulated using MagmaSoft® in order to determine the best casting system. Hereby, two favored options were identified and hence two models were created for each. All together four bells were cast. Geometrical and acoustical measurements of the cast bells showed that the deviance of all four from the model, regarding geometry as well as resonant frequencies, was rather small, see Fig. 5. The final result coincides well with the model. Yet, with the idea being successfully implemented, new prospects have come up with respect to optimization procedures taking aesthetic aspects into account. A comprehensive video can be found at: https://youtu.be/Ha6cxOm_vCk.
Vibroacoustics of Vehicles and Machines

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Research Focus
- Computational acoustics (FEM, BEM)
- Virtual prototyping
- Identification of uncertain parameters
- Lightweight material characterization
- Non-destructive testing for damage detection
- Sound propagation in flow
- Normal modes in external acoustics
- Acoustics in porous media

Competence
- Vibrational and acoustical measurements
- Computational acoustics (FEM, BEM)
- Modal analysis
- Vibroacoustic simulation
- Fluid-structure interaction
- Self-sustained vibrations
- Structural-acoustic optimization
- Identification of admittance boundary conditions

Infrastructure
- 3D laser Doppler scanning vibrometer (Polytec)
- Multichannel measurement system (B&K)
- Acoustic camera (B&K)

Courses
Various courses, training sessions and workshop modules have been developed and were offered at graduate and undergraduate levels during the last academic year.
- Introduction to Vibroacoustics
- Computational Acoustics
- Applied FEM in Vibroacoustics
- Stochastic Finite Element Method in Vibroacoustics
- Modeling in Vibroacoustics
- Sound Radiation
- Colloquium on Acoustics
- Industry Related FE-Analysis in Vibroacoustics
- Vibroacoustic Signal Processing

Selected Publications 2018
- S. Marburg, A pollution effect in the boundary element method for acoustic problems, J. of Theoretical and Computational Acoustics 26 (02), 1850018 (2018)
- P. Langer, K. Sepahvand, C. Guist, J. Bär, A. Peplow and S. Marburg, Matching experimental and three dimensional numerical models for structural vibration problems with uncertainties, J. of Sound and Vibration 417, 294-305, 2018
- K. Weisheit and S. Marburg, Model Reduction Technique for Analysing Friction-Induced Vibrations and Radiated Sound, Int. J. of Automotive Engineering 9 (4), 178-185, 2018
The highlight for the Plasma Material Interaction Group in 2018 was the commissioning of the new high-current source SIESTA for precise erosion and retention studies of plasma facing materials.

**Validation of the 3D Sputter Code SDTrimSP-3D**

SIESTA, the ‘Second Ion Experiment for Sputtering and TDS Analysis’ is a high-current ion source for erosion and retention studies with focus on wall materials for fusion devices. The system is composed of a DuoPIGatron-type ion source, three consecutive grids for ion extraction, acceleration and beam focusing, a differential pumping stage, a dipole magnet for mass filtering, a quadrupole doublet lens, a target chamber, a load-lock, and a chamber for thermal desorption spectrometry. The acceleration potential of the source can be varied between 0.5 and 10 kV. The target chamber has a base pressure of $10^{-8}$ mbar and an operating pressure of $5 \times 10^{-7}$ mbar. The target can be rotated to study angle-dependent effects and can be heated via electron-impact heating up to 1300 K for high temperature erosion and implantation studies. The target chamber is equipped with an in-situ magnetic suspension balance. The operating parameters of the ion source were optimised to achieve the maximum ion current at the target for various gas species and accelerating potentials. The typical beam footprint at the target has an area of 0.5 cm$^2$ and at ion impact energies of 2 keV/D, the maximum achievable flux density with D$^+$ is $6 \times 10^{19}$ D m$^{-2}$s$^{-1}$.

Dedicated experiments were performed with SIESTA to fully validate the sputter code SDTrimSP-3D with well-defined 3D targets whose surface morphology and composition changed during ion bombardment. These targets consisted of Si and Ta columnar structures of approximately 200 nm in height, 100 nm in diameter and spaced 200 nm, distributed in an orthogonal formation on a mirror-polished Si substrate. Scanning electron microscopy (SEM) imaging prior to exposure was employed to construct a 3D model of the target morphology for the corresponding SDTrimSP-3D simulations. The samples were exposed to a 5 keV Ar$^+$ beam at various fluence steps. The sample morphology was characterized at various positions before and after each fluence step via SEM imaging of ‘focused ion beam’ (FIB) cross sections. Several exposure geometries were investigated. Cross-section images of the samples were compared with the sample morphology modelled by SDTrimSP-3D, providing excellent agreement with the experimental data at all fluence steps. In the case of the Ta sample, SDTrimSP-3D was able to correctly model the geometry of erosion and deposition of both the Ta columns and the Si substrate, thereby validating its use for fully 3D targets of variable composition exposed under geometrically complex scenarios.
Dependence of Oxidation on the Surface Orientation of Tungsten Grains

The surface orientation of crystals has an influence on various material properties, for example on oxidation. A method was developed to correlate the oxidation rate for individual single-crystal grains with their surface orientation. The surface orientation of many grains of polycrystalline, recrystallized tungsten samples was determined using electron backscatter diffraction (EBSD). Subsequently, the samples were oxidized, resulting in a height increase depending on grain orientation. The relative height for each grain was extracted by confocal laser scanning microscopy (CLSM). The absolute values of the oxide layer thickness of the (100) surface orientation were measured by SEM on FIB-prepared cross sections. The relative heights from the CLSM were used to calculate the absolute height of the grains with surface orientation {110}, {210}, {211} and {111}. Figure 3a) provides a map of the thickness of the oxide layer whereas figures 3 b) and c) show the surface orientation of (selected) grains. With the graphic tool GIMP, figures 3a) and 3c) were overlaid highlighting the grain orientation dependent oxidation (figure 3d)).

To verify the above mentioned method for oxide layer thickness determination, grains with surface orientation {110}, {210}, {211} and {111} were also measured using FIB-prepared cross sections. In figure 4 the comparison between oxide layer thicknesses deduced form CLSM and FIB-prepared cross section is shown. The grains with the {100} surface orientation have the highest oxidation rate which is two times higher than those with the lowest oxidation rate. The grains with {111} surface orientation belong to those with lowest oxidation rate, while the {110} surface orientation has an intermediate rate. The good agreement between the CLSM and the FIB measurements provides confidence that it is possible to use the CLSM to determine the absolute thickness of the oxide layer. Since the CLSM can perform millions of height measurements in a minute the method described above opens up the possibility to evaluate crystal dependent properties like oxidation and sputter-erosion for random crystal orientations providing valuable input for first principle calculations of the material properties.

![Figure 3: Example of merging data from different sources: (a) height profile from CLSM of an oxidised W sample; (b) orientation map of the W grains obtained by EBSD before oxidisation; (c) selection of grains with misorientation of less than 10° to low index surfaces; (d) overlay of (a) and (c) highlighting the differences in oxidation for low index grains.](image)

![Figure 4: Grain dependent oxidation of W at 870 K for 30 min. The thickness of the oxide layer is plotted against the surface orientation of grains misoriented less than 10° to five (hkI) planes. The values from relative CLSM measurements are shown as points. The absolute thickness values obtained on FIB-prepared cross sections are shown as bars to compare them with the calculated values from the CLSM. The figure includes data from samples of five independent oxidation experiments and the ‘#’ symbol stands for the number of measurements. The mean values with their standard deviations as error bars are also plotted.](image)
Plasma Material Interaction

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Research Focus
- Detailed understanding of complex interaction processes between plasma and material
- Development of novel materials with improved properties for high heat-load applications
- Integration of new materials into plasma-facing components

Competence
- Measurement and modeling of erosion, surface composition and hydrogen retention of materials
- Laboratory-scale production of thin coatings
- Laboratory-scale production of tungsten fibre reinforced materials
- Design and laboratory scale manufacturing of tungsten fibre reinforced plasma facing components
- Performance and analysis of high heat flux tests of inertially and actively cooled materials and components
- Thermo-mechanical analysis of high heat flux components

Infrastructure
- Tandem-accelerator for surface analysis
- High heat flux ion beam test stand
- Manipulator in the fusion device ASDEX Upgrade
- Low energy plasma source
- Energy and mass filtered ion beam
- Scanning electron microscopy (SEM with focused ion beam (FIB), X-ray spectroscopy (EDX/WDX), electron backscattering diffraction (EBSD)) for loads up to 10 kg
- Atomic force microscope (AFM)
- X-ray diffraction (XRD)
- Confocal laser scanning microscope, digital microscope, optical microscope
- Photo electron spectroscopy (XPS)
- Magnetron sputter devices
- Laser flash analysis
- Vacuum ovens for thermal treatment and desorption

Courses
- Plasma Physics for Engineers
- Plasma Material Interaction

Research Group at:
Max-Planck-Institut für Plasmaphysik,
launded by MPG/HGF and supported by EUROfusion

Selected Publications 2018
(Journal Papers)
Thermo-Fluid Dynamics

Modelling and high fidelity simulation of thermo-acoustic instabilities

In 2018 we made considerable progress in the development of modelling concepts and simulation software for combustion dynamics and combustion noise. Particular emphasis was put on model order reduction and uncertainty quantification.

Dr. Luca Magri, Lecturer at Cambridge University, was awarded a Hans Fischer Junior Fellowship by the TUM Institute of Advanced Studies. He will collaborate with us during the next three years on the prediction and control of extreme events in turbulent reacting flows, employing artificial intelligence and adjoint methods. Dr. Anh Khoa Doan, who recently completed his doctorate at Cambridge University, will support these efforts as post-doctoral research associate in the TFD group.

In highly competitive selection processes we successfully secured funding for a total of six doctoral researchers from the European Commission’s Marie Sklodowska Curie Actions and from ANR/DFG. During the next three years, these funds will support research activities on reduced order modelling and machine learning for thermoacoustic instabilities in (annular) aero-engine combustors, with emphasis on liquid and alternative fuels. Localized unstable eigenmodes in such configurations will be scrutinized by applying recent developments in the physics of non-Hermitian systems. The projects will be carried out in collaboration with research groups in Cambridge, Eindhoven, Genua, Le Mans, Keele, Paris, Trondheim and others.

Research Focus

In 2018, the research efforts of the TFD group have focused almost exclusively on thermoacoustic combustion instabilities. This type of self-excited instability results from a feedback between fluctuations of heat release rate and acoustic perturbations of velocity and pressure, and may occur in combustion applications as diverse as domestic heaters, gas turbines or rocket engines. Possible consequences are increased emissions of noise or pollutants, limited range of operability or severe mechanical damage to a combustor. Thermoacoustic instabilities have hindered the development of low-emission, reliable and flexible combustion systems for power generation and propulsion. Due to their multi-scale and multi-physics nature, the prediction and control of such instabilities is a challenging problem with a wide variety of exciting research challenges.

Analytical Models of Flame Dynamics

Analytical models for the response of a premixed flame to acoustic perturbations often rely on a convective velocity model, where a perturbation that propagates with a velocity of the order of the mean flow speed, generates local perturbations of flame shape and surface. In a recent paper (Steinbacher et al, 2018) we have scrutinized the origin and nature of such convective perturbations in flow-flame-acoustic interactions. The velocity field induced by an acoustic perturbation was decomposed into irrotational-potential and vortical parts, which are both computed using a ‘classical’ analytical method, i.e. Schwarz-Christoffel mapping. The respective effect of each contribution to the flame response was evaluated. In contradiction to the widely accepted premise that vorticity shed at the point of flame anchoring accounts for the convective nature of flow perturbations, it was found that the potential velocity field dominates the flame response, while vortex shedding has only a negligible impact. Based on the observation that the potential part displaces predominantly the flame base, a novel flame-base-displacement model was proposed, which compares well with high-fidelity CFD data at early times, i.e. right after an acoustic perturbation is imposed. However, growth of advected flame front perturbations leads to increasing discrepancies for later times, presumably due to exothermic effects generating vorticity via the Darrieus-Landau mechanism. The important conclusion developed from this study is that in order to properly represent the causality of flow-flame interactions, exothermic effects must be taken into account.
Follow-up work by the same authors investigated the consequences of flame geometry for the linear response of laminar premixed flames to acoustic perturbations. Building on our seminal works on the impulse response of premixed flames, corresponding analytical models were derived for slit, Bunsen and wedge type flames; their respective characteristics were analyzed and validated against high-fidelity numerical simulation. Motivated by the poor agreement between numerical and analytical flame response predictions, particularly for slit flames, an extension to the incompressible-convective velocity model was proposed, which employs a Gaussian kernel function. Such a kernel disperses the flame response in time and leads to very good agreement with simulation as well as experimental data. Detailed analysis of the temporal development of flame shape and surface allowed development of explanations for characteristic features of transfer functions of various flame types. A paper will appear in Combustion and Flame in early 2019.

An analytical model for the response of technically premixed flames to equivalence ratio perturbations was developed and validated by Albayrak et al. (2018). The flame impulse response to a local, impulsive, infinitesimal perturbation that is transported by convection from the flame base towards the flame surface is computed with Model Order Reduction. The TFD group pioneered the utilization of system identification (SI) in order to estimate low-order models of flame dynamics from high-fidelity simulation data. Most recently, Merk et al. (2018) employed advanced SI techniques in order to estimate concurrently impulse and frequency responses as well as combustion noise source terms of a turbulent, premix swirl flame. In a joint project with Ecole Centrale Paris it was confirmed that quantitative agreement with experiment is exceptionally good. Furthermore, advanced SI techniques allow the uncertainty of results to be quantified (see below).

Impulse or frequency responses suffice to fully characterize flame dynamics at low perturbation amplitudes, i.e. in the linear limit. At higher amplitudes, nonlinear effects become important, use of flame describing functions is pervasive in this regime. However, this approach is only weakly nonlinear in the sense that it completely ignores the effects of higher harmonics. Häringer et al. (2018) have formulated an extended flame describing function (xFDF), which takes into account higher harmonics in both input and output. Fortunately, the generation of this type of nonlinear reduced order model does not require more time series data than the generation of a standard describing function. It was shown in the case of a strong instability of a laminar flame that the xFDF brings significant improvement in prediction of limit cycle frequencies and amplitudes.

The studies by Merk et al. and Häringer et al. concentrated on model order reduction (MOR) for the flame dynamics. Beyond that, MOR of a complete model for
thermoacoustic stability analysis is important to reduce computational requirements, and facilitate uncertainty quantification or robust design in thermoacoustics (see below). In 2018 we have seen significant progress in this regard; in collaboration with the Inst. for Automatic Control (Prof. Boris Lohmann) the suitability of three established MOR algorithms for thermoacoustic stability analysis was scrutinized. Interestingly, it was found that acoustic modes are not always an optimal choice for modal MOR.

For systems that are influenced by several parameters and system variables, dimensional analysis based on Buckingham’s \( \pi \)-theorem allows the minimum number of non-dimensional groups that govern the problem at hand to be identified. Surprisingly, this classical approach has not seen much application in thermoacoustic stability analysis. Silva et al. (2018) deduced a set of non-dimensional \( \pi \)-groups from a modal expansion of the quasi-1D Helmholtz equation with a time-lagged heat source. It was found that the non-dimensional frequencies and growth rates of the fundamental thermoacoustic mode is dominated by only two \( \pi \)-groups. Physical interpretations of these two \( \pi \)-groups were developed, and it was shown that stability maps of three distinct thermoacoustic configurations can be represented consistently in terms of the two \( \pi \)-groups.

A novel analytical approach for dimensionality reduction in thermoacoustic stability analysis was developed by Guo et al. (2018). This approach determines by projection the relationship between variations of flame impulse response coefficients and variations of modal growth rates, effectively reducing the dimensionality of the problem to one. When applied to a problem of forward uncertainty quantification, this allowed a reduction of computational cost by more than three orders of magnitude compared to Monte Carlo simulation.

Projects
- FVV ROLEX project ‘Hybrid Reduced Order/LES Models of Self-eXcited Combustion Instabilities in Multi-Burner Systems’
- ANR/DFG NoiseDyn project ‘Identifikation des Verbrennungslärms und der Dynamik eingeschlossener turbulenter Flammen’

Uncertainty Quantification

Thermoacoustic instabilities are highly unpredictable, because they respond in a very sensitive manner to slight changes in operating or boundary conditions. Consequently, instabilities are detected often only in full combustor tests during the late stages of development, resulting in significant overruns of development cost or time. It is essential to deploy robust and reliable simulation methodologies that include strategies to quantify the uncertainty of model predictions and their sensitivity to parameter changes.

The TFD group has developed and applied successfully a variety of strategies for uncertainty quantification in thermoacoustics. Residual and covariance analysis as part of advanced system identification (Merk et al., 2018) in combination with non-intrusive polynomial chaos expansion (Avdonin et al., Comb. & Flame, 2018; J. Eng. GTP, 2018), or analysis. Silva et al. (2018) deduced a set of non-dimensional \( \pi \)-groups from a modal expansion of the quasi-1D Helmholtz equation with a time-lagged heat source. It was found that the non-dimensional frequencies and growth rates of the fundamental thermoacoustic mode is dominated by only two \( \pi \)-groups. Physical interpretations of these two \( \pi \)-groups were developed, and it was shown that stability maps of three distinct thermoacoustic configurations can be represented consistently in terms of the two \( \pi \)-groups.

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active subspace allow, e.g. to estimate the length of time series required to reduce the uncertainties of combustion modelling and system identification to a desired level (Guo et al., J. Eng. GTP, 2018). The development of low-dimensional surrogate models by exploiting adjoint numerical solutions, by analytical means (Guo et al., 2018), or most recently with Gaussian process models, has played an increasingly important role in these efforts.

Project
- CSC Scholarship, AG Turbo COOREFLEX

Fig. 5: Workflow for estimating CFD time series length required to achieve desired confidence in system identification (see Guo et al., JEGTP 141 (2), 2018)
Thermo-Fluid Dynamics

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Simon van Buren, M.Sc.

Research Focus
■ Thermo- and aeroacoustics
■ Turbulent reacting flow
■ Heat and mass transfer

Research Competence
■ Modelling and simulation
■ Stability analysis
■ System identification
■ Model reduction
■ Uncertainty quantification
■ AVBP, OpenFOAM, Matlab
■ taX

Courses
■ Engineering Thermodynamics (MSE)
■ Wärmetransportphänomene
■ Grundlagen der Mehrphasenströmung
■ Introduction to Nonlinear Dynamics and Chaos
■ Grundlagen der numerischen TFD
■ Computational Thermo-Fluid Dynamics
■ Simulation of Thermofluids with OpenSource Tools

Selected Publications 2018
Safe Embedded Systems

Development, control, verification and validation of dependable cyber-physical systems

The activities of the Assistant Professorship of Safe Embedded Systems (SES) focus on the development of formal methods and tools to improve the dependability of cyber-physical systems. These methods are applied throughout the different phases of the development and implementation of a system, from the formalization of its requirements to its long-life support. As part of the Department of Mechanical Engineering, these activities play an interface role between the formal methods developed in the computer science field and applications in mechanical engineering.

Model-Based Testing of Embedded Systems

Validation by testing is a mandatory procedure for safety-critical controllers. However, the validation of embedded logic controllers is often only considered in the later phases of their development. Thus, if specific non-functional requirements related to testing are not considered initially in the specification models, this can lead to the impossibility of validating the behavior of a controller by means of testing.

In order to focus on aspects of interest, such as the so-called nominal behavior of a cyber-physical system, in an early phase, SES further developed an approach which allows modelling simple features of the physical behavior and to combine them with the specification models. This approach requires limited expert knowledge about the physical behavior but leads to a drastic reduction in the test sequence length.

The current focus in this area is the extension of the existing approaches to timed and hybrid systems.

Dynamic Software Update of Programmable Controllers

With the advent of Industry 4.0 and the Internet of Things, maintaining software is becoming more and more crucial. One aspect of maintenance is the undisturbed deployment of software updates.

Dynamic software updating is the concept of applying software changes while guaranteeing the availability of services. In production automation systems this method can reduce downtimes, increase the efficiency, and increase the safety of the plant due to more regular security updates. On the other hand, when not applied carefully, it can lead to the failure of the system.

While this concept already exists, it is far from being commonly applied. The goal is to make dynamic software updating simple to implement for the user and provably safe for deployment. An additional aspect is the deployment to distributed systems.

In 2017, SES started a new project on the development of methods to formalize and implement IEC 61499 models into the Erlang Runtime System; thus, supporting an industrial standard in the field of production automation and benefiting from the experience of dynamic software updating in the telecommunications field.

Project

Dynamic Software Update of Programmable Logic Controllers (BMWi ZIM)
Safe Embedded Systems

Test Automation Assistant Systems

In the context of functional software testing on system or integration level, there is only limited access to source code or system models. Nevertheless, all available information should be used to support the test engineers as effectively as possible. Several aspects of the test automation actions have been identified as valuable targets. In particular, flexible and adaptive test execution, which dynamically takes into account feedback from test runs for test case selection, was addressed. An upcoming assistant system addresses the failure recognition based on historic test runs and learned symptoms.

Project
- Flexible, Adaptive Automation of Testing Procedures by Means of Software Agents (internal)

Supervisory Control Theory

Supervisory control theory (SCT) is a model-based approach that permits automatic generation of correct-by-construction supervisory controllers. Thanks to the SCT approach, which uses mathematically proven algorithms, generated controllers no longer need to be verified. The designers can then focus more on the requirements definition and specification modeling. A set of specifications allows each requirement (functional and non-functional requirements, safety and liveness requirements, optimization criteria, etc.) to be specified independently. Then, synthesis algorithms are applied on the set of specification and plant models to generate a supervisory controller. The supervisory controller obtained is then guaranteed to be deadlock-free and maximally permissive (all the specifications are fulfilled and only these specifications are fulfilled).

In 2018, SES further investigated the obstacles to a wide application of SCT in industry. First, a formal approach using a signal-based formalism was developed further. This aims at reducing the gap between the classical event-based approach of SCT and industrial applications using signals and data flows to represent and exchange sensors and actuator values. Secondly, SES also investigated the integration of SCT methods from a broader systems engineering perspective. The goal is to establish good practice and business rules to simplify the application of SCT in the production automation industry.

Projects
- A Signal-Interpreted Approach to Supervisory Control Theory (internal)
- Application of Supervisory Control Theory to the Production Automation Industry (internal)

Robust Diagnosis for Ambient Assisted Living

According to the World Health Organization, the percentage of the world’s population aged over 60 is expected to double in the next decades; it will increase from 12% in 2015 to 22% in 2050. Ambient Assisted Living (AAL) integrates sensors in an unobtrusive intelligent way that can track the health status of elderly people at home and detect early signs of diseases by monitoring their ‘activities of daily living’.

SES is working on the development of reliable AAL methods that are capable of monitoring elderly people without intruding into their lives. An important aspect of the reliability of such systems lies in the capability of handling sensors’ faults. Indeed, a fault in one of the sensors of the AAL could lead to misleading results in activity recognition (false positives or negatives). This could have dramatic consequences for the health of the inhabitant in emergency situations.

Also, recent results have demonstrated the efficiency of AI techniques applied to artificially augmented datasets for automatic room recognition and activity detection.

Project
- Robust Diagnosis for Ambient Assisted Living (DAAD)
Research Focus
- Formal methods for verification and validation
- Formalisation and control of discrete event systems

Competence
- Model-based component and system testing
- Supervisory control theory
- Dynamic software update
- Ambient assisted living

Infrastructure
- Test bench for (safety) programmable logic controllers
- Didactic platform for supervisory control
- Demonstrators for dynamic software update

Courses
- Basics of Dependable Systems
- Control of Discrete Event Systems
- Safe Embedded Systems
- Fault-Tolerant Control and Supervisory Control Theory Lab

Selected Publications 2018
- Canlong Ma; Claudius Jordan; Julien Provost: SATE: Model-Based Testing with Design-to-Test and Plant Features. 14th Workshop on Discrete Event Systems (WODES 2018), 2018
- Claudius Jordan; Judit Cuezva Herrero; Julien Provost: Extension of the Plant Feature Approach Introducing Temporal Relations. 14th IEEE International Conference on Automation Science and Engineering – CASE 2018, 2018
- Laurin Prenzel; Julien Provost: PLC Implementation of Symbolic, Modular Supervisory Controllers. 14th Workshop on Discrete Event Systems (WODES 2018), 2018
- Florian Pflitzer; Carina Mieth; Wolfgang Liertz; Julien Provost: Event-driven production rescheduling in job shop environments: Application to sheet metal production processes. 14th IEEE International Conference on Automation Science and Engineering – CASE 2018, 2018
Industrial Management and Assembly Technology

Perspectives for production

The Chair for Industrial Management and Assembly Technology is one of the largest research centers in the field of production engineering in Germany. With the opening of the laboratories for additive manufacturing as with other members of the TUM in the field of additive manufacturing will be expanded.

Founded in 1875 the Institute for Machine Tools and Industrial Management (iwb) at the Technical University of Munich is one of the largest research institutions for production technology in Germany. It encompasses two chairs at the Faculty of Mechanical Engineering in Garching near Munich. The research structure at iwb is represented by individual topic groups. Our scientific employees develop solution strategies for the efficient production of tomorrow.

The Production Management and Logistics topic group pursues the goal of increasing effectiveness and efficiency in production. One research focus is the development of methods for change and technology management, as well as factory planning and analysis. In addition, the topic group researches competence-based work and production systems against the background of demographic change and the increasing digitalization of the production environment.

In the next few years iwb will be involved in the EU Horizon 2020 research project ‘PreCoM’, which investigates the concept of predictive maintenance in conjunction with production planning, in order to increase machine availability. The results offer companies a very innovative business model with the opportunity to position themselves on the market with customer-innovated products, and to strengthen Germany’s position as a business location in the long term.
Assembly Technology and Robotics

The Assembly Technologies and Robotics research group addresses the processes regarding the last step in the production chain. Here, the assembly process has a significant influence on the cost and quality of the end product; thus innovative ideas and technologies are required to achieve cost-, energy- and planning-efficient solutions. Particularly, the digitization and planning of assembly processes, including the operating resources such as robots, transportation and automation technologies are the main research areas being investigated by our team.

Based on digital models, concepts are being developed by our researchers to generate an automated design, selection and configuration of assembly systems. Particular attention is here being paid to the industrial robot as a universal tool for the automation of processes in production. Furthermore, the global necessity of alternative and sustainable energy resources has encouraged our researchers to investigate new manufacturing and assembly technologies, addressing the production of lithium-ion batteries. A large part of the work is therefore oriented towards the future area of electromobility and decentralized energy storage. In this connection, a research line was developed at iwb for the production of large-format lithium-ion battery cells from electrode fabrication to cell and module assembly. This offers a unique platform to research the relationship between production and product quality, as well as the processing of new materials and the integration of new technologies for the fabrication of next generation batteries.

Projects

- Automated assembly planning based on CAD product data
- Cell-Fi – Acceleration of electrolyte absorption through optimized filling and wetting processes
- CyMePro – Cyber-physical measurement technology for 3D digitizing in networked production
- ExZellTUM II – Center of Excellence for Battery Cells at the Technical University of Munich
- FELIZIA – Solid electrolytes as enabler for lithium cells in automotive applications
- FORobotics – Mobile, ad-hoc cooperating robot teams
- ProMoA – Product-based automatic model-based system development
- ProKal – Process modeling of the calendering of high-energy electrodes
- SPICY – Silicon and polyanionic chemistries and architectures of Li-ion cell for high energy battery
The Production Management and Logistics research group is working on projects aimed at enhancing effectiveness and efficiency of production. The research scope covers three main fields of interest. The first field comprises the design of an effective manufacturing change management and the management of production technologies as well as factory planning. The second field conducts research on the efficient integration of human resources in an increasingly digital and networked production environment. These fields are complemented by research on optimization methods for industrial application and on approaches for efficient exploration of required data. The group’s wide-ranging expertise in all areas of production management and logistics is based on current and former comprehensive research. Furthermore, the research group is equipped with a real production environment through the Learning Factory for Lean Production (LSP) and a lab that supports research, teaching and training in the context of human resources in production.

**Projects**
- PreCoM – Condition monitoring and predictive maintenance integrated production planning
- Efficient data management for the use of mathematical optimization models in the production strategy
- Individual and dynamic worker information
- SFB 768 – Subproject B5: Systemic change management for the design of change cycles in production
- SFB 768 – Subproject B4: Model-based prognosis and evaluation of change impacts in production
- SFB 768 – Subproject D1: Supporting the design of cycle management of PSS innovation processes by diagnosing and resolving inconsistencies between models of different domains
- Smart interfaces
- Big data in logistics planning
- Mittelstand 4.0 Augsburg Competence Center
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Research Focus
■ Production management and logistics
■ Assembly technology and robotics

Competence
■ Innovation management in production
■ Human being in the factory
■ Optimization for industrial practice
■ Battery production
■ Cyberphysical assembly lines
■ Industrial robotics

Infrastructure
■ Additive manufacturing laboratories for metal and plastics
■ Cutting machine tools
■ Laser tools
■ Friction welding equipment
■ Industrial robots
■ Environmental/safety and teaching laboratories
■ Energetic and geometrical parameters
■ Material analysis systems
■ Simulation environments
■ Production line for battery cells
■ Environmental/safety and teaching laboratories
■ Material analysis systems
■ Learning factory for lean production

Courses
■ Assembly Technologies
■ Engineering 4.0 – Agile and Interdisciplinary Development of Mechatronical Production Systems
■ ERP – Systems-Practical Course
■ Factory Planning
■ Human Factors in Production Engineering
■ Industrial Management
■ Lean Production Practical Course
■ Management of Production Enterprises (for Teachers)
■ Mechatronical Development Projects in Industrial Practice
■ Networked Production
■ Practical Course for Mechatronical Development Processes and Project Management
■ Practical Course Industrial Robots
■ Production Management
■ Production Planning and Control – Practical Course
■ Project Management
■ Project Management – Seminar
■ Seminar Soft Skills for Engineers in Development and Production
Selected Publications 2018


Bauer, H., Brandl, F., Lock, C., Reinhart, G.: Integration of Industrie 4.0 in Lean Manufacturing Learning Factories


Berger, C., Hoffmann, U., Braunreuther, S., Reinhart, G.: Modeling, simulation, and control of production resource with a control theoretic approach


Hawer, S., Schönmann, A., Reinhart, G.: Guideline for the Classification and Modelling of Uncertainty and Fuzziness


Schnell, J., Günther, T., Knoche, T., (...), Passerini, S., Reinhart, G.: All-solidstate lithium-ion and lithium metal batteries – paving the way to large-scale production


Schönmann, A., Dengler, C., Reinhart, G., Lohmann, B.: Anticipative strategic production technology planning considering cyclic interactions


Weydanz, W. J.; Reisenweber, H.; Gottschalk, A.; Schulz, M.; Knoche, T.; Reinhart, G.; Masuch, M.; Franke, J.; Gilles, R.: Visualization of electrolyte filling process and influence of vacuum during filling for hard case prismatic lithium ion cells by neutron imaging to optimize the production process

Zhai, S., Reinhart, G.: Predictive maintenance as an enabler for maintenance-integrated production planning
Applied Mechanics

Development, simulation and experimental investigation of complex dynamical and mechatronic systems

The Chair of Applied Mechanics is a leading research center in the field of dynamics of mechanical and robotic systems. The core of its activities focuses on the development of novel simulation and experimental techniques for efficient analysis of complex structural dynamics, and on the design, construction and control of advanced robotic machines.

The research is organized in three main areas: Dynamic Simulation and Numerical Techniques, Experimental Dynamics, and Robotics and Mechatronics. Each research group bundles specific expertise, monitors international advances and actively discusses future research directions.

Dynamic Simulation and Numerical Techniques

Designing and optimizing high-tech systems necessitate accurate and efficient modeling. The expertise and research focus of the chair is mainly on model reduction aspects, parallel computing strategies and numerical techniques to simulate structural dynamics. The simulation of advanced mechanical structures that undergo large deformations, such as microelectromechanical systems or wind turbine blades, often requires long computation times. When the engineer’s task is to optimize such structures regarding their vibration behavior, it is highly desired to reduce the computation time of the underlying numerical models. One approach to achieve this goal is nonlinear model reduction. In current research, the chair develops model reduction techniques that are able to reduce the computation time for parametric geometric nonlinear finite element models that must be solved within dynamic optimization tasks. Herein, basis updating techniques have been developed to achieve good accuracy of reduced models with large parameter changes while keeping the effort for the reduction step small.

Most classical model order reduction methods take exclusively mass and stiffness properties of dynamical systems into account, but neglect damping effects. Thereby, only real-valued undamped vibration modes are considered. However, if damping significantly influences the dynamic behavior of the system, the approximation quality might be poor. Therefore, we modify classical modal order reduction methods by using complex damped vibration modes to obtain good approximations of damped systems.

Another competence of the chair is the finite element tearing and interconnecting (FETI) method, which is a class of parallel, iterative solvers for structural dynamics. The research focuses on linear and nonlinear dynamics and the application to large flexible multibody systems. Herein, the recycling of gathered information during the solution process is crucial due to the fact that the same or similar systems are solved repeatedly. Problems with local highly nonlinear processes still lead however to performance issues. Therefore we investigate asynchronous time integration methods and merge them into the FETI framework.

The chair is also participating in a European training network called EXPERTISE, which is an abbreviation for experiments and high-performance computing for turbine mechanical integrity and structural dynamics in Europe. The main goal of the project is to develop advanced tools for the dynamic analysis of large-scale models of turbine components. Therefore, a parallel FETI solver has been implemented in AMfe using MPI communication.
Experimental Dynamics

Dynamic testing is regularly performed in our lab to validate models and test constructions. In addition, experimental dynamic techniques are part of our research aiming at improving the quality of the identification under real conditions. As an example, a self-tracking laser-Doppler vibrometer system is under development to perform in-operation monitoring.

Another goal of our scientific work is the transfer of this contactless, non-destructive measurement method into a new class of materials: hydrogels. These often soft and fragile materials are used especially in the field of tissue engineering and 3D biofabrication to develop tissue replacement processes. First experiments could prove the feasibility of using laser-Doppler vibrometry for the mechanical characterization of hydrogels, biomaterials and engineered tissue equivalents. In future steps, this technique will be integrated directly into 3D biofabrication processes to enable the production of three-dimensional structures possessing a stiffness-related anisotropy ensuring their proper mechanical functionality.

To interpret a structure’s dynamic behavior correctly under operational loads, such as a running wind turbine, our chair is working in the field of operational modal analysis (OMA). With this technique, large structures are accessible to measurements without the need to isolate them from any external and unknown influences. Instead, these unknown loads (wind, traffic, etc.) are the source of the vibration that is measured and engineers can extract modal parameters based on these measurements. The method works well in civil engineering applications,
where systems can be seen as linear and time-invariant. Our objective is to enhance OMA techniques so they can be applied in real-life applications in the domain of mechanical engineering, where problems are often non-linear.

The research on experimental substructuring deals with specific coupling techniques, used to build full dynamic models of complex assemblies. The assembly models can be composed of dynamic measurements on real subcomponents and numerical models of not yet existent subcomponents. The numerical models can then be subjected to design optimizations in order to improve the dynamic behavior of the full assembly. Transfer path analysis (TPA) is a key technique to model the excitation loads coming from vibration sources, e.g. electric motors. The results of applying the TPA excitations to the virtual assembly model can be used to listen to a machine that does not yet exist. Furthermore, TPA allows characterizing the sources, so that the vibration level in the assembly with different coupled passive structures can be predicted. A further extension to this current numerical/experimental hybrid modelling is the construction of actual numerical-experimental mixed subcomponent models with a method based on substructuring called system equivalent model mixing (SEMM). This novel modelling technique tries to incorporate the advantages of both numerical and experimental modelling techniques. Furthermore, current research also includes the modelling of better interface models: the main objective here is to identify interface effects between substructures (e.g. friction and contact).

Substructuring methods are also used in so-called real-time hybrid testing. This special hardware-in-the-loop technique numerically simulates structural components for which models are available, and exchanges in real-time forces and displacements on the interfaces with a real hardware component in the lab. Furthermore, different numerical and experimental methods are investigated on a wind turbine in an experimental dynamics lab. Modal analysis techniques are applied to improve substructuring and model order reduction techniques. The research field of rotor dynamics includes techniques to characterize the rotor dynamics as well as the dynamic behavior of seals and bearings. Reduced component models are set up and validated on several test rigs in the experimental dynamics lab. In this way, influences such as seal instabilities and bearing effects on rotor systems can be determined.

Furthermore, multi-physical systems like active magnetic bearings are investigated with a focus on the modeling and experimental validation of the nonlinear magnetic behavior. The chair also explores new monitoring approaches for rotating machinery using accelerometers built of micro-electro-mechanical systems (MEMS) in wireless sensor nodes for fault prediction. Thereby, reduced rotor models are coupled with the experimentally determined dynamics of rotating machinery. Combinations of signal- and model-based methods implemented on sensor nodes aim to identify overload conditions and structural changes. Model-based monitoring, fault detection and control is another research interest of the chair. To account for aging effects in common rail diesel injectors that can appear over the lifetime of an engine, model-based identification and control methods have been developed in cooperation.
Applied Mechanics

with the Chair of Internal Combustion Engines. Numerical and experimental results show the great potential in improving long-term engine efficiency and controlling exhaust emissions.

Projects

- Real-time substructuring for complex systems (internal)
- Substructuring and transfer path analysis for creating virtual acoustic prototypes (BMW)
- Rotor dynamics for turbo pumps in space propulsion systems (BaySt- MWMET)
- Rotor dynamics with active magnetic bearings (internal)
- Modeling of common rail injectors for fault detection and control (DFG)
- Dynamics analysis of large-scale models of turbine components (EXPERTISE)
- Model reduction and experimental substructuring (Iranian Ministry of Research, Education and Technology)
- In-operational measurement on a wind turbine test bench (Chinese Scholarship Council)
- Mechanical monitoring with MEMS sensor network (Siemens)
- Integration of laser-Doppler vibrometry into 3D biofabrication work-flows (DFG)
- Operational modal analysis of non-linear systems (internal)

Robotics and Mechatronics

The chair has a long tradition in designing, constructing and controlling robots for novel applications. Based on expertise in autonomous legged robots, the chair has developed and steadily improved the high-performance humanoid robot LOLA in recent years. The complexity of biped locomotion through cluttered and dynamically changing environments reaches from the detection of obstacles and separation from possible contact partners to the generation of stable walking patterns as well as local stabilization for compensation of sensor and model errors to increase the overall robustness against unforeseen disturbances.

As the coordination of signals within the planning stage is critical, especially in consideration of the hard real-time requirements and the limited onboard computational power, a novel walking pattern generation framework has been developed. The new design combines enhanced safety, robustness, modularity and efficiency. Furthermore special focus lies on easy parallelization and thread-safety to exploit the increasing multi-core performance of today’s compute units.

At the same time, new techniques for planning and controlling robot locomotion in the multi-contact setting, i.e. when using additional arm-environment contacts, are investigated. Aside from reduced models approximating the full multi-body dynamics of the robot for real-time control, various methods for perceiving the environment, extracting appropriate support areas and planning feasible contact sequences are developed.

To enable robots to sense their environment and evaluate contact properties, a flexible tactile sensor design has been developed at the chair. In contrast to conventional force sensors, tactile sensors allow the measurement of the contact geometry and not only the resultant forces on an object. This low-cost design is based on a piezo resistive polymer.

Recently, bio-inspired, dynamic bipedal gait has become a research focus. In collaboration with kinesiologists human gait and control strategies for walking and running are investigated in order to identify fundamental principles of legged locomotion and assess their applicability to bipedal robots. Similarities and differences in terms of behavior and control between rigidly built, fully actuated walking robots and walking on compliant, motor-redundant natural legs will be identified. The results are expected to impact various domains including gait rehabilitation and assistance but also posture and balance control in humanoids.

The knowledge gained on simulation of human gait is further utilized to develop a real-time hybrid substructuring method to test foot prostheses during the development phase. A real prototype prothesis is mounted on the chair’s hexapod, which imitates human walking and couples the dynamics of the real foot prosthesis with the simulation through a 6 dof force transducer.

In addition to the development of humanoid robots, the research group also investigates methods for motion cueing, which mainly targets driving simulators in the automotive industry. Due to the high requirements on the simulator’s dynamics, parallel robots are used whose special kinematics must be considered. The research focuses on the perceived dynamical motion from the driver’s perspective. In recent years, the mechanical structure of driving simulators has become more complex; thus a global optimization scheme was developed.
Another research topic is the external stabilization of robot manipulators, which focuses on the development and verification of methods to improve the path accuracy of industrial robot manipulators via external means, without making changes to the robot itself. A stabilization unit with an extra set of actors is employed between the robot and the tool. The stabilization unit estimates the current dynamics of the robot arm using acceleration sensor feedback and utilizes advanced vibration control techniques to uncouple unwanted vibrations of the robot manipulator from the tool to increase the accuracy of the desired process.

We also cooperate with the Department of Orthopedics and Sports Orthopedics, to investigate the application of robotic manipulators to examine the range of movement of human joints. We investigate compliant motion control to explore the motion space without overstressing the tested joint.

**Projects**
- Real-time planning for flexible and robust walking of a humanoid robot (DFG)
- Gait control of a humanoid robot in uneven terrain (DAAD)
- Multi-contact planning and control of biped walking robots (internal)
- Tactile feedback and force control of biped walking robots (internal)
- High-precision control of flexible robot systems (internal)
- Model predictive and filter-based control strategies for motion cueing algorithms (BMW)
- Identification and control in robot-driven joint biomechanics (Department of Orthopedics and Sports Orthopedics)
- External stabilization of robot manipulators (internal)
- Testing of human foot prostheses using real-time hybrid substructuring (internal)
Applied Mechanics

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Karamooz Morteza, M.Sc.
Steven Klaassen, M.Sc.
Dipl.-Ing. Andreas Krinner
Dipl.-Ing. Michael Leistner
Dong Li, M.Sc.
Johannes Maierhofer, M.Sc.
Dipl.-Ing. Johannes Rutzmoser
Andreas Seibold; M.Sc.
Philipp Seiwald, M.Sc.
Nora-Sophie Staufenberg, M.Sc.
Felix Sygulla, M.Sc.
Christian Wagner, M.Sc.
Dipl.-Ing. Robert Wittmann
Daniel Wahrmann, M.Sc.
Romain Pennec, M.Sc. (Goodyear)
Sascha Schwarz, M.Sc. (HS München)

External Ph.D. Candidates
Benjamin Krämermeier, M.Sc. (BMW)
Samuel Krügel, M.Sc. (Siemens)
Dipl.-Ing. Martin Münster (BMW)

Research Focus
- Modeling and simulation of dynamical systems
- Vibration analysis and rotor dynamics
- Mechatronics and robotics
- Experimental dynamics

Competence
- Finite element modeling in dynamics
- Model reduction and substructuring
- Time integration and solvers
- Multiphysical modeling
- Trajectory planning and control of robots
- Biped robots
- Modal identification

Infrastructure
- Mechanical and electronic workshop
- Vibration and dynamic test lab
- Robotic lab
- Dynamics teaching lab

Courses
- Technical Mechanics (Statics, Elasticity and Dynamics)
- Technical Mechanics for Electrical Engineering
- Machine Dynamics
- Simulation of Mechatronic Systems
- Technical Dynamics
- Dynamics of Mechanical Systems
- Robot Dynamics
- Applied Biorobotics
- Multibody Dynamics
- Structural Dynamics
- Experimental Vibration Analysis
- Seminars in Applied Mechanics
- Mechanical Vibration Lab
- Vibration Measurement Lab
- Robot Dynamics Lab
- Structural Dynamics Lab

Selected Publications 2018
- Hildebrandt, Arne-Christoph; Schwier, Simon; Wittmann, Robert; Wahrmann, Daniel; Sygulla, Felix; Seiwald, Philipp; Rixen, Daniel; Buschmann, Thomas: Kinematic Optimization for Bipedal Robots. Autonomous Robots, 2018 (in print)
- Hofmann, Oliver; Rixen, Daniel J.: Aging tolerant control of direct injection engines. Control Engineering Practice 77, 2018, 201-212
- Wagner, Christian; Tsunoda, Wataru; Berninger, Tobias; Thümmel, Thomas; Rixen, Daniel: Estimation of Rotordynamic Seal Coefficients Using Active Magnetic Bearing Excitation and Force Measurement. In: Lecture Notes in Mechanical Engineering. Springer International Publishing, 2018
Thermodynamics

Technology-driven thermo-fluid dynamics research

Our research guideline is the proposition that scientific research in an engineering school should be focused on problems with high technological relevance. A key to realizing our mission is the close cooperation with industry in general and in particular with partners who – developing their top-class global products at the leading edge of technology – have encountered barriers that might be overcome by fundamental research.

Our partner industries are improving their technologies towards a lower carbon footprint, integration with renewable power sources and environmental compatibility. Their research needs are reflected in our three research clusters: The increase of fuel efficiency and operational flexibility of gas turbines and large reciprocating engines at low pollutant emissions requires fundamental research on pollutant formation and emission, reliability, combustion instabilities and multi-phase phenomena. Safety issues in nuclear power plants and in the process industries are addressed by our work on detonation and on two-phase flows. Finally, further research is devoted to the grand challenge of providing clean water to the world.

The appreciation of our technologically oriented research approach in the technical community is reflected by two ASME Gas Turbine Awards for the best publication of the year on gas turbines and numerous best paper awards which our research group has received during the past two decades from several organizations.

Combustion Emissions and Reliability

Deflagration-to-Detonation Transitions in Ducts and Obstructed Channels

Severe accidents in nuclear power plants can be accompanied by the production of large amounts of hydrogen (H₂) and carbon-monoxide (CO). The formation of a flammable mixture cloud is highly probable because of the wide ignition limits of the fuel-air mixtures. Moreover, the usage of explosive gases in technical applications, such as chemical plants, increases significantly the need for safety analysis to prevent severe accidents. The research focuses on the hazardous deflagration-to-detonation transition (DDT), which creates high pressure loads on the containing structure, as well as on the important early stage of flame acceleration, establishing the history of the flame. In the early stage of flame propagation, enlargement of the flame surface area is the main driver for flame acceleration.

The existing experimental infrastructure of the GraVent explosion channel was extended, allowing the investigation of all stages of flame acceleration in homogeneous and inhomogeneous H₂-CO-air mixture distributions. A gas mixing system allows for preparation of individual H₂-CO mixtures. Results obtained are compared with H₂-Air mixtures of previous research projects.

The extension of the existing numerical CFD framework in OpenFOAM aims for large-scale detonation simulations with a wider applicability regarding facilities and the possibility to introduce further fuels. Primarily, the extension of the framework towards syngas (CO+H₂) will allow for the simulation of realistic accident scenarios in nuclear power plants with core melt down. Furthermore, the framework can be used in any other safety analysis regarding syngas as fuel. By applying the existing numerical H₂-air framework to smooth pipe accident scenarios of the chemicals company BASF SE, it was shown that the large-scale CFD framework can be adopted for the safety interests of the chemical industry as well. Typical conditions within chemical plants, such as elevated pressures and varying gas compositions, must be considered. The smooth pipe cases shall be investigated by 2D simulations to minimize the computational costs. For this purpose, a 2D version of adaptive mesh refinement has been implemented. Analysis of turbulence production and consideration of flame instabilities to increase flame acceleration after ignition is ongoing.
**Internal Combustion Engines**

**Motivation and Objectives**
Since dual-fuel combustion of natural gas with diesel pilot ignition is a promising approach to address future emission standards, this topic is the subject of several current studies at the Thermodynamics Institute. Characterization and optimization of pilot ignition in the premixed natural gas/air charge can lead to an increase in efficiency. Another investigation tackles the formation of NO\(_2\) under these conditions, a toxic pollutant that is increasingly emitted at certain loads. The third ongoing project aims to reduce the fuel slip – caused by quenching effects in the homogeneously mixed charge – by controlling the mixture formation with high pressure direct injection of natural gas.

**Experimental Investigations**
The ignition and combustion processes in homogeneous charge methane/air mixtures were investigated in a dynamically chargeable combustion cell under engine-like conditions. It could be shown that ignition probability and intensity are strongly influenced by the amount of pilot fuel, pilot injection pressure, air-fuel ratio and the number of injection holes. The investigations have revealed that in most cases the pilot fuel suffers from too high dilution due to its small quantity and long ignition delays. This results in a small number of ignited sprays and consequently leads to longer combustion durations. Furthermore, the experiments confirm that the natural gas of the background mixture influences the autoignition of the diesel pilot oil. The investigation of natural gas high pressure direct injection combustion with diesel spray piloting was performed on a rapid compression machine. The variation of spatial and temporal overlap of the pilot spray and gas jet shows how the ignition behavior is governed by the interaction between them. In both experiments, high-speed imaging of flame luminescence and of shadowgraphy were applied.

**Numerical Investigations**
The effect of fuel substitution on the ignition probability of the resulting fuel blend was studied using detailed reaction mechanisms. An auto-ignition model capable of handling mixtures of two fuel types with significantly different reactivity was developed and successfully implemented in a commercial CFD software package. With these tools ignition and heat release in dual-fuel diesel engines are investigated for the two cases of homogeneous charge and high pressure direct injection of gaseous fuel. Detailed kinetics simulations in homogenous reactors revealed the thermodynamic conditions responsible for the significant NO-NO\(_2\) conversion observed in these engines. High emissions of NO\(_2\) were shown to be caused by small amounts of unburned hydrocarbons (due to flame quenching in the lean methane-air charge) reacting with NO during the expansion stroke and in the exhaust system.

**Related Projects**
- Optimization of Diesel Pilot Ignition in Dual-Fuel Engines with High Mean Effective Pressures
- Investigation of Direct Injection Dual-Fuel Combustion with Flexible Fuel Combinations
- Numerical Simulation of NO to NO\(_2\) Conversion in Dual Fuel Engine

**Combustion Instabilities and Noise**
Thermoacoustic instabilities in gas turbine combustors and rocket engines arise if the energy resulting from a feedback loop between the flame’s heat release (driving) and the resonant acoustic modes of the chamber exceeds the natural acoustic damping of the combustor. They manifest as high-amplitude, self-sustained pressure pulsations that may increase emissions and even damage the system’s hardware. Avoiding these instabilities is therefore a challenge of major technical relevance.

**High-Frequency Transversal Thermoacoustics in Gas Turbine Combustors**

**Motivation and Objectives**
This project focuses on high-frequency thermoacoustic instabilities in lean-premixed gas turbine combustor applications for power generation. Their accurate prediction constitutes the main goal of this work, which in turn allows applying mitigation measures.
Methods and Approaches
In previous years, research activities at the institute provided deep insight into the high-frequency thermoacoustic feedback mechanisms of swirl-stabilized combustion systems, both experimentally and numerically. The focus is now extended towards reheat combustion systems that exhibit a so-called ‘reheat flame’ with areas mainly stabilized via auto-ignition. Experimental observations of the feedback mechanisms are subsequently modelled and introduced as source terms into the institute’s acoustic prediction tools based on linearized Euler equations (LEE). In that sense, tools to account for the damping due to vortex shedding have been extended. A Helmholtz decomposition approach is used to separate LEE solutions into their acoustic and vortical sub-modes. This establishes detailed investigations of interactions between both sub-modes and thus the vortex shedding mechanism.

Key Results
Modulation of the flame dynamics through acoustics is observed in the reheat test rig in the high-frequency domain, both as a response to external forcing and as a self-excited instability. Altogether, by accounting for the acoustic driving and damping, a complete picture of the linear stability behavior of a combustor is obtained.

Combustion Instabilities in Rocket Engines

Motivation and Objectives
In order to support the reliable design of thermoacoustically stable rocket engines, the prediction of high-frequency combustion instabilities and the assessment of counter measures is the objective of this project.

Methods and Approaches
Numerical simulations are carried out with focus on the frequency domain. Eigensolutions of the linearized Euler equations are computed, describing modes and frequencies of the acoustic oscillations in the combustor. Absorbers are accounted for by impedance boundary conditions and a dome can be coupled to the chamber via a transfermatrix. Source terms in the energy equation represent flame feedback. Experimentally, studies are carried out on a cold-flow rocket engine configuration.

Key Results
The impact of an absorber ring on the acoustics of a cold-flow combustion chamber has been studied. A numerical analysis revealed the underlying process leading to the formation of split-modes. While a fixed absorber impedance corresponds to a single mode of each type, the frequency-dependence of the absorber impedance allows for the appearance of multiple modes of one type for a single absorber geometry. Between neighboring modes, a continuous transition of mode shape and frequency is observed when the absorber impedance is changed. An experimental validation of the eigenfrequencies showed the validity of the results.

The hybrid stability prediction method has been enhanced to cover engines with significant heat release in the convergent nozzle section. On this basis a first analysis of several virtual thrust chamber demonstrators, defined by ArianeGroup and featuring key aspects of future engine developments, has been conducted.
**Motivation and Objectives**

Low frequency instabilities or so-called low frequency rumble in aero engine combustion chambers may lead to unacceptable audible noise and to component wear. Avoiding these instabilities requires the development of accurate prediction tools, which goes along with a thorough understanding of the physical mechanisms behind them. The project’s main objectives are the investigation of acoustics and flame dynamics in air-staged rich-lean combustion chambers (RQL) of aero engines. The novel aspects to be addressed are flame response at rich conditions and during burnout while mixing with the second stage air takes place.

**Methods and Approaches**

The new approach is to separate the rich primary zone from the lean burnout zone, allowing experimental investigation of the two combustion zones independently from each other and the development of thermoacoustic models for each. During the investigations of the rich primary zone the complexity of the combustion will be gradually increased starting from a premixed methane flame to a non-premixed kerosene flame with atomization, spray dispersion and evaporation, as in real aero-engines. The research on the lean burnout zone focuses on the impact on acoustics on heat release and on the interaction of entropy waves with acoustics. The measurement techniques for the two combustion zones consist of optical and acoustical methods. The acoustical excitation will be realized via two sets of speakers placed up- and downstream of the reaction zones. Based on the experimental data thermoacoustic models will be developed which can be used to predict combustion instabilities in aero engines with RQL-combustion chambers.

**Numerical Approach**

The numerical method includes a combination of linear field method with network approaches together with analytical methods. The linear field methodology consists of CFD/LNSE method, where the modeling task is to calculate the acoustic processes in the combustion chamber (basket and transition) based on linearized Navier-Stokes equations (LNSE). In general, the hybrid approach, separating the calculation of mean flow field and perturbation in time domain will help to identify the acoustic behavior of combustion chambers and associated damping elements at comparatively low cost. Using the network approach, the peripheries including the pilot, the mixing injectors, as well as the vane simulation section are characterized acoustically, and the corresponding transfer matrices or impedances are determined. The influence of the dampers is captured using the available analytical models for calculating the damper impedance. Ultimately, the calculated impedances will be coupled to the numerical domain to estimate the total damping of the combustor.

**Key Results**

According to the numerically predicted instantaneous pressure distribution in the tubular combustor, the estimated high-frequency mode shapes are complex and diverse. Hence, it is essential to identify the critical modes and to quantify the corresponding growth rates to optimize the dampers’ properties. The dampers are commonly located at the combustion chamber between the transition section and the front panel.
Influence of Water Injection on Thermoacoustics of Spray Combustion Flames

Motivation and Objectives
Water injection in gas turbine combustors reduces the flame temperature and therefore allows an increase in power output without emission penalties. However, the addition of water leads to combustion instabilities. This effect is especially severe for the combustion of liquid fuels, which are in the focus of the project. Which impact water addition has on the thermoacoustic stability of combustors with prevaporization and premixing of liquid fuel and water is the basic question to be addressed. Comparisons will be made with the results of a previous project on the thermoacoustic stability of premixed natural gas flames with water injection.

Experimental Approach
Experiments are run on a gas turbine combustion test rig, which is retrofitted for spray combustion operation. An emulsion is generated from water and fuel prior to injection into the combustion chamber in order to provide optimum interaction of liquid fuel and water leading to homogeneous temperature reduction in the entire flame zone required for minimum NOx generation. Flame transfer functions and thermoacoustic driving and damping rates are extracted from dynamic pressure measurements to quantify the impact of the water on combustion stability.

Transport Phenomena

Chemical Hydrogen Storage in Liquid Organic Carriers

Motivation and Objectives
The storage of hydrogen in so-called ‘liquid organic hydrogen carriers’ (LOHC) is a promising approach to enable a future energy supply based on renewable energy sources. Although in theory the LOHC technology offers numerous advantages over established approaches to gaseous or cryogenic hydrogen storage, a broad implementation is still hindered by severe practical problems. Most of these problems are caused by the dehydrogenation step. The basic challenge in dehydrogenation originates from the low molecular mass of hydrogen, which leads to large volume flows of the gas phase consisting of gaseous hydrogen, which is released from the liquid carrier contacting the surface of the solid catalyst.

Approach to solution
The research on liquid organic hydrogen carriers at the Institute of Thermodynamics aims at the development of guidelines for the optimal design of dehydrogenation reactors. Therefore, experimental studies are conducted on the power density, catalytic efficiency and operational range of several established types of multiphase reactors. Furthermore, technologically relevant aspects of the LOHC technology, like the long-term stability of the carrier molecule or the thermodynamic equilibrium between loaded and unloaded carrier, are evaluated.

Key Results
Within the last year, the thermodynamic equilibrium of the occurring phases and species of the LOHC N-Ethylcarbazole was extensively measured and physically modeled. The resulting model is based on the fundamentals of chemical and phase equilibria making simplifying assumptions like perfect mixing behavior. The validity of the equilibrium model was confirmed by measurements spanning most of the technologically relevant pressure and temperature range. In future, the developed model will be implemented in a process simulation environment allowing further studies on several dehydrogenation reactor configurations.
Thermodynamics

Two-phase Flow in Subcooled Boiling Close to Critical Heat Flux

Motivation and Objectives
For microprocessors, medical X-ray machines or power electronics for off-shore wind turbines, single-phase flow often fails to meet the cooling requirements. Gradual switching to two-phase cooling systems can be seen across many industries. This leads to an increasing demand for modelling of two-phase heat transfer phenomena independently of system geometry, the boiling surface material or the fluid used.

Approach to Solution
At the Institute of Thermodynamics, fundamental experiments to uncover the processes of evaporative heat transfer at the wall are conducted, accompanied by numerical studies. The experiments provide highly focused experimental data for the validation of CFD-based critical heat flux models. The focus is particularly on gathering data about the morphology of the two-phase flow very close to the heated wall. Measurements are carried out using a variety of measurement techniques, ranging from conventional thermocouples and pressure sensors to high-speed videometry and fiber-optical micro probes developed at the institute.

Key Results
It was found that inlet subcooling is the main influence parameter on void fraction. An analysis of the dynamic behavior of the void along the entire boiling curve up to fully developed film boiling revealed a sudden peak in void fraction at the wall upon reaching critical heat flux in conjunction with a significant increase in bubble velocity close to the wall. The experimental data have been used to develop a calibration procedure of a state-of-the-art CFD boiling model.

Transport Phenomena in Desalination and Water Treatment

Motivation and Objectives
Today, the majority of newly installed desalination plants are membrane systems. The currently applied membrane desalination technologies are at a high development state and exhibit a low specific energy requirement, low plant complexity, and reduced investment cost in comparison to thermal systems. However, membrane systems significantly suffer from fouling. Suspended or solved solids of an organic and inorganic nature can clog the membrane and the channels. To overcome this drawback, cost-intensive and often environmentally harmful pre-treatment or cleaning are applied. Thus, the objective of the current studies is to develop operation strategies that mitigate fouling to reduce energy requirements and to permit reliable long-term operation.

Approach to Solution
We develop strategies to mitigate fouling by studying the impact of operational parameters on crystal growth or colloid deposition. In the field of reverse osmosis (RO) and related technologies, pulsating feed flows were applied in experiments to mitigate colloidal fouling. Vacuum membrane distillation (VMD) was investigated during the last few years to reach high water recovery and treat brines or highly contaminated waste waters. As membranes can be harmed by the growth of salt crystals on the membrane surface, the influence of operating conditions on scaling of different salts and the impairment of the membranes was investigated.

Key Results
Feed flow pulsations avoid the build-up of a cake layer and thus are an alternative to increasing the feed velocity in order to reduce fouling and pressure losses in the module. This leads to larger service intervals and a more efficient process.
Thermodynamics

In the field of VMD, we observed inorganic scaling in the feed channel of a VMD system while monitoring the membrane quality using tracer-based laser induced fluorescence (LIF). From the findings, operation strategies and operation windows were derived in which secure and reliable operation is possible.

Solar Cooling by Coupling of PV and Compression Chillers

Motivation and Objectives
Compression chillers (CC) directly coupled with photovoltaic (PV) systems (PV-CC) have gained increased attention in the field of solar cooling, mainly due to the decreasing costs of PV systems and the low investment costs of conventional compression chillers. Nevertheless, PV-driven compression chillers face challenges regarding dynamic operation and part-load behavior.

Approach to Solution
A crucial challenge for PV-CCs is to improve the ability to react to changes in PV power generation and to load variations in the electric demand of household appliances. Therefore, controllers to operate the PV-CC at a desired electrical power were developed and the dynamics of the considered swash-plate and scroll compressors were investigated.

Key Results
The figure shows the results of a hardware-in-the-loop (HiL) simulation, considering the thermal and electrical demand of the household and PV power generation.

![Result of HiL simulation: desired and measured power of scroll and swash-plate compressor over time](image)

The scroll compressor shows few oscillations and reacts instantly to the desired power signal, but has limited part-load capability. Therefore, the project aims at the improvement of its part-load behavior in subsequent studies.

Thermal Control of Photovoltaic Cells in Desert Environment

Motivation and Objectives
PV panels suffer from the harsh environmental boundary conditions, especially in desert regions. During the day, the PV efficiency decreases due to high module temperatures. At night, a crucial topic is the ‘mud formation’ occurring when the surface temperature is lower than the dew point of the ambient air. Condensed water and dust form a cake layer on the PV surface that reduces the transparency of the panels’ glass cover and thus also the PV efficiency. Therefore, the present project aims to develop a strategy to avoid mud formation.

Approach to Solution
Crucial for the project are the properties of the surrounding desert soil. The soil is used as thermal storage to avoid (1) overheating of the panels during daytime and (2) mud formation during night-time. Rear cooling was added to a PV panel to reject heat from the module and store it in underground heat storage. At night, the heat is recovered, and the PV modules are heated to temperatures above the dew point. The system was modelled in MATLAB/Simulink and the model was validated experimentally.

Key Results
It was found that a simple heat storage system can keep the PV panel surface temperature 1-2 K higher than the dew point and avoid condensation and mud formation at night. The study is continuing to investigate the phenomena of the condensation and its effect of mud formation and the PV power by visualization and image processing techniques.
Awards and Honors

Golden Teaching Award
The Fachschaft Maschinenbau awards the best practical courses in the Bachelor and the Master curriculum each year and thus rewards the respective trainers for their untiring and successful commitment at the forefront of teaching. After Jochen Brückner-Kalb in 2007 (heat transport phenomena) and Robert Kathan in 2008 and 2009 (Thermodynamics II), another golden generation of trainers seems to arouse students’ enthusiasm for thermodynamics. This year Norbert Heublein and Moritz Bruder were awarded the Golden Teaching Award 2018 for the practical courses in thermodynamics (Bachelor’s degree). For Norbert Heublein it is his third consecutive award after the Golden Teaching Award 2017 and second place in 2016 for the same course.

WATT Master’s Thesis Award
The Scientific Working Group Technical Thermodynamics (WATT) awarded Malte Stelzner a prize for his excellent Master’s thesis ‘Zyklenstabilität und chemisches Gleichgewicht des Wasserstoffspeichers N-Ethylcarbazol’, which was supervised by Norbert Heublein. The award was presented to him in the form of a certificate at the last Thermodynamics Colloquium in Kassel. Part of the prize was participation at the Colloquium, where he presented his excellent work to the German thermodynamics community.

Willy Messerschmitt Prize 2018
After 2008 (Dr.-Ing. Jutta Pieringer), 2013 (Dr.-Ing. Jannis Gikadi) and 2016 (Dr.-Ing. Thomas Fiala) the Willy Messerschmitt Prize has gone this year to Dr.-Ing. Vera Hoferichter for her dissertation on ‘Boundary Layer Flashback in Premixed Combustion Systems’. Flame flashback into the premixing section has been a challenge in the design of gas turbine burners since the beginning of the application of premixed combustion systems. For highly reactive fuels; flame flashback inside the low velocity region of the burner wall in particular is a major issue. In the presence of combustion instabilities, boundary layer flashback can be triggered by induced velocity oscillations at the burner exit.
Vera Hoferichter investigated experimentally the effect of velocity oscillations on boundary layer flashback characteristics of turbulent hydrogen-air flames depending on oscillation amplitude and frequency. Two flashback regimes were discovered: For low oscillation amplitudes, the flashback limits in terms of minimum flow velocities in the oscillation cycle correspond to the well-established flashback limits of unconfined flames. At high oscillation amplitudes, however, the flame periodically enters the burner duct. Flashback occurs if the maximum flow velocity in the oscillation cycle falls below the flashback limit of flames confined in ducts. As the two limiting cases of confined and unconfined flames are of special interest in the design of gas turbine burners, quantitative semi-analytic prediction models were developed and validated by Vera Hoferichter based on qualitative descriptions of the flashback processes introduced in previous studies.

New IAS Rudolf Diesel Industry Fellow at the Thermodynamics Institute
Dr. Mirko Bothien has been awarded a Rudolf Diesel Industry Fellowship by the Institute of Advanced Studies (IAS). Rudolf Diesel (1858-1913) was a TUM student with Professor Carl von Linde, the first thermodynamics professor at TUM. After Dr. Bruno Schuermans from GE Power, who made major contributions to the research on high frequency combustion at TUM, Dr. Mirko Bothien is the second Rudolf Diesel Industry Fellow at the Thermodynamics Institute. His fellowship will last three years from 2018 to 2021.
Dr. Mirko Bothien is Head of Combustor Technology, Gas Turbine R&D at Ansaldo Energia Switzerland. He is responsible for the development of technologies for premix and reheat combustors and for thermoacoustics in technology and product development. Currently, he has 13 direct reports covering all disciplines required for gas turbine combustor development. He is an expert for thermoacoustics in technical reviews and he is responsible for university relations of Ansaldo’s combustor department. Furthermore, he is a Member of the Board of the Norwegian CCS research consortium.
Dr. Mirko Bothien recently received the prestigious Early Career Award of the Global Power & Propulsion Society (GPPS) for his outstanding professional achievements.
Thermodynamics

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Research Focus
■ Combustion emission and reliability
■ Combustion instabilities and noise
■ Transport phenomena

Competence
■ Experimental and theoretical study of combustion and thermo-acoustics
■ Stability analysis of combustion systems
■ Experimental and theoretical study of low-emission constant pressure and constant volume combustion
■ Simulation of flow, heat-transfer and combustion
■ Experimental and theoretical study of two-phase flow and boiling

Infrastructure
■ Mechanical workshop, electronics workshop
■ Combustion/combustion instability research: test cells for experiments from lab to engine scale, 40bar laminar flame rig, atmospheric single burner rigs 50-1000kW, annular combustor 1500kW, HP rig 10bar/500kW, water channel for fluid dynamics and mixing studies, 80/200mm rapid compression machines, dynamical constant volume combustion cell, detonation channel
■ Two-phase flow research: boiling loop, water-air two-phase loop, test rigs for studies of catalytic process
■ Tools: high speed (HS) PIV, PIV, LDV, PDA, HS LIF, CW lasers, HS cameras 40 kfps, intensifiers, spectrometers, filters, digital holography, emission analyzers, dynamical temperature and pressure probes, cluster for scientific computing, numerous codes (CFD, LNSE, LEE), acoustics, reaction kinetics, etc.

Courses
■ Thermodynamics I + II
■ Combustion
■ Desalination
■ Energy Optimization of Buildings
■ Solar Engineering
■ Automotive Air Conditioning
■ Thermo-Fluidodynamics Lab
■ Combustion Technology Lab
■ Solar Technology Lab
■ Data Acquisition and Controls Lab

Selected Publications 2018

Technical Staff
Prof. Dr.-Ing.
Thomas
Sattelmayer
In this year we intensified and expanded joint research and teaching cooperation with other universities. Students from France and the USA spent their internship or research summer in our department. In contrast to the years before, when we focused on publishing, in 2018 more effort was put into applications for research funding (DFG) and joint R&D with companies. New cooperation contracts with sporting goods companies and also with a Swiss outdoor journal resulted from these efforts. We were able to maintain a constant number of staff and to successfully finish the habilitation review of one of our former staff members, Dr. Böhm.

From our 2018 activities five highlights are worth mentioning:
- Comparison study on touring ski bindings investigating safety and performance behavior.
- Organization and hosting the first joint conference on sport informatics and sport technology spinfortec 2018 in cooperation with TUM Sport and Health Sciences. Student workshop over two days prior to the conference.
- Invitation to participate in the exhibition Highlights of Physics in September 2018 in Dortmund.
- Beginning of an R&D cooperation with global player PUMA Europe on the future of wearables.
- Book chapter in the Routledge handbook ‘Modelling and simulation in sport and exercise’

More Safety with Improved Protection Gear

For protection against head injuries, helmets are worn both in the leisure and industrial sector. Especially for police and military personnel, safety helmets are part of the basic safety equipment. Their protective function comes at a price of additional mechanical and thermal burdens for the wearer. Our research deals with their intended purpose as well as the quantification of those burdens and possible solutions.

Images of escalating riots, as in Hamburg during the G20 Summit in summer 2017 or in autumn 2018 in France, show in an alarming way, what violence police and security staff can be exposed to. Therefore, protective helmets are part of the standard equipment for every police officer, who goes into action in this kind of scenario.
For optimized protection of the sensitive human head-neck system, ballistic helmets dampen local impacts and thus reduce the risk of skull fractures. Additionally, their inertial properties shall decrease head acceleration and prevent the wearer from concussion and possibly lethal brain injuries. As a consequence, the loading on the cervical spine due to the weight of the helmet should not be underestimated.

Biomechanical multibody systems allow a non-invasive method to investigate a variety of load cases up to severities, that exceed the possibilities of volunteer studies by far. We harness our expertise in biomechanical modelling to quantify occurring loads on the head-neck system in critical situations to identify possible risk factors for severe injuries.

Due to their properties and the closed surface, safety helmets act as an additional insulation layer and hinder the body’s thermoregulation. This initially leads to unpleasant temperatures and a high humidity in the area between head and helmet. In the case of excessive heat, the thermoregulation can get off balance and lead to health problems. One of the research topics of the Associate Professorship is to improve thermal comfort of personal protection equipment.

In order to determine the microclimate between head and helmet objectively, a measuring system was developed in cooperation with Reutlingen University – Faculty of Textile & Design. By applying the measuring system shown above, both temperatures and relative humidity can be measured. This allows conclusions to be drawn about the thermal properties of the helmets and to generate solutions for reducing thermal discomfort. On that note, a concept of an active cooling system has been developed, implemented in a functional model and proved initially. The infrared images on the right show the skin temperature before and after use of the active cooling system. The thermal discomfort, caused by the ballistic helmet, was significantly reduced.

Towards Better Performance with Optimized Sport Equipment

3D-printed Midsoles for Running Shoes
Ideally improving performance and the prevention of overuse injuries go in line with each other. Whereas there is no doubt that the performance of running footwear has reached very high levels, the rates of running injuries have remained relatively unchanged over the last 40 years. Our research tries to systematically include the athletes’
perception of shoe discomfort or sense of effort as an additional factor into shoe design. Today’s possibility to produce 3D-printed sole structures with varying elasticity and damping properties even being locally different offers a great research opportunity to combine subjective feedback with material changes. In one of our 2018 studies, different lattice structures of the midsole were produced with a selective laser sintering (SLS) printer. Cushioning properties of the printed midsoles are tested with an impactor device (objective measurement). In the next step, discomfort perception of the cushioning impact is rated by runners through a questionnaire. Lastly, the potential gap between subjective and objective measurements are identified and compensated with a new lattice structure produced by rapid prototyping.

**Future Aspects**

We believe that measuring perception parameters in parallel with other shoe characteristics such as cushioning will help in designing a new generation of running shoes. Ongoing studies evaluate other shoe characteristics (weight and traction) in parallel with discomfort perception. The future goal is to produce running shoes with the lowest risk of injuries without a trade-off in performance.

**Understanding the Interaction between Athlete Equipment and Environment**

**Sensors from Head to Toe**

At the ‘Highlights der Physik’ exhibition in Dortmund in September 2018, we presented a skiing mannequin equipped with multiple wearable sensor systems. Related to our work on a mechatronic ski binding, the dummy was wearing knee angle measuring underpants as well as a sock to determine pressure distribution inside the ski boot. With this sock we try to estimate the external loads acting on the foot and thus on the body. A shirt for measuring upper body movements completes posture detection. With a highly precise GPS-IMU system the position and the speed of the skier can be recorded. A sports watch
including a heart tracker, a body core temperature sensor and a micro-climate sensor network between helmet and head add physiological measurements to the biomechanical supervision of the skier. The event was organized by the Deutsche Physikalische Gesellschaft, the Federal Ministry of Education and Research and TU Dortmund University. The exhibition attracted 45,000 visitors.

Health, Wellness and More Fun Through Technical Support

Supporting Dynamic Sitting with Artificial Intelligence

Physical inactivity caused by long hours of computer use leads to musculoskeletal disorders also known as functional backpain. The support of dynamic sitting is regarded as an effective countermeasure. Real-time feedback systems may provide a verifiable improvement of motion behaviour at the computerized workplace. The purpose of our work was to design an intelligent feedback system that motivates dynamic sitting using real-time visual feedback. This should increase the awareness and the ability to reflect one’s own motion behaviour. Our system consists of a motion capturing unit which feeds an artificial neuronal network (ANN) for the identification of motion patterns plus a graphic representation for visual feedback. Four polymer threads sewed on a functional shirt (see picture to the right) serve as a measuring system. Their data is collected with a microcontroller board.

A smiley presented in the web-browser signals physical inactivity by changing its colour and facial expression. Positive feedback results when the user varies their sitting posture constantly. Moreover, the movement data is analysed with an ANN. This allows the user to check in a histogram, if he or she has an equal use of the six postures the shirt categorizes.
Research Focus

- Performance of sport equipment
- Improved performance of sport equipment
- Safety and protection gear to avoid overloads
- Thermo-physiology in sport garment design
- Footwear – sport surface interaction
- Electric and muscle-powered lightweight vehicles

Competence

- Muscular-skeletal models and simulation
- 3D-motion analysis (optical, inertia, DGPS)
- Electromyography (EMG) and spirometry
- Measurement of external loads and plantar pressure
- Development of physical models (foot and ankle, knee, lower leg)

Infrastructure

- Mobile skin- and core-temperature measurement
- Multi-body simulation software SIMPACK®
- Mobile EMG and spirometry
- Video-based motion analysis (Simi Motion)
- Leg surrogate with loading device
- Instrumented bicycle
- 5-axis fatigue testing device for bicycle frames
- Ski boot flexibility test rig, simulating real ground reaction forces

Courses

- Basic Skills of Science
- Applied Biomechanics
- Sports Technology
- CAD-Basics
- Practical Ergonomics
- Digital Human Modeling
- Advanced Biomechanics
- Sports Engineering
- Field Studies Sport Technology
- Interdisciplinary Research Project

Publications 2017/18 to date

The research of the Institute for Energy Systems (LES) focuses on future energy systems.

In line with our vision of an efficient and renewable future energy system, research at the Institute for Energy Systems focuses on the efficient utilization of renewable (e.g. biomass or geothermal heat) and fossil sources to generate power, heat or fuels and chemicals. Our work can be divided into four areas: Evaporation and Thermodynamic Cycles, Power Generation, Energy Storage and Solid Fuel Conversion. In each of these areas, we drive the development of components and processes through a combination of fundamental experiments, material characterization, pilot-scale testing and modelling at different scales. Energy system studies complement the above and allow us to evaluate on a larger scale the impact of the technologies and processes investigated, to assess their interaction and identify where research is most valuable.

We cooperate with research institutions and industrial companies on a number of national and international research projects. Key competences in the field of modeling and simulation are CFD simulations of gas-solid reactors (e.g. combustion, gasification, thermochemical storage, methanation), NOx chemistry, deposition and slagging tendencies, process simulations and optimization, as well as energy scenario simulations. The expertise of the institute is also reflected in the large number of operated test rigs and applied measurement technologies.

The mechanical workshop, electronics lab and chemical lab are also essential parts for the experimental capabilities at our institute.

Figure 1: Research structure at the Institute for Energy Systems

Solid Fuel Conversion

More-efficient carbon conversion and the reduction of ash-related problems is the aim of the research conducted in the field of solid fuel conversion. Different areas are investigated, including combustion, gasification, high temperature carbonization (HTC), gas cleaning and gas conditioning.

The EU-project Biofficiency, which started in 2016, aims at the development of next-generation, biomass-fired CHP plants. The project approach addresses current bottlenecks in solid biomass combustion, namely enhanced deposit formation, corrosion and ash utilization by a variety of promising new technologies. The goal is to deepen the understanding of biomass combustion, to improve current biomass pre-treatment technologies, as well as to contribute to the field of biomass ash utilization.

A new project, ReGasFerm, investigates the fermentation of synthesis gas produced in an entrained flow gasifier to alcohols. The research focus lies on determining the influence of gas impurities in the synthesis gas on the biological alcohol production to improve process efficiency and define gas-cleaning requirements. To achieve this, bacteria growth and alcohol production rates are investigated with synthesis gas with different concentrations of gas contaminants like HCN, NH₃, H₂S, etc. Additionally the formation and decomposition mechanisms of gas impurities during gasification and subsequent, as well as in-situ gas cleaning processes are investigated. In order to come closer to the goal of achieving a “zero waste” biorefinery, waste streams from the process shall be investigated for their gas-cleaning
suitability. In the end, the cleaned synthesis gas from the gasifier will be used in the fermentation reactors to demonstrate the complete process.

In the project HotVeGas, experiments on the institute’s test rigs and computational fluid dynamic (CFD) simulations are applied in order to gain a more detailed understanding of several high-temperature gasification processes. The insights will be used to enhance fuel flexibility for integrated gasification combined cycles (IGCC) as different fuels and mixtures of fuels can be used, as well as operational flexibility when considered in combination with electrolysis in polygeneration processes.

**Projects**
- Bioefficiency (Horizon 2020)
- HotVeGas III (BMWi)
- ReGasFerm (BMBF)

### Evaporation and Thermodynamic Cycles

Various projects at our institute are underway to maximize efficient use of heat for power generation and district heating. With a stronger presence of renewable energy sources in the power grid, combined cycles and coal-fired thermal power plants are subject to more frequent, steep, faster and larger load changes. The evaporator, as a component in thermal power plants, and its dynamic behavior is of great relevance for power plant operators. To investigate the evaporation process under dynamic conditions, an evaporation test rig, in operation at the institute since 2017, is used to measure temperature gradients close to the critical point and calculate heat transfer coefficients. The test rig at the institute is one of the few test facilities worldwide where the necessary conditions can be achieved. The knowledge in this field is used in the new project ATHLET-IVTTS in which the simulation code ATHLET is evaluated with regard to its performance to predict stationary and transient heat transfer close to the critical point.

The use of heat at low temperatures, like waste heat from industry and geothermal heat, with organic Rankine cycles (ORC) is also a focus of research and is investigated at the institute by means of process simulations and experiments. The Geothermal Alliance Bavaria focuses on efficiency-enhancing designs of ORCs in combination with suitable working fluids and possibilities of flexible heat decoupling. All this is done in the context of the geothermal potential in southern Germany, keeping in mind the applicability at other sites around the world. The test rig in Figure 2 was designed and has been built at the institute and is operational since 2018 when it produced its first power output.

**Projects**
- ATHLET-IVTTS (BMWi, GRS)
- Bavarian Geothermal Alliance (GAB)
- GRAME
- ICER

### Power Generation

As in our other research areas also, in the case of power generation the primary objective is to increase the efficiency of power generation technologies. Another important factor regarding the efficiency impact a technology has on the surrounding energy system is the flexibility of a power generation process. A more flexible process allows for more favorable interaction with a changing energy system that is increasingly dominated by fluctuating renewable sources. A Siemens gas-and-steam power-plant simulator (SPPA-T3000) is hosted at the Institute for Energy Systems, which makes it possible to simulate various power plant processes, and to test the control system of power plants and improve their flexibility. In the project Energy Valley Bavaria, dynamic power plant simulations are used in order to improve the flexibility of combined cycle and coal-fired power plants by means of improved process control.

A technology potentially allowing for very high exergetic efficiencies and therefore efficient power generation are solid oxide fuel cells (SOFCs). Within the framework of the SYNSOFC project funded by the DFG, the use of SOFCs in combination with a biomass gasifier for gen-
Generating electricity from biomass is investigated. The goal is to develop SOFCs that show a high tolerance against biogenic contaminants. The expertise gained during the SYNsoFC project is applied and combined with process design knowledge in the new project BioCORE. Started in 2018 it focuses on the development of a new, highly efficient fuel cell system to more efficiently use biogas from fermentation processes in a reversible system. This allows for long-term storage of fluctuating renewable electricity and ultra-high efficient use of biogas with a single system. The nature of the technologies’ dual use allows for twice the amount of flexibility that can be offered to the energy system compared to a “producer only” technology.

**Projects**
- BioCORE (BMBF)
- COOREFLEX-turbo (BMWi, AG Turbo)
- Energy Valley Bavaria
- SynSOFC (DFG)
- Baseflex

Another possibility to enhance the flexibility of a process embedded in an energy system is the use of storage options. To this end, thermal and thermochemical storage options, as well as CO₂ utilization (P2X, syntheses), are investigated at the Institute for Energy Systems. The new project TWIST builds on the findings of the predecessor project TcET and further investigates the use of the calcium oxide/calcium hydroxide reaction system in a steam-driven fluidized bed for high temperature heat storage. Apart from the reaction kinetics, focus of the current project is the characterization of the cycle stability of the particles and the derivation of heat transfer coef-
The objective of this research field is to define techno-economic boundary conditions and to identify the potential of the technologies investigated at the institute. As such, energy system studies are an important element in each of our projects. At the Institute for Energy Systems two different methodologies are used and developed in order to perform system studies. One is the linear optimization-based, open-source tool urbs, originally developed at the Chair of Renewable and Sustainable Energy Systems. The other one has been programmed at our institute and has not yet been named. It is based on mixed integer linear programming. The model simulates which power plants or storage systems produce the necessary electrical output to satisfy the load at every timestep. A variety of sub-models are implemented, such as partial load efficiencies, restricted load change rates and minimal downtime for power plants. The model was originally developed to simulate large energy systems as in Germany and Europe, but can also be used to optimize the energy production of small regions, industry parks or the scheduling of single production units. This model finds application in the projects E2Fuels and HotVeGas III.

In the BMWi project Clean-Tech-Campus the software urbs is improved and applied in order to allow districts and industrial sites or university campuses to optimize their energy generation portfolio across the heating, cooling and electricity sector, taking into account carbon emission goals in the future and expected cost developments. The methodology and the software is developed and validated together with four partners from inside and outside TUM, using the TUM campus Garching as an exemplary energy system. Pilot technologies with an impact on the energy system are defined and will be implemented in a subsequent project.

Projects
- Clean-Tech-Campus (BMWi)

System Studies also contribute to the following projects:
- E2Fuels (BMWi)
- HotVeGas III (BMWi)
Energy Systems

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Research Focus
- Solid fuel conversion
- Evaporation and thermodynamic cycles
- Power generation
- Energy storage

Competence
- Combustion and gasification of solids
- Steam cycles, flexible geothermal and waste heat utilization
- Operation of pilot- and lab-scale test facilities
- Process simulations and CFD simulations
- Energy system simulation/optimisation
- Fuel and gas analysis
- Fluidisation and heat transfer in (solid particle) fluidized beds

Infrastructure
- Fuel analysis laboratory and thermogravimetric analysis
- Mechanical workshop and electronics laboratory
- Experimental facilities and test rigs at pilot and demonstration scale (in particular, combustion, gasification and fluidization reactors, as well as ORC and heat transfer)

Courses
- Basic Course in Reaction Thermodynamics
- Chemical Reactors
- Electricity and Heat Storages
- Energy and Economy
- Energy from Biomass and Residuals
- Energy Systems I
- Numerical Methods for Energy Systems
- Process Technology and Ecology in Modern Power Plants
- Renewable Energy Technology I/II
- Seminar: Sustainable Energy Systems
  (formerly Energy Systems II)
- Seminar: Thermal Energy Systems
- Solarthermal Power Plants
- Steam Turbines
- Sustainable Energy Systems
- Thermal Power Plants
  (M.Sc. Power Engineering)
- Thermodynamics in Energy Conversion
  (M.Sc. Power Engineering)

Selected Publications 2018
Machine Elements

Calculation, simulation and experimental analysis of gears, synchronizers, clutches and rolling element bearings

Research at the Institute of Machine Elements (FZG) focuses on the development of methods and tools for reliable determination of fatigue life, efficiency, friction and vibration characteristics of gears and transmission elements.

The Institute of Machine Elements is also known as the Gear Research Centre (FZG). The primary focus of research activities at FZG is the development of methods and tools for reliable determination of fatigue life, efficiency and vibration characteristics of gears and transmission elements. At FZG, state-of-the-art facilities for the examination and testing of different machine elements – such as gears, synchronizers, clutches and rolling element bearings – are available.

Research projects at FZG range from theory-oriented fundamental research to application-related work. These projects are financed and supported by different organisations. Many are initiated, financed and supervised by the Forschungsvorarbeiten Antriebstechnik e.V. (FVA), usually together with the Arbeitsgemeinschaft industrieller Forschungsvereinigungen (AIF). Other important research partners include the Deutsche Forschungsgemeinschaft (DFG), the federal ministry of economic affairs and energy (BMWi), the Deutsche Wissenschaftliche Gesellschaft für Erdöl, Erdgas und Kohle e.V. (DGMK), the Bayerische Forschungsstiftung (BFS), the Forschungsvereinigung Verbrennungskraftmaschinen (FVV) or the Stahlforschung. In addition, many application-oriented projects are run in direct cooperation with industry partners.

In teaching, the machine elements course represents, with relevant lectures, central and group practical courses, basic training in mechanical engineering. Within the scope of the lectures, the students learn to select machines and machine elements properly, to design them and to calculate their properties. This knowledge is then applied in practice to design and calculation examples within the lecture-related exercises. A very important learning objective is that the students practise communicating in the ‘engineers’ language’ – with sketches and drawings. Practical relevance and topicality are also an important criterion for lectures on special subjects. Last but not least, this is ensured through lectures given by executives from industry.

Research on all kinds of gear drive is one of the main research fields of the institute. Further important aspects of research in automotive powertrain components and applications have evolved, such as synchronmesh systems, multidisc clutches and rolling element bearings. The consideration of fatigue life, efficiency, friction and NVH behavior of gears and transmission elements is in the foreground of research activity at FZG.

Many research topics deal with the simulation of the load-carrying capacity of the components: cylindrical, bevel, hypoid and worm gears, as well as multidisc clutches, synchronizers and rolling element bearings. The methods used are often programmed as application software and are thereby easily accessible for practical application. For the development of a method, simulation models for the load case are usually developed and validated through extensive tests with samples. The following selected projects give an exemplary insight into FZG’s research activities.

**Speed4E: Design of a Hyper-High-Speed Powertrain for EV to Achieve Maximum Ranges**

Speed4E is the follow-up project to the collaborative research project Speed2E within which the opportunities and challenges of high-speed electric drivetrains were investigated. The electric motors (EM), power electronics (PE) and the high-speed transmission were evaluated within a speed range up to 30,000 rpm. In Speed4E, a cooperative project team of five academic and seven industrial cooperating partners is involved, coordinated and led by FZG. The Speed4E battery electric driveline is highly integrated and modular. Hence, the project has grown in complexity, making it necessary to rethink most of the components. The project Speed4E can be subdivided into three levels:
At subsystem and components-level, the improvement in power density is achieved through an increase in maximum drive speed up to 50,000 rpm. The transmission consists of two sub-transmissions: a single-speed and a double-speed transmission. The power flow of both sub-transmissions can be split up according to the driver’s and transmission’s requirements. The relevant shifting strategies can be optimized for maximum efficiency and/or optimal NVH behavior. The two electrical motors in Speed4E are represented by an induction motor and a permanent-magnet synchronous motor. As a consequence, the project allows an individualized investigation of the potential and challenges of the different motor technologies. The power electronics is highly integrated and designed in order to limit electrical losses in the connections to the motors.

At system level, an integrated and holistic thermal management is developed, including the electric and mechanical components. The heat produced by the electric components will be used efficiently to heat up the oil that will lubricate the gearbox. To achieve this goal, an innovative water-based fluid will be developed, that can absorb both, the cooling and the lubrication. The relevant behavior of the system will be simulated to enhance the components before manufacture. CFD and dynamic simulations will show potential to improve the efficiency and the NVH behaviour. In the hyper-high-speed planetary gearbox, the lubricant system is optimized in particular regarding the lubrication of the planet gears and bearings. The whole drivetrain is to be integrated into an EV and also be tested on track. At vehicle level, optimal operating strategies for power electronics, electric machines and especially the gearbox will be developed to achieve maximum ranges. Moreover, a highly integrated double E architecture was designed to achieve maximum light-weight and to meet these special constraints. To meet the requirements of a series vehicle during the design, focus was put on scalability, modularity and all wheel drive capability.

Thermo-Mechanical Simulation of Synchronizers

Synchronizers are widely used in gear boxes of car and truck transmissions. These machine elements synchronize the rotational speed of the output shaft and the gear wheel to be engaged to ensure smooth gear changing. For the synchronization process, a cone clutch with up to three friction interfaces is used to accelerate or decelerate different rotational speeds between output shaft and gear wheel. After synchronization, torque is transferred by a positive dog clutch. Multi-cone synchronizers are especially used in lower gears as their torque capacity is higher than that of single-cone synchronizers. Higher friction torque results in faster shifting times, but the greater complexity of multi-cone synchronizers makes them more expensive and can raise the drag torque. In applications with high loads, carbon is used as a friction layer because it can stand higher surface pressure, friction work and power compared to other friction linings. Due to the low thermal conductivity of carbon friction linings, multi-cone synchronizers, which have small thermal mass and worse cooling compared to single-cone systems, exhibit high surface temperatures during the engagement which damage both friction lining and lubricant. Optimizing costs and improving efficiency of up-to-date gear boxes require knowledge about the thermal behavior of single and
Machine Elements

multi-cone synchronizers with carbon friction linings. The surface temperature is difficult to measure, as any thermocouple disturbs the temperature distribution. Therefore, the thermal behavior during clutch engagement is investigated in thermo-mechanical simulations. Consecutive static mechanical and transient thermal simulations were performed. The whole engagement is divided into several steps. The deformation under static load is calculated. Both pressure distribution and displacement are input data for the heat flux calculation on the friction surface. The resulting temperature field of the thermal simulation is then again input parameter for the static mechanical simulation. The simulation ends when the kinetic energy of the inertia is completely transferred into heat. The research aims to evaluate pressure and temperature distribution on the friction interface. The picture below shows an example of a single- and double-cone synchronizer’s pressure/temperature distribution. Due to the lower stiffness of the single-cone synchronizer’s blocker ring, the pressure and temperature distribution can become inhomogeneous. The single-cone synchronizer has an approximately 45 K higher maximum temperature on the friction surface on the highest load stage and the hot spot concentrates on a smaller area. The results of the thermo-mechanical simulations correlate well with experiments on the test rig. The deterioration of single-cone synchronizers, run with the same specific load parameters, is lower than that of double-cone synchronizers as the maximum surface temperature is lower. FEM parameter variations show ways to improve the performance of these synchronizers. The same type of simulation is also applied on wet multi-plate clutches to investigate spontaneous damage phenomena on friction plates.

UltraFan: A Hundred Sensors for Evaluating Excitation and Efficiency Behavior of Planetary Gear Stages

Due to their high power density compared to parallel axis gear stages, planetary gear stages are widely used in a variety of applications. For example, planetary gearboxes with a maximum size of some millimeters are used in servo gearheads or planetary gearboxes with an outer diameter of up to several meters, such as in cement mills. The efficiency and noise behavior of gearboxes is increasingly gaining in importance. Considering the electrification of automotive transmission systems, maximum ranges of the EVs are required while the noise behavior of the gearbox is no longer masked by an internal combustion engine. In numerous further applications, the design of the gear box is focused on an adequate efficiency and NVH behavior.

For example, Rolls Royce is currently developing a new aircraft engine for large aircraft – the so-called UltraFan, going into service from 2025. By incorporating a gearbox to drive the fan with lower speed and higher torque, a reduction of CO\textsubscript{2} and noise emissions by about 25% can be achieved. The new engine has to fulfill the noise emission targets for noise transmitted into the cabin as structure-borne noise or radiated to the ambience as airborne noise.

To research excitation and efficiency behavior of the transmission, a specially adapted test rig was designed and built up at FZG. Since a test rig with a nominal power of more than 80 MW of the original transmission cannot be integrated into the FZG test lab, the powertrain had to be scaled down accordingly, with respect to the properties noise behavior and efficiency.

The downscaled UltraFan gearbox test rig is built in a back-to-back configuration with two planetary gearboxes
loaded against each other. Consequently, the electrical motor running the rig only needs to compensate for the power losses of the gearbox power train. The 200 kW motor can drive the test rig with more than 3.5 kW of circulating power.

The figure above illustrates the planetary gearbox preloading test rig. On the left of the image, the test gearbox ② is shown, where most of the measurement equipment is located. In the middle, there is the slave gearbox ③. Two concentric shafts, the sun and carrier shaft connect the two gearboxes ④. The shafts have been designed to decouple the gearboxes dynamically and to measure the torque on one shaft. The electric motor ①, which provides the power losses, is shown on the right-hand side of the figure. The motor is connected to the sun shaft via the motor shaft ⑤.

To collect the relevant data to evaluate the excitation and efficiency behavior, over 100 sensors are applied to the rig, most of them at the test gearbox. The sensors and their approximate positions are shown in the following figure.

The development and design of the test rig was successfully finished in 2018 so that all the sensors were validated and the evaluation works correctly.
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Research Focus
- Experimental examinations and simulations of gear systems and components
- Load-carrying capacity, efficiency and NVH of cylindrical, bevel, hypoid and worm gears
- Durability and friction behavior of multidisc clutches and synchronizers

Competence
- Calculation, simulation and experimental analysis of load-carrying capacity, efficiency and NVH of gears
- Standardization: DIN/ISO/CEC
- FVA/VDI/DGMK
- Failure analysis, seminars, training sessions

Infrastructure
- Test facility (> 80 test rigs)
- Measuring laboratory
- Materials laboratory
- Lubricants laboratory
- Electro/electronic laboratory
- Workshop
- Gear grinding machine LGG 280
Courses

- Machine Elements I + II
- Drive-Systems Technology for Vehicles
- Planetary Gearboxes
- High-performance Gears for Marine Drives, Wind Energy Plants and Industrial Applications
- Design of Gearboxes with Cylindrical Gears
- Bevel and Hypoid Gears for Vehicle Drive Systems
- Special Section Machine Elements – Rolling Pairing
- Synchromesh Systems and Multidisc Clutches

Selected Publications 2018:

The Overall Equipment Effectiveness (OEE) within the machine and plant manufacturing domain with its increasing demands to produce customer-specific and individual products in shorter innovation cycles is the research focus of the Institute of Automation and Information Systems (AIS). To improve the required Cyber-Physical Production Systems (CPPS), AIS develops methods, notations, algorithms and architectures to increase the OEE. Research areas are Model-Based Engineering, Self-X-CPPS, Human-Machine Interaction, and Machine Learning and Smart Data.

To improve the OEE of machines, agents and learning approaches have been developed to support the operation of CPPS. In the field of Model-Based Engineering, inconsistency management across disciplines and along the life cycle is investigated to enable a seamless integration of the data through the engineering workflow. In the field of Human-Machine Interaction, solutions for information aggregation and representation for the human are developed including speech recognition, Augmented Reality (AR) and adaptive training systems to support the individual operator according to his/her skills and requirements. The aggregation and analysis of data to gain Smart Data from Big Data enables predictive maintenance and process/product optimization.

Embedded systems and their software in the mechatronic industry (products and automated production systems) are becoming more and more important. AIS adapts methods and approaches from the computer science domain for the needs of the machine and plant manufacturing domain. Therefore, approaches like technical debt, product lines, family mining, artificial neural networks or ontologies are introduced to address the challenges of real-world scenarios in automation – often together with partners from industry. In 2018, AIS held two big events supporting transfer of knowledge within the automation community. With the focus on scientific exchange, the 14th IEEE International Conference on Automation Science and Engineering (CASE) was hosted in Munich with participants from all over the world. A more industry-related event with top-class speakers was the Automation Symposium, where industry and academia had the chance to exchange viewpoints for mutual benefits.
Self-X-Cyber-Physical Production Systems

Methods to establish and improve the design of self-x (e.g. self-organizing, self-learning and self-adapting) automation software in automated production systems were evaluated, e.g. in intralogistics. With order-related manufacturing of individualized products, which require different production steps and, thus, different ways through the manufacturing system, it is necessary to design the automated MFS (aMFS) to be flexible and reconfigurable. Within the scope of Industry 4.0, multi-agent systems (MAS) are regarded as a suitable approach for implementing a decentralized, flexible and modular control architecture in which software agents control parts of a system. Therefore, AIS applies an agent-based approach for the control of heterogeneous aMFSs, which automatically allows changes to the aMFS layout during runtime without error-prone re-engineering of the control software. Due to their modular design, aMFSs are particularly well suited for the implementation of this approach, as they can be divided into smaller material flow modules (MFMs), which can then be combined to a desired aMFS layout. Thereby, a MFM is an encapsulated unit that executes one or more logistics functionalities, communicates with other MFMs and consists of mechanical hardware and corresponding control software. Moreover, each MFM brings along a representation of itself, which is used to create the visualization of the current aMFS layout for the human-machine interface flexibly. Inside this visualization, currently available routes through the aMFS including their properties are visualized. In summary, the software architecture developed allows a central intelligence to act as an interface to higher-level systems while increasing the flexibility and reconfigurability of the aMFS by distributing the control to the individual MFMs at the same time. The approach was successfully implemented at the Hybrid Process Model Demonstrator.

AIS also applies agent-based approaches to entire CPPS to increase adaptability and flexibility. Hereby, knowledge bases are used to represent the well-accepted Product Process Resource (PPR) structure. Explicitly distinguishing between those three views greatly helps to manage the relations among them. For instance, a product agent, i.e. an intelligent product, can interact with available resources in a smart factory to identify its ideal production sequence. The underlying ontologies, i.e. formalized knowledge bases, are well suited to enable such state-of-the art approaches. Engineers can even reuse models created during engineering the system to build such ontologies. It is expected that knowledge based systems, which include agent-based approaches, will enable companies to meet the individual requirements of all their customers.

Additionally, AIS has introduced a modular, model-based development procedure for intralogistics systems. Based on a meta model, which allows the formal description of the frequently reused hardware modules, the Programmable Logic Controller (PLC) control code for these modules is generated automatically. The generated code
Model-based methods are a promising approach to handle the increasing complexity of mechatronics systems but still require research to handle cross-disciplinary development. A special focus is put on the human and organization as an essential part of an interdisciplinary CPPS in the Collaborative Research Center (CRC) 768. One major issue is how different domain-specific models can be connected. Therefore, dependencies between models and intra-model change impacts are investigated. Methods like standardized model-interfaces defined using meta modeling and model-coupling, as well as ontologies are researched for inconsistency management. Model transformation and formal methods for consistency checking are applied. With step-by-step guidance of building knowledge bases in the collaborative development process, the chair developed methodologies to enable automatic inconsistency detection in the engineering data flow. Different modeling languages are investigated and corresponding tool environments are adapted. To save costs during the development of Automated Production Systems (aPS), automatic data exchange across tools and disciplines is strengthened in industrial projects. A further transfer project of the CRC 768 with industry was granted in 2018. Visualization of inter- and intra-model dependencies are also under observation.

In addition, being a member of the coordination board of the Priority Program (PP) 1593, research in the field of CPPS evolution management is conducted together with German institutes in the field of software engineering. A special focus is, among others, put on regression verification as well as estimation of maintainability effort. Aside from scientific competence, one of AIS’ main objectives is to apply the fundamental results for industrial settings rapidly. Thereby, AIS collaborates with small and medium-sized German enterprises (SMEs) to improve the engineering process. Novel application and industry projects were set up in the field of model-based testing of variant-rich systems, industrial communication architectures and its modeling to estimate time behavior and safe communication aspects in trains. In addition, automated configuration and code generation for process engineering systems, model-based testing of safety functions, as well as semantic code analysis is tackled.

**Projects**

- DFG Project – Gesteigerte Flexibilität in heterogen aufgebauten Materialflussystemen auf Basis intelligenter Softwareagenten in selbstkonfigurierender Fördertechnik (SiKiOn)
- DFG Project – Model-Driven Evolution Management for Microscopic Changes in Automation Systems (MoDEMMICAS)

**Recent Event – CASE 2018**

Knowledge from the development and operation of production plants was the topic of the 14th IEEE International Conference on Automation Science and Engineering – CASE 2018 that is the flagship conference of the IEEE Robotics and Automation Society (IEEE RAS). CASE 2018 was hosted at TUM (General Chair: Prof. Vogel-Heuser)

**Model-Based Engineering**

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**Reuse of Automation Software by Mastering Variants and Versions**

Machine and plant manufacturers often face the challenge of implementing a planned reuse strategy for control projects. A long history of parallel variants, whose software have been created by ‘Copy, Paste and Modify’, complicates the transition. Current results include the development, planned reuse and quality assurance of IEC 61131-3 based control software.

- Refactoring of existing control software, by transferring them into a family model, in order to (semi-)automatically transfer the growing variety of variants of automa-
tion software projects into a software product line with a high degree of reuse.

- In code analysis, the architecture and complexity distribution of functions within industrial control software is analyzed using a developed code analysis tool. A particular focus is on the implementation of common critical functionalities, such as error detection and correction, production data acquisition, operating mode selection and the human-machine interface. Also, company-specific rules can be mapped.

- Insights from the industrial control code are used to develop architectural patterns for control tasks depending on the processes to be controlled, machine types and domains. ‘Best Practice’ architecture patterns are created to demonstrate the benefits of the object-oriented extension of the IEC 61131-3 standard and to support its application in industrial control software development.

- Efficient testing and test management of variants and versions from the requirements to the result of the test through systematic test procedures in order to better control product quality in the future.

Further innovations in the field of quality assurance enable the verification of complex error handling routines via targeted manipulation of expected control input signals, the systematic semi-automatic testing of machines with the involvement of the plant operator, as well as the fully automatic analysis of plant circuits for the guided search for defects in electrical engineering.

The surveys conducted give a deep insight into the current state of software development and the weaknesses identified. On the other hand, the cooperation with industry allows the relevance and industrial applicability of the research results to be ensured.

### Machine Learning and Smart Data

To gain value from the enormous amount of data recorded during engineering and operation of industrial systems, an increasing part of the research conducted at AIS is dedicated to the transformation of Big Data into Smart Data. Within this scope, AIS applies a variety of data analysis algorithms to data gathered from the manufacturing (EU project IMPROVE, Bavarian project M@OK) and process industry (BMWi Project SIDAP). Within these projects, data acquisition, curation and preprocessing often becomes as important as the machine-learning methods themselves.

Architectural solutions are developed for data aggregation and integration (as challenging parts of the data collection), which enable flexible acquisition of data from a variety of sources within CPPS. Data compression methods are developed to reduce the large amount of data generated by an aPS and therefore facilitate the network communications between plant and database. In the phase of data preparation and preprocessing, AIS develops routines for the assessment of data quality in industrial data sets. Furthermore, as another important preprocessing step, automatic classification of process data into operational phases by considering the different behavior of production processes and plants is investigated. Once the preprocessing is completed, a combination of various machine-learning approaches can be used to analyze data for patterns indicating upcoming malfunctions, necessary maintenance, alarm floods and
product quality. Within the scope of plant malfunctioning, an image analysis method based on video data is applied by AIS to detect leakages in process plants. In the field of maintenance, data-driven methods are proposed to reduce the plant downtimes through early detection of valve failures. Furthermore, methods such as conditional probability analysis and hierarchical clustering are used for alarm data mining with the aim of root-cause analysis. All the above approaches require a balanced combination of Big Data methods, process understanding and input of expert knowledge. AIS is experienced in applying these to a great variety of different industries and use cases. The above experiences make AIS a reliable and experienced research institute and partner to transform big industrial data into Smart Data, including sensor, actuator and alarm data.

Projects

■ EU Project – Innovative Modelling Approaches for Production Systems to Raise Validatable Efficiency (IMPROVE)

■ BMWi Project – Skalierbares Integrationskonzept zur Datenaggregation, -analyse, -aufbereitung von großen Datenmengen in der Prozessindustrie (SiDAP)

■ VDI/VDE Project – Online Echtzeit-Wissensmanagement, Data-Mining und Machine-Learning für den Maschinen- und Anlagenbau (M@OK)

Recent Event – Automation Symposium 2018

Big data approaches and data mining promise the extraction of knowledge from a large amount of data. How can the data, for example, be collected from existing plants? How can plants be retrofitted in a targeted manner? What amount of data is required for the analysis? To examine these questions, AIS organized the Automation Symposium 2018 on September 27, 2018 at the Garching campus on the topic of ‘Production and Availability Optimization with Smart Data Approaches’. More than 80 participants from industry learned about and discussed the latest developments in research and industry on innovative approaches to big data, data analysis and industry 4.0 in production.

Human Machine Interaction

The EU project INCLUSIVE develops concepts for the adaptation of factory environments to the increasingly diverse capabilities of today’s operators. The project considers characteristics such as the age or the education of the worker to adapt the user interface of industrial machines. AIS focusses on the development of virtual training systems and assistance systems that are adapted to the characteristics of operators. Virtual training systems familiarize workers with industrial machinery in a safe and controlled environment that is adaptable to the requirements of the user and the task. The requirements of older operators can be addressed by adaptations of the visual presentation and the interaction techniques. A study with a representative user group indicated the benefits of adaptive virtual training. Speech-based assistance systems provide support in a way that is especially suitable for experienced workers or during manual procedures that require visual attention. Such systems can reduce the complexity of the instructions for inexperienced operators, or provide less instruction for experienced operators with previous knowledge. Evaluations indicate that the adaptations allow improvements in subjective perception, for instance usability, and objective measurements such as task completion time. The results are evaluated in industrial use cases. The use cases address the maintenance of a woodworking machine and the control of a robot cell for metal bending. The user interfaces developed and the training and support systems are implemented and evaluated with industrial users.

To support the cycle-oriented design of innovation processes for product service systems, the goal of sub-project D2 of the CRC 768 is to develop an appropriate interaction and visualization approaches. For this purpose, a method for the interactive visualization of model dependencies, which arise during the innovation process, is developed. Such a visualization approach can increase the cross-discipline understanding of the actors involved in the innovation process by linking their mental models.
Furthermore, resolving inconsistencies in the model dependencies is simplified by the visualization of possible recommendations for action.

Projects
- EU Project – Smart and Adaptive Interfaces for Inclusive Work Environment (INCLUSIVE)
- EU Project – Innovative Modelling Approaches for Production Systems to Raise Validatable Efficiency (IMPROVE)
- DFG Project – Interactive Visualization and Navigation in Heterogeneous Models (CRC 768, subproject D2)

Demonstrators at AIS; from discrete event to batch processes, considering logistics, industrial communication and human machine interaction.
Automation and Information Systems

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Research Focus
- Model-based Engineering for integrated engineering
- Machine Learning and Smart Data to improve OEE
- Self-X-CPPS with agents for distributed, intelligent control systems
- Human-Machine Interaction for better operation

Competence
- Ontologies and semantic technologies
- Meta-modelling and model coupling
- Variant and version management
- Modeling notations
- Service-oriented-architecture and multi-agent systems
- Verification, regression verification and model checking
- Simulation of holistic mechatronic systems including operator interaction
- Data modeling, data integration and data transformation
- Machine-learning techniques, knowledge models, knowledge acquisition and decision-making techniques
- Augmented and virtual reality and multi-modal human machine interfaces

Infrastructure/Demonstrators
- myJoghurt demonstrator: Complex hybrid plant lab model, which operates with market-leading automation devices – see http://i40d.ais.mw.tum.de
- 48 modular production plants for teaching software engineering for embedded systems
- Neutralization plant – industrial test-bed to evaluate model-based and data driven methods in process engineering domain
- Extended Pick and Place Unit – demonstrator for handling plant evolution including safety, modes of operation and novel communication technologies – see http://www.dfg-spp1593.de
- Self-X Material Flow System – demonstrator for self-x capabilities in the intralogistics domain
- VR Wall – demonstrator for assistance of the operator handling complex information by using the expanded possibilities of visualization and interaction
- Communication demonstrator for analyzing and benchmarking various different real-time communication technologies, which might arise, based on Ethernet.
- Code Analysis Platform – analysis of IEC 61131-3 based automation software considering direct and indirect dependencies between software artefacts

Courses
- Basics of Modern Information Technology 1+2
- Industrial Automation 1+2
- Industrial Software Engineering 1+2
- Development of Distributed Intelligent Embedded Mechatronic Systems
- Manufacturing Execution Systems in Producing Industries
- Practical Course Automation
- Practical Course Development of Distributed Intelligent Embedded Mechatronic Systems
- Practical Course Industrial Software Engineering
- Practical Course Simulation Technology

Selected Publications 2018
Metal Forming and Casting

Process and material qualification for metal forming, blanking and casting

The Chair of Metal Forming and Casting focuses on the three production processes: casting, blanking and metal forming. In 2018 over 40 scientists worked at the institute on research projects, which vary from fundamental research to industrial application.

Casting

The Casting Research Group focuses on:

- Molding material
- Tooling technology and material characterization
- Continuous and compound casting

Rising interest in additive manufacturing technology in various different industries has been observed in recent years. For technical applications, metal parts are of special interest due to their mechanical properties. To manufacture metal parts by means of an additive technology, the methods “Selective Laser Sintering” (SLS) and “Selective Laser Melting” (SLM) have been established. The downside of both technologies is the need for costly metal powders and high production times. Here the novel process ‘Droplet Based 3D-Printing’ has potential advantages. In this process, a metal part is built up by adding molten material droplet by droplet on a build platform. A joint research project at the Technical University of Munich between the Chair of Micro Technology and Medical Device Technology (MiMed, Prof. Lüth) and the Chair of Metal Forming and Casting (utg, Prof. Volk) focuses on this promising technology. A prototype printing machine designed for aluminium alloys was set up in the laboratory at MiMed, which is now used to analyse the influences of alloy composition, thermal conditions and other process parameters on the bonding process between individual droplets. The behavior of each droplet upon deposition on the part is crucial to the parts density, geometrical accuracy and mechanical properties. Current results show, that it is possible to obtain metal parts with over 98% relative density and mechanical properties comparable or superior to those of conventionally cast parts. Local temperatures during the impact of an arriving droplet on the printed parts have a major impact.
Metal Forming and Casting

on mechanical properties as well as on the resulting density. As the global temperature field depends on the parts geometry, it is challenging to obtain a constant part quality with constant part properties. Therefore numerical simulations are used to predict global temperature fields and to adjust process parameters accordingly. Future work will especially address the implementation of support materials, to enable the production of complex three-dimensional geometries by means of droplet-based 3D printing.

Demonstrator part fabricated by ‘Droplet Based 3D-Printing’ with the aluminium alloy AlSi12

Projects
■ Incremental Casting – The Generative Droplet-based Manufacturing of Parts Using Aluminium Alloys (DFG)
■ In-situ Strain Measurement During the Solidification of Aluminium Alloys Using Fibre Bragg Gratings (DFG)
■ In-situ Strain Measurement During the Solidification of Aluminium Alloys Using Fibre Bragg Gratings II (DFG)
■ μ-core – Microstructure-based Method for Calculating Technological Properties of Inorganic Bounded Sand Cores (DFG)
■ Prediction of Core Fracture during Decoring of Cast Components (DFG)
■ Energy- and Material-efficient Production of Copper Composites Using Horizontal Continuous Casting (DBU)
■ Casting and Characterization of Cu-Al-bilayer Composites (DFG)
■ Deformation and Control of Bonding Properties in Aluminium Composites in the Combination of Compound Casting and Forming (DFG)
■ In-situ Measurement of Deformation Induced Formation of Martensite in Austempered Ductile Iron (DFG)

Blanking

The Blanking Research Group focuses on:
■ Enhanced understanding of blanking processes
■ Wear of blanking tools
■ Optimization of material processing and part quality
■ Processes with analogies to blanking

Within the framework of the DFG priority program SPP 2013 ‘Targeted Use of Forming Induced Residual Stresses in Metal Components’, it was possible to augment the chair’s laboratory equipment with a new analysis method. The new nanoindenter, in combination with an adopted calculation method, enables the highly spatially resolved determination of residual stress.

By definition, residual stresses are intrinsic quantities of a closed system, which means that no direct information about the state of the residual stress can be obtained beyond its system boundaries. For their determination, derived quantities must be defined, e.g. stress-induced changes of the lattice plane spacing or occurring surface strains. Consequently, the conversion of strain values into residual stress values is of great importance. For the local measurement of residual stress, for example on electrical sheets (sheet thickness: 0.2 mm to 0.5 mm), the applied measurement method must have as high a spatial resolution as possible in order to be able to map the residual stress over the sheet thickness. Well-known methods such as the borehole method, dismantling methods, neutron diffraction or X-ray diffraction do not provide sufficient local resolution to measure the residual stresses over the sheet thickness. In addition to the methods mentioned above, residual stresses can be determined by instrumented indentation testing. Nanoindentation allows the exact definition of the sample area to be examined in the sub-μm range, whereby the size of the indentation is in the range of 1 μm to 5 μm. This makes it possible to scan even small sheet thicknesses with high spatial resolution. Using a stress-free reference sample or a reference with

Blanking Research Group
a known residual stress, the force-displacement curve recorded in the indentation test can be used to determine the residual stress of a specimen. For this purpose, the resulting three-dimensional stress distribution under the indenter geometry is determined directly by means of contact-mechanical modelling using an extended Hertz approach. In close cooperation with the suppliers of hardware and software, the Nanoindentation Intrinsic Stress Calculation Method (NIISC Method) for determining the residual stress is being continuously developed at the Chair of Metal Forming and Casting.

Projects
- Reduction of Sliver During Trimming of Aluminum Sheets (AiF)
- Wear Curves of Cutting Punches through Targeted Fatigue (AiF)
- Influence of Edge Manufacturing on the Fatigue Behavior of Different Steel Grades Under Cyclic Load (AVIF)
- Improvement of Tool Life Through Adjustment of the Tip Clearance of Punching Dies to the Breakthrough-force (AiF)
- HyBMS – Punching of Hybrid Components with a Minimal Degree of Damage (AiF)
- Lubricant-free Forming by Affecting Thermoelectric Currents (DFG)
- Manufacturing of Electromagnetic Components from Non-grain Oriented Electrical Steels (DFG)
- Sources and Prediction of Slug Pulling (AiF)
- Characterization and Utilization of Process-induced Residual Stresses for the Manufacturing of Functional Surfaces by Near-Net-Shape Blanking Processes (DFG)
- Thermomechanical Interaction in the Shear Cutting Affected Zone (DFG)
- Formability Improvement of Shear Cut Surfaces of Iron-manganese
- Sheet Metal by Optimized Cutting Parameters (FOSTA Stahlanwendung e.V.)
- Focused Use of Residual Stress in Electrical Steel as Means of Improving the Energy Efficiency (DFG)
- Compact unit for cost-effective punch speed adjustment (AiF)

Metal Forming

The Metal Forming Research Group focuses on:
- Material characterization
- Qualification of processes

The understanding and optimization of forming processes is the topic of this research group. Besides wide-spread processes such as deep drawing or bending, also joining and driving processes are studied. Almost every project includes finite element simulations to gain deeper process insight and to improve the processes themselves. The understanding of the material behavior and the use of adequate material models is essential for the successful simulation of forming processes. Therefore, the characterization of materials is a key topic in the research group. Depending on the process, also the strain rate and temperature sensitivity have to be included in the material model in addition to the quasi-static material properties. The second key topic is the qualification of processes. The focus lays on tooling and Industry 4.0.

One exemplary project, which combines parts of both research groups, is the ‘Improvement of High Strain Rate Superplasticity of Aluminum Materials by Equal Channel Angular Pressing of Sheet Metal Products’. The following section describes this project in more detail.
Metallurgy and Casting

Research Project: Improvement of High Strain Rate Superplasticity of Aluminum Materials by Equal Channel Angular Pressing of Sheet Metal Products

Motivation
Superplasticity refers to the ability of polycrystalline metals to reach high strains under temperature and low forming speeds without failing in the forming process. Due to the slow strain rates, the areas of application for superplastically produced components have so far been limited to small and very small series. High-speed superplasticity is a form of superplasticity that can service larger series due to higher forming speed. It occurs in aluminum alloys with a fine-grained and round microstructure and is based on rotations and displacements of the grains.

Project objectives
The main goal of this project is the significant increase of the forming speed while reducing the temperature during the superplastic forming of aluminum materials to increase the efficiency of the process. This is achieved through the targeted production of sheet metal semi-finished products with suitable material properties in the Equal Channel Angular Pressing (ECAP) process. Figure 2 shows the ECAP process. A sheet metal blank is pressed through an angled die. The shear stresses promote the formation of small angle grain boundaries.

Figure 1: Scheme for superplasticity

Figure 2: ECAP tool

Figure 3 shows the microstructure of a metallic material before and after treatment by the ECAP method. The average grain size is reduced by about 40% due to the process, allowing for high-speed superplasticity.

Figure 3: Microstructure of AZ31 before (a) and after (b) the ECAP process. Grain size a) = 14 μm and b) = 8.4 μm

Projects
- New experimental approach for yield loci determination using a modified Nakajima setup (DFG)
- Experimental investigation of arbitrary non-linear load paths using a feedback controller in combination with a conventional sheet metal testing machine and a special tool for cruciform specimens (DFG)
- Improvement of high strain rate superplasticity of aluminum materials by equal channel angular pressing of sheet metal products (DFG)
- Lightweight forging – Intelligent lightweight design through multi-component processes (AiF)
- Investigation of scalability and robustness of roller clinching processes (DFG)
- Anisotropic generalized forming limit concept (DFG)
- Inline-quality control in pressing tools (BMW AG)
- Methodology for the design of free-form bending tools (MAN SE)
- Development of a geometry-based method for compensation of process-related dimensional deviations of bulk formed parts (DFG)
Metal Forming and Casting

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Hannes Weiss, M.Sc.
Markus Welm, M.Sc.
Matthias Werner, M.Sc.

Research Focus
■ Tooling technology and material characterization for metal forming and casting
■ Engineering and planning processes

Competence
■ Empirical and mathematical model design
■ Numerical simulation (CFD, FEM, FVM, etc.)
■ Testing rig design and construction
■ Modeling and simulation of serial production processes
■ Fundamental research on innovative production techniques
■ Validation and implementation of new testing methods

Infrastructure
■ Hydraulic presses, high-speed punching presses, triple-action blanking press, servo presses
■ Rotational cutting line
■ 3D printer for inorganically bound core sands
■ Measurement instrumentation (residual stress, surface, geometry, mechanical properties)
■ Various tools for deep drawing, blanking and bending
■ Casting equipment
■ Core blowing machine
■ Mechanical workshop

Courses
■ Principles of Engineering Design and Production Systems
■ Basics of Casting and Metal Forming
■ Metal Forming Machines
■ Virtual Process Design for Metal Forming and Casting
■ Casting and Rapid Prototyping
■ Manufacturing Technologies
■ Marketing Engineering and Purchasing
■ Production Management in the Commercial Vehicle Sector
■ Development of Car Body Parts
■ Casting in Vehicle Construction
■ Forging and Manufacturing Technology for Powertrain and Chassis in Automotive Technology

Selected Publications 2018
■ Eder, Matthias; Gaber, Christian; Nester, Winfried; Hoffmann, Hartmut; Volk, Wolfram: Innovative measurement technique to determine equibiaxial flow curves of sheet metals using a modified Nakajima test. CIRP Annals - Manufacturing Technology, Elsevier Ltd, 2018, 265-268
Internal Combustion Engines

Engine design and simulation, combustion technologies, and experimental evaluation

The focus of the Chair of Internal Combustion Engines is to extend the efforts on the reduction of engine-out emissions by enhancing combustion technology, engine after-treatment, emission measurement techniques, and the knowledge on fuel properties and fuel composition. Favorable emission behavior, a high efficiency and low complexity of internal combustion engines will be crucial in the future, as alternative drive technologies emerge. Especially for long-distance or high-power applications, internal combustion engines will for a long time ensure clean and sustainable mobility and energy supply today and tomorrow. In individual mobility, traditional concepts will be increasingly combined with electric powertrains to achieve lower local pollutant emissions.

A highlight in 2018 were the first experiments with a new combustion concept combining the low pollutant emissions of spark ignited combustion with the high efficiency of compression ignition. Engine experiments under real-world conditions have proved a 20% reduction in fuel consumption. This revolutionary efficiency increase is achieved with a very lean and knock-resistant homogenous mixture and a pre-chamber ignition system. A conventional spark plug ignites the mixture in the pre-chamber and the resulting pre-combustion triggers the autoignition of the cylinder filling at an optimal combustion timing. The combustion has a high thermodynamic efficiency as knocking does not occur and the high power density allows downsizing of the engine. The so-called ‘spark assisted compression ignition’ (SACI) was originally developed for high-speed engines in motor sports and has the potential to be used in highly efficient range-extender units for electric vehicles in the future.

Combustion Technologies – CFD-Simulation – Emission Reduction

The reduction of engine emissions and fuel consumption are drivers for the improvement of combustion technology. Engines for gasoline, diesel, and natural gas are developed and built at the institute and are available for industrial or public-funded research projects. A key competence for the realization of our engine concepts is the application of professional CFD simulation software, which is used to predict and optimize the gas exchange.
Internal Combustion Engines

In past decades the injection pressure of modern diesel engines increased from 1000 bar up to 3000 bar and there is a similar trend in direct-injection gasoline engines where modern systems today operate at c. 350 bar. Our research activities include all steps of injection system development. Key competences are various simulations containing 1-D hydraulic, 3-D multiphase flow, as well as spray simulation. At several test benches hydraulic and optical measurements of injectors with various fuels are carried out. In the past year, the testing capability was extended to provide a chilling system for the measurement of injection processes under cold-start conditions. In dynamic driving cycles and real-world driving, most of the tailpipe pollutant emissions occur during the first seconds after engine start when after-treatment systems have not yet reached their light-off temperature. In a recently completed DFG-funded project, an open-loop control for diesel common-rail injectors is under development in collaboration with the Institute of Applied Mechanics. The aim is to maintain an optimal injection rate throughout the entire lifetime of a common-rail injector subjected to coking, wear, etc. For this purpose, different injector signals are evaluated in order to determine the injection rate using available signals in engine operation.

Projects
- DFG project ‘Optimierung des Einspritzverhaltens von Dieselinjectoren unter dem Einfluss von Alterungser-scheinungen des Injectors’
- Several projects funded by industry partners

Injection Systems – Spray Measurement – Optical Diagnostics

Gasoline injection at different temperatures measured with the Mie-scattering method.

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Projects
- DFG project ‘Optimierung des Einspritzverhaltens von Dieselinjectoren unter dem Einfluss von Alterungser-scheinungen des Injectors’
- Several projects funded by industry partners
Friction Measurement – Tribology – Engine Mechanics

Reducing piston assembly friction is a central task when improving the efficiency of modern internal combustion engines. Piston, piston rings, liner and lubricating oil form a complex tribological system operating in a field of constantly alternating velocities, pressures, and temperatures. Therefore, a special research engine containing a measurement device using the floating liner method was developed at the institute. It allows measurement of the piston assembly friction with a highly accurate resolution up to 2 N under fired conditions. That enables the detection of optimization potential by experimental analysis. A second research engine was built, containing several sensors to measure crank-angle resolved motions of the piston and the piston rings. Furthermore, the oil film thickness and oil transportation phenomena are measured during fired engine operation. Recently, even optical insight on the cylinder surface was prepared by means of a glass window in the liner. The measurement results of the three engines allow a deeper understanding of the behavior and dependencies of engine tribology. Particulate emissions for example can result from lubricating oil which is transferred into the combustion chamber. This effect can be made visible with the glass-liner engine setup.

Projects
- FVV project ‘Kolbenring-Öltransport Glasliner II’
- DFG project ‘Entwicklung eines kosten- u. verbrauchs-günstigen Split- Verbrennungsmotors III’
- BFS Project ‘Truck 2030 – Bayerische Kooperation für Transporteffizienz’
- Several projects funded by industry partners

Natural Gas Engines – Combustion – Emissions – Simulation

Combustion in a high-pressure dual-fuel engine: after a small quantity of diesel fuel has been injected and started combustion, natural gas is injected under high pressure and ignites easily. The luminous regions indicate a diffusive gas flame.

Natural gas is an important step to cope with CO₂ reduction targets and future energy demand. Moreover, surplus energy from renewable sources can be used to synthesize hydrogen and methane. However, further development is needed to fulfill future emission legislation with high efficiency combustion. Current research projects focus on emissions of unburned hydrocarbons like methane or formaldehyde. The goal is to understand the influence of engine parameters like valve timing, ignition, equivalence ratio and gas quality. Alternative combustion processes are another focus to overcome the trade-off between emissions and efficiency. Stratified or diesel-like combustion processes (see photo) are promising techniques and will allow highest loads without restrictions from knocking while keeping lowest emission levels and highest efficiency with highly volatile gas qualities. The 5 l single cylinder research engine features an optically accessible combustion chamber. Combined with CFD simulations a deep insight into innovative combustion processes is now possible.

Projects
- BMWi project ‘Flex Di: Flexible direkteinspritzende Motoren für die Schiffahrt’
- STMUV project ‘Minimierung der Emissionen von NOx beim Betrieb von Biogas-BHKW’
- EU project ‘HERCULES 2’
- Several projects funded by industry partners

Combustion engines can reduce their output of GHG emissions and contribute to the transition towards alternative energy by enhancing the efficiency of energy conversion and by exploiting CO₂ neutral primary energies. Sustainable biofuels and synthetic fuels can replace fossil fuels and offer the additional benefit of clean combustion. Oxymethylene ethers are a promising synthetic alternative for fossil diesel because they do not form soot particles during combustion. Current projects are working on the best blend of different OME chain-lengths to achieve optimal efficiency and lowest emissions (see diagram). Modern methods for the measurement of ultra-low particle emissions are needed for this and other advanced engine concepts. Cooperating closely with industry, we help to improve such measurement techniques. Another field of our research is the utilization of thermodynamic losses from coolant or exhaust. The thermodynamic Rankine cycle for instance allows enthalpy to be harvested from hot exhaust gas and electric power to be produced by means of a steam turbine.

Projects

- BMWi project ‘XME Diesel – (Bio-)Methylether als alternative Kraftstoffe in bivalenten Dieselmotoren’
- BMEL/FNR project ‘OME – Umweltfreundliche Dieselkraftstoffadditive’
- BMWi project ‘TruckER – Rankine Kreislauf für Nutzfahrzeuge mit ganzheitlichem Energiemanagement’
- BFS project ‘Sub-Zero emission diesel engine’
- Several projects funded by industry partners
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Martin Daniel
Siegfried Geiger
Dipl.-Ing. Christian Hödl
Kai Möbius
Patrick Ottiger
Dipl.-Ing. Ulrich Tetzner
Markus Weiß

Research Focus
- Combustion technologies
- Gas engines
- Engine tribology and mechanics
- Fuel injection technologies
- Alternative fuels and biofuels
- Exhaust gas after-treatment and measurement

Competence
- CAD construction
- CFD calculation
- Thermodynamic simulations
- Hydraulic simulations
- Mechanical simulations
- Engine measurement techniques

Infrastructure
- Engine test rigs (13)
- Gasoline, diesel and gas engines (>15)
- Injection test rigs (2)
- Optical and laser diagnostics
- Mechanical workshop
- Electronic workshop

Courses
- Combustion Engines
- Engine Thermodynamics
- Mechanics of Combustion Engines
- Methods of Engine Calibration
- Injection Technology
- Measurement Techniques
- Fuels for Combustion Engines
- Several practical courses

Key Publications 2018
- Peer, Johann; Stadler, Andreas; Zimmer, Thomas; Härtl, Martin; Wachtmeister, Georg; Sauerland, Henning: A Novel Approach towards Stable and Low Emission Stratified Lean Combustion Employing Two Solenoid Multi-Hole Direct Injectors. SAE International Journal of Engines 11(2), 2018
Computational Mechanics

Application-motivated fundamental research in computational mechanics

The Chair for Computational Mechanics (LNM) is committed to what can best be described as cutting-edge ‘application-motivated fundamental research’ in a broad range of research areas in computational mechanics. Applications span all fields of engineering (mechanical, biomedical, aerospace, civil, chemical) and the applied sciences.

With a strong basis in both computational solid and fluid dynamics, the current focus lies on multifield and multiscale problems as well as on computational bioengineering. In all these areas, LNM covers the full spectrum from advanced modeling and the development of novel computational methods to sophisticated software development and application-oriented simulations on high performance computing systems. Meanwhile, the research activities at LNM also include optimization, inverse analysis, uncertainty quantification as well as experimental work. In collaboration with leading researchers worldwide as well as national and international industrial partners, LNM expedites projects at the front line of research. For more details and updated information please do visit our webpage www.lnm.mw.tum.de/home.

Computational Multiphysics – Coupled and Multiscale Problems

The interaction of different physical phenomena plays an essential role in most engineering applications. The modeling of such multiphysics problems is one of our main areas of research. We have developed robust and efficient modeling approaches and computational methods for various coupled problems. Those problem classes comprise a.o. fluid-structure interaction, electro-chemical, thermo-mechanical, opto-acoustic, coupled re-active transport, poro-fluid-transport and thermo-fluid-structure-contact interaction problems. Also the interplay of effects on different scales plays an important role in many scientific and engineering applications. Therefore, there has been increasing interest in modeling so-called multiscale phenomena both mathematically and computationally. We tackle multiscale problems both in CSD and CFD. While in the first group the focus is on the modeling of heterogeneous materials, in the second group the focus is on turbulent flows and complex fluids.

Simulation of a charge process of an all-solid-state lithium-ion battery

Time sequence of flow-driven squeezed elastic structures with consistent treatment of fluid-structure-contact interaction (visualization of flow velocities and deformed solids)
Computational Solid, Structural and Fluid Dynamics

Computational structural and solid dynamics (CSD) is one of the classical core disciplines within the fast-growing field of computational mechanics. Our research activities in computational structural and solid dynamics cover a wide range of methods, from nonlinear solid (hybrid FE meshes, isogeometric analysis) and structural models (beams, shells) and corresponding finite element technology (EAS, ANS, F-Bar) to material modeling (hyperelastic-

ty, viscoelasticity, elastoplasticity) at finite strains. Another focus are complex material phenomena such as anisotropy, fiber components, damage, fracture and multiscale modeling of heterogeneous materials.

Computational contact dynamics represent a particularly challenging class of structural mechanics problems due to the non-smooth character of the underlying laws of physics (e.g. non-penetration) and the strong nonlinearities introduced by the corresponding geometrical constraints. In addition, complex interface phenomena (friction, adhesion, etc.) need to be taken into account with sophisticated computational models. Here, our research emphasizes the development of robust and efficient contact formulations and discretization methods in the context of finite deformations and non-matching meshes/ non-conforming interfaces. Lately, this main focus has been successfully extended towards contact with wear, coupled thermo-mechanical contact and beam-to-beam contact. Furthermore, strongly coupled fluid-structure interaction (FSI) with contact is another current research field.

Computational fluid dynamics (CFD) is the other core discipline in computational mechanics. We are one of the very few groups worldwide that do original research in both CSD and CFD. Our focus in CFD is on incompressible and weakly compressible flows. We develop novel discretization methods for flow problems as well as novel approaches for turbulent flows based on large eddy simulation (LES) and detached eddy simulation (DES). Our CFD application codes have been run on large supercomputers with more than 100,000 cores. Another focus is on multiphase flows and flows coupled to other fields as in fluid-structure interaction, electro-chemistry or reactive transport problems.
Computational Mechanics

Computational Bioengineering and Biophysics

Our research in the biomedical engineering area includes a variety of different fields. In all of them we collaborate with experts from medicine, biology or biophysics. Some activities are the development of a comprehensive coupled multiscale model of the respiratory system, of a model for rupture risk prediction of abdominal aortic aneurysms, comprehensive cardiac modeling, simulation of surgical procedures or cellular modeling. In recent years we have also successfully entered the area of biophysics, where we have developed a novel, theoretically sound and highly efficient approach for the Brownian dynamics of polymers. Based on this unique approach we meanwhile are able to study and answer a number of open questions in the biophysics community.

Vascular Growth and Remodeling in Aneurysms
(Emmy-Noether Group headed by Dr. C. Cyron)

Aneurysms are focal dilatations of blood vessels that often grow over years and finally rupture. Rupturing aneurysms are among the leading causes of mortality and morbidity in industrialized countries. While over the last decades our general understanding of the biomechanics of aneurysms has advanced substantially, the factors governing their growth – although the key to develop future therapies – remain poorly understood. In February 2015, Dr. Christian Cyron established the Emmy-Noether group for vascular growth and remodeling in aneurysms at the Institute for Computational Mechanics. It aims at exploring the biomechanical and biochemical mechanisms governing the growth of aneurysms, with the perspective of exploiting these for the development of future therapies and computer-aided diagnosis. To this end, the Emmy-Noether group will combine advanced methods from computational mechanics with state-of-the-art medical imaging technology and machine learning. The Emmy-Noether program of the German Research Foundation (DFG) was established in 1999 to support groundbreaking projects of young researchers. Since then the DFG has been supporting only eight Emmy-Noether groups in the area of mechanics and mechanical design.
In intensive care units (ICUs) in Germany, roughly 400,000 patients receive mechanical ventilation every year. Seventy thousand of those patients develop a severe complication of the lung known as acute respiratory distress syndrome (ARDS). For 28,000 patients, this complication is fatal. The key to reducing mortality and chronic disease is accurate personalized mechanical ventilation. Currently, doctors resort to trial-and-error schemes in their often unsuccessful search for such a ventilation. If they do not find it, the patient is likely to die.

In 2018, Kei Müller, Jonas Biehler, Karl-Robert Wichmann, and Prof. Wolfgang Wall started an EXIST-Forschungstransfer project that aims to provide life-saving personalized information for optimal ventilation of severely ill patients. Their project ‘Ebenbuild’ musters highly innovative computational methods to model the mechanics of the human lung along with the most progressive technologies available in machine-learning, data science, and image processing. Their goal is to found a digital healthcare company that will improve patient health as well as cost efficiency and flexibility of clinics by shaping the best practice in mechanical ventilation.
Guest Scientists
Prof. Dr. Bernhard Schrefler
Dr.-Ing. Anh-Tu Vuong

Research Focus
- Computational fluid dynamics
- Computational solid and structural dynamics
- Computational contact mechanics
- Multiphysics/coupled problems
- Multiscale problems
- Reduced-dimensional modeling
- Uncertainty quantification
- Inverse problems
- Optimization
- Artificial intelligence
- High performance computing

Competence
- Contact dynamics
- Discretization methods
- Experimental (bio-)mechanics
- Fluid dynamics
- Fluid-structure interaction
- Inverse methods
- Material modeling
- Optimization
- Solid dynamics
- Solvers/AMG
- Thermo-fluid-structure interaction
- Transport phenomena
- Uncertainty quantification
- Machine learning

Infrastructure
- Three HPC clusters
- Biomechanics lab (including uniaxial and biaxial testing machines)

Courses
- Engineering Mechanics I, II and III
- Numerical Methods for Engineers
- Nonlinear Continuum Mechanics
- Finite Elements
- Finite Elements in Fluid Mechanics
- Nonlinear Finite Element Methods
- Biomechanics – Fundamentals and Modeling
- Discontinuous Galerkin Methods
- Growth and Remodeling in Biological Tissue
- Computational Contact and Interface Mechanics
- Finite Element Lab
- Computational Biomechanics Lab
- Engineering Solutions for Biomedical Problems
- Numerical Methods for Engineers Lab
- TM Applets
- Computational Solid and Fluid Dynamics (MSE)
- Visualization Techniques in Computational Mechanics

Selected Publications 2018
Astronautics

Real-time telerobotics in space – planetary and lunar exploration – human spaceflight – spacecraft technologies and nano-satellites – spaceflight systems engineering

- Multi-disciplinary research and development of technologies for satellite systems, human and robotic space exploration, teleoperation and communication.

Satellite Technologies

MOVE-II CubeSat

The CubeSat program MOVE (Munich Orbital Verification Experiment), initiated in 2006, focuses on the hands-on education of students, complementing theoretical coursework knowledge and state-of-the-art aerospace engineering. The program’s second CubeSat, MOVE-II, was launched into a 575 km sun-synchronous orbit on December 3rd, 2018 and has been operated since then. MOVE-II is an educational cooperation between the Institute of Astronautics and the student group ‘Wissenschaftliche Arbeitsgemeinschaft für Raketentechnik und Raumfahrt’ (WARR) with more than 200 students involved so far. Besides the educational aspect, the project is intended as a platform for validating new technologies in space. The 1.2 kg satellite carries a self-developed attitude determination and control system, two radio transceivers and four deployable solar panels held down by a reusable shape memory mechanism. The research payload of the MOVE-II satellite will characterize novel 4-junction solar cells in the actual space environment. The MOVE-II project is funded by the German Aerospace Center (DLR) under research grant 50RM1509.

Figure 1. The MOVE-II CubeSat before launch (left) and its launch on a Falcon 9 from Vandenberg Air Force Base, California (right). Image credit right: SpaceX

IRESA

The Intelligent Redundant Spacecraft Actuator is a joint project between the Institute of Astronautics at TUM and the independent research institute ‘Forschungsgemeinschaft Werkzeuge und Werkstoffe FGW e.V.’. It focuses on the development of a servo-actuator for spacecraft based on shape memory alloys. The modular-designed actuator shall be capable of rotatory as well as translator displacement and is designed for hold-down and release mechanisms, as well as solar array pointing or antenna pointing mechanisms in space. The IRESA project is funded by the German Aerospace Center (DLR) under research grant 50RP1750.
Exploration Technologies

**PROSPECT**

The instrument package PROSPECT is currently being developed under contract to the European Space Agency (ESA) for the Russian Luna-27 mission to the lunar south pole region. The instrument consists of a drill system called PROSEED, which acquires soil samples from the lunar subsurface, and the gas analysis instrument ProSPA for the extraction of volatile species from the sample and the subsequent gas analysis. The TUM Institute of Astronautics has been involved in the instrument development in Phase A and B since 2014, and will continue its support in developing the flight instrument, which is to be launched in 2023. The tasks for TUM include the thermal design, analysis and test of the sample ovens used for in-situ thermal processing and extraction of volatiles from lunar regolith. A laboratory setup for sample conditioning and experimental demonstration of the volatiles extraction process has been established at TUM for this purpose. With respect to future in-situ resource utilization, the chemical reduction of lunar regolith simulants with hydrogen was demonstrated, a process that can be applied to produce water on the Moon. ProSPA is led by The Open University (UK), as part of the overall PROSPECT payload package led by Leonardo Finmeccanica S.p.A. (Italy).

**LUVMI**

The international Lunar Volatiles Mobile Instrumentation (LUVMI) consortium of five partners from the European science and space industry cooperatively designs a mobile instrument to access and analyze lunar regolith in permanently shadowed regions on the Moon. LUVMI is funded by the European Commission as part of the Horizon 2020 framework ‘Leadership in Enabling and Industrial Technologies-Space’ and coordinated by the Belgian company Space Applications Services. The system consists of a mobile payload support platform that can support a number of instruments for the analysis of the lunar polar regolith and prospecting for volatile resources. The main payload of the LUVMI rover is the Lunar Volatiles Scout (LVS), which has been developed by TUM in cooperation with The Open University (UK). The LVS is a miniature soil sampling instrument that can be inserted into the lunar regolith, where a heating element thermally extracts volatile compounds, such as water. The

Figure 2. The Russian Luna-27 lander with ESA’s PROSPECT payload. Image credit: ESA/Roscosmos

Figure 3: The LUVMI rover prototype (left, image credit: Martyna Hodges, The Open University) and the integrated LVS in the thermal-vacuum test facility (right)
gases released are captured and analyzed in situ by an integrated miniature mass spectrometer. In 2018 the LUVMI consortium successfully assembled the first LUVMI prototype rover, which was demonstrated during an outdoor test campaign in the dunes of Noordwijk (NL) during December. In addition, the LVS instrument was integrated and tested at TUM. Drilling, gas extraction and gas analysis were demonstrated under simulated lunar conditions in a thermal vacuum chamber for a first characterization of the full LVS instrument.

**V HAB**

To fully assess the long-term operation and stability of life support systems (LSS) for exploration missions, static analysis methods are insufficient. Establishing mass balances and selecting technologies based on average performance values is a fast and proven method for feasibility studies. Once the initial system design becomes more detailed, dynamic simulations are required. The Virtual Habitat (V HAB) modelling tool, a MATLAB®-based simulation software, enables the dynamic simulation of life support systems, the humans occupying the simulated habitat and the mission that is being performed, for more complex analyses. The simulation system V HAB was validated in 2013 by comparing data from a virtual model of the international space station LSS with actual flight data. Since then, a range of new capabilities has been added to V HAB’s already broad spectrum.

Current efforts in the V HAB project are the development of a hardware test setup for plant growth within the framework of closed bio-regenerative LSS. The initial setup of the system without the enclosure has been finished and an electronic control system based on a microcontroller was implemented, which allows remote access and control of the system. An initial growth experiment using lettuce and tomatoes was performed to identify further optimization and improvements for the setup as well as verify the basic functionality. The test provided valuable insight into different still existing problems with the test setup and serves as a showcase for engineering challenges in designing bio-regenerative life support systems. Furthermore, the development of V HAB is progressing steadily and version 2.2.0 was released this year. It features improvements in usability and simulation speed, as well as a new thermal and electrical simulation domain to enable modelling of combined processes. Additionally, documentation and tutorials to learn V HAB were created in the form of a comprehensive Wiki. This also serves as alpha testing for planned open source releases in the future. The next steps planned for V HAB are a graphical user interface based on XML drawing tools like draw.io. Instead of implementing a full UI for V HAB the XML data created will be converted into a V HAB system by using a V HAB XML library. Using this approach, users can easily create V HAB models, without requiring multiple MATLAB® licenses.

**TherMoS**

The Thermal Moon Simulator (TherMoS) is a dynamic simulation tool for the thermal environment and dynamics of moving objects on the lunar surface. It allows precise simulation of temperatures on the Moon for big scenes of hundreds of km over long periods of several years. Recently, the capabilities of TherMoS were extended towards faster computation in ray-tracing as well as solving the thermal model of the Moon. It is now possible to simulate illumination conditions at the lunar poles precisely where low solar elevation angles of only up to ~1.55° can occur in the worst case. Improvements cover the Sun being represented as a disc-shaped radiator as well as a detailed digital elevation model of the lunar south pole with a resolution of 50 m per pixel. The ray-tracing algorithm based on Nvidia Optix can now make use of GPU clusters, which strongly accelerates the computation time for radiation. For this purpose, NVIDIA supported TUM with their hardware grant, donating a Quadro P6000 GPU.
Technologies for Operating Robots in Space

RACOON
The RACOON laboratory features a satellite proximity operations simulation environment consisting of a hardware-in-the-loop simulator that represents position and attitude of two spacecraft in close proximity, such as during rendezvous and docking maneuvers. The laboratory provides realistic lighting conditions with simulated Sun and Earth and hardware sensors to simulate realistic sensor data for the development of new spacecraft technologies and novel control algorithms. The real-time capabilities allow the inclusion of a human operator into the control loop for research in the area of human-spacecraft interaction, such as studies of optimal human-machine interface designs or operator workload evaluations. In 2018, technology developments for on-orbit telerobotics missions focused on vision-based 3D-reconstruction and experimental human-machine interface studies. 3D-object reconstruction for virtual reality scenarios is already used in terrestrial systems, including UAV image processing. The use of this technology for on-orbit servicing (OOS) missions was investigated in feasibility and performance tests under realistic environmental orbital conditions. Experimental human-spacecraft interfaces using virtual reality technologies were developed to enhance the environmental awareness of spacecraft operators during on-orbit servicing missions.

LISA
Teleoperated on-orbit servicing and space debris removal missions, a key research area of the TUM Institute of Astronautics, require near real-time transmission of multi-channel video signals and spacecraft sensor and control information, which can exceed data rates of 20 Mbps. Recent research projects at TUM have developed novel high-gain antennas as low-loss direct radiating array antenna systems (Lightweight Inter-Satellite Antenna, LISA), both as mechanically or electronically (beam-forming) steerable antennas in copper-galvanic waveguide designs. These projects are funded by the German Aerospace Center (DLR) under research grants 50YB1113 and 50YB1333.

Figure 6: The RACOON laboratory (left) provides 11 degrees of freedom to allow realistic remote-controlled rendezvous and docking maneuvers assisted by head-up displays with a virtual representation of the scene (right).

Figure 7: Corrugated horn with metal matrix carbon fiber (left) and polarizer electroplated on 3D-printed lost core (right).
The research project CFRM-HF (DLR grant 50YB1533) is a development of alternative manufacturing methods for integrated waveguide designs, based on the established copper galvanic process in LISA. Here two objectives are investigated: 1. Carbon fiber reinforced copper – to reduce weight and thermal expansion of the copper parts; 2. Additive manufactured cores – to reduce the costs and enable highly integrated waveguide designs. In 2018 the potential of both manufacturing techniques were tested (Figure 7).

CopKa
CopKa is a cooperative technology development and demonstration of a multi-sensor-based emergency service mission, using data from an unmanned aerial vehicle (UAV) helicopter and other imaging data sources, transmitted over Ka-band satellite links. The project develops and tests novel communication architectures as well as supporting rapid antenna pointing technologies, and demonstrates the integrated system in various test scenarios in cooperation with the TUM firefighting services. The CopKa emergency use scenario represents a synergetic satellite communication system to the RACOON on orbit servicing architecture. The UAV copter and local cameras can be controlled over the Ka-band satellite communication link to provide enhanced situation awareness from the remote accident site to the emergency services coordinators at the control center or home base. The CopKa system must not interfere with local first responders and therefore requires novel control environments including virtual reality technologies for safe and partial autonomous operations from the control center.

In recent years four exercises were successfully carried out with the firefighter brigades. In two exercises the teleoperation of the UAV over a geostationary earth orbit (GEO) satellite relay was demonstrated, which supported the emergency coordination of a large-scale exercise with the firefighter brigade ‘München-Land’ with the CopKa system. After proving a number of innovations and the functionality of the system itself the project’s final demonstration was performed smoothly in November using all parts of the system to present the results and capabilities in preparation for consecutive projects. CopKa is funded by the German Aerospace Center (DLR) under grant 50YB1523.
Research Focus
- Spacecraft/CubeSat nano-satellite and subsystem development
- Human and robotic exploration technologies, lunar regolith processing and resource extraction, analysis of life support systems/habitats/space suits
- Teleoperation technologies for operating robots in space, on-orbit servicing and novel satellite communication systems

Competence
- Systems engineering tools for development of complex systems
- End-to-end satellite communication
- Dynamic simulation of life support systems
- Lunar regolith handling and processing, resource extraction from lunar regolith
- Thermal analysis and design for satellite systems and planetary exploration environments

Infrastructure
- Machine and electronics workshops
- Cleanroom (Class 8)
- Thermal-vacuum facilities
- Lunar regolith handling facilities
- Hypervelocity accelerators
- Proximity operations simulator
- Ground station (K-, S-, UHF/VHF band)
- Mission control center
- Remotely operated telepresence drones

Courses
- Introduction to Spaceflight
- Spacecraft Technology 1 & 2
- Human Spaceflight
- Spacecraft Design
- Systems Engineering
- Orbit- and Flight-Mechanics
- Near-Earth Objects
- Space Transportation Systems
- Innovation and Technology Transfer
- Ballistic Missiles of the Third World
- Benefits of Spaceflight
- Advanced Systems Engineering
- Aviation and Space Medicine
- Space Environment and its Simulation
- On-Orbit Dynamics and Robotics
- Stars and Cosmos
- Space Communications and Operations
- Practical Course on Astronautics
- Practical Course on Spaceflight Electronics
- Practical Course on Systems Engineering
- Practical Course on Spacecraft Thermal Analysis and Test
- Practical Course on High Velocity Impact Simulations

Selected Publications 2018
Materials Science and Mechanics of Materials

Experimental and theoretical characterization of metallic materials

For many decades technological advances have been closely linked to the availability of appropriate materials. The Institute of Materials Science and Mechanics of Materials (WKM) concentrates on processing – microstructure – (mechanical) properties – relationships of load bearing metallic materials such as high strength steels, titanium, nickel, aluminum and tungsten alloys. Research is performed employing theoretical, numerical and experimental techniques with equal importance on multiple length scales. The associated State Material Testing Laboratory serves as an important interface to industry with respect to research oriented (off routine) testing of materials.

In 2018 research activities were directed towards plasticity and failure of gas turbine sealing systems, hot isostatic pressing of aluminum alloys in combination with precipitation hardening, additive manufacturing of dental restorations, hot isostatic pressing of iron-nickel-titanium-aluminum-chromium high entropy alloys, and measurement and numerical prediction of residual stresses in steels and nickel-base alloys. Much effort is devoted to fundamental research in crystal plasticity modelling and its application in engineering problems.

Direct Aging of Hot Isostatically Pressed A356 Aluminum Cast Alloy

Hot isostatic pressing (HIPing) is employed to improve the fatigue resistance of aluminum cast components in order to meet the high demands defined by automotive and aircraft industries. HIPing increases the part’s fatigue resistance by several orders of magnitude by eliminating casting porosity. The high pressure exerted during the densification process reduces the diffusivity of silicon and magnesium atoms and results in a lower critical cooling rate at which an oversaturated condition of dissolved silicon and magnesium atoms within the aluminum matrix can be achieved. Previous research at WKM demonstrated that temperature changes in advanced hot isostatic presses are high enough to perform aging at elevated temperatures immediately after hot isostatic pressing without the necessity of separate solution annealing.

Murali et. al. (JOM 49 (1997) 29-33) found that pre-aging at room temperature, as done in the industrial process route followed at present, reduces the age hardenability during delayed aging at elevated temperatures. The objective of a current research project at WKM is devoted to studies on the pressure affected diffusivity in aluminum cast alloys as proposed by Murali et. al. and serves to develop a fully integrated process that comprises not only hot isostatic pressing and solution annealing but also aging at elevated temperatures within the pressure vessel. First results clearly demonstrate that aluminum cast material which was...
To meet the ever-growing demands for the efficient operation of gas turbines, a minimum clearance between the rotating and the stationary components is of great importance. A lack of control over this clearance often leads to interface rubbing. As a result, thermo-mechanical loads arise that can critically damage both components. Maintaining operational reliability and high efficiency requires seal systems that can tolerate rubbing. Honeycomb labyrinth seals can fulfill this task.

In collaboration with the Karlsruhe Institute of Technology, the University of Bayreuth and the MTU Aero Engines AG, a three-dimensional microstructure-based simulation approach for the honeycomb structure was developed. This simulation approach contributes to a better understanding of the possible failure mechanisms during rubbing. For this purpose, a crystal plasticity material model was set up to describe the deformation behavior of the polycrystalline Ni-base superalloys Hastelloy X and Haynes 214. To calibrate the material model, simulations on a representative volume element (RVE) discretized with a realistic three-dimensional periodic mesh were carried out. Subsequently, the calculated results obtained on the RVE were validated using stress-strain curves experimentally determined at different temperatures and strain rates. In the model of the honeycomb structure, different geometries and microstructures are investigated under various loading conditions. The predicted numerical results highlight the importance of three factors influencing the failure behavior of the honeycomb structure. These are a large contact area, a small grain size and in particular the additional material between the cell walls from a preceding brazing process. The results also reveal the importance of local field quantities, such as local heterogeneous stress distribution, if one aims at the identification of the exact location of failure of the honeycomb structure occurring during rubbing. A detailed failure analysis and the investigation of alternative honeycomb geometries are the subject of on-going research.

**Rubbing of Seal Systems in Gas Turbines**

![Schematic representation of a seal system in a gas turbine with a detailed view of the polycrystalline Ni-base superalloy honeycomb structure (Source: WKM)](image)

**Project**
- **Anstreifvorgänge in Turbinen – Experimentelle Untersuchung und Modellierung** (DFG, WE 2351/14-1)

**Partners**
- Universität Bayreuth, Lehrstuhl für Metallische Werkstoffe, Ludwig-Thoma-Str. 36b, 95447 Bayreuth
- Karlsruher Institut für Technologie, Institut für Thermische Strömungsmaschinen, Straße am Forum 6, 76131 Karlsruhe
- MTU Aero Engines AG, Dachauer Str. 665, 80995 München
Model-based Prediction of Surface Integrity in Cutting of Ti-6Al-4V

Due to their high specific strength and thermal as well as corrosive stability, titanium alloys are frequently used as lightweight construction materials in the aerospace industry. Besides strength and mass requirements, numerous applications pose strict demands on fatigue life under hostile thermo-mechanical dynamic loading conditions and on dimensional tolerances of the structural elements. To this end, it is necessary to consider the influence of manufacturing processes on surface integrity and in particular on residual stresses of the component, since these not only interfere with dimensional and topographical demands but may also promote a major mode of mechanical failure through surface crack initiation and propagation.

Currently, designing critical lightweight structures often requires repeated design and prototyping iterations to account for surface integrity due to the complexity of the involved effects in the manufacturing process as well as the restriction of most experimental methods of residual stress determination on a-posteriori measurements. In order to improve the economy of this design process, current research aims both at a better theoretical understanding and modeling of the formation and alteration of residual stresses during manufacturing as well as improved in-process measurement methods. By combining and advancing these efforts, it is ultimately aspired to integrate fast predictive theoretical models and in-process measurement devices into real-time process controllers.

At WKM, we focus specifically on the theoretical and experimental investigation of residual stresses resulting from milling of Ti-6Al-4V. For this rather weakly thermally conducting high strength alloy, particularly large thermo-mechanical loads arise in cutting, potentially causing significant property changes near the surface and low tool life.

From the theoretical perspective, we seek to derive real-time capable models to predict residual stress distributions and incorporate both the cutting parameters as well as in-process measured quantities and disturbances like tool wear. For this purpose, we combine available semi-analytical approaches for thermo-elasto-plastic problems with finite element analysis and model order reduction techniques thereby allowing us to investigate the distinct influences of the process parameters while minimizing computational cost.

Experimentally, we rely on a variety of metallographic analysis methods available at WKM and X-ray diffraction combined with successive electro-chemical material removal in order to determine residual stress depth profiles resulting from various cutting conditions and hence to validate our models.

Building upon this research, we direct our efforts towards the solution of the inverse problem in the context of a real-time process control system that permits manufacturing according to predefined measures or requirements for the residual stress distribution.

Project

- Modellbasierte Bestimmung der Randzoneneigenschaf-ten bei der Fräsbearbeitung von Ti-6Al-4V (DFG, KR 3687/4-1), Schwerpunktprogramm ‘Oberflächenkondi- tionierung in Zerspanungsprozessen’ (SPP 2086)

Partner

- Technische Universität München, Lehrstuhl für Werkzeugmaschinen und Fertigungstechnik, Boltzmannstr. 15, 85748 Garching
Micromechanical Behavior of Nickel-base Superalloys

Ni-based superalloys are known for retaining significant resistance to thermomechanical loading at elevated temperatures and are therefore frequently employed in gas turbines. Most of these alloys are hardened by nanocrystalline precipitates of the γ′- and/or the γ″-phase. Beyond the typical class of dislocation slip in fcc systems, many further effects are known to govern the plastic deformation behavior of Ni-based superalloys, such as dynamic strain ageing, Kear-Wilsdorf lock formation and anomalous yielding. These effects are especially relevant at high temperatures. Further development of gas turbines is both an economic and an ecologic imperative, also necessitating applied basic research on this class of materials.

At WKM, we shed light on the plastic deformation mechanisms of different Ni-based superalloys, utilizing diffraction techniques and simulating the plastic deformation of polycrystalline aggregates within the framework of established crystal plasticity based models. This yields valuable information on these engineering materials on the grain and sub-grain level.

One important focus of this project is in-situ neutron diffraction during uniaxial tensile loading, performed on polycrystalline Haynes 282 and Inconel 718 specimens. Like most diffraction techniques performed on polycrystals, neutron diffraction studies crystal lattice spacings and, hence, elastic strain components of those crystallites which are aligned (with a representative of a certain family of crystallographic directions) along the measurement direction within the respective gauge volume. In the case of multiple crystallites fulfilling these criteria, their respective signals are superimposed.

To interpret and discuss this experimental data, a continuum micromechanical model is set up to describe the stress and strain fluctuations in a polycrystalline aggregate on grain level induced by uniaxial loading. A cubic micromechanical unit cell is constructed containing a set of grains, followed by applying a set of periodic boundary conditions. This simulates the response of an infinite three-dimensional array of identical cells containing the virtual grain structure. To describe the constitutive response on a granular scale, a phenomenological formulation of the classical continuum crystal plasticity framework based on the multiplicative decomposition of the deformation gradient is applied. Appropriate postprocessing of the simulation results allows a direct comparison to the experimental data.

It could be shown that Haynes 282 unexpectedly exhibits a significantly non-monotonous microstrain evolution close to the yield point. This points at effects related to those at play in materials with upper and lower yield point. As these effects are most pronounced on the sub-grain level, future studies will include a comparison of model predictions and measurements on intergranular misorientations.

Project

Entwicklung von Typ II Eigendehnungen in Abhängigkeit der Mikrostruktur in Nickelbasislegierungen (DFG, KR3687/3-1)

Partners

Karlsruher Institut für Technologie, Institut für Anwendete Materialien – Werkstoffkunde, Engelbert-Arnold-Str. 4, 76131 Karlsruhe
Technische Universität München, Forschungs-Neutronenquelle Heinz Maier-Leibnitz (FRM II), Lichtenberg-str. 1, 85748 Garching
High Entropy Alloys

High entropy alloys (HEA) show sluggish lattice diffusion and an excellent resistance against plastic deformation at elevated temperatures. These properties result from a high lattice distortion, which originates from an equimolar or near-equimolar composition of at least five elements. Previous studies have also shown that non-equimolar compositions can lead to these HEA-typical material properties. As a result, the strict HEA-definition has been relaxed and additional material compositions were declared as HEA. A promising approach to arrive at applicable materials is the production of HEA based on conventional alloys. The aim is to effectively supplement outstanding properties and process-related empirical values of existing materials with those of HEAs. It is a great challenge to produce alloys from elements that have fundamentally different properties. At WKM, HEA are produced via powder metallurgy. For this purpose, pre-alloyed powders (iron- or nickel-based) are combined with elemental powders (Al, Ti, Cr). The powders are mechanically alloyed using a planetary ball mill, which leads to a chemical homogenization on the microscopic scale. The mechanically alloyed powder is filled into titanium capsules. These capsules are sealed and compacted via hot isostatic pressing, resulting in a chemical homogeneous and dense microstructure.

Solubility Equilibria in the Theuric Acid-Ammonium Urate-Water System

Ammonium hydrogenurate (NH₄HU) is one of the sparingly soluble organic substances, which deposit in the human body and cause many diseases. E.g. formation of calculi in the urinary tract, uric acid nephropathy and gouty arthritis. The solubilities of these substances play an important role in the investigation of pathogenesis, effective prophylactic and ultimate therapy.

Solubility constants reported in the literature for ammonium hydrogenurate show a large scatter. In our study, the solubility of NH₄HU(s) was measured as a function of p[H] = -lg([H⁺]/mol dm⁻³) (4.5 to 8) and temperature (25 °C and 37 °C) at constant ionic strength, I = 0.300 mol dm⁻³ NH₄Cl, which is similar to the ionic strength of urine.

Highly reproducible values for the solubility product (Kₛ₀) of NH₄HU(s) were obtained. The first dissociation constants (K₁) of uric acid determined in this project agrees well with values obtained in previous studies of uric acid solubilities in electrolyte solutions relevant to urolithiasis. This study confirms earlier findings that in the ionic strength range of urine, the solubilities of uric acid and hydrogenurates as a function of p[H] can be described consistently by unique values of their solubility constants (Kₛ, Kₛ₀) and the first dissociation constant of uric acid (K₁).

Partner

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Research Focus
■ Testing and modelling of metallic high performance alloys (iron-, nickel-, titanium- and aluminum-based alloys)
■ Residual stress determination via diffraction (X-rays, neutrons) and mechanical methods
■ Microstructure-based numerical modelling
■ Electron and light microscopy
■ Mechanical testing
■ High entropy alloys
■ Crystal plasticity modelling

Competence
■ High-resolution scanning electron microscopy
■ Diffraction techniques
■ Material testing on demand

Infrastructure
■ Material testing equipment
■ Light and electron microscopes
■ X-ray diffractometers
■ Hot isostatic press
■ Dilatometers and annealing simulator
■ Electrical and mechanical workshops

Courses
■ Materials Science I & II
■ Engineering Materials Technology I & II
■ Engineering Mechanics for Business Sciences
■ Fracture Mechanics/Plasticity Theory
■ Tensor Calculus for Engineers
■ Finite Elements in Mechanics of Materials
■ Electron Microscopy
■ Laboratory Courses on Materials Science, Mechanics of Materials and Finite Element Methods

Selected Publications 2018
DOI: 10.1002/mawe.201700274
■ J. von Kobylinski, R. Lawitzki, M. Hofmann, C. Krempaszky, E. Werner: Micromechanical behavior of Ni-based superalloys close to the yield point: a comparative study between neutron diffraction on different polycrystalline microstructures and crystal plasticity finite element modelling. Continuum Mech. and Thermodyn. To be printed. DOI: 10.1007/s00161-018-0720-0
Biochemical Engineering

Industrial biotechnology

Industrial biotechnology (‘white biotechnology’) makes use of microorganisms or enzymes for the industrial production of chemicals like special and fine chemicals, building blocks for agricultural or pharmaceutical products, additives for manufacturing, as well as bulk chemicals and fuels. Renewable resources and CO₂ are the favored raw materials for industrial biotechnology. The Chair of Biochemical Engineering deals with all aspects of the technical use of biochemical reactions for industrial biotechnology. The research focus is on bioreactors and biocatalysis, as well as on (gas-) fermentation and isolation of bioproducts.

A new digitized bioprocess laboratory is under construction at the Institute of Biochemical Engineering for the knowledge-based automation and digitalization of bioprocess development in order to be able to drastically shorten development cycles in industrial biotechnology in the future (photo: Tobias Hase, TUM)

Bioreactors and digitalization

The effective generation of process information represents a major bottleneck in microbial process design and optimisation. An approach to overcome the necessity for a large number of time- and labour-consuming experiments is miniaturisation and parallelisation of stirred-tank reactors along with automation of process management and digitalization of bioprocess development.

Highlight
Experimental design, resource planning of the devices in the bioprocess laboratory and evaluation of the experimental results have so far only been carried out intuitively according to the level of education and individual knowledge of the respective scientist. Consequently, the objective of a new digitized bioprocess laboratory at the Institute of Biochemical Engineering is the use of intelligent software components for knowledge-based experimental design, for the procedural control of parallelised and automated laboratory experiments in real time and for on-line data evaluation, in order to be able to drastically shorten development cycles in bioprocess design in the future.

Projects
- Multi-parameter analytics in parallel bioreactors
- Automation of bioprocess development
- Digitalization of bioprocess development
Biocatalysis

Great demands are placed on the optical purity of building-blocks for the production of pharmaceuticals. Due to the high natural selectivity of biocatalysts, biocatalysis appears to be a favorable method for the purpose of chiral syntheses. Major research interests are the development of new reaction engineering methods and devices to intensify whole cell biotransformations of hydrophobic, unstable and/or toxic substrates up to the technical scale.

Highlight
The activity of an industrially important enzyme isolated from a cyanobacterium which catalyzes the stereoselective reduction of alkenes was improved by a factor of 10 by rational exchange of loop regions of the protein which are supposed to interact with the electron transport metabolite nicotinamide adenine dinucleotide (NADH). A whole-cell biotransformation process was developed for efficient production of a chiral precursor useful for the synthesis of e.g. an anti-malaria drug.

Projects
- Biocatalytic conversion of D-galacturonic acid with recombinant *Saccharomyces cerevisiae*
- Cellular envelopes for multi-enzyme syntheses
- Asymmetric synthesis with optimised ene-reductases
- Production of terpenoid glucosides by recombinant *Escherichia coli*
- Oxidations with recombinant *Glucobacter oxydans*

Fermentation

Making use of microorganisms for the production of chemicals from renewable resources is the core of industrial biotechnology. Reaction engineering analyses of metabolically optimized producer strains and metabolic analyses of microorganisms in production processes are necessary for efficient bio-production on an industrial scale.

Highlight
A new microbial production process was designed for the production of the aromatic amino acid L-tryptophan (dietary supplement for use as an antidepressant) from the byproduct of biodiesel production (glycerol) and ammonia making use of recombinant *Escherichia coli*.

Projects
- Population heterogeneity in industrial scale bioprocesses
- Metabolic control analyses of microbial production processes
- Production of aromatic amino acids with recombinant *Escherichia coli*
- Production of single-stranded DNA with recombinant *Escherichia coli*
- Reaction engineering analysis of recombinant *Aspergillus niger*
Biochemical Engineering

Gas Fermentation

Special microorganisms are able to produce chemicals with carbon dioxide as the sole carbon source. Electrons may be supplied from sunlight, hydrogen or carbon monoxide. Bioprocess engineering is the key to make use of these energy sources for the microbial production of chemicals from carbon dioxide emissions.

Highlight

A new continuous process was established for the microbial production of alcohols from CO-rich synthesis gas in a cascade of stirred-tank bioreactors. The strictly anaerobic bacterium *Clostridium carboxidivorans* grows in the first pH-controlled reactor and produces organic acids from synthesis gas. Biomass and organic acids are continuously transferred into the second reactor where the acids are reduced by the bacteria to alcohols making use of the synthesis gas as well.

Projects

- Mass production of microalgae in open photobioreactors
- Production of anti-oxidants with microalgae
- Microalgae processes in open photobioreactors with reduced water consumption
- Gas fermentation with *Clostridium carboxidivorans*
- Gas fermentation with *Clostridium aceticum*
- Multi-purpose reactor for gas fermentations

Bioprocess Integration

In many cases, downstream processing is by far the most cost-intensive step of a bioprocess. Often, multistep bioseparations are required, yielding rather low product yields. Therefore, existing bioseparation processes should be improved and combined to reduce the number of process steps. The focus is on bioprocess integration of fermentation/biocatalysis and downstream processing.

Highlight

Technical protein crystallization may become an economically attractive alternative to chromatography but so far protein crystallization is not applied due to an incomplete understanding. An industrially important enzyme was rationally modified, expressed, purified and crystallized to generate large crystals suitable for neutron diffraction studies at the Heinz Maier-Leibnitz Center (MLZ) in Garching. The neutron structure provided new insights into the reasons why divalent magnesium (Mg²⁺) or manganese (Mn²⁺) ions are necessary for its activity. Molecular-dynamics simulations enabled rational modifications of this enzyme to improve the crystallization process.

Projects

- Novel methods for packing of preparative chromatography columns
- Preparative purification of proteins via extraction
- Engineering of proteins for the control of crystallization processes
- Modeling and molecular dynamics simulation of protein crystals
Biochemical Engineering

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Anton Rückel, M.Sc.
Dominik Schäfer, M.Sc.
Jacqueline Wagner, M.Sc.
Jeremy von Posching, M.Sc.
Nikolas von den Eichen, M.Sc.
Kristin Schoppel, M.Sc.

Technical Staff
Norbert Werth
Markus Amann

Research Focus
- Micro-bioprocess engineering
- Bioreactors
- Biocatalysis
- Fermentation
- Gas fermentation
- Microalgal bioprocesses
- Bioprocess integration

Competence
- Design and automation of bioreactor systems
- Bioprocess development and optimization
- Metabolic analysis of microbial reactions in bioreactors
- Metabolomics
- Downstream processing

Infrastructure
- Stirred-tank bioreactor systems up to a 100 l scale
- Flat-panel photobioreactor systems with high-power LEDs
- Parallel bioreactor systems automated with lab robots
- Anaerobic work benches/sterile laminar flow work benches
- Syngas lab (CO₂, CO, H₂)
- Phage lab
- Cooled lab (4°C)
- Digitized bioprocess lab
- Mechanical workshop
- Analytical lab (LC-MS, flow cytometry, GC, LC, etc.)

Courses
- Biochemical Engineering Fundamentals
- Biochemical Engineering
- Bioprocesses
- Bioprocesses and Bioproduction
- Industrial Bioprocesses
- Bioreactors/Bioreaction Engineering
- Environmental and Biochemical Engineering
- Separation of Macromolecular Bioproducts
- Practical Training on Biochemical Engineering
- Practical Training on Bioprocess Engineering

Selected Publications 2018

Book 2018
Machine Tools and Manufacturing Technology

Perspectives for production

The Chair of Machine Tools and Production Engineering (iwb) is one of the largest research centers in the field of production engineering in Germany. With the opening of the laboratories for additive manufacturing at iwb in 2018, the cooperation within the research groups of the institute as well as with other members of TUM in the field of additive manufacturing, is being expanded.

Founded in 1875, the Institute for Machine Tools and Industrial Management (iwb) at the Technical University of Munich is one of the largest research institutions for production technology in Germany. It encompasses two chairs at the Department of Mechanical Engineering in Garching near Munich. The research structure at the Institute for Machine Tools and Industrial Management is represented by individual topic groups. Our scientific employees develop solution strategies for efficient future production.

The main task of the Machine Tools topic group is the interdisciplinary development, design and optimization of machine tools and the implementation of a suitable methodological approach. One area of focus is the investigation and optimization of the dynamic behavior of machine structures. Methods for the simulation and experimental analysis of the structural behavior, control and cutting processes of machine tools are used. The topic group for Joining and Cutting Technology focuses on laser material processing, friction welding and intelligent joining system technology. The team makes use of a wide range of competencies in the areas of process investigation, technology consulting, systems engineering and simulation. The Additive Manufacturing topic group supports companies in mastering current and future challenges with a focus on process development, process monitoring and simulation of additive manufacturing technologies. The topic group offers expertise in processing of metallic materials using laser and electron beam melting (LBM and EBM), binder jetting, as well as wire and arc additive manufacturing (WAAM).

For the next few years iwb will be involved in the EU Horizon 2020 research project ‘PreCoM’, which investigates the concept of predictive maintenance in conjunction with production planning, in order to increase machine availability.

PreCoM – Predictive Cognitive Maintenance Decision Support System. (c) iwb

Spannung (MPa, von Mises)

ASIMOV – Anatomy-specific implant anchorage using optimized deformation properties. (c) iwb
Machine Tools

The main task of this thematic group is the interdisciplinary development, construction and optimization of machine tools, as well as the implementation of a suitable methodical approach. One focal area is the investigation and optimization of the dynamic behavior of machine structures. For this purpose, methods for simulation and experimental analysis of the structural behaviour, control and machining processes of machine tools are used. Furthermore, tools and procedures for the development of control software are developed. The control design of complex systems forms an important basis for the development and implementation of integrated adaptive structures and control methods to improve the dynamic machine properties.

Projects

- ASIMOV – Anatomy-specific implant anchorage using optimized deformation properties
- FORobotics – Mobile, ad-hoc cooperating robot teams
- Local damping modelling for simulation and optimisation of the dynamic behaviour of machine tools
- MeDiC4Hyd – Method for simulation and optimization of dynamic behavior – Data type selection in condition monitoring to increase resource efficiency of machine tools-hydraulic power units
- PreCoM – Condition monitoring and predictive maintenance integrated production planning
- REGULUS – Resource-efficient production of large-volume aerospace structural components
- Vibration-assisted machining of difficult-to-machine materials
- ShapeAM – Capability of additive manufacturing technologies for the production of functional components with high quality requirements for industrial use
- SPP surface conditioning
- StroMiS – Study for the technical-economic analysis of power generation from micro power plants in series production
- SynErgie – Copernicus project for the energy turnaround

Additive Manufacturing

Additive manufacturing offers great design freedom but also involves novel challenges and research opportunities. Scientists of the research group Additive Manufacturing strive to provide solutions to these challenges across a broad range of additive manufacturing technologies, including among others electron beam melting (EBM), laser beam melting (LBM) and powder-binder-based 3D printing (3DP). The efforts comprise both soft- and hardware topics, i.e. simulation and process monitoring and also process development and the qualification of new materials. With the opening of the laboratories for additive manufacturing at iwb in 2018, the cooperation within the research groups of the institute, as well as with other members of the TUM in the field of additive manufacturing, is being expanded. The development of this research topic is further supported by the EOS M400 machine which is located at the Ludwig Boelkow Campus in Ottobrunn for the manufacturing of, and research with, large-scale components produced by laser beam melting. The financial support of the DFG to enable this research opportunity is greatly appreciated.

Projects

- Ascent AM – Simulation of laser beam melting of engine components
- HM-Tools – Development of a process for carbide processing using powder bed-based 3D printing for complex carbide tools
- ProSim – Increasing process understanding in laser beam melting
- REGULUS – Resource-efficient production of large-volume aerospace structural components
Joining and Cutting Technology

Technical products go through several joining and separating steps before completion. These processing steps are particularly relevant for the high quality and economic success of the production. The topic group for Joining and Cutting Technology focuses on laser material processing, friction welding and intelligent joining system technology. The team makes use of a wide range of competencies in the areas of process investigation, technology consulting, systems engineering and simulation.

Projects

- Click&Weld – Increasing the industrial applicability of friction stir welding through a knowledge-based and user-friendly operating concept
- ExZellTUM II – Center of Excellence for Battery Cells at the Technical University Munich II
- FOREL2 – Research and Technology Centre for Resource-Efficient Lightweight Structures in Electric Mobility 2
- FSW-Leg – Synthesis of non-equilibrium alloys by friction stir welding processes
- MobaReg – Development of a process torque-based temperature control for friction stir welding
- ProLasKu – Increase in process efficiency and weld seam quality in laser beam welding of copper materials through innovative system technology
- PROLEI – Process chain for joining endless fibre-reinforced plastics with metals in lightweight structures
- ReakPat – Reactive metallic microparticles for thermal joining
- REVIDEBATT – Resonances, vibrations, shocks, external mechanical forces and reconnaissance methods for lithium-ion batteries
- ReVeBa – Computer-aided distortion minimization in laser beam welding of complex component structures
- RoKtoLas – Robot-guided, scanner-based optical coherence tomography for remote laser beam welding for flexibilizing process chains in car body construction
- SPP1640/A6: Binding mechanisms for friction stir welding of mixed joints
- SurfaLib – Surface pretreatment of battery materials
Research Scientists
Andreas Bachmann, M.Sc.
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Hon.-Prof. Dr.-Ing. Sigfried Petz

Visiting Lecturer
Dr.-Ing. Andreas Wendt

Administrative Staff
Ursula Fourier-Kamp
Monika Medvegy
Sandra Pichlmeier
Silvia Zacherl

Research Focus
Machine tools
Joining and cutting technology
Additive manufacturing

Competence
Process development, process observation and simulation in additive manufacturing.
Laser manufacturing technology
Friction welding
Intelligent joining system technology
Process and structural behaviour
Intelligent machine tools
Hybrid manufacturing technologies

Infrastructure
Additive manufacturing laboratories for metal and plastics
Cutting machine tools
Laser tools
Friction welding equipment
Industrial robots
Environmental/safety and teaching laboratories
Energetic and geometrical parameters
Material analysis systems
Simulation environments
Production line for battery cells
Environmental/safety and teaching laboratories
Material analysis systems
Learning factory for lean production

Courses
Adhesive Bonding
Business Excellence
Practical Courses in Metal Cutting Manufacturing Processes
Joining Technologies
Laser Technology
Machine Elements and Manufacturing Technologies
Metal Cutting Machine Tools 1 – Fundamentals and Components
Metal Cutting Machine Tools 2 – Analysis and Modeling
Metal Cutting Manufacturing Processes
Occupational and Industrial Safety
Practical Course Additive Manufacturing
Practical Course Development of Machine Tools
Practical Course in Welding Technologies
Practical Course; Machine Tools
Principles of Engineering Design and Production Systems – Project
Qualitymanagement
Selected Publications 2018

- Bachmann, A., Krutzinger, M., Zaeh, M.F.: Influence of the welding temperature and the welding speed on the mechanical properties of friction stir welds in EN AW-2219-T87
- Bayerlein, F., Bodensteiner, F., Zeller, C., Hofmann, M., Zaeh, M.F.: Transient development of residual stresses in laser beam melting – A neutron diffraction study
- Kleinwort, R., Platz, J., Zaeh, M.F.: Adaptive active vibration control for machine tools with highly position-dependent dynamics
- Kleinwort, R., Semm, T., Falger, P.M., Zaeh, M.F.: Integration of an Android Application into the Learning Factory for Optimized Machining
- Kleinwort, R., Weishaupl, P., Zaeh, M.F.: Simulation-based dimensioning of the required actuator force for active vibration control
- Krutzinger, M., Marstatt, R., Costanzi, G., (...) Haider, F., Zaeh, M.F.: Temperature control for friction stir welding of dissimilar metal joints and influence on the joint properties
- Liebl, C., Popp, R.S.H., Zaeh, M.F.: Approach for a Systematic Energy Data Generation and Evaluation
- Popp, R.S.H., Liebl, C., Zaeh, M.F.: A Multilevel Procedure to Evaluate the Energy Flexibility Potential of Production Machines
- Schlather, F., Hoel, V., Oefe, F., Zaeh, M.F.: Tolerance analysis of compliant, feature-based sheet metal structures for fixtureless assembly
- Schulz, J., Popp, R.S.-H., Scharmer, V.M., Zaeh, M.F.: An IoT Based Approach for Energy Flexible Control of Production Systems
- Seidel, C., Zaeh, M.F.: Multi-scale Modelling Approach for Contributing to Reduced Distortion in Parts Made by Laser-based Powder Bed Fusion
- Wimmer, S., Ellinger, J., Zaeh, M.F.: A cutting force model for finishing processes using helical end mills with significant runout
- Zaeh, M.F., Pieczona, S.J.: Adaptive inverse control of a galvanometer scanner considering the structural dynamic behavior
Product Development and Lightweight Design

Multi-disciplinary design, design methods, design tools, design processes, numerical optimization

We invent, design and optimize technical systems.

Our laboratory’s research and teaching is about engineering design, i.e. the creation of concrete solutions to specific problems. This is particularly challenging when the solution and its elements are entirely unknown. In so-called top-down approaches, the development focus is on the desired features of the new product rather than on already existing solutions or their elements. Both methods from product development, such as creativity techniques, and methods from lightweight design, such as physical surrogate modelling, help to explore the unknown and find a way to new solutions to complex problems. For complex problems, it is often important to consider the entire system by adopting a holistic and interdiscipli- nary view. In both lightweight design and in product development, all relevant requirements on a product, all aspects of feasibility and constraints on realization, and all interactions of all system components have to be taken into account. How to treat the resulting complexity is an important sub- ject of our research and teaching. We cover a large span of different quantitative and qualitative methods ranging, for example, from new numerical optimization techniques from lightweight design to qualitative development meth- ods, e.g. related to design structure matrices.

Think.Make.Start. – Applied Innovation for all Students at TUM

Since its founding in 2015, the cross-faculty innovation format Think.Make.Start. has brought students from the ME, EI, IN and SoM faculties together in interdisciplinary teams to solve problems with innovative approaches and technologies in an agile, creative and customer-centric way. In 2018, students of all other TUM faculties could for the first time also apply for participation and get to know their entrepreneurial potential thanks to new central funding through a partnership with TUMentrepreneurship. In addi- tion to three events at the Garching research campus, one event was offered for the first time at the TUM headquar- ters in close cooperation with the Faculty of Architecture. While two events had no thematic focus in order to offer the participants maximum autonomy, the other events dealt with the main topics applied AI and UrbanTech. A total of 180 students were selected this year from more than 530 applicants from all 14 TUM faculties. Of the 38 teams formed as part of the event, 13 are still working on their project today and are striving to start a company.

At LPL, we are planning to further strengthen the format in 2019 through further cooperation with chairs from other faculties.

For more information on projects and news visit www.thinkmakestart.com.
IDAGMED – Interdisciplinary Agile Medical Engineering Development

In recent years, several multi-parametric screening systems for work with living tumor cells have been developed at our project partner. The basic elements of these systems are either bio-electronic chips to monitor living cells or microtiter plates, which are equipped with electronic or optical chips for the detection of physiological signals of the cells. To unite the different disciplines that collaborate in medical engineering, an agile development process was used and the interdisciplinary collaboration was analyzed by the laboratory for product development and lightweight design.

In this research project, the usage of the microtiter plate was enhanced and prepared for a broader utilization. The overall costs were reduced as additive manufacturing techniques are applied.

During the development, a profitable integration of the different disciplines in the product development process was pursued, especially in an agile environment. The results, which contained the science-relevant conclusions for the application of agile methods in interdisciplinary teams in a medical engineering development, were documented and the enhancement of the microtiter plate served as a use case. In the project a biocompatible 3D-printed microtiter plate was developed, that fulfills multiple requirements of the corresponding tumor screening procedure.

Project
■ IDAGMED

STRUctural health monitoring BAsed Test EXecution

STRUbatex started at the Laboratory of Product Development and Lightweight Design (LPL) at the beginning of this year. In the age of high-performance computers, we use many FE models and other simulation tools in the structural design process. In the aerospace area, it is mandatory to verify these simulations with hardware tests. Regarding fatigue, for economic reasons it is important to avoid component failure during a certification test. Due to big scattering in fatigue data (for instance in S-N curves) and thus in fatigue computations, it is not possible to determine the exact time of final fracture. This is why many inspections are carried out during fatigue tests.

LPL uses strain data of already attached sensors in hardware tests to reduce these inspection times. Furthermore, the chair deals with the question of where best to place these sensors to anticipate fatigue failure early on. As a first attempt, LPL investigates coupons and researches new fatigue computation methods.

Project
■ STRUBATEX
Cost Management

In the area of cost management, the early phases of the product life cycle, the cost responsibility of designers and the necessary cooperation between various internal departments and external corporate points are emphasized. Designers and engineers are supported by the research activities of the laboratory in various areas. Methods and tools are designed to enable cost estimates during early phases of product development and to make them thorough and reliable. Cost reduction is the goal of many projects, but also value topics e.g. integrated value engineering (IVE), are transferred into practical application, extended with variant portfolio optimization. In addition to direct costs, the analysis and estimation of indirect costs is increasingly coming to the fore. Exploring new possibilities from digitalization the laboratory is currently conducting research with industrial partners on supporting cost estimation by artificial intelligence (AI) application.

Projects
- FVA e.V.
- Diverse companies
Active protheses are currently a very relevant topic in Germany and the world. The study by Bidiss et al. detailing device abandonment states that the most frequent physical factors causing abandonment of the device are: too heavy, too hot or not enough tactile feedback from the device itself.

The main objective of this project is to address all these issues on multiple fronts and to design and develop a low-cost, modular prosthetic hand for trans-radial amputees. It will be a fully actuated hand with degree of freedom (DOF) comparable to that of a human hand.

The wrist will be designed as a snap-on interface that connects to the electronics housed in the forearm (patient side). It integrates a sensory system composed of proprioceptive and exteroceptive sensors and a customized embedded controller, both employed to implement automatic grasp control and potentially to deliver sensory feedback to the amputee. It should be able to perform everyday grasps and point the index finger independently. The weight and speed (closing time: 1.5 seconds) is comparable or lesser than commercial prostheses. It should lift an 8 kg suitcase and stably grasp up to 2 kg cylindrical objects. The focus of the prosthesis project will be to make a lightweight design that can give haptic and/or tactile feedback back to the amputee and make it easier for them to use it on a daily basis. The hand will be hardware-functional by the end of the first year.
Product Development and Lightweight Design

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Management
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Eva Körner
Bernhard Lerch
Edith Marquard-Schmitt
Marion Riedel
Josip Stokie
Robert Weiß
Katja Zajicek

Research Scientists
Lucia Becerril, M.Sc.
Jan Behrenbeck, M.Sc.
Dr. Hugo d’Albert
Matthias Funk, M.Sc.
Kristin Gövert, M.Sc.
Dr.-Ing. Helena Hashemi Farzaneh
Dipl.-Ing. Christoph Hollauer
Niklas Kattner, M.Sc.
Lukas Krischer, M.Sc.
Dipl.-Ing. Martin Mahl
Dr. Mayada Omer
Simon Pfingstl, M.Sc.
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Sebastian Rötter, M.Sc.
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Sebastian Schweigert-Recksiek, M.Sc.
Rilian Shao, M.Sc.
Julian Stumpf, M.Sc.
Dr. Anand Vazhapilli Sureshbabu
Jakob Trauer, M.Sc.
Dominik Weidmann, M.Sc.
Julian Wilberg, M.Sc.
Duo Xu, M.Sc.

Research Focus and Competences
■ Design methods and tools
■ Process simulation
■ Multidisciplinary design optimization
■ Cooperative design
■ Solution spaces
■ Cost management
■ Topology optimization
■ Lightweight structures
■ Vibrating systems
■ 3D printing
■ Metamaterials
■ Humanoid robotics
■ Hands-on product development
■ Bio-inspired design

Infrastructure
■ Computer cluster
■ CAD and several FEM tools
■ Design optimization tools
■ Workshop for metal and fiber composites
■ Mechanical and environmental test facilities
■ Extensive measurement devices
■ Non-destructive testing
■ Precision engineering workshop
■ Innovation lab for student projects with 3D printers

Courses
■ Multidisciplinary Design Optimization
■ Cost Management
■ Methods of Product Development
■ Product Development and Design
■ Lightweight Design
■ Lab course: Finite Element Method (FEM) with Application to Aerospace Structures
■ Design and Partitioning of Vibrating Systems
■ Lab Course: Development of Humanoid Robots
■ Think.Make.Start.

Selected Publications 2018
■ Erschen, Stefan; Duddeck, Fabian; Gerdts, Matthias; Zimmermann, Markus: On the Optimal Decomposition of High-Dimensional Solution Spaces of Complex Systems. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems 4 (2), 2018
■ Gövert, Kristin; Lindner, Manuel; Lindemann, Udo: Survey on agile methods and processes in physical product development. ISPIE Innovation Symposium. The International Society for Professional Innovation Management (ISPIM), 2018
■ Held, Maximilian; Weidmann, Dominik; Kammerl, Daniel; Hollauer, Christoph; Mörtl, Markus; Omer, Mayada; Lindemann, Udo: Current challenges for sustainable product development in the German automotive sector: A survey based status assessment. Journal of Cleaner Production 195 (2018): 869-889
■ Schweigert-Recksiek, Sebastian; Lindemann, Udo: Improvement Opportunities for the Collaboration of Design and Simulation Departments – An Interview Study. DESIGN 2018. 2018
■ Vogt, Marc Eric; Duddeck, Fabian; Wahle, Martin; Zimmermann, Markus: Optimizing tolerance to uncertainty in systems design with early- and late-decision variables. IMA Journal of Management Mathematics, 2018
Honorary Doctorates

Herbert Kraibühler, 2015, in recognition of his remarkable achievements and ideas in the research and development of innovative plastic processing and additive manufacturing machinery

Reimund Neugebauer, 2012, in recognition of his outstanding achievements in the research and development of resource-efficient mass production technology and innovative mechatronic manufacturing systems

Norbert Reithofer, 2011, in recognition of his outstanding achievements in the research, development and realisation of new production technologies and innovative, future-oriented organisational forms for production

Bernhard Fischer, 2009, in recognition of his remarkable achievements in the research, development and realisation of efficient and environmentally friendly power generation technologies

Manfred Wittenstein, 2008, in recognition of his exceptional achievements and ideas in the research and development of innovative propulsion systems and forward-looking company leadership

Dieter Spath, 2007, in recognition of his outstanding research and development achievements in the connection between technical competence, industrial science and management

Frank E. Talke, 2005, in recognition of his exceptional research and development achievements in the mechanics and tribology of magnetic memory systems and his international work in the area of engineering education

Burkhard Göschel, 2004, in recognition of his exceptional research and development achievements as well as his ideas in the field of mechatronics for the automotive industry

Volker Kronseder, 2003, in recognition of his remarkable achievements and ideas in the research and development of innovative bottling plants and plastics machines as well as for his company leadership

Ali Hassan Nayfeh, 1999, in recognition of his exceptional and internationally recognised scientific contributions in the field of non-linear dynamics and their applications in engineering science

Bernd Pischetsrieder, 1997, in recognition of his outstanding achievements in company leadership and his innovative ideas in holistic system technology and system integration

Rudolf Rupprecht, 1995, in appreciation of his exceptional engineering-related achievements in the field of company leadership and contributions to maintaining Germany as an economic powerhouse

Raymond Viskanta, 1994, in recognition of his remarkable scientific achievements in the fields of radiation energy transmission as well as heat and materials transportation

Wolfgang Bürgel, 1993, in recognition of his excellent achievements in the engineering aspects of material flow and production logistics

Hans Jürgen Matthies, 1991, in recognition of his outstanding scientific, technical and commercial/organisational achievements in agricultural engineering and for special contributions in deepening our understanding of oil hydraulics

Gerhard Pahl, 1990, in recognition of his scientific achievements in design and its relationship to machine components and computer-aided technology

Rudolf Quack, 1990, in recognition of his outstanding scientific achievements in firing and control technology

Eberhard von Kuenheim, 1988, in recognition of his outstanding technical achievements in the area of automotive and production technology and company leadership

Hans Dinger, 1987, in recognition of his outstanding achievements in the engineering science of combustion engine construction

Hans-C. Koch, 1986, in recognition of his exemplary technical and scientific achievements in the entire field of car production technology

Helmuth Glaser, 1981, in recognition of his groundbreaking scientific work in thermodynamics, especially refrigeration and process technology and his successful career as an academic educator and publisher of scientific writings

Erwin Sick, 1980, in recognition of his contribution to the scientific and constructive development of optical devices with electronic signal processing

Ernst Gassner, 1979, in recognition of his great contributions to theoretical and experimental research in operational stability

Only honorary doctorates since 1979 are shown here.
<table>
<thead>
<tr>
<th>Name</th>
<th>Professorship</th>
<th>Lecture Title</th>
<th>Since</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr.-Ing. Alexander Alekseev</td>
<td>Plant and Process Technology</td>
<td>Grundlagen der Kälteerzeugung und Industrielle Tieftemperaturanlagen</td>
<td>SS 12</td>
</tr>
<tr>
<td>Prof. Ph. D. P. Vellayani Aravind</td>
<td>Energy Systems</td>
<td>Thermodynamics in Energy Conversion</td>
<td>WS 10/11</td>
</tr>
<tr>
<td>Axel Becker</td>
<td>Aircraft Design</td>
<td>Luftverkehrsszenarien</td>
<td>SS 12</td>
</tr>
<tr>
<td>Dr. rer. nat. Manfred Benthaus</td>
<td>Energy Systems</td>
<td>Stromnetze und Energiemärkte</td>
<td>SS 15</td>
</tr>
<tr>
<td>Dr.-Ing. Johann Blaha</td>
<td>Materials Science and Mechanics of Materials</td>
<td>Werkstoffe für Motoren und Antriebsysteme: Otto- und Dieselmotoren</td>
<td>SS 09</td>
</tr>
<tr>
<td>Prof. Dr.-Ing. Ulrich Butter</td>
<td>Helicopter Technology</td>
<td>Hubschrauber-Flugmechanik und -Flugregelung</td>
<td>WS 10/11</td>
</tr>
<tr>
<td>Dr. Antonino Cardella</td>
<td>Nuclear Technology</td>
<td>Kernfusion Reaktortechnik</td>
<td>SS 10</td>
</tr>
<tr>
<td>Dr.-Ing. Johann Dambrock</td>
<td>Flight System Dynamics</td>
<td>Navigation und Datenfusion</td>
<td>WS 08/09</td>
</tr>
<tr>
<td>Dr.-Ing. Rainer Demuth</td>
<td>Aerodynamics and Fluid Mechanics</td>
<td>Aerodynamik von Hochleistungsfahrzeugen</td>
<td>WS 08/09</td>
</tr>
<tr>
<td>Dr. rer. nat. Jörg Ellinger</td>
<td>Materials Science and Mechanics of Materials</td>
<td>Werkstoffe für Motoren und Antriebsysteme: Luftstrahl-antriebe, extreme Anforderungen an besondere Materialien</td>
<td>SS 06</td>
</tr>
<tr>
<td>Peter Göttel</td>
<td>Industrial Management and Assembly Technologies</td>
<td>Projekmanagement für Ingenieure</td>
<td>WS 07/08</td>
</tr>
<tr>
<td>Dr. Franz Grell</td>
<td>Helicopter Technology</td>
<td>Luft- und Raumfahrtmedizin für Ingenieure</td>
<td>WS 15/16</td>
</tr>
<tr>
<td>Dr. rer. nat. Michael Grünewald</td>
<td>Vibroacoustics of Vehicles and Machines</td>
<td>Praktische Aspekte der technischen Akustik</td>
<td>SS 11</td>
</tr>
<tr>
<td>Dr.-Ing. Marcus Heindl</td>
<td>Medical Engineering</td>
<td>Werkstoff- und Schadensanalyse an Kunststoffteilen</td>
<td>SS 11</td>
</tr>
<tr>
<td>Dr.-Ing. Matthias Heller</td>
<td>Flight System Dynamics</td>
<td>Flugdynamische Herausforderungen hochgradig-reglergestützter Konfigurationen</td>
<td>SS 09</td>
</tr>
<tr>
<td>Dr.-Ing. Jörg Henne</td>
<td>Turbomachinery and Flight Propulsion</td>
<td>Technologie und Entwicklung von Triebwerken der nächsten Generation</td>
<td>WS 07/08</td>
</tr>
<tr>
<td>Dr.-Ing. Robert Huber</td>
<td>Applied Mechanics</td>
<td>Anwendungsorientierte Simulation mechatronischer Systeme</td>
<td>WS 13/14</td>
</tr>
<tr>
<td>Dr.-Ing. Carsten Intra</td>
<td>Metal Forming and Casting</td>
<td>Produktionssmanagement im Nutzfahrzeugsektor</td>
<td>WS 13/14</td>
</tr>
<tr>
<td>Dr.-Ing. Oliver Knab</td>
<td>Space Propulsion</td>
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