The cover illustration shows the department’s building in Garching, 2018 (photo Tobias Hase, TUM) and the Munich Polytechnic School’s building in 1868 (engraving from 1869). Image editing by Fa-Ro Marketing.
150 Years
Mechanical Engineering
Enabling Future
1868 – 2018

Annual Report 2018
## Content

### Preamble

9

### 150 Years of Mechanical Engineering

Milestones in the History of the Department of Mechanical Engineering 12
Science – Politics – Industry 27
Contract Research vs. Free Research 28
Fundamental Research vs. Applied Research 31
The Influence of Politics 33

### Selected Highlights 2017

35

### The Department of Mechanical Engineering

Governance 48
Facts and Figures 50
Department Board of Management 51
Department Council Mechanical Engineering 52
Central Services 54
Honors Awarded During the Department Day 56
Ranking Results 58
Research 59

### Divisions of the Department of Mechanical Engineering

Aerospace 62
Automotive 64
Energy 65
Materials 66
Mechatronics 68
Medical Technology 69
Process Engineering 70
Production and Logistics 71

### Teaching at the Department of Mechanical Engineering

Studying at the TUM Department of Mechanical Engineering 74
International Students and Students’ Exchange 78
Assistance for Students Offered by the Central Examination Services Office 80
Public Funds to Improve Conditions of Study at the Department of Mechanical Engineering 81
Diversity 82
Central Teaching Unit 83
Student Council 85

### Faculty of the Department of Mechanical Engineering

Appointments 88
Retirements 90
Department Members 91
Reports of the Institutes

Prof. Dr.-Ing. Nikolaus Adams
Aerodynamics and Fluid Mechanics

Prof. Dr. phil. Klaus Bengler
Ergonomics

Prof. Dr. rer. nat. Sonja Berensmeier
Bioseparation Engineering

Prof. Dr. Carlo L. Bottasso
Wind Energy Systems

Prof. Dr.-Ing. Klaus Drechsler
Carbon Composites

Prof. Dr.-Ing. Johannes Fottner
Materials Handling, Material Flow, Logistics

Prof. Dr.-Ing. Michael W. Gee
Mechanics and High Performance Computing

Prof. Dr.-Ing. habil. Dipl.-Geophys. Christian Große
Non-destructive Testing

Prof. Dr.-Ing. Volker Gümmer
Turbomachinery and Flight Propulsion

Prof. Dr.-Ing. Oskar J. Haidn
Space Propulsion

Prof. Dr.-Ing. Manfred Hajek
Helicopter Technology

Prof. Dr.-Ing. Florian Holzapfel
Flight System Dynamics

Prof. Dr.-Ing. Mirko Hornung
Aircraft Design

Prof. Dr.-Ing. Hans-Jakob Kaltenbach
Flow Control and Aeroacoustics

Prof. Dr.-Ing. Harald Klein
Plant and Process Technology

Prof. Phaedon-Stelios Koutsourelakis, Ph.D.
Continuum Mechanics

Prof. Dr.-Ing. Andreas Kremling
Systems Biotechnology
Content

Prof. Dr. rer. nat. Oliver Lieleg
Biomechanics 179

Prof. Dr.-Ing. Markus Lienkamp
Automotive Technology 182

Prof. Dr.-Ing. habil. Boris Lohmann
Automatic Control 187

Prof. Dr. rer. nat. Tim C. Lüth
Micro Technology and Medical Device Technology 191

Prof. Dr. rer. nat. Tim C. Lüth (interim)
Medical Materials and Medical Implant Design 196

Prof. Rafael Macián-Juan, Ph.D.
Nuclear Technology 201

Prof. Dr.-Ing. Steffen Marburg
Vibroacoustics of Vehicles and Machines 205

Prof. Dr. Rudolf Neu
Plasma Material Interaction 209

Prof. Wolfgang Polifke, Ph.D.
Thermo-Fluid Dynamics 212

Prof. Dr. Julien Provost
Safe Embedded Systems 215

Prof. Dr.-Ing. Gunther Reinhart
Industrial Management and Assembly Technologies 218

Prof. Dr. Ir. Daniel Rixen
Applied Mechanics 222

Prof. Dr.-Ing. Thomas Sattelmayer
Thermodynamics 226

Prof. Dr.-Ing. Veit Senner
Sport Equipment and Materials 235

Prof. Dr.-Ing. Hartmut Spiethoff
Energy Systems 240

Prof. Dr.-Ing. Karsten Stahl
Machine Elements 243

Prof. Dr.-Ing. Birgit Vogel-Heuser
Automation and Information Systems 249
Prof. Dr.-Ing. Wolfram Volk
Metal Forming and Casting 254

Prof. Dr.-Ing. Georg Wachtmeister
Internal Combustion Engines 259

Prof. Dr.-Ing. Wolfgang A. Wall
Computational Mechanics 264

Prof. Prof. h.c. Dr. rer. nat. Ulrich Walter
Astronautics 268

Prof. Dr. mont. habil. Dr. rer. nat. h.c. Ewald Werner
Materials Science and Mechanics of Materials 274

Prof. Dr.-Ing. Dirk Weuster-Botz
Biochemical Engineering 280

Prof. Dr.-Ing. Michael F. Zaeh
Machine Tools and Manufacturing Technology 284

Prof. Dr. Markus Zimmermann
Product Development and Lightweight Design 288

Appendix
Honorary Doctorates 296
External Lecturers in WS 16/17 und SS 17 297
Habilitations 2017 298
Doctorates 2017 298
Dear reader,

Enabling the future – ever since 1868 Mechanical Engineering at the Technical University of Munich has been the front runner in developing technical solutions for the challenges of our society at the cutting edge of research and technology.

Carl von Linde, the pioneer of refrigeration, and Johann Bauschinger, a renowned mathematician and materials scientist, as founding professors of the Department, as well as our students, Rudolf Diesel, inventor of the diesel engine, and the pioneers in aviation Willy Messerschmitt and Claude Dornier are among the illustrious circle of TUM engineers. Sustainable mobility, transport and energy conversion and disruptive technologies in manufacturing caused by digitalization are the most prominent challenges today. As much as in the early days of engineering, these challenges can only be met by fundamental research in engineering sciences, i.e. mechanics, fluid mechanics, thermodynamics and engineering design from which innovation and creative solutions emerge. Fundamental engineering science, however, finds its orientation only in the applied engineering sciences on which it is firmly grounded. The epitome of the synergy between applied and fundamental engineering science was Ludwig Prandtl, one of our most prominent graduates, who developed the mathematical foundation of aerodynamics and boundary layers and thus enabled modern aeronautical engineering (c.f. Highlights on pp. 31-42)

Since about the 1980s, cooperation with industry has gained ground and became one of the most important sources for research funding throughout the years 1995 to 2005. After the move to Garching, between 2005 and 2015, third-party funding almost tripled, motivating restructuring through new governance approaches and implementation of a strategic mid-range vision for further departmental development (c.f. Strategic Governance, p. 44).

In order to maintain the balance between applied research, as a response to one of the first evaluations of a German university department, the department agreed to accept peer-reviewed scientific publications and funding through peer-reviewed public foundations as an additional criteria for research performance, along with successful cooperation with industry. Most international rankings are based on publication data, and the success of the governance measures is reflected in the fact that TUM Mechanical Engineering is now ranked at top international positions worldwide and at position 1 or 2 among its German peers (c.f. Rankings, p. 54). At the same time, TUM Mechanical Engineering became the top-performer at TUM with respect to DFG funding, except for TUM Medical (c.f. Research, p. 55).

150 years’ culture of excellence does not allow us to rest on our laurels. We are in the midst of an intensive process of redesigning our study programs to meet the future engineering challenges; already reflected in at early semesters of the Bachelor program, enabling students to define and master their focus during the subsequent Master’s programs. (c.f. Studying p. 69)

For the fourth time now, we have compiled the achievements and topical research results of TUM Mechanical Engineering in this report. We hope that it helps our partners in academia and industry to consolidate or establish contact with us, stimulate the interest of prospective students and junior researchers to join us, and – last but not least – ourselves, the faculty and researchers as a live exchange platform on our research and teaching activities.

Prof. Dr.-Ing. Nikolaus Adams, Dean
History of the department
Dr. Matthias Georgi
Mag. Anton Zwischenberger
Neumann & Kamp
www.historische-projekte.de
150 Years of Mechanical Engineering
The History of the Department

The Munich Polytechnic School's new building inaugurated in 1868 and designed by Gottfried Neureuther, one of school's founding professors; engraving from 1869.

‘The organic provisions for the new Polytechnic School in Munich have been granted approval by His Majesty the King, and the relevant royal ordinance will be published in the government gazette today.’ These were the words used by the Allgemeine Zeitung in Augsburg, one of Germany’s leading newspapers, when it announced the establishment of the Technical University of Munich (TUM) as a Polytechnic School on 24 April 1868. This was also the date on which the history of today’s Department of Mechanical Engineering began.

The Allgemeine Zeitung continued: The school ‘comprises one general department and four technical schools: for engineers, architects, mechanics and chemical engineers. These five departments will teach both mathematical and natural sciences as well as the arts of drawing, construction and engineering, mechanical and chemical technology in their full scope.’ Literature, cultural history, aesthetics, law, geography, history etc. were ‘taught within the boundaries matching the audience’.

The school was given university status from the beginning. During its first year, a total of 24 professors and 21 lecturers taught approximately 350 students. The different positions of the academic instructors were distinguished as follows: ‘The professors at the Polytechnic School are public servants. They are divided into full professors (with the rank of collegial councillor) and associate professors (with the rank of collegiate assessor).’ Moreover: ‘[T]he senior teachers will share teaching with an appropriate number of assistant teachers as well as readers.’ There were explicit rules for students with regard to both behaviour and teaching: ‘[T]he audience is subject to the institute’s disciplinary code’ and ‘each student must be occupied at the school at least three hours per day.’ Students’ admission was also regulated: ‘The Polytechnic School only admits students who have reached the age of seventeen and who have completed a technical middle school (equivalent to a Realgymnasium).’ The latter was a secondary school with a focus on sciences.

The Department of Mechanical Engineering has its origins in the mechanics school, Department IV, Mechanical-Technical Department. At the time of its founding, theoretical mechanics was still part of mathematical physics at the General Department, and Technical Mechanics was part of the Engineering Department. This department dealt with geodesy, civil engineering and the field of infrastructure. To guarantee the school’s success it issued the following statement in 1868: ‘Indeed, only capable teachers and directors are able to breathe life into it (the Polytechnic School).’
Milestones in the History of the Department of Mechanical Engineering

1868 Establishment of the Munich Polytechnic School

First Study Programme of the Mechanical-Technical Department
Carl v. Linde, Chair of Theoretical Machine Science, lectures on engines in general; steam engines. H.C.A. Ludewig, Chair of Mechanical Engineering, lectures on: the construction of simple machine parts; the construction of active machine parts; the construction of machines and engines (each including lecture and tutorial). F. Klingенfeld, Chair of Descriptive Geometry, lectures on: machine science; mechanical technology; mechanical drawing (lecture and tutorial). Johann Bauschinger, Chair of Technical Mechanics and Graphical Statics (part of the engineering department until 1874), lectures on: technical mechanics; elementary mechanics.

1873 The Mechanical-Technical Laboratory headed by Johann Bauschinger which was established in 1871 moves into a laboratory building of its own. This later results in the establishment of the State Materials Testing Institute for Mechanical Engineering which is located at the Chair of Materials Science and Material Mechanics (Ewald Werner) today.

1875 Carl von Linde sets up the Laboratory of Machine Science. With the newly-established Laboratory of Theoretical Machine Science the Munich Polytechnic School was ahead of all other German technical universities in scientific knowledge for nearly twenty years. The objective of this laboratory was to conduct various ‘proof-of-principle’ studies in order to create better calculation principles. One of the first experiments concerns the determination of the properties of superheated steam. For the first time, Linde also includes the theory of refrigeration engines and refrigeration technology in his field of teaching.

Establishment of the Chair of Mechanical Technology, Egbert v. Hoyer is appointed as full professor. The focus of his work is on both textile engineering and paper technology.

A half-yearly certificate for Ludwig Frühwein from the Polytechnic School, 1868

Sketches and annotations from one of Carl Linde’s early lecture concepts
The History of the Department

The Paradigm of Mechanical Engineering Evolves
The paradigm of modern mechanical engineering evolves during the second half of the 19th century and the beginning of the 20th century. Both engineers and scientists develop basic mechanisms such as the one of the diesel engine and the refrigeration engine. Thermodynamics and fluid mechanics are perfected as scientific disciplines essential to mechanical engineering. Institutionally, mechanical engineering outgrows the small inventors’ workshops. It is taught at universities and industrial enterprises set up research departments.

1877 Renaming of the Munich Polytechnic School to Technische Hochschule München (Munich Technical University or THM).

1880 Rudolf Diesel graduates with the best marks since the university was established and is awarded an honorary degree. During the first few decades of its existence students are given a report each semester like at a conventional school. Diplomas are only granted for ‘outstanding achievements’ by the department on application. Only twelve diplomas are granted to graduates between the establishment of the school in 1868 and 1900.

1886 Johann Bauschinger publishes his study entitled: ‘On the changes of the elastic limit and of the strength of iron and steel caused by elongation and squeezing, by heating and cooling and by frequently repeated strain.’ He thus describes the so-called ‘Bauschinger effect’ later named after him, i.e. the change in the elastic limit of a metal or an alloy following a deformation which determines the direction; a workpiece is initially bent in one direction. If it is then bent in the opposite direction it shows a reduction in strength. This is caused by primarily induced dislocations in the material (faults or impurities).

1894 August Föppl, who succeeds Johann Bauschinger, begins to corroborate his theoretical work in the field of technical mechanics with practical experiments.

1897 The ‘Föppl’ is released: August Föppl publishes the first part of his ‘Lectures on Technical Mechanics’. The standard reference work is printed in numerous editions and remains the central textbook for mechanical engineering over decades. It is still published today.

The Werder traction engine and bend testing machine, acquired by Johann Bauschinger in 1870, served for over 100 years in the Mechanical Technical Laboratory, before it went to the Deutsche Museum; photo from 1916.

From left to right: The engineer Rudolf Diesel, director of the Maschinenfabrik Augsburg, Heinrich von Buz and Moritz Schröter, Professor of the Munich Technical University, 1897.

View of the old Linde testing laboratory before it was handed over to the university. In the foreground is the oxygen condenser, photo from 1901.
1898 Ludwig Prandtl obtains his degree in mechanical engineering at the Munich Technical University. He then works as an assistant to August Föppl, who was to become his father-in-law later. However, in 1899, he had to submit his thesis on ‘Occurrences of Tilting. A Case of Unstable Elastic Equilibrium’ to the LMU (Ludwig-Maximilians-Universität) in Munich. He made important contributions to a basic understanding of fluid mechanics and developed the boundary layer theory.

**Name of the Department**

Over the past 150 years, the present-day Department of Mechanical Engineering has had various names. In 1868 the department’s history begins as ‘Mechanical-Technical Department’. Around the year 1900 its name changes to ‘Mechanical Engineers Department’. In the 1930s it is called ‘Department of Mechanical Engineering’, and in the 1940s ‘Department of Mechanical and Electrical Engineering’. In 1974 the Electrical Engineering section becomes a department in its own right while the Department of Mechanical Engineering remains. A reconstruction of the exact dates – apart from the last renaming in 1974 – is not possible. Transitions were fluid each time the name changed, and the old and new names of the department were used in parallel over many years.

**Ca. 1900** Around 1,000 students attend courses at the Department of Mechanical Engineers.

**1901** The Munich Technical University is granted the right to confer doctorates and is thus put on a par with Munich University. This was preceded by complicated negotiations with both the Bavarian and Prussian Ministries of Education. It was the universities in particular which feared a debasement of the doctoral degree and voiced harsh protests in the run-up to the decision.

**1902** Carl von Linde returns to the Munich Technical University as associate professor of Applied Thermodynamics. It is on his initiative that the Laboratory for Technical Physics is set up. Ludwig Burmester begins his lectures on kinematics at the Technische Hochschule, making the theory of the wheel gear an important part of the curriculum.
The History of the Department

**Laboratory for Technical Physics**
Since its establishment, the aim of the Laboratory for Technical Physics has been the experimental application of theoretically obtained knowledge. Research is also carried out although the Technical University does not have an official research assignment. This teaching model sets an example for many other technical universities and is applied to this day. The purpose of the laboratory is later explained by Wilhelm Lynen, Professor of Mechanical Engineering at the THM from 1909 onwards: ‘The student must deal with the machines himself, (…) he must see with an open eye, hear with his ear strained, feel with his hands, to understand how they behave when idling and under full load, at the highest speeds and at high temperatures.’

1906 Rudolf Camerer is appointed as full professor at the department, establishing the Chair of Hydroelectric Power Plants. In addition, an Institute of Hydraulic Machines and Plants is attached to the Chair.

1907 Establishment of the Chair of Lifting Equipment and Conveying Systems which is filled by a crane construction expert from the industry, Rudolf Krell. Aircraft designer Claude Dornier graduates at the department.

1913 Modernisation of the technical laboratory. The Institute of Machine Tools and Industrial Engineering includes materials testing, ferrous metallurgy and the forming of metals through external forces in its focus of activity.

**The Paradigm of Mechanical Engineering is Improved**
The establishment of the groundwork of the paradigm was followed by a period in which the mechanisms, principles and works of mechanical engineering were improved and specified. Machines which work on established principles, for example, become smaller and more efficient. Mechanical engineering is perfected by lubricants, new materials and shapes of toothed wheels in gear mechanisms as well as numerous other detailed solutions.

1923 Willy Messerschmitt is awarded a degree; he establishes Messerschmitt Flugzeugbau GmbH in Bamberg while still studying. In 1923 he comes first in a gliding competition on the Rhön hills with his graduation project of a glider named ‘S 14’.

1924 Establishment of the first chair and an Institute of Agricultural Machinery at a German university.

1925 Wilhelm Nußelt is appointed as full professor at the Chair of Theoretical Machine Science and teaches thermodynamics there. The ‘Nusselt number’ is named after him. It describes the convective heat transmission between a solid surface and a flowing fluid.
1930/31 Willy Messerschmitt is awarded a teaching assignment on the construction and design of aircraft.

1932/33 Establishment of a second Chair of Technical Mechanics. This is maintained until W. Kaufmann is conferred emeritus status. It mainly conducts research on the mechanics of fluid and gaseous bodies.

1935 The Chair of General Design Theory and Machine Elements with trial field, workshop, carpenter’s shop and test facility is established under the direction of Erich Böddrich. In-depth arms research is carried out and the trial field is extended. It is evacuated to Schäftlarn Monastery between 1942 and 1945.

1936 The Chair of Metallurgy and Metals Science is established.

1936 Establishment of the Chair of Aircraft Engines and Engine Science under the direction of Kurt Schnauffler. During the following years a research institute for aviation and motor vehicle engines is set up at the Kapuzinerhözi, north of the Botanical Gardens. The original plan to move the entire THM there was discarded because of the course of the war. Today the location at Schragenhofstrasse accommodates the engine laboratory of the Chair of Internal Combustion Engines.

From the very beginning, government aid for AK Flieg was based on military considerations.
The History of the Department

Nazi Era
In 1933, the Department of Mechanical Engineering – like the entire THM – becomes part of the Nazi system. The university is brought into line, partly by force, partly by conviction, partly out of anticipatory obedience; University members of Jewish origin are expelled, as are those with politically undesirable views. In 1933, Christian Prinz, Professor of Mechanical Engineering, encounters hostility from students because of his ‘red’ attitude and develops a stomach ulcer from which he dies a short while later. Guido Zerkowitz, Associate Professor of Mechanical Engineering, is dismissed because of his ‘non-Aryan’ extraction. In 1938, he is one of the last German scientists to join the Technion in Haifa (today the Technical University of Israel) in what is then Palestine. Mechanical engineer Erwin Hinlein is sentenced to two years hard labour imprisonment following a perjury trial under nebulous circumstances during which he loses his doctor’s degree. After his release he is deported to the Riga-Kaiserwald concentration camp where he dies in 1944.
The department conducts research for the army, for example in the fields of torpedo propulsion, petrol injection and substitute fuels for car and aircraft engines. Non-military research is continued on a small scale.
The Munich Documentation Centre for the History of National Socialism is currently conducting a study on the history of the department during the Nazi era. Moreover, both the department and the whole university are debating how to deal with awards of honorary doctorates and honorary senatorships which were either conferred during the Nazi era or were conferred later on individuals who had been active Nazis.
1940 The Chair of Materials in Mechanical Engineering is carved out from Chemistry in 1940 and is assigned to the Department of Mechanical and Electrical Engineering.

1942 The Chair of Aircraft Construction is established at the THM under the direction of Julius Krauß. The first attempt at setting up such a chair had taken place in 1929 but had failed due to funding problems. Krauß had been a Senior Lecturer since 1936. From 1942 onwards, lectures are held on the subjects of aircraft components, aircraft design, aircraft stability and in-flight measuring techniques, and research on these subjects is conducted.

1945 Discontinuation of teaching at the THM. Closing down of the Chairs of Aircraft Engines and Engine Science and of Aircraft Design. Beginning of the ‘denazification’ procedures at the THM. This initially causes the loss of two thirds of its university lecturers. There are 24 lecturers employed by the Department of Mechanical Engineering in 1945/46. Thirteen of these are dismissed, four of whom are reinstated by 1953.

After the Second World War, many academics tried to hide their Nazi past by making false declarations in the obligatory questionnaire concerning involvement in the Nazi party.

To begin with, the American military government took a very hard line with regard to denazification and ordered the majority of the teaching staff to be dismissed. According to the list of lecturers, the former rector Lutz Pistor was arrested, while the subsequent rector Hans Piloty was cleared.
The History of the Department

1945/46 Both staff and students are involved in the reconstruction of the badly damaged university. Students team up in construction crews with the prospect of being given priority in re-enrolment in exchange for their help.

1946 Resumption of teaching at the THM. About 3,000 students are accepted – most of them war veterans. Besides studying, the students have to commit themselves to fifty hours of auxiliary service work per semester. Applicants who have completed school in 1946 are not admitted.

1950 Renaming and realignment of the Chair of Aircraft Engines and Engine Science which had been set up in 1936. It is then called Chair of Internal Combustion Engines and is headed by Wilhelm Endres. During the following years it goes through more changes in name. For many years, for example, it is called Chair of Internal Combustion Engines and Motor Vehicles. Today, this chair exists under the name Chair of Internal Combustion Engines.

1951 Gustav Niemann establishes the Chair of Machine Elements and works in the fields of toothed wheels and gear manufacturing on which he publishes some pioneering works.

The 'Bockerlbahn' train transporting rubble away from the university building.

University applicants carrying out reconstruction work on the university premises, 1946. Those applicants who had not participated in the war had to clear rubble for many months, before they were accepted for a course of study.

The Student Ancillary Service hour card of the applicant Karl Rihazek, 1947/48. This applicant worked for 1,058 hours, before he was able to start his studies.
The History of the Department

1952 Ernst Schmidt succeeds Wilhelm Nußelt. He gains a reputation chiefly with his research in all fields of heat transmission, gas turbine design and water vapour research. The 'Schmidt number' is named after him which describes the ratio between diffusive momentum transport and diffusive mass transfer. During Schmidt's tenure the Chair of Thermal Engines, Refrigeration Technology, Heating and Ventilation is extended and renamed Chair of Technical Thermodynamics.

1953 Establishment of the Chair of Process Engineering with Friedrich Kneule and Hans von Seybel. Process engineering as a field of study had been set up by Friedrich Kneule and Hans von Seybel in 1950.

1954 After the signing of the 'Paris Agreements', West Germany regains its air sovereignty. This leads to a Chair of Aircraft Construction being established with an affiliated Institute of Lightweight Construction and Aeronautical Engineering. Julius Kraus, who had already worked at the Chair of Aircraft Design in 1942 and had been dismissed in 1945 is appointed as professor at the newly-created Chair of Aircraft Design. During the 1960s the department puts its focus on aerospace technology. In 1964 the Chair of Aircraft Construction is converted into a Chair of Lightweight and Aircraft Design and, from 1978 onwards, into a Chair in Lightweight Design.

1955 The Chair of Theory of the Wheel Gear and Kine-matics is renamed Precision Engineering and Micro Technology and is headed by Richard Unterberger and Rudolf Beyer.

1956 The Chair of Thermal Engines, Refrigeration Technology, Heating and Ventilation is extended in size and is renamed Chair of Technical Thermodynamics.

1957/58 The Chair of Technical Mechanics and the Institute of Fluid Mechanics are both taken over by Erich Truckenbrodt.

1962 Establishment of the Chair of Ergonomics under the direction of Heinz Schmidtke. In 1965, the Institute of Labour Physiology is set up, headed by Wolf Müller-Limmroth. After the latter has been conferred emeritus status in 1990, the two merge to form the joint Chair of Ergonomics.

1965 The Chair of Engineering Design is newly-established. Based on machine elements and working with examples of outstanding machines and engines, it aims to convey the skills necessary for designing by retracing their design steps. The THM is thus the first German university to implement this new discipline.
The History of the Department

The machine hall at the Institute for Electrical Drive Machines and Systems in the Luisenstrasse (Arch. G. Hassenpflug)

Set-up for drawing electron and ion paths (Institute for Technical Electronics)

Demonstration of gyrostatics. Professor Kurt Magnus (1912–2003), Chair B of Mechanics, giving a lecture for beginners, 1980
The History of the Department

1965/66 Introduction of the Chair of Aerospace Engineering. Both Franz Josef Strauß, the future Bavarian State Premier and his fellow party member, State Secretary Erwin Lauerbach, played a particularly important part in this.

1967 The Institute of Machine Tools and Industrial Engineering moves the focus of its research to information technology and production engineering.

1968 Establishment of the Chair of Metal Forming and Casting. Its main focus is on the use of novel, high-strength materials and aluminium in sheet metal parts production.

1970 THM is renamed Technische Universität München (TUM), (Technical University of Munich or TUM).

Use of Microprocessors – New Perspectives for Mechanical Engineering
The first microprocessors enter the market at the beginning of the 1970s. They open up new perspectives for mechanical engineering and, during the following years, serve as tools for significantly enhancing the possibilities in mechanical engineering. Processor-controlled machines enable greater precision. Computer calculations and simulations speed up research and reduce its costs at the same time. The field of robotics emerges and the automation of even complex production steps is made possible. Information technology is an integral part of mechanical engineering.

1974 The different divisions at the Department of Mechanical Engineering are set up with chairs, laboratories and institutes combined to form major institutes:

- Labour Physiology
- Precision Engineering, Design, Machine Elements
- Automotive Technology, Materials Handling and Agricultural Engineering
- Aerospace Technology
- Mechanics, Thermodynamics, Hydraulics and Energetics
- Process Engineering
- Materials Science and Processing Sciences.

The Department is split into a Department of Mechanical Engineering and a Department of Electrical Engineering and Information Technology.

1976 Establishment of a Chair of Joining Technology headed by Gerd Habenicht. The central research focus of this chair is the joining of components of different shapes and functions and materials in a manner which is suitable for both their functions and for production.

1977 Research at the Chair of Precision Engineering and Micro Technology is not confined to the classic topics such as equipment design based on either purely electronic or electromechanical principles. It also opens up new fields such as ink printing, microsystems engineering, propulsion technology, optical measurement technology, etc.

1981 The Chair and Institute of Machine Tools and Industrial Management Technologies puts a focus on two new research topics: industrial robotics and assembly technology.

1989 The collaborative research centre no. 255 ‘Transatmospheric Flight Systems – Basics of Aerothermodynamics, Propulsion Systems and Flight Mechanics’ is set up, co-ordinated by Gottfried Sachs. Its objective is the development of capabilities for aerodynamically borne, stable maximum speed flight with air-breathing propulsion systems while meeting extreme performance requirements with regard to both workload and range.

1990 For the first time, the TUM budget exceeds the threshold of one billion German marks. The proposed relocation of the Department of Mechanical Engineering to Garching meets with resistance from students. In June 1990 they stage a bicycle demonstration to point to Garching’s poor transport connection. Almost 5,000 students are enrolled at the Department of Mechanical Engineering.

1991 Restructuring of the department: chairs who conduct research on the same topics are combined to form institutes:

- Institute of Mechatronics
- Institute of Materials and Processing
- Institute of Production Technology
- Institute of Process Technology
- Institute of Mechanical and Automotive Engineering
- Institute of Astronautics
- Institute of Energy Engineering

Electrical Engineering
In 1901 the first Chair of Electrical Engineering is established at the department. Electrical engineering is initially viewed as part of mechanical engineering. However, it grows increasingly more independent. In 1948 the department is split into two independent parts consolidated in the department, one for mechanical engineering and the other for electrical engineering. During the 1960s there are discussions about the department’s separation into two independent ones, and this is finally executed in 1974.
The History of the Department

1992 Establishment of the Chair of Information Technology in Mechanical Engineering. This takes into account the increasing significance of information technology in mechanical engineering. ‘[Our aim is] not only to utilise the potential for innovation connected with the arrival of information technology in mechanical engineering but to make the problems which accompany the new technologies controllable. Only if we succeed in this will our mechanical engineering be able to maintain its leading position’, founding professor Klaus Bender emphasises.

1993 The collaborative research centre no. 365 ‘Environmentally Compatible Drive Technology for Vehicles’ is set up headed by Bernd-Robert Höhn. The objective of this special field of research is the simulation, layout and design of the Full Hybrid.

1997 Inauguration of the new department building on the Garching research campus with approximately 60,000 sq. metres floor space.

Garching
The construction of the department’s new campus in Garching is unique at the time – it is not public building authorities which carry out the project planning but BMW which is intended to speed up building. After a construction phase of only six years – and without exceeding the budget – the new campus is completed in 1997. The building is aligned along a central covered axis which provides access to all chairs, the lecture halls, library, administration offices and the cafeteria. Its architecture follows an exact requirement analysis and is optimised for use as a place of research and study while exceeding the boundaries of the laws governing the construction of university buildings in force at the time. Even the students are involved in the building by designing the seating of the lecture halls. However, not all plans are implemented. For a while, there were discussions about setting up a ‘Pilsstube’ (a kind of pub), directly on the main axis.
2000 The new Chair of Automotive Technology is created from parts of the Chair of Internal Combustion Engines and Motor Vehicles established in 1936 and the Chair of Agricultural Machinery and is led by Bernd Heißing. Thus, the automotive sector which shapes the department is given a dedicated professorship.

2000/01 The department begins to implement the so-called ‘Bologna reform’ process. One Bachelor’s and one Master’s degree course each in mechanical engineering are set up alongside the traditional degree courses.

2001 The collaborative research centre no. 582 ‘Market-oriented Production of Customised Products’ is set up, headed by Udo Lindemann. The Chair of Hydraulic Machines at TUM is granted the sum of 400,000 DM for research on, and the development of ‘fish-friendly’ turbines.

2006 The TUM is awarded the status of ‘Excellent University’ within the framework of the ‘excellence cluster’ CoTeSys (Cognition for Technical Systems), scientists at the Department of Mechanical Engineering conduct research on the basics of perception-coupled motion control and its implementation through information processing mechanisms.

Digitisation in Mechanical Engineering – a new Paradigm?
Moore’s law states that the computing power of processors doubles every one to two years. During the first decade of the new millennium the affordable computing power attains speeds which enable a redesign, even the re-thinking, not only of communication and media but also of technology and, in particular, mechanical engineering. Computers are no longer just tools in mechanical engineering but are becoming the core of previously unthinkable new applications.

2008 The collaborative research centre no. 768 ‘Managing Cycles in Innovation Processes – Integrated Development of Product Service Systems Based on Technical Products’ is set up, headed by Udo Lindemann. Birgit Vogel-Heuser is appointed head of this centre in 2013, leading it into its third funding period. The collaborative research centre TRR 40 ‘Technological Foundations for the Design of Components of Future Aerospace Transportation Systems Subject to High Thermal and Mechanical Stress’ is set up, headed by Nikolaus Adams. The main research focus of this collaborative research centre is on new technologies for chemical main stage rocket engines for future generations of civilian launchers.
The History of the Department

2011 The department is the first institution at TUM to be evaluated. The assessors confirm its outstanding research results. During the following years the department succeeds in considerably enhancing its scientific profile. Under the project management of Markus Lienkamp, TUM presents the MUTE at the IAA Motor Show for the first time – a joint project by 20 departmental professorships. The MUTE is solely electrically-powered. It has a maximum speed of 120 km/h and a minimum range of 100 kilometres.

2014 The eLi14 is a vehicle designed by the TUFast student group. It sets the Guinness world record as ‘Most Efficient Electric Vehicle’.

2015 Nikolaus Adams wins the ERC Advanced Grant ‘NANOSHOCK – Manufacturing Shock Interactions for Innovative Nanoscale Processes’. This research project examines which mechanisms and properties enable the controlled formation of shocks in very complex environments – such as living organisms. These questions are to be studied and answered with the help of modern computer simulation models and some carefully selected experiments.

2016 Travelling from one place to another at almost the speed of sound – that is the idea behind the ‘Hyperloop Pod Competition’ of visionary Elon Musk. Out of initially 700 teams, 30 teams are selected to build a prototype at the end. The WARR study group at the Department of Mechanical Engineering at TUM is one of these teams. In August 2017, the team wins the maximum speed competition with its Hyperloop Pod II and establishes a new speed record with 324 km/h.

In 2015, Cevotec, a spin-off from the Technische Universität Munich, is set up by scientists of the Chair of Carbon Composites at the Department of Mechanical Engineering and wins the important start-up competition ‘Weconomy’ in 2016. The Cevotec founders develop a fully automated manufacturing method that not only makes the production of carbon parts more efficient but also reduces the amount of material required.

2014 A new helmet-mounted sighting instrument developed by scientists at the Chair of Helicopter Technology is introduced. The ‘augmented reality’ device enables helicopter operations in poor visibility, increasing the safety of both pilots and any passengers on board.

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2017 The department sets up its first cross-chair cluster ‘Additive Manufacturing’. In addition to investments made by the chairs involved, the department contributes more than €500,000 in start-up aid to establish this pioneering topic. Successful maiden flight of the Sagitta unmanned flying wing. Other participants in this ‘open innovation initiative’ by aircraft manufacturer Airbus, besides TUM, are research institutes of the German Aerospace Centre DLR, the Universität der Bundeswehr in Munich, the Technical University in Ingolstadt and the TU Chemnitz.

2018 After enhancing the department’s scientific profile following its evaluation in 2011, the department has consistently maintained top level positions in major international research rankings; no. 1 in Germany in both the Times Higher Education Ranking and the NTU Ranking – continuously among the Top 10 in Europe and the Top 40 worldwide.
The History of the Department

Science – Politics – Industry

The Department in a Field of Tension

‘It’s a difficult relationship, the industrial sector and higher education, time and time again.’ (Prof. Hajek) – ‘Applied research and basic research don’t always have to contradict each other.’ (Prof. Lienkamp) – ‘We have to accept political decisions.’ (Prof. Adams).

It is not just questions of research, external funds and higher education bureaucracy that the faculty is concerned with. There are also major issues of responsibility, freedom and the benefits of science. How is research funded? Who makes decisions about issues and the subjects of research? What influence do social developments or political decisions have on science? Conflicting concepts soon emerge: contract research versus free research; fundamental research versus application-oriented research; research trends versus research tradition. These questions are not new; they have been the subject of discussion in the sciences, at TUM and in the department for generations.

Here we take a look back at the history of the department, and through exemplary stories show how former generations answered these questions. The different ways in which these issues are currently being tackled will then be outlined on the basis of interviews with five professors.

The Founding of the Department

The industrialisation of continental Europe began in the early years of the 19th century. In Bavaria, too, factories sprang up with industrial production methods, and from 1835, the railway followed, with the first line travelling between Nuremberg and Fürth. A short time later, the first Bavarian shipping company was founded and canal construction was driven forward. Industrial companies were established such as the locomotive factory J.A. Maffei or the Sander'sche Maschinenfabrik und Eisengießerei, the Sander machine works and iron casting company and the Maschinenfabrik Klett & Comp. machine works, both of which were the forerunners of MAN. During the second half of the 19th century, Bavaria experienced a veritable wave of industrialisation.

At the same time, from 1805, political visions were being created; Bavaria became a kingdom. It was a political goal of the Bavarian kings to promote technology in Bavaria. In particular, the territorial gains of Franconia – linen production in Upper Franconia – and Augsburg – the textile industry – played an important role. Additionally, the example of Paris awakened a desire for more, with its École Polytechnique, which had been in existence since 1794. The first attempt in Bavaria had already failed after six years. In 1833, the ‘Polytechnische Centralschule’ closed its doors again. From then on, technical training in Munich focussed on architecture. Instead, polytechnics opened in Nuremberg and Augsburg, with a focus on the main areas of scientific interest of their respective locations. In Nuremberg, these were the casting and metal works, while in Augsburg, wool and cotton manufacture. In Munich, a ‘Faculty for Higher Technical Officers’ was established at the University of Munich, with architecture and the preservation of historical monuments being retained as the field of study. In 1848, Maximilian II, the third Bavarian king, took over the government. He promoted commerce and the industrial sector and founded the State Ministry of Trade and Public Works, the precursor to today’s Ministry of Economic Affairs. Ludwig II, who occupied the Bavarian throne after 1864, made a second attempt in 1868 and founded the Munich Polytechnic School. Department IV of the School, the Mechanical-Technical Department, is where life began for today’s Department of Mechanical Engineering. There, knowledge about fundamental mechanical principles was to be gathered, expanded and disseminated. Specialists were to be trained with a specific technical perspective on the world. Both on the part of the state, whose political will to design technology had intensified, as well as of the industrial sector, which was rapidly prospering, demand for these specialists was increasing. Against this political and economic background, the second attempt at founding a technical training facility was a success.
The History of the Department

Contract Research vs. Free Research

1871 Laboratories Working on Behalf of the Industrial Sector

In 1871, Johann Bauschinger founded the Mechanical-Technical Laboratory. Today, it is known as the State Material Material Testing Agency for Mechanical Engineering (Staatliche Materialprüfamt für den Maschinenbau; MPA), which regards itself as a service provider for the industrial sector. Bauschinger’s original plan envisaged something different. From his perspective, the laboratory was intended above all to promote mechanical engineering research. It was only gradually that it began to be used differently. The original additional objective of inspecting materials and construction parts in exchange for money increasingly replaced the research activity.

A similar development occurred with Carl von Linde’s Laboratory of Machine Science. While it was also originally intended as places of research and learning, his laboratory established in 1875 quickly became a hub for inspecting and testing industrial products and providing advice to companies. Moritz Schröter in particular, who succeeded von Linde in 1879 and who was a distinguished expert in the field of technical thermodynamics, further expanded this main field of activity. The independent scientific work of the Technical University meant that industrial products obtained a type of quality seal after they had been inspected. Over the years, this became one of the department’s most important areas of work.

Almost all publications about theoretical mechanical engineering were written on behalf of the industrial sector. Around 80 percent of the articles published by Schröter were about steam engines and turbine inspections. This activity was also criticised in specialist circles: Hans Lorenz, a contemporary of Schröter and Professor for Mechanical Engineering at the University of Halle, argued that: ‘Schröter contents himself with publishing extensive acceptance tests without drawing any notable conclusions from them, which was always the risk entailed by the impetus from the industrial sector with its commercial interests.’

As well as testing the functioning of machines, the mechanical engineering professors also produced assessment reports. These could be presented as evidence in cases of dispute, technical failure or accidents, or patent proceedings. Linde stressed that: ‘For the lack of understanding among members of the patent office department in question, there is less to be gained from strictly physical proof (which they are unfortunately unable to comprehend) than through a certain explanation regarding the resulting facts of the case from an authoritative agency.’ Linde was convinced by the benefits of assessment reports. In a letter to his teacher, Gustav Zeuner, he wrote that the task of science was to assist in ensuring that justice prevailed with the aid of non-partisan judgements. However, in daily practice, the independent nature of the professors, who as state officials exuded an aura of non-partisanship, was considerably limited, as Linde’s example shows.

On Linde’s initiative, in 1887 the Munich Polytechnic Association built a test station for refrigeration machines, which was supervised by Schröter. At the test station, other producers of refrigeration machines were to be given the opportunity of having the quality of their machines tested. Since the test station was in effect under Linde’s control, however, and thus under the control of one of the owners of the Gesellschaft für Linde’s Eismaschinen AG (‘Linde’s Ice Machine Company’), other companies did not trust the independent nature of the test station. During the station’s five-year existence, only three companies had their refrigeration machines tested there, apart from those produced by Linde’s company.
The History of the Department

Just how important these independent assessment reports were for new developments was reflected in the story of Rudolf Diesel. When Diesel presented his engine, the innovative potential of his invention was confirmed by several professors – Schröter, Linde and Zeuner. Although Diesel’s thermodynamic predictions were incorrect, he received sufficient support for his invention from the industrial sector. This can be traced back in part to the major influence of the assessment report. In this report, for example, Carl von Linde emphasised that: ‘[I] can only confirm my view already expressed verbally to you, that the path you have taken is taking you directly and accurately to your goal of achieving the fuel consumption required for mechanical work which according to our current knowledge of physics and taking into account the current state of mechanical engineering should be regarded as the most ideally suitable.’ However, Carl von Linde noted that the calculations made by Diesel were too optimistic, and that, in the best scenario, a third of the value of the theoretical degree of efficiency calculated by him could be achieved.

2018 Sample Contracts and Acquired Freedom

Five professors – five positions on the issue of industrial research versus scientific independence, commonalities and differences.

The five professors consider the issue from different perspectives, with a view to the entire department, and with a focus on their own professorial chair. They all regard themselves as being free and uninfluenced by the industrial sector. With regard to their own professorial chairs, they stress that the origin of the questions initially plays no role; it is important that questions are being asked of the respective field of specialism at all. They claim that com-

We don’t have to accept everything that the industrial sector offers us. That’s a very positive situation here in the department. Prof. Werner
commercial businesses can make a considerable contribution here. In most cases, it is not a question of being told what to do by the industrial sector, but a case of constructive collaboration (Wachtmeister). Werner emphasises that: ‘We are not obliged to take on all the requests made by the industrial sector.’ Lienkamp regards it as being a task of the TUM to be a thorn in the side of the industrial sector. ‘We don’t get involved in the industrial sector’s everyday business’ (Hajek). When approaching problems, there are generally differences between the industrial sector research departments and the faculty. In the industrial sector, experience plays a far greater role. At the university, however, problems are considered at greater depth and in a more analytical way. However, the independence of their work is not just a result of the strength of their own professorial chair and of the professor involved. Throughout the university, contracts have been developed which must be signed by the partners and external funders. These contracts secure extensive freedoms for the higher educational institution, the department and the researchers. These include the freedom to publish and freedom regarding personnel.

With regard to the general development of the department, there are clear differences of opinion among the professors. The spectrum ranges from: proximity to the industrial sector is increasing in the department, and the industrial sector is attempting to increase its influence over the department, in the view of Werner, to: independence is increasing and today’s department – unlike the situation one to two generations of professors ago – is no longer an extended workbench, as Adams described it. The distance from the industrial sector is increasing, possibly because an increasing number of professors are from academic backgrounds and have not worked in the industrial sector. The earnings from working in the private sector are far higher than at the university. At the same time, proximity to the industrial sector is increasing, since more and more institutes are founding start-ups in order to market their products themselves.

There is agreement when it comes to the sense and purpose of their work. Without scientific work at the department, the industrial sector would be lacking important input; without the external funds provided by the industrial sector, important means would be lacking not just for research, but also for teaching. There is also agreement with regard to the fact that the industrial sector only provides a portion of external funds. One third comes directly from the industrial sector, one third are public funds intended to promote the teaching of mechanical engineering, while one third comes from a combination of public funding and industrial participation. Adams stresses in this context that the Department of Mechanical Engineering is the strongest department at TUM with regard to DFG funding, and currently has two collaborative research centres.
The History of the Department

Fundamental Research vs. Applied Research

1895 The Dispute Between Theoreticians and Practitioners

When professors of German higher education institutions, including the well-known cinematographer and mechanical engineer Franz Reuleaux – the academic teacher of Carl von Linde – visited the World Exhibition in Chicago in 1893, they were presented with the USA as a forerunner in technical sciences. The German higher education teachers visited the large machine and electrical technology laboratories and sat in on teaching units with demonstrations and experiments. They took these impressions back to Germany with them, and in 1895, together with the Association of German Engineers, (Verein Deutscher Ingenieure, or VDI), they wrote the ‘Aachen resolutions’.

In these resolutions, the professors of mechanical engineering demanded the construction of modern laboratories and a practical orientation in teaching and study. The basic subjects such as mathematics should be downgraded to auxiliary sciences. According to the authors of the resolutions, the teaching at the technical universities was too theoretical. Young engineers received extensive tuition in mathematics, while experiments and practical tests were a rarity. The German mathematicians resisted these demands. They stressed the importance of mathematics as a basic science and warned against making research and teaching too application-oriented and superficial.

Members of the Munich Technical University also got involved. At that time, the Department of Mechanical Engineering has its own machine laboratory. Carl von Linde had established the laboratory in 1875, around 20 years earlier than at other technical universities in Germany. Linde had taken on the idea from the ETH Zürich, separating the teaching of mechanical engineering from machine construction and dividing the teaching into descriptive and theoretical mechanical engineering. While descriptive teaching overlapped with some areas of machine construction, the theoretical teaching of mechanical engineering comprised three focal content areas – kinematics, engines and mechanical heat theory. With this approach, Linde created the precursors of kinematics and hydraulics, refrigeration technology and thermodynamics as subjects.

At the time of the dispute between theoreticians and practitioners at the Technical University of Munich, the teaching of mathematics was also adjusted to the needs of the engineers. The university was therefore following a path of beneficial compromise and was able to go some way to meeting the demands of the ‘Aachen resolutions’.

In 1895, mechanical engineer Egbert von Hoyer was made Director of the Technical University of Munich. While he was not a radical defender of the rights of the practitioners, he did commit to increasing the practical element in the teaching programme in Munich. Walther von Dyck, Professor of Mathematics at the Technical University of Munich, was outraged: ‘The mere suspicion that someone wishes to teach more than simply pure practical applications is sufficient to severely impair our mission.’ Together with mathematicians from other technical universities, as well as mathematics-oriented engineers, he did all he could to convince the ‘practitioners’ of the benefits of a basic education in mathematics. He succeeded in retaining mathematics as a basic science in mechanical engineering.

The dispute flared up again when during the 1898/1899 university year, technical physics was introduced as a subject in the general department. Rudolf Diesel expressed his admiration for the idea: ‘What a wonderful, new field; that has attracted too little attention to date’. The development was not met with much appreciation by mechanical engineering professors Paul von Lossow and Otto von Grove. In their view, the technical departments alone should be responsible for educating engineers who would later work in the industrial sector.

The dispute between theoreticians and practitioners died down at the turn of the century. Both sides were given the right to award doctorates. Also, after 1895, the laboratories were made subordinate to the theoretical mechanical engineering faculty. In this way, the position of the theoreticians was strengthened instead of that of the practitioners as had been expected.
The History of the Department

2018 Consolidation of Fundamental Research

In 2018, the subject is no longer disputed along such fundamental lines. The practical element has been established in teaching, although the question of how much mathematics is necessary as a minimum has still not been finally resolved today – particularly with a view to the reduced teaching plans as part of the eight-year grammar school syllabus. In research, the relationship between fundamental research and applied research has been subject to strong fluctuations over the decades. In general – and here, the five professors interviewed agree – the excellence initiative has led to a situation in which the reputation of fundamental research has improved and today, more research is being conducted on fundamental topics.

Lienkamp and Adams stress that the actual question should be how the department or the university overall should react to these new demands of increasing interdisciplinarity. Should it be left to the commitment of the individual researcher and their networking skills, or should new structures be created?

Currently, we are too strong in the field of application research. But this is subject to cycles and it will change again. Prof. Werner

2018 Consolidation of Fundamental Research

However, what exactly is fundamental research? Adams explains that fundamental research deals above all with the development of mathematical and physical simulation models, while applied research tends to focus on experiments. Wachtmeister puts it in a similar, albeit less abstract, way. In his sector, he says, fundamental research tends to deal with mechanics, thermodynamics, etc., while applied research looks at gears, production technology and engines, whereby the five professors regard the polarising comparison as being problematic and possibly no longer in keeping with the times. The collaboration between application-oriented researchers and researchers who tend to prefer fundamental research is necessary, he claims, in order to develop and realise new ideas – in the ideal scenario in an interdisciplinary manner and beyond department boundaries.

Research by our chair is up to 90 percent application-oriented. However, the tendency is moving very strongly towards fundamental research, including for mechanical engineering. Prof. Wachtmeister

Not everyone can conduct fundamental research. But when the applied researchers collaborate with fundamental researchers, new results emerge. That’s our opportunity in mechanical engineering, since we have the people who understand the application. Prof. Adams

Currently, we are too strong in the field of application research. But this is subject to cycles and it will change again. Prof. Werner

Lienkamp and Adams stress that the actual question should be how the department or the university overall should react to these new demands of increasing interdisciplinarity. Should it be left to the commitment of the individual researcher and their networking skills, or should new structures be created?
The Influence of Politics

1954 The Establishment of Air and Space Travel at the Department

There are countless examples of the influence of politics and society on research at the Technical University of Munich in its 150-year-old history. The creation of the Institute for Aviation and Astronautics after the Second World War is one.

In 1954, Julius Krauß received the professorship for airplane construction, which was associated with an institute for lightweight construction and aviation technology. Krauß had already been Professor Ordinarius for aircraft construction at the THM from 1942 to 1945. Without political decisions being made at the highest level – the Federal Minister for Special Affairs at the time, and later Minister of Defence, Franz Josef Strauß, was an enthusiastic amateur pilot – the establishment of the professorial chair would not have been possible.

At first, the preconditions for the creation of such a research focus appeared unfavourable. While before and during the Second World War, there had already been aviation research at THM, it was forced to close at the end of the war following pressure by the Allies. In 1950, the Bavarian federal state government had already begun first discussions with the Allies regarding the resumption of aviation research. The German federal government was also highly interested in developing its own aviation and astronautics industry and research. Here, the key player was Franz Josef Strauß. The passionate pilot was particularly committed to re-establishing the aviation industry and aviation research, and ensured that this branch industry and research was located in Bavaria, specifically in and around Munich.

Finally, on 23 October 1954, the ‘Paris Agreements’ were signed, which brought the Allied occupation status in the Federal Republic of Germany to an end. Now, German research could again participate in national and international aviation and astronautics projects. The reaction of the THM was immediate; that same year, Krauß was awarded the professorship for aircraft construction.

In the years that followed, Munich became a centre for aviation and astronautics. Strauß consciously pursued technology- and industry-oriented policies. He persuaded the entrepreneur Ludwig Bölkow to relocate his company, Bölkow Entwicklungen KG, from Stuttgart to Ottobrunn near Munich, which he did in 1958. In 1961, the analysis and test facility of the German Federal Ministry of Defence (IABG) was founded in Ottobrunn. In 1963, a division at the Max Planck Institute for Physics and Astrophysics was turned into a separate sub-institute – the Max Planck Institute for Extraterrestrial Physics – and one year later was moved to Garching.

At this point in time, the professorial chair for aircraft construction was further expanded – supported by the aircraft industry companies. In Ernst Schmid, who in 1952 became Professor for Theoretical Mechanical Engineering and Technical Thermodynamics, the THM already had an expert in combustion processes in aircraft engines and temperature measurement at high flying speeds. In 1957, Erich Truckenbrodt, who had formerly been the head of the aerodynamic division of the aviation company Heinkel, was brought to the department. Shortly after his arrival, he had three new wind channels built for aerodynamics tests. The scientific council at the THM recognised the new opportunities presented by the political developments, and suggested that a professorial chair for astronautics should be established. Truckenbrodt, who at that time was the dean of the faculty, then succeeded in having an institute for aviation and astronautics technology established at the department, which traditionally was not involved in aviation. He was supported by the CSU in his endeavour, in order to create a link between the Bavarian aviation and astronautics industry with science. Now, Munich was the fourth German federal higher education centre for aviation and astronautics, alongside Aachen, Braunschweig and Stuttgart.

Just a short time later, the professorial chairs of the institute were given complex research tasks. Between 1965 and 1970, the chair researched aircraft engines on behalf of the Federal Ministry of Defence, on flat engines with deflection combustion chambers for a planned VTOL aircraft. Research contracts were also received from other countries, from the Research and Technology Agency (RTA), a sub-organisation of the NATO Military Committee. In this way, under the aegis of Truckenbrodt, important numerical methods for transient and stationary flow processes were researched, as were hypersonic flows, which were of great importance to the astronautics projects that were just beginning in the Federal Republic at that time.
The History of the Department

2018 Politics and the Future of Mobility

Science does not occur in a vacuum. Politics, which is designed to define the guiderails of social activity, sets the general direction. Here, higher education institutions during the National Socialist period, with their inhumane approach, are a negative example. Like the example of aviation and astronautics described above, new fields of research can be quickly established under the influence of politics. Sometimes, however, politics reacts in unforeseeable ways. In 2007, for example, the professorial chair for nuclear technology was established. At that time, power generation through nuclear power stations was still considered to be future-oriented technology, which would make an important contribution to securing energy supplies in Germany. In 2011, in the wake of the Fukushima catastrophe, the German federal government decided to phase out nuclear energy.

Currently, a question about the future is again under discussion: the issue of the future of mobility. Is the combustion engine here to stay, or does the future belong to the electric engine? In the view of Wachtmeister and Lienkamp, here, the influence of politics over the department can be clearly felt. The chair for vehicle technology under Lienkamp, with its focus on electromobility, is enjoying an upturn in its fortunes. During the 13 years (four in industry, nine at the TUM) in which Leinkamp has been working on the topic, electromobility has been through some difficult times. ‘Now, the subject has really taken off!’ he says. However, unexpectedly, and contrary to what the politicians have been saying, the level of state funding for conducting research into the combustion engine has been raised recently rather than decreased.

Colleagues may be asked for political advice, but even so, science doesn’t play a key role, either in the decision against the use of nuclear energy or when it comes to whether or not we should only drive with batteries in the future. We have to adjust to that fact. Prof. Adams

The combustion engine can be a component for the mobility of the future. With new fuels produced from regenerative energy, the combustion engine will contribute to saving CO₂ Prof. Wachtmeister

With regard to the issue of what mobility will look like in the future, there is agreement in part between the professorial chairs. For the years to come, they forecast that both technologies will be used alongside each other. The statement that the combustion engine has a future (total energy balance, CO₂-neutral fuels, the mathematical impossibility of e-mobility that covers all requirements) contrasts with the claim that the use of the combustion engine will come to an end in the foreseeable future (total energy balance, new battery technology, local emission elimination, properly functioning infrastructure).

Perhaps here, politics will have the final word. However, there is one further influential factor that cannot be calculated: the consumer. As was the case with digital cameras or flat screens, things can change very quickly.

The subject of electromobility has now really taken off. But we’ve also been through difficult times with regard to electromobility. Prof. Lienkamp
Selected Highlights 2017

Geothermal drilling site in Unterhaching
The Department of Mechanical Engineering Opened an ‘Additive Manufacturing Cluster’

Additive manufacturing holds a diverse range of opportunities for mechanical engineering and the Technical University of Munich. In recognition of this potential, the ‘TUM Mechanical Engineering Additive Manufacturing Cluster’ was launched in September 2017, with support from Professor Michael F. Zaeh, the Head of the Institute of Machine Tools and Industrial Management. The cluster offers a platform for discussion that allows participants to pool and share their knowledge and equipment. Everyone is talking about additive manufacturing. We hear about new process innovations and applications almost every day. The Department of Mechanical Engineering has been actively participating in research into additive manufacturing processes for several years.

Together, We Can Achieve More!
The spectrum of existing methods of additive manufacturing is so diverse that it cannot be fully mastered by a single department. The ‘Additive Manufacturing Cluster’ was therefore launched in autumn 2017 as a platform for the various chairs of the Department of Mechanical Engineering to share their experience, ideas, equipment, and project findings. The response was overwhelming. On 22nd September 2017, 31 members of the department attended a total of 15 presentations and engaged in an enthusiastic discussion about the future of additive manufacturing. Interest in this platform had not wavered by the second round of seminars on 26th January 2018. Accordingly, it was decided at the end of January that the activities of the ‘Additive Manufacturing Cluster’ should be intensified. In future, department-wide cluster meetings will be held three times a year. The meeting in the first quarter of each year will be organized as an industrial colloquium, allowing the department to discuss their work with industry representatives.

From Q3 2018 onwards, interested parties will also be able to find information about the participating departments and their additive manufacturing equipment on the cluster webpage.

**Life Sciences, Aerospace, Manufacturing Processes**
The department already has a significant breadth and depth of experience. Three subfields of additive manufacturing have been identified: life sciences, aerospace, manufacturing processes. For example, the Department of Aerospace Engineering has developed its own universal 3D-printing platform that combines three different additive manufacturing techniques. The Department of Medical Engineering studied the production of ‘medical grade’ polymer materials by additive manufacturing. The research performed by this department sparked off a start-up company for manufacturing high-tech medical products. The Chair of Carbon Composites took the research into composite materials further by developing a series of novel approaches for uniform materials testing. The Institute of Machine Tools and Industrial Management (iwb) focuses on researching the manufacturing processes themselves. Since 2017, the iwb has expanded its competencies in the area of directed energy deposition processes, and is now exploring wire and arc-based additive manufacturing, as well as existing powder-bed approaches. Wire and arc additive manufacturing is characterized by fast build speeds.

**Favourable Conditions**
In the future, the cluster hopes to act as a catalyst for thematically innovative applications by fostering collaboration between two or more departments. At the iwb, an additive manufacturing laboratory spanning over 100 square metres is currently under construction. This laboratory will offer excellent infrastructure for the iwb and other bodies of the Department of Mechanical Engineering.

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The DFG-funded Collaborative Research Center (CRC) 768 ‘Managing Cycles in Innovation Processes’ is currently in the 10th of 12 funded years. It is based on the collaboration of Technical University and Ludwig-Maximilians-University Munich. The CRC 768 involves the following institutes of the Department of Mechanical Engineering: Institute of Automation and Information Systems, Institute of Product Development, Institute of Machine Tools and Industrial Management, and Chair of Automatic Control. The SFB 768 provides methods and models to manage cyclic innovation processes in an interdisciplinary way, including technical, economic and social perspectives.

The focus of the SFB 768 is on the market area of combining products and services to so-called product service systems (PPS). Managing and shaping innovations in PPS under consideration of cyclic influences is the objective of the SFB 768, aiming to support German companies to evolve their position in the market with methods and domain-spanning coupled models.

In 2017, an industrial colloquium was successfully organized with top-class representatives from globally active companies to discuss and mutually enrich ideas within the interactive workshops; Inconsistency Management, Stakeholder Integration, Knowledge Management and Change Management. The transfer of research results to industry and the transfer of industry expertise to academia was a great benefit for all participants. Additionally, the event’s participants experienced substantiated speeches from different industry domains within the context of PPS and Cyber-Physical Production Systems (CPPS), moderated discussions and an atmospheric get together.

The year 2017 was very fruitful for CRC768: the massive open online course (MOOC) was launched, as well as the first prototype of a publicly accessible platform, called ‘Gestaltenplattform’. This platform collects, recaptures and presents research results of the CRC768 over the last 10 years, to benefit closer cooperation and exchange between industry and science.

To achieve holistic management of innovation processes, the perspective has been extended to a socio-technical view. In seventeen sub-projects from mechanical engineering, economics, business informatics, psychology and sociology, a unique interdisciplinary research perspective on innovation processes is developed and is being continuously strengthened. Within the transfer projects, the research results are validated using real industry scenarios.
and valuable feedback from domain experts is brought back to academia.

By transferring the knowledge gained and findings to industry – e.g. through transfer projects, workshops or the industry colloquium mentioned above – managers and decision makers are enabled to find the best available path in the often confusing landscape of possible decisions between technology, organization and qualification.

Thus, the SFB 768 offers companies effective concepts to manage the innovation cycles of their systems and PPS.

To integrate students into the multidisciplinary research field and enable participants to understand the mechanisms behind innovations and manage the interdependencies in a cooperative interdisciplinary way, the interdisciplinary lecture series ‘Managing Innovations’ was offered, supported by an online channel with selected training sessions.

www.sfb768.de
SFB TRR 40: Technological Foundations for the Design of Thermally and Mechanically Highly Loaded Components of Future Space Transportation Systems

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 an increase in efficiency in 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 developed 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 TRR 40 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.

Contact

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Instantaneous snapshots of a nitrogen jet in hydrogen: (a) Temperature; (b) Vapor fraction on a molar basis; (c) Hydrogen density; (d) Relative difference in density
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. Shock waves are discontinuities in the macroscopic fluid state that can lead to extreme temperatures, pressures and concentrations of energy. A classic example of the generation of shock waves is the supersonic boom of an aircraft or the pressure wave originating from an explosion.

Funded by the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation program with an Advanced Grant for Prof. Adams, in this project we are developing numerical methods that are capable of predicting multi-phase shock wave interactions and are continuously optimizing our software framework for the latest high-performance computing architectures. Our mission is to improve the understanding of complex physical phenomena with the help of numerical tools. As an example, we investigate the underlying mechanisms of applications such as kidney-stone lithotripsy, which ultimately is the fundamental problem of gas-bubble collapse impact on interfaces and biomaterials. With a detailed knowledge of the physics, we aim to help to improve treatments in cancer therapy or drug delivery by harnessing the enormous potential of shock wave-induced interactions someday. We continuously develop and improve our numerical methods and computer capabilities and offer our simulation framework to the public. Our research code ‘ALPACA’ is available under open-source license (www.aer.mw.tum.de/abteilungen/nanoshock). Interestingly, solving the inviscid and per se unstable Euler equations using spatial schemes with increasingly high order is subject to new challenges. Due to the fact that numerical dissipation no longer suppresses the effect of floating-point inaccuracies, symmetric test cases like an implosion problem or the Rayleigh-Taylor instability tend to lose symmetry. We have improved our numerical algorithms and actual implementations to ensure perfect symmetry of low-dissipative test problems.

* 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).
Selected Highlights 2017

Communication Activities


Master’s Theses


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In 2017 TUM researchers, jointly with their project partners from industry and academia, successfully conducted the first flight campaign of the SAGITTA technology demonstrator. During two flights in South Africa the flying testbed showed its safe operation in flight. Multiple technologies of five TUM institutes were on board this aircraft. The aircraft manufacturer Airbus Defence & Space initiated its open innovation initiative SAGITTA in 2010. Sagitta, meaning arrow in latin, signifies the target air vehicle configuration, which was designed exactly like the tip of an arrow (diamond wing). In very close cooperation between industry and multiple research institutes, from DLR, the University of the German Armed Forces, the Technische Hochschule Ingolstadt as well as the Technical Universities of Chemnitz and Munich, are jointly developing technologies for future unmanned air vehicles (UAV). As part of the project the individual technologies were integrated and tested for their applicability on the flying testbed. Within TUM four institutes and one TUM-IAS Focus Group contributed to the project:

**Institute of Aircraft Design**
Besides the overall aircraft design of novel UAVs with low wing span, novel flight control devices as well as novel propulsion integration and control concepts were in the focus of research. New means of controlling the air vehicle, such as thrust vectoring techniques, as well as novel active flap systems, are key enablers for such diamond-shaped aircraft. In close cooperation with the Institute for Aerodynamics and Fluid Mechanics a radical new split flap system for the wing tip has been developed, promising increased efficiencies and better performance. This flap system has already been tested during the first flights of Sagitta.

**Institute of Aerodynamics and Fluid Mechanics**
Diamond shape wings with a high leading edge sweep show specific flow phenomena, such as separated leading edge vortices for example. A better understanding of such flow characteristics as well as methods to actively effect those flow conditions were in the focus of research at the institute. For the flying testbed the institute was responsible for all aerodynamic data and windtunnel measurements, amounting to more than 15,000 datapoints for multiple variants of the configuration.
Institute of Lightweight Structures
Flaps and movable devices of aircraft show gaps and discontinuities, which result in additional drag and noise among other effects. The design, manufacturing and testing of flexible, shape-adaptive structures were at the center of research at the Institute for Lightweight Structures, to close the gaps and increase the overall efficiency of such systems.

Institute of Flight System Dynamics together with TUM-IAS Focus Group ‘Aircraft Stability and Control’:
One key challenge for UAV is to ensure a safe flight, as there is no pilot on board who could react to unexpected behavior due to system failures, external disturbances (turbulence, gusts) or model errors. Therefore, the Institute of Flight System Dynamics together with the TUM-IAS Focus Group ‘Aircraft Stability and Control’ developed an innovative autoflight system (AFS) for SAGITTA which enables fully automatic flight missions from take-off to standstill after landing. Since the novel aircraft configuration had never been flown before, it was a major design driver for the AFS to cope with the widest possible spectrum of model uncertainties. The researchers were rewarded with extremely successful flight tests. Both flights of SAGITTA could be accomplished fully automatically and demonstrated excellent flying characteristics.

Besides the successful flight campaign a large amount of expertise as well as conference publications and journal articles have been provided to the public domain. With the return of the demonstrator to Germany, the researchers are eager to extract more valuable data from the successful flights to further proceed in the research on UAVs.

Contact

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Geothermal-Alliance Bavaria (GAB)

Funded by the Bavarian State Ministry for Education, Science and the Arts and coordinated by the TUM School of Engineering, three major universities in Bavaria have joined forces in the Geothermal-Alliance Bavaria (GAB): the Technical University of Munich, the Friedrich-Alexander University Erlangen-Nuremberg and the University of Bayreuth. The aim of the project is to push research in the field of geothermal energy on a variety of scientific fields, such as geology, chemistry, thermal process engineering and electrical engineering with the ultimate goal of strengthening the use of deep geothermal energy as a domestic energy source.

To phase out nuclear and fossil-fuel energy, alternative ways of providing district heating and electricity have to be explored. In the molasse basin of southern Bavaria, the conditions for using deep geothermal energy reservoirs as a domestic and reliable energy source are very favorable. To access the reservoir and extract the thermal energy efficiently and economically, a variety of research questions need to be addressed.

The project is organized in five sub-projects, designed in a holistic approach to cover the fields of geothermal energy research as completely as possible.

The GAB partners focus on the following research subjects:
- the design of efficient and flexible power plants;
- the development and implementation of monitoring tools for geothermal power plants;
- to improve the understanding of deep geothermal reservoirs in order to maximize the success rate in exploration;
- to increase the reliability of the thermal water cycle; and
- to better understand the geological requirements for petrothermal reservoirs in Northern Bavaria and investigate their potential.

In addition, the joint Master’s program ‘GeoThermie/GeoEnergie’ commenced in WS2017/18 at the Technical University of Munich and the Friedrich-Alexander University of Erlangen-Nuremberg.

www.mse.tum.de/gab

Contact

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On September 15, 2017, the glider prototype Mü 31 successfully carried out its maiden flight. It was built by students of the academic fliers’ club Akaflieg Munich at the TUM research campus near Garching. Akaflieg Munich is an association of students from all three Munich universities who share their common passion for aviation. Founded in 1924 with the motto ‘Design, build and fly’, the Akaflieg Munich is the eldest student group at TUM. More than 30 aircraft prototypes have been designed, of which two thirds have flown successfully. Nowadays, five prototypes are still in regular use at the club’s airfield close to Königsdorf. The objective of the students’ activities is to combine theoretical knowledge from lectures with practical experience in the design and manufacture of aircraft. In the recent project, more than 150 students were involved in research, design and manufacturing activities. Currently, approximately 40 students are actively working on different projects. The design of the recent glider Mü 31 aims at drag reduction by optimization of the wing-fuselage transition. It is based on the series aircraft ASW 27, has a 15 m span and was modified by the students according to the results of theoretical aerodynamic studies and wind tunnel tests. The implemented adaptations of the airfoils as well as the geometry of wing and fuselage yield increased performance by reducing induced and interference drag. The design and the construction of the inner wing section and the fuselage have been done completely by the students. Manufacture of the first parts for the load test structures started in 2008. Different load tests were required by the certification authority (LBA) to enable full certification according to the JAR-22 requirements. The actual prototype was built from 2012 onwards and performed its first flight in September 2017. To the great relief and joy of the team, the Mü 31 flew without difficulty. However, this is not the end of the project. The next steps will involve a vibration test and different flight tests. They are necessary to show compliance of the flying and handling characteristics of the aircraft with the requirements. As soon as all requirements are fulfilled, the prototype will be fully certified and included in flight operations.

Before the Mü 31, the Akaflieg designed and built the Mü 30 ‘Schlacro’, which is an aerobatic and towing aircraft, that first flew in the current configuration in 2007. The certification process was completed in 2012 and the aircraft is nowadays regularly used in flight operations. Also, the follow-on project has already been defined: The students want to build a high performance aerobatic glider for the ‘Unlimited’ competition class. They are currently working on the design and want to start manufacturing the first parts this year.
‘WARR’ (in German, short for Scientific Workgroup for Rocketry and Spaceflight) is a scientific workgroup based at the Technical University of Munich (TUM). It was founded by students in 1962. Ever since, it has given students the opportunity to gain hands-on experience in space technology projects. Today, WARR consists of four main project groups. The first group is WARR Rocketry. In December 2017 the students successfully carried out a two-week test campaign on the testing grounds of the German centre for aviation and astronautics (DLR) in Lampoldshausen. The goal was to verify their self-developed engine ‘Battleship’, a hybrid rocket engine that will be used for the planned height research rocket WARR Ex-3, which is intended to reach a maximum flight altitude of 30 km and triple the speed of sound.

WARR Satellite Technology, in cooperation with the Chair of Astronautics (LRT), develops a CubeSat satellite called MOVE-II. It was developed and built by more than 120 students over a period of two years. At the end of November 2017, the development finally came to an end. MOVE-II is ready for delivery and will be launched by a Falcon-9 rocket in 2018.

In early December 2017, the WARR Space Elevator Team participated at SPEC2017, an international competition in Mito, Japan. The so-called ‘one.third’ space elevator was by far the fastest climber in the competition and so the team won the SPEC2017 speed award.

WARR Hyperloop is also all about high speed. In August 2017, the team managed to win the SpaceX Hyperloop Pod Competition for the second time, with a brand new concept and design that went with a top speed of 324 km/h – the fastest speed ever reached by a Hyperloop pod. Already in January 2017, WARR Hyperloop had won prizes for ‘Fastest Pod’ and ‘Best Performance in Flight’ at the first Hyperloop Pod Competition.
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.
- 25% 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>2014</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
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<tr>
<td>Total</td>
<td>1,102</td>
<td>1,065</td>
<td>1,019</td>
<td>1,066</td>
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<td>Full Professors</td>
<td>29</td>
<td>30</td>
<td>29</td>
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<td>Associate Professors</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
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<tr>
<td>Scientific Staff</td>
<td>824</td>
<td>796</td>
<td>759</td>
<td>763</td>
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<tr>
<td>Non-scientific Staff</td>
<td>211</td>
<td>207</td>
<td>201</td>
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<tr>
<td>Apprentices</td>
<td>28</td>
<td>22</td>
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### Students

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<th>2014</th>
<th>2015</th>
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<tr>
<td>Total</td>
<td>5,726</td>
<td>5,620</td>
<td>5,447</td>
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<td>Bachelor</td>
<td>2,744</td>
<td>2,401</td>
<td>2,176</td>
<td>2,301</td>
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<tr>
<td>Freshmen per year</td>
<td>679</td>
<td>684</td>
<td>652</td>
<td>619</td>
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<tr>
<td>Graduations per year</td>
<td>593</td>
<td>802</td>
<td>542</td>
<td>481</td>
</tr>
<tr>
<td>Total Students</td>
<td>2,041</td>
<td>2,375</td>
<td>2,592</td>
<td>2,702</td>
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<tr>
<td>Master</td>
<td>838</td>
<td>1,028</td>
<td>965</td>
<td>894</td>
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<tr>
<td>Freshmen per year</td>
<td>532</td>
<td>626</td>
<td>589</td>
<td>763</td>
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<tr>
<td>Graduations per year</td>
<td>164</td>
<td>136</td>
<td>142</td>
<td>177</td>
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Additional categories include doctoral and exchange students and others

### Doctoral Programme

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<th>2017</th>
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<tr>
<td>Defenses</td>
<td>164</td>
<td>136</td>
<td>142</td>
<td>177</td>
</tr>
</tbody>
</table>

### Funding

<table>
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<th>2016</th>
<th>2017</th>
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<tr>
<td>State Budget</td>
<td>1,727,456 Euros</td>
<td>1,628,877 Euros</td>
<td>1,625,670 Euros</td>
<td>1,582,706 Euros</td>
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<tr>
<td>Additional Tuition Funds</td>
<td>1,914,375 Euros</td>
<td>1,913,690 Euros</td>
<td>1,785,204 Euros</td>
<td>1,869,155 Euros</td>
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<tr>
<td>State Positions</td>
<td>519</td>
<td>509</td>
<td>501</td>
<td>508</td>
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<tr>
<td>Acquired Research Funding</td>
<td>48,582,963 Euros</td>
<td>55,302,894 Euros</td>
<td>53,930,633 Euros</td>
<td>52,707,849 Euros</td>
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<tr>
<td></td>
<td>22,651,978 Euros</td>
<td>26,412,923 Euros</td>
<td>27,592,955 Euros</td>
<td>30,042,462 Euros</td>
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<tr>
<td></td>
<td>25,930,985 Euros</td>
<td>28,889,972 Euros</td>
<td>26,337,678 Euros</td>
<td>22,665,387 Euros</td>
</tr>
</tbody>
</table>
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.

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**Department Board of Management**

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.
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 (01.10.2017-30.09.2018), 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**

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Franziska Ochsenfarth
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Daniel Schneider
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Permanent Guests
(without voting rights)

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Dr. Helena Hashemi Farzaneh
(Deputy women’s representative)
helena.hashemi@tum.de

Annika Ulherr
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Chong Wang
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Richard Kern
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Cornelia Härtlina
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Women’s Representative

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frauenbeauftragte@mw.tum.de
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**
The Department Management assists the Dean in academic self-administration and the coordination of administrative processes in the department.

Dr. Till von Feilitzsch
Dr. Thomas Wagner

The following units are assigned to the Department Management:

**Assistance to the Dean**
This unit 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

**Information Technology**
This unit supports central services staff regarding IT matters.

Robert Klopp, IT Administration

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

Cornelia Kirsten, Administration

**Quality Management and Controlling**
The section ‘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
Antje Asbach, Databases
Cornelia Härtling, Budget Planning
and Reporting System
Stephan Hartl, Accounting
Atiye Korkmaz, on parental leave

**Academic Affairs**
The section ‘Academic Affairs’ deals with academic procedures such as honorary doctorates and professorships, lectureships, awards and prizes as well as departmental events. In addition, this section assists the Dean in building management and in granting permission in relation to such management.

Dieter Grimm, Section Head
Central Teaching Unit
This section 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. 83 f.

Dr. Birgit Spielmann, Section Head
Franziska Glasl, Deputy
Tamaris Pohl, Center of Key Competencies
Susanne Lösel, Center of Key Competencies
Luise Poetzsche, Center of Key Competencies
Amelie Zauner, Center of Key Competencies
Po Sang Lam, Graduate Center
Stefanija Stiebre, Graduate Center

Student Services
This section is the central information office for students and potential students regarding degrees, degree courses abroad and degree course organization. It also administers and organizes degree courses 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 and organization.

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

Examination Affairs
The section ‘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
Maria Schottenheim
Raffaella Zuber
Daniela Bösl, TUMonline Examination Administration

Master’s Degree
Examination Board
Anett Geckert, Secretary to the Examination Board
Claudia Matheis
Romy Scholz

Internships in Industry
Lisa Lauterbach

Information Technology
Information Technology at the Department of Mechanical Engineering designs and documents central IT systems of the department. It is the interface with the external services provided by the TUM. The Information Officer (IO) coordinates the use of IT in the department and advises the institutes on the development of an efficient IT infrastructure. Campus-wide IT systems are coordinated by the CIO/IO board.

N.N., IO of the Department
Nicole Siegmund, Deputy
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 2017

300 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 some of the student groups at the department presented their work and their successes in designing, building and driving cars, planes, space rockets and satellites.

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 newly introduced strategy of the department ‘MW 2030’ (see photo). The strategy covers three areas: teaching, research and personnel. One step already made is to start much earlier in creating new professorships and also new ways to achieve that.

77 of the invited doctorate 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.

Prof. Lüth was awarded the newly-created Egbert von Hoyer medal for outstanding merit at the department in honour of his achievements as former Dean.
### Honors Awarded During the Department Day

#### Doctorate Prizes Awarded

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<tr>
<th>Prize Name</th>
<th>Recipient</th>
<th>Dissertation</th>
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<tr>
<td>Rudolf Schmidt-Burkhardt Memorial Prize</td>
<td>Dr.-Ing. Christoph Meier</td>
<td>‘Geometrically Exact Finite Element Formulations for Slender Beams and Their Contact Interaction’</td>
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<td>Department Prize</td>
<td>Dr.-Ing. Thomas Emmert</td>
<td>‘State Space Modeling of Thermoacoustic Systems with Application to Intrinsic Feedback’</td>
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<td>WITTENSTEIN Prize</td>
<td>Dr.-Ing. Benedikt Schott</td>
<td>‘Stabilized Cut Finite Element Methods for Complex Interface Coupled Flow Problems’</td>
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<td>ARBURG Prize</td>
<td>Dr. rer. nat. Andreas Schmideder</td>
<td>‘Kontinuierliche Prozessführung in miniaturisierten Rührkesselreaktoren’</td>
</tr>
<tr>
<td>RENK Propulsion Technology Prize</td>
<td>Dr.-Ing. Thomas Lohner</td>
<td>‘Berechnung von TEHD Kontakten und Einlaufverhalten von Verzahnungen’</td>
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<tr>
<td>Willy Messerschmitt Prize</td>
<td>Dr.-Ing. Andreas Hein</td>
<td>‘Heritage Technologies in Space Programs – Assessment Methodology and Statistical Analysis’</td>
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<tr>
<td>Manfred Hirschvogel Prize</td>
<td>Dr.-Ing. Christian Gold</td>
<td>‘Modeling of Take-Over Performance in Highly Automated Vehicle Guidance’</td>
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#### Study Prizes Awarded

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<tr>
<th>Prize Name</th>
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<th>Dissertation</th>
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</thead>
<tbody>
<tr>
<td>Department Prize – Best Degree</td>
<td>Johannes Ellinger, M.Sc.</td>
<td>Best overall grade of all Master’s degrees</td>
</tr>
<tr>
<td>Department Prizes – Excellent Degrees</td>
<td>Alexander Heilmeyer, M.Sc.</td>
<td>Second-best overall grade</td>
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<td>Robert Scholz, M.Sc.</td>
<td>Third-best overall grade</td>
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<td></td>
<td>Dominik Meier, M.Sc.</td>
<td>Fourth-best overall grade</td>
</tr>
<tr>
<td>ARBURG Prize</td>
<td>Benjamin Winkeljann, M.Sc.</td>
<td>Master’s thesis ‘Friction and Wear on the Cornea-Contact Lens-Interface Lubricated with Biopolymers’</td>
</tr>
<tr>
<td>SGL Group Award</td>
<td>Georg Siroky, M.Sc.</td>
<td>Master’s thesis ‘Coupled Atomistic-Continuum Models for Strength Prediction in Fiber-Polymer Composites’</td>
</tr>
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</table>
Ranking Results

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 8 in Europe) and in second position within Germany.

Placement Worldwide for Mechanical Engineering: TUM
Mechanical Engineering: 35 (2017)

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.

http://ranking.zeit.de/che2016

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 17) and now holds the top position in Germany.

Placement Mechanical Engineering worldwide:
Mechanical Engineering of the TUM: 37 (2017)
At the TUM Department of 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 at a constant rate. 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, within one decade, this number increased by more than a factor of five. This indicates that research at the department is of tremendous interest to fellow scientists all over the world.
CubeSat MOVE-II was developed and built by more than 120 students over a period of two years.
Divisions of the Department of Mechanical Engineering
Aerospace

The entire chain from concepts of operations down to system and component testing in the aerospace field is mapped at the Department of Mechanical Engineering – everything from overall aircraft design down to material and structural principles, propulsion and aerodynamics.

A hallmark of this research field is its integration in the excellent research environment in Munich featuring industrial partners such as Airbus, Airbus Helicopter, Airbus Defence & Space, MTU Aero Engines, IABG, Liebherr Aerospace, Kayser-Threde as well as Munich Aerospace, Universität der Bundeswehr (University of the German Armed Forces) and the DLR.

First Flight of SAGITTA Technology Demonstrator in South Africa

In 2010 Airbus Defence & Space started its open innovation project SAGITTA. In a joint research cooperation scientists of multiple universities, DLR and industry have teamed up to progress technologies for unmanned air vehicles. After seven years the team carried out the first flight of SAGITTA at the Overberg test range in South Africa. Five institutes of Technical University of Munich contributed to the demonstrator. Within the overall project TUM researchers worked on overall design aspects, detailed aerodynamic phenomena, novel flight control devices, robust flight control algorithms and systems, the propulsion system and novel structural concepts. In both flights the air vehicle showed predicted behaviour and performed fully automated missions, including automated take-off and landing. The team showed its capability to handle even highly complex systems like the 3m span demonstrator in a collaborative environment. All partners are now looking forward to further exploit the capabilities that the demonstrator is able to provide as a test platform.

Collaborative Research Center ‘Fundamental Technologies for the Development of Future Space-Transport-System Components under High Thermal and Mechanical Loads’

The fourth biannual summer program of the TRR 40 Collaborative Research Center ‘Fundamental Technologies for the Development of Future Space-Transport-System Components under High Thermal and Mechanical Loads’ was held during the month of August 2017 at the Technical University of Munich under the auspices of the German Research Foundation (DFG). Fifteen research groups have been created by researchers of the TRR 40 and visiting researchers, based on proposals received from China, France, Switzerland, India, Japan, Canada and the USA. In an intense four-week period of activity, these groups drove forward their projects and rigorously scrutinized their process with intermediate and final project reviews. Project work was accompanied by lectures and special subjects of interest to the research delivered by distinguished lecturers:

- Dr. Philipp Tran, ArianeGroup, Paris, France
- Dr. Hendrik Riedmann, ArianeGroup, Munich, Germany
- Dr. Sergey Frolov, Semenov Institut, Russia

Subjects of the research projects were focused on the numerical prediction and experimental characterization of physically complex flows, injection, reacting flows, combustion instabilities and combustion modelling. Synergies have been created by exchanging simulation models and experimental techniques, making sophisticated computer codes and experimental facilities available and by intense exchange of scientific experience and knowledge. A thematic focus on simulations of the model combustion chamber in comparison with pre-existing experimental results provided for by the group of Prof. O. Haidn are part of the report series of 2017 followed by the individual presentation of the results of the respective participating groups.

www.aer.mw.tum.de
www.fsd.mw.tum.de
www.llb.mw.tum.de
www.lls.mw.tum.de

www.aer.mw.tum.de
www.lft.mw.tum.de
Aerospace

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

The Chair of Carbon Composites (LCC) 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 launch in March 2018.

To increase the performance of the rockets LCC 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 pressforming 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.

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.

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The CFRP-module with integrated sensors and measurement system is part of REXUS mission XXIII with a scheduled launch window in mid-March 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.

www.lcc.mw.tum.de
Automotive

The automotive field is one of the most important ones at the Department of Mechanical Engineering. Almost every institute is involved via a most diverse range of projects.

In addition to vehicle and usage concepts, particular emphasis is also placed on the powertrain, driver assistance systems as well as the use of new materials and the production process. One focal area is how to ensure the viability of individual transport through efficient vehicles in the face of increasing resource shortages. The Munich metropolitan area probably has the highest density of prestigious car manufacturers in the world, a very important factor for this field. Key scientific challenges lie in understanding combustion processes and the properties of materials.

Project QoStreet

Map and navigation services represent an indispensable foundation for many innovative applications in the vehicle. In addition to static road information such as traffic signs and traffic lights, dynamic events e.g. traffic jams and construction sites are assigned to the map data. Numerous background data can be processed by the vehicle and therefore support the optimization of the energy consumption or improve the active safety. The aim of the project ‘QoStreet’ is to develop and validate a method for the classification of the road surface based on smartphone sensory data. The surface type should be determined as well as the quality of the road. This is to be done with the help of smartphone sensor data, which were recorded in the course of numerous fleet tests at the Chair of Automotive Engineering. In particular, weather data in the context of the BMVI provide additional information, which are necessary in the classification process. The results can be used to increase driving safety and driving comfort.


Project IMAGinE

Within the Project IMAGinE – Intelligent maneuver automation – cooperative hazard avoidance in real time, the TUM researches together with automotive manufacturers, suppliers and scientific research institutes cooperative advanced driver assistance systems (ADAS). The research initiative is supported by the German Federal Ministry of Economics and Energy. The objective of the project IMAGinE is the development of new ADAS which enable vehicles and infrastructure to cooperate with each other. Therefore, the exchange of information as well as the coordination and decision making between intelligent systems and drivers will be realized. The proof of concept will be demonstrated by six representative functions.

http://imagine-online.de

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Contact
A sustainable energy supply is one of the essential requirements for the future of our society. The goals of reducing CO₂ emissions, achieving cost effectiveness and societal acceptance make for a field fraught with controversy.

The Department of Mechanical Engineering has been a hotbed of research in energy technology and thermodynamics ever since the days of Carl von Linde and Wilhelm Nußelt. The department has a particularly excellent reputation in the areas of combustion technology and the development of very efficient power stations. Our research and teaching portfolio in renewable energy has been expanded considerably in recent years, e.g. through the new Institute of Wind Energy, although institutes covering biomass, geothermal and solar energy have existed for even longer.

CleanTechCampus Garching

The TUM Garching Campus with more than 15,000 students and 3,500 employees is already ranked among the biggest university locations in Germany. If the rapid growth of previous years continues, there has to be a realignment of the energy supply. In cooperation with the Chair of Renewable and Sustainable Energy Systems, the Centre for Sustainable Building, the research group ‘Control of Renewable Energy Systems’ and the ZAE Bayern, the Institute for Energy Systems develops holistically, sustainable and transferable energy concepts taking the Garching Campus as an example.

Wind Energy

The Wind Energy Institute works towards the goals of increasing the penetration of wind energy, reducing its cost and mitigating its impacts. Current on-going projects at the institute range from basic scientific investigations to the solution of application-oriented problems. An area of particularly active research is the modeling and understanding of wake interactions, which enables new smart ways of controlling wind farms for improved power capture and reduced loading. Wind tunnel tests conducted with scaled wind turbine models are used to validate simulation tools and to demonstrate control strategies prior to full-scale testing. Other activities at the institute span all main wind-energy-relevant scientific disciplines, including aerodynamics, structures, dynamics, materials and design, with a strong focus on multi-disciplinarity and a system-engineering point of view.

Energy Valley Bavaria – Flexible Power Stations

The ‘Energy Valley Bavaria’ project consists of an interdisciplinary team investigating the effects of the energy revolution on generation systems and electricity grids. Investigative research is carried out at the Institute of Thermodynamics on increasing the flexibility of gas turbines and analysis is carried out at the Institute of Energy Systems on the dynamic behaviour of steam generators. The results form the basis of dynamic process simulations which illustrate all the processes at work in power stations.

Contact

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<th>Coordinator</th>
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<td>Prof. Dr. Carlo Bottasso, Wind Energy</td>
<td>Prof. Dr.-Ing. Harald Klein, Plant and Process Technology</td>
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Materials

Materials make the manufacture of constituent parts possible, transmit forces, determine the efficiency levels of machines and the compatibility of medical implants. All three major materials categories, polymers/plastics, metals and ceramics as well as those derived from them, e.g. carbon composites and other composite materials, play a significant role in research and teaching at the department.

Key research areas include ultra-precise antennae which can be used in space for satellite navigation, manufacturing medical components in sterile environments for use in the human body or the automated manufacture of load-bearing vehicle or aircraft parts. The State Materials Testing Laboratory in Mechanical Engineering (part of the Bavarian government) is another highlight which illustrates how our wide-ranging material analyses enable deep insights into all solid materials and provide a natural interface to various branches of industry interested in the application of advanced materials based on their properties.

DeMAND ‘Dynamic aircraft MAterial property Database’

The DeMAND project was set up to carry out a mechanical material characterization program to deliver a dynamic material property data base for typical aircraft materials, with a special focus on seat and crash-absorbing structures of small aircraft. For a number of aluminum and steel alloys, fiber-reinforced polymer matrix composites and foam materials, dynamic tests will be carried out over a wide range of strain rates, ranging from quasi-static loading up to high strain rates of 500 s⁻¹. The project brings together renowned experts in the areas of test method development, static and dynamic testing of aircraft materials and structures as well as simulation and design of aeronautical crashworthiness structures. For each strain rate regime, the optimal test equipment was identified and is available within the consortium. The equipment ranges from standard universal testing machines (quasi-static loading) to special servo-hydraulic high speed testing machines (medium strain rates) to split-Hopkinson bars (high strain rate testing). This ensures the determination of high quality material data and complete stress-strain curves from static up to high strain rate loading, allowing the derivation of the strain rate dependent material behavior for all material properties needed for predictive crashworthiness simulations.

Funded by Horizon 2020
www.cleansky.eu

Residual stresses

Residual stresses and their redistribution may significantly affect the resulting material/component behavior during processing/fabrication and operating life. Particularly in components of thermomechanically processed alloys of complex microstructures, residual stresses act on various length scales. At elevated temperatures, the mechanisms governing the microstrain/microstress accumulation may significantly change, e.g. nickel-base superalloys exhibit a thermal activation of cube slip systems in addition to their octahedral slip systems. The interplay of these slip systems promotes the formation of Kear-Wilsdorf locks within the γ’-phase and results in a yield stress nearly not decreasing or often even increasing with increasing temperature (anomalous yielding effect).

In this context, research activities are focused on the evolution of the intergranular and interphase microstrains in different nickel-base superalloys (Inconel 718 and Haynes 282) during loading and unloading at room temperature and at elevated temperatures. Owing to the simultaneous accessibility of different crystallographic directions and
High Heat Flux Components for Future Fusion Reactors

In magnetically confined fusion plasmas, the hot plasma core is largely separated from the first wall. Nevertheless high-energy particles can escape from the confined plasma and collide with the surrounding wall. Additionally, electromagnetic radiation from the plasma reaches the wall material depositing substantial power. In the case of burning fusion plasma, the neutrons produced enter the wall material and alter its characteristics through lattice distortion and transmutation.

The research of the Plasma Materials Interaction Group is carried out at the Max Planck Institute for Plasma Physics. The group develops metal matrix composites and prepares mock-ups for plasma facing components for a future fusion reactor together with other European fusion laboratories. They are tested in the group’s high heat flux neutral beam facility with reactor relevant heat loads.

Supported by EUROfusion
www.euro-fusion.org

Thermally and mechanically loaded tensile specimen clamped in the Eulerian tensile testing machine mounted on the neutron diffractometer STRESS-SPEC. This setup allows to study of the evolution of intergranular and interphase micro-strains during macroscopic plastic deformation at elevated temperatures up to 800 °C. (Source: FRM II)

High heat flux component with tungsten fibre reinforced copper tube as cooling channel and tungsten armour (left). The actively water-cooled component was subjected to cyclic high heat flux tests surviving 300 pulses at 20 MW/m² for 10 s under conditions relevant to a future fusion reactor. During testing (centre; photograph taken in the visible spectral range) the component reaches thermal equilibrium after 5 s at surface temperatures of 1500 °C (right).

An accompanying rigorous characterization of microstructural aspects on different length scales is accomplished by light- and electronmicroscopy (SEM/ TEM), 3D-atomprobe tomography, small angle neutron scattering, as well as X-ray diffraction.
**Mechatronics**

- **Mechatronics** focuses on the analysis, design and construction of active systems enabled by the symbiotic interaction between mechanical components, actuators, sensors and computer control. The TUM Department of Mechanical Engineering hosts several experts dealing with a diversity of applications.

**SafetyNet – Train-wide Availability of Local Sensor Data**

Local feedback loops between sensors and corresponding actuators, e.g. between the speed sensor and the wheel slip control are state of the art in train control systems. The communication systems between local controllers and mechatronic train components ensure functionality in public transportation, containment of fault is mandatory since errors could have a catastrophic impact. Shortcomings of these local control systems are vulnerability against disturbances of local sensor data for instance caused by local slip. A train-wide model for time critical applications for example the speed control is missing. The aim of the project Safety Net is the examination of train-wide communication systems that tackle highest requirements regarding safety and real-time together with partners from industry.

[www.ais.mw.tum.de](http://www.ais.mw.tum.de)

**3D Printing**

In the field of 3D printing the Chair of Micro Technology and Medical Device Technology accompanies the further development of the ARBURG freeformer. Unlike in conventional additive manufacturing techniques, with ARBURG Plastic Freeforming (APF), qualified standard granulates are used. The goal is warpage-minimized manufacturing where tiny droplets build the parts on the basis of a process specific G-code generated from an STL file.

[www.mimed.mw.tum.de](http://www.mimed.mw.tum.de)

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**Contact**

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<th>Coordinator</th>
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<td>Prof. Dr.-Ing. Boris Lohmann, Automatic Control</td>
<td>Prof. Dr.-Ing. Veit Senner, Sport Equipment and Materials</td>
<td>Prof. Dr. Markus Zimmermann, Product Development and Lightweight Design</td>
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Medical Technology

Medical technology is one of the highest value generating sectors in Germany and across the world.

The highly interdisciplinary field of medical technology is represented in several chairs and numerous projects at the Department of Mechanical Engineering. In addition, there is an intensive exchange with clinical institutions, especially the Klinikum Rechts der Isar. For many years, the participating chairs have worked together successfully and with a sustained interest of the students in designing the Master's program in medical technology. Emphasis is placed on the development of medical mechatronic systems, medical materials, smart medical devices, cell-based medical technology and biomechanical simulations. The possibilities of additive manufacturing in medical technology also offer exciting perspectives. It can be used, for example, to adapt medical devices anatomically and biomechanically to individual patient needs or to implement highly function-integrated systems for minimally invasive surgical interventions. Life science was therefore established as a pillar of the activities of the newly founded Faculty Cluster Additive Manufacturing.

3D printer of the KUMOVIS spin-off for the production of medical plastic parts from the biocompatible high-performance polymer PEEK (polyether-ether-ketone). The system is characterized by a patented laminar air flow around the printed part, which allows an exact adjustment of the printing temperature up to 400 °C and clean room conditions as a basis for the production of medical products.

Multi-body simulation and FEM analysis to describe the biomechanical conditions in the spine and the intervertebral discs as a basis for the development of biomechanically and patient-individually adapted intervertebral disc implants.

Droplet-based Additive Manufacturing of Metal Parts

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 allows for cost-effective 3D-printing of aluminum parts without any intermediate steps.

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Process Engineering

Process engineering is a key technology for all production industries.

Process engineering at the Department of Mechanical Engineering is focused on thermal process and plant engineering, bioprocess and biochemical engineering, systems biotechnology and bioseparation engineering. The mission is to solve process engineering challenges of the future in an interdisciplinary environment and with respect to industry sectors such as chemistry, biotechnology, pharma and environmental engineering. Process engineering at the Department of Mechanical Engineering forms the engineering science core of the interdisciplinary TUM Research Center for Industrial Biotechnology with a pilot plant on an m3-scale operated in Garching.

Kopernikus – SynErgie: Synchronized and Energy Adaptive Production Technology for Flexible Alignment of Industrial Processes Towards Fluctuating Energy Supply

The central approach of the BMBF-funded Kopernikus project SynErgie is to adapt industrial production processes from several industry sectors to fluctuating energy supply from renewable sources. Thereby, energy costs as well as CO₂ supply can be lowered significantly within the next years. At the Institute of Plant and Process Technology the flexible operation of air separation plants (FlexASU) is investigated.

Gasfermentation: CO₂ and CO-rich Gases as Carbon Sources for the Production of Chemicals

The objective of this national collaborative research initiative funded by BMBF are new bioprocesses for the production of alcohols and low molecular-weight carbohydrates (monomers for polymerization) from CO₂/H₂ or CO-rich gases using metabolically engineered bacteria. The Institute of Biochemical Engineering works on the reaction engineering analysis of CO₂/H₂ and CO conversion with acetogenic bacteria and on the design and characterization of new bioreactor concepts for continuous gasfermentations.

SysBioTerp: An Integrated Systems Biology Platform for the Sustainable Production of Structurally Minimized Taxoid Bioactives

The project aims to construct an economically and ecologically efficient platform for the scalable production of taxoid natural products from renewable resources. In an interdisciplinary group of altogether eight partners (four coming from TUM) theoretical as well as experimental strategies are combined for a rapid technology transfer and an accelerated time-to-market scenario. The Systems Biotechnology group works on theoretical methods for the optimization of the production process as well as on the optimization of the cellular system. The Bioseparation Engineering group is focused on process design as well as on purification strategies for a continuous production process.

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Photobioreactors for studying the production of fuels and chemicals from CO₂ (photo: Tobias Hase, TUM)
Production and Logistics

Production technology is – in addition to the automotive industry – Germany’s top export and one of the pillars of the Department of Mechanical Engineering since its inception.

For a long time, special emphasis has been placed on integrating enhancements into the entire process chain, from the design phase to the customer, rather than considering individual stages in isolation. Closely related to this are fundamental research and application, such as the question of how to simulate and suppress oscillations in production machinery, how to implement models for optimization of the design and production process, or how new materials can be processed resource-efficiently. A sample of production technology highlights follows:

Increasing Electric Drive Efficiency by an Optimized Production Process

In order to convert electric into kinetic energy in an electric drive, magnetic fields must be generated. Therefore the magnetic properties of the electric drives’ main component, the so-called electrical sheet metal, are decisive for its efficiency. It has been shown, that the manufacturing process of the electrical sheet metal has a negative influence on its magnetic properties. This is mainly due to the residual stresses induced in each processing step. Especially when looking at the blanking process, the manufacturing parameters have a significant impact on the magnetic properties. Using optimized blanking parameters can decrease the losses and the electricity demand of an electric drive.

This work is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 218259799 and carried out in the research unit project – ‘FOR 1897 – Low-Loss Electrical Steel for Energy-Efficient Electrical Drives’.

SynErgie – Synchronized and Energy-adaptive Production Technology for Adapting Industrial Processes to a Fluctuating Energy Supply – Project Cluster Production Infrastructure

The SynErgie project, with its more than 50 partners, aims to create within the next ten years all technical and market requirements in line with legal and social aspects in order to effectively synchronize the energy demand of German industry with the volatile energy supply. SynErgie thus contributes to the cost-efficient realization of renewable energies and enables Germany to develop into an international leader for flexible industrial processes and technologies.

The project ‘SynErgie’ is funded by the Federal Ministry of Education and Research (BMBF). We would like to thank the BMBF for its excellent support. For more information, see www.kopernikus-projekte.de
Production and Logistics

Self-Configuring Automated Material Flow Systems

Material flow systems are mostly operated by an individual central control. As part of an interdisciplinary project the chairs AIS and fml modularized the hard and software to create autonomous modules which automatically configure transport interfaces and a material flow strategy. As a result of the common interdisciplinary project from the chair AIS and fml, the material flow system is easily convertible. Funded by the German Research Foundation (DFG) (GU 427/25-1, VO 937/24-1)

aComA

Within the cooperative project aComA, the institutes AIS and fml have been working on the development of a model-based approach dealing with the same modularity of the mechanical components as well as a layout-oriented editor to improve the software engineering of material flow systems. To improve the exchangeability between the mechanical components, an approach of automatic backwards compatible software has been developed based on the research field ‘clone detection’ from computer science. Funded by the Bavarian Research Foundation (BFS) (AZ-1098-13).

KobotAERGO – Adaptive Collaborative Robots as an Age-matching Companion for Ergonomic and Flexible Material Handling

Based on intelligent handling systems, so-called intelligent assist devices (IAD) or cobots, the research project developed an ergonomic support considering object size as well as user perception related adaptation. The aim was to enable people to cope with more complex handling processes more efficiently, effectively, and satisfactorily by applying adaptive support.

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Teaching at the Department of Mechanical Engineering
Studying at the Department of Mechanical Engineering

With about 4800 enrolled students (in winter semester 2017/18), 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 classical, in-depth teaching in 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) are being offered by the Department of Mechanical Engineering.

In addition, the Department of Mechanical Engineering collaborates with other TUM departments and offers 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), 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 as well as the joint Master’s program ‘Aerospace Engineering’ with the Nanyang Technological University (NTU) and the German Institute of Science and Technology (GIST) in Singapore. Furthermore, the department has signed more than 70 ERASMUS agreements with 87 universities in 21 countries and offers 14 double degree programs with renowned universities such as the École Centrale Paris, EPFL Lausanne and the KTH Royal Institute of Technology, Stockholm.

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<tr>
<th>BACHELOR’S DEGREE PROGRAM</th>
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<td>Mechanical Engineering</td>
<td>Aerospace</td>
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<td>Automotive and Combustion Engine Technology</td>
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<td>Energy and Process Engineering</td>
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<td>Mechanical Engineering</td>
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<td>Mechanical Engineering and Management</td>
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<td>Mechatronics and Information Technology</td>
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<td>Medical Technology and Engineering</td>
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<td>Nuclear Technology</td>
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<td>Product Development and Engineering Design</td>
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<td>Production and Logistics</td>
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Degree programs being offered by and in charge of the TUM Department of Mechanical Engineering. Source: www.mw.tum.de/de/studium/studiengaenge/bachelor/ and www.mw.tum.de/de/studium/studiengaenge/master, accessed 12/01/2017.
Bachelor’s Degree Program
‘Mechanical Engineering’

The Bachelor’s degree program ‘Mechanical Engineering’ addresses students interested in natural sciences and technology. Within the three-year program (six semesters), students acquire fundamental knowledge, basic methodological skills as well as soft skills required for a mechanical engineer. The program has a total of 180 credits of 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 physics, language skills, and general motivation. Excellent applicants are directly admitted 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.

New Curriculum
With the beginning of the winter semester 2017/18 new Subject Examination and Study Regulations entered into force.

What is new?
■ The modules ‘Principles of Engineering Design and Production Systems’, ‘Foundations of Business Administration I’ and the ‘Lab Course in Experimental Physics for Engineering’ are no longer obligatory basic subjects. Furthermore, in the 5th and 6th semesters, practical courses have been replaced by an additional supplementary module and the lecture ‘Mathematical Tools’. This module imparts knowledge about the implementation of scientific-engineering models and methods by means of conventional programming languages. The main focus is placed on MATLAB combined with Simulink and Stateflow.
■ The new module ‘Uncertainty and Data in Mechanical Engineering’ (3rd semester) enables students to model engineering problems containing uncertainty. Having successfully passed the course students will be capable of estimating parameters of probabilistic models, obtaining confidence intervals and testing hypotheses as well as implementing these tasks in MATLAB.
■ The nine week internship in industry can be substituted by a team project where students learn how to solve mechanical engineering problems. They work together in small groups during the semester to examine an engineering problem. Accompanying the students’ engineering work, soft skill teaching contents support them regarding team work, time and project management as well as product presentation.
■ In addition to the Bachelor’s thesis, students have to take part in the seminar ‘Scientific Practice’, where research strategies (approach to and use of literature), good scientific practice (correct way to quote), scientific writing in English and presentation techniques are taught.

Profile
During the first four semesters of the program, students acquire profound knowledge of mathematics, the natural 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 semesters, students choose five out of 37 specialized Bachelor modules from a broad variety of options. Specific recommendations for the different Master’s programs are available. These modules as well as the Bachelor’s thesis prepare students either to work as an engineer or to continue their studies in one of the ten specialized Master’s degree programs. Moreover students do an internship in industry or a team project. The curriculum of the Bachelor’s degree program is illustrated in the figure below.

Master’s Degree Programs

The Department of Mechanical Engineering offers ten Master’s degree programs which enable students to deepen their knowledge of selected disciplines acquired during the Bachelor’s degree program. Each of the two-year programs has a total of 120 ECTS credits.

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.

Profile

During the first three semesters, students choose twelve out of more than 160 Master modules, which are specialized courses consisting of at least three 45 minute units per week. Additionally, students have to take two (out of about 130) practical courses 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 and soft skills workshops from a broad variety of options. Opportunities to gain insight into research are offered within the ‘semester project’ and the Master’s thesis, which are supervised by professors and scientific assistants. The curriculum of the Master’s degree program is illustrated in the figure below.

Facts and Figures

Since winter semester (WS) 2010/11, the total number of students has varied between 4300 and 4900. About 15% of the student body is female. As shown in the first figure on page 73, 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 second figure illustrates the number of first semester students starting the B.Sc. program and M.Sc. programs at the Department of Mechanical Engineering during the last eight years. The number of B.Sc. freshmen varies between 500 and 900, the exception being 2011 when two age groups of Bavarian high school pupils started studying simultaneously. The number of first semester students starting their Bachelor’s degree in Mechanical Engineering has never been lower (521) than in the winter semester 2017/18.

The last figure shows the number of graduates from each of the degree programs after the standard duration of study, which is six semesters for the B.Sc., four semesters for the M.Sc., and ten semesters in the ‘Diplom’ degree programs.

Curriculum of the Master’s degree programs at the TUM Department of Mechanical Engineering.
Number of full-time students enrolled in degree programs offered by the TUM Department of Mechanical Engineering (at the beginning of each winter semester).

Number of students starting their studies 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.)

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.)
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

More than 25% (TUM: 24%) 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.¹

Students from more than 80 nations study at the department – the biggest groups being Austrians, followed by Chinese and Spanish students.²

Development of the number of international full-time students enrolled at the Department of Mechanical Engineering

Source: Registrar’s office (TUM), 09/2017

See footnote 1

¹

²

Development of the prime nationalities of international full-time students
**Students’ Exchange**

TUM students are offered several possibilities for spending 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 TUM 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.

The 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 at the promotion of 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 2017/18, 151 exchange students from 27 nations are studying at the Department of Mechanical Engineering. During the winter term 2017/18 more than 16% of the incoming exchange students of TUM have been enrolled at the Department of Mechanical Engineering and another 43 students have been registered as full-time M.Sc. students within the framework of the TIME double degree programs.

**Outgoing Exchange Students**

The Department of Mechanical Engineering not only aims at increasing its international student body, but also pursues its goal to increase 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 70 ERASMUS+ agreements with 87 universities in 21 European countries. Most of the department’s partner institutions are in France (12), Spain (12), Italy (8), Sweden (6) and the UK (5). In 2017/18 the number of students going abroad has slightly declined for the first time since 2013/14, yet it nevertheless seems to have stabilized at a level of around 300 outgoing students per year.

[Graph showing the development of the number of mechanical engineering students going abroad]

In addition, the centrally organized TUMexchange program enables selected students of the department to study overseas at one of more 120 partner universities. Moreover a joint degree B.Sc. program ‘Engineering Science’ and a joint M.Sc. program ‘Material Science’ with Paris Lodron Universität Salzburg have been signed and ten TIME double degree agreements in Brazil, France, Italy, Sweden, Switzerland and Spain have been concluded with renowned associate universities such as Groupe Ecoles Centrales, KTH Stockholm and Ecole Polytechnique Fédérale de Lausanne (EPFL).

3 Sources: International Center (TUM): Online database ‘Moveon’; Students’ Services Department of Mechanical Engineering (TUM)

4 See footnote 3
**Assistance for Students Offered by the Central Examination Services Office**

The Central Examination Services Office is a centralized point of contact that students can use for all exam-related questions, with the participation of the secretary of the examination board and the internship office. Its areas of responsibility include all exam-related topics, from admissions procedures during the application process, to the mandatory industrial internships associated with a given degree programme, to grading and examination practices for the Bachelor’s and Master’s courses offered by the faculty. The office provides advice and guidance to around 5,000 students of the Department of Mechanical Engineering on these topics.

To improve this service, an FAQ page has now been published on the faculty homepage. This page is regularly updated and will gradually become a comprehensive source of reference. The FAQs allow students to find general information about exam-related questions outside of individual consultation hours. Students can then contact the relevant persons directly if further clarification is needed.

The study equivalence recognition table serves a similar purpose and is also regularly updated. This table lists all examinations and diplomas that are currently recognized by the official process, listed by country, allowing students to plan and evaluate potential study programmes abroad more accurately and determine in advance which programmes are most likely to be recognized when they return. No other university offers as comprehensive a table of this type.

www.mw.tum.de/fileadmin/w00btx/www/Lehre/Anerkennungen_andere_Hochschulen_WS17_18.pdf

Similarly, for industrial internships, we also provide excellent support to students as they search for the most relevant internship for them. We offer a sorted list of locations and companies with around 460 entries, which applicants and current students can use to gain a head-start on finding a suitable employer for their manufacturing internship. The list is not limited to companies from Germany, with entries from throughout Europe and the rest of the world.

www.mw.tum.de/vorpraktikum

Given the non-negligible proportion of students who drop out of their courses, the early warning system operated by Arno Buchner, the secretary of the Bachelor’s degree examination board, is of invaluable assistance. The early warning system was recognized by the Academicus prize in 2016 (see Annual Report 2016). It is aimed at students with below-average academic progress who are at risk of failing their studies.

This integrated system is founded on examination data from TUMonline. It identifies students at risk of exmatriculation at an early stage, opens a dialogue with them, and connects them with supportive resources. This allows early shortcomings and the resulting risks for the continuation of studies to be identified promptly. Some students have already responded well to the resources proposed to them and have sought assistance from the relevant sources. This allowed them to significantly enhance the results of their own efforts and ensure that their studies unfold successfully. However, it will only become clear after a few semesters whether this system can sustainably reduce the drop-out rate in the medium term.
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 faculties, one or more campuses, in particular effective priority teaching programmes and university-wide structural programmes to improve conditions of study.

2. **Departmental 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 Advisory Service.

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:

A detailed list of projects funded can be downloaded from the website [www.mw.tum.de](http://www.mw.tum.de).
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 by almost three quarters from 11% to 18.4% 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 10% in 2017. 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 24.6% of all students are international, more than twice the number in 2011, and 15% 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 for doctoral candidates as part of the Graduate Center Mechanical Engineering, as well as training key competencies for Bachelor and Master students of the department in the Center of Key Competencies.

The Center of Key Competencies 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 training to complement their technical knowledge. The Center of Key Competencies focuses on the development of skills such as effective team work, constructive solution of conflicts or convincing presentations. One out of our various offers, focuses on the education of Bachelor students. Ending with the new Bachelor, we want to use this opportunity to review the last 20 years of the Tutoring System Garching:

20 years of Tutoring System Garching – A Shortcut

The Tutoring System Garching has been one of the cornerstones in educating Diploma and Bachelor students over the last two decades. Although some aspects may have changed within the last 20 years, one objective has always remained the same: To support young people in connecting with each other, handling challenging projects and being prepared – for university and for life.

In interactive workshops, small groups of students work together on topics such as communication and feedback, presentational skills, time management and learning strategies, teamwork and meeting management. These workshops are based on scientific fundamentals and on an activity and experience focused approach. The methods included in the workshops consist of input, practical tasks, role play and peer counseling. In the second half of the Tutoring System students take part in different projects to experience how to work on a project as a team. These workshops were held by tutors, experienced students with a special qualification to design, run and evaluate workshops and lead their teams for a whole year. In eight days of training the tutors are prepared for the workshops by trainers of the Center of Key Competencies. During their time as a tutor they receive feedback on their workshops to further develop their skills. The coordinator of the program at the Center of Key Competencies always provides help and support for over 50 tutors each semester. After one year as a tutor the participants develop skills in leading a group, project management and giving workshops.

These are the highlights of 20 years of the Tutoring System Garching:

1996 The Tutoring System Garching was founded out of a student initiative and was supported by the Chair of Product Development. It has been under the leadership of Prof. Dr.-Ing. Udo Lindemann, Department of Product Development. It started with eight tutors and was supervised by the chair.

2007 After more than ten years there were more participants than places to offer. Due to this high demand, two tutoring groups with 15 tutors each have been educated each year and up to 450 undergraduate students have taken part in the program, since summer semester 2008.

2010 The Tutoring System Garching left the Department of Product Development and was assigned to the Study Office of the Department of Mechanical Engineering.

2011 The Center for Key Competencies was found to train soft skills at the Department of Mechanical Engineering and took over the responsibility for the Tutoring System Garching.
Central Teaching Unit

2012 ‘TUTOR for everyone’! All freshmen started to take part in the Tutoring System Garching. In numbers, up to 800 freshmen were trained by 55 tutors. The students gained four “soft skills” credits in two semesters, a workshop and a project semester. Here they learned to plan and construct prototypes just like products to facilitate the start of the day – ‘Startup your day’.

2017 With the new Bachelor program we said goodbye to the Tutoring System Garching. The Center of Key Competencies started a new period with ‘Key Competencies for the start into your studies’. Although some parts remained the same, the new seminar focuses on preparing students for their life at university.

Then as now, the Tutoring System Garching pursues two goals: giving students a first orientation at the university within their first semester and extending their social, methodological and personal competencies. We are looking forward to the next 20 years to come!

Graduate Center

As part of the TUM Graduate School the Graduate Center Department of Mechanical Engineering supports the institutes in creating the best possible environment for doctoral candidates. That is why the Graduate Center offers several subject-specific and professional courses. To guarantee the high standard of good scientific work, the seminar ‘Good Scientific Practice’ is mandatory for all doctoral candidates at the Department of Mechanical Engineering. In 2017 the seminar was offered 23 times and 276 doctoral candidates participated. Good scientific practice is not only an important point for doctoral candidates, it is also very important for the professors of the department, who also give courses on this subject.

The seminar combines the standards for good scientific practice, the process of their own research topics and practical tips for writing their dissertation.

Content of the seminar ‘Good Scientific Practice’:
■ Guidelines for the safeguarding of good scientific practice,
■ Core elements of scientific work and sharpening one’s identity in science,
■ Phases in the scientific writing process,
■ Quotation rules and records of scientific progress,
■ Exposé – how to start the dissertation,
■ Scientific expression and scientific argumentation strategies.

Another very important part of Ph.D. candidates’ tasks is teaching or supervising students. About 50% of the doctoral candidates spend 11-30% of their working time in teaching or supervising students. For this reason in May 2012 organization of the event ‘Fit in Teaching’ started in cooperation between doctoral candidates, the Department of Teaching and Learning and the Graduate Center.

At this event doctoral candidates get advice on giving lectures in the academic environment and supervising. In 2017 we offered the Seminar ‘Fit in Teaching’ for the 10th time and since 2012 about 300 doctoral candidates have participated.

Topics of the workshops during the event were:
■ How to supervise and assess student research projects,
■ Teaching tricks – digital tools for efficient teaching,
■ Evaluation and feedback – mandatory or a chance,
■ Understanding the unconscious bias,
■ Didactic planning of lectures,
■ Interaction in lectures.

In summary the Graduate Center is responsible for the concept of courses to guarantee the high standard of scientific work of all doctoral candidates.

Contact

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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 of the department's students. 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 divided into individual departments, which work in close collaboration to improve and ensure good academic conditions at our faculty.

Event Department

The summer semester 2017 started with the Student Council’s workshop weekend, dedicated to various topics ranging from improvements in the study conditions to the range of courses. Throughout the whole year regular blood donation events were organised in cooperation with the Bavarian Red Cross and the initiative ‘Talente Spenden’. This was an excellent opportunity for the members of Garching campus to do a good deed. During the warm days of June the various different student councils on Garching Campus organised ‘GARNIX Festival’, in co-operation with the Student Council of Technical University of Munich. During the GARNIX various tournaments, such as beach volleyball, basketball and football were held on campus. For the third time in a row the Student Council supported the ‘TUM Junge Akademie’ in running the ‘TUM Campus Run’ with nearly 1000 participants. Moreover the department was supported by the Student Council at the ‘Tag der Fakultät’, graduation day, where graduates could enjoy freshly mixed drinks at the council’s cocktail bar. After a second workshop weekend in the early winter months, it was time for some more solemn days which were highlighted by the festive Christmas tree in the foyer of the department and the organisation of a big Christmas market in front of the department building. Many other small events like a pub crawl and a poker competition aimed at pleasing the students during the year.

Magazine of the Student Council

The Student Council published six issues of its magazine ‘Reisswolf’. This year the topics for each issue ranged from news about the new Bachelor study regulation, reports of voluntary work or car reviews. The traditional ‘Lehrstuhlerie’ continued to introduce the different chairs of the department. Less serious topics were published in ‘Klopapier’, the humorous and entertaining poster in the restrooms of the department. Furthermore articles from university groups contribute to every issue.
Print Shop

As in previous years, the print shop of the Student Council printed all kinds of lecture notes, collections of old exams and the free magazine “Reisswolf” in large editions. The lecture notes and collections of old exams could be purchased in our store, open on working days. It was possible to offer this large amount of documents for lectures, seminars and lab courses, thanks to the great cooperation with numerous institutes. This year the documents on offer were increased, as it was possible to gain new scripts in cooperation with existing and new institutes. Furthermore, the design of the covers was changed and the lecture notes are now covered in fresh and appealing colors, and a new printing press was purchased to improve and ensure the quality of our scripts.

International Department

In 2017 the International Department tackled the task of evaluating and adjusting their program according to student feedback from previous terms. For the second time the buddy program did not take the form of people meeting up at a Welcome Event, but rather they could sign up online. This favored students being brought together according to their preferred language, country or university. Since the Welcome Event was one of the most important pillars in our program and the meet and greet on those evenings was welcomed by all students, we decided to add an event at the beginning of the winter term, called ‘Speedfriending’. For that event we provide a place for students to get together and get to know each other in short conversations. This tries to simplify social networking between domestic and international students. In addition we still maintain our regular pub evening program during the winter and summer terms.

Last but not least, we held a big Erasmus Christmas Party a week before the Christmas break. There we set up a buffet table and asked every guest to bring culinary delights from their home country to the dinner.

We are also very proud of our contribution to the new Bachelor regulations and the improvements achieved, now enjoyed by our freshmen. 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 enlarge our national and international relationships by attending the ‘Fachschaftentagung Maschinenbau’, the ‘KOMET’ and the European Mechanical Engineering Student Council Congress.

Freshman Department

The job of the Freshman Department is to care for all the freshmen who begin their studies at the department. For the third time the POWER – the orientation week – was organized which included a city rally through Munich, a traditional Bavarian breakfast with wheat beer and ‘Weißwurst’ and a sport event. All the important information regarding study courses and university life were given to the students in a two-day information event at the start of the winter term. Moreover we informed possible future students at numerous events during the year.

Public Relations Department

This year the Public Relation Department organised the ‘BASSD’, the Basic and Advanced Studies and Science Day. During this event the students were informed about the various possibilities available after their basic studies and on how they could get more information about academic work at the institutes and the working life of scientific employees and Ph.Ds. Moreover the Public Relations Department answered incoming request throughout the year from students of all ages and countries and general requests addressed to the Student Council.

www.fsmb.de

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 ‘Studienzuschusskommission’ (committee for study allowances), more than 300 applications were granted to advance the quality of teaching.
The humanoid robot LOLA is 180 cm tall and weighs approximately 55 kg.
In 2017, one new full professor, an adjunct professor and four honorary professors were appointed to the TUM Department of Mechanical Engineering.

**Prof. Dr.-Ing. Markus Zimmermann**

Prof. Lindemann (head of the Chair of Product Development) and Prof. Baier (head of the Chair of Lightweight Structures) retired almost simultaneously in 2016. The department took this opportunity to merge both chairs and to create a new Chair of Product Development and Lightweight Design, thus raising the potential to focus on design aspects of lightweight structures. The materials aspects of lightweight structures are well addressed in other chairs, such as Carbon Composites, Materials Science and Mechanics of Materials as well as Metal Forming and Casting.

The department is proud of having won Prof. Zimmermann (b. 1976) for this position. He studied Engineering Sciences at the Technical University of Berlin, the University of Michigan, Ann Arbor, and the École Polytechnique, Palaiseau, and achieved his doctorate at MIT under the supervision of Prof. Aberyaratne on multi-scale modeling, non-local material models, numerical simulation of cracks and phase boundaries. Thereafter, he joined the BMW group, where he became team manager for driving dynamics in the Department of Architecture Layout and Preliminary Design. Despite his industrial career, Prof. Zimmermann has never stopped publishing research results in refereed scientific journals.

**Prof. Dr.-Ing. Matthias Gaderer**

Prof. Gaderer (b. 1968), head of Regenerative Energy Systems at the TUM Straubing Center of Science has been appointed adjunct professor of the Department of Mechanical Engineering in order to strengthen its ties to the Straubing Center of Science. Gaderer studied process engineering at TU Graz and KTH Stockholm. He subsequently worked in industry on process engineering projects in Switzerland and Austria. In 1999 he took up a position at the Bavarian Center for Applied Energy Research (ZAE Bayern) in Garching, Munich, where he was instrumental in setting up a biomass research unit. After obtaining his doctorate at TUM in 2008 he was responsible for the area of decentralized energy systems and thermal biomass utilization at the Institute of Energy Systems. In 2015 Gaderer was appointed professor of regenerative energy systems at Straubing Center of Science.

**Hon.-Prof. Dott. Antonio Cardella**

Prof. Cardella (b. 1953) has been appointed to the department as Honorary Professor for Nuclear Fusion Technology at the Chair of Nuclear Technology. He studied Nuclear Technologies at the Università degli Studi di Palermo and has held several positions in industry and academia since then, including an associate professorship at the Italian ‘Ministerio dell’ Università e della Ricerca Scientifica’. Since 1994 he has been seconded by the European Commission to various positions in relation to fusion technology, including the JT60SA project in Japan. Since 2010 he has been teaching at the TUM Department of Mechanical Engineering with great personal commitment. Prof. Cardella will create an important link to IPP.
Hon.-Prof. Dr.-Ing. Marco Einhaus

Prof. Einhaus (b. 1967) has been appointed to the department as Honorary Professor for Occupational and Industrial Safety at the Chair of Machine Tools and Manufacturing Technology. He studied Civil Engineering and Environmental Technology at the University of the Armed Forces in Neubiberg and later achieved his doctorate at TU Chemnitz. After various positions with the armed forces related to occupational safety he became technical supervisor with the Mutual Indemnity Association Metal (Berufsgenossenschaft Metall Nord Süd), supervising several large-scale construction projects such as the Allianz Arena, BW Welt and others. Since 2009 he has been teaching occupational and industrial safety with great success.

Hon.-Prof. Dr.-Ing. Matthias Heller

Prof. Heller (b. 1966) has been appointed to the department as Honorary Professor for Highly Augmented Aircraft at the Chair of Flight System Dynamics. He studied aerospace engineering and achieved his doctorate at TUM. Later, he worked with EADS CASSIDIAN Air Systems, first as a research and development engineer within the department Flight Mechanics & Flight Guidance, then as expert advisor in flight mechanics for the entire BUCASSIDIAN Air Systems. He has been appointed Rudolf Diesel Industry Fellow of TUM IAS twice, in 2010 and in 2014. Since 2010 he has been teaching flight dynamics design challenges of highly augmented aircraft at the TUM Department of Mechanical Engineering with great personal success.

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

Prof. Kolb (b. 1964) has been appointed to the department as Honorary Professor for Climate Control and Refrigeration at the Chair of Thermodynamics. He studied mechanical engineering and achieved his doctorate at TUM. After a position with Webasto he moved to DENSO and finally became director of the DENSO Engineering Center Northern Europe. Since 2009, Prof. Kolb has been teaching automotive climate control and refrigeration with great success.
Willibald A. Günthner

On 30 September 2017, Prof. Willibald A. Günthner, Ordinarius of the Chair for Materials Handling, Material Flow, Logistics, entered into retirement.

Willibald A. Günthner can look back on a long career in logistics. After studying mechanical engineering from 1973 to 1978, he gained his doctorate at the Chair and Institute for Materials Handling under Professor Siegfried Böttcher at the Technical University of Munich. At the same time, he also completed studies in work and economic studies. In 1985, Günthner moved to the industrial sector as a technical manager at Max Kettner. After working for the company for four years, he returned to academia as professor for materials handling and material flow at the Technical University in Regensburg. In 1994, he followed an invitation to join the Technical University of Munich as Böttcher’s successor in the Chair.

In the newly renamed Chair for Materials Handling, Material Flow, Logistics, Günthner placed a stronger research and teaching focus on material flow and logistics. Key achievements from his 23 years as a professor at TUM are research results such as ‘pick by vision’, picking with data glasses, and more efficient, more reliable crane evaluation using the NODYA programme. Günthner recognised the trend towards digitalisation in intralogistics at an early stage, and was a co-initiator of the concept of an ‘internet of things’ – the basic idea that spawned the fourth industrial revolution (Industry 4.0).

As well as leading numerous research projects and research groups, Günthner was also active in the Department of Mechanical Engineering and was chairman of the Bachelor degree examination board. With the goal of promoting technical logistics as an academic discipline, he founded the ‘Wissenschaftliche Gesellschaft für Technische Logistik e.V. (WGTL)’, the scientific body for technical logistics, together with other logistics professors. Günthner was also involved in the German federal association for logistics, the ‘Bundesvereinigung für Logistik’ as deputy chairman of the scientific advisory board, and was also chairman of the board of the ‘Gesellschaft Produktion und Logistik’, a member of the Association of German Engineers (VDI) in the field of technical logistics.
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
➤ Page 100

Prof. Dr.-Ing. Klaus Drechsler
Carbon Composites
www.lcc.mw.tum.de
- Composite materials and process technology
- Textile technology
- Lightweight design

Prof. Dr. phil. Klaus Bengler
Ergonomics
www.lfe.mw.tum.de
- Micro ergonomics
- Human-machine interaction
- Digital human modeling
- Cooperative systems and automation
➤ Page 109

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 115

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 118

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
➤ Page 127

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
➤ Page 132

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 Faculty of Civil Engineering
➤ Page 137
<table>
<thead>
<tr>
<th>Department Members</th>
</tr>
</thead>
</table>
| **Prof. Dr.-Ing. Volker Gümmer**  
Turbomachinery and Flight Propulsion  
[www.ltf.mw.tum.de](http://www.ltf.mw.tum.de)  
- Aerodynamics of turbomachinery  
- Propulsion technology  
- Design concepts for gasturbine components  
- Gasturbine systems and cycles  |
| **Prof. Dr.-Ing. Mirko Hornung**  
Aircraft Design  
[www.ils.mw.tum.de](http://www.ils.mw.tum.de)  
- Scenario analysis, future trends and technologies  
- Aircraft design (civil and military)  
- Analysis and evaluation of aircraft concepts  |
| **Prof. Dr.-Ing. Oskar J. Haidn**  
Space Propulsion  
[www.lfa.mw.tum.de](http://www.lfa.mw.tum.de)  
- Thrust chamber technologies  
- High pressure combustion  
- In-space propulsion  
- Green propellants  
- Combustion dynamics  
- Turbopump technologies  |
| **Prof. Dr.-Ing. Hans-Jakob Kaltenbach**  
Flow Control and Aeroacoustics  
[www.aer.mw.tum.de](http://www.aer.mw.tum.de)  
- Active and passive flow control  
- Prediction and mitigation of flow noise  
- Aircraft, automotive and railway aerodynamics  |
| **Prof. Dr.-Ing. Manfred Hajek**  
Helicopter Technology  
[www.ht.mw.tum.de](http://www.ht.mw.tum.de)  
- Aeromechanical modeling and test of rotors  
- Modelling and simulation of rotocraft flight  
- Multi-rotor configurations  |
| **Prof. Dr.-Ing. Harald Klein**  
Plant and Process Technology  
[www.apt.mw.tum.de](http://www.apt.mw.tum.de)  
- Process design  
- Equipment design methods  
- Modeling and thermodynamic property data  |
| **Prof. Dr.-Ing. Florian Holzapfel**  
Flight System Dynamics  
[www.fsd.mw.tum.de](http://www.fsd.mw.tum.de)  
- Modeling, simulation and parameter estimation  
- Flight guidance and flight control  
- Sensors, data fusion and navigation  
- Trajectory optimization  |
| **Prof. Phaedon-Stelios Koutsourelakis, Ph.D.**  
Continuum Mechanics  
[www.contmech.mw.tum.de](http://www.contmech.mw.tum.de)  
- Uncertainty quantification in computational science and engineering  
- Bayesian formulations for inverse problems  
- Atomistic simulation of materials  |
Department Members

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
► Page 176

Prof. Dr. rer. nat. Oliver Lieleg
Biomechanics
www.mw.tum.de/de/bme/startseite
- Mechanics of biomaterials
- Biological hydrogels
- Biomedical/biophysical engineering
► Page 179

Prof. Dr.-Ing. Markus Lienkamp
Automotive Technology
www.ftm.mw.tum.de
- Vehicle concepts
- Electric mobility
- Vehicle control and dynamics
- Driver assistance systems
► Page 182

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
► Page 187

Prof. Dr. rer. nat. Tim C. Lüth
Micro Technology and Medical Device Technology
www.mirned.mw.tum.de
- Medical navigation, robotics, and control architectures
- Rapid prototyping
- Technology for an aging society
► Page 191

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
► Page 196

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
► Page 201

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
► Page 205
Department Members

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
► Page 209

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
► Page 212

Prof. Dr. Julien Provost
Safe Embedded Systems
www.ses.mw.tum.de
- Fault-tolerant systems
- Formal verification and validation
- Distributed control systems
- Diagnosis of automated systems
► Page 215

Prof. Dr.-Ing. Gunther Reinhart
Industrial Management and Assembly Technologies
www.iwb.mw.tum.de
- Production management and logistics
- Automation and robotics
- Assembly technology
► Page 218

Prof. Dr. Ir. Daniel Rixen
Applied Mechanics
www.amm.mw.tum.de
- Numerical methods for technical dynamics
- Experimental structure dynamics
- Multiphysical models
► Page 222

Prof. 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
► Page 226

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
► Page 235

Prof. Dr.-Ing. Hartmut Spliethoff
Energy Systems
www.es.mw.tum.de
- Systems studies
- Combustion and gasification of solid fuels
- Steam cycles
► Page 240
Department Members

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
► Page 243

Prof. Dr.-Ing. Wolfgang A. Wall
Computational Mechanics
www.inm.mw.tum.de
- Multifield problems
- Multiscale problems
- Computational biomechanics and biophysics
► Page 264

Prof. Dr.-Ing. Birgit Vogel-Heuser
Automation and Information Systems
www.ais.mw.tum.de
- Model-based and integrated engineering
- Distributed control systems
- Quality management and human factors
► Page 249

Prof. 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
► Page 268

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
► Page 254

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
► Page 274

Prof. Dr.-Ing. Georg Wachtmeister
Internal Combustion Engines
www.lvk.mw.tum.de
- Gas and diesel engines
- Injection processes
- Exhaust gas aftertreatment
► Page 259

Prof. Dr.-Ing. Dirk Weuster-Botz
Biochemical Engineering
www.biovt.mw.tum.de
- Microbial bioprocess engineering and industrial biotechnology
- Biocatalysis and fermentation
- Bioprocess integration
► Page 280
Department Members

Prof. Dr.-Ing. Michael F. Zaeh
Machine Tools and Manufacturing Technology
www.iwb.mw.tum.de
- Machine tools
- Manufacturing processes
- Joining and cutting technologies
► Page 284

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
► Page 288

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. Johann Dambeck
Flight System Dynamics

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

Hon.-Prof. Dr.-Ing. habil. Raymond F. Freymann
Applied Mechanics

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

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 EI)

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Aerodynamics and Fluid Mechanics

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

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Industrial Management and Assembly Technologies

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

Hon.-Prof. Dr.-Ing. Karl Viktor Schaller
Automotive Technology

Hon.-Prof. Dr. rer. pol. Werner Seidenschwarz
Product Development and Lightweight Design

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Aerodynamics and Fluid Mechanics

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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.-Ing. Dr. rer. nat. Otto Brüller
Mechanics

Prof. Dr. rer. nat. Heiner Bubb
Ergonomics

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

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

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

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

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

Prof. Dr.-Ing. Dr.-Ing. E. h. Joachim Heinzl
Precision Engineering and Micro Technology

Prof. Dr.-Ing. Bernd Heißing
Automotive Technology

Prof. Dr.-Ing. Hartmut Hoffmann
Metal Forming and Casting

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. Gero Madelung
Aircraft Engineering

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 Stichlmair
Fluid Process Engineering

Prof. Dr.-Ing. habil. Johannes Straub
Thermodynamics

Prof. Dr.-Ing. Klaus Strohmeier
Apparatus and Plant Engineering

Prof. Dr.-Ing. habil. Hans M. Tensi
Mechanical Engineering

Prof. Dr.-Ing. habil. Heinz Ulbrich
Applied Mechanics

Prof. Dr. rer. nat. Dieter Vortmeyer
Chemical Process Engineering
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 2016-17 was 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 highlight in 2016-17 was the successful operation start of the large shock-tube facility, and the kick-off of two interdisciplinary DFG projects with the institutes IWB and FZG, where the institute brings in its expertise on advanced flow-simulation methodology. Dr. Lin Fu, graduating from the institute in 2017, received a Postdoctoral Fellowship from Stanford University, and M.Sc. Thomas Paula received the Willy Messerschmitt award for his Master Thesis absolved at the German Association for Aero- and Astronautics. Last but not least, from the NANOSHOCK project the first CFD code spin-off was opened for perusal by the scientific community: https://www.aer.mw.tum.de/abteilungen/nanoshock/news

Experimental and Numerical Investigation of Cavitating Two-phase Flows and Cavitation-induced Erosion

Motivation and Objectives
The formation of vapor bubbles in a liquid due to pressure reduction is called ‘cavitation’. Flows involving cavitation feature a series of unique physical properties such as discontinuous jumps in the speed of sound from O(1000) m/s to O(1) m/s, a jump in density of up to four orders of magnitude, and intense compressibility effects, such as the formation of intense shock waves with post-shock pressures of more than 1GPa. Flows involving cavitation occur in a wide range of technical systems. In particular, injection systems for combustion engines, high pressure hydraulics, naval propellers and biomedical applications are prone to cavitation and cavitation-induced material erosion.

Our objective is to develop efficient and accurate simulation approaches for predicting all dominating phenomena in cavitating flows including shock-wave formation and propagation, with the goal to provide the groundwork for the design optimization of future technical devices.

Approach to Solution
We perform fundamental experiments using a shock tube and state-of-the-art high speed cameras/sensors to investigate collapse processes of gas und vapor bubbles embedded in a liquid-like gel. These experiments are used to enhance physical understanding of involved fluid dynamics and serve as reference data to our numerical investigations. For about one decade, mathematical models and numerical approaches for efficient and accurate predictions of cavitating flow phenomena have been developed at the institute. A series of numerical approaches, including state-of-the-art large-eddy simulation (LES) schemes enable high performance computing with linear scaling on HPC systems, such as SuperMUC. Our approaches are ‘monolithic’ in a sense that all fluid components involved (liquid, vapor, inert gases) are handled in a consistent way. Shock-wave formation due to collapsing vapor patterns is resolved by application of time steps smaller than one nanosecond. The resulting loads on material surfaces – and thus the potential of material erosion – are obtained without the need for additional models. Fundamental research is funded by the European Union (Project ‘CaFE’), while applied research is performed in collaboration with several automotive suppliers, the U.S. Office of Naval Research and with the European Space Agency.
Aerodynamics and Fluid Mechanics

Detected Collapse Events
Stable Vapor-sheet and Gas are damping -> less collapse events

Jet characteristics:
Hydraulic Flip: Reduction of spray angle
Experiments show same [Sou, 2007; Pratama 2014]

Key Results

Spray angle and erosion analysis in generic injector components.

Numerical Methods for Computational Fluid Dynamics
Physical Consistency of High-resolution CFD

Motivation and Objectives
CFD tools in physical or engineering applications can never reach numerical resolution levels where the truncation error of the discretization schemes enters its asymptotic limit. It thus is of high practical relevance to design schemes that have good scale resolution properties whenever numerical resolution is sufficient for relevant flow scales, and whose truncation error functions as a physically consistent subgrid-scale model when not. In the past, this research concept has led to the development of the first physically consistent and practically successful implicit LES model. Currently, the notion of employing model uncertainty and truncation errors as physical-model surrogates is being pursued on several levels.
Aerodynamics and Fluid Mechanics

Approach to Solution
Concepts of physical design of modeling and discretization error have been successfully employed for further development of high-resolution schemes and targeted ENO schemes that are suitable for underresolved computations of turbulent and non-turbulent flows. The physically consistent implicit LES model ALDM has been applied to turbulent shock-boundary-layer interaction at unprecedented Reynolds numbers. Extending the general concept to numerical models for fluctuating hydrodynamics, the manipulation of modeling errors within the dissipative-particle-dynamics model is investigated to explore spontaneous long-range correlations in turbulent flows. Physical effects of truncation errors in particle-discretizations may also lead to relaxation processes that allow for highly effective mesh generation and domain partitioning methods. Both have been developed to a pre-commercialization demonstration level.

Key Results

Smoothed Particle Hydrodynamics Method for Simulating Free Surface Flow

Motivation and Objectives
Smoothed particle hydrodynamics (SPH) is a purely mesh-free Lagrangian method developed for astrophysical applications. Since these pioneering works, the SPH method has been successfully applied for numerical simulations of solid mechanics, fluid dynamics and fluid-structure interaction. Concerning the computation of hydrodynamic problems, the present methods either lead to violent pressure oscillations or excessive dissipation and are not able to reproduce correct physical phenomena reliably.

Approach to Solution
We present a low-dissipation, weakly-compressible SPH method for modeling free-surface flows exhibiting violent events such as impact and breaking. The key idea is to modify a Riemann solver which determines the interaction between particles by using a simple limiter to decrease the intrinsic numerical dissipation. The modified Riemann solver is also extended for imposing wall boundary conditions. Numerical tests show that the method resolves free-surface flows accurately and produces smooth, accurate pressure fields.
Numerical Modeling of Interface Networks

Motivation and Objectives
Multi-region problems can occur when the motion of more than two immiscible fluids is to be described. In this case the interface network, separating the different fluid regions, evolves in time due to interactions of the different fluids across interface segments. These interactions can often be described by local fluid properties. Due to the complexity of the topology, numerical modeling of the evolution and interactions near the interface network are long-standing challenges for the research community.

Approach to Solution
We have developed a high-resolution transport formulation of the regional level-set approach for an improved prediction of the evolution of complex interface networks. The approach thus offers a viable alternative to previous interface-network level-set method.

Key Results

Constant normal driven flow of an interface network with three regions at different time instance

Three-dimensional dam-break problem simulated with \( dp = \frac{H}{30} \) (the total fluid particle number \( N = 27000 \)): free-surface profile compared with experiment.
Aircraft and Helicopter Aerodynamics

Motivation and Objectives
The long-term research agenda is based on the continued improvement of flow simulation and analysis capabilities in the context of aircraft and helicopter performance enhancement and drag reduction. Specific research activities are dedicated to the reliable prediction of flow separation onset and progression in the context of vortex dominated flow and control of leading edge vortex systems, development of a novel ROM framework for aeroelastic analysis, helicopter drag reduction of rotor hub and engine intake by shape optimization and flow control, development of propeller performance and optimization tool chain with respect to electrically driven flight vehicles and fluid-structure interaction of membrane-type lifting surfaces applied to wind turbine rotors.

Approach to Solution
The investigations have been performed using both wind tunnel experiments and state-of-the-art numerical simulations. In-house codes are continuously elaborated further 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. Commercial CFD codes are applied to flow control problems and helicopter aerodynamics addressing unsteady loads analysis and aeroacoustics.

Key Results
Modal Decomposition for Vehicle Aerodynamics

A new modal decomposition approach is employed for analyzing temporally resolved flow field data from detached eddy simulation (DES) using the open source CFD environment OpenFOAM®. Velocity components are temporally filtered with moving average filter before being interpolated to a coarser equidistant mapping mesh. These filtering operations reduce the amount of spurious numerical oscillations in the data to be analyzed and cut off high frequency, low energy content. In order to extract the most dominant flow structures for in-depth analysis, an incremental variant of dynamic mode decomposition (DMD) was found to be most useful. DMD generates modes of distinct frequency that can be reconstructed in time. Several modifications to an already existing variant are implemented to increase the applicability for large data sets, mainly reducing the required amount of memory, which is the most limiting factor in modal analysis for industrial applications with large data sets. The modes represent flow structures of vortex shedding and stationary recirculation processes. Reconstruction enables tracking of structures to their respective excitation mechanisms and allows for identification of geometrical features that introduce strong perturbations to the flow. Strong perturbations lead to an increase in potential for viscous dissipation in the wake of bluff bodies and thus to generally lower base pressure and increased drag.

The DrivAer reference model in notchback configuration with structured underbody, engine bay flow, open wheel houses and open rotating rims is simulated in wind tunnel conditions with a rolling road system. The results from CFD are processed using the DMD approach described above and the most dominant flow structures are visualized and discussed. Small scale detachments that are generated far upstream of the mean detachment line of the vehicle’s rear end travel downstream along the surface, triggering large-scale structures in the wake. The frequency of those structures is also dominant in the frequency spectra of the integrated force coefficient.

Publications
- Kiewat, Haag, Indinger, Zander, ‘Low-Memory Reduced-Order Modelling with Dynamic Mode Decomposition Applied on Unsteady Wheel Aerodynamics’, 2017 ASME Fluids Engineering Division Summer Meeting

![Iso-surfaces of the streamwise velocity component of the most dominant DMD mode at 9Hz](image-url)
Laminar-turbulent Transition with Chemical (Non-)Equilibrium in Hypersonic Boundary-Layer Flows

Motivation
Blunt bodies returning from space are subject to immense heat loads leading to ablation. Roughnesses on these ablating surfaces can induce laminar-turbulent transition in an otherwise laminar flow. Laminar-turbulent transition increases the heat load on the surface. This self-energizing effect can lead to a catastrophic failure of the spacecraft. The role of the chemical modelling in high-temperature boundary layers in equilibrium and non-equilibrium is the main focus of the numerical work.

Approach to Solution
Direct numerical simulations (DNS) are conducted on national HPC facilities such as SuperMUC and HLRS. Results show that roughness wakes are subject to an increased instability in the presence of chemical reactions and non-equilibrium effects.

Key Results

Computational setup for a roughness patch on a re-entry capsule

DNS results from vortical disturbances induced by surface roughness in a reacting environment. The wake of the roughness elements becomes unstable and laminar-turbulent transition takes place.
Aerodynamics and Fluid Mechanics

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Research Foci
■ 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
■ Aerodynamik des Flugzeugs I
■ Aerodynamik des Flugzeugs II
■ Grenzschichttheorie
■ Angewandte CFD
■ Gasdynamik
■ Turbulente Strömungen
■ Aerodynamik bodengebundener Fahrzeuge
■ Aerodynamik der Bauwerke
■ Aerodynamik von Hochleistungsfahrzeugen
■ Instationäre Aerodynamik I
■ Instationäre Aerodynamik II
■ Numerische Berechnung turbulenter Strömungen
■ Numerische Methoden für Erhaltungsgleichungen
■ Aerodynamik der Raumfahrzeuge – Wiedereintrittsaerodynamik
■ Particle-Simulation Methods for Fluid Dynamics
■ Biofluid Mechanics
■ Grundlagen der experimentellen Strömungsmechanik
■ An Introduction to Microfluidic Simulations
■ Physics of Fluids
■ Strömungphysik und Modellgesetze
■ Praktikum Aerodynamik des Flugzeugs
■ Praktikum Simulation turbulenter Strömungen auf HPC-Systemen
■ Praktikum Experimentelle Strömungsmechanik
Selected Publications 2017

- Buzica, Andrei; Bartasevicius, J.; Breitsamter, C.: Experimental investigation of high-incidence delta-wing flow control. Experiments in Fluids 58: 131, 2017
- Kiewat, M.: Low-Memory Reduced-Order Modelling with Dynamic Mode Decomposition Applied on Unsteady Wheel Aerodynamics. American Society of Mechanical Engineers (ASME) Fluids Engineering Division Summer Meeting (FEDSM), 2017
- Piquee, J.; Breitsamter, C.: Numerical and Experimental Investigations of an Elasto-Flexible Membrane Wing at a Reynolds Number of 280,000. Aerospace, 2017
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 2017 was to further increase the activities in the area of cooperative interaction between human and vehicle or human and robot on a global level. National and internationally funded project proposals were successful to continue the fundamental research at the institute.

The second focus was to intensify the developments 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 further national and international projects, the cooperation and interaction of vehicles and pedestrians was examined. For this purpose, the pedestrian simulator of the chair was used.

1. Human Modeling

Product and workspace designs belong to the main tasks of ergonomics. Today, emerging ergonomic problems can be solved or evaluated more efficiently and competitively with digital human models. The development of biomechanical, physiological, anthropometrical and cognitive models is the main task of the research group ‘Human Modeling’. Biomechanics, physiology and anthropometry can already be precisely modelled and simulated. Therefore, reliable predictions of the influence of single factors on discomfort, load, workload and human performance are possible. Human beings are complex systems, whose parameters can influence each other. For instance discomfort and workload depend on an interaction of factors. However an interdisciplinary approach for a holistic human model is still missing.

Basic research, crosslinking individual systems, modeling approaches and application-oriented studies are used for a further development of physical, numerical and theoretical models. Different fields of application for as holistic as possible models are automotive, mobility, production, logistics and sports. The human modeling considers in addition to objective parameters of load, also workload and subjective measures, as comfort and discomfort in the following projects:

- UDASim – Global Discomfort Assessment for Vehicle Passengers by Simulation (BMBF/KMU Innovativ, completed 2017)
- RAMONA – Realisation of Automated Mobility Concepts in Public Transportation (BMWi, started in July 2017)
- Truck 5.0 – Concepts of Truck Cabins for 2030/35 (MAN.TUM, started April 2016)

The RAMONA research project: Realisation of Automated Mobility Concepts in Public Transportation

By using autonomous buses, local authorities and operators hope to make public transport more efficient, safe and flexible. However, a number of questions are raised regarding the potential use of such vehicles: How do passengers deal with the new situation? What are possible opportunities and risks caused by automated and flexible mobility concepts? What frameworks are necessary for a successful application?

The research project RAMONA (Start: July 2017, End: June 2020) tries to answer these and other questions. The project will not focus on the technical feasibility of autonomous systems but rather on how automated mobility concepts can be integrated into existing public transport systems and how passengers will accept those systems. The project will work with a Wizard-Of-Oz method, in which the user thinks they are operating with an autonomous system. However, in reality, a hidden operator drives the bus. Alongside this investigation, the project consortium will perform virtual experiments to evaluate possible interaction and communication models between different
road users (e.g. pedestrian and bus) and to design the interior and exterior of an autonomous bus. The Chair of Ergonomics will work on this project together with the German Aerospace Center (DLR, Institute for Transport Research, Institute for Vehicle Concepts, and Institute for Traffic System Technology), the Hochschule Esslingen, the Berlin Transport Company (BVG), the Association of German Transport Companies (VDV) and the Berlin Senate Department for the Environment, Transport and Climate Protection.

**Truck 5.0 – Concepts of Truck Cabins for Future Vehicles**

In this day and age, the automobile industry has to manage a huge challenge: on the one hand, traffic and transport volume is increasing more and more; on the other hand fuel consumption has its limits. This trade-off is well known, but the problem it presents has not yet been solved. Particularly trucks with their high drag coefficient are not exactly known to be environmentally friendly. To improve the environmental footprint of the trucks, the legal length regulations will be changed so that the cabs have a more aerodynamic shape. An aerodynamic exterior design has a natural effect on the interior of the vehicle and consequently on the driver’s workplace.

Against this background and in the context of the three-year research project “Concepts of Truck Cabins for Future Vehicles” funded by MAN Truck & Bus AG, fundamental investigations into future drivers’ workplaces will be carried out. This fundamental investigation can be summarised in three main aspects; view and seating position, roominess and cabin layout, and ingress and egress motion. The subtopic ‘view and seating position’ focuses on the effects of the lateral and vertical movement of the seating position on the direct view of a truck driver. The work package ‘roominess and cabin layout’ deals with new cabin layouts and their impact on the driver’s feeling of roominess. Finally the truck ingress will be investigated in terms of motion strategies and the desired entering geometry.

**2. Automated Driving**

Next to the advances in sensor and actuator technologies, the human factors aspect of automated driving keeps on contributing towards the goal of self-driving cars. The Chair of Ergonomics has had its share so far in adding to the research base that will one day allow fully autonomous systems to be built. Complying with the international known SAE J3016 standard definition most research concentrated on Level 3 – conditionally automated driving, in which an automated system controls the vehicle in both lateral and longitudinal direction under normal circumstances. The challenge of successfully handing back the driving task to a human driver in case such a system reaches its functional limit has been and continues to be a complex endeavor. Multiple influences, like distraction through secondary tasks, basic trust in such systems and the danger of sleepiness through an insufficiently challenged human driver, have been the focus of research on highway roads. Pushing forward new environments, like urban areas as well as the interaction with a wider range of different traffic participants, pose new challenges for the development of automated cars.
In addition, new concepts of dividing the driving task between the machine and the human become the center of attention for the ongoing research. Finally, the human-centered approach of designing automated driving functions raises issues of how to take into account every driver’s individual preferences on the road.

PAKoS – Personalized, Adaptive, Cooperative Systems for Automated Vehicles

In three years’ time, the project PAKoS aims at introducing an automation manager capable of displaying the full use case of an automated vehicle. This process starts with the possibility for the driver to prepare the automated vehicle remotely via a smartphone app in a way that it already suits the driver’s personal preferences upon arrival. During the drive the aim is to monitor and identify the user state and then to use this information to adapt the automated driving functions appropriately. The third big part of PAKoS focuses on a new way of handling the take-over process during which the driver has to regain full control of the vehicle. Unlike the conventional binary switch from automation to driver, a cooperative approach is investigated, in which automation and driver simultaneously control the vehicle during the take-over process.

To tackle these interdisciplinary challenges, a consortium of nine German partners was formed: Karlsruher Institute of Technology, Technical University of Munich, Fraunhofer Institute of Optronics, System Technologies and Image Exploitation, Robert Bosch GmbH, BMW AG, Spiegel Institute Mannheim GmbH & Co. KG, Videmo Intelligent Video Analysis GmbH & Co. KG, mVise AG, b.i.g. security.

3. Interaction & Cooperation

The research group investigates interaction processes between a human agent and one or multiple cooperative partners. These partners can represent other humans as well as technological devices such as robots, vehicles or aircraft. In the context of cooperation, it is important to balance partially competing individual and shared goals of the parties involved, which can be achieved by diverse mechanisms of communication. Metrics are to be developed to allow for the performance-oriented assessment of cooperation across multiple domains. With regard to robots, effective strategies are required for both locomotive and evasive actions by designing legible and predictable movements. A robot’s motion can implicitly convey intentions to the human agent, who, visually perceiving and interpreting the respective information, reacts by performing certain movements themselves within
the shared space. The adequate design of movement strategies thus fosters the achievement of both individual and shared goals. In general, acceptance and trust of the human operator have to be considered in addition to the interpretation of human movements. Concerning automated vehicles, similar mechanisms apply to the design of driving behavior. To ensure smooth procedures, driving strategies must be unambiguous and easily recognizable to other traffic participants such as human drivers, cyclists, and pedestrians. Accordingly, methods have to be defined for the design and evaluation of unequivocal and safe trajectories.

Telepresence System for Wizard-of-Oz Studies

Automated and autonomously moving robotic systems are increasingly merging in human dominated areas and therefore will have to interact and coordinate with pedestrians in public and private spaces. The Human-Robot Interaction group (part of Cooperative Systems and Automation) at the Chair of Ergonomics applies a commercially available robotic telepresence system to investigate social interactions in Wizard-of-Oz experiments. The robot is controlled via keyboard, mouse or gamepad and hotkeys are programmed to enable repeatable robot movement behavior, initiated by the wizard. Present research activities target the identification and quantification of implicit (non-verbal) communication via movement cues of mobile robot systems. Based on the concept of legibility (behavior that leads to understanding the robot’s intentions) and predictability (behavior that meets the human observer’s expectations and lets the user anticipate future states), robotic movements are investigated and evaluated in quantitative (e.g. motion and eye tracking, physiological measures) and qualitative (e.g. questionnaires, interviews, video feed rating) studies with participants. For more information please do not hesitate to contact Jakob Reinhardt (Jakob.reinhardt@tum.de) or Jonas Schmidtler (jonas.schmidtler@tum.de).

The collaborative research project IMAGinE (Intelligent maneuver automation – cooperative hazard avoidance in real time) will develop new and innovative assistance systems which will support the cooperative driving of the future.

To realize the potential for cooperation between vehicles and between vehicles and the infrastructure major technological challenges need to be solved. IMAGinE will take on these challenges by – for the first time – implementing communication protocols for automated information exchange in real time as well as the alignment and the decision-making processes between intelligent systems and drivers. The human factors aspect in this project targets questions regarding the driver’s motivation to cooperate with other drivers and the driver’s acceptance of assistance systems that facilitate cooperative maneuvers.

While the research project is organized (vertically) into six sub-projects its contribution to current and future research endeavors in the field of connected and assisted driving becomes visible (horizontally) through five core innovations:

- Cooperative functions
- Shared environment perception model
- Communication mechanism for cooperative behavior
- Simulation environment for cooperative driving maneuvers
- Human-machine interaction

The project will run for four years – beginning on September 1, 2016. First results are available. The IMAGinE consortium is formed by twelve renowned companies and research institutions in Germany: Adam Opel AG (project coordinator), BMW AG, Continental Teves AG & Co. oHG, Daimler AG, Hessen Mobil – Straßen- und Verkehrsmanagement, IPG Automotive GmbH, MAN Truck & Bus.
PedSiVal – Cross Platform Validation of Pedestrian Simulators

Stimulated by technological progress and a growing concern for vulnerable road users, pedestrian simulators have become a valuable and flexible tool to analyze hazardous traffic constellations and the interaction with recent technologies (e.g. vehicle automation). At the same time, the abstraction inherent to any simulation results in differences between virtual and naturalistic environments, potentially altering human behavior and thus compromising the generalizability of experimental results.

To investigate the level of agreement in perceptual, decisional and motoric processes, PedSiVal employs a threefold approach:

- To assess the influence of technological characteristics, two diverse simulator settings are compared. While the French IFSTTAR employs a CAVE consisting of ten projection screens, at the Chair of Ergonomics the environment is displayed via a head-mounted device. Differences include the potential for stereoscopic vision and the visibility of the own body in contrast to an avatar.
- To evaluate more generally the employment of a virtual environment, human behavior on a test track is compared to a matching simulated environment.
- To gain insight into behavior biased neither by differences in perceptual cues, nor by observer effects or experimental artificiality, data from naturalistic traffic observations are gathered at various locations in Munich.

Identifying the kind and magnitude of potential differences is essential to allow for the sound and meaningful interpretation of existing results and to support the design of future studies promoting traffic safety and efficiency.

interACT – Designing cooperative interaction of automated vehicles with other road users in mixed traffic environments

As automated vehicles (AVs) will be deployed in mixed traffic, they need to interact safely and efficiently with other traffic participants. The interACT project will be working towards the safe integration of AVs into mixed traffic environments. In order to do so, interACT will analyze today's human-human interaction strategies, and implement and evaluate solutions for safe, cooperative, and intuitive interactions between AVs and both their on-board driver and other traffic participants.

Across three European countries (Germany, Greece, & the UK), data will be collected on how human traffic participants interact in real traffic conditions. Specific situations will be identified to enable meaningful comparisons. This data will inform the development of interaction models that identify the main communication needs of road users in future traffic scenarios incorporating AVs. These interaction models will then be used to improve software algorithms and sensor capabilities for recognizing the intentions of surrounding road users, and predicting their behaviours, enabling real cooperation between AVs and other road users. On the vehicle side, the AV itself will be controlled by a newly developed Cooperation and Communication Planning Unit that integrates the planning algorithms, provides synchronized and integrated interaction protocols for the AV, and includes a safety layer that is based on an easy-to-verify software with novel methods for fail-safe trajectory planning. In addition, the interACT project team will use a user-centered design process to develop, implement and evaluate novel human-machine interaction elements for communicating with surrounding road users.

interACT results will be demonstrated using driving and pedestrian simulators and two vehicle demonstrators.
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 of 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
- Arbeitswissenschaft/Ergonomics
- Produktergonomie
- Produktionsergonomie
- Softwareergonomie
- Menschliche Zuverlässigkeit
- Ergonomisches Praktikum
- RAMYSIS Praktikum
- Versuchsplanung & Statistik
- Human Factors of Automated & Cooperative Driving
- Interaction Programming & Prototyping

Selected Publications 2017
Bioseparation Engineering

Process development and intensification, particle technology, 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 COMSOL and COSMO-RS for modelling and simulation.

2017 was a particularly successful year for the Bioseparation Engineering Group. The small group can look back on three completed Ph.D. theses, seven peer-reviewed papers, and one patent application. In addition, we launched two new third-party funded projects with various academic and industrial partners. In one project, we focus on a multi-scale approach to better understand a potential-controlled chromatography for process intensification. In the second project, we work closely with industry to establish a new sustainable process for purifying small protective solutes.

New Stationary Phases

New stationary phases are essential in bioseparation sciences; classical phases are already well developed and reach 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
- New conductive materials for potential-controlled chromatography
Bioseparation Engineering

**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 in the whole of the separation step.

![Structure of Paxlitacel (drug to treat cancer)](source: Ljubomir Grozdev, M.Sc.)

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**
- BMBF Biotechnology 2020+ initiative – rational design of peptide-surface interactions
- Design of new affinity tags for the purification of recombinant proteins
- Development of new stationary phases for antibody purification

**Process Development**

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

**Projects**
- BMBF Project – HOBBIT – Development of a sustainable separation process for purifying small protective solutes
- BMBF e:Bio initiative – SysBioTerp – innovative strategies for a sustainable production of bioactive molecules
- BMBF Project – S3kapel – Multiscale simulation for electrochemical separation processes

![Hydrodynamics in a packed bed chromatography](source: Lukas Gerstweiler)
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

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, OpenFoam, 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)
- 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 2017
- Schoemig V, Isik E, Martin L, Berensmeier S: Solid liquid extraction of porcine gastric mucins from homogenized animal material, RSC Adv., 2017, 7, 39708-39717
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 has become the number one renewable source of energy in the world, and it is expected to play an ever-growing 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 a multidisciplinary and a system-engineering point of view. Some of the most exciting on-going projects at the institute are briefly described in the following.

Design of Wind Turbines

The design of wind turbines is an extremely complex multi-disciplinary 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?
- Will future extremely large blades look similar to the current ones, or are there better and possibly radically different ways of designing blades?
- How can we hedge against the myriad uncertainties that plague the design and operation of wind turbines and farms? How can we achieve more robust designs and reduce safety factors?

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’

Blade of a 3.4MW wind turbine designed by WEI researchers for the international collaborative project IEA Wind Task 37 on wind systems engineering.
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 by 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 is the use that 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?

### Projects

- 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’

### Experimental Testing

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?

Top: LES simulation of a single G1 wind turbine; bottom: wake interactions for three aligned G1 wind turbines.
Wind Energy

Experimantal activities at WEI are not limited to scaled testing. In fact, within a joint project with the research cluster WindForS (Windenergie-Forschungsschwerpunkte), we are working on the development of an experimental test site in complex terrain. The test facility, funded by the German 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.

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, respectively of 1 and 0.6 meters of diameter) 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 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-Forschungsschwerpunkte), we are working on the development of an experimental test site in complex terrain. The test facility, funded by the German 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.

Projects

- BMWi project ‘WINSENT – Wind Science and Engineering in Complex Terrains’
- EU H2020 project ‘CL-WINDCON – Closed Loop Wind Farm Control’
- Industrial project ‘Wind Farm Control’
- Industrial project ‘Development and Testing of Scaled Offshore Wind Turbine Models’
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 turbines 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 the use of cooperative control, can we mitigate wake losses or reduce loading? Does the use of smart cooperative control lead to new ways of designing future wind farms? And, by using cooperative control, can we also improve the way existing wind farms operate today?
- Can we operate wind farms in a way more similar to what is done for other conventional energy sources, and can this help in the integration of a higher share of wind in the grid?
- What knowledge on the 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?

Projects

- EU H2020 project ‘CL-WINDCON – Closed Loop Wind Farm Control’
- BMWi project CompactWind ‘Erhöhung des Flächenenergieertrags in Windparks durch avancierte Anlagen- und Parkregelung’
- 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’
- One Ph.D. position (Chinese Scholarship Council)
Wind Energy

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Research Foci
■ Modeling and simulation of wind energy systems
■ Multidisciplinary design
■ Aeroservoelasticity, loads and stability
■ Control of wind turbines and 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
■ Aeroservoelasticity

Selected Publications
We were very proud that SGL Group has renewed its commitment to endowing our Chair of Carbon Composites (LCC) at the Technical University of Munich (TUM), which began eight years ago. The agreement for a six-year extension was signed by TUM president Prof. Wolfgang A. Herrmann and the SGL Group’s CEO, Dr. Jürgen Köhler in February 2017.

As another highlight in 2017 more than 20 doctoral candidates completed their doctoral theses at our chair. We are very delighted that most of our graduates are entering the industry and broadening the network to our industrial partners.

Process Technology for Fibers and Textiles

The Process Technology for Fibers and Textiles group focuses on improving manufacturing technologies that arrange the fibers in their desired orientation within a composite component. The group’s three research teams cover the fields of braiding technology, automated fiber placement and tailored textiles. With highly developed processing equipment, the fibers can be brought into shape in an automated and reproducible way.

Team Braiding Technology – Third Prize at the AVK Award

The Industrievereinigung Verstärkter Kunststoffe e.V. (AVK) celebrated their Innovation Award on 18th September 2017 at the 3rd Composite Congress during the 12th Composite Europe in Stuttgart. The Chair of Carbon Composites (Technical University of Munich) won the category ‘Processes & Procedures’ in cooperation with the industrial partner Munich Composites GmbH, a spin-off of the chair which develops and produces high performance composites. The partners submitted an innovative process to produce carbon fiber bicycle rims. Hand lay-up of prepeg, the de facto standard in sporting goods manufacture, is a very labor intensive and hence expensive process. Instead the new process uses a combination of automated winding and braiding with subsequent RTM injection. A specifically developed removable core system enables consistent net shape preforming and a high fiber volume content. With the new process, it is possible for Munich Composites to competitively produce CFRP bicycle rims in Germany in an affordable price range. AVK regarded this innovative process worthy of their prestigious award.

LCC managed to win an AVK Award for the third time in a row after being awarded with first prizes in the ‘Research and Science’ category in 2015 and 2016.

Team Automated Fiber Placement

The Chair of Carbon Composites (LCC) at Technical University of Munich (TUM) 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 rocket mission and is now ready for the launch in March 2018.
Reducing the structural weight of a rocket allows higher payloads, higher apogees or reduced fuel consumption. DLR operates sounding rockets to perform experiments during its sub-orbital flight. The modular structures of these rockets are typically made out of aluminum. To increase the performance of the rockets TUM has developed and implemented a manufacturing concept for a thermoplastic CFRP-module with integrated fiber optic sensors as part of a project funded by the Federal Ministry for Economic Affairs and Energy.

A module consists of a thin cylindrical shell with bulky load input rings on both ends as a bolting interface to the neighboring modules. The manufacturing was split into separate steps for the load input rings and the cylindrical shell. The rings were manufactured by pressforming of long fiber reinforced thermoplastic granules (LFT). Thermoplastic automated fiber placement (TP-AFP) was used for the manufacturing of the shell structure. The closed loop control of the TP-AFP process parameters allows an in situ consolidation of tapes on the substrate and on the previously manufactured load input rings. This way there is no need for a subsequent consolidation in an autoclave. Polyetheretherketone (PEEK) was used as a matrix polymer due to the high mechanical and thermal loads.

**Public Funded Projects**
- AIF project ‘FullCycle’
- AIF project ‘Accurat 3’
- BMBF project ‘MAIsandwich’
- BMBF project ‘InSensoFlecht’
- BMWi project ‘AirCarbon2’
- BMWi project ‘TELOS’
- BFS project ‘ISP’
- DFG project ‘DR 204/10-1’
- EU project ‘INSCAPE’

Test Set-up with integrated CFRP-module representing a major milestone in the REXUS mission XXIII

**Process Technology for Matrix Systems**

The Group ‘Process Technology for Matrix Systems’ addresses the robust and efficient processing of matrix systems for the production of continuous fiber reinforced composite parts.

On the one hand, the basic understanding of matrix systems, the characterization of impregnation properties of the fiber material for optimized processing, and process engineering are central for the group. On the other hand, associated issues such as tool technology, surface sealing, and process integration are key activities of the group.

**Team Processes and Production Systems**

The Chair of Carbon Composites is represented in the steering committee of the Competence Cluster for Additive Manufacturing of the Department of Mechanical Engineering to address composite materials for high temperature applications. The investigations are focused on the processing method called fused filament fabrication (FFF). The main target has to be to change the part design approach to maximize the benefit of the increased freedom of design and potential of additive processing.

Constructions like ‘gyroids’ for example can combine features like heat exchange with mechanical load to multi-functionalize the structure (see figure). These constructions show the new freedom of design, without limitations for tool access, for printed parts to address new business
opportunities for highly complex and functional parts. Additionally the LCC is participating in Solvay’s AM Cup and has been chosen as one of eleven finalists from all over the world. The AM Cup is a competition for processing new PEEK materials comparing maximum achievable mechanical properties, freedom of design, detailing and testing capabilities. Through the AM Cup, Solvay aims to find an institute capable of advancing their research to further industrial impact.

Team Hybrid Materials and Structures – LCC Winner of JEC Innovation Award
Forward Engineering GmbH has applied on behalf of a project consortium consisting of KraussMaffei Technologies GmbH, Alpex Technologies GmbH, DIEFFENBACHER GMBH, SAERTEX GmbH & Co. KG, Henkel AG & Co. KGaA, Albert Handtmann Metallgusswerk GmbH & Co. KG and the Chair of Carbon Composite (TUM) for this year’s JEC Innovation Award for the development of a T-RTM roof frame. The consortium has been awarded during the JEC show in Paris in the category ‘Automotive, structural’. The production of the roof frame was demonstrated for the first time during the K 2016 with live production in two minutes cycle time at the booth of KraussMaffei. The result is a cost-efficient roof structure, made of hybrid textiles in multi preform, functional resin areas and integrated metal inserts out of one tool. The new near-net-shape technology for shell-shaped components is a further highlight to minimize material- and process cost.

Material Behaviour and Testing
The group ‘Material Behavior and Testing’ focuses on the investigation of the material response of fiber-reinforced polymer matrix composites. At the testing laboratories of the LCC a broad spectrum of state-of-the-art test methods and equipment is available, covering thermo-analytical methods, rheology and microscopy, experimental methods to measure permeability and drapeability of UD and textile preforms, as well as static and high strain rate mechanical testing. The DeMAnD project as a highlight was set up to carry out a mechanical material characterization program to deliver a dynamic material property data base for typical aircraft materials, with a special focus on seat and crash absorbing structures of small aircraft. For a number of aluminum and steel alloys, fiber-reinforced polymer matrix composites and foam materials, dynamic tests will be carried out over a wide range of strain rates, ranging from quasi-static loading up to high strain rates of 500 s⁻¹. The project brings together renowned experts in the areas of test method development, static and dynamic testing of aircraft materials and structures as well as simulation and design of aeronautical crashworthiness structures. For each strain rate regime, the optimal test equipment was identified and is available within the consortium. The equipment ranges from standard universal testing machines (quasi-static loading) to special servo-hydraulic high speed testing machines (medium strain rates) to split-Hopkinson bars (high strain rate testing). This ensures the determination of high quality material data and complete stress-strain curves from static up to high strain rate loading, allowing the derivation of the strain rate dependent material behavior for all material properties needed for predictive crashworthiness simulations.

Public Funded Projects
- AIF project ‘DRAHT’
- AIF project ‘Vertis’
- AIF project ‘Slokav’
- AIF project ‘SchwingIn’
- EU project ‘ImCoLoR’

Public Funded Projects
- COMET K1 v-3.08
- EU project ‘DeMAnD’
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Dipl.-Ing. Swen Zaremba

Research Focus
- Process technology for fibers and textiles
- Process technology for matrix systems
- Simulation
- Material behavior and testing

Competence
The 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 labor
- Computing cluster

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 2017
Materials Handling, Material Flow, Logistics

Basic and applied research in logistics engineering

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

Digitalization and automation are two mega trends in logistics. Rapid progress in digitalization enables a deep link of information between production and supply. Therefore, optimized systems which dynamically consider more accurate location, state and demand data in real time and without failure can be achieved even under volatile circumstances. A broad study conducted by the chair fml shows that static control approaches are predominant in present systems and, moreover, that automated in-plant milk-runs are exceptional cases, though discussed a lot. The chair fml therefore develops dynamic algorithms implemented in a control system and sets up a modular prototype showing different automated handling units which merge to form an autonomous in-plant milk-run.
Sustainable Logistics Systems

As one of last year’s mega trends a huge focus in industry lies on sustainability which is also affecting logistics operations. That is why the chair fml likewise works on related projects; for example, the project FFZ70 described below. Following on from the pilot project H2Intradrive the new project is mainly about economically efficient fleet operation of hydrogen-powered industrial trucks. Using battery-operated trucks in intralogistics presents various disadvantages, such as long loading times, that can be eliminated by retrofitting to energy efficient fuel cell systems. Combined with installing the related hydrogen infrastructure they form a sustainable and highly available technology. Previous projects often lacked profitability and were accompanied by complex modifications; standardized and efficient solutions ready for the market do not yet exist. The project partners thus aim to elaborate ample concepts for economical efficiency, service, interfaces, lifetime validation, a plug-and-play solution and a general standardization of processes.

Projects
- FlexiFuel (EU)
- PräVISION – Methodenentwicklung zur präventiven Steigerung der Arbeitssicherheit an Flurförderzeugen mit Umsetzung eines Assistenzsystems durch Fusion und Analyse von 2D- und 3D-Bilddaten (DGUV)
- Teilautomatische Palettenaufnahme als Fahrerassistenzsystem für Flurförderzeuge (Jungheinrich)

Innovative Conveyor Technology

A pallet pick-up assistance system uses 3D camera input to assist forklift drivers.

Pallet pick-up is a standard task in intralogistics scenarios mainly performed by forklifts. Inexperienced drivers and drivers with time pressure in business operations can damage the pallet or goods with the forks when entering the free openings of a standard pallet. To avoid such damage, a novel advanced driver assistance system (ADAS) is developed to assist the driver while picking up a pallet. The new ADAS detects the target pallet with a 3D camera. Based on the determined relative position between the pallet and forklift an optimal trajectory for a collision-free pick-up is calculated. The ADAS takes over the entire steering function to ensure that the forklift follows the trajectory correctly. Driving and brake pedal are still operated by the driver. The steering function is returned to the driver after the pallet has been picked up. The aim of the research project is the construction of a prototype to show the technical feasibility.

Projects
- Entwicklung von Energieeffizienzklassen für Regalbediengeräte (IGF)
- FFZ70 – Einsatz von 70 wasserstoffbetriebenen Flurförderzeugen im BMW-Werk Leipzig (BMVI)
- Lebenszykluskosten intralogistischer Systeme (Jungheinrich)
Especially in the beginning, technology-oriented startups often focus on key issues like technical development, financing and marketing. They often consider logistics aspects only in a later development phase, when a lot of money, capacity and manpower have already been spent on special processes, unfavorable supplier contracts or inefficient storage of material. To give advice on how to create efficient logistics, the chair fml develops a flexible logistics concept for technology-oriented startups called ‘StartupLog’. This concept grows with the startup and is especially tailored to its requirements. The basis is a development model which defines the development stages of technology-oriented startups. Using different characteristics and indicators a startup can easily classify itself into one of the phases and can derive the logistics challenges that currently have to be considered. For each logistics challenge, startup-specific methods are developed in the project, which will be summarized in a guideline.

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 within this field are both the development of new calculation methods for mobile cranes in order to significantly increase calculation accuracy and the realization of user-oriented control systems to simplify crane operation. Many crane types are operated with radio controls that allow free operator movement while moving the load in the desired way and thus assure maximum flexibility and safety. However, the operator still needs to calculate the individual movement for each drive in a way that the hook movement matches the operator’s wish. Depending on the number and type of drives (e.g. slewing, trolley movement, hydraulic cylinders) this calculation requires a substantial amount of experience and con-
centracy effort and hence causes fatigue problems that result in safety issues and high manipulation times. The research project ‘Intuitive Crane Control’ aims to develop a human machine interface that automatically takes both crane design (number of drives, crane kinematics) and operator orientation into account and thus allows the operator to directly control the hook movement from his point of view. As a result, the operator no longer needs to calculate the individual movement of each drive. Instead, he uses the remote control levers to move the hook in an intuitive way with a single lever movement in the desired moving direction. Consequently, crane operation becomes significantly faster, safer and easier to learn.

Projects
- Intuitives Laststeuerungskonzept – Entwicklung eines intuitiven Steuerungskonzept für Lasthebemaschinen (IGF)
- Systematischer Vergleich der dynamischen Beanspruchungen von Gittermast-Fahrzeugkranen mit den Ergebnissen der quasistatischen Auslegung nach DIN EN 13001
- Abbildung der dynamischen Beanspruchungen von Fahrzeugkranen und Lkw-Ladekranen in quasistatischen Berechnungen (DFG)

The growing number of global competitors requires companies to be highly innovative and willing to invest. While large companies can absorb R&D investment through their sales volume, this investment is often not feasible for small and medium-sized enterprises (SME). In order to enable SME to exploit the potential offered by digitalization, the project Mittelstand 4.0 raises awareness of the benefits and opportunities of Industry 4.0 and helps companies to develop the skills required for a successful implementation.

For this purpose, the chair fml as part of the Mittelstand 4.0 center participates in the realization of a Mittelstand 4.0 mobile, which is a truck equipped with various Industry4.0 demonstrators for live experiences at local companies and events. Furthermore, the Mittelstand 4.0-Akademie offers versatile qualification measures. To set examples for a successful implementation, small projects are carried out in different SME. The focus of the chair fml in these projects is to show how the quality and efficiency of logistics alongside the production chain can be improved by using digital technologies.
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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

Infrastructure
■ 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

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
■ Development Process for Mobile Machine Tools
■ Conveying of Bulk Goods
■ Planning of Intralogistics Systems in an International Context

Publications 2017
Mechanics and High Performance Computing

Parallel algorithms and high performance computing in computational continuum mechanics

Research activities of the Mechanics & High Performance Computing Group in 2017 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.

Hybrid Preconditioning for Surface-Coupled Problems

When solving coupled problems in a monolithic fashion, powerful preconditioning techniques are crucial to obtain an efficient solution scheme. In our group, we are interested in monolithic solvers for fluid-structure interaction problems, where a fluid and a solid domain exchange coupling information at their common coupling surface. Starting from well-established physics-based block preconditioners, that are known to accumulate the error at the coupling surface, we developed a novel hybrid preconditioner. It is based on an overlapping domain decomposition, that purposely exhibits subdomains that span across the fluid-structure interface. By performing cheap but accurate subdomain solves in an additive Schwarz manner in combination with the existing physics-based block preconditioners, the number of iterations of the linear solver as well as the total solution time could be reduced remarkably. Furthermore, scalability of the proposed methods has been demonstrated.

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. Since it is impossible to exactly specify a simulation model on a patient-specific basis, the best one can do is to incorporate all available information into the model in a probabilistic manner. This knowledge often stems from noisy input parameters or is based on posterior statistic from Bayesian inference. We are working on efficient UQ strategies that are able to represent uncertainties in personalized simulations and quantify their effects on the quantities of interest.
Mechanics and High Performance Computing

Functional Modeling of the Heart and an Extravascular Assist Device (VAD)

Due to the decreasing number of transplantable hearts and deficiencies in current heart-assist device technologies, novel concepts for 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.

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 a resulting heart insufficiency. At the same time, heart transplantations are limited to the amount of donor organs, which has been declining during the past decade. A promising technology is 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 develop an 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.
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.

Parametric model order reduction for large scale problems

Model order reduction (MOR) is a technique under current research, which aims at a decrease of computational effort in large-scale problems. The basic idea is to find a low dimensional subspace for the problem’s solution, while at the same time the quality of the solution shall be retained in comparison to a direct solution of the large-scale problem.

We aim at developing a MOR framework for finite element mechanical analysis of abdominal aortic aneurysms. The reduction shall be performed for material as well as geometric parameters determining the mechanical properties as well as the geometry of the aneurysms. The intended framework faces several complexities such as model nonlinearities, patient-specific geometries and the guarantee of small error bounds.
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. The groupwise statistics for the classification require the estimation of an averaged geometry, a template, of both the symptomatic/known ruptured (rupture-prone) and asymptomatic AAA cohort found in the exemplary database. Then, each template is mapped to every AAA surface of both cohorts. The mapping properties are used for the classification and to understand the shape variability of each cohort.

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 wrong 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, mechanobiology of AAA, morphing strategies for the positioning of the SG and material modeling of the superelastic behavior of nitinol.
Research Focus
- High performance parallel computing and efficient algorithms
- Parallel algorithms and scalable software
- Inverse problems
- Numerical models in vascular biomechanics and mechanobiology

Competence
- Computational continuum mechanics
- Design and realization of parallel software
- Coupled multifield problems
- Algebraic multigrid methods
- Biomechanics and mechanobiology
- Soft image registration and inverse problems

Courses
- Engineering Mechanics 1 (B.Sc Engineering, MSE)
- Engineering Mechanics 2 (B.Sc. Engineering, MSE)
- Advanced Parallel Computing and Solvers in Engineering (M.Sc. Mech. Engineering)
- Nonlinear Continuum Mechanics (M.Sc. Materials Science & Engineering, MSE)

Peer-Reviewed Publications 2017
Non-destructive Testing

Quality control, non-destructive testing and structural health monitoring

The focus of the Chair of Nondestructive Testing in the field of mechanical engineering in 2017 was to establish NDT methods for the inspection of fiber reinforced materials (CFRP and GFRP) together with partners in the automotive and aeronautic industries.

Further research is 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 constructions of the infrastructure, the development of self-healing techniques for concrete 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.

Computed Tomography of Otto Lilienthal's Gliding Apparatus

More than 125 years ago, Otto Lilienthal laid the foundation for modern aviation with his innovative gliding apparatus, the ‘Normal Segelapparat’. Only four specimens of the gliding apparatus have survived to this day, one of them at home in the Deutsches Museum in Munich. Computed tomography investigations carried out by the Chair of Non-destructive Testing in collaboration with Airbus have for the first time provided a glimpse into the inner workings of the construction design. The images will help researchers and conservators from the Chair of Restoration, Art Technology and Conservation Science as well as the Deutsches Museum during restoration.

Self-healing Materials

The aim of this project is the development of structures made of self-healing concrete having an inherent healing mechanism that becomes active when a crack appears, thus rendering manual crack repair completely obsolete. In order to obtain such automatic crack closure, European project partners are investigating the use of PU-based polymer precursors, superabsorbent polymers and bacteria. The role of the Institute of Non-destructive Testing is to support the design of such healing agents as well as the development of testing methods as tools for the stakeholders to prove self-healing efficiency. Experimental results of small-scale tests confirm the capability of selected NDT methods to characterize material properties plus the healing process and its efficiency.
Non-destructive Testing

Concrete Pavement 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, for example, horizontal cracks or delaminations within the pavement structure due to heat-induced stress or detrimental chemical influences. Although several non-destructive testing methods can be applied to concrete pavements most of the conventional techniques like ultrasonics 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 is financed by the German Federal Highway Research Institute (BAST), under the authority of the Federal Ministry of Transport and Digital Infrastructure (BMVI).

Simulation of wave field in concrete plate and radiated sound waves.

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. This task will be achieved not only with standard non-destructive methods like acoustic emission analysis and ultrasound transmission methods but also with coda-wave interferometry.

Concrete cylinder during compression test
Non-destructive Testing

MISTRALWind

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 aim, a concept for inspection and monitoring of structural parts of wind turbines is 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 is 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 have successfully been applied to a full size 3 MW Wind Turbine. The results are 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 will be 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 is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi).

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 in 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. In cooperation with industrial partners, new approaches to computed tomography are developed as well. In order to complete the picture of the processes during testing, numerical simulations using the Finite Element Method are conducted alongside the experimental work.

Hydro Acoustic Tracking Concept

In order to monitor the migration of fish, especially downstream of hydro-power plants, the development of a hydro-acoustic measurement concept is the goal of the project. A tomographic approach is therefore necessary to cover a finite volume of water. The built-up prototype showed promising results during test measurements at a model plant of the Obernach Research Institute (Chair of Hydraulic and Water Resources Engineering).
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
- NDT Seminar

Selected Publications 2017
- Iliopoulos, Sokratis N.; Malm, Fabian; Grosse, Christian U.; Aggelis, Dimitrios G.; Polyzos, Demosthenes (2017): Concrete wave dispersion interpretation through Mindlin’s strain gradient elastic theory. The Journal of the Acoustical Society of America 142 (1), 2017

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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 built up strongly, with respect to both human resource and research activities 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 General Electric (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 GE, MTU Aero Engines, Rolls Royce 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. Each of these is 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 turbine 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 a 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 be of active type. 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 facility FRANCC (Fundamental Research and New Concepts Compressor) is 2020. Stability enhancement on compressors is an area of research, which the institute has been pursuing since year 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 Impulsau blasung und Einsaugen (2015-2018, AG Turbo, Cooreflex, Vorhaben 1.1.6)
- Conceptual Design and Build of a Large-Scale Low-Speed Research Compressor Rig (2017-2020, LTF PV)
- 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 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 a key topic in current and future research, carried out on a whole helicopter engine, individual compressor components, or most simply in a wind-tunnel arrangement. On the numerical side, 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 also be 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 experimentally investigated. 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.

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)
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 of the aerodynamic behavior may be identified – again, research is required to develop multi-disciplinary approaches and simulations, which allow the opportunities given in this field to be taken. 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 is focused on the quantification of the benefits and the conceptual design of novel heat exchanger geometries, which allow better matching of the required engine architecture and the desired reductions in weight and size. In this context, additive manufacturing methods are expected to provide the ability to geometrically optimise the aero-thermal design features of heat exchangers. Also, integration of heat exchangers with adjacent components such as compressor stages is being adressed within the scope of the advanced design and make concepts research. Beyond this, enhanced methods for heat exchange/transfer were investigated. Numerical modeling of the thermo-structural behavior of turbine disks with integrated heat pipes has been carried out, which demonstrated the large potential of this heat management approach.

Projects

- Advanced Seal Design (2016-2018, EU, FlexTurbine, WP3)
- Conceptual Design and Numerical Investigation of Novel Inter-Cooling Heat Exchangers (2017-2020, LTF PV)
- Options of Rotor Drum Life Monitoring in Large Steam Turbines (2017, IA)
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 engine in a stable and efficient way across the entire flight envelope. Part of the 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 at supersonic conditions into the outer portion of the radial compressor of the engine. It is tested on the institute’s Allison 250 testbed. The novel system allowed a reduction in the starting time of the engine from approximately 25 seconds down 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 a real helicopter environment.

Projects
- Konzeption und Erprobung eines Schnellstartsystems für Hubschraubergasturbinen am Beispiel der Allison 250 (2013-2017, LTF PV)
Turbomachinery and Flight Propulsion

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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 2017
- Inzenhofer, André; Haikonen, Joona; Hupfer, Andreas (2017): Multi-objective topology optimization with the sko-method 6 (14), p. 387. DOI: 10.1007/s00158-017-1757-6
- Tobias Schmidt, Sina Eisenmann, Velislav Velikov, Andreas Hupfer, Volker Gümmer: Analysis of an Auxetic Casing Structure for Tip Clearance Control under Various Temperature and Pressure Conditions. ISABE Conference 2017
- Zimmermann, A.-L., Giepman, R. H. M., Nguyen Tran, Q. T., Aalburg, C., Gümmer, V.: Design of a static test rig for advanced seals and air bearing testing. ISROMAC Conference 2017
- D. Paukner, J. Nowak, V. Gümmer, O. Haidn: Improved flammability for hydrogen fuelled scramjets with preinjection catalytic radical farming. ISABE Conference 2017
- André Inzenhofer, Thomas Lahni, Volker Gümmer, Bernd Becker, Patrick Grothe, Frank Heinichen: Using Annulus Contouring to Compensate Compressor Mis-Matching Effects in the Presence of Casing Treatments. ISABE Conference 2017
Space Propulsion

Liquid propellant rocket engine technologies

In 2017 our focus in the field of space propulsion has been equally distributed between experimental and numerical research into various aspects of injection, ignition, combustion and heat transfer in methane/oxygen combustion applications for rocket engines. Particularities of cryogenic injection and atomization under low pressure conditions and an ignition system based on resonance phenomena have been investigated within a project jointly funded by the Brazilian CsF, the Chinese CSC, Munich Aerospace and TUM. Studies of the behavior of methane/oxygen injectors towards their impact on flame dynamics, combustion performance and heat transfer were the key topics within projects funded by DFG, BFS and Ariane Group. In addition, the group continued its effort in design and operation of turbo-pump components for liquid propellant rocket engines.

Prof. Dr. Haidn was invited as a keynote lecturer to four international propulsion conferences among which the 38th APTIS Conference in Dalian, China was the most prestigious. In addition, the Harbin Institute of Technology, a member of the Chinese C9 League Universities appointed Prof. Dr. Haidn as Guest Professor.

Rocket Propulsion Technologies

In the field of rocket propulsion technologies, the group is focusing within 3 different projects funded by DFG and BFS on numerical as well as experimental aspects of methane/oxygen combustion, a propellant combination which has recently seen increasing interest worldwide. An aspect all three projects have in common is the desire to further the understanding of dominating phenomena behind injector/injector and injector wall interaction which are key for flame dynamics and combustion stability and heat loads to the combustion chamber walls. Studies on flame anchoring process and flame dynamics for various injection conditions and start sequences have clearly revealed the importance of an appropriate timing of the injection conditions during engine start-up for flame anchoring and combustion stability, see Figs. 1-3 which show a sketch of the experimental set-up, an image of the anchored flame and the impact of the propellant mixture ratio on the axial distribution of the flame emission intensity. Specifically designed experimental single (Fig. 1) and multi-injector setups (Fig. 4) allowed us to identify and quantify phenomena unique for this propellant combina-
tion such as the necessity to not only resolve the velocity and temperature boundary layer to values smaller than $y^+ < 1$ but take into account the finite rate chemistry in sufficient detail which have been missing in almost all numerical tools applied so far for such applications. This finding is an outcome of a modeling workshop with international participation of renown experts such as the Japanese Space Agency (JAXA) and the Ariane Group particularly dedicated to identify strengths and weaknesses in numerical models and tools. Fig. 5 demonstrates the temperature stratification in the combustor but shows as well the majority of the heat release has already taken place within the first 200 mm of the combustion chamber, a fact which is validated by the wall pressure profiles, see Fig. 6, where after the steep decrease within the first part of the chamber, the rate of decrease becomes nearly constant after 200 mm.

Technologies for Green In-Space Propulsion

A key problem of in-space propulsion systems is the transient start-up period of such thrusters since during the first phase the propellants are injected into the combustion chamber at very low pressures which enforces flash vaporization of the fluids since although at cryogenic temperatures the propellants are in a state superheat, see Fig. 7 which shows the nucleation barrier as a function of the bubble diameter and the rainbow signal of a single droplet.
The group applied a modified global rainbow refractometry to investigate the cryogenic propellants spray droplets (i.e. liquid oxygen, liquid methane and, for comparison reasons, liquid nitrogen). The refractive index and the probability distribution of the droplet sizes are retrieved from the global rainbow pattern with the inversion methods using the complex angular momentum scattering theory, see Fig. 8 which shows the measured rainbow signal of a liquid methane and liquid oxygen spray, respectively. A detailed evaluation of the results shows that the deduced temperatures from the rainbow signal agree well with the temperatures measured by thermocouples, with discrepancies less than 7.5% for the tested sprays at temperatures ranging from 80K to 110K. The temperature measurement uncertainties are analyzed to be within ±1.0K. Applying Saengkaew’s methods, the inversed droplets size distribution shows bimodal or even multimodal characteristics in the measurement probe volume, see Fig. 9.

Interestingly, the flashing experiments revealed the formation of solid nitrogen and methane but not of solid oxygen, a behavior which can be easily attributed to the differences in thermos-physical properties of these molecules.
The research activities of the group are part of the project KonRAT at the Ludwig Bölkow Campus: ‘Komponenten von Rakentriebwerken für Anwendungen in Transportsystemen der Luft- und Raumfahrt’. The partners in this project strive to create a professional network including universities, research institutions and industry in order to enhance the competences in the fields of turbopumps for liquid rocket engines and powder-based additive layer manufacturing for space applications.

A design methodology for each component of the turbopump, i.e. inducer, impeller, volute and turbine, has been developed. With the help of numerical simulations the design of the turbopump components is optimized within an iterative loop. Thereby detailed flow analyses play a crucial role for targeted geometry modifications and new design concepts. Fig. 10 provides an overview of our approach to start with flow analyses for all the different components and once a promising performance is found for these, in a second attempt analyses are performed for a setup where all components are linked together.

The experimental investigation of turbopump components is an essential step in order to evaluate the capability of new turbopump designs. Therefore, a new test bench has been developed and installed at the facilities of the Division Space Propulsion where it is possible to investigate pump components with respect to their hydrodynamic properties as well as their cavitation behavior, see Fig. 11.

The experiments are performed under subscale conditions with reduced rotational speeds and with water as a surrogate for the cryogenic fuels and oxidizers commonly used in liquid rocket engines. Based on a scaling logic, that has been developed as well, this approach allows integration of experimental data as early as possible in the design process of newly developed pump components. The research performed at this test bench focuses on the operational stability of pumps over a wide range of operating conditions and operation in off-design conditions.
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
- Raumfahrantantriebe 1 (Grundlagen, SS)
- ZÜ Raumfahrantantriebe 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 Raumfahrantantriebe (WS, SS)

Publications
Journals
- Silvestri, S., Kirchberger, C., Schlieben, G., Celano, M.P., Haidn, O.J., Experimental and Numerical Investigation of a Multi-Injector GOX/GCH4 Combustion Chamber, accepted for Transactions of the JSASS, Aerospace Technology Japan

Invited Conferences
Helicopter Technology

Performance, efficiency and safety for rotorcraft

Helicopter rotor blades operate in a wide range of flow conditions, but with a fixed geometry which is optimized only for a small sub-set of the complete flight regime. An obvious way to increase the efficiency of conventional rotors would be an adaptive blade geometry which allows selection of the optimal shape in terms of power or thrust. The European Commission has awarded a research contract to a team of universities and research institutions including the Institute for Helicopter Technology to investigate solutions for morphing rotor blades during the coming 42 months. A group of four researchers will develop models for such morphing structures and validate their simulations with experimental results.

Rotorcraft Downwash and Dynamic Interface Modeling for Real-Time Simulations

Rotorcraft downwash – as the flow field below the rotor disc is usually called – and more specifically its effect on the aircraft is perceived by pilots as so-called ‘ground effect’. In simulation models, this effect is mostly represented by a dependency of the lift on the distance between rotor and ground. Pilots operating on ship decks, oil rig platforms or wind energy platforms experience, however, a time-varying version of this ground effect which requires higher piloting skills and more training. Commercial pilot training simulators do not represent this dynamic behavior at a satisfactory level since they lack physics-based downwash models. The Institute for Helicopter Technology has realized the coupling of a novel Lattice-Boltzmann based fluid simulation model with external air wake – from ship decks, platforms, etc. – and rotor aerodynamics (inflow) modeling, including the feedback on the flight dynamics and handling qualities for piloted simulation of rotorcraft. A research grant from the U.S. Office of Naval Research enables a cooperation with the U.S. Naval Academy and the George Washington University who contribute valuable experimental data to support and validate our simulation results. Funded by the German Ministry of Economic Affairs and Energy, this modelling approach is additionally pursued with a target application on platforms in offshore windfarms. Partners are DLR and the Universities of Stuttgart and Tübingen.

Modelling and Testing of Counter-Rotating Rotors

Co-axial (also known as counter rotating rotors) are still a rare species of rotorcraft. 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 interaction 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 available: An ultra-light (max. 450kg) 2-seater rotorcraft is modelled, flight tested and evaluated under 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. But co-axial rotor configurations are also viable candidates when aiming at the high-speed flight regime. Therefore, the existing cooperation with the University of Texas has been continued under the umbrella of VLRCOE.

Blade clearance vs. flight speed
Material from Renewable Resources in Aerospace Applications

Hybrid structures combining carbon and flax fibers should be applied in replacing a conventional carbon composite structure for a helicopter cockpit door. 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 the Technical University Chemnitz and the Institute for Bioplastics and Biocomposites at the University of Applied Sciences and Arts in Hannover.

AREA – Autonomous Rotorcraft for Extreme Altitudes

Our partnership with DLR has the aim to bring an autonomous rotorcraft up to altitudes of 9000m. Now, the project has reached an important milestone with successful test flights in Switzerland. The all-electric drone, with a take-off weight of 36 kg and its unique flying qualities, has shown the desired response to a newly developed controller. Since the successful first flight took place in August 2016, more than 100 starts have been performed, accumulating a total of 4 flight hours. The flight dynamics model represents the aircraft’s behavior with a high fidelity and could thus be used for the controller development. All systems are working as expected and the performance parameters correspond with predictions – necessary preconditions for the high attitude flight trials in 2018.

As a last formal step, the flight clearance for test flights in Argentina was received in early December.
Helicopter Technology

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

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 manufacturing of composite rotor blades
- Sensor integration in light weight structures

Infrastructure
- Research helicopter simulator with 6 channels, image, terrain and image data bases 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

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 2017
- Wirth, D., Hajek, M.: Probabilistic Methodology for Multi-Fidelity Model-Based Robust Preliminary Design of Rotorcraft, American Helicopter Society 73rd Annual Forum, Fort Worth, TX, 2017
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 incept 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 2017 the Institute of Flight System Dynamics was able to draw upon and continuously expand its successes from previous years in the domain of flight guidance and control. For several years the institute now operates a Diamond DA42M-NG general aviation aircraft 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, full automatic flight had already been demonstrated, ranging from automatic take-off via waypoint en-route flight to automatic landing. Based on this success, additional flight hours were gathered and experience was gained in 2017. In particular, performance of the flight control system was improved and the robustness to external disturbances was evaluated. Furthermore, an active stick was installed into the DA42 for manned flight experiments, including angle of attack limitation and stall protection.

Besides the Diamond DA42 the Institute of Flight System Dynamics is also involved in the development of flight control systems for additional different types of aircraft. One example, where the efforts really paid off, was the maiden flight of the unmanned SAGITTA Demonstrator at the Overberg test range in South Africa in July 2017. Within the ‘Open Innovation’ initiative led by aircraft-manufacturer Airbus, the unmanned aerial vehicle (UAV) has been newly developed in a collaboration of partners from academia and research. Designed as an innovation- and technology-demonstration platform, the diamond-shaped flying wing has a wingspan of 3 m and a take-off weight of about 150 kg.

The institute and the focus group ‘Aircraft Stability and Control’ at the Institute for Advanced Study (IAS) have developed an innovative flight control system for the SAGITTA Demonstrator that enables fully-automatic operation of the aircraft. The major challenge of the development was to ensure a safe flight of the UAV, as there is no pilot on board who could react to unexpected behavior.
Since the novel aircraft configuration had never flown before, design and testing of the automatic control system were conducted exclusively with simulation models. Unfortunately, such models inevitably represent the behavior of the real aircraft merely up to a certain degree of accuracy, i.e., they exhibit a broad band of multiple uncertainties. It was thus a major driver for the design of the automatic flight control algorithms to ensure sufficient flight performance even if the aircraft behaved very differently in reality than in simulation. The effort of the engineers was rewarded with extremely successful flight tests. The maiden flight of the SAGITTA Demonstrator could be conducted fully automatically and exactly as planned. Since the aircraft and flight control system performed so well during the whole first-flight mission, a second flight in identical configuration was conducted successfully with additional mission segments just after the maiden flight.

**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 depends 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 2017 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
- Navigation system integration architectures with graceful degradation capability and professional data fusion algorithms

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

With the fast-growing market of unmanned aircraft systems (UAS) new needs 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 gains 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 vertically 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 is becoming a large subject 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 future aircraft configurations and maximizing their robustness against unforeseen disturbances and uncertainties – even the loss of one or more control effectors.

For the development of the 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, such as minimizing energy and maximizing safety.

It is a long way from the idea of an aircraft until the first prototype is 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.
Over the last years, the work of the Flight Safety Team at the institute has raised attention at several international airlines and agencies. Besides the ongoing projects, bilateral cooperations have been strengthened in 2017. 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 develop 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 leads a working package that was mainly carried out in 2017. In April 2017, a consortium meeting was organized at TUM premises in Garching. 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 also gave presentations at the EOFDM Conference 2017 in Cologne.

To allow the functionalities 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 intensified in 2017. While the first steps of a cooperation had been taken in the previous years, first discussions at management level were carried out in 2017 and cooperative plans for the future were developed. The experience in flight data analyses gained at the institute raised attention at several European airlines and agencies. As a result, the research group is part of the consortia 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 of Chalmers University of Technology, who held a well visited series of lectures on ‘Advanced Topics in Optimal Control’. Furthermore, Professor Joseph Z. Ben-Asher from Technion University returned for a visit under the TUM August-Wilhelm Scheer Visiting Professorship Program. Besides his inspiring lecture on the application of game theory in aerospace, we made big steps forward in our joint research topic on optimization and optimal control based flight control law testing. This method employs nonlinear optimization algorithms to find ‘worst-case’ system inputs (pilot commands, disturbances) and parameters that may drive the system to or beyond the safety boundaries, additionally providing information on the sensitivity of distinct parameters.

ATM research was continued by developing extended bilevel algorithms to determine the optimal arrival times and trajectories. These results will build the foundation of a new research project starting in 2018. 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. The skOPTing project focused on determining optimal trajectories for ski jumpers is ongoing. The current development stage is the system identification using optimal control methods. Data will be obtained during measurement campaigns scheduled for this winter.

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 in-house developed optimal control tool Falcon.m (www.falcon-m.com).

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)
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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 FTD)
- 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 2017
- Drees, Ludwing; Müller, Manfred; Schmidt-Moll, Carsten; Gontar, Patrick; Zwirglmaier, Kilian; Wang, Chong et al. (2017): Risk analysis of the EASA minimum fuel requirements considering the ACARE-defined safety target. In: Journal of Air Transport Management 65, pp. 1-10
- Felux, Michael; Cirici, Mihaela-Simona; Lee, Jiyun; Holzapfel, Florian (2017): Ionospheric Gradient Threat Mitigation in Future Dual Frequency GBAS. In: International Journal of Aerospace Engineering 2017
- Höhndorf, Lukas; Siegel, Joachim; Sembiring, Javensius; Kopitz, Phillip; Holzapfel, Florian (2017): Reconstruction of Aircraft States During Landing Based on Quick Access Recorder Data. In: AIAA Journal of Guidance, Control, and Dynamics, pp. 1-6
- Nürnberg, Kota; Hochstrasser, Markus; Holzapfel, Florian (2017): Execution time analysis and optimisation techniques in the model-based development of a flight control software. In: IET Cyber-Physical Systems: Theory & Applications 2 (2)
Aircraft Design

Applied aircraft design for civil aviation and unmanned aerial systems

First flight – These are magical words for any aircraft designer. The highlight of long and intense activities in designing, manufacturing, integrating and testing is the first time a new aircraft gets airborne. In 2017 the first flight of the SAGITTA UAV demonstrator took place successfully in South Africa. In addition, initial flights started with an advanced vertical take-off and landing UAV providing new capabilities for unmanned systems. These practical demonstrations clearly showed the capabilities of the Institute for Aircraft Design to cover the whole range from initial design up to inflight technology demonstrations.

In the realization of effective demonstrator vehicles new manufacturing techniques like additive layer manufacturing have been included to enable even more efficient rapid prototyping.

These new approaches also enabled new design features and even innovative functionalities which open up new design spaces. Further progress will allow for even lighter and smaller demonstrator aircraft concepts.

SAGiTTA First Flight

The development of new technologies and their demonstration on a flying demonstrator air vehicle have been the core challenges of the Airbus Defence & Space led research cooperation SAGITTA. In an open innovation approach scientists of multiple universities, DLR and industry have teamed up to progress technologies for unmanned air vehicles. After seven years the team enabled the first flight of SAGITTA at the Overberg test range in South Africa. The Institute for Aircraft Design contributed with its overall design capability and has been responsible for the propulsion system as well as for novel flight control devices of the diamond-shaped air vehicle. With two flawless flights the team showed its capability to handle even highly complex systems like the 3m span demonstrator in a collaborative environment. We are looking forward to further exploit the capabilities that the demonstrator is able to provide as a test platform. It has been a big success.
Fixed Wing VTOL UAS

Combining the superior cruise performance of a fixed wing aircraft with the vertical take-off capabilities of a multicopter leads to so-called transition UAVs. Combining both flight phases in one configuration is challenging. As part of a joint research project with AUTEL Robotics, the integration of a 5kg electric fixed-wing VTOL UAV demonstrator took place, which was presented at the Consumer Electronics Show 2017 in Las Vegas. The successful maiden hover flight followed at the end of January, the first transition to forward flight in March. Subsequently, three more prototypes with modifications like full composite structure, improved wing tip tilt mechanism and new internal fuselage layout were manufactured and test flown. Along with the prototyping and test flight program, fixed-wing VTOL research was continued on topics like:
- the influence on propeller performance by blocking the in- or outflow
- electromagnetic compatibility on electric VTOL UAV
- range and endurance extension with hybrid combustion-electric powertrains or high energy batteries
- approaches to reduce the aerodynamic drag of inactive rotors
- thermal management of electric powertrains
- redundant electric motor design
- fixed-wing VTOL UAV configuration studies
- conceptual design tool improvements

The realization of systems and components for the demonstrators made massive use of rapid prototyping processes, like 3D printing and hybrid structural concepts. This allowed a radical reduction of the time from design to test and thus faster concept maturation.

Noise and Fleet Assessment

Environmental effects of air transportation are a crucial challenge for the aviation industry. Whereas on the global level, gaseous emissions, such as CO₂, represent the major focus of environmental assessments, on a local level, noise emissions in the vicinity of airports are the main concern. The Institute for Aircraft Design thus undertakes research in the area of aircraft noise emission and noise exposure at the airport level. Following the expected increase in air traffic and a continuing urbanization, noise emissions at city airports become an increasingly relevant research topic. The Institute for Aircraft Design supported an interdisciplinary group design project at Bauhaus Luftfahrt that developed a sophisticated concept for inner-city airports, called ‘CentAir Station’. An aircraft, designed to meet the special needs of inner-city operations, was evaluated by the institute in terms of noise reduction by comparing advanced, noise-mitigating aircraft operations. Therein, significant potential for noise savings could be shown, for instance of continuous descent operations (CDOs), in particular in combination with increased glide slope angles.

Further research at the institute focusses on the assessment of future airport noise exposure and the evaluation of corresponding impacts. Therein, methods and tools are developed to model the impact of noise-reduced aircraft types, of specific aircraft retirement behavior, or of aircraft introduction strategies on future airport noise exposure. The resulting methods may be used for technology assessment of new aircraft concepts at airport level or for the prioritization of possible noise reduction strategies.
Utilizing flight control devices, not only for single functions but applying a multi-functional approach as already used in military aircraft design, may lead to reduced system complexity and thus reduced weight and enhanced performance on aircraft level. In 2017, the aircraft design group focused its related research on the following topics:

- Development of an integrated design approach for advanced flight control systems with multi-functional flight control devices
- Parameterized mass estimation tool for flight control systems
- Preliminary design tool for advanced flight control system architectures
- Advanced high-lift control systems with distributed electric drive architectures

One promising approach for a multi-functional architecture is a distributed electric drive architecture. This provides the opportunity to enable advanced high-lift control systems with multifunctional control surfaces driven by electrical actuators. The aircraft design group has developed three distributed system architecture concepts using electrical actuators. The system architectures were developed in an iterative design process to fulfill the high-lift system requirements, and comply with safety regulations. Finally, it can be stated, that distributed system architectures show advantages regarding overall system mass and direct operating costs compared to a conventional system architecture.
Flexible Wing Demonstrator

As part of the European Commission funded FLEXOP project, the Institute for Aircraft Design is responsible for the design, manufacturing, integration and testing of the unmanned demonstrator aircraft enabling in-flight investigations on highly flexible wings. With flight tests planned for mid 2018 the tasks during 2017 were focused on detail design as well as manufacturing, integration and first ground test of the FLEXOP demonstrator UAV. Further subsystem tests with a mock-up of the airbrake, as well as tests with the integrated modular propulsion unit (engine, enginemount & ECU) were conducted. Since no consumable off-the-shelf actuators fulfill the driving requirements of active flutter control, the design and integration of a high frequency/high torque actuator for flutter dampening into the most flexible wing set was a major achievement. The electric and control engineering was conducted by our Hungarian partners of MTA SZTAKI, whereas the hardware and integrational design was conducted by the Institute for Aircraft Design and the Institute for Lightweight Structures. The assessment of minimum implications on the aeroelastic characteristic of the aircraft was ensured by full finite element models coupled with aerodynamic simulations. The resulting design is currently being manufactured and will be tested in a mock-up configuration to verify the design strategy. The idea of a virtual aircraft model, which allows virtual flight tests to predict aircraft loads and performance is part of the national LuFo funded research project VitAM. The combination of structural and aerodynamic models with an application aiming for highly flexible wing structures into a unified coupled aeroelastic aircraft model are in the research focus of the project.

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. Furthermore, dynamic flight maneuvers on a reduced order model are performed to investigate the dynamic behavior. Within the investigated methods, the number of degrees of freedom are typically reduced from millions to some hundreds, without loss of the most important dynamic aircraft properties. The methods enable investigation of wing instabilities due to gusts or flutter with high accuracy at an early aircraft design stage.
In 2016, DLR & NASA initiated the first student aircraft design challenge, asking for innovative concepts addressing two distinct areas of aviation: (1) low noise subsonic airliners, (2) new generation supersonic transport aircraft. At TUM three teams were formed; two addressing the low noise subsonic aircraft and one team coming up with a proposal for a next generation supersonic airliner. In Germany seven universities participated, also competing with the American counterparts supported by NASA. The winner of the first DLR & NASA challenge is a TUM team with three aeronautical students. Their concept of a novel URBANLINER concept utilizing enhanced propulsion technologies in very close interaction with enhanced aerodynamics of the wing convinced the evaluators of DLR & NASA. The team worked very enthusiastically on their concept and came up with very innovative solutions.

Aircraft Design Course: Design and Fly an aircraft within one semester – The use of additive manufacturing, a kit-like set of common components, as well as the application of well-proven, off-the-shelf radio control equipment, finally makes it possible. Simulating a real customer, the students of the Winter Semester 2016/17 were challenged by a request for proposal, which asked for a 1m wingspan unmanned aircraft, tasked to perform the best endurance as well as the best range with a given lithium-polymer battery. The students formed two competing teams, which finally proved the airworthiness of their designs in February 2017.
Aircraft Design

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

Competence
- Scenario technique
- Aircraft design (manned/unmanned, military & civil)
- Aircraft and system integration and verification (UAVs, prototypes)
- Propulsion integration, electrical and hybrid propulsion systems
- Operational assessment: noise, airport, capacity, cost

Infrastructure
- Integrated aircraft design environment
- Laboratory for demonstrator aircraft
- Experimental UAS (e.g. IMPULLS UAV)
- Propulsion integration lab
- Mission simulation
- Airport simulation

Courses
- Fundamentals in Aeronautics (jointly with the Institute for 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 2017
Flow Control and Aeroacoustics

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

The focus of the research group in 2017 was the development, testing and usage of research tools for the numerical prediction of flow and sound fields and the improvement of model-scale experiments in wind tunnels.

Our research dealt with topics in three focus areas, including the numerical and experimental modeling of the wake evolution of wind turbines, the numerical and experimental modeling of self-noise from splitter attenuators and generic flow control studies. An achievement was the successful application for substantial computer resources for large-scale computations to be carried out with the LRZ facilities for high-performance computation on massively parallel computer systems. They form the basis for the ongoing investigations.

Control of a Three-dimensional Shear Layer by Oblique Vortices

An established open-loop flow control method for the mitigation of flow separation is oscillatory blowing and suction through holes or slots in the vicinity of the separation location on a body immersed in a flow. The artificial insertion of steady or propagating vortices enhances the momentum transfer across the shear layer. In order to better understand the role of forcing parameters numerical investigations have been carried out by means of large-eddy simulation for the generic configuration shown in Fig. 1. It consists of a turbulent boundary layer approaching a swept backward-facing step geometry. Vortices are generated by wall-normal blowing and suction along the step edge in terms of a wave propagating along the z-axis.

Using a suitable choice of the forcing parameters angular frequency and wave-length along the z-axis oblique vortices are generated that are primarily advected by the mean flow in the shear layer as shown in Fig. 2. Their mixing capability depends on their strength (related to the forcing amplitude), their spacing and their orientation. For the generic configuration a maximum efficiency in terms of shortening of the reattachment length was observed for a train of vortices with their axes deviating by an angle of 50° from the direction of the step edge. The achievement was similar for both the planar case with the mean flow normal to the step and for an inflow profile oriented in an angle of 40° towards the step.

![Figure 1: Generic geometry for the investigation of open-loop flow control by oscillatory blowing and suction along a strip aligned with the step edge.](image)

![Figure 2: Isosurfaces of the second invariant of the velocity gradient tensor for turbulent flow across a backward-facing step subject to harmonic forcing by means of a wave propagating along the step edge.](image)
Numerical and Experimental Modeling of the Influence of Ground Roughness on the Wake Evolution of Wind Turbines

In order to identify the power produced by a model-scale wind turbine (such as shown in Fig. 3) from the voltage and current of the attached generator, the mechanical and other losses of the drive train have to be known. Within the Eurotech collaboration on wind energy (Greentech project 03 Wind managed under the auspices of IGSSE) our partners at EPFL (group of Prof. F. Porte-Agel) offered us the possibility to calibrate the motors/generators for two model-scale wind turbines in the facilities of the WIRE lab at Lausanne which has recently acquired a suitable miniature torque meter. In combination with our force measurements these calibrations are mandatory for a proper determination of the dependence of thrust and power coefficients $c_T$ and $c_P$ as function of tip-speed ratio and yaw angle under different roughness conditions.

Figure 3: Model-scale wind turbine for the experimental investigation of the wake evolution over rough terrain in the atmospheric boundary layer wind tunnel of the Chair of Aerodynamics and Fluid Mechanics. The rotor diameter is about 450 mm.
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
■ Usage of wind-tunnel at the Institute of Aerodynamics and Fluid Mechanics
■ Test set-up of a microphone array

Courses
■ Continuum Mechanics (for B.Sc. Engineering Sciences of MSE), 50%
■ Grundlagen der numerischen Strömungsmechanik
■ Aeroakustik
■ Strömungsbeeinflussung
■ Numerische Strömungsakustik
■ Praktikum Numerische Strömungs­simulation
■ Praktikum Numerische Strömungs­akustik

Publications 2017
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 with a strong focus on thermal separation processes like distillation, rectification, absorption and desorption, heat exchange and membrane processes. The research is organized in the three focus areas of process design, equipment design methods, modelling as well as 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

Energy intensive chemical production processes like alumina production and air separation can contribute to stabilize fluctuating electric energy grids and markets. However, chemical production processes are presently not designed for dynamic operation modes with rapid load and process changes. Therefore, it is necessary to demonstrate which process and equipment modifications are required in order to operate processes like air separation under severe dynamic conditions. Within the SynErgie consortium of the long term BMBF project Kopernikus the energy intensive process for air separation units (ASU) was selected as a fast track example. As a target air separation plants will be enabled to contribute to stabilize fluctuating electric energy grids and markets which will be required when renewable energy sources such as wind and solar power will lead in the long term to fluctuating energy supply.

Picture of a typical air separation plant (provided by Linde AG)
Modeling and Thermodynamic Property Data

A dynamic model for open algae ponds was developed in MATLAB at the Institute of Plant and Process Technology. The model takes real weather data for selected locations as input and enables the process engineer to optimize the design of large raceway-type algae ponds. The developed tool is essential since there is virtually no practical experience available on the behavior of these large ponds. A possible CO₂ source is flue gas of power plants which can either be used directly as feed for the algae pond or from which the CO₂ can be captured and then used as a pure CO₂ feed gas. Both options are covered in the MATLAB model. Although growing algae in open ponds has been done for decades, there is still a lot of research necessary on how to efficiently grow algae in large systems with a surface area per pond of 10 ha and greater and therefore produce biofuels economically. At the Institute of Plant and Process Technology a control scheme for CO₂ supply has been developed with the fully dynamic MATLAB model. It can be seen that for high yield algae a minimum of three injection points are required for an algae pond with a length of 1340 m and a width of 30 m. This ensures that the pH-value stays within the range of 9.5 and 10.5. The exemplary simulated location shown is Everglades, Florida, taking a full year of available meteorological data.

Equipment Design Methods

In the chemical industry bubble columns are used as multiphase reactors. In the literature numerous experimental studies investigate the regimes of homogeneous and heterogeneous bubble flow with low gas velocities up to 0.4 m/s and propose correlations for the prediction of the gas content. At the Institute of Plant and Process Technology a bubble column with a diameter of 300 mm and a total height of 5.5 m was operated at high gas velocities up to 1.2 m/s. Different mixtures of water and 72.7% invert sugar solution were used to selectively vary the properties of the liquid, especially the viscosity. The photograph shows heterogeneous bubble flow in the blue-colored solution in the column. A comparison of the measurement data with different correlations for homogeneous bubble flows shows clear deviations, whereas some correlations show similar tendencies for the heterogeneous bubble flow. Based on a semi-empirical approach, the measured gas content for the heterogeneous flow of bubbles can now be described for varying material properties with a maximum deviation of ± 20%. The model for dimensioning mass transfer columns based on CAD data of packing elements, which was developed at the institute, was successfully extended to structured packings. The required coefficients were gained from simulations with computational fluid dynamics. The picture shows a representative element of structured packing which is irrigated with liquid. The model can be used for a more efficient design of distillation and absorption columns.
PLANT AND PROCESS TECHNOLOGY

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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 and 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
- Paper Technology

Selected Publications 2017
- Rarrek, A.; Rehfeldt, S.; Klein, H.: Evaluation of the performance of a simulation model for open algae ponds and investigation of the operating behavior of open algae ponds over a one-year period for different locations, Chemical Engineering Research and Design 125, 2017, 523-537
Continuum Mechanics

Predictive computational modeling

The focus of the Continuum Mechanics Group in 2017 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 calibration and validation of computational models using experimental data, b) uncertainty propagation in multiscale systems, c) design/control/optimization of complex systems under uncertainty, and d) the extraction of governing equations from data in multiscale systems where effective models (or closures) remain elusive.

A highlight was the organization of the international Symposium on ‘Machine Learning Challenges in Complex Multiscale Physical Systems’ which took place in TUM-IAS during January 9-12 2017. It featured talks from several internationally-renowned scientists in the areas of computational physics, machine learning, uncertainty quantification and computational mathematics. In addition, there were three panel discussions on the outstanding challenges in Bayesian statistics and machine learning, in multiscale modeling and in uncertainty quantification.

Nonlinear Forward and Inverse Stochastic Problems with Applications in Medical Diagnostics

This project is concerned with the numerical solution of high-dimensional, model-based, Bayesian inverse problems. Our motivating application stems from biomechanics where several studies have shown that the identification of material parameters from deformation data can lead to earlier and more accurate diagnosis of various pathologies. We attempt to overcome two of the most important limitations, namely the high-computational cost and the quantification of model errors, by proposing a paradigm shift. Namely, we rephrase the solution of partial differential equations (PDEs) appearing in continuum thermodynamics as a problem of probabilistic inference (probabilistic programming) where unknown state variables are treated as random fields (Figure 1). The solution of the inverse, PDE-constrained problem for solid mechanics problems can be carried out by adjoint-free, second-order methods over the joint space of displacements, stresses and unknown material parameters. The method generalizes to nonlinear problems while the maximum-a-posteriori estimate recovers the results obtained by the mixed finite element method derived from the Hellinger-Reissner variational principle (Figure 2).

Figure 1: Visualization of the proposed, intrusive probabilistic approach for the solution of PDE-constrained inverse problems by employing probabilistic graphical models where nodes corresponding to element-wise dened quantities are entangled by physical (conservation laws) and phenomenological (constitutive) laws as well as observational data.

Figure 2: Maximum-A-Posteriori stress field $\sigma_{\text{vonMises}}^{*}$ and material parameter $\psi^{*}$ associated with the inverse problem as recovered by our probabilistic white-box model using a Taylor-Hood mixed function space.
Continuum Mechanics

Coarse-Graining in Equilibrium Statistical Mechanics

The macroscopic behavior and properties of engineering materials depend on the microscopic characteristics which are not accounted in typical continuum-based models. In this project we operate on the atomistic scale, and employ coarse-grained (CG) models as a computationally efficient means to study large numbers of atoms over extended spatio-temporal scales.

A data-driven approach to CG has been proposed within the the multidisciplinary joint project ‘Predictive Materials Modeling’ with the Hans Fischer Senior Fellow and TUM Ambassador, Prof. N. Zabaras (Viola D. Hank Professor of Aerospace and Mechanical Engineering, Director of the Computational Science and Engineering Laboratory, University of Notre Dame, USA). The method developed makes use of generative probabilistic models and employs a parametrized probabilistic mapping from coarse-to-fine-scale descriptions which implicitly defines the coarse variables. The coarse-variable model is sequentially refined by adding features providing the largest anticipated information gain. In the context of peptide simulations, the dimension has been reduced by a factor of 30, while still capturing the main properties and revealing configurational similarities in the coarse space as depicted in Figure 3a. Predictions that reconstruct the full atomistic picture, are probabilistic and account for uncertainties due to limited fine-scale simulation data and information loss as a result of dimensionality reduction (Figure 3b).

Well-established methods for the solution of stochastic partial differential equations (SPDEs) typically struggle in problems with high-dimensional inputs/outputs. Such difficulties are only amplified in large-scale applications where even a few tens of full-order model runs are impractical. While dimensionality reduction can alleviate some of these issues, it is not known which and how many features of the (high-dimensional) input are actually predictive of the (high-dimensional) output. In this project, we advocate a Bayesian formulation that is capable of perform-

Model-order and Dimension Reduction of Random Heterogeneous Media

Figure 3: Predictive Coarse-Graining

(a) Representation of the training data in the reduced (two dimensional) latent space of Alanine Dipeptide. Three clusters, corresponding to the characteristic configurational modes (α, β-1, β-2), arise in the latent space.

(b) Probabilistic prediction of the deviation of the radius of gyration from a common α-helix
Physics-constrained, Data-driven Discovery of Coarse-grained Dynamics

This project is concerned with the discovery of data-driven, dynamic, stochastic coarse-grained models from fine-scale simulations with a view to advancing multiscale modeling. Many problems in science and engineering are modeled by high-dimensional systems of deterministic or stochastic, (non)linear, microscopic evolution laws (e.g. ODEs). Their 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. The combination of high-dimensionality and disparity of time scales has motivated the development of coarse-grained (CG) formulations. These aim at constructing a much lower-dimensional model that is practical to integrate in time and can adequately predict the outputs of interest over the time scales of interest. The challenge in multiscale physical systems such as those encountered in non-equilibrium statistical mechanics, is even greater as apart from the identification of an effective model, it is crucial to discover simultaneously, a good set of CG state variables.

In this project, we treat the CG model as a probabilistic state-space model where the transition law dictates the evolution of the CG state variables and the emission law the coarse-to-fine map (Figure 6). Naturally, one of the most critical questions pertains to the form of the CG evolution law which poses a formidable model selection issue. Correct identification of the right-hand side terms involved can also reveal qualitative features of the coarse-scale evolution such as the type of constitutive relations. In order to avoid overfitting as well as endow the estimates with robustness even in the presence of limited data, we invoke the principle of parsimony that is reflected in the sparsity of the solutions.
Continuum Mechanics

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L. Felsberger (M.Sc. thesis)
F. Bott (Semester thesis)
H. von Kleist (Bachelor's thesis)

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.
■ Uncertainty Quantification in Mechanical Engineering (SS)
■ Modeling in Structural Mechanics (WS)

M.Sc.
■ Atomistic Modeling of Materials (WS)
■ Bayesian Strategies for Inverse Problems (SS)
■ Journal Club Uncertainty Quantification (WS-SS)

MSE
■ Continuum Mechanics (WS)
■ Probability Theory and Uncertainty Quantification (WS)
■ Uncertainty Modeling in Engineering (SS) (Top Teaching Trophy 2014, 2015, 2016)

Publications 2017
Archival Journal Publications
■ A. Quaglino, S. Pezzuto, P.S. Koutsourelakis, A. Auricchio, and R. Krause, Fast uncertainty quantification in patient-specific cardiac electrophysiology meeting clinical time constraints, accepted for publication International Journal for Numerical Methods in Biomedical Engineering, December 2017

Contributions to Scientific Conferences and Symposia
■ C. Grigo, P.S. Koutsourelakis, Coarse-grained models for PDEs with random coefficients, SIAM Computational Science and Engineering Conference, March 2017, Atlanta, GA, USA
■ I. Franck and P.S. Koutsourelakis, Uncertainty and constitutive model error quantification, GAMM 2017, March 2017, Weimar, Germany
■ M. Koschade, P.S. Koutsourelakis, Bayesian Multi-Fidelity Optimization under Uncertainty, SIAM Computational Science and Engineering Conference, March 2017, Atlanta, GA, USA
■ C. Grigo, P.S. Koutsourelakis, Reduced-Order Models for PDEs with Random Coefficients, UNCECOMP June 2017, Greece
■ M. Schöberl, N. Zabaras, C. Grigo, P.S. Koutsourelakis, Probabilistic Coarse-Graining: from Molecular Dynamics to Stochastic PDEs, SIAM Workshop on Parameter Space Dimension Reduction July 2017, Pittsburgh, PA, USA
■ P.S. Koutsourelakis, Physics-convergent machine learning: from molecular dynamics to stochastic PDEs, 46th Workshop on High-Performance Computing – Uncertainty Quantification and HPC, Invited Talk, University of Bern, September 2017
■ M. Schöberl, N. Zabaras, P.S. Koutsourelakis, Bayesian Coarse-Graining, European Congress on advanced materials and processes (EUROMAT), September 2017, Greece
Systems Biotechnology

Model-based metabolic engineering for bacterial systems

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

Systems Biotechnology focuses on 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. The heterologous protein production with microorganisms becomes more and more an important pillar in various fields of biotechnology. Combing theoretical methods with experimental studies we systematically analyze the population behavior in dependence of different load strength. Here, a new experimental approach that allows monitoring of mRNA as well 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.

Fundamentals for Experimental Analysis and Mathematical Modeling of Cellular Networks

Regulation of transcriptional and biochemical processes in a bacterial cell is essential for survival in changing environmental conditions and the understanding of the events taking place is pivotal for the use of bacteria in industrially interesting applications. Research of the Systems Biotechnology Group targets different key regulatory devices, like the phosphotransferase system in Pseudomonas putida or the ComRS two component system in Streptococcus mutans. The experimental information derived either in the group’s own laboratory or by collaboration partners gives rise to mathematic models that contribute to a better understanding of cellular processes.

Another research focus lies on the establishment of a co-culture between a photosynthetically active organism extruding sugar molecules together with heterotrophic organisms capable of producing industrially interesting compounds. To this end a photobioreactor is employed which allows the cultivation and collection of a vast amount of data used to describe the population-based variations in the overall process.

Project
- e:biofilm, BMBF e:Bio initiative

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 are 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 macromolecules in adverse conditions. The current applications of ectoine cover a wide range of different fields like biomedicine, cosmetics, support roles in analytic and industrial processes and bioremediation.

Projects
- OPHELIA – optimization of Halomonas elongata for industrial applications, BMBF e:Bio initiative
- 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 make the processes more efficient.

**Project**
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 Master ‘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 2016-17
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.

In our highly interdisciplinary projects, we work together with chemists, pharmacists, 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 2017 were the development of a contact lens coating that prevents tissue damage on the cornea and the detection of two types of hydrophobic biofilm surfaces where the former is related to lotus leaves and the later to rose petals.

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.

Project
- Mucin coatings on contact lenses

Microfluidic Chips for Diffusion Studies

PDMS microchips are a versatile platform to study the behavior of fluids on 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
- Barrier properties of mucin hydrogels
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 are also interested in how different chemical environments affect those material properties. By doing so, we hope to develop new strategies for the removal of biofilms from surfaces.

Project
- SFB 863: Mechanics of bacterial biofilms

(Bio-)Hybrid-Materials

A combination of osmotic pressure and synthetic DNA constructs allows for the temporally controlled release of nanoparticles from a hydrogel matrix.

Examples for such hybrid materials are hydrogels with programmable drug release kinetics.

Project
- Triggered nanoparticle release from hydrogels
Biomechanics

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Research Focus
- Biological (hybrid-)materials
- Cartilage and cartilage surrogate 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
- Biomedical Materials and Technologies
- Lab Course: Characterization of Soft Materials
- Biophysics Lab Course for Biochemistry Students

Publications 2017
- S. Kesel, B. von Bronk, C. Falcón García, A. Götz, O. Lieleg and M. Opitz, Matrix composition determines the dimensions of Bacillus subtilis NCIB 3610 biofilm colonies grown on LB agar, RSC Advances, 7, 31886-31898 (2017)
- B. Winkeljann, K. Boettcher, B. Batzer and O. Lieleg, Mucin coatings prevent tissue damage at the cornea-contact lens-interface, Advanced Materials Interfaces, 4, 19, 1700186 (2017)
Automotive Technology

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

Under the direction of Prof. Lienkamp, the Institute of Automotive Technology deals with all the requirements of mobility. Particular emphasis in research is on electro mobility, as well as its components and infrastructure. There are five research groups with different subject areas: Vehicle Dynamics and Control Systems, Driver Assistance and Safety, Vehicle Concepts, Electric Vehicle Components and Smart Mobility.

Mobility for Africa – testing of the ‘aCar’ and presentation at the IAA 2017

With the objective of providing sustainable mobility for rural regions in sub-Saharan Africa the Institutes of Automotive Technology, Metal Forming and Casting, Industrial Design and Strategy and Organization have developed the first prototype of the aCar project. In order to verify the estimated assumptions regarding environments of use and vehicle design, the first prototype has been tested in Ghana. Another highlight in 2017 was the development of the second prototype and its presentation to the public at the IAA.

The objective of the on-site vehicle trial was the conformation of assumptions regarding electric vehicle design, driving profile of prospective users and environmental conditions. Various user tests verified the aCar’s range. Furthermore, the tests proved the assumptions regarding the external influences like temperature, road profile and traffic flow. Conducting driving dynamic tests, driving safety and cross-country mobility under conditions prevailing in sub-Saharan Africa were secured. Thereby the experience gained, emphasize the aCar’s ability to tackle the challenges of providing sustainable mobility.

Prototype testing in Kumasi, Ghana
After concluding the vehicle testing, the development team focused on the International Automotive Show in Frankfurt where the second prototype was presented to the public. Improvement priority was further development of the aCar’s design in order to enable local production of the vehicle’s interior and exterior as well as the final assembly of the overall vehicle. Exemplary for this development is the new passenger compartment, characterized by a simple assembly concept through a plug and adhesive system. Additional new components, like winch, work lights and waterproofed switches, increase everyday suitability in sub-Saharan Africa. After the successful presentation to the public the approval and vehicle trial are scheduled for the next months.

**globalDrive**

Every year the Institute of Automotive Technology at the Technical University of Munich hosts the globalDrive Project. In this student project, international teams of eight students work on future mobility concepts. To identify the trendsetting topics in the field of mobility, the German students stay abroad for a few weeks to start the cooperation. In the final stage of the project, the international partners come to Munich to finish and present the final prototype.

**SCUBE**

Together with the Nanyang Technical University and TUMCREATE, both located in Singapore, one team developed a micro mobility concept for the still growing metropolis of Singapore. To solve the first and last mile problem and by that enhancing usage of the public transport system, the autonomous driving device ‘Scube’ was developed. Scubes are free-floating devices, which are shared among the users of the public transport infrastructure. Driving on
two wheels and stabilizing itself, Scube is able to operate with a very small footprint. Driven autonomously, Scube features an active tilting system to keep the passenger free from sheering forces and ensure a comfortable ride. To travel longer distances, the team proposes the novel bus system ‘Scube-Trans’. Scubes can attach themselves to this bus system, which travels above the traffic and therefore never needs to stop.

Entry Mobility for India
The concept consists of a modular bike with a multifunctional frame and a separate electric propulsion unit, which can also be attached to any other existing bike. This enables the customers who own a bike already to only purchase the propulsion unit and retrofit with a major cost advantage compared to the whole system. If the customer later on feels the need for more features, like better design or increased payload, he or she can simply upgrade by purchasing the frame at a later point in time. But the whole system is offered with a cost advantage compared to separate purchase.

The propulsion consists of a compact mid-mounted electric motor. It can be attached to almost any kind of bike just by replacing the bottom bracket and cranks. The separate detachable portable battery module can be mounted to the down tube or on the rack of the bike. To make the vehicle more attractive and increase performance, the propulsion unit includes a hand throttle so that the driver can use his bike without even the need to pedal. However, pedals can then still be used to extend the range of the vehicle and in case recharging is not possible. With this setup, a potential customer is able to carry passengers or goods more comfortably and extend his or her mobility radius.

The design of the vehicle is more motorcycle-like to create a more appealing and sportier image compared to fragile-looking standard bike frames. A bigger set of tires are available to take over suspension functionality and hence provide more comfort, especially on bad roads. The wheelbase is longer to provide more space and the frame has a low step-through to also ensure that female riders wearing a traditional Indian Sari do not encounter problems.

Beside the ‘typical’ vehicle features, the concept also offers extra features due to its modular design. The frame comes with special mounting holes for different add-ons. They can be footboards, a rack or a lateral tube structure that, together with a net, serves as a lightweight but high-bearing cargo space.

In addition to the modular frame, the concept also includes a second-life option for the frame. If parts of the vehicle are broken and it needs to be disposed of entirely, the frame can still be reused and easily converted into a bike trailer, a wheelbarrow or even a simple three-wheeler. Because of the special design of the frame with lateral holes, two frames with their respective back wheels can easily be combined with a few crossbars. The new vehicle which results can be used as a transportable marketplace or a trailer for several passengers.

Tele-Operated Driving
It was the first time in Europe that 5G-enabled tele-operated driving was used to control a consumer vehicle remotely – in this demonstration, the vehicle was located at Surrey University (5GIC) and was controlled from the MBB Forum venue, London ExCel. The end-to-end network latency was less than 10 milliseconds and air interface latency was less than 1 milliseconds, which enabled the driver to control a vehicle remotely from 50 kilometers away, with only 24 cm braking deviation when it was driven at approximately 90 km/h.

The Institute of Automotive Technology has been researching into controlling a vehicle remotely since 2009. From projects like the EU-Project PROMOTHEUS or the
competitions of the U.S. Department of Defense (DARPA Challenges), it can be stated that today autonomous driving is only possible in certain less complex scenarios. Especially in the field of urban traffic with many different road users and confusing road topology autonomous cars will not be able to perform like a human in the next couple of years.

Therefore, a viable approach is to bring back a human driver into the control loop in order to deal with the complexity of the situation. A wireless data transmission (5G at the demo) connects the human driver with the vehicle. A server handles communication and can perform computationally intensive tasks or provide additional information from the internet. Further, a Car2Server communication is being developed simultaneously, which apart from the tele-operation, is able to provide information to the driver, like road situations lying ahead.

**New Projects**

**Vehicle Dynamics and Control Systems**
- Optimal body movement for highly automated driving
- Development of a methodology to support strategy decisions in motorsports
- Compensation of modified suspension parameters using steering control

**Driver Assistance and Safety**
- Safety assessment of highly automated vehicles
- Intelligent maneuver automation – cooperative risk prevention in real time
- Classification of damage risk under the influence of advanced driver assistance systems

**Vehicle Concepts**
- ACAR – Vehicle concept for sub-Saharan Africa
- SIM2GETHER – Collaboration platform for interdisciplinary simulation
- Topology optimization of electric drive trains for four-wheel drive vehicles

**Electric Vehicle Components**
- The rapid aging characterization of battery systems
- Lifetime analysis and prediction for battery-powered products
- Second-life of lithium-ion vehicle batteries

**Smart Mobility**
- Hydrogen mobility concept
- WATE – Web-based analysis tool electro mobility
- QOSTREET – Classification of road surface quality with big data

**GlobalDrive**
- Fusion of high-precision map data in the automotive industry
- Intelligent travel features in public transport of the future
- 'Pimp my Twizy' – Increasing the performance and range of an electric vehicle through optimized thermal management
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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 captur 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 2017
■ Fries, Michael; M. Kruttschnitt; M. Lienkamp: Multi-objective optimization of a long-haul truck hybrid operational strategy and a predictive powertrain control system, IEEE Twelfth International Conference on Ecological Vehicles and Renewable Energies (EVER), Monaco, 2017
Automatic Control

Model-based analysis and design allow for the successful control of complex dynamical systems

The institute 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 intelligence. Moreover, a Collaborative Research Centre puts a spotlight on the modeling and analysis of nontechnical systems. New cooperations within a DFG Priority Program and within a joint international ANR-DFG funding initiative were established. Concerning application, highly challenging problems include the treatment of vibrations in mechanical systems and in automobiles, the robust control of multicopters, the control of unstable robots, and the feedback control of technical and nontechnical industrial processes.

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 of our research include nonlinear disturbance compensators and 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 below) combined with vehicle-to-infrastructure (V2I) communication. The so-called hybrid suspension system, developed at our institute, 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 Institute of Automatic Control.

High-Performance Control of Constrained Fast Systems

There is huge 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 a 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 locally stabilizes an operating point. 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 resides in 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 institute conducts further research focusing on regulation and tracking tasks using different nonlinear approaches, like command governors and extended linearization.

Distributed Parameter Systems/Energy-based Modeling and Control

For the discretization and control of distributed parameter systems, we develop new techniques that preserve or are inspired by an energetic model structure. Examples are all kinds of transport and diffusion phenomena, e.g. the flow of pressured air through a tube or heat transfer in a catalytic foam. Also flexible mechanical structures can be represented in this spirit within the port-Hamiltonian framework. Current research highlights are:

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

**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 adjustable structure-preserving discretization schemes in space and time, which are applicable to systems of arbitrary dimension and geometry.

**Control of flexible mechanical systems based on PH models.** We develop feedforward and feedback controllers for distributed parameter systems based on structured numerical models in PH form. The flexible link lab manipulator serves as a test bench for experimental validation.
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.

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.

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. Just recently, the free and open-source sssMOR-Toolbox has been extended by the new pssssMOR toolbox for parametric model reduction.
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, and learning control

Competence

- Mechatronic systems design and control
- Modeling, analysis and control of technical and non-technical processes
- Control and optimization
- Adaptive 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 Regelungstechnik 1-3
- Regelung von Systemen mit verteilten Parametern
- Advanced Control
- Nonlinear Control
- Lab Course "Computergestützter Regelungsentwurf"
- Lab Course "Moderne Methoden der Regelungstechnik"
- Lab Course "Reglerimplementierung auf Mikrocontrollern"

Publications 2017

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.

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 allows for the cost effective 3DP of aluminum parts without any intermediate steps.

Patient Individual Hand Rehabilitation Robot

A frequent consequence of stroke is limited hand function. As there are high anthropometric variances in hand and finger anatomy, a patient individual hand rehabilitation robot was developed. The individual design ensures an ergonomic interface which allows longtime wearing of the device. In order to provide cost-effective production, we propose an automated design process. The individual fingers are manufactured monolithically using the selective laser sintering of polyamide. The fingers are moved by wires, connected via Bowden cables to a servo motor. The device presented is portable and can be used for repetitive training as well as for grasping things.
Additive Manufacturing Technologies

The claim in additive manufacturing changes 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. Current 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. This way unwanted effects like curling can be reduced and dimensional accuracy can be improved.

Augmented Reality in Laparoscopic Partial Nephrectomy

Laparoscopic partial nephrectomy allows the surgical resection of kidney tumors with the aim of partially preserving kidney function. For intraoperative imaging a laparoscope is used, which allows only superficial imaging of the abdominal cavity. Additionally, a laparoscopic ultrasound probe can be used to gain information about the subsurface of the organ in order to determine the resection line for the removal of the tumor. Usually, images from the laparoscope and the ultrasound system are displayed on separate screens. Matching information from both imaging sources to the anatomical context in the mind is challenging and error-prone.

The aim of this project, which is funded by the German Research Foundation (Deutsche Forschungsgemeinschaft), is to improve laparoscopic partial nephrectomy in the field of intraoperative imaging and visualization of information by integrating augmented reality features by superimposing additional information gained with the ultrasound probe onto the laparoscopic image.
Micro-Micro Macro Manipulator System

Micro-surgeries in the middle ear require the surgeon to manipulate extremely delicate structures with fine tools, while staying in a non-ergonomic posture for extended periods of time. This strain on the surgeon may negatively affect the outcome of the operation. Therefore, a micro-manipulator was developed at our institute, capable of using standard surgical instruments and controlled via a console. In order to increase the applicability and versatility of the micro-manipulator, a macro-manipulator was introduced, a lightweight 6DoF robot with a reach of 0.8 m. An adapter system was developed to connect the micro-manipulator to the tip of the robot arm. Using the macro-manipulator drastically increases the workspace. Furthermore, additional features were introduced, such as a simultaneous control of both micro- and macro-manipulator, hands-on-manipulation and autonomous repositioning. Additionally, a new approach to control the robot was developed, circumventing the built-in controller and directly accessing the communication bus. This allows for the direct control of each individual joint by a user-written application as well as configurations using a different number of arm elements. The project is funded by the German Research Foundation (Deutsche Forschungsgemeinschaft).

Patient Individual 3D Printed Heart Valve Models for Operation Planning

Heart valve reconstructions are complex operations. To improve the planning of heart valve reconstructions our institute collaborates with TOMTEC Imaging Systems GmbH, the Klinikum rechts der Isar (Cardiovascular Imaging) and the Ludwig-Maximilians-Universität München (Cardiosurgery) in a project funded by the German Federal Ministry of Education and Research (Support programme: ‘KMU-innovativ: Medizintechnik’, Contract number: 13GW0115A). The aim of the project is to design patient individual 3D printed heart valve models for operation planning and surgical templates for the realization of the planning. From 3D ultrasound image data of patients’ hearts, the heart valves are segmented and models of the heart valves are 3D printed. Heart surgeons can use these models to plan the reconstruction preoperatively with conventional surgical techniques. Based on the planning at the model, a surgical template to assist the heart surgeon with the realization of the planning during the operation is designed.
Automated Design Process of Manipulators for Minimally Invasive Surgery

Since minimally invasive surgery is distinguished by significant benefits for the patient, today’s research focuses on the development of novel instruments for this advancing field. The developed Single Port Overtube Manipulator (SPOT) is designed as an overtube structure for standard endoscopes and possesses working channels that fit for standard endoscopic instruments. Thereby, the system can be adapted to the equipment the surgeon is used to. For the actuation a novel electrical control unit can be used beside the established mechanical control unit. The shape of the manipulator (i.e. workspace of the manipulator arms) can easily be adapted to the patient’s anatomy by using the automated design process in combination with 3D printing as the manufacturing method. Furthermore, the design process now allows for the adaption of the system to different surgical tasks. Thereby, current research focuses on the investigation on thin-walled structures fabricated using additive manufacturing and their clinical evaluation.

Kinematic Design and Rapid Prototyping

This project focuses on supporting the design of kinematic linkages. Therefore software tools are developed to support, accelerate and reduce the costs of the design processes. These are based on state-of-the-art methods of kinematic design as well as those being subject of research and are integrated into CAD software. Furthermore, this project investigates the similitude of original mechanisms and model mechanisms manufactured with rapid prototyping techniques. This work is done in collaboration with BMW AG and Webasto Edscha Cabrio GmbH and is funded by the Bayerische Forschungstiftung (BFS).
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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

Publications 2017
Medical Materials and Medical Implant Design

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

The Chair of Medical Materials and Medical Implant Design is significantly involved in the Master’s program Medical Technology and Engineering. In research and teaching, the team deals with production technologies and materials for medical technology, with a particular focus on plastics technology.

The year 2017 was marked in research and teaching mainly by an intensification of polymeric additive manufacturing. Driven by the approval of an EXIST Transfer of Research grant, 3D printers for demanding medical materials (PEEK, TPE, silicone) could be developed. In addition, the chair has taken over a coordinating role in the Community of Practice ‘IoT & Materials’ of the Zentrum Digitalisierung.Bayern. Furthermore, the foundation of three startups was realized and supported in cooperation with UnternehmerTUM (KUMOVIS GmbH, inveox GmbH, essentim GmbH). International cooperation has been established with MIT (Soft Robotics), TUM Asia (medical polymer technology) and Addis Ababa University (medtech for developing countries).

Individualized Medical Technology – Palate Plates for the Treatment of Cleft Lip and Palate

Cleft lip and palate represents with an incidence of 1 in 700 newborns the most common craniofacial birth impairment. Without treatment the malformation would harm breast feeding, hinder voice and auditory development, and the visual appearance would remain distorted. As a presurgical treatment nasoalveolar molding (NAM) addresses reduction of the cleft gap and improvement of nasal symmetry by use of an intraoral guiding plate, which encourages the alveolar segments to grow towards each other. In the project RapidNAM a system was developed to design the NAM plates within 10 minutes in a fully automated process based on just a single impression taken initially. The plates are manufactured additively. So far already six patients have been treated with such automatically generated NAM plate sets.
**Polymer Technology – Novel Plastics with Germicidal Effect**

Germs are found in all areas of everyday life and can lead to dangerous infections. To reduce the risk of infection in sanitary facilities and hospitals, surfaces with antimicrobial properties can be used. The aim of the project AntiMik is to obtain polymer compounds with antimicrobial properties for the preventive reduction of microorganisms in the health care sector. Nano-scale, photocatalytically active titanium dioxide (TiO$_2$) is incorporated into different polymer matrix systems. The TiO$_2$ induces radicals on the surface that have the potential to kill germs. The objective of this project is to identify and process matrix-filler combinations with a high germ reduction rate and resistance against material ageing.

![Agar plate with grown bacteria colonies to assess antimicrobial polymer compounds](image)

**Medtech in Least Developed Countries – Robust 3D Printed Prostheses for the Poorest**

Approximately 1 billion people live in so-called least developed countries (LDC). Driven by the initiative of the students, the project ‘MedTech for LDC’ creates a knowledge and cooperation basis for the development of medical devices that can be manufactured and marketed under the conditions in LDCs. In a first approach, a cooperation was established with Addis Ababa University and the NGO Cheshire Services Ethiopia, which provide the children of the poorest with simple prostheses.

![Student Fabian Jodeit with his Ethiopian cooperation partners](image)

![Robust 3D-printed prosthesis for use in least developed countries](image)
Dental Technology – Novel Dental Veneers Made of Thermoplasts

The high priority of functioning, aesthetically pleasing teeth motivates the continuous optimization of dental prostheses and the materials used for them. As an alternative to currently used ceramics, thermoplasts or combinations of a ceramic framework and a polymeric veneer are being used increasingly. In order to exploit the advantages of thermoplasts and at the same time to meet the mechanical and optical requirements of dentures, the TherverTech project in cooperation with the Poliklinik für Zahnärztliche Prothetik of LMU Munich has developed a new method for veneering ceramic crowns and bridges with high-performance thermoplasts (e.g. PEEK).

Smart Technology – Integration of IoT Electronics into Medical Plastic Parts

The research group ‘IoT & Polymers’ systematically investigates the interaction between plastics and their processing on the one hand and IoT electronics on the other. Use in the medical environment places special demands on IoT-augmented plastic parts. These include strains from sterilization or disinfection processes as well as the use in the organism’s aqueous environment with a risk of short-circuit and corrosion. Research focuses on integration strategies with coatings and casting compounds for cushioning mechanical forces in the injection molding process, surface technologies for optimizing composite materials with regard to conformal integration, and the investigation of the influence of plastics on electromagnetic waves. Suitable materials for the realization of plastic-electronic composites are identified with regard to their biocompatibility and bioprotective effect (prevention of the release of toxic and allergenic substances).

Regenerative Medicine – Automated Production of Patient’s Own Therapeutic Blood Products

Platelet rich plasma (PRP) is generated from a patient’s own blood by centrifugation. Platelets contain growth factors, which guide tissue regeneration and enhance healing. Thus, PRP can be therapeutically applied to wound sites to support the body’s healing process. However, in current systems numerous manual steps in the manufacturing processes lead to reduced reproducibility of the quality of this patient’s own therapeutic agent. Therefore, a centrifugation system enabling fully automated production of PRP has been developed and is now being launched on the market. Optimization and expansion of the system to produce various blood products offering a broad therapeutic field is currently under investigation.
Additive manufacturing (3D-printing) is seen as a disruptive technology in production. Especially for medical applications additive manufacturing will be a key technology to produce small series products as well as individualized implants. Starting as a student project in 2015, the team AM Medical developed a printer for the processing of established medical-grade plastics based on FFF (fused filament fabrication). The team is now funded by EXIST Transfer of Research and recently founded the KUMOVIS GmbH. The KUMOVIS printer enables an economically feasible processing of medical-grade high performance plastics such as PEEK and flexible plastics (e.g. TPE). Additionally the team is working on the fabrication of filaments to guarantee a complete production process chain fulfilling medical standards like biocompatibility and the absence of particles.

Lab 4.0 – Highly Function Integrated Smart Bioreactors

Laboratory medicine is often given little consideration in the context of health care because it lacks direct patient contact. Nevertheless, it is very significant in terms of health economics. In addition to tasks in classical diagnosis (e.g. blood and tissue examinations), laboratory medicine also plays a major role in future-oriented procedures such as stem cell or autologous blood therapy. Outside of high-tech blood analysis laboratories, many activities in biomedical labs are still performed by hand at high cost and risk of human errors (e.g. sample confusion, miss-handling). The aim of the research area ‘Lab 4.0’ is therefore the development of highly function integrated, autonomous and process-monitored systems for the cultivation of biological samples.
Medical Materials and Medical Implant Design

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

Competence
- Polymer processing
- Additive manufacturing
- Material 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, FFF, 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 2017
Nuclear Engineering

Nuclear engineering and nuclear safety

The focus of the Institute of Nuclear Engineering in 2017 was placed on activities for the development of multi-physics nuclear safety methodologies with coupled code systems; the simulation of the behavior of plant components under off-operation conditions; experimental two-phase flow thermal-hydraulics; the development of uncertainty methodologies for multi-physics applications, the simulation of nuclear fuel behavior; the development of advanced molten salt reactor concepts; and the development of a methodology for the characterization of local instability in nuclear reactors. Most of this work has been carried out in collaboration with other German and international research institutes (NBJC (PL), KIT (D), ITU (D), GRS (D)) and university departments (UPV (E), KTH(S), Chalmers (S), etc).

Highlights for 2017 were the participation in the large EU-CORTEX Project awarded this year for the development of experimental and analytical methodologies for nuclear reactor dynamics and the publication of an article in the prestigious International Journal of Multiphase Flow.

Nuclear Reactor Safety Analysis of Current and Future Reactor Designs

The safe operation of nuclear reactors requires the evaluation of their safety with sophisticated computational methods. The most advanced ones are based on multi-physics approaches by coupling computer codes able in order to simulate the processes driving the response of nuclear systems. We make use of the computational fluid dynamics (CFD) codes ANSYS/CFX and OpenFOAM to couple in real time with state-of-the-art multi-dimensional time-dependent neutronic codes (PARCS). Dynamic feedback can be then calculated and the detailed local description obtained of the thermal-hydraulics and neutron flux distribution is used for full system analyses with codes such as TRACE and ATHLET.

In 2017 the focus was on the development of uncertainty and sensitivity methodologies for coupled multi-physics applications for liquid metal fast reactors in the context of the SESAME Project; the application and expansion of a novel spectral methodology for local analysis of instabilities in reactor cores in the context of the CORTEX Project and the development and application of local methods to describe neutron flux oscillations inside fuel assemblies. This last project has produced a coupled (ANSYS/CFX-PARCS) modelling system capable of calculating very detailed neutronic thermal-hydraulic feedback, which can reproduce neutron flux oscillations caused by perturbations in the moderator-coolant flow and by the movement of the fuel assemblies.

Projects

- Development and Assessment of Methodologies for the Analysis of Neutron Oscillations in PWRs Fuel Assemblies (BMWi)
- Development of a Methodology for Local BWR Stability Analysis (StMWFK)
- SESAME Project on Uncertainty Analysis applied to Liquid Lead Cooled Reactors (EURATOM)
- CORTEX Project on Neutron Flux Oscillations (EURATOM)
Experimental Two-Phase Flow Thermal-hydraulics

At the Institute 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. The three facilities are instrumented with high speed cameras, and continuous and pulsed lasers with particle velocimetry techniques. In 2017 a special section in COLLIDER has been designed and installed that contains a hoop in the safety injection, similar to advanced PWR designs. Experiments will be carried out in order to determine the effect of such a device in the hold-up of coolant in the leg during LOCA mitigation operations. Such a facility is unique in the world.

Experiments in the three facilities have provided very valuable data for the assessment of system codes and CFD calculations, and have resulted in the development of new correlations for condensation and counter-current flow limitation models with entrainment. Collaboration with the Universidad Politecnica de Madrid has continued and a new program for the simulation of bubble condensation in turbulent flows has started with the University Jaume I in Spain.

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

The dual fluid reactor (DFR) is a new concept of nuclear reactor conceived at the Institute of Solid Matter and Nuclear Physics (IFK) in Berlin. It consists of a molten salt core and second molten metal as coolant. Such a configuration provides the DFR with many advantages compared to other current and advanced reactor concepts. The DFR can destroy the long-lived radioactive isotopes in spent nuclear fuel, thus removing the need to supervise nuclear waste for very long periods of time. The reactor is also extremely efficient in the use of the available nuclear fuel resources, because it can breed new fuel as it operates and it can use thorium and uranium as fuel. In 2017 we have continued our research together with the IFK in order to analyze the neutronic characteristics of the design and to determine its safety under a series of operating strategies. The ultimate goal is to converge in an optimized and safe design that can be eventually built. The work has made use of coupled analysis computer programs and models based on the codes ATHLET, TRACE-PARCS and SERPENT, ANSYS/CFX and COMSOL. These models have proven their usefulness in design optimization and safety studies and will be the basis for further design efforts planned for 2018 in collaboration with the Center for Nuclear Research (NCBJ) in Poland and the TU Dresden.

In collaboration with the IFK, a project has been carried out aimed at studying the chemical processing needed for the on-line elimination of the fission products from the DFR.

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 of experimental and analytical techniques for bubble condensation (with Universidad Jaume I, Castellon (E))
Material and Mechanical Fuel Behavior Analysis

The safe and economic operation of nuclear reactors depends to a large extent on the behavior of the nuclear fuel. We carry out research in this topic through a series of projects on model development and the simulations of fuel rod and fuel assembly behavior for a large range of operating and transient conditions. The use of thorium fuel-cycle in future reactors is becoming a hot topic around the world because of its better performance in terms of nuclear waste compared to the current uranium cycle. During 2017, a project was completed that expanded the capabilities of the fuel analysis code TRANSURANUS, in collaboration with the Institute for Transuranic Elements (ITU) in Karlsruhe, to the simulation of thorium-based fuels \((\text{Th,Pu})_2\text{O}_3\) and \((\text{Th,U})_2\text{O}_3\) by including models for fission gas release, thermal properties, burn-up and fracture dynamics models with very good results. Another on-going project looks into the long-term creep deformation of PWR (pressurized water reactor) fuel assemblies (FA), also known as FA bow. A sophisticated mechanical model has been developed with ANSYS that also contains fuel structure interactions. Such a development makes it possible to carry out studies of fuel assembly displacements and full core mechanical oscillations. Finally, a collaboration with the CEA and E.On Kernkraft (today PreusserElektra) on the behavior of new fuel materials in LWRs has produced very interesting insights into their properties and open the possibility of using them in the future.

Projects
- Development of models for the prediction of thorium-based fuel (E.On Kernkraft)
- Experimental and analytical analysis of the performance of nuclear fuel under LOCA conditions (E.On Kernkraft)
- Mechanical analysis of bowing in PWR fuel assemblies (E.On Kernkraft)
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 Thermalhydraulics in Nuclear Systems
- Advanced and Future Nuclear Reactor Systems
- Radiation and Radiation Protection
- Nuclear Fusion Technology
- Nuclear Safety Seminar
- Use of System Analysis Codes in Nuclear Safety

Selected Publications 2017
- Al Issa, S., Macian-Juan, R., CFD validation of new Nu-Re correlations for the condensation of large steam bubbles directly injected into a flow in a vertical pipe and effects of bubbles forces upon momentum transfer, International Journal of Multiphase Flow, 94, 173-188, (2017)
In 2017, the Chair of Vibroacoustics of Vehicles and Machines put emphasis on multidisciplinary research and development and establishing the new test facilities. Research funds have been successfully launched to continue fundamental and applied research at the Chair. The purchase and establishment process of experimental test facilities started in 2016 have been completed.

Research Projects

Innovative and more efficient strategy on modeling vibroacoustic systems (BFS)
This project concentrates on the modeling process of vibroacoustic problems. The case study is the engine-transmission unit in a vehicle, with a special focus on bolted assemblies. An assembly is the combination of monolithic components joined together. The joint area is a vulnerable point in structural dynamics and has to be carefully investigated.

Development of the sound-optimized Pianissimo stages (ZIM, SBS+FH Zwickau)
With the help of modern CAE methods, the innovative development process of the stage podium SBS-BP-PP-1, ‘Pianissimo’ with an updated list of requirements in combination with a vibroacoustic optimization substantially differs from the state of the art development processes of stage podiums. While introducing the new methodology of utilizing CAE methods, the manufacturer can increase the technological performance level. Virtual simulations together with experimental tests provide useful information about possible sources of excessive vibration and sound emission to keep them at a minimum level. In this way, an optimized stage podium with improved stage elevator performance is developed. Further, the project provides realistic minimum noise level criteria to support requirements of tender documents.
Decoupling Coupled Structural-Acoustic Systems: Investigation of Structural Acoustic Damping Mechanisms (DFG)

In the framework of a project within the DFG priority program 1897 ‘Calm, Smooth and Smart’, dissipation of kinetic energy of vibrating structures into the acoustic far field is studied. It can be understood as radiation damping and is particularly relevant for weakly damped structures, such as sandwich panels and musical instruments. The mathematical access to radiation damping involves the coupled equations of time-harmonic elastodynamics and acoustics, which are addressed respectively by means of finite and boundary element methods and solved monolithically. The main work packages include systematic investigation of radiation damping and the derivation of numerical formulation, which enable an efficient consideration of the phenomenon in decoupled structural simulations. Overall, the project aims for a better understanding of the effect of acoustic radiation damping and to estimate its relevance in future research.

Modal quantities and their usage for evaluation of radiated sound power (DFG)

In order to describe acoustic sources, the sound power is often used as a variable, since it is independent of the position of the viewer. The sound power can only be adequately determined if the sound source is examined under free-field conditions, i.e. the source is in a reflection-free environment, so the influence of the surrounding room does not influence the results. If one wants to produce this condition in a computer-aided simulation, then special methods are required, such as the so-called infinite element method (IFEM), which can map the properties of an infinitely large surrounding area with a finite number of discrete degrees of freedom and for a physically correct decay of the sound pressure with increasing distance. Subject of the research of this project is the decomposition of the vibrations in the acoustic exterior domain into orthogonal eigenvectors or modes, whose superposition again results in the real vibration behavior. In order to be able to reduce the computational effort, those modes are to be identified by means of mathematical criteria, which already provide a sufficiently accurate result for the sound pressure or the radiated sound power when superimposed, so that the complete basis of modes need not be considered and calculated.

Sound emission of multi-layer composites with non-linear and locally varying damping properties (DFG)

The project goal is focused on the simulation of sound radiation caused by the vibroacoustic behavior of thin-walled structures. Lightweight structures of multi-layer fiber reinforced composites and hybrid metal-plastic composites offer high damping capabilities and a high stiffness-weight ratio. The mechanical properties of such components are influenced by interfaces and local inhomogeneities resulting in uncertainties and non-linearities of the characterizing parameters. The investigations are focused on the simulation of amplitude depending damping by finite-element procedures.
Experimental Test Facility

In 2017, the Chair of Vibroacoustics of Vehicles and Machines purchased two major scientific measurement systems, namely a PSV500 3D-scanning-laser-Doppler vibrometer (LDV) from Polytec and a 56-multi-channal acquisition system from Brüel & Kjaer. The following measurements and analysis methods can be conducted using both systems:

- Contact-free excitation and three dimensional measurements of structural dynamics of large structures at virtually an infinite number of measurement points
- Operational and experimental modal analysis (excitation force of modal shaker between 1N and 600N)
- Measurement and visualization of operational deflection shapes (ODS)
- Measurement of high frequency Lamb wave propagation up to 10MHz
- Sound source localization with the help of an acoustic camera and/or a sound intensity probe
- Long time field measurements of various physical quantities such as sound pressure level (SPL), sound intensity, structural velocity and acceleration, rotational speed, dynamic forces
- Bi-naural sound measurements for psycho acoustic analysis
- Measurement of room acoustic parameters such as SPL, reverberation time, speech intelligibility
- Sound wave visualization through refractor vibrometry

Furthermore, the chair received two new laboratory rooms both of which will be equipped with large vibration isolated tables for measurements with high scientific precision and quality.

Interactive Acoustic Apps in Research and Teaching

In lectures or exercises physical problems can be clearly demonstrated with experiments. Depending on the experiment, special laboratory conditions may be necessary or the set up and tidying requires a considerable amount of time. Using modern simulation tools, however, numerous phenomena of acoustics and vibration theory can be demonstrated clearly and with little effort. In the form of interactive apps in the web browser, the chair develops a range of freely-accessible applications for teaching in school and further education, which can help visualize acoustic phenomena without further ado in the lecture or subsequently on the computer or on the touch screen of a tablet computer or smartphone for understanding and trial. Among the applications already developed are apps for the acoustics of musical instruments, vehicles in the wind channel, vibrations of bells and glasses and the effect of acoustical grating).

Humboldt Fellow

Due to the long-term collaboration with Associate Professor Vasant Matsagar from the Indian Institute of Technology in Delhi, his Humboldt application was accepted as a research fellow in the early 2017. He has attended a German course in Munich and will be working from the end of October to end of February 2018 at the Chair. In addition to his professional background in structural dynamics, he will focus on the field of vibration reduction and modeling uncertainties together during his stay at the Chair.

Using an application for vibrations of bells on a tablet computer in a bell tower during a student tutorial
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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 offered in 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
- Philosophy of Nature and the Philosophical Basis of Acoustics
- Vibroacoustics in Industrial Practice
- Introduction to Philosophy for Engineers
- Ethics for Engineers

Selected Publications and Keynotes

Keynotes at International Conferences
- Steffen Marburg. Surface Contribution Analysis Using Non-Negative Intensity, the 13th International Conference on Theoretical and Computational Acoustics (ICTCA2017), 30 July to 3 August 2017, Vienna, Austria
- Steffen Marburg. Conventional Boundary Element Techniques: Recent Developments and Opportunities, INTER-NOISE 2017, the 46th International Congress and Exposition on Noise Control Engineering, 27-30 August 2017, Hong Kong, China
- Kheirollah Sepahvand. Identification of random elastic and damping parameters of composite structures, 3rd International Conference on Mechanics of Composites (MECHCOMP3), 4-7 July 2017, Bologna, Italy
The highlight for the Plasma Material Interaction Group in 2017 was the manufacture and successful testing of a high heat flux component with tungsten fibre-reinforced copper tube as cooling channel.

**Tungsten Fibre-Reinforced Copper Tubes for High Temperature Applications**

The highlight for the Plasma Material Interaction Group in 2017 was the manufacture of a high heat flux (HHF) component mock-up equipped with a tungsten fibre-reinforced copper ($W_f$-Cu) tube as cooling structure and its successful testing in the HHF test facility GLADIS. A major challenge in view of the design of a magnetic confinement nuclear fusion demonstration power plant (DEMO) is the reliable exhaust of power and particles. In such a reactor, highly loaded plasma facing components (PFCs) have to withstand severe particle and heat flux as well as considerable neutron irradiation. Existing PFC designs are based on monolithic tungsten (W) and copper (Cu) materials. Such an approach, however, bears engineering difficulties as W and Cu are materials with inherently different thermo-mechanical properties and their preferred operating temperature windows do not overlap. Against this background, W-Cu composite materials are promising candidates regarding the application to the cooling structure of highly loaded PFCs. The $W_f$-Cu composite had been developed during the previous year (see Annual Report 2016) as a material that provides enhanced high-temperature strength for use at elevated temperatures ($> 300 \, ^\circ C$). Cylindrical W fibre preforms were braided using fibres with a nominal diameter of 50 $\mu$m. In order to fill the whole width of the tube wall with reinforcing W fibres multi-layered preforms with 17 plies were manufactured by means of mandrel overbraiding. They were manufactured (in collaboration with ITV Denkendorf) in such a way (high braiding angle, see Fig. X1 left) that the thermomechanical properties in hoop direction of the tube are optimised. Finally, the composite material is manufactured by centrifugally melt infiltrating Cu into the fibrous W preform. Simulations based on homogenisation of a representative volume element (RVE) as well as experiments confirm that the mechanical performance at 300 $^\circ C$ is enhanced by more than a factor of two compared to state-of-the-art Cu alloys already at a fibre volume fraction of 0.2. W armour monoblocks were joined to the $W_f$-Cu tube (in collaboration with ENEA Frascati) and a twisted swirl tape was inserted into the tube in order to enhance the heat transfer to the coolant. The actively water-cooled component (Fig. X1 right) was subjected to cyclic high heat flux tests in the GLADIS ion beam facility surviving 300 pulses at 20 MW/m$^2$ for 10 s (the time to reach thermal equilibrium is about 5 s) under DEMO relevant conditions (water inlet temperature 130 $^\circ C$, pressure 4 MPa). With these very successful tests the component qualified for the next round of experiments which are supported by the European fusion consortium ‘EUROfusion’.

**Project**

- Supported by EUROfusion (2017)
Tungsten (W) is currently the most promising candidate as armour material of the first wall in a future fusion power plant. Since 2014, the Garching fusion experiment ASDEX Upgrade (AUG) operated by the Max-Planck-Institute for Plasma Physics has been using bulk tungsten tiles at its most loaded area, the divertor, receiving up to 20 MW/m² of heat load. Since the base operating temperature of AUG is room temperature, where bulk tungsten behaves mostly brittlely, cracks in most of the tiles were observed after only a few hundred plasma discharges. A possible option could be the use of more ductile W heavy alloys (W-HA) as they are produced commercially by several companies. W-HAs consist of up to 97 weight % W and Ni/Fe admixtures. In comparison to bulk W, these materials are considerably cheaper due to the facilitated sintering process and they show improved machinability and ductility at room temperature. Their major drawbacks, in view of the application in fusion experiments, are the rather low melting temperature (~1500 °C) and their magnetic properties. In order to explore their feasibility, W-HAs from two suppliers (Plansee Composite Materials GmbH (D185) and HC Starck Hermsdorf GmbH (HPM 1850)) were investigated concerning their thermal and magnetic properties and subjected to screening tests and cyclic loading in the high heat flux test facility GLADIS.

The magnetisation of these materials is moderate (~2 Am²/kg) and saturates already at low magnetic field (~2000 Oe). The thermal conductivity at room temperature is a factor of two smaller than that of pure W (80 W/(mK)), but in contrast to W it increases with temperature leading to a similar thermal performance above 700 °C. High heat flux tests with power loads of up to 20 MW/m² and surface temperatures of up to 2200 °C were performed. As expected, a surface modification was observed when the melting temperature of the binder phase was exceeded. However, the failure behaviour under overload is very benign: segregation of Ni/Fe in the topmost micrometres, but the bulk structure was not affected under the conditions tested here. Long term exposure of one W-HA tile in AUG (with the so-called ‘Divertor-Manipulator’ – see Annual Report 2014) under the highest possible power and energy injection confirmed the rather positive results of the GLADIS HHF tests. It was therefore decided to equip the divertor with 28 W-HA tiles, preferentially at locations where the mechanical load (due to electromagnetic forces) is expected to be highest. First results revealed the expected positive properties. Depending on ongoing investigation on their hydrogen retention and their behaviour under neutron irradiation W-HAs could even qualify as armour material in a future fusion reactor at locations with intermediate heat load.

Fig. X2 a) and b): Scanning electron micrograph with orientation contrast of W heavy alloy (HPM 1850, 2% Ni, 1% Fe). The yellow squares mark the regions with higher magnification; c), d), e) EDX maps showing the distribution of W, Ni and Fe, respectively.
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
- 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 neutral beam test stand
- Manipulator in the fusion device ASDEX Upgrade
- Scanning electron microscopy (SEM with focused ion beam (FIB), X-ray spectroscopy (EDX/WDX), electron backsc. diffract. (EBSD)) for loads up to 10 kg
- Atomic force microscope (AFM)
- X-ray diffraction (XRD)
- Confocal laser scanning microscope
- Photo electron spectroscopy (XPS)
- Magnetron sputter devices
- Laser flash analysis
- Vacuum ovens for thermal desorption

Courses
- Plasma Physics for Engineers
- Plasma Material Interaction

Selected Publications 2017
Thermo-Fluid Dynamics

High performance simulation with added value

In 2017 we have made significant progress in the development of modelling concepts and simulation software for combustion dynamics and combustion noise. Furthermore, consequences of intrinsic thermoacoustic feedback for the convective scaling of eigenfrequencies were elucidated.

Thomas Emmert was awarded the Dissertation Prize of the Faculty of Mechanical Engineering for his doctoral thesis ‘State Space Modeling of Thermoacoustic Systems with Application to Intrinsic Feedback’.

Wolfgang Polifke and Camilo Silva contributed a course with the title ‘Systemidentifikation bei Unsicherheiten – Nix g’naus woas ma ned’ to the Ferienakademie Sarntal.

Research Focus

In recent years, the research efforts of the TFD group have focused almost exclusively on thermoacoustic combustion instabilities. This type of self-excited instability results from 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 very challenging problem with manifold exciting research opportunities.

Linearized (Reactive) Flow Solvers

Analysis of thermoacoustic combustion instabilities is typically based on linearized perturbation equations for compressible reactive flow, with important effects of convection by mean flow. A discontinuous Galerkin finite element method with superior accuracy and stability for this type of equation has been developed in the TFD group. Combined with the state-space framework of the in-house taX software, this method makes possible the computation of transfer functions and thermoacoustic eigenmodes with unprecedented speed and flexibility. Inclusion of a linearized source term for species production and heat release allows the explicit inclusion of flow-flame-acoustic coupling in the computation of thermoacoustic eigenmodes, which has hitherto not been possible. Inertial waves as well as entropy waves can also be described in this framework. First results on the propagation speed of inertial waves, the effect of inertial waves on flame dynamics, and the source term of entropy waves have been achieved and published. Such fundamental investigations of flow-flame-acoustic interactions provide important guidance for the proper formulation of analysis and design tools for thermoacoustic stability.

Project

AG Turbo COOREFLEX, FVV ‘Vorhersage von Flammentransferfunktionen’

Axial velocity of the unstable, intrinsic thermoacoustic eigenmode of a swirl burner (from Meindl et al., submitted to J. Comp. Phys).

Uncertainty quantification

Thermoacoustic instabilities are highly unpredictable, because they respond in a very sensitive manner to slight changes in operating or boundary conditions. As a result instabilities are detected often only at the later stages of development in full combustor tests, 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, such as non-intrusive polynomial chaos expansion, or active subspace. The development of surrogate models by analytical means, or by exploiting adjoint numerical solutions, has played an important role in these efforts.

Project

CSC Scholarship, AG Turbo COOREFLEX

Combustion noise

In the past year, the TFD group has developed characteristic-based, state-space boundary conditions, which allow to impose non-trivial acoustic impedances at the computational domain boundaries in a robust and flexible manner. Furthermore, advanced techniques for system identification were introduced, which estimate noise models as well as confidence intervals from time series data generated by high-fidelity simulations. Combining these techniques with large eddy simulation of turbulent combustion makes possible the accurate and efficient prediction of combustion noise. Furthermore, eigenmode analysis of the spectral distribution of pressure fluctuations elucidates the interplay between combustion noise generation, flame dynamics and thermoacoustic resonances. The results emphasize the necessity of including full two-way coupling in simulations of flow-flame-acoustic interactions.

Project

DFG/ANR NoiseDyn
Thermo-Fluid Dynamics

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
- taX

Courses
- Engineering Thermodynamics (MSE)
- Wärmetransportphänomene
- Wärme- und Stoffübertragung
- Grundlagen der Mehrphasenströmung
- Grundlagen der numerischen TFD
- Computational Thermo-Fluid Dynamics
- Simulation of Thermo-Fluid Dynamics with OpenSource Tools

Selected Publications 2017
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 requirement 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

Model-based testing is a mandatory procedure for safety-critical controllers. However, the validation of a logic controller is often only considered in the later phases of its development. Thus, if specific non-functional requirements related to testing are not initially considered in the specification models, this could lead to the impossibility of validating the behavior of a controller by means of testing. In 2017, SES extended its design-to-test approach for discrete event systems. This approach aims at improving the testability of controllers and reducing the additional human workload required to test critical logic controllers reliably. Also, to guide, in the early phase, the effort of testing to the nominal behavior of a cyber-physical system, SES has developed an approach which permits the extraction of simple features from 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.

Projects

- Design-to-test and testing with plant features approaches for black-box testing of programmable controllers (internal)
- Test and verification of machine-learning-based systems (internal)

Dynamic Software Update of Programmable Controllers

Current industrial automation plants are controlled by programmable logic controllers (PLC), soft-PLCs or industrial PCs. Using a software-based PLC or an industrial PC enables the implementation of new methods such as dynamic software updating (DSU).

Since the lifetime of a production facility can be very long, the need to update the software at some point is inevitable. It may include the implementation of new features, an increase in performance, or simple bug fixes. Depending on how severe this change is, the update of the facility may not be feasible due to downtimes caused by the shutdown, update and restart phases of the plant. By using DSU, modifications of the model can still be prepared offline and follow the same modelling procedure as before, but the downtime can be drastically decreased and in the best case completely eliminated, thus increasing the productivity of the plant.

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

Project

- Dynamic Software Update of Programmable Logic Controllers (BMWi ZIM)
Supervisory control theory (SCT) is a model-based approach that permits the automatic generation of correct-by-construction supervisory controllers. Thanks to the SCT approach, which uses mathematically proven algorithms, generated controllers do not need to be verified anymore. The designers can then focus more on the requirements definition and the specification modeling. A set of specifications permits 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 2017, SES further investigated the obstacles to a wide application of SCT in industry.

First, a formal approach using a signal-based formalism was investigated. This aimed at reducing the gap between the classical event-based approach of SCT and industrial applications using signals and dataflows to represent and exchange sensor and actuator values.

Secondly, SES also investigated the integration of SCT methods in 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 world’s population percentage of people 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. In emergency situations, this could have dramatic consequences for the health of the inhabitant.

Project
- Robust Diagnosis for Ambient Assisted Living (DAAD)
Safe Embedded Systems

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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

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 2017
- Canlong Ma; Julien Provost (2017): A model-based testing framework with reduced set of test cases for programmable controllers. In: 13th IEEE Conference on Automation Science and Engineering
- Claudius Jordan; Canlong Ma; Julien Provost (2017): An Educational Toolbox on Supervisory Control Theory using MATLAB Simulink Stateflow – From Theory to Practice in one week. In: 8th IEEE Global Engineering Education Conference
Industrial Management and Assembly Technology

Perspectives for production

The Chair for Industrial Management and Assembly Technology is one of the largest research centers in Germany. In 2017 we considered in particular the possibilities of how humans can be integrated into the objectives of Industry 4.0. In addition, the further development of electromobility in Germany’s production area was specifically targeted.

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.

In addition to all technological developments in the context of industry 4.0 humans also play a central role in the factory of the future. In order to be able to make reliable statements about the potential and dangers of its networking with the production system, the research field ‘Man in the factory’ set up and commissioned an experimental and learning laboratory. With the Mittelstand 4.0 Competence Center Augsburg, a contact point for digitization and industry 4.0 topics is available for small and medium-sized companies in the region of Bavaria. In line with the structural conditions on site, the center’s range of services is geared to manufacturing industry, which is strongly represented there.

The focus is on industry and craft enterprises in mechanical engineering, the manufacturing of metal products and electronic products as well as vehicle construction. The center’s offer is of course also available to companies from other sectors. An important field of research is the planning and control of autonomous production that is based on cyber-physical systems, where the customer-innovated products will be produced. It is linked directly to the open-innovation platform to ensure that the customer is always well informed of the feasibility of their design, and at the same time receives a delivery schedule and cost estimate.

In the next few years the 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.
Production Management and Logistics

The research group Production Management and Logistics 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

- SFB 768 – Managing cycles in innovation processes, sub-projects, B4 ‘Model-based forecasting and assessment of change impacts in production’, and B5 ‘Systemic change management for the design of change cycles in production’ in the funding phase II, and the transfer project T2 ‘Cyclically Oriented Assessment and Planning of Technology Sequences and Equipment for Assembly Processes’ (DFG)
- Intelligent logistics planning based on big data (BMW)
- Efficient data management for the use of mathematical optimization models in the production strategy (BMW)
- Individual and dynamic worker information (MAN)
- Efficient preproduction development of variant-rich small series production (MAN)
- Predictive cognitive maintenance decision support system (EU)
- Mittelstand 4.0 – Competence Center Augsburg (BMWi)

Courses at the new ‘Learning factory for lean production’
The robotics research group addresses the processes regarding the last step in production chain. Here, the assembly process has a significant influence on the costs and quality of the end product, thus innovative ideas and technologies are required for achieving 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 relationships 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

- Cell-Fi – Acceleration of electrolyte uptake through optimized filling and wetting processes
- CyMePro – Cyber-physical metrology for 3D digitization in networked production
- ExZellTUM II – Center of Excellence for Battery Cells at the Technical University of Munich II
- FELIZIA – Solid electrolytes as enablers for lithium cells in automotive applications
- FORobotics – Mobile, ad-hoc cooperating robot teams
- ProMoA – Product-based automatic model-based system development
- ProKal – Process modelling of the calendering of high-energy electrodes
- SPICY – Silicon and polyanionic chemistries and architectures of Li-ion cell for high energy battery
Industrial Management and Assembly Technology

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Research Focus
- Production management and logistics
- Assembly technology and robotics

Competence
- Battery production
- Cyber-physical assembly systems
- Industrial robotics
- Production technology management
- Human factors in factory environments
- Industrial optimization and data analytics

Infrastructure
- Production line for battery cells
- Industrial robots
- Environmental/safety and teaching laboratories
- Energetic and geometrical parameters
- Material analysis systems
- Simulation environments
- Additive manufacturing laboratory
- Cutting machine tools
- Laser tools
- Friction welding equipment
- Industrial robots
- Learning factory for lean production

Courses
- Factory Planning
- Human Factors in Production Engineering
- Methods of Company Management
- Assembly, Handling and Industrial Robots
- Management of Production Enterprises for Teachers
- Practical Course CAD/CAM-Systems
- Practical Course ERP-Systems
- Practical Course Industrial Robots
- Practical Course Production Planning and Control
- Practical Course Lean Production
- Seminar Production Management
- Practical Soft Skills for Mechatronic Processes in Development and Production
- Engineering 4.0 – Agile and Interdisciplinary Development of Mechatronic Production Systems
- Practical Course for Mechatronical Development Processes and Project Management
- Computer Integrated Manufacturing
- Networked Production – Industry 4.0

Published Book
- Reinhart, Gunter (Hrsg.) Handbuch Industrie 4.0, Geschäftsmodelle | Prozesse | Technik, ISBN 978-3-446-44642-7

Selected Publications 2017
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 necessitates 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 many advanced mechanical structures that undergo large deformations, such as microelectromechanical systems or wind turbine blades, often requires long computation times. One approach to reduce computation time is model order reduction, which has been a central research interest at the chair for many years. Recently, so-called simulation-free hyper reduction methods that can significantly reduce simulation time have been developed and implemented in the chair’s Python-based finite element research code (AMfe). In current research, these methods are extended to parametric systems to be used for optimization and real-time control applications.

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.

The chair is also participating in a European training network called EXPERTISE, which is short 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. Currently, the research focuses on the application of FETI methods to increase the parallel scalability of turbine models, and an experimental approach for dynamic identification of blade-to-blade interfaces.

Projects

- Varying manifolds and hyper-reduction for geometrically non-linear structures (internal)
- Model order reduction of parametric nonlinear mechanical systems for influencing vibrations (DFG)
- Substructuring for nonlinear components (internal)
- Domain decomposition techniques for dynamic problems (internal)
- Domain decomposition methods for large flexible multibody systems (internal)
- Elasto-hydrodynamic lubricated contacts in multibody dynamical systems (internal)
- Aerodynamic noise prediction of treaded tires using a hybrid aero-acoustic methodology (National Science Foundation Luxemburg)
- Dynamics analysis of large-scale models of turbine components (EXPERTISE)
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 in real conditions. As an example, a self-tracking laser Doppler vibrometer system is under development to perform in-operation monitoring and new laser measurement techniques are tested for the characterization of biomaterial. The research on experimental substructuring deals with specific assembly techniques, which can be used to build up full models based on the measured dynamics of real components. The methods of dynamic substructuring and transfer path analysis provide a promising combination for the development of optimally tuned structural and vibro-acoustical systems, using both measured and modeled components. Current research involves better models for the interface dynamics between parts and numerical design optimization for lower overall sound transmission. 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, active magnetic bearings are investigated with a focus on the modeling and experimental validation of the nonlinear magnetic behavior. 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 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. Besides, the chair explores new monitoring approaches for rotating machinery using accelerometers built of micro-electro-mechanical systems (MEMS) in a sensor network for fault prediction. Thereby, combinations of signal- and model-based algorithms are implemented on sensor nodes and verified on real machines.

Projects
- Real-time substructuring for complex systems (internal)
- Substructuring methodology for transfer path analysis (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 faults detection and control (DFG)
- Interface dynamics identification in bladed disks (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)
Robotics and Mechatronics

The chair has a long tradition in designing, constructing and controlling robots for novel applications. Based on the expertise in autonomous legged robots, the institute has developed a high-performance humanoid robot (LOLA) in recent years. Autonomous navigation of mobile robots in cluttered environments is a difficult task. Especially, if biped robots are considered, for which continuous high-level paths must be planned alongside discrete footstep locations in the lower-level planning stage. New algorithms have been developed to allow the robot to navigate autonomously through previously unknown environments. The ability to step over small obstacles while avoiding big obstacles shows the superiority of this approach.

To avoid robot-obstacle collisions in a dynamic environment, real-time perception methods for detecting possible obstacles are investigated. Herein the focus lies on locating objects and approximating them by geometric primitives, so called Swept Sphere Volumes (SSV), which allow efficient distance calculations to meet the real-time requirements.

Furthermore, new techniques for planning and controlling robot locomotion in the multi-contact setting, i.e. using the arms of a humanoid robot, are investigated. Aside from reduced models approximating the dynamics of the robot for real-time control, various methods for perceiving the environment and extracting appropriate support areas 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.

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 been becoming more complex, thus a global optimization scheme was developed to distribute the redundant degrees of freedom of the motion system.

We also cooperate with the Department of Orthopedics and Sports Orthopedics, to investigate the application of robotic manipulators to investigate 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 Prof. dr. ir. Daniel Rixen

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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
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.

External Ph.D. Candidates
Dipl.-Ing. Martin Münster (BMW)
Sascha Schwarz, M.Sc. (HS München)
Romain Pennec, M.Sc. (Goodyear)
Samuel Krügel, M.Sc. (Siemens)

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
■ 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 2017
■ Géradin, M., Rixen, D.: Impulse-based substructuring in a floating frame to simulate high frequency dynamics in flexible multibody dynamics. Multibody System Dynamics, 2017
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 optimizing 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 for 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 that our research group has received during the past two decades from several organizations.

Combustion Emissions and Reliability

1. Boundary Layer Flashback in Premixed Combustion of Highly Reactive Fuels

Motivation and Objectives
If modern gas turbines are operated on highly reactive fuels such as hydrogen, flame flashback inside the burner's wall boundary layer is a major issue which limits stable and safe operation. A detailed understanding of the underlying physical mechanism as well as tools to predict the flashback limits are of great interest in the design of gas turbine burners.

Approach to Solution
Boundary layer flashback is numerically investigated with large eddy simulations. Combustion is modeled with finite rate chemistry including detailed diffusion modelling. This improves the insight into the mechanisms leading to flashback.

Key Results
The numerical model can reproduce the boundary layer flashback limits of flames confined in a duct. All relevant physical effects are thus accounted for by the chosen modelling approach.

Furthermore, it was shown that the existence of average boundary layer separation is not a distinct criterion for the occurrence of confined boundary layer flashback. Instead, flashback is triggered if local flow separation zones at the flame bulges are large enough to locally promote flame propagation.

2. Operational Flexibility of Gas Turbine Power Plants

Motivation and Objectives
To balance the increasing share of volatile power from renewable power sources, highly flexible conventional power plants are needed. Gas turbine power plants have the potential to quickly adjust to changing power demand but their operating range is limited by emission

\[ \text{OH}^* \text{-chemiluminescence of the swirl stabilized jet burner with syngas injection} \]
Towards very low loads, i.e., high turn-down as a sudden strong increase of CO and UHC emissions occurs whereas high NOx emissions limit the high-power end of the range.

**Low Load Operation of In-line Syngas Generation**

To extend the turn-down the fuel can be converted to syngas with a higher reactivity than natural gas. Theoretical system analysis shows the feasibility and potential of the process. Experimental investigations of the combination of a fuel pre-processor which produces syngas with a hydrogen content of 30%, and two different generic gas turbine combustors prove the technical feasibility. The lean limit of premixed combustion in terms of flame temperature for the two combustion concepts could be produced by 150-200K below the limit for natural gas. This corresponds to a decrease of 15-20% thermal power without violating CO emission limits.

**Modeling of CO-Emissions for Gas Turbine Combustors Operating at Part Load Conditions**

Load decrease in gas turbines is limited by a sharp rise of CO-emissions as the flame temperature decreases and chemistry gets inhibited. The objective of this project is a CFD-based model, which can predict CO in combustion systems operating at part-load conditions. The model supports the development of combustion systems fulfilling future emissions legislation. So far, the model is formulated and implemented. Furthermore, we conducted experimental measurements at atmospheric conditions for validation. In the following, validation using real engine data will assess the performance at realistic conditions.

**3. Explosion Research: Lean Hydrogen-Air Explosions**

Severe accidents in nuclear power plants can be accompanied by the production of large amounts of hydrogen and carbon monoxide. The formation of a flammable mixture cloud is highly probable because of the wide ignition limits of the fuel-air mixtures. The research focuses on the hazardous deflagration-to-detonation transition (DDT), which creates high pressure loads on the containing structure, and on the important early stage of flame acceleration as well. In the early stage of flame propagation, enlargement of the flame surface area is the main driver for flame acceleration. In lean hydrogen-air mixtures, flame front wrinkling caused by flame front instabilities is a major cause of flame enlargement. Hence, these effects need to be included in models for time averaged reaction source term. Temporally high resolved optical measurement techniques (OH-PLIF and shadowgraphy) are employed to evaluate the flame front behavior in the initial phase of flame propagation. This data is used for the development and the validation of the model. Investigations were focused on the evaluation of microscopic flame front curvature and showed a strong accelerating effect that must be incorporated in future models.

Additionally, the existing experimental infrastructure of the GraVent explosion channel is extended, allowing the investigation of homogenous and inhomogeneous H2-CO-air mixture distributions. The extension of the existing numerical CFD framework in OpenFOAM aims for large-scale detonation simulations with a wider fuel flexibility and the possibility of further introduction of other fuels. By applying the existing numerical H2-air framework to smooth pipe accident scenarios of the chemicals company BASF AG, it was shown that the large-scale CFD framework can be adopted for the interests of the chemical industry as well.

**4. 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 NOx under these conditions, a toxic pollutant that is increasingly emitted at certain loads. The third ongoing project aims to reduce 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
Thermodynamics

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.

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-NO₂ conversion observed in these engines. High emissions of NO₂ were shown to be caused by small amounts of unburned hydrocarbons which originate from flame quenching in the lean methane-air charge, which 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 NO₂ Conversion in Dual Fuel Engine

Combustion Instabilities and Noise

1. High-Frequency Transversal Thermoacoustics

Motivation and Objectives

High-frequency thermoacoustic instabilities in gas turbine combustion chambers result from constructive interferences between combustion heat release and acoustic oscillations. They physically manifest themselves as high-amplitude, self-sustained pressure pulsations in the combustion chamber. Potential consequences range from hardware damage, increased pollutant production to system failure. Avoiding these instabilities requires a thorough understanding of the physical mechanisms, for the development of prediction models and mitigation tools. Research activities in recent years were focused on swirl stabilized combustion systems and allowed a deep insight to be gained into the high-frequency thermoacoustic

Two-stage, reheat combustor experiment for the investigation of high-frequency thermoacoustic instabilities
feedback mechanisms, both experimentally and numerically. To further develop a comprehensive understanding of physical flame response mechanisms to high-frequency pressure pulsations, the focus is extended towards reheat combustion systems, which represent a highly relevant technology for modern gas turbine systems for electrical power generation.

Methods and Approaches
A state-of-the-art test rig for investigation of reheat flame dynamics has been designed, commissioned and experiments on the reheat flame response were conducted. The experiment features a special design that promotes the first transverse acoustic resonant mode, while simultaneously allowing the establishment of a characteristic reheat flame with areas dominantly stabilized by auto-ignition processes. The institute's acoustic prediction tools, know-how and methodologies were employed in an iterative design process to implement an experiment that allows for both in-depth academic studies by applying respective acoustic and flame diagnostic measurement techniques whilst reproducing characteristic flame features at lab scale. This experiment is the basis of future investigations to gain insight into distributed source terms that capture the underlying physics of high-frequency reheat flame response.

Key Results
The novel reheat combustor experiment represents realistic reheat flame features as found in industrial systems and allows for an extensive scope of investigations. The specific combustor design of the rig has been optimized simulating its thermomechanical and fluid dynamic characteristics. The acoustic design, sought to predominantly excite the first transverse mode, is developed by means of analytic approaches together with computational aero-acoustics in the frequency domain. In addition to this, a priori linear stability assessments are carried out to maximize the flame-acoustics constructive feedback. This rig design was successfully commissioned and is now used to conduct investigations to establish insights into the physics of reheat flame dynamics and to provide validation data for the development of analytical and numerical prediction models for thermoacoustic stability assessment tools as well.

2. Annular Combustor Damping

Motivation and Objectives
A major concern in modern industrial gas turbines is the occurrence of combustion instabilities. Annular combustors burning under lean conditions are susceptible to self-sustained azimuthal oscillations. A widely used countermeasure is the use of passive damping devices to suppress high amplitude pressure pulsations. Efficient dissipation of acoustic energy by such resonators and hence the disruption of the thermoacoustic feedback cycle, requires appropriate dimensioning and an effective placement strategy especially in the case of annular combustors.

Experimental Approach
Different damper configurations with respect to the number of dampers, their spatial distribution and the amount of purge air are investigated and compared to the baseline case without dampers. To assess the stability quantitatively three methods for damping rate computation from dynamic pressure data have been developed: The first method is based on the analysis of the decay of the pulsating pressures after sudden shut-down of sirens providing single frequency acoustic excitation. The second method employs so-called Lorentzian fitting to the pressure spectra resulting from turbulent combustion noise and the third method consists of the analysis of the autocorrelation of the acoustic pressures.

Numerical Approach
The measured damping rates serve as a validation database for a numerical methodology based on the linearized Euler equations to predict the stability margin of the rig quantitatively in a wide operating range, and to assess the influence of different damper configurations and fuel-stagings on the thermoacoustic stability to deduce basic guidelines for the application of passive damping concepts in annular combustors.

Related Projects
In a similar project, the application of the damping devices in a can-combustor is investigated in high frequency regime. To avoid high-frequency vibrations,
the increase in the acoustic damping of the combustion chamber is of central importance. This requires precise modeling tools which are not yet state of the art. Therefore, the purpose of this project is to develop a hybrid method for the damping calculation of can combustion chambers used in the high efficiency machines. This includes a combination of non-linear and linear field methods with network methods and the aim of creating a hybrid process that is as efficient as possible. In this context, two methods are introduced. The first approach is the 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 the other approach, perturbed non-linear non-conservative Euler (PENNE) equations will be implemented for computational aero acoustic (CAA) simulations. 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.

3. Combustion Instabilities in Rocket Engines

Motivation and Objectives
High frequency combustion instabilities arise from the interaction of field fluctuations due to the combustor acoustics with the heat release from the combustion. Consequences of unstable operation can reach up to destruction of the engine and thus mission failure. The prediction of these instabilities and the assessment of counter measures is the objective of this project, to support the reliable design of thermo-acoustically stable rocket engines.

Methods and Approaches
Numerical simulations are carried out in the frequency domain. Eigensolutions of 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 transfer matrix. Source terms in the energy equation account for flame feedback. Experimentally, studies are carried out on a cold-flow rocket engine configuration.

Key Results
For the stability predictions in rocket combustors, analysis has been extended to different propellant combinations. The modes in a hydrogen and a methane fueled engine without flame feedback have been compared with each other. Computational and qualitative differences in the cut-on behavior have been observed. In contrast to \( \text{H}_2 \), for \( \text{CH}_4 \) higher modes can be cut on in the front chamber part, before lower modes are cut on at the rear end. Further numerical and experimental studies have been continued examining the modification of chamber acoustics by the application of an absorber ring. The mode split observed previously has been studied with respect to the absorber design and a significant influence on the mode shape as well as eigenfrequencies has been found.

Transport Phenomena


Motivation and Objectives
In nuclear engineering the heat transfer in both reactor core and steam generator are of great interest regarding the safe operation of a nuclear power plant. Beyond a critical value of the heat flux (CHF), film boiling can occur. This boiling crisis and the departure from nucleate boiling must be avoided under all circumstances.

Approach to Solution
The experimental work conducted at TUM is aimed at providing detailed experimental data about CHF condi-
Thermodynamics

Double fiber probe inserted into a two-phase flow

Measurements for validation of CFD-based critical heat flux modeling. Special interest is placed on gathering data about the morphology of the two-phase flow close to CHF in the immediate vicinity of 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 optical micro-fiber probes. The latter, shown in the figure representing a double fiber probe, provide a way of measuring the local void fraction, bubble velocity and bubble diameters inside a flow channel.

Approach to Solution
Mainly two desalination techniques are currently investigated at the Institute: reverse osmosis (RO) and vacuum membrane distillation (VMD). The thermal driven process of VMD can operate at salinities that go beyond the limits of RO, which has to overcome the osmotic pressure of saline solutions. This is a necessary feature especially in brine treatment of desalination plants or waste water treatment up to the so-called zero liquid discharge (ZLD).

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 the classical CFD boiling model, as shown in the figure below.

2. Transport Phenomena in Desalination

Motivation and Objectives
Water processing and its related power consumption within the constraints of an ecologically sustainable use of globally essential resources has become one of the major challenges of the 21st century. During the last decade research on the recovery of potable water from saline water has therefore undergone a paradigm shift from a product-centered activity to a comprehensive interdisciplinary field.

Concerning VMD, during the last years the institute has built up a research infrastructure to investigate the technology from multi-effect industrial systems down to heat and mass transfer phenomena in the membrane channels with respect to scaling behavior and membrane wetting. Continuing the work of the last years a new model of a multi-effect VMD system has been successfully completed. This tool developed can be used to optimize plant design of multi-effect VMD systems and decrease the energy consumption with respect to high concentrated saline solutions and possible scaling effects.
3. Solar Cooling by Coupling of PV and Compression Chillers

**Motivation and Objectives**
Thermal conditioning of residential buildings plays a major role in the energy consumption of countries in a temperate climate as well as in the hot and humid climate of countries in the Gulf region. The market share of HVAC devices powered by renewable energy is low for both regions. This issue is addressed in the PVCool project of the Institute of Thermodynamics at TUM and the Hamad Bin Khalifa University (HBKU) in Doha, Qatar, started in March 2017.

![Compressor section of the test-rig with swash-plate compressor (left) and scroll compressor (right)](image)

**Approach to Solution**
Compression chillers (CC) directly coupled with photovoltaic (PV) systems (PV-CC) have gained increased attention, mainly due to the decreasing costs of PV systems and the low investment costs of conventional compression chillers, which makes them more and more economically feasible. However, one of the main challenges in PV-CC is their unsteady operation and need for low part load capability under fluctuating solar irradiation. Therefore, a swash-plate compressor is integrated into a CC for residential buildings and tested under desert and temperate climate boundary conditions.

**Key Results**
In a first step, experimental comparisons between swash plate compressor and scroll compressor, that is commonly used in HVAC applications, were executed under steady state conditions. It could be shown, that the part load capability of the swash-plate compressor is substantially lower than for the scroll compressor. The coefficient of performance of the swash plate compressor is slightly lower than the COP of the scroll compressor. These promising first results lead to further investigations comparing the dynamic operation of the two compressor types.

4. Energy Efficient Heat Source Management During the Initial Heat-up Period of Vehicle Cabin

**Motivation and Objectives**
Even in current, combustion-engine powered vehicles, cabin-heating in winter conditions is mainly provided by the heat rejection of the drivetrain. Consequently, development goals to achieve higher effective efficiency and lower fuel consumption entail decreasing waste heat production. As a result, in particular diesel engine-powered vehicles have to deal with insufficient heat supply to the vehicle cabin under low ambient temperatures.

**Approach to Solution**
Present investigations are focused on the influence of different engine operation modes of a state-of-the-art automotive six-cylinder diesel engine on its energy balance and its emissions especially under low-load conditions. Primarily, the parameters affecting the combustion process and the intake system are investigated. Additionally, load point shifting due to electrical loads is examined. As an evaluation criterion, a new kind of efficiency factor is introduced.

**Key Results**
Cabin heating has a crucial influence on the thermal- and emission behavior of the engine. Therefore, the amount of heat or enthalpy transferred to the environment must be reduced significantly. This can be achieved most effectively by increasing the EGR rate and the charge air temperature. Indirect charge air cooling systems, for example, are advantageous for both measures.

5. Low Dimensional Modelling of Flow and Mixing in Automotive HVAC Units Using Proper Orthogonal Decomposition

**Motivation and Objectives**
Passenger comfort has become a major aspect in modern vehicle air conditioning concepts. Therefore, the temperatures at the outlets of the HVAC units are controlled and measured using temperature sensors. These sensors provide the most important value for the automatic climate control (ACC). To predict the temperatures at the outlets a novel proper orthogonal decomposition (POD) based approach is investigated to avoid costly sensors and enable model-based control of the HVAC unit.
Approach to Solution
The POD method is widely used to extract dominant flow features from spatio-temporal flow observations. By using only the most dominant features, or so-called POD modes, a low dimensional model of the flow field can be formulated. In this work, the POD is applied to the mixing process in the HVAC unit to find a correlation between input and output parameters, in terms of volume flow rates and enthalpy flow rates, respectively. By coupling the POD model with traditional modeling techniques, a low dimensional description of the HVAC unit is obtained.

Key Results
The approach was applied and evaluated on a real HVAC unit of a sport utility vehicle. A fluid resistance network was established to calculate the volume flow rates at the outlet. By combining the fluid resistance network with the POD approach the outlet temperatures can be computed. As a major outcome it could be shown that the accuracy of the model is comparable to the measurement uncertainty of the sensors (+/- 2K). Furthermore, the application of the model for model-based control was demonstrated.

Awards and Honors
Golden Teaching Award
Norbert Heublein won the Department of Mechanical Engineering Golden Teaching Award in the category ‘Bachelor Exercises’ on behalf of the department’s students as a recognition for his commitment and performance in teaching Thermodynamics I.

WATT-Master’s Thesis Award
The Scientific Working Group Technical Thermodynamics (WATT) awarded Simon Tartsch a prize for his excellent Master thesis ‘Aufbau eines optischen Schatten-Mess-systems und Durchführung von Verbrennungsuntersuchungen’, which was supervised by Markus Grochowina. The award was presented to him in the form of a certificate at the last Thermodynamics Colloquium in Dresden. Part of the prize was participation at the colloquium, where he presented his excellent work to the German Thermodynamics Community.

ASME Turbo Expo Best Technical Paper Award
At TurboExpo 2017 Stefan Bauer, Balbina Hampel and Thomas Sattelmayer received the Best Paper Award of the ASME IGTI Microturbines, Turbochargers & Small Turbomachinery (MTST) Committee for their 2016 paper: ‘Operability Limits of Tubular Injectors with Vortex Generators for a Hydrogen Fueled Recuperated 100Kw Class Gas Turbine’.

ASME Turbo Expo Best Technical Paper Award

ASME Dedicated Service Award
At Turbo Expo 2017 in Charlotte, Christoph Hirsch received the ASME Dedicated Service Award, which honors unusual dedicated voluntary service to the ASME marked by outstanding performance, demonstrated effective leadership, prolonged and committed service, devotion, enthusiasm and faithfulness. The award is presented to selected individuals who have served the ASME for at least ten years.

2017 GPPS Innovation Award
Thomas Sattelmayer has been selected as the recipient of the 2017 Global Power & Propulsion Society (GPPS) Innovation Award. This annual award is given in recognition of outstanding technical and professional contributions to the gas turbine industry.

New Honorary Professor at the Chair of Thermodynamics
Dr.-Ing. Alexander Kolb was appointed Honorary Professor at the Technical University of Munich. He is Director of the Engineering Center Northern Europe of the Thermal Europe Center of DENSO Corporation, Kariya, Japan. Since winter term 03/04 he has been teaching the Master course ‘Automotive Air Conditioning/Refrigeration Technology’ and the corresponding exercises. In addition to his teaching activities, Dr. Kolb has supported research at the TUM in many ways in the past.
Technical Staff
Josef Dorrer
Gerhard Giel
Jens Hümmer
Ogulcan Kocer
Joel Rieger
Thomas Schleussner
Bernhard Strobl
Claus Wimmer

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 and II
■ Combustion
■ Desalination
■ Energy Optimization of Buildings
■ Solar Engineering
■ Automotive Air Conditioning
■ Thermo-Fluidynamics Lab
■ Combustion Technology Lab
■ Solar Technology Lab
■ Data Acquisition & Controls Lab

Selected Publications 2017
Sport Equipment and Materials

Sustainable support for sports and health through technology

- TUM’s broad knowledge from very different scientific disciplines helps us to realize our chosen holistic approach to better understand the interaction between athlete, equipment and environment. In 2017 we extended our internal network starting a close collaboration with the Chair of Micro Technology and Medical Device Technology (MiMed) of Professor Lüth.

From our 2017 activities four highlights are worth mentioning:
- Development and realization of a new test bench to quantify ski boot flexibility.
- Co-organization of 23rd University Day of the German Society of Sport Science ‘Innovation & Technology in Sports’ held at TUM.
- Intensification of our collaboration with Reutlingen University on the field technical garment and wearables. Common student project at Environmental Research Station ‘Schneefernerhaus’ (Zugspitze).
- Start-off R&D project (ZIM) realizing non-invasive real-time measurement of core temperature integrated into ballistic police helmets.

Towards Better Performance with Optimized Sport Equipment

Improving the performance in both top-level and leisure-time sports is one motivation of our work. The focus is on optimizing the energy transfer between athlete and equipment and on reducing the inherent energy loss. On the equipment level we try to achieve this by:
- better weight to stiffness ratio (i.e. bicycle frame),
- using energy storage and return effects,
- optimized heat- and moisture management of sport garments (i.e. new infills for down jackets),
- improved fitting to the individual (i.e. golf shaft).

An excellent example of our efforts towards optimized performance of sport equipment is demonstrated in a study which has been performed by one of our Master students (Pablo Weber, 2017). The goal was to characterize different suspension settings of mountain bikes and to answer the question if these have an influence on the perceived subjective riding experience of advanced bikers. Using a special suspension-tuning system (ShockWiz™) the performance of four identical enduro mountain bikes were tuned differently thus achieving...
response characteristics such as ‘aggressive’, ‘efficient’, ‘balanced’ and ‘playful’.

All test bikes and their suspensions were equipped with sensors – standardized measurements on a test bench confirmed physically measurable spreads of the four setups. To answer the above question on the relationship between objective and subjective parameters a blind test was performed. The selected ten subjects – all with approximately the same body weight – had to rate the performance of the bikes under widely standardized field conditions and always against the same reference bike. Variance analyses confirm significant differences in perception and evaluation, thus paving the way for further research on mechatronic suspension systems.

**Improved Fitting Through Customized Sport Equipment**

A good core stability has a high impact in different fields of physical activity like rehabilitation, performance improvement and injury prevention. Especially during fast distal segment movements and initiation of force development, high activity and hence stability of the core muscles is essential. Through a holistic activation of hand- and arm muscles we want to achieve an equal activation of essential core muscle groups and therefore improve athletic performance. We aim to develop an individualized exoskeleton-glove that activates the aforementioned muscles.

A high level of manufacturing quality for these gloves is possible through our collaboration partner, the Chair of Micro Technology and Medical Device Technology (MiMed) of Professor Lüth. State-of-the-art additive manufacturing techniques will be used to create these gloves. Using our expertise in scientific methodology, we will validate their efficacy in performance during a subsequent validation study.

Through high-precision measurement of human surface and joint properties, and additive manufacturing, we aim for a real customization for everyone in the near future.
Understanding the Interaction between Athlete, Equipment and Environment

Psycho-physics has pervasive and significant practical applications in different fields such as neuroscience, robotics but also for sports engineering. The meaning for sports engineering becomes clear if we look at the factor ‘(dis)comfort’. This variable is considered as one of the important criteria for athletes selecting and tuning their sport equipment. It may also have an impact on sport injuries and performance. One related question is whether there is a relationship between objective biomechanical parameters (i.e. plantar pressure distribution or joint angles) and the perceived ratings of the athletes. Running and especially on various type of terrain offers perfect boundary conditions to investigate this question. Systematically different types and levels of perturbations are imposed to runners (i.e. additional weight in the boots) and their perceptions of perturbations are gathered. Simultaneously objective variables such as center of pressure, vertical force, joint kinematics and EMG are measured. First observations indicate that the athlete seems to maintain his/her running pattern even if major equipment modifications have been made.

Health, Wellness and More Fun Through Technical Support

Sports and physical activity are often considered as ‘the preventive medicine not taken’. Clearly, this puts emphasis on the so-called self-management of health since people are individually responsible for their physical activity and well-being. Today, the advancement of sensing technologies, embedded systems, wireless communication, nano-technologies and miniaturization potentially makes it possible to develop smart systems for monitoring activities and vital parameters. In the last few years, a multitude of wearable devices, such as activity trackers, smart watches or inertia sensors have come to the market. They assist as a virtual coach, monitor physiological parameters or even serve as a feedback system. The future of wearable devices with sensors close, on or even in the body seems to be bright.
Sports equipment and materials

Sports engineering not only takes care of developing those systems or improving their accuracy and usability. It is also in charge to validate them against gold standards. Regarding these issues, we are currently focusing on the validation of some current state wearable devices, e.g., multisport watches (GARMIN Forerunner® 920XT, Polar V800) and fitness trackers (GARMIN vivosmart® HR, TomTom Touch, Fitbit Charge 2, Withings Pulse Ox). The aim of this extensive study is to determine the accuracy of estimation of certain physiological parameters. These parameters include heart rate, energy consumption, the body fat percentage as well as the cardiorespiratory fitness level. Based on the results, the estimation of physiological parameters of future wearable devices shall be improved. In addition to that, we are also working on the development of new non-invasive measurement systems monitoring hydration status and glucose concentration.

More safety with improved protection gear

In alpine skiing, knee injuries remain a major safety issue. Systematic analysis of injury situations and human anatomy suggest that mechatronic ski bindings may provide a solution. The key aspect of mechatronic ski bindings is the release algorithm. Two of the needed parameters of that algorithm are the knee angle and the muscle activity of the leg while skiing. Both parameters help to identify critical situations, which might lead to an increased risk of a knee injury. The algorithm would react by accordingly adjusting the release settings of the ski binding. Besides the research to establish the algorithm(s), we also have to develop functional close-to-body measurement systems being able to provide real time data on knee kinematics and muscle state of the skier. In collaboration with University of Applied Sciences Reutlingen we have developed a prototype of skiing underpants which are able to measure the knee angle.

We also work on the integration of sensors to register the level of the major leg muscles’ activity.
Research Focus
- 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
- Skiboot 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
- Interdisciplinary Research Project

Publications 2017
Energy Systems

Power generation and solid fuel conversion

The focus of the Institute for Energy Systems in 2017 was to investigate future power generation systems and solid fuel conversion processes.

Our research can be divided into four areas: power plant technology, renewable energy, modeling and simulation, as well as measurement technology. We cooperate with research institutions and industrial companies on a number of national and international research projects. The expertise of the institute is also reflected in the large number of operated test rigs and applied measurement techniques. The mechanical workshop, electronics lab and chemical lab are also essential parts for the experimental operability at our institute.

Key competences regarding modeling and simulation are CFD simulations of combustion and gasification processes, entire process simulations, burner design, form optimization of blade and seal geometry, as well as the simulation of deposition and slagging tendencies. Furthermore, a Siemens GuD 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.

Renewable Energy

The use of biomass for electricity and heat production has moved increasingly into focus. In the biomass work group, the goal is to investigate and solve problems and limitations that arise in the thermal use of biomass. Key aspects are the reduction of emissions and unburned materials, trace elements like sulfur and chlorine compounds, as well as alkalis and particles. Together with Suncoal Industries GmbH, focusing on the process of hydrothermal carbonization (HTC), the conversion of biochar in an entrained flow gasifier is investigated. A procedure for the treatment and methanation of the product gas from a biomass gasifier is developed as well. The processed gas has to meet the criteria for integration into the natural gas grid. Furthermore, within the framework of the SYNSoFC project, the use of solid oxide fuel cells (SOFCs) in combination with a biomass gasifier for generating electricity from biomass is investigated. The goal is to develop SOFCs that show a high tolerance against biogenic contaminants. The new EU project Biofficiency aims, among other things, at the development of next generation, biomass-fired CHP plants, an increase in efficiency at elevated steam temperatures and the reduction of emissions – i.e. \( \text{CO}_2 \), particulates, \( \text{CO} \), \( \text{NOx} \) and \( \text{SO}_2 \).

Projects

- Biofficiency – Highly-efficient biomass CHP plants by handling ash-related problems
- FLUHKE – Entrained flow gasification with biochar
- FNR – Thermal use of biomass in high-temperature processes
- SYNSoFC – Solid oxide fuel cells
- SNG – Decentralized production of synthetic natural gas from biomass

Power Plant Technology

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 interest for flexible power plants. To investigate the evaporation process under dynamic conditions, an evaporation test rig was put into operation at the institute in 2017. Further test rigs include an oxyfuel combustion chamber and two entrained flow reactors. The oxyfuel combustion of coal is one of the three main research routes for the development of coal-fired power plants with \( \text{CO}_2 \) capture and storage (CCS) systems. The aim is to develop and demonstrate combustion and boiling systems on a commercial scale. Coal power plants based on IGCC technology (integrated gasification combined cycle) mainly use entrained flow gasifiers and offer the advantage of high efficiency and an opportunity for effective CCS.
The primary objective of the work at the institute is to lay the necessary foundations for the long-term development of future, highly efficient high-temperature gasification processes with integrated hot gas cleaning and optional CCS for IGCC power plants and processes for the development of synthetic fuels. Further projects, like the EU project OnCord, which is coordinated by the institute, investigate the use of coal and its inorganic constituents as a protective agent to prevent the formation of alkali metal chlorides at both laboratory/test rig and industrial scale.

Projects
- Energy Valley Bavaria – High pressure evaporation facility
- OnCord – Online corrosion monitoring for combined combustion of coal and chlorine-rich biomasses
- HotVeGas – High-temperature gasification and gas purification
- KorrMind – Development of a corrosion reduction concept
- COOREFLEX-turbo – Performance and characteristics of modern dynamic sealing concepts

Modeling and Simulation

Modeling and simulation of solid fuel conversion play an important role in several projects, e.g. HotVeGas and SNG. Computational fluid dynamic (CFD) simulations are applied in order to gain a more detailed understanding of several combustion and gasification processes. Furthermore, entire process simulations aim at evaluating the complete power plant system and possible synergies. As the flexibility of power plants gets into the focus of the operators – in addition to efficiency and economy – the interaction of power plant processes during dynamic operation is investigated by means of dynamic simulations of power plants. An improved process understanding helps to develop better operating strategies and optimized power plant configurations. Two different power plant types are investigated: combined cycle power plants and coal-fired power plants. The use of heat at low temperatures, like waste heat and geothermal heat, with organic Rankine cycles (ORC) or the Messelhorn cycle is also a focus of research and is examined at the institute by means of process simulations and experiments. Since 2016 several projects regarding process simulation have started: The CleanTechCampus Project, for example, aims to improve the CHP plant on site. The Bavarian Geothermal Alliance focuses on efficiency enhancing designs of ORCs in combination with suitable working fluids and possibilities of flexible heat decoupling.
Energy Systems

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Research Focus
■ Power plant technology
■ Renewable energies
■ Modeling and simulation
■ Measurement technology

Competence
■ Combustion and gasification of solid
■ Steam cycles and waste heat utilization
■ Operation of pilot- and lab-scale test facilities
■ Process simulations and CFD simulations
■ Laser measurement technologies
■ Fuel and gas analysis

Infrastructure
■ Fuel laboratory and thermobalances
■ Mechanical workshop and electronics laboratory
■ Experimental facilities and test rigs (in particular combustion and gasification reactors)

Courses
■ Basic Course in Reaction Thermodynamics
■ Chemical Reactors
■ Energy and Economy
■ Energy from Biomass and Residuals
■ Power and Natural Gas: Grids and Regulation
■ Energy Systems I
■ Electricity and Heat Storages
■ Numerical Methods for Energy Systems
■ Process Technology and Ecology in Modern Power Plants
■ Renewable Energy Technology I/II
■ 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 2017
Machine Elements

The Institute of Machine Elements, also known as ‘Gear Research Centre’ (FZG), is an internationally renowned research centre for gears and transmissions. 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. FZG has state-of-the-art facilities for the examination and testing of different machine elements – such as gears, synchronizers, clutches and rolling element bearings.

The research projects of FZG range from theory-oriented fundamental research to application-related work. The projects are financed and supported by different organisations. A large number of these projects are initiated, financed and supervised by the Forschungsvereinigung Antriebstechnik e.V. (FVA), usually together with the Arbeitsgemeinschaft industrieller Forschungsvereinigungen (AiF). Other important research partners include the Deutsche Forschungsgemeinschaft (DFG), the federal ministry for economic affairs and energy (BMWi), the Deutsche Wissenschaftliche Gesellschaft für Erdöl, Erdgas und Kohle e.V. (DGMK), the FVV or the Stahlforschung. In addition, many application-oriented projects are requested and commissioned directly by industry.

Our education lecture series and exercises in machine elements represent the basic training of mechanical engineering. In the lectures, students learn to select machines and machine elements properly, to design them and to calculate their properties. This knowledge is then applied practically to design and calculation examples within the lecture-related exercises. A very important aspect of this is that the students learn to communicate in the ‘engineer’s language’ – with sketches and drawings. Practical relevance and topicality are also an important criteria for lectures with special subjects. Last but not least, this is ensured by lectures given by executives from industry.

Research on the load-carrying capacity of gear drives is one of the main research areas of the institute. Further important aspects of research in automotive applications have evolved, such as synchromesh systems, multidisc clutches and rolling element bearings. The consideration of fatigue life, efficiency friction and vibration behavior of gears and transmission elements is in the foreground of research activity at FZG.

A large number of the research topics deals with the load-carrying capacity of the components cylindrical, bevel, hypoid and worm gears, as well as multidisc clutches, synchronizers and rolling element bearings. The results of many research projects at FZG are gained from theoretical and experimental investigations carried out simultaneously. These validated methods are often programmed as application software and thereby comfortably accessible for practical application. For the development of a method, simulation models for the load case are usually developed and validated by extensive tests with samples. The following selected projects give an exemplary insight into the research activities of FZG.

Innovative High-Speed Powertrain Concept for Highly Efficient Electric Vehicles

Due to its high power density and lightweight design, high-speed powertrain concepts are increasingly used in electrified vehicles. Because of the high input speeds, new design challenges arise in terms of efficiency, lubrication, load capacity and NVH behavior, which were investigated in the BMWi joint research project ‘Speed2E’. Within this project, a new powertrain layout based on two identical electrical machines and one joint gearbox was developed and investigated.

In order to determine the power requirements of the electromechanical powertrain, a reference vehicle of the C segment, which includes compact-class vehicles for suburban use, was defined. Based on this reference, a compact powertrain based on a front-wheel drive was designed resulting in a maximum vehicle velocity of up to...
to 160 kph. Two identical permanent magnet synchronous machines drive the axle gear with up to 30,000 rpm.
The electric motors operate with separate optimized AC/DC converters, which are supplied by a direct current voltage source. Hence, the car's battery system was not part of this project.

The powertrain's gearbox consists of two separate sub-transmissions, which are mechanically connected via a common final drive. Sub-transmission I consists of a two-stage cylindrical gear drive with a gear ratio of 21, reaching the desired vehicle velocity of 160 kph at the maximum speed of the electric machine. To investigate the impact of the extremely high input speeds on acoustic behavior and efficiency, different types of gears were applied to the high-speed stage of sub-transmission I. Sub-transmission II consists of three stages and features two speeds: a high run-up gear ratio of 32 and an overdrive gear ratio of 15 for high efficiency at high vehicle velocity.

The flexible distribution of power supply to both sub-transmissions is used to provide operating strategies with reduced energy consumption or noise emissions.

It also enables seamless shifting using dog clutches with an optimized electric synchronization. This requires an operational strategy, which influences the shifting of sub-transmission II and therefore the power distribution between both electric motors and sub-transmissions. The whole powertrain was installed and tested at FZG. Within the scope of the experimental investigations, both efficiency as well as NVH performance was optimized. In order to reduce load dependent power losses, a low-loss test gear set was developed and tested, showing a significant increase in efficiency. By adjusting the operational strategy, the overall energy consumption within a given driving cycle decreased even more. Using another test gear set enabled investigations beyond the gear's resonance frequency and showed huge potential for high-speed applications.

In the follow-up BMWi joint research project ‘Speed4E’, the input speed will be increased above 30,000 rpm and a newly developed powertrain will be installed in a car. Hence, the vehicle integration of the high-speed powertrain will be an important part of the follow-up project, starting in 2018.
Optimized Lubrication and Energy Efficiency of Geared Power Transmissions

The development of energy- and resource-efficient geared transmissions has become a major concern in industry. This is mainly driven by environmental requirements and resource scarcity. Geared power transmissions require lubrication in order to reduce friction in loaded rolling elements and to dissipate frictional heat. Several research projects at FZG address the lubrication and energy efficiency of geared power transmissions. Besides experimental investigations, focus is put on the physical understanding of mechanisms by support of numerical modelling.

As the lubrication of geared transmissions is difficult to predict at the design stage, the DFG project STA 1198/14-1 in cooperation with Prof. Adams from AER/TUM aims at developing efficient CFD (computational fluid dynamics) simulation models to predict the oil flow and no-load gear losses. Various operating conditions including kinematic, geometrical and oil-specific parameters are investigated. Consequent validation is performed at a no-load power loss test rig by measuring the loss torque and the oil flow with a high-speed camera. The results contribute to an optimized lubrication and efficient design of geared transmissions. On the one hand, lubrication has to be sufficient to avoid any damage to machine elements. On the other hand, the lubricant volume has to be as small as possible to reduce the no-load power loss, which is due to hydraulic losses and ventilation.

Load-dependent gear losses are caused by friction between loaded gear flanks in relative motion. Its reduction by use of DLC (diamond-like carbon) coatings is addressed in the IGF project 18490 N (FVA 585/II). The potential of DLC coatings to improve load capacity and to reduce friction is well known. However, the thermophysical mechanisms of friction reduction in elastohydrodynamically lubricated (EHL) gear contacts with separated surfaces is largely unexplored. Experimental investigations at the model and gear test rigs show significant reduction of friction and load-dependent gear loss by up to 40%. Thermal EHL simulations indicate that this is mainly due to the low thermal inertia of DLC resulting in a thermal insulation and low effective viscosity in EHL gear contacts.

The potential of pure and reinforced thermoplastic gears for application in geared power transmissions is investigated in the IGF project 18414 N (FVA 785/I). Thermoplastic EHL contacts are completely different to steel EHL contacts and not well understood. Investigations are performed experimentally at model and gear test rigs as well as theoretically by means of thermal EHL simulations. The figure above illustrates exemplarily the deformation and temperature distribution of a hybrid EHL contact of steel and polyamide 6.6 (PA66). The high surface conformity leads to low hydrodynamic pressure compared to steel contacts for the same load applied and thus very low friction. The low thermal inertia of thermoplastic material affects the local contact temperature and its tribological performance. The appropriate usage of optimized thermoplastic gears in geared power transmissions can push its limits of energy and resource efficiency.
Calculation of Load Distribution in Complex Gear Systems

Planetary gear sets are widely used in industry and automotive applications. Compared to a basic cylindrical gear pair, they offer high transmission ratios and high power densities due to load sharing across several planet gears. They usually consist of a central sun gear, several planetary gears (orbiting round the sun as well as rotating on their own axes) and an outer ring gear. The planet gears’ axes are mounted on a planetary carrier, which forms the third coaxial shaft, in addition to the sun gear’s shaft and ring gear’s shaft.

When in need for even higher transmission ratios, more than one planetary gear set can be arranged sequentially, as was done in the gearbox shown below. Load-induced deformations and manufacturing or assembly-related errors influence local peaks of the tooth load and the load deviation in the meshes of planetary gear sets. In modern transmission systems, deformations of transmission elements and associated displacement of gear wheels in tooth contact can be compensated by modification of the tooth geometry.

The design of flank modifications in planetary gear systems is based on the reliable and accurate calculation of the three-dimensional positions of the central shafts and the load sharing behavior between the planets. Practical methods used previously often neglect these influences and assumed equal load distribution between the planets and central shafts in non-deflected positions. With the FZG’s simulation approaches, load distribution, load sharing behavior between planets and deformation in arbitrarily coupled planetary gear sets can be calculated and tooth flank modifications can be designed.

The 3D graphics show the nominal and the deformed (exaggerated) state of an example multi-stage planetary gear set from which gear flank load distributions can be calculated.

Using this elastic deformation analysis, the influence of different carrier angular positions on the momentary load distribution of each gear mesh is determined, as shown in the diagram above (showing mesh load over tooth width for several carrier positions). This deformation and load distribution information can serve as a base for flank micro-geometry modification design. Applying these micro-geometry modifications in the manufacturing process allows for a favorable load distribution during operation. With this at hand, an optimized load carrying capacity or noise excitation behavior can for example be achieved.
Machine Elements

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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
- Synchronmesh Systems and Multidisc Clutches
Selected Publications 2017:

Automation and Information Systems

Engineering and operation of intelligent, reconfigurable, distributed cyber-physical production systems

- The increasing demand to produce customer-specific, individual products in shorter innovation cycles within the machine and plant manufacturing domain require Cyber Physical Production Systems (CPPS) with higher Overall Equipment Effectiveness (OEE). The main research goals of the AIS are methods, notations, algorithms and architectures to increase OEE. Research areas are Model-Based Engineering, self-X-CPPS, human-machine interaction and analysis and aggregation of big data.

To increase the overall equipment effectiveness of machines, agents and learning approaches have been and are being developed to improve the operation of CPPS. In the field of model-based engineering, inconsistencies management across disciplines and along the life cycle were 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 were developed including speech recognition and Augmented Reality (AR) to support the individual operator according to his/her skills and requirements. The aggregation and analysis of big data to gain smart data from big data enables predictive maintenance and process/product optimization. Embedded Systems and its software in the mechatronic industry (products and automated production systems) are getting more and more important. The AIS adapts methods and approaches from the computer science domain with the needs of the machine and plant-manufacturing domain. Therefore, approaches like technical debt, product lines, family mining and neuronal nets or ontologies are introduced to address the challenges in automation in real-world scenarios often together with partners from industry.

Methods applied at the Institute of Automation and Information Systems
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. Research in the domain of intralogistics was focused on reducing the effort for new development and extension of existing Material Flow Systems (MFSs). Generally, the hardware modules, which are combined to form a MFS, are reused frequently (an example for such a hardware module is a roller conveyor). The project aComA (BFS Project) transferred this reuse into the control software of MFSs and 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 was successfully used to control the industry size self-X material flow demonstrator. Furthermore, the model-based description is used to automatically analyze and adapt the interfaces of hardware modules to implement a backward compatibility of newer modules with an existing MFS. To increase the flexibility of MFSs and allow an easy adaption of the system layout to requirements arising during the operation phase of a MFS, the project iSiKon (DFG Project) introduced a decentralized, agent-based control approach for MFSs. Therefore, an MFS is divided into hardware modules, which are each equipped with a PLC and represented by a module agent. The use of a multi-agent system allows adding or removing modules to or from a MFS without the need to change the control program of the MFS’s other modules. Additionally, an approach for self-healing was implemented based on a state control according to the OMAC State Machine Standard. This approach enables a plant to independently react to a failure and take measures to attempt to resolve an occurring error state before the plant operator has to intervene.

Projects
- DFG Project – Increased flexibility in heterogenous material flow systems based on intelligent software in self-configuring modules
- DFG Project – Model-Driven Evolution Management for Microscopic Changes in Automation Systems
- DFG Project – Self-Maintenance of Mechatronic Modules
- BFS Project – Automatische Codegenerierung für modulare Anlagen

Model-Based Development

To handle the increasing complexity of mechatronics systems model-based approaches are most appropriate but still need research to handle cross-disciplinary development. The question of interest is how different domain-specific models could be connected, how the information flow between models could be automated and how inconsistencies between models should be managed. Therefore, dependencies between models were investigated, intra-model change impacts explored and methods like standardized model-interfaces defined using meta modeling and model-coupling as well as ontologies for inconsistency management. 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. Different modeling languages are investigated and adapted for the different domains of mechatronics.
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 to smart data. Within this scope, the chair AIS applies a variety of data analysis algorithms to data gathered from manufacturing industry (EU project IMPROVE) and process industry (BMWi Project SIDAP) as well as other important industries such as semiconductor manufacturing. Within these projects, data acquisition, curation and preprocessing often becomes as important as the machine learning methods. For data aggregation and integration as challenging parts of data collection, architectural solutions are elaborated, which enable a flexible acquisition of data from a variety of sources within CPPS. In the phase of data preparation, AIS develops routines for the evaluation of data quality and standardized procedures for data preparation itself. Amongst others, methods based on conditional probability are developed in order to replace missing values in incomplete datasets. Furthermore automatic outlier detection methods are introduced using statistical approaches. Another important preprocessing step is the automatic classification of process data into operation phases, taking into account the different behavior of production processes and plants during these phases. Several methods e.g. k-means clustering or self-organizing maps...
This field of research addresses the design and evaluation of human-machine interfaces (HMI) for operators as well as engineering support systems. The increasing capabilities of production systems and the availability of big data require intuitive user interfaces and visualization techniques. New challenges for the design of industrial HMI arise from the increasing diversification of the workforce driven by the demographic change. The EU project INCLUSIVE targets the development of automation systems that adapt to the capabilities of human operators. A part of the approach are virtual training systems that allow the initial training of manufacturing and changeover procedures using virtual reality technologies. User profiles that describe age, education, and the mental model of the trainees are used to adapt the training system and the style of information presentation to the capabilities of the user. Multimodal training systems (e.g., using haptic or speech-based interaction) allow more effective training that can be adapted to the capabilities of elderly or disabled users. The state of the users is tracked in real-time using emotional speech analysis and eye-tracking to detect stressful situations and errors in mental models. Support during the work process is provided by multimodal assistance systems that guide operators during procedures using speech and visual instructions.

To support the cycle-oriented design of innovation processes for product service systems, the goal of subproject 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)
- BMWi Project – Skalierbares Integrationskonzept zur Datenaggregation, -analyse, -aufbereitung von großen Datenmengen in der Prozessindustrie (SIDAP)

(modification of the well known neuronal nets) are examined and adapted to serve as classification methods for operation phases. Once the preprocessing is completed, an intelligent combination of various approaches can be used to analyze data for patterns indicating upcoming malfunctions, necessary maintenance and shortcomings in product quality. Machine learning methods like neuronal nets and Markov chains as well as statistical approaches like regression are used to predict machine faults or product quality. Thereby the signals are considered in time-domain as well as frequency-domain. All above approaches require a balanced combination of big data methods, process understanding and input of plant specialist knowledge. The Chair of AIS is experienced in applying these to a great variety of different industries. The above experience makes the chair of AIS a reliable and experienced research institute and partner to transform industrial big data into smart data, including sensor, actuator and alarm data.
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Josef Wagner
Johannes Werner

Apprentice
Jana Eggert

Doctoral Theses finished in 2017
Dr.-Ing. Thomas Aicher
Hang Li (Chinese Council scholarship)

Research Focus
- Model-based engineering
- Quality management
- Distributed, intelligent control systems
- Software agents, service-oriented architectures
- Machine learning
- Human-computer interaction

Competence
- Cyber-physical production systems
- Smart data
- Human factors
- Improvement of the engineering during the whole life cycle of products and production lines for hybrid processes using and adapting methods from computer science, e.g. pattern recognition and software engineering.
- Matching data and models along the life-cycle of CPS and CPPS in different domains

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 software engineering for embedded systems
- Neutralization plant – test bed for the process engineering domain
- Extended Pick and Place Unit – demonstrator for 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 handling complex information by using the expanded possibilities of visualization and interaction
- Communication Demonstrator for analyzing different real time communication technologies based on Ethernet

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 2017
Metal Forming and Casting

Process and material qualification for metal forming, blanking and casting

The Chair of Metal Forming and Casting (utg) focuses on the three production processes: casting, blanking and metal forming. In 2017 over 40 scientists worked at the institute on research projects which vary from fundamental research to industrial application.

Virtual production and simulation

| New technologies and processes in the field of casting | New technologies and processes in the field of blanking | New technologies and processes in the field of metal forming |

Process stability and capability

Casting

The research group ‘Casting’ focuses on:
- Molding materials
- Residual stress analysis and material characterization
- Tooling technology for (high pressure) die casting
- Continuous and composite casting

Copper composite materials are used in many technical applications today. These compounds are produced mostly by joining of the basic materials, especially via roll bonding processes. The bonding mechanism of these solid-state joining techniques is based on a cold welding process to establish adhesive bonding. Therefore, extensive chemical, thermal and mechanical preparation of the bonding partners and post-treatment of the compounds are required to ensure the formation of a suitable bonding. Horizontal continuous compound casting of copper materials could be an adequate alternative to this energy- and resources-consuming processes. Thus, it will be possible to replace the chemical and mechanical preparation of the bonding surfaces and increase the output by reducing

Horizontal continuous compound casting
cracking of higher-strength alloys, which can occur in roll processes. Furthermore, the utilization of the casting heat of the substrate results in conservation of energy, because no additional thermal pretreatment is necessary. Therefore, the producibility of continuous composite casting of selected copper alloys needs to be qualified in this joint research project in cooperation with industrial partners. First the required conditions to achieve a proper metallurgical bonding between the copper alloys have to be determined by means of static composite casting experiments using sand moulds and permanent moulds. Based on the results of the basic composite casting experiments, the continuous casting process is established. Therefore, the horizontal continuous casting device located at the utg is modified. Numerical simulations are applied to design a composite mould system which is integrated into the existing continuous casting equipment. Thereby, the comprehension of the correlation between the quality of the compound and the casting conditions is gained. Furthermore, the numerical simulation of the casting process has to be validated to help industrializing the new process in the future.

Projects
- Incremental Casting – The Generative Droplet-based Manufacturing of Parts Using Aluminium Alloys (DFG)
- Opti Alloy – Mechanical Strength Calculation Based on Microstructure (BFS)
- In-situ Straining Measurement During the Solidification of Aluminium Alloys Using Fibre Bragg Gratings (DFG)
- μ-Kern – Microstructure-based Method for Calculating Technological Properties of Inorganic Bound Sand Cores (DFG)
- Energy- and Material-efficient Production of Copper-composites Using Horizontal Continuous Casting (DBU)
- Casting and Characterization of Cu-Al-bilayer Composites (DFG)
- FORPRO² – Efficient Product and Process Development by Knowledge-based Simulation (BFS)
- In-situ Measurement of Deformation Induced Formation of Martensite in Austempered Ductile Iron (DFG)

Blanking

The increased demand for lightweight constructions in industrial production requires the design, manufacture, and use of application oriented components. Forming and blanking processes have many advantages over machining processes like optimized productivity and a fiber orientation which is adapted to the specific task. The latter results in increased mechanical characteristics and fatigue strength of formed metal components. However, residual stresses greatly influence the performance of components manufactured by forming or blanking procedures. The state of residual stress is mainly responsible for component failure, especially under cyclic loads. For this reason, residual stresses are currently considered as highly unfavorable and as having a negative impact on a component’s feasibility. Efficient models and experimental testing equipment for operational stability have already shown promising results for the potential usefulness of internal stresses. The control and alteration of these stresses in order to achieve a positive impact on relevant characteristics of components manufactured by forming or blanking processes is the objective of the DFG priority program 2013, which is coordinated by the Chair of Metal Forming and Casting. Among these manufacturing processes, near-net-shape-blanking processes (NNSBP) are one possibility to produce functional surfaces in an economic way. These
cutting processes are characterized by a high plastic deformation and thus induce residual stresses in the produced part. Up to now, residual stresses induced by metal forming operations have not been subject to focused investigations in the sense of a suitable use of their tensile and compressive components to ensure targeted part-specific residual stress profiles, especially when a cost and time-intensive heat treatment should be avoided. By a variation of the process parameters the influence on the formation of the residual stress state is identified and used for a targeted utilization. To that end, experimental as well as numerical experiments are performed. On the basis of the residual stress states generated and their time-stability in the produced parts, the component strength is derived by a residual stress model. Core of the investigation is a predictive residual stress model for closed cutting lines to determine process parameters for part specific load requirements. This allows an increase in the quality as well as the lifetime of parts manufactured by NNSBPs.

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)
- Influence of Process-related Altering Die Clearance on Tool Wear (AiF)
- 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)
- Geometry and Feasibility Prediction of Sheet Metal Parts with Embossings Made of High-strength and Ultra-high-strength Steels (AiF)
- 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)

Metal Forming

The research group ‘Metal forming’ focuses on:
- Qualification of materials
- Qualification of processes, tools and machinery

The qualification of materials is a key topic of this research group. In this area, especially the determination of quasi-static properties as well as the investigation of the strain rate and temperature sensitivity of the materials are focused on. The knowledge gained is the basis for the understanding of the material behavior in forming processes and high quality finite element simulations. The latter helps to gain deeper process insights and understanding of the forming processes. They are part of nearly every project in the metal forming group and are the starting point for the qualification of processes, tools and machinery. As an example for our work, our part within the research initiative ‘Lightweight Forging’ (www.massivleichtbau.de) is presented in more detail.

Research Project Lightweight Forging

Motivation
The continuous pressure in the automotive industry to reduce a car’s weight forces the engineers to look for new areas to which apply lightweight design. Therefore, power train, chassis and with them the gear box, are being focused on. Today, gear wheels within the gear box are solid components.

Approach
We investigate along the gear wheels’ whole process chain. Beginning with the design phase, heading over to production phase and ending with the final product, we look for possibilities to apply lightweight design. This leads to the proposal of gear wheels in differential design (figure 1 and 2). Numerical investigations on the combinations of different designs, materials and manufacturing techniques detect and allow us to understand interdependencies. Subsequently to the numerical investigations, prototypes are manufactured for real world testing.
At utg we manufacture wheel bodies only. We look into the manufacturing techniques deep drawing and fine blanking. These manufacturing techniques are already taken into account during the wheel bodies’ design phase. Manufacturing of the gear ring and joining it with the wheel body is conducted at our partner institute IWT in Bremen. Finally, there will be endurance trials at another partner institute, the FZG in Munich, to ensure the durability of the designed gear wheels.

**Conclusion**

Within the research project Lightweight Forging we have developed and manufactured promising designs for lightweight gear wheels. Weight savings of 35% (189 g) with the stapled sheet metal wheel body have been achieved. The numerical investigations predict the load capacities of the new gear wheel designs and a solid gear wheel to be on the same level. This allows replacement of the solid gear wheel with one of the new designs.

**Projects**

- Prevention of Surface Deflections of Sheet Metal Parts (AiF)
- Improving the Time Dependent Evaluation Method of Tests for the Determination of the Forming Limit Curve and Developing of a Numerical Equivalent Model (AiF)
- Optimized Risk Management in Press-shops for Minimizing Breakdown Costs in Case of Facility Downtime (BMW AG)
- Hole Roller Clinching of Multi-Material-Lightweight Joints (DFG)
- Connection Optimization of Progressive Die Components (AiF)
- Inline-Quality Control in Pressing Tools (BMW AG)
- Stiffening of Cambered Sheet Metal Designs: Numeric Bead Optimization by a Coupled Algorithm Considering Nonlinear Forming Limits (DFG)
- Anisotropic Generalized Forming Limit Concept (DFG)
- Intelligent Lightweight Design Through Multi-component Processes (AiF)
- Production-compatible Design of Deep-drawn Parts (BFS)
- Process-integrated Compensation of Geometrical Deviations for Bulk Forming (IMU)
- Suitable Representation of Sharp Character Lines for Large Scale Production (BMW AG)
- Improvement of High Strain Rate Superplasticity of Aluminum Materials by Equal Channel Angular Pressing of Sheet Metal Products (DFG)

**Results**

To date we have successfully manufactured a gear wheel with stapled sheet metal wheel body (figure 3). First deep-drawn wheel bodies have been produced as well. As soon as gear wheels with both types of wheel bodies exist, we will conduct static tests to investigate the force needed to push the wheel body out of the gear ring in axial direction and how much torque the gear wheels can transmit. This will allow us to validate our numerical results.
Metal Forming and Casting

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Research Focus
■ Industrial engineering
■ Tool design
■ Engineering and planning processes

Competence
■ Process chain car body sheet
■ Alternative metal forming processes for small batch production and prototyping
■ Cutting surface quality, wear, accuracy
■ Tool technology
■ Molding materials
■ Continuous casting
■ Residual stress analysis and material characterization

Infrastructure
■ Hydraulic press, high speed punching press, triple-action blanking press
■ 3D printer for inorganically bound core sands
■ Measurement instrumentation (residual stresses, surface, geometry, mechanical properties, …)
■ Various tools (cold and heated)
■ Stamping and bending machine
■ Rotational cutting line
■ Casting equipment
■ Craftermever
■ Core blowing machine
■ 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 2017
■ Volk, W.; Gaber, Ch.: Investigation and Compensation of Biaxial Pre-strain during the Standard Nakajima- and Marciniak-test Using Generalized Forming Limit Concept. Procedia Engineering, 207, 2017
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.

A highlight in 2017 were the first experimental results using dimethyl carbonate (DMC) and methyl formate (MeFo) as fuel in a spark ignited engine. These fuels burn with ultra low emission of particles and also reduce NOx and hydrocarbon emissions significantly. DMC and MeFo are E-fuels, that means they can be produced using green electricity as primary energy and thus feature a carbon-neutral means of energy storage for mobile applications which require high energy density. At the same time, their low emission of pollutants reduces the necessary efforts of exhaust after-treatment and contributes to the improvement of air quality.
Internal Combustion Engines

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 phase, in-cylinder swirl, tumble or turbulence, and the phases of fuel injection, mixture formation, and combustion. Simulation results are used to design improved geometries of the combustion chamber or injector nozzles and are then validated on one of our 13 engine test benches. Engine out emissions are measured by means of up-to-date FTIR technology and a modern particle counting system. We use component test benches to evaluate hydraulic behavior and spray parameters of fuel injectors. Simulative and experimental tools allow fast and effective optimization of both emission behavior and engine efficiency. Test runs on the research engines are planned and evaluated with statistical methods (design of experiments, DOE) to reduce time and costs for the testing procedure.

Projects
- BStmW project ‘sim2gether – Kollaborationsplattform zur interdisziplinären Simulation’
- Several projects funded by industry partners

Injection Systems – Spray Measurement – Optical Research

In the past decades the injection pressure of modern diesel engines has increased from 1000 bar up to 3000 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. Furthermore, at several test benches hydraulic and optical measurements of injectors with various fuels are carried out. A current project is focusing on the hydraulic behavior of orifices in injection systems to validate simulation results. Part of the task is the development of a hydraulic test bench including measurement techniques to investigate the high dynamic fluid flow properties in combination with cavitation and thermal effects. The main target is to analyze hydraulic elements by using innovative measurement techniques and gain information about physical effects to optimize the design of future injection systems. Furthermore an open-loop control is under development in collaboration with the Institute of Applied Mechanics whose 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 by available signals in engine operation.

Projects
- BFS project ‘Messung und Berechnung des Düsendurchflusses’
- DFG project ‘Optimierung des Einspritzverhaltens von Dieselinjectoren unter dem Einfluss von Alterungser scheinungen des Injectors’
- Several projects funded by industry partners

End of a gasoline injection event (from top to bottom): poor atomization in the end bears the risk of soot formation and injector coking.
Reducing piston assembly friction is a central issue of 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 the piston assembly friction to be measured 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 up, 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 inside the liner (see above). The measurement results of the three engines establish a deeper understanding of the behavior and dependencies in the tribological system.

Projects
- FVV project ‘Kolbenring-Öltransport II’
- FVV project ‘Kolbenring-Öltransport Glasliner’
- 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

Utilization of natural gas can be one step to cope with future energy demand. Surplus energy from renewable sources can be stored as hydrogen or methane. 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 are promising techniques and could 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 the combustion process is now possible.

Projects
- FVV project ‘Formaldehyd’
- FVV project ‘Mitteldruck 30 bar bei Gasmotoren’
- BFS project ‘Effizienzsteigerung von Dual-Fuel Motoren durch Optimierung der Zündung bei effektiven Mitteldrücken über 24 bar’
- BMWi project ‘Flex DI: Flexible direkteinspritzende Motoren für die Schifffahrt’
- BStmW project ‘Optimierter Verbrennungsmotor für landwirtschaftliche Biogas Mini-BHKW’
- EU project ‘HERCULES 2’
- Several projects funded by industry partners


Fossil fuels are becoming more and more scarce and European CO₂ saving policies have been introduced to fight global warming. 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. With promising progress in the field of clean burning diesel ongoing, in 2017 two new fuels for spark ignited engines (‘Otto engines’) were investigated at the Chair of Internal Combustion Engines. Dimethylcarbonate (DMC) and methyl formate (MeFo) were for the first time tested as pure substances in a research engine, delivering substantially lower emissions of particles, NOₓ and hydrocarbons compared to conventional gasoline. Modern methods for the measurement of ultra-low particle emissions are needed for this and other advanced engine concepts. Cooperating closely with the 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 harvesting of enthalpy from hot exhaust gas and the production of electric power by means of a steam turbine.

Projects
- BMWi project ‘XME Diesel – (Bio-)Methylether als alternative Kraftstoße in bivalenten Dieselmotoren’
- FNR project ‘OME – Umweltfreundliche Dieselkraftstofffadditive’
- 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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Patrick Ottiger
Ferdinand Springer (until 09/17)
Edgar Thiele (until 05/17)
Dipl.-Ing. Ulrich Tetzner
Markus Weiß

Research Focus
■ Combustion technologies
■ Gas engines
■ Friction measurement
■ 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
  (High-Speed Engines, TEAM, Hardware-in-the-Loop)
Computational Mechanics

Application-motivated fundamental research in computational mechanics

The Institute 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, 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, thermomechanical, opto-acoustic, coupled reactive 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.
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 (hyperelasticity, 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 bio-physics, 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.
Computational Mechanics

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Prof. Bernhard Schrefler

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
- 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

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)

Selected Publications 2017
Astronautics

Real-time telerobotics in space – exploration and human spaceflight – spacecraft technologies and nano-satellites – spacecraft technologies and nano-satellites – spaceflight systems engineering – hypervelocity-laboratory

In 2017, the Institute of Astronautics (LRT) continued its multi-faceted research for the development of novel satellite and space exploration technologies including:

- Spacecraft/CubeSat nano-satellite and sub-system development,
- Real-time teleoperation technologies for on-orbit servicing including novel satellite communication systems, applications and architectures,
- Human and robotic exploration technologies, incl. lunar regolith processing and resource extraction, and analysis of life support systems of habitats and space suits,
- Space environment testing including high velocity impact physics, lunar dust abrasion/damage mitigations, and micrometeoroid/space debris simulation and assessment.

Satellite Technologies – MOVE-II CubeSat

The CubeSat program MOVE (Munich Orbital Verification Experiment), initiated in 2006, focused on the hands-on education of students, complementing theoretical classwork knowledge in state-of-the-art aerospace engineering. The program’s second CubeSat, MOVE-II, is currently undergoing final tests and will be launched into a 575 km sun-synchronous orbit in mid-2018. MOVE-II is an educational cooperation between the LRT and the student group ‘Wissenschaftliche Arbeitsgemeinschaft für Raketechnik und Raumfahrt’ (WARR) with overall more than 130 students involved so far. MOVE-II is also intended as a platform for validating new technologies in space. The 1.2 kg satellite will carry 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 DLR (German Aerospace Center – Space Administration) research grant no. FKZ 50RM1509, managed by Dipl.-Phys. Christian Nitzschke at the DLR Space Administration in Bonn.
Exploration Projects

**PROSPECT**

The instrument package PROSPECT, developed under contract to the European Space Agency (ESA) for the upcoming Luna-27 mission to the lunar South Pole, makes use of the gas analysis instrument ProSPA (PROSPect Sample Processing and Analysis). LRT was involved in the Phase A and Phase B study of this instrument and supported the development of sample ovens for the in-situ thermal processing and extraction of volatiles from lunar regolith with feasibility studies and thermal design. The involvement of LRT also includes the development of a breadboard for sample conditioning and experimental demonstration of the volatiles extraction process. 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) under the Italian prime contractor Leonardo Finmeccanica S.p.A.

**LUVMI**

The international Lunar Volatiles Mobile Instrumentation (LUVMI) consortium of five partners from European science and space industry cooperatively design a mobile instrument to access and analyze lunar regolith in permanently shadowed regions (PSR) on the Moon. LUVMI is funded by the European Commission as part of the program Horizon 2020 ‘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 (see Figure 3) that can support a number of instruments for the analysis of the lunar pole environment. The main features of the instrument will be the Volatiles Sampler (VS), which is developed by LRT, and the Volatiles Analyzer (VA), developed by The Open University. The VS is a miniature
soil sampling instrument, inserted into the lunar regolith, where a heating element will thermally extract volatile compounds. The VA will capture the volatiles and guide them to a miniature mass spectrometer. In 2017 the LUVMI consortium successfully passed its mid-term review by the European Commission. In the coming year LUVMI will see the integration of the complete rover platform and instruments, which will then be tested in simulated lunar conditions.

ROBEX – Robotic Exploration in Extreme Environments

The project ROBEX (HA-304), financed by the Helmholtz Alliance, examines challenges and synergies in robotic deep sea exploration as well as robotic space exploration. LRT participates with experimental work on abrasive effects of accelerated lunar dust particles on typical spacecraft materials and thermal aspects on robotic planetary operation, such as traverse planning of rovers on the lunar surface, temperature stability of samples and possibilities of energy savings. LRT also provides additional thermal design support for future instruments to be used on the surface of the Moon. Work on lunar dust particle impacts focuses on the identification and quantitative characterization of possible damages to technical surfaces and in more detail on polymer spur gears. Wear of technical surfaces might be a serious problem for long-term missions on the lunar surface, especially because of the sharp-edged lunar regolith particles. Therefore, several technical surfaces including aluminum alloys and polymers were investigated using a test setup for abrasive wear. As part of the project ROBEX, LRT also developed advanced planetary thermal modeling tools. The current tool chain for traverse planning optimizes rover trajectories with regard to terrain properties (i.e. slopes, stay out zones, etc.) and runs a thermal simulation afterwards. TUM used this tool chain in order to study a potential landing site between craters Faustini, Shoemaker, and Nobile close to the lunar south pole. A lunar rover shall drive on the surface of the Moon in the search of volatile elements. The environment at the region of interest changes with time with temperatures of the surface of the Moon ranging from 25 K up to about 300 K. Hence, planning of traverses becomes important in order to meet scientific goals whilst also meeting engineering requirements. Furthermore, LRT helped to define the thermal design of an instrument box, called Remote Unit (RU), which houses a seismometer, an electronic board, and a communication system. The design was developed to withstand conditions during several lunar day cycles (Phase A study). Additionally, TUM supports DLR in a study for an optical instrument in a 3U Cubesat form factor that can operate in the polar regions of the Moon.

Satellite-based Cooperative Autonomous Drones Swarm

The LRT participates in the DLR-financed project SKAD (Satellitengestützter Kooperativ-Autonomer Drohnen-schwarm), which is led by OHB and started in November 2016. SKAD is a Phase 0 study and investigates possible mission architectures to explore Valles Marineris on Mars and search for water and life on the red planet using a cluster of cooperative, autonomous vehicles. The cluster consists of a small satellite and several ground vehicles for example rovers, hominids, and UAVs. LRT research within SKAD focuses on the communication architecture and the instrumentation for sample handling.

V HAB – Modeling and Simulation of Life Support Systems

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 (first V HAB-related dissertation). Five additional disserta-
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 lab 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 2017, 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. User studies characterized an experimental Human-Spacecraft-interface using acoustic feedback to spacecraft operators for enhanced environmental awareness during on-orbit servicing missions.
Space Communication Technologies and Architectures

Teleoperated on-orbit servicing and space debris removal missions, a key research area of LRT, require near real-time transmission of multi-channel video signals and spacecraft sensor and control information which can exceed data rates of 20 Mbps. DLR-funded research projects 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 (LISA projects completed in 2016).

CFRM-HF is a development of alternative manufacturing methods for integrated waveguide designs, based on the established copper galvanic process in LISA. Thereby, 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 the last year several standard waveguide parts have been manufactured to investigate the influence of the additive manufactured core on the RF-performance. Furthermore, the deposition and embedding of carbon fibers in a copper matrix with attached flanges was investigated.

CopKa is a cooperative technology development and demonstration project of a multi-sensor-based emergency services mission, using data from a 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 SatCom link to provide enhanced situation awareness from the remote accident site to the emergency services coordinators at the control center/home base. The CopKa system must not interfere with local first responders and therefore requires novel control environments including virtual reality technologies for safe, partial autonomous operations from the control center.

In the last recent years three exercise were successfully carried out with the fire fighter brigades. In two exercises we demonstrated teleoperation of the UAV over a GEO satellite relay and supported the emergency coordination of a large-scale exercise with the fire fighter brigade München-Land with the CopKa system.

These satellite communication projects are funded by DLR (German Aerospace Center – Space Administration) research grants no. FKZ 50YB1113 (LISA Ka-band electronic steering), FKZ 50YB1333 (LISA Ka-band mechanical steering), FKZ 50YB1533 (Hybrid Manufacturing CFRMHF) and FKZ 1523/1524 (CopKa Comm. Architectures), by BMWi/DLR Space Administration in Bonn.
Research Foci
- Real-time telerobotics in space (RACOON) and space communication technologies (CopKa, CFRMHF, LISAES, LISAMS+).
- Exploration Technologies, with space life support systems (V HAB, V SUIT) and lunar in-situ resource exploration and utilization (ROBEX, PROSPECT, MARVIN, LUVMI, SKAD, BLTAS).

Competence
- Systems Engineering tools for development of complex systems
- 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 chambers
- Proximity operations simulator
- Groundstation (Ka-, S- and UHF/VHF band communication)
- Mission control center
- Hypervelocity accelerators
- Remotely operated telepresence drone (DJI Matrice M600 Pro)

Astronautics-related Courses
- Fundamentals of Spaceflight
- Space System Design/Technology
- Spacecraft Technology I/II/GIST
- Spacecraft Design (summer school)
- Orbit- and Flight Mechanics
- Orbit Dynamics and Robotics
- Human Spaceflight
- Aerospace Medicine
- Systems Engineering
- Advanced Systems Engineering
- Stars and Cosmology
- Spaceflight Environment and Simulation
- Near Earth Objects
- Applied Systems Engineering Lab
- Hypervelocity Technologies Lab
- Spaceflight Technologies Lab
- Systems Engineering Lab
- Spaceflight Thermal Design Lab

Selected Publications 2017
In addition to the following peer-reviewed journal and conference publications, more than 74 academic theses were completed in 2017 (54 bachelor/semester theses, 20 master theses and one Ph.D. thesis).


- C.T. Olthoff: 'Validation of the Virtual Spacesuit using Apollo 15 Data', 47th International Conference on Environmental Systems, 16-20 July 2017, Charleston, South Carolina


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 (offroutine) testing of materials.

In 2017 research activities were directed toward plasticity and failure of gas turbine sealing systems, hot isostatic pressing of aluminum alloys in combination with precipitation hardening, the hot isostatic pressing of iron-nickel-titanium-aluminum-chromium high entropy alloys, plasticity of high strength sheet steels for automotive applications and measurement of residual stresses. Much effort is devoted to fundamental research in thermodynamically based modelling of additive manufacturing and crystal plasticity modelling and its application in microelectronics.

Combined Hot Isostatic Pressing and Heat Treatment of Aluminum Cast Alloys

Aluminum cast alloys have multiple applications in the automotive and aeronautical industries. In the field of aircraft applications, high demands on the fatigue resistance lead to the necessity for a special production route that ensures high component quality. Hot isostatic pressing (HIP) is commonly used to reduce casting porosity of cast materials thereby significantly increasing the material’s fatigue resistance. For the aluminum cast alloy A356 (Al + 7% Si + 0.3% Mg) this is usually done in a separate process step preceding the regular heat treatment, which comprises solution annealing and aging. Solution annealing followed by rapid cooling results in an oversaturated condition with magnesium and silicon atoms dissolved in the aluminum matrix. During aging at elevated temperatures precipitates are formed that lead to a significant increase in strength. Due to the very limited capability to perform rapid temperature changes, standard hot isostatic presses can hardly be used for a combined process consisting of densification, homogenization and aging. With an advanced HIP technology made accessible to WKM in a joint research project, it became possible to achieve significantly higher quenching rates in the HIP process. Mechanical properties characterization at WKM served to ensure that quenching rates are high enough to achieve an oversaturated solid solution, which then allows aging to be performed directly after hot isostatic pressing. This opens up the possibility to shorten the time at room temperature between solution annealing and aging. Thereby, the overall process time can be reduced further and the material’s strength can be increased within this fully integrated process.

Partner

Magnus Ahlfors, M.Sc.; Quintus Technologies AB, Quintusvägen 2, 72166 Västerås, Sweden
Crystal Plasticity in the Field of Microelectronics

Growing demands on performance and durability of integrated circuits require an understanding of possible failure mechanisms like crack initiation within the interlayer dielectric (ILD) and surface roughening of the metallization plate. One main cause for these phenomena arises from the mismatch in thermal expansion between the materials involved (conductor paths and metallization plate are made of aluminum and the surrounding ILD of silicon oxide) leading to thermo-mechanical loads and, consequently, to various types of damage. Throughout their life, the electronic components undergo millions of load cycles, so that an experimental life cycle analysis during the development process is costly and may not be feasible.

In cooperation with the Max-Planck-Institut für Eisenforschung, a crystal plasticity material model was developed which takes into account microstructure, grain orientation, grain size and thermal expansion behavior of the metallic components involved and the temperature dependency of the constitutive material parameters. Currently, a comprehensive review of this material model named DAMASK is being prepared for publication. There, one of the examples shows the utilization of crystal plasticity in the field of microelectronics. In this study the influence of the microstructure of the conductor paths on the probability of crack initiation is investigated. Since brittle failure occurs within the ILD, the maximum principal stress is considered as a measure to quantify the likelihood of the occurrence of brittle failure. The texture of aluminum components affects the stress level within the ILD as well as within the conductor paths. The investigations suggest that randomizing the predominant texture which arises from the manufacturing process increases the lifetime of the microelectronic component.

High Entropy Alloys

High entropy alloys (HEA) represent a new approach in materials design. Initially, HEAs were defined by their equiatomic or near equiatomic composition. At least five different elements take a random arrangement in the crystal lattice. This leads to extreme lattice distortion, which results in a great resistance against plastic deformation and a sluggish lattice diffusion even at high temperatures. Previous studies on HEA showed that also non-equiaxial compositions form a random solid solution and reach HEA-characteristic material properties. Due to this, the strict definition of HEA has been relaxed and additional material compositions were declared as HEA. A promising research approach is the production of HEA based on conventional alloys. The aim is to effectively combine outstanding properties and process technologies of existing material systems with the advantages of HEA compositions.

At WKM, conventional powder alloys and elemental powders are combined with the aim of achieving HEA compositions. For this purpose, powder mixtures are encapsulated and compressed via hot isostatic pressing. Microstructural analysis of the solid materials produced is performed via light microscopy, scanning electron microscopy as well as EDX and XRD methods. Mechanical
Achieving high aerodynamic efficiency in gas turbines requires minimal clearance between the rotating and the static components. This clearance can vary during operation, e.g. due to thermal expansion or dynamic loads. As this clearance cannot be controlled sufficiently, rubbing can occur locally, during which both the rotor and the stator can be damaged critically. To ensure high reliability and efficiency of the entire engine, seal systems that can tolerate even extreme rubbing are necessary. Labyrinth seals with special rubbing materials on the stator are able to meet these requirements. However, rubbing processes in such seal systems are not yet completely understood. The interactions of the numerous influencing parameters as well as the extreme conditions during rubbing, such as high temperatures and high rubbing velocities, complicate the investigations. In collaboration with the Karlsruhe Institute of Technology and the University of Bayreuth, WKM contributes to a better understanding of the rubbing process in labyrinth seals. It is the aim of the research project to develop suitable models and tools that allow the design of labyrinth seals of future gas turbines as well as the reliable prediction of performance and lifetime of the seals.

WKM conducts fully three-dimensional multiscale finite element simulations with a microstructure-sensitive modeling approach featuring attributes such as crystal orientation, grain size and grain size distribution. The model is also applicable for deformations at high temperatures and high strain-rates. Various rubbing conditions are investigated to find out possible drivers for crack formation that can lead to failure of both rotor and stator.

**Project**

- Anstreifvorgänge in Turbinen – Experimentelle Untersuchung und Modellierung (DFG, WE2351/14-1)

**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

characteristics are determined by hardness and compression testing. The resulting microstructure of the material in dependence of the composition and process parameters is another focus of the current investigation. Additionally, expected phases are predicted via calculation of phase diagrams (CALPHAD method) using a thermodynamic database for HEA. Due to the sluggish diffusion reported, mechanical alloying will be necessary in addition to heat treatments to achieve a homogeneous distribution of the alloying elements.
Measurement, Redistribution and Relaxations of Residual Stress

Residual stresses, typically acting on different length scales depending on the mechanisms they originate from, can be beneficial or detrimental for the material and component performance. As a consequence of compressive macroscopic stresses near the surface of a component, the accumulation of micro-cracks can be reduced and the lifetime of the component can be extended. In contrast, tensile macroscopic stresses can lead to spontaneous cracking which can reduce strength and toughness.

A redistribution of residual stress may result either from the removal of portions of a workpiece during machining or from stress relaxation in the material due to diffusion processes and plays a central role for most experimental techniques applied for residual stress analysis. Residual stress redistributions may lead to undesired distortions of the whole component during machining to its final shape or during the component’s operating life. The macroscopic temperature-dependent damping behavior of the material can provide important information about the governing (microscopic) diffusion processes, as it results from energy dissipation by internal friction caused by (thermally activated) migration of crystal lattice defects during loading/deformation.

In this context, research activities of WKM focus on investigations of (residual) stress redistributions both on macroscopic and microscopic scales as well as on the identification of the underlying microscopic mechanisms. This includes the application and further development of experimental techniques involving diffraction and mechanical methods. To investigate the diffusion processes governing residual stress relaxation, the macroscopic damping behavior of the materials is investigated by dynamic mechanical spectroscopy using an instrumented torsion pendulum and the impulse excitation method.

Besides the semi-destructive hole drilling method, which is an effective way of determining near-surface residual stresses, dissection/slitting methods like boring of cylinders are applied to analyze axisymmetric residual stress distributions in cylindrical specimens. In most cases, an accompanying residual stress analysis via X-ray diffraction on the specimen’s surface is promising.

Neutron diffraction offers the possibility of a spatially-resolved, phase-specific and non-destructive residual stress analysis up to several centimeters below the component’s surface. In-situ neutron diffraction experiments play a central role within the research activities of WKM focusing on the evolution of the intergranular and inter-phase microstrains of different nickel-base superalloys (Inconel 718 and Haynes 282) during loading and unloading at room temperature and at elevated temperatures. Haynes 282, due to its good creep strength, thermal stability and weldability, is developed for avian and land-based applications and exhibits a low diversity of precipitates and a small lattice misfit, opening up the possibility of an in-depth study on the micromechanics of the anomalous yielding effect. A complementary rigorous characterization of both microstructural aspects and their kinetics on different length scales is accomplished by light- and electronmicroscopy (SEM/TEM), 3D-atomprobe tomography, small angle neutron scattering, as well as X-ray diffraction. These combined experimental techniques will help to identify the mechanisms governing the different microstrain-accumulation behavior of these alloys.

Project

■ Entwicklung von Typ II Eigendehnungen in Abhängigkeit der Mikrostruktur in Nickelbasislegierungen (DFG, KR3687/3-1)

Partners

■ Karlsruher Institut für Technologie, Institut für Ange wandte Materialien – Werkstoffkunde, Engelbert-Arnold-Str. 4, 76131 Karlsruhe
■ Forschungs-Neutronenquelle Heinz Maier-Leibnitz (FRM II), Technische Universität München, Lichtenberg-str. 1, 85748 Garching
Plasticity and Failure of High-Strength Sheet Materials for Automotive Applications

The desire to produce steel sheet material with a low content of alloying elements but high strength and excellent formability has led to the development of microstructure-strengthened steels. Among these are the ferritic-martensitic dual-phase (DP) steel grades. They are produced from alloys containing mostly only iron and carbon with the aid of a multi-step heat treatment. Their microstructures consist of a soft matrix of ferrite, reinforced with dispersed, hard grains of martensite. Due to their multi-phase nature, DP steels can be produced with widely varying microstructural constitution.

Research activities at WKM related to DP steels focus on the study of their heat treatment-induced microstructural residual stresses and strains, their untypical plastic deformation behavior and their damage behavior. To attain an understanding of the complex mechanisms which occur in DP-steel microstructures during processing, forming, service or damage, it is necessary to conduct systematic mechanical studies on the micro and macro-levels. For this purpose, a simulation model based on micro-continuum mechanics and tessellated (i.e. computer generated) three-dimensional microstructures was developed at WKM.

With the aid of this model, most currently the impact of the heat treatment-induced microstructural residual stresses and strains on the deformation behavior of DP steels was demonstrated. Of particular importance in this regard is the fact that this impact cannot be studied correctly with the aid of simpler two-dimensional modeling approaches, as were extensively used in the past. Systematic variations in the simulations revealed which processing-induced field quantity impacts the individual peculiarities of the DP steels.

It could be shown, that regardless of the martensite content, the heat treatment-induced residual stresses and strains are qualitatively unaltered. Primary and secondary causes for continuous yielding (a peculiar property of the DP steels) could be identified. These are heat treatment-induced plastic strains (figure, top right) and the deviatoric component of the residual stresses (figure, bottom right). The latter causes an unsymmetrical stress-strain behavior of the material in tension and compression, as well as a reduced Young’s modulus in the unaged material state. Another important finding of this work is that heat treatment-induced quantities impact the macroscopic mechanical behavior of the DP steels only up to roughly 1% of macroscopic strain.

**Project**

Micromechanical modeling of the formability and failure of DP steels

**Partner**

voestalpine Stahl GmbH, voestalpine-Str. 3, 4020 Linz, Austria

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Two DP-steel model microstructures (top left; martensite: shaded, ferrite: transparent), differing only in martensite phase fraction and their heat treatment-induced phase specific residual stresses and strain distributions. Top right: plastic equivalent strain, the primary cause for continuous yielding; Bottom left: hydrostatic stress, the driving quantity behind micro-damage; Bottom right: von Mises stress (the deviatoric stress component), the primary cause for reduced Young’s modulus and yield-asymmetry in tension and compression. (Source: WKM)
Materials Science and Mechanics of Materials

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Jens Reuter, B.Sc.

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 2017
- S. Welzenbach, T. Fischer, F. Meier, E. Werner, S. Ulan kyzy, O. Munz: Temperature distribution of a simplified rotor due to a uniform heat source. Continuum Mech. and Thermodyn. in press. DOI: 10.1007/s00161-017-0600-z
- T. Fischer, S. Welzenbach, F. Meier, E. Werner, S. Ulan kyzy, O. Munz: Modeling the rubbing contact in honeycomb seals. Continuum Mech. and Thermodyn. in press. DOI: 10.1007/s00161-017-0608-4
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 $\text{CO}_2$ are the favored raw materials for industrial biotechnology. The Institute 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.

Bioreactors

The effective generation of process information represents a major bottleneck in microbial production process development and optimization. An approach to overcome the necessity of a large number of time- and labor-consuming experiments in lab-scale bioreactors is miniaturization and parallelization of stirred-tank reactors along with automation and digitalization.

Highlight

A new miniaturized laser-based sensor system has been established for parallel online measurement of optical densities as reference for microbial cell mass concentrations in 48 individual single-use stirred-tank bioreactors which are operated in a bioreactor unit on a shoe-box scale and automated with a lab robot.

Projects

- Multi-parameter analytics in parallel bioreactors
Biochemical Engineering

**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 6 by rational exchange of loop regions of the protein which are supposed to interact with the electron transport metabolite nicotinamide adenine dinucleotide (NADH).

**Projects**

- Polymeric nano-compartment for biocatalytic applications
- Membrane functionalization of nanoscale enzyme membrane reactors
- Surface functionalization of nano-scale enzyme membrane reactors
- Cellular envelopes for multi-enzyme synthesis
- Production of N-acetylneuraminic acid using epimerases from cyanobacteria
- Asymmetric syntheses with optimized ene-reductases

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**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 efficient production of up to 225 g L⁻¹ L-erythrulose (tanning agent used in cosmetics) from meso-erythritol making use of a recombinant *Gluconobacter oxydans* provided by TUM Microbiology (Prof. Liebl).

**Projects**

- Population heterogeneity in industrial scale bioprocesses
- Metabolic analyses of recombinant microorganisms from production processes
- Production of single-stranded DNA with *Escherichia coli*
- Production of terpenoid glycosides by recombinant *Escherichia coli*
- Reaction engineering analysis of recombinant *Gluconobacter oxydans*

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*Model of an enzyme useful for the stereoselective reduction of alkenes which was improved by rational exchange of loop regions (colored in red) (copyright: Klermund, TUM)*

*Pilot-scale fermentations were performed at the TUM Research Center for Industrial Biotechnology (photo: Tobias Hase, TUM)*
**Gas Fermentation**

Special microorganisms are able to produce chemicals with carbon dioxide as sole carbon source. Electrons may be supplied from sunlight or hydrogen gas. Bioprocess engineering is the key to make use of these energy sources for the microbial production of chemicals from carbon dioxide on an industrial scale.

**Highlight**

New open thin-layer cascade photo-bioreactors made of pond liner were designed and operated up to pilot scale for the evaluation of new microalgae production processes at physically simulated dynamic climate conditions with respect to light (LED), temperature and air humidity (e.g. Mediterranean summer in Spain) in the TUM Algae TechCenter located at the Ludwig Bölkow Campus in Ottobrunn.

**Projects**

- Modeling of microalgae cultivation in open photobioreactors
- Characterization of new microalgae for open photobioreactors
- Mass production of microalgae in open photobioreactors
- Production of anti-oxidants with microalgae

**Bioprocess Integration**

Bioprocess integration 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**

A three-dimensional deterministic model applying computational fluid dynamics (CFD) coupled with the discrete element method (DEM) was developed and validated to simulate chromatographic column packing behavior during either flow or mechanical compression.

**Projects**

- Non-stationary hydrodynamics of chromatography columns
- 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

In many cases, downstream processing is by far the most cost-intensive step of a bioprocess. Often, multiple-step
Biochemical Engineering

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Norbert Werth
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Research Focus
- Micro-bioprocess engineering
- Bioreactors
- Biocatalysis
- Fermentation
- Gasfermentation
- 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 labs (CO₂, CO, H₂)
- Phage lab
- Cooled lab (4°C)
- Electronic/mechanical workshop
- Analytical lab (LC-MS, flow cytometry, GC, LC, etc.)

Selected Publications 2017

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
Machine Tools and Manufacturing Technology

Perspectives for production

- The Chair for Machine Tools and Manufacturing Technology is one of the largest research centers in Germany. In 2018 collaboration will be improved both within the institute’s research group and with other members of TUM in additive manufacturing.

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. With regard to light-weight structures that are optimally adapted to the respective loads, bionic approaches such as the adaptation of natural honeycomb and grid structures have proven to be particularly suitable for achieving the desired goals in the area of additive production processes.

With the objective to use the suitable material in any location, the research activities focus on the area of joining and separating cutting technologies focus on producing joints of dissimilar metals or metal to plastics that so far could not be produced.

The formerly Augsburg-based research capabilities for additive manufacturing, both machines and personnel, will be moved to a newly constructed lab within the iwb experimental hall at the beginning of 2018. This will improve the collaboration both within the institute’s research group and with other members of TUM.

The development of this research topic is further supported by a new 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.

For the next few years the 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.

![Laser beam melting (LBM)](image)

Automated simultaneous 5-axis milling of a topology-optimized, patient-specific implant
Machine Tools

In the context of the Machine Tools working group, we analyze and optimize cutting production systems. The studies focus on the examination of dynamic machine behavior, the cutting process and influential thermal factors. Thanks to the consideration of aspects of instrumentation and control, the study horizon is expanded beyond purely mechanical structures to complex mechatronic systems. Modern simulation methods, such as the finite elements and multiplebody simulation, are used for these examinations in order to reflect the machine features in detail. By coupling these with developed cutting-force models, interactions between structure and process can be demonstrated. Furthermore, energy-related aspects which interact with the machine properties are in the focus of the investigations. The energy efficiency of machine tools is becoming more and more a competitive factor.

Projects

- **SynErgie** – Synchronized and energy-adaptive production technology for adapting industrial processes to a fluctuating energy supply – project cluster production infrastructure
- **E²D** – Improvement of the energy efficiency by damping of machine structures
- **Local damping modeling for simulation and optimization of the dynamic behavior of machine tools**
- **Increasing the working accuracy of milling robots**
- **HyPoGaL** – Highly dynamic nonlinear control of galvanometer laser scanners
- **FORobotics** – Mobile, ad-hoc cooperating robot teams
- **PreCoM** – Predictive cognitive maintenance decision support system
- **CutSim III** – Modelling, simulation and compensation of shape deviations in the milling process thermal processing influences for complex machining processes
- **BaZMod** – Component-specific machine configuration in the production by cyber-physical additional modules
- **TOPOS** – Development, manufacturing and testing of topology-optimized osteosynthesis plates

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. The formerly Augsburg-based research capabilities for additive manufacturing, both machines and personnel, will be moved to a newly constructed lab within the iwb experimental hall at the beginning of 2018. This will improve the collaboration both within the institute’s research group and with other members of TUM. The development of this research topic is further supported by a new 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

- **HMTools** – Development of a process chain on the basis of 3D printing for the production of hard metal tools
- **AscentAM** – Adding simulation to the corporate environment for additive manufacturing and simulation-based compensation of warpage
- **KonRAT** – Development of a small-scale powder atomization plant and additive manufacturing of large parts for aerospace applications
Joining and Cutting Technology

Technical products go through several joining and separating steps until completion. These processing steps are particularly relevant for the high quality and economic success of the production. The aim of the research and development activities is to optimize production processes in terms of quality and productivity. For this purpose, the researchers have access to a machine park with modern laser beam sources, friction welding equipment and a wide range of measuring and analysis instruments. The team’s expertise ranges from process analysis, systems engineering and technology consulting to process simulation.

Projects

- **ExZellTUM II** – Excellence center for battery cells at the Technical University of Munich
- **FOREL II** – Research and technology center for resource efficient lightweight structures for electromobility
- **FSWLeg** – Synthesis of non-equilibrium alloys using friction stir processes
- **PROLEI** – Process chain for joining fiber reinforced polymers to metals in lightweight structures
- **ProLasKu** – Enhancement of process efficiency and weld seam quality for laser welding using innovative system technology
- **RegTemp** – Temperature control during friction stir welding
- **ReVeBa** – Computer-based minimization of distortions for laser welding of complex structures
- **SurfaLIB** – Surface modifications of battery materials
- **ZAktSiLA** – Design and development of a prototype of a central active safety device for the monitoring of remote high-performance laser beam systems in industrial applications
- **RoKtoLas** – Robot-guided, scanner-based optical coherence tomography for remote laser beam welding for flexible process chains in car body construction
- **RevisedBatt** – Resonances, vibrations, shocks, external mechanical forces and detection methods for Lithium-Ion Batteries
- **SPP 1640 (3rd funding phase)** – Binding mechanisms during friction stir welding of mixed compounds
- **Click&Weld** – Increased industrial applicability of friction stir welding through a knowledge-based and user-friendly operating concept
- **MoBaReg** – Process torque based temperature control for friction stir welding

*Absorption measurement of green laser radiation using an integrating sphere*

*Wire and arc additive manufacturing at iw*
Machine Tools and Manufacturing Technology

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Research Focus
- Machine tools
- Joining and cutting technology
- Additive manufacturing

Competence
- Process and structural behaviour of machine tools
- Smart machine tools
- Hybrid manufacturing technologies
- Laser technology
- Friction welding
- Joining and cutting of CFRP
- Process development and process management in additive manufacturing
- Simulation in additive manufacturing

Infrastructure
- Additive Manufacturing Laboratory
- 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
- Industrial robots
- Environmental/safety and teaching laboratories
- Energetic and geometrical parameters
- Material analysis systems
- Simulation environments

Courses
- Machine Elements and Manufacturing Technologies
- Metal Cutting Manufacturing Processes
- Metal Cutting Machine Tools
- Joining Technology
- Laser Technology
- Quality Management
- Practical Course Additive Manufacturing
- Practical Course Development of Machine Tools
- Practical Course Metal Cutting Machine Tools
- Practical Course Welding Technologies
- Principles of Engineering Design and Production Systems

Selected Publications 2017
Product Development and Lightweight Design

Multi-disciplinary design, numerical optimization, modelling and simulation, design methods, tools and processes

Joining the two former laboratories for product development and lightweight design offers great potential for research synergies.

In November 2017, the new laboratory was founded after merging the two labs for product development and lightweight structures. The two scientific disciplines provide a good balance between similarities and differences for synergy. They share a strong focus on engineering design with a comprehensive and interdisciplinary view, and are concerned with methods and tools to cope with complexity. At the same time, they are different in breadth and depth: while product development aims at applicability to a broad range of technical disciplines, lightweight design is about specific solutions to technical problems. The accomplishments of both former labs in 2017 are presented – for the last time in two separate parts. In 2018, we will re-align research directions to optimally combine the long and successful history of product development and lightweight design at TUM with new impulses from engineering science and needs from industry. The primary focus of our future research will be on design and optimization of complex technical systems in particular from aerospace and automotive.

Part I: Lightweight Design

Morphing Wings

A concept for a morphing leading edge of a sailplane wing is developed in the project MILAN. Preliminary studies showed great potential for total aircraft drag decrease of up to 12% compared to conventional designs by morphing the front part of the wing in between a high speed and a low speed, high lift configuration, 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. Topology optimization is used to generate the geometry of the compliant mechanism ribs. First designs were accomplished using commercial topology optimization software. Currently a new topology optimization software environment is under development including finite strain theory and stress constraints.

Project

- Milan (by Prof. Hornung)
Highly Flexible Aircraft

Future airliner wings have an increased aspect ratio for lowering drag and the structure is extensively optimised in the direction of lightweight design. Therefore the next generation of wings are inherently highly flexible and implicate further challenges in the aeroelastic design. The idea of a virtual aircraft model, which allows virtual flight tests to predict aircraft loads and performance, is part of the 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 in research focus. High fidelity coupled CSM-CFD methods are used for highly accurate load and aerodynamic drag prediction.

Rotating CFRP Disks for Neutron Spectroscopy

Carbon fiber reinforced plastic disks with a diameter of up to 1000 mm and rotational speeds in vacuum aimed for up to 500 Hz (30,000 rpm) are studied for their vibration behavior at the Laboratory of Lightweight Structures. One specific application of such disks is the neutron time-of-flight spectroscopy. These disks have one or more cut-outs, which causes stress peaks in the structure. The strength and the vibration behavior of such disks are researched in detail, and proper design and material selections are made. The interaction between the disk and the hub on which the disk is mounted, as well as the structural dynamics of the whole system, are considered. In particular, the effect of the membrane stiffening of the disk, which is caused by the centrifugal forces during rotation, is quantified.

Therefore, staggered fluid-structure-interaction methods in combination with a trim algorithm is developed. Furthermore, dynamic flight manoeuvres on a reduced order model are performed to investigate the dynamic behaviour. 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. The method enables to investigate wing instabilities due to gusts or flutter in an early aircraft design stage with high accuracy.

Project

- Vitam-Flex (by Prof. Hornung)

An improved design is generated by numerical design optimization methods, which also take strength and manufacturing constraints into account.

The computed results are validated by experimental testing.
Satellite Antenna

The thermoelastic deformation behavior of a satellite antenna is investigated in the project H2KAR, which is a collaborative project with the space supplier companies INVENT GmbH and HPS GmbH, funded by the German Federal Ministry of Economic Affairs and Energy (BMWi). Thermoelastic deformations occur during orbiting of the satellite in space, which causes temperature changes of up to +150°C and -150°C. The deformations are investigated by heating the antenna and measuring the deformations by photogrammetry and temperatures with infrared thermogrammetry. A concept for measuring temperatures and strains on the reflector surface with a fiber-optical sensor was developed, evaluated and qualified for use in orbit. A Rayleigh-backscattering fiber optical sensor can measure temperatures or strain continuously over the whole length of the fiber, in contrast to classical fiber optical measurement methods. The fiber was bonded on the reflector backsurface with a new high precision bonding process. The sensor was finally tested in an environmental test campaign consisting of vibration-, acoustic- and thermal vacuum tests, which simulate the conditions of the launch and in orbit. First results show that the sensor withstands the applied environmental loads.

Project
- H2Kar (by Prof. Hornung)

Flexible Flap Gap Cover

The use of fiber reinforced elastomeric materials for an elastic flap gap cover for a passenger aircraft wing is investigated in the project FlexMat, in collaboration of the German Aerospace Center (DLR), Invent GmbH and TUM, with funding from the German Federal Ministry of Economic Affairs and Energy (BMWi). The elastomer material EPDM serves as matrix material, which is reinforced by unidirectional carbon fiber reinforced epoxy. The elastomeric material makes the composite shear compliant, which can be used for morphing purposes. A new manufacturing process for thin fiber reinforced elastomeric composites has been developed and evaluated. Homogenization-based simulation methods were used for prediction of the material behavior.

Project
- FlexMat (by Prof. Hornung).
Part II: Product Development

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 department for product development in various areas. Thus, methods and tools are designed to enable cost estimates during early phases of product development and to make them thorough and reliable.

Projects
- FVA e.V.
- diverse companies

Systems Engineering

The Laboratory for Product Development and Lightweight Design has a long tradition in integrated product development. In recent years, research activities of systems engineering were performed to react on the increasing interdisciplinarity of product development and to benefit from synergies. Research focus of the laboratory is the development of product architectures as an important link between requirements analysis and design of individual components. Methodologically seen, the lab mainly works based on the approach of structural complexity management.

A major result in this field is the guideline developed for a market-oriented top-down modularization tailored to machine and plant engineering.

Project
- DFG SFB project A10 – Analyzing the dynamics of cyclic interactions in PSS
Product Development and Lightweight Design

Innovation & Creativity

The current research activities of the Laboratory for Product Development and Lightweight Design in the field of innovation and creativity aim at the integration of relevant knowledge from various disciplines of product development. The lab mainly refines design methodologies and adapts processes in companies. An essential component of research are applications within an industrial environment. Research helps to develop sustainable product architectures, find new ideas using methodologies of the Open Innovation toolbox and implements new organizational models following the principles of open organization.

Projects
- IDAGMED project – Interdisciplinary agile medical engineering development
- KMEagil project – Implementation of agile methods in small and medium sized enterprises to improve development processes
- PE-SEMINAR – Development of a Cocoa Pod Peeling Machine for Cocoa Plantations in Cameroon

Engineering Design Process

Research activities on engineering design processes focus on the development of efficient procedures for the design of complex technical products and product service systems (PSS). The most important premise when analyzing and improving processes is the company- and situation-specific support of developers. In particular, the underlying product structure, the organizational conditions and the dynamics of internal and external factors for a targeted design process are taken into account.

Projects
- DFG SFB project B1 – Cycle-oriented planning and coordination of development processes
- DFG SFB project C2 – Lifecycle-driven decision methodology in product-service system
- DFG SFB project D1 – Cyclemanagement design of PSS innovation processes through diagnosis and dissolving of inconsistencies between models of different domains

The Systemic Change Management Approach
Product Development and Lightweight Design

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Research Focus
- Adaptive and shape morphing structures
- Hybrid material structures
- Large space structures
- Model-based design optimization methods

- Innovation & creativity
- Systems engineering
- Engineering design processes
- Cost management

Competence
- Numerical modeling and optimization of mechanical systems
- Adaptive structures and smart materials
- Design optimization methods
- Structural mechanics and design concepts
- Mechanical and environmental testing
- Systematic development of complex products
- Methods in engineering design
- Cost optimization in engineering design

Infrastructure
- Computer cluster with 250 processors
- CAD and several FEM tools
- Design optimization tools
- Workshop for metal and fiber composite parts
- Mechanical and environmental test facilities incl. cryogenic temperatures
- Extensive measurement systems
- Non-destructive materials and part inspection
- Precision engineering workshop
- Innovation lab for student projects with 3D printer

Courses
- Analysis and Design of Composite Structures
- Practical Course Lightweight Structures
- Light Weight Structures
- Smart Structures
- Multidisciplinary Design Optimization
- Laboratory course: Finite Element Method (FEM) in Aerospace Structures
- Aerospace Structures
- Product Design and Development
- Methods of Product Development
- Cost Management in Product Development
- Management of Business Strategies

Lectures in Collaboration with Further Institutes
- Basics of Engineering Design and Production Systems

Selected Publications 2017
- Becerril, Lucia; Knoll, Marvin; Kattner, Niklas; Lindemann, Udo: Visualizing Information Flow in Engineering Change Management Processes. Proceedings of the 19th International DSM Conference, Espoo (Finland), 11-13 September 2017
- Böhmer, Annette Isabel; Hostettler, Rafael; Richter, Christoph; Lindemann, Udo; Conradt, Jörg; Knoll, Alois: Towards Agile Product Development – The Role of Prototyping. ICED17, Proc. of the Int. Conf. on Engineering Design 2017, Vancouver (Canada), 21-25 August 2017, 1-10
- Carro Saavedra, Cristina; Morales Quiles, Jose; Lindemann, Udo: Characteristics of Design Situations Influencing the Knowledge to Reuse. R&D Management Conference, 2017
- Schmied, Christian; Gebhardt, Marcel; Mörtl, Markus; Lindemann, Udo: Expert Based Approach to Analyse and Influence Indirect Cost of Engineering Changes. ICED17, Proc. of the Int. Conf. on Engineering Design 2017, Vancouver (Canada), 21-25 August 2017, 663-672
- Wilberg, Julian; Triep, Isabell; Hollauer, Christoph; Omr, Mayada: Big Data in Product Development: Need for a Data Strategy. Proceedings of PICMET ’17: Technology Management for Interconnected World, Portland International Center for Management of Engineering and Technology, Portland (USA), 2017
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 transport

**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.*
## External Lecturers in WS 16/17 und SS 17

<table>
<thead>
<tr>
<th>Name</th>
<th>Professorship</th>
<th>Lecture Title</th>
<th>Since</th>
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</thead>
<tbody>
<tr>
<td>Dr.-Ing. Alexander Alekseev</td>
<td>Plant and Process Technology</td>
<td>Grundlagen der Kälteerzeugung und Industrielle Tief-temperaturanlagen</td>
<td>SS 12</td>
</tr>
<tr>
<td>Univ.-Prof. Ph. D. P. Veelayani Aravind</td>
<td>Energy Systems</td>
<td>Thermodynamics in Energy Conversion</td>
<td>WS 10/11</td>
</tr>
<tr>
<td>Dr. rer. nat. Manfred Berthaus</td>
<td>Energy Systems</td>
<td>Stromnetze und Energiemärkte</td>
<td>SS 15</td>
</tr>
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<td>Werkstoffe für Motoren und Antriebssysteme: Otto- und Dieselmotoren</td>
<td>SS 09</td>
</tr>
<tr>
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<td>Helicopter Technology</td>
<td>Hubschrauber-Flugmechanik und -Flugregelung</td>
<td>WS 10/11</td>
</tr>
<tr>
<td>Prof. Antonino Cardella</td>
<td>Nuclear Technology</td>
<td>Kernfusion Reaktortechnik</td>
<td>SS 10</td>
</tr>
<tr>
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<td>Flight System Dynamics</td>
<td>Navigation und Datenfusion</td>
<td>WS 08/09</td>
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<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.-Ing. Marco Einhaus</td>
<td>Machine Tools and Manufacturing Technology</td>
<td>Arbeitsschutz und Betriebssicherheit</td>
<td>WS 09/10</td>
</tr>
<tr>
<td>Dr. rer. nat. Jörg Ellinger</td>
<td>Materials Science and Mechanics of Materials</td>
<td>Werkstoffe für Motoren und Antriebssysteme: 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>Projektmanagement 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 Grünwald</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>Prof. Dr.-Ing. Andreas Hupfer</td>
<td>Turbomachinery and Flight Propulsion</td>
<td>Konstruktionsaspekte bei Flugantrieben</td>
<td>SS 16</td>
</tr>
<tr>
<td>Dr.-Ing. Carsten Intra</td>
<td>Metal Forming and Casting</td>
<td>Produktionsmanagement im Nutzfahrzeugsektor</td>
<td>WS 13/14</td>
</tr>
<tr>
<td>Dr.-Ing. Oliver Knab</td>
<td>Space Propulsion</td>
<td>Raumfahrantriebe 2</td>
<td>WS 09/10</td>
</tr>
<tr>
<td>Dr.-Ing. Alexander Kolb</td>
<td>Thermodynamics</td>
<td>Kraftfahrzeug-Klimatisierung/Kältetechnik</td>
<td>WS 03/04</td>
</tr>
<tr>
<td>Dr.-Ing. Detlef Koschryn</td>
<td>Astronautics</td>
<td>Near-Earth Objects for Engineers and Physicists</td>
<td>SS 15</td>
</tr>
<tr>
<td>Dr.-Ing. Jürgen Letschnik</td>
<td>Astronautics</td>
<td>Space Communication and Operations</td>
<td>SS 16</td>
</tr>
<tr>
<td>Dr.-Ing. Heiko Meyer</td>
<td>Automation and Information Systems</td>
<td>Prozessleitsysteme in der verarbeitenden Industrie und ihre vertikale Integration</td>
<td>WS 11/12</td>
</tr>
<tr>
<td>Dr.-Ing. Oswin Ottinger</td>
<td>Carbon Composites</td>
<td>Kohlenstoff und Graphit – Hochleistungswerkstoffe für Schlüsselindustrien</td>
<td>WS 10/11</td>
</tr>
<tr>
<td>Dr.-Ing. Herbert Pfab</td>
<td>Automotive Technology</td>
<td>Baumaschinen</td>
<td>SS 00</td>
</tr>
<tr>
<td>Dr. Hans-Willi Raedt</td>
<td>Metal Forming and Casting</td>
<td>Massivumformung und Fertigungstechnik für Antriebstrang und Fahrwerk im Automobil</td>
<td>WS 15/16</td>
</tr>
<tr>
<td>Dr.-Ing. Robert Reiter</td>
<td>Machine Tools and Manufacturing Technology</td>
<td>Die Digitale Fabrik in der Automobilindustrie und im Flugzeugbau</td>
<td>SS 05</td>
</tr>
<tr>
<td>Dr.-Ing. Rainer Stetter</td>
<td>Industrial Management and Assembly Technologies</td>
<td>Mechatronik-Entwicklungsprojekte in der Praxis</td>
<td>SS 07</td>
</tr>
<tr>
<td>Dr.-Ing. Joachim Thomas</td>
<td>Machine Elements</td>
<td>Kegel- und Hypodizahnräder für Fahrzeugantriebe</td>
<td>SS 09</td>
</tr>
<tr>
<td>Dr.-Ing. Lothar Wech</td>
<td>Automotive Technology</td>
<td>Verkehrsunfall-Analyse und passive Fahrzeugsicherheit</td>
<td>WS 03/04</td>
</tr>
<tr>
<td>Dr.-Ing. Christian Weiner</td>
<td>Carbon Composites</td>
<td>Liefer- und Wertschöpfungskette Composites</td>
<td>WS 10/11</td>
</tr>
<tr>
<td>Dr.-Ing. Christian Wende</td>
<td>Medical Engineering</td>
<td>Einführung in das Patent-, Marken- und Musterrecht für Ingenieure</td>
<td>SS 11</td>
</tr>
<tr>
<td>Dr.-Ing. Andreas Wendt</td>
<td>Machine Tools and Manufacturing Technology</td>
<td>Unternehmensexzellenz</td>
<td>SS 17</td>
</tr>
</tbody>
</table>
### Habilitations 2017

<table>
<thead>
<tr>
<th>Name</th>
<th>Topic</th>
<th>Mentor</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr.-Ing. Thorsten Schindler</td>
<td>Angewandte Mechanik</td>
<td>Prof. dr. ir. Daniel Rixen</td>
<td>April 14, 2017</td>
</tr>
</tbody>
</table>

### Doctorates 2017

<table>
<thead>
<tr>
<th>Name</th>
<th>Topic</th>
<th>Supervisor</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr.-Ing. Florian Behncke</td>
<td>Beschäftigungsgerechte Produktentwicklung. Abstimmung von Produktaufbau und Liefervernetzwerk in frühen Phasen der Entwicklung</td>
<td>Prof. Dr.-Ing. Udo Lindemann i.R.</td>
<td>January 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Paul Stuke</td>
<td>Vertical interior cooling system for passenger cars: Trials and evaluation of feasibility, thermal comfort and energy efficiency</td>
<td>Prof. Dr. phil. Klaus Bengler</td>
<td>January 19, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Patrick Saal</td>
<td>Quantitative Phasenanalyse von ausferitischen Gusseisen mittlere der Neutronendiffraktometrie</td>
<td>Prof. Dr.-Ing. Wolfram Volk</td>
<td>January 25, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Arolovist Ufer</td>
<td>Entwicklung und Validierung einer Technologie zur wirtschaftlichen Herstellung geometrisch komplexer Langfaser-Preforms unter Großserienrandbedingungen</td>
<td>Prof. Dr.-Ing. Klaus Drechsler</td>
<td>January 31, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Stefan Langer</td>
<td>Kritische Änderungen in der Produktpartentwicklung – Analyse und Maßnahmenableitung</td>
<td>Prof. Dr.-Ing. Udo Lindemann i.R.</td>
<td>February 2, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Sarah Poschenrieder</td>
<td>Prozess zur skalierbaren Herstellung von Nanokompartmenten aus ABA-Triblock-Copolymeren</td>
<td>Dr. rer. nat. Kathrin Castiglione, TUM Junior Fellow</td>
<td>February 3, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Maximilian Zimmer</td>
<td>Berechnung und Optimierung von Geometrie und Eingriffsverhalten von Verzahnungen beliebiger Achslage</td>
<td>Prof. Dr.-Ing. Karsten Stahl</td>
<td>February 3, 2017</td>
</tr>
<tr>
<td>Dr. rer. nat. Anja Koller</td>
<td>Reaktionskinetik des lichtabhängigen Wachstums von Scenedesmus spec. in Flachplattenphotobioreaktoren</td>
<td>Prof. Dr.-Ing. Dirk Weuster-Botz</td>
<td>February 6, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Mathias Peter Hartmann</td>
<td>Analysis and Compensation of Process Induced Deformations in Composite Structures</td>
<td>Prof. Dr.-Ing. Klaus Drechsler</td>
<td>February 8, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Christin Hözel</td>
<td>Belastungsschutzhülle für das Hand-Arm-System bei manuellen Montageaufgaben</td>
<td>Prof. Dr. phil. Klaus Bengler</td>
<td>February 14, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Felix Günther</td>
<td>Beitrag zur Co-Simulation in der Gesamtsystementwicklung für den Kraftfahrzeugs</td>
<td>Prof. Dr.-Ing. habil. Heinz Ulbrich i.R.</td>
<td>February 14, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Rainer Rieck</td>
<td>Discrete Controls and Constraints in Optimal Control Problems for...</td>
<td>Prof. Dr.-Ing. Florian Holzapfel</td>
<td>February 15, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Stefan Küglermeier</td>
<td>Modellierung der akustischen Wellenausbreitung in Raketen...</td>
<td>Prof. Dr.-Ing. Thomas Sattelmayer</td>
<td>February 21, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Nan Chen</td>
<td>Experimental and Numerical Investigation of a Centrifugal Compressor Stage with Variable Inlet Guide Vanes</td>
<td>Prof. Dr.-Ing. Oskar Haidn</td>
<td>February 21, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Hans-Christian Roth</td>
<td>Design of nano-scale enzyme carriers and their separation from highly viscous liquors</td>
<td>Dr. rer. nat. Sonja Berensmeier</td>
<td>February 23, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Elias Breunig</td>
<td>High Precision Alignment and Integration of Modular X-Ray Space Mirrors via a Synthesis of Simulation, Experiment and the Deflectometry Method</td>
<td>Prof. Dr.-Ing. Horst Baier i.R.</td>
<td>February 23, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Charalampas Daniilidis</td>
<td>Planungssollwerte für die systematische Analyse- und Verbesserung von Produktaufbau</td>
<td>Prof. Dr.-Ing. Udo Lindemann i.R.</td>
<td>March 6, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Jan-Fabian Meiss</td>
<td>Produktionstechnologische Anforderungsmanagement</td>
<td>Prof. Dr.-Ing. Gunther Reinhart</td>
<td>March 6, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Sebastian Eberhardt</td>
<td>Large-eddy simulations of supersonic mixing with application to scramjets</td>
<td>Prof. Dr.-Ing. Nikolaus Adams</td>
<td>March 7, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Constantin von Saucken</td>
<td>Entwicklerzentrierte Hilfsmittel zum Gestalten von Nutzererfordernissen</td>
<td>Prof. Dr.-Ing. Udo Lindemann i.R.</td>
<td>March 8, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Johannes Kirn</td>
<td>Investigation of a shape adaptive aircraft wing leading edge with pneumatic actuation</td>
<td>Prof. Dr.-Ing. Horst Baier i.R.</td>
<td>March 8, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Florian Kohlhuber</td>
<td>Fahrtaugliche Adaption physikalischer Fahrzeug- und Reifendynamik-Regel-Systeme</td>
<td>Prof. Dr.-Ing. Markus Lienkamp</td>
<td>March 14, 2017</td>
</tr>
</tbody>
</table>
### Doctorates 2017

<table>
<thead>
<tr>
<th>Name</th>
<th>Topic</th>
<th>Supervisor</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. rer. nat. Benjamin Kick</td>
<td>Reaktionstechnische Untersuchungen zur Herstellung von Einzelstrang DNA mit dem Bakteriophagen M13</td>
<td>Prof. Dr.-Ing. Dirk Weuster-Botz</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Andreas Ebner</td>
<td>Konzeption eines Virtual Reality unterstützten, teambasierten Planungssystem für die Baustelleneinrichtungsplanung</td>
<td>Prof. Dr.-Ing. Willibald Güntner i.R.</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Philipp Andersch</td>
<td>On the Modeling and Analysis of Helicopter Rotor Dynamics for a Frictional Blade Attachment</td>
<td>Prof. Dr.-Ing. Manfred Hajek</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Ludwig Friedmann</td>
<td>Echtzeit-Simulation des Rotorabwinds von Hubsschraubern und Kippropflugzeugen mit der Lattice-Boltzmann Methode</td>
<td>Prof. Dr.-Ing. Manfred Hajek</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Matthias Friemel</td>
<td>Methoden zur Charakterisierung des thermoelastischen Verhaltens dimensionsstabiler CFK-Werkstoffe bei einer hohen Zahl von Temperaturzyklen</td>
<td>Prof. Dr.-Ing. Horst Baier i.R.</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Fubiao Zhang</td>
<td>Physically Integrated Reference Model Based Flight Control Design</td>
<td>Prof. Dr.-Ing. Florian Holzapfel</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Michael Mihatsch</td>
<td>On the efficient numerical modeling of nonlinear self-excited thermoacoustic oscillations</td>
<td>Prof. Wolfgang Polilke, Ph.D.</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Joona Arttu Alarik Haikonen(geb. Seppälä)</td>
<td>Topology Optimization of Thermally Loaded, Additively Manufactured Turbo Components</td>
<td>Prof. Dr.-Ing. Oskar Haidn</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Stefan Jaensch</td>
<td>Sparse Variational Bayesian algorithms for large-scale inverse problems with applications in biomechanics</td>
<td>Prof. Phaedon-Stelios Koutsourelakis, Ph.D.</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Ulrich Kleihans</td>
<td>Fly Ash Formation and Deposition during Pulverized Fuel Combustion: Numerical and Experimental Investigations</td>
<td>Prof. Dr.-Ing. Hartmut Spliehoff</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Benedikt Schott</td>
<td>Stabilized Cut Finite Element Methods for Complex Interface Coupled Flow Problems</td>
<td>Prof. Dr.-Ing. Wolfgang Wall</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr. rer. nat. Ludwig Klemund</td>
<td>Surface Functionalization of Nano-scale Membrane Reactors for Multienzyme Syntheses</td>
<td>Dr rer. nat. Kathrin Castiglione, TUM Junior Fellow</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Peter Sachnik</td>
<td>Methodik für günstige Schnittflächen beim Scherschneiden</td>
<td>Prof. Dr.-Ing. Wolfram Volk</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Oliver Oberinger</td>
<td>Modellbildung und Berechnung von Rotor-Zelle Kopplungserscheinungen am Hubsschrauber und deren Interpretation mittels Energieflussmethoden</td>
<td>Prof. Dr.-Ing. Manfred Hajek</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Joachim Kreutzer</td>
<td>Messmethoden für die Detektion der Flüssigkeitsaufnahme zur Prämierung von Dehydratation</td>
<td>Prof. Dr.-Ing. Tim C. Lüth</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Ioanna Michailidou</td>
<td>Design the experience first – A scenario-based methodology for the design of complex, tangible consumer products</td>
<td>Prof. Dr.-Ing. Udo Lindemann i.R.</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Franz Vietler</td>
<td>Visual Augmentation for Rotorcraft Pilots in Degraded Visual Environment</td>
<td>Prof. Dr.-Ing. Manfred Hajek</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Tim Fricke</td>
<td>Flight Control with Large Time Delays and Reduced Sensory Feedback</td>
<td>Prof. Dr.-Ing. Florian Holzapfel</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr. rer. nat. Constantin Nowald</td>
<td>Nanoparticle/Biopolymer Systems for Medical Applications</td>
<td>Prof. Dr. rer. nat. Oliver Lieleg</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Christoph Ebel</td>
<td>Hochgeschwindigkeitsumformungen für die Fertigung von Faserverbundbauteilen</td>
<td>Prof. Dr.-Ing. Klaus Drechsler</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Wolfgang Raffelt</td>
<td>Hochdruck-RTM-Prozessentwicklung für die automobile Grobserie</td>
<td>Prof. Dr.-Ing. Klaus Drechsler</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Petra Fröhlich</td>
<td>Process development and validation of thermoplastic complex shape thermoforming</td>
<td>Prof. Dr.-Ing. Klaus Drechsler</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Thomas Kopp</td>
<td>Einfluss der Werkzeugstiffheit auf Scherschneidprozess und Werkzeugverschleiß beim offenen Schnitt</td>
<td>Prof. Dr.-Ing. Wolfram Volk</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Felix Schranner</td>
<td>Weakly Compressible Models for Complex Flows</td>
<td>Prof. Dr.-Ing. Nikolaus Adams</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Arne Herberg</td>
<td>Planung und Entwicklung multifunktionaler Kernelemente in komplexen Systemarchitekturen und -portfolios</td>
<td>Prof. Dr.-Ing. Udo Lindemann i.R.</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Oliver Schneider</td>
<td>Prozessaufnahmemethode zur Unterstützung des RFID-Einsatzes in der Intralogistik</td>
<td>Prof. Dr.-Ing. Willibald Güntner i.R.</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Fabiola Cappia</td>
<td>Investigation of high burnup UO2 fuels in Light Water Reactors</td>
<td>Prof. Rafael Macián-Juan, Ph.D.</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Philipp Seidenspinner</td>
<td>Methoden zur Vorselektion sauerstoffhaltiger Kraftstoffkomponenten</td>
<td>Prof. Dr.-Ing. Georg Wachtmeister</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Johannes Neumayer</td>
<td>Charakterisation und Simulation von adhesiv bonded joints with laminated adherends for crash applications</td>
<td>Prof. Dr.-Ing. Klaus Drechsler</td>
<td>April 17, 2017</td>
</tr>
<tr>
<td>Name</td>
<td>Topic</td>
<td>Supervisor</td>
<td>Date</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>------------------------------------------------------------------------</td>
<td>------------------------------------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Dr.-Ing. Vera Hoferichter</td>
<td>Boundary Layer Flashback in Premixed Combustion Systems</td>
<td>Prof. Dr.-Ing. Thomas Sattelmayer</td>
<td>May 5, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Falk Schröder</td>
<td>Vorgehensweise zur Implementierung von logistischen Kennzahlensystemen im Umfeld der Automobilindustrie</td>
<td>Prof. Dr.-Ing. Willibald Günthner i.R.</td>
<td>May 9, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Alexane Margossian</td>
<td>Forming of tailored thermoplastic composite blanks: material characterisation, simulation and validation</td>
<td>Prof. Dr.-Ing. Klaus Drechsler</td>
<td>May 9, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Johannes Wolfgang Stock</td>
<td>Remote-Laserstrahltrennen von kohlenstoffaserverstärktem Kunststoff</td>
<td>Prof. Dr.-Ing. Michael Zäh</td>
<td>May 9, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Andreas Johanning</td>
<td>Methodik zur Ökobilanzierung im Flugzeugentwurf</td>
<td>Prof. Dr.-Ing. Mirko Hornung</td>
<td>May 10, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Matthias Bittner</td>
<td>Utilization of Problem and Dynamic Characteristics for Solving Large Scale Optimal Control Problems</td>
<td>Prof. Dr.-Ing. Florian Holzapfel</td>
<td>May 11, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Daniel Häffelin</td>
<td>Verfahren zur Integration von Folien in den RTM-Prozess (resin transfer molding) für endlosfaserverstärkte Schalenteile</td>
<td>Prof. Dr.-Ing. Klaus Drechsler</td>
<td>May 12, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Andreas Hees</td>
<td>System zur Produktionsplanung für rekonfigurierbare Produktionsinne</td>
<td>Prof. Dr.-Ing. Gunther Reinhart</td>
<td>May 16, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Stefan Grubwinkler</td>
<td>Fahrprofile-basierte Energieverbrauchsprädiktion für vernetzte Elektrofahrzeuge</td>
<td>Prof. Dr.-Ing. Markus Lienkamp</td>
<td>May 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Lars Holt</td>
<td>Improvement and validation of a computer model for the thermo-mechanical fuel rod behavior during reactivity transients in nuclear reactors</td>
<td>Prof. Rafael Macián-Juan, Ph.D.</td>
<td>May 18, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Reinhold Franz Johann Meier</td>
<td>Über das Fließverhalten von Epoxidharzsystemen und vibrationsunterstützte Harzinfiltrationsprozesse</td>
<td>Prof. Dr.-Ing. Klaus Drechsler</td>
<td>May 19, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Marcus Arnold</td>
<td>Verbesserung der Materialeigenschaften von CFK durch den gezielten Einsatz von thermoplastischen Fadengelegen</td>
<td>Prof. Dr.-Ing. Klaus Drechsler</td>
<td>May 19, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Clotaire Geoffray</td>
<td>Uncertainty Propagation Applied to Multi-Scale Thermal-Hydraulics Coupled Codes: A Step Towards Validation</td>
<td>Prof. Rafael Macián-Juan, Ph.D.</td>
<td>May 19, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Fedor Baklanov</td>
<td>Platform-autonomous Fault-tolerant Attitude/Heading Reference and Navigation Systems</td>
<td>Prof. Dr.-Ing. Florian Holzapfel</td>
<td>May 24, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Christopher Buchmann</td>
<td>Untersuchungen zur Steigerung der Prozessrobustheit bei der Fertigung faserverstärkter Luftfahrtauteile</td>
<td>Prof. Dr.-Ing. Klaus Drechsler</td>
<td>May 24, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Martina Wickel</td>
<td>Änderungen besser managen – Eine datenbasierte Methodik zur Analyse technischer Änderungen</td>
<td>Prof. Dr.-Ing. Udo Lindemann i.R.</td>
<td>May 24, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Stefan Walser</td>
<td>Development and Application of a Fourier Transform based Methodology for the Identification of Instability in Boiling Water Reactors at a local Scale</td>
<td>Prof. Rafael Macián-Juan, Ph.D.</td>
<td>May 30, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Peer Helmbrecht</td>
<td>Die Änderung von Fahrverhaltensmustern durch Nutzung eines Elektrofahrzeuges – Gewöhnung an die fahrdynamischen und konzeptionellen Besonderheiten und Anwendung effizienter Fahrstrategien</td>
<td>Prof. Dr. phil. Klaus Bengler</td>
<td>May 31, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Jörg Pause</td>
<td>Bewertung der Wissensqualität von Kostenenelementen für Kalkulationen am Beispiel der Automobilproduktion</td>
<td>Prof. Dr.-Ing. Gunther Reinhart</td>
<td>June 7, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Veronika Schöning</td>
<td>Prozessentwicklung zur Gewinnung von Mucinen aus tierischem Gewebe</td>
<td>Prof. Dr. rer. nat. Sonja Berensmeier</td>
<td>June 19, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Thaddäus Baier</td>
<td>Entwicklung und Verifizierung eines Konzepts zur Robusten Regelung der Seitenbewegung zukünftiger Kleinflugzeuge</td>
<td>Dr.-Ing. Matthias Heller, Rudolf Diesel Industry Fellow at TUM-IAS</td>
<td>June 19, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Philipp Gwinner</td>
<td>Schwingungsarme Achsgetriebe elektromechanischer Antriebsstränge – Auslegung schwingungsarme Stirnradverzahnungen für den automobilen Einsatz in hochdrehenden, elektrisch angetriebenen Achsgetrieben</td>
<td>Prof. Dr.-Ing. Karsten Stahl</td>
<td>June 19, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Liang Si</td>
<td>Towards a Robust In-Situ Health Monitoring and Identification Technique for Thin-walled Fiber Composite Structures under Various Types of Adverse Disturbances</td>
<td>Prof. Dr.-Ing. Horst Baier i.R.</td>
<td>June 21, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Johannes Coy</td>
<td>Ein neues Verfahren zur Quantifizierung von Parkinson-symptomen für die Tiefenhirnstimulation – Verfahren, Gerät und klinische Bewertung</td>
<td>Prof. Dr. rer. nat. Tim C. Lüth</td>
<td>June 22, 2017</td>
</tr>
<tr>
<td>Name</td>
<td>Topic</td>
<td>Supervisor</td>
<td>Date</td>
</tr>
<tr>
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</tr>
<tr>
<td>Dr.-Ing. Hansjörg Schultheiß</td>
<td>Zum Verschleißverhalten einsatzgeharteter Zahnradpaarungen in Abhängigkeit des Schmierungsmechanismus bei Fett-</td>
<td>Prof. Dr.-Ing. Karsten Stahl</td>
<td>June 23, 2017</td>
</tr>
<tr>
<td></td>
<td>schnierung</td>
<td></td>
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</tr>
<tr>
<td>Dr.-Ing. Michael Josef Sebastian</td>
<td>Untersuchungen zu dem Betriebsverhalten und den Betriebsgrenzen einer mehrstufigen Scramjet Brennkammer</td>
<td>Prof. Dr.-Ing. Oskar Haind</td>
<td>June 28, 2017</td>
</tr>
<tr>
<td>Gurtner</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dr.-Ing. Christian Heise</td>
<td>Survivable Flight Control with Guaranteed Stability and Performance Characteristics</td>
<td>Prof. Dr.-Ing. Florian Holzapfel</td>
<td>June 28, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. David Kelterborn</td>
<td>Erweiterung eines Systems vorbestimmter Zeiten zur Bewertung der körperlichen Belastung in der Produktionslogistik</td>
<td>Prof. Dr.-Ing. Willibald Günther i.R.</td>
<td>June 29, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Veronika Bühler (geb.</td>
<td>Gradual Impregnation during the Production of Thermoplastic Composites</td>
<td>Prof. Dr.-Ing. Klaus Drechsler</td>
<td>July 3, 2017</td>
</tr>
<tr>
<td>Radlmaier)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dr.-Ing. Christian Pötsch</td>
<td>Experimentelle Untersuchungen zur inneren und äußeren Gemischbildung am hochaufgeladenen Ottomotor mit Luftmengenbegrenzung</td>
<td>Prof. Dr.-Ing. Georg Wachtmeister</td>
<td>July 3, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Danilo Schmidt</td>
<td>Increasing Customer Acceptance in Planning Product-Service Systems</td>
<td>Prof. Dr.-Ing. Udo Lindemann i.R.</td>
<td>July 4, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Steffi Hoppenheit</td>
<td>System zum proaktiven Bestandsmanagement von Langsamdrehern</td>
<td>Prof. Dr.-Ing. Willibald Günther i.R.</td>
<td>July 6, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Christina Pfaffinger</td>
<td>Reaktionstechnische Untersuchungen zur Lipidherstellung mit Nannochloropsis sp. in verschiedenen Photobioreaktern</td>
<td>Prof. Dr.-Ing. Dirk Weuster-Botz</td>
<td>July 7, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Kristina Speth</td>
<td>Experimentelle Untersuchungen zur Stickoxidbildung und -minderung bei der Verbrennung von Biomassen und Hausmüll</td>
<td>Prof. Dr.-Ing. Hartmut Spleithoff</td>
<td>July 7, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Lisa-Magdalena Herbst</td>
<td>Entwicklung einer Methodik zur Ableitung raumfunktionaler Kundenanforderungen in der Automobilentwicklung</td>
<td>Prof. Dr.-Ing. Udo Lindemann i.R.</td>
<td>July 10, 2017</td>
</tr>
<tr>
<td>(geb. Schmid)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dr.-Ing. Fabian Michael Distel</td>
<td>Methodische Auslegung ultraschallbasierter berührungsloser Handhabungssysteme</td>
<td>Prof. Dr.-Ing. Gunther Reinhart</td>
<td>July 10, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Paul Bockelmann</td>
<td>Process Control in Compression Molding of Composites</td>
<td>Prof. Dr.-Ing. Klaus Drechsler</td>
<td>July 13, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Daniel Roppenecker</td>
<td>Entwicklung und Validierung eines generativ gefertigten Snake-Like Manipulators für die minimal-invasive Chirurgie</td>
<td>Prof. Dr. rer. nat. Tim C. Lüth</td>
<td>July 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Theodosia Kourkoutsaki</td>
<td>A Multiphysics Simulation Toolkit Developed to Address Scale-up Challenges of Out-of-Autoclave Composites Manufacturing</td>
<td>Prof. Dr.-Ing. Klaus Drechsler</td>
<td>July 17, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Christoph Schütz</td>
<td>Trajectory Planning for Redundant Manipulators – Optimization, Real Time Methods, Agricultural Robots</td>
<td>Prof. Dr.-Ing. habil. Heinz Ulrich i.R.</td>
<td>July 18, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Xiang Wang</td>
<td>Analysis and Evaluation of the Dual Fluid Reactor Concept</td>
<td>Prof. Rafael Macián-Juan, Ph.D.</td>
<td>July 20, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Michael Jürgens</td>
<td>Grenzflächenphänomene metallisch z-verstärkter Kohlenstofffaserverbundverbindungen</td>
<td>Prof. Dr.-Ing. Klaus Drechsler</td>
<td>July 21, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Kristina Däuschinger</td>
<td>Abruststeuerung bei Bedarfsschwankungen in der automobilen Beschaffungs- und Produktionslogistik</td>
<td>Prof. Dr.-Ing. Willibald Günther i.R.</td>
<td>July 24, 2017</td>
</tr>
<tr>
<td>(geb. Laschinger)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dr.-Ing. Burkhard Seifert</td>
<td>Performance Improvements of Humidification-Dehumidification Desalination Systems with Natural Convection</td>
<td>Prof. Dr.-Ing. Thomas Sattelmayer</td>
<td>July 26, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Peter Stich</td>
<td>Interaktiver simulationsgestützter Entwurf mechatronischer Verarbeitungssysteme</td>
<td>Prof. Dr.-Ing. Gunther Reinhart</td>
<td>July 27, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Christian Roth</td>
<td>Multi-dimensional Coupled Computational Modeling in Respiratory Biomechanics</td>
<td>Prof. Dr.-Ing. Wolfgang Wall</td>
<td>July 28, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Denis Kiefel</td>
<td>Quantitative Porositätscharakterisierung von CFK-Werkstoffen mit der Mikro-Computertomografie</td>
<td>Prof. Dr.-Ing. Christian Große</td>
<td>August 3, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Claas Olthoff</td>
<td>Dynamic Simulation of Extravehicular Activities</td>
<td>Prof. Dr. rer. nat. Dr. h.c. Ulrich Walter</td>
<td>August 7, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Sebastian Heckner</td>
<td>Zerstörungsfreie Prüfmethoden zur Oberflächencharakterisierung von kohlenstofffaserverstärkten Kunststoffen</td>
<td>Prof. Dr.-Ing. Christian Große</td>
<td>August 8, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Josef Haßberger</td>
<td>Numerical Simulation of Deflagration-to-Detonation Transition on Industry Scale</td>
<td>Prof. Dr.-Ing. Thomas Sattelmayer</td>
<td>August 18, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Charlotte Eisenhauer</td>
<td>Hoch drapierbare, konturgetreue, variabelaxiale Verstärkungstextilien für faserverstärkte Kunststoffe</td>
<td>Prof. Dr.-Ing. Klaus Drechsler</td>
<td>September 5, 2017</td>
</tr>
<tr>
<td>Name</td>
<td>Topic</td>
<td>Supervisor</td>
<td>Date</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>----------------------------------------------------------------------</td>
<td>-------------------------------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Dr.-Ing. Benjamin Lütke</td>
<td>Dynamic Stall on a Pitching Double-Swept Rotor Blade Tip</td>
<td>apl. Prof. Dr.-Ing. Christian Breitsamter</td>
<td>September 8, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Philipp Maximilian Schäffer</td>
<td>Consolidation of carbon fiber reinforced Polyamide 6 tapes using laser-assisted tape placement</td>
<td>Prof. Dr.-Ing. Klaus Drechsler</td>
<td>September 8, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Andreas Loos</td>
<td>Strömungsbeeinflussung durch Nabenstrukturierung in deckbandlosen Statoren von Axialhochdruckverdichtern – Numerische Untersuchungen</td>
<td>Prof. Dr.-Ing. Oskar Haidn</td>
<td>September 14, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Stephan Lellek</td>
<td>Pollutant Formation in Premixed Natural Gas Swirl Flames with Water Injection</td>
<td>Prof. Dr.-Ing. Thomas Sattelmayer</td>
<td>September 15, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Klaus Moser</td>
<td>Methode zur Untersuchung des Betriebsverhaltens stufenloser Umschlingungsgetriebe</td>
<td>Prof. Dr.-Ing. Bernd-Robert Höhn i.R.</td>
<td>September 18, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Ulrich Lammer</td>
<td>Funktionsvereinigung in der Lagertechnik</td>
<td>Prof. Dr.-Ing. Willibald Günther i.R.</td>
<td>September 18, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Julia Freis</td>
<td>Wechselwirkungen und Auswirkungen von Planungsalternativen auf die Gesamtenergiebilanz und die CO₂-Emissionen von Logistikzentren</td>
<td>Prof. Dr.-Ing. Willibald Günther i.R.</td>
<td>September 18, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Hermann Hajek</td>
<td>Längsdynamik und Antriebsakustik von elektrifizierten Straßenfahrzeugen – Beschreibung und Gestaltung des emotionalen Erlebens</td>
<td>Prof. Dr. phil. Klaus Bengler</td>
<td>September 19, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Tobias Rammelmeier</td>
<td>Vermeidung und prozessintegrierte Erkennung von Kommissionierfehlern auf Basis der Pick-by-Vision-Technologie</td>
<td>Prof. Dr.-Ing. Willibald Günther i.R.</td>
<td>September 19, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Natalie Mayer</td>
<td>Integrated simulation approach from process simulation to structural analysis for composite components considering manufacturing effects</td>
<td>Prof. Dr.-Ing. Klaus Drechsler</td>
<td>September 19, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Robin Taubert</td>
<td>Einfluss von nichtlinearer Materialverhalten auf die Erstellung und Auswirkung von Zwischenlaserbrücken in Verbundaminaten</td>
<td>Prof. Dr.-Ing. Klaus Drechsler</td>
<td>September 21, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Michael Krause</td>
<td>Modeling Driver Distraction</td>
<td>Prof. Dr. phil. Klaus Bengler</td>
<td>September 21, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Thorsten Nikolaus Hans</td>
<td>Finite Element Simulation of the braiding process</td>
<td>Prof. Dr.-Ing. Klaus Drechsler</td>
<td>September 25, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Samuel Reimer</td>
<td>Bio-Kinematic Design of Individualized Lift-Assist Chairs for the Support of Sit-to-Stand Movement</td>
<td>Prof. Dr. rer. nat. Tim C. Lüth</td>
<td>September 27, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Mathias Martin Dibon</td>
<td>Fast Valves for Massive Gas Injection in Tokamaks</td>
<td>Prof. Dr. Rudolf Neu</td>
<td>September 29, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Konrad Entsfellner</td>
<td>Ein modular konfigurierbares Assistenzsystem zur Perforatorführung bei der Stapedotomie</td>
<td>Prof. Dr. rer. nat. Tim C. Lüth</td>
<td>October 4, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Lin Fu</td>
<td>Numerical methods for computational fluid dynamics</td>
<td>PD Dr.-Ing. Xiangyu Hu</td>
<td>October 5, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Martin Dorn</td>
<td>Modeling of the transient hydrodynamic behavior of preparative chromatography columns</td>
<td>Prof. Dr.-Ing. Dirk Weust Botz</td>
<td>October 6, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Eva Klenk</td>
<td>Ein analytisches Modell zur Bewertung der Leistung von Routenzugsystemen bei schwankenden Transportbedarfen</td>
<td>Prof. Dr.-Ing. Willibald Günther i.R.</td>
<td>October 9, 2017</td>
</tr>
<tr>
<td>Dr. rer. nat. Tom Schwarzer</td>
<td>Membrane functionalization of nano-scale enzyme membrane reactors for asymmetric synthases</td>
<td>Dr. rer. nat. Kathrin Castiglione, TUM Junior Fellow</td>
<td>October 12, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Michael Roth</td>
<td>Efficient Safety Method Kit for User-driven Customization</td>
<td>Prof. Dr.-Ing. Udo Lindemann i.R.</td>
<td>October 18, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Qixiong Li</td>
<td>Ablagerungsbildungsmechanismen – Modellbildung und Simulation der Partikelablagernung im Brennraum bei Rapsöl-betrieb</td>
<td>Prof. Dr.-Ing. Georg Wachtmeister</td>
<td>October 19, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Emad Sadeghipour</td>
<td>A New Approach to Assess and Optimize the Frontal Crash Compatibility of Vehicle Structures with Focus on the European Fleet of Passenger Cars</td>
<td>Prof. Dr.-Ing. Markus Lienkamp</td>
<td>October 19, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Andreas Ehrl</td>
<td>Determination of Transport Parameters of Binary Electrolyte Solutions for the Use in Numerical Simulations</td>
<td>Prof. Dr.-Ing. Wolfgang Wall</td>
<td>October 24, 2017</td>
</tr>
<tr>
<td>Dr. rer. nat. Sebastian Schwaminger</td>
<td>Nano-bio interactions at the aqueous interface of iron oxide nanoparticles</td>
<td>Prof. Dr. rer. nat. Sonja Berensmeier</td>
<td>October 24, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Kilian Förner</td>
<td>Nonlinear Aeroacoustic Characterization of Resonators</td>
<td>Prof. Wolfgang Polifke, Ph.D.</td>
<td>October 25, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Josef Huber</td>
<td>Verfahren zur Klassifikation von Ungänzen bei der optischen Prüfung von Batteriespeichereparaten</td>
<td>Prof. Dr.-Ing. Gunther Reinhart</td>
<td>October 26, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Mathias Sommerer</td>
<td>Multiple-Use-Technologien in der Fusionsforschung und industriellen Anwendungen: Mikrostrukturrelle Aspekte des thermozyklischen Bruchverhaltens von Wolfram</td>
<td>Prof. Dr. mont. habil. Dr. rer. nat. h.c. Ewald Werner</td>
<td>October 26, 2017</td>
</tr>
<tr>
<td>Name</td>
<td>Topic</td>
<td>Supervisor</td>
<td>Date</td>
</tr>
<tr>
<td>-------------------------------</td>
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<td>-----------------------------------------------------------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Dr.-Ing. Nepomuk Heimberger</td>
<td>Strukturbasierte Koordinationsplanung in komplexen Entwicklungsprojekten</td>
<td>Prof. Dr.-Ing. Udo Lindemann i.R.</td>
<td>October 26, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Steffen Kahler</td>
<td>Analyse der Lastflexibilität von industriellen KWK-GuD-Kraftwerken</td>
<td>Prof. Dr.-Ing. Hartmut Spliethoff</td>
<td>October 27, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Daniel Kammel</td>
<td>Modellbasierte Planung von Produkt-Service-Systemen</td>
<td>Prof. Dr.-Ing. Udo Lindemann i.R.</td>
<td>October 27, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Maximilian Strebel</td>
<td>Spontanschäden an nasslaufenden Lamellenkupplungen</td>
<td>Prof. Dr.-Ing. Karsten Stahl</td>
<td>November 2, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Sonja Hofauer</td>
<td>Fahrer-Fahrzeug-Interaktion einer automatisierten, kraftstoff-</td>
<td>Prof. Dr.-Ing. Markus Lienkamp</td>
<td>November 6, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Markus Baar</td>
<td>Kennwerte zur Tragfähigkeit kleinmodulärer Kronenradverzahnungen</td>
<td>Prof. Dr.-Ing. Karsten Stahl</td>
<td>November 7, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Karl Simon Radler</td>
<td>Periodic Free Vortex Wake Simulation</td>
<td>Prof. Dr.-Ing. Manfred Hajek</td>
<td>November 10, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Mark-Philipp Kurowski</td>
<td>Modellierung und Simulation der Verschlackung bei der Kohlevergasung</td>
<td>Prof. Dr.-Ing. Hartmut Spliethoff</td>
<td>November 13, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Jae You</td>
<td>Aerocoustic Characteristics of a Shrouded Helicopter Tail Rotor</td>
<td>apl. Prof. Dr.-Ing. Christian Breitsamter</td>
<td>November 13, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Ugur Karban</td>
<td>Scale-resolved and stochastic approaches for noise prediction in</td>
<td>Prof. Wolfgang Politke, Ph.D.</td>
<td>November 14, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Bernhard Sauerer</td>
<td>Ordnungsreduzierte Simulationsmodelle und Berücksichtigung der</td>
<td>Prof. Dr.-Ing. Horst Baier i.R.</td>
<td>November 14, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Christin Rapp</td>
<td>Atmosphärische Plasmabeschichtung von orthopädischen Implantaten</td>
<td>Prof. Dr.-Ing. Harald Klein</td>
<td>November 14, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Alexander Belitzki</td>
<td>Rechnergestützte Minimierung des Verzugs laserstrahlgeschweißer</td>
<td>Prof. Dr.-Ing. Michael Zäh</td>
<td>November 16, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Verena Knott</td>
<td>Evaluation von Exoskeletten zur Lastenhandhabung in der Logistik</td>
<td>Prof. Dr. phil. Klaus Bengler</td>
<td>November 21, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Carolin Wickborn</td>
<td>Erweiterung der Flankentragfähigkeitsberechnung von Stirnrädern in der</td>
<td>Prof. Dr.-Ing. Karsten Stahl</td>
<td>November 23, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Felix Meier</td>
<td>Einfluss der Aluminium-Mikrostruktur auf das Schädigungsverhalten von</td>
<td>Prof. Dr. mont. habil. Dr. rer. nat. h.c. Ewald Werner</td>
<td>November 23, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Jose Ignacio Tijero Cavia</td>
<td>Simulation of thorium material properties under fission reactor</td>
<td>Prof. Rafael Macián-Juan, Ph.D.</td>
<td>November 24, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Thorsten Gläsner</td>
<td>Reduzierung der Kanterrissempfindlichkeit von Mehrphasenstäben durch 2-</td>
<td>Prof. Dr.-Ing. Hartmut Hoffmann i.R.</td>
<td>November 27, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. David Allaverdi</td>
<td>Systematic identification of Flexible Design Opportunities in offshore</td>
<td>Prof. Dr.-Ing. Udo Lindemann i.R.</td>
<td>November 29, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Thomas Aicher</td>
<td>Automatic backwards compatibility of automated material flow software</td>
<td>Prof. Dr.-Ing. Birgit Vogel-Heuser</td>
<td>November 29, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Ulrich Mandel</td>
<td>Mechanism Based Constitutive Model for Composite Laminates</td>
<td>Prof. Dr.-Ing. Klaus Drechsler</td>
<td>November 29, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Georg Meingafner</td>
<td>Methodik zur Untersuchung des Reibungsverhaltens nasslaufender</td>
<td>Prof. Dr.-Ing. Karsten Stahl</td>
<td>December 4, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Theo Fabian Kiesel</td>
<td>Flexible Multi-Body Simulation of a Complex Rotor System Using 3D Solid</td>
<td>Prof. Dr.-Ing. Steffen Marburg</td>
<td>December 4, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Alexander Lang</td>
<td>Im Spannungsfeld zwischen Risiken und Chancen – Eine Methode zur</td>
<td>Prof. Dr.-Ing. Udo Lindemann i.R.</td>
<td>December 5, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Sebastianus Petermeijer</td>
<td>A vibrotactile interface to support the driver during the take-over</td>
<td>Prof. Dr. phil. Klaus Bengler</td>
<td>December 5, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Fabian Hellmundt</td>
<td>Adaptive Flight Control for Fault Tolerance</td>
<td>Prof. Dr.-Ing. Florian Hotzapfel</td>
<td>December 6, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Timm Severin</td>
<td>Computational Fluid Dynamics Assisted Design of Thin-Layer Cascade</td>
<td>Prof. Dr.-Ing. Dirk Weuster-Botz</td>
<td>December 6, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Tanut Ungwattanapanit</td>
<td>Optimization of Steered-Fibers Composite Stiffened Panels including</td>
<td>Prof. Dr.-Ing. Horst Baier i.R.</td>
<td>December 8, 2017</td>
</tr>
<tr>
<td>Name</td>
<td>Topic</td>
<td>Supervisor</td>
<td>Date</td>
</tr>
<tr>
<td>---------------------</td>
<td>----------------------------------------------------------------------</td>
<td>--------------------------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Dr.-Ing. Seung Oh</td>
<td>Modellierung und Entwicklung eines Flurförderzeugreifenmodells als Mehrkörpersystem</td>
<td>Prof. Dr.-Ing. Willibald Günthner i.R.</td>
<td>December 15, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Patrick Stenner</td>
<td>Erprobungsplanung zur Konzeptabsicherung von Elektrofahrzeugen</td>
<td>Prof. Dr.-Ing. Markus Lienkamp</td>
<td>December 15, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Sebastian Kehl</td>
<td>Bayesian Calibration of Nonlinear Cardiovascular Models for the Predictive Simulation of Arterial Growth</td>
<td>Prof. Dr.-Ing. Michael Gee</td>
<td>December 19, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Myriam Koch</td>
<td>Methodik zur Einführung von Jobrotation in der Logistik</td>
<td>Prof. Dr.-Ing. Willibald Günthner i.R.</td>
<td>December 19, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Markus Spindler</td>
<td>Zwei-Schichten-Architektur zur modellbasierten Erstellung der Steuerungssoftware für automatisierte Materialfluss- systeme</td>
<td>Prof. Dr.-Ing. Willibald Günthner i.R.</td>
<td>December 20, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Anja Kölzsch</td>
<td>Active Flow Control of Delta Wing Leading-Edge Vortices</td>
<td>apl. Prof. Dr.-Ing. Christian Breitsamter</td>
<td>December 20, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Georg Götz</td>
<td>Methode zur Steigerung der Formatflexibilität von Verpackungsmaschinen</td>
<td>Prof. Dr.-Ing. Günther Reinhart</td>
<td>December 21, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Martin Schmid</td>
<td>Kognitive Prozesssteuerung zur Steigerung der Ressourcen- effizienz in der Druckindustrie</td>
<td>Prof. Dr.-Ing. Günther Reinhart</td>
<td>December 21, 2017</td>
</tr>
<tr>
<td>Dr.-Ing. Andreas Hasbeek</td>
<td>An Integrative Evaluation of Airline Pilots’ Manual High-Precision Flying Skills in the Age of Automation</td>
<td>Prof. Dr. phil. Klaus Bengler</td>
<td>December 22, 2017</td>
</tr>
</tbody>
</table>
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