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Institute of System Dynamics and Control

DLR

Contents

Robotics and Mechatronics Center (RMC)

The Robotics and Mechatronics Center (RMC) is a cluster consisting of the Institutes of Robotic and Mechatronics (RM) and System Dynamics and Control (SR) at the DLR site in Oberpfaffenhofen and the Institute for Optical Sensor Systems (OS) in Berlin. It is the DLR competence center for research and technology in the area of robotics, mechatronics, system dynamics, and optical sensor systems.

The broad expertise of the center is based on mechatronics. As a key technology of our industrial society, it stands for the highest possible integration of mechanics, optics, electronics, and information technology (software) to create devices ranging from intelligent components to autonomous robotic systems. Accordingly, the work of the RMC is focused on interdisciplinary designs and realistic simulations. Furthermore, the realisation of complex mechatronic systems and human-machine-interfaces as well as their control and intelligent programming comprise major research elements.

The technologies and systems developed in the RMC are primarily applied in the research fields of space robotics, aviation, and transport. The developed technologies have direct effects and applications in other socially relevant fields such as medical technology, factories of the future, and personal robotic assistance. Technology transfer is thus a major objective of the RMC.

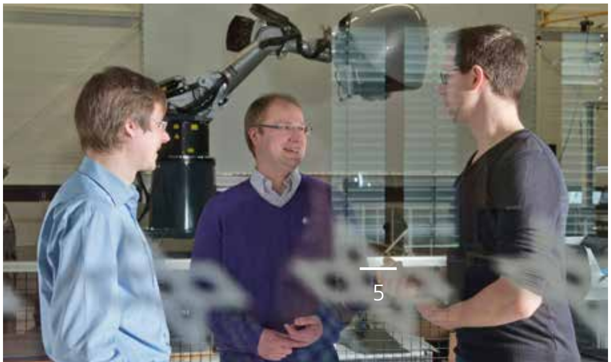
Institute of System Dynamics and Control (SR)

The rapid progress in the fields of microprocessors, sensors and software technology makes it possible to implement intelligent and efficient control functions in mechatronic systems. The Institute of System Dynamics and Control works on the enhancement and application of advanced control methods, in view of improving performance, energy efficiency, safety and comfort in complex controlled systems.

The primary objectives of the institute are innovative solutions for space robots and space flight systems, aircraft, road and rail vehicles as well as technology transfer to industrial robots and wind power plants. The institute works closely together with industry and research partners as well as with numerous DLR institutes. The solutions are based on the holistic design as well as optimal and robust control of the underlying dynamic systems.

For the physical modelling and simulation of the system performance, the institute leads the development and establishment of international modelling standards such as Modelica and the Functional Mock-up Interface (FMI) and develops model libraries for various fields of application.

The institute demonstrates its expertise in the complete development chain from computer aided design down to hardware tests with its test benches and research vehicles such as the DLR Robotic Motion Simulator and the DLR ROboMObil.



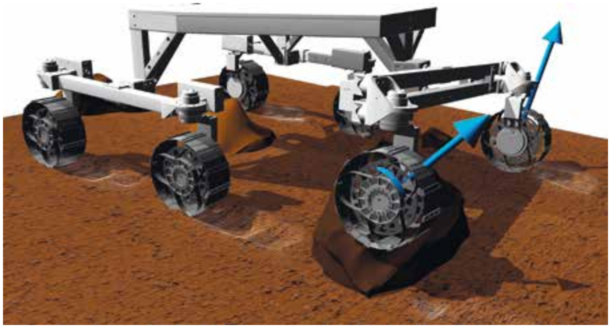
Space

As part of the RMC key research subjects planetary exploration and on-orbit servicing, significant contributions in simulation, design optimisation, verification and control of space systems and their individual subsystems are being made. Our research focuses on the planetary rovers' wheel-soil interaction, landers' mobility on asteroids, satellite manoeuvres including docking contact dynamics, and the assessment of conventional and reusable launcher systems.

On-orbit servicing

The Institute of System Dynamics and Control develops models and technologies for robotic servicing, repair and disposal of satellites. Activities include verification and improvement of satellite docking systems and development of "Guidance, Navigation and Control (GNC)" strategies for service satellites. For the realisation of this goal, highly accurate and flexible multi-body and contact dynamics models play a crucial role.

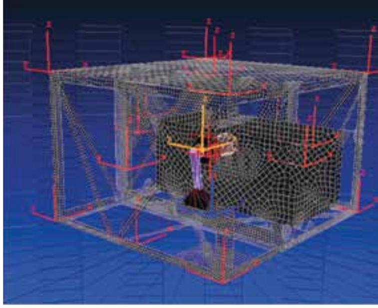
As part of the ESA "Clean Space Initiative", new technologies are developed to remove space debris out of satellite orbits (Active Debris Removal, ADR). These technologies include GNC solutions that allow an integrated control of a servicing satellite with a mounted robot arm, to be able to fly to and grasp inactive satellites and remove them from the orbit. In an ESA project, the SR institute has developed an appropriate simulation tool for the Envisat ADR Scenario (eDeorbit), within which necessary GNC algorithms are implemented and successfully demonstrated regarding fly-around, rendezvous, docking, detumbling and de-orbiting of an uncooperative target.



Planetary exploration

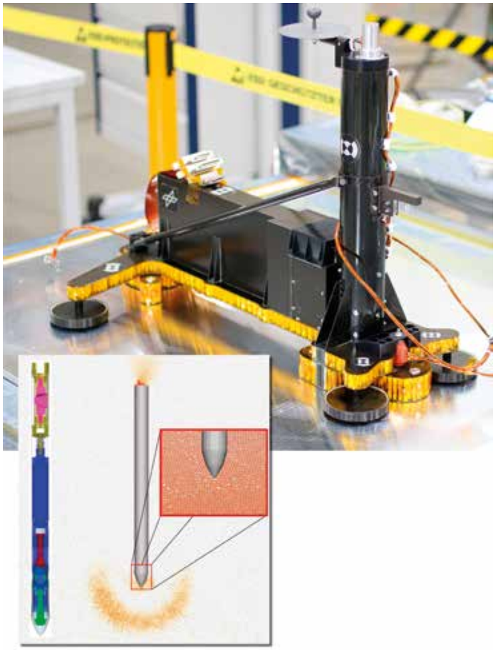
The SR institute provides simulation expertise for applications dedicated to the field of robotic planetary exploration. The collected know-how is both stored and accessible via libraries for further scientific use and also applied to space missions with planetary rovers (e.g. ExoMars rover; ESA), asteroid landers (e.g. MASCOT mobility unit; JAXA), or sub-surface operations (e.g. InSight HP3; NASA). System dynamics prediction and verification as well as model-based control and failure detection are the focus of the work.

Terramechanics is a major key to success in planetary exploration missions. Therefore, the SR Rover Simulation Toolkit for mobility system design provides access to a variety of soil interaction models like real-time capable solutions, models featuring plastic soil deformation and complex particle models for wheels as well as sub-surface operations. Model validation is based on experimental single-wheel and system-level tests as well as on available mission data.



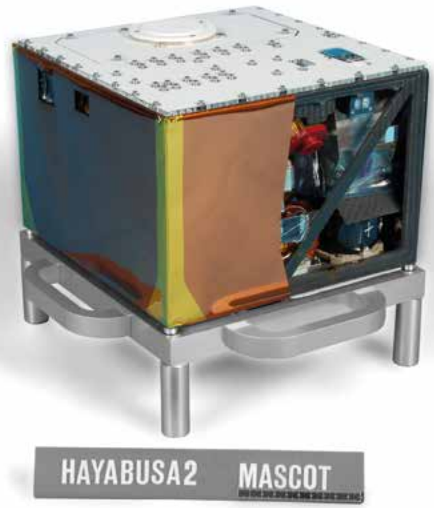
InSight – beneath the surface of Mars

For NASA's InSight mission to Mars, DLR provides the HP3 instrument. Its main "thermal sensor", a self-impelling nail nicknamed the "Mole" will hammer itself 5 metres beneath the Martian surface to measure the heat flux. At the SR institute, multi-body dynamics models have been coupled with complex particle models of the Martian soil in order to make high-fidelity predictions on the Mole's penetration performance. Optimisations based on these models led to adaptions of the inner spring-mass system of the hammering mechanism, which decreased the number of strokes needed to reach the desired depth to 25% compared to the original prototype, while maintaining the same amount of input power.



MASCOT – leaping on asteroids

The DLR lander MASCOT has already started its journey – piggyback on JAXA's Hayabusa-II – to the asteroid Ryugu in December 2014. After the descent and landing in 2018, an internal mobility mechanism designed at the sister institute RM will turn the shoe-box-sized MASCOT lander upright to its measurement position and is able to relocate the lander to new measurement destinations on Ryugu. At the SR institute, optimal acceleration profiles for this mechanism are identified based on multi-body simulations in conjunction with high-fidelity soil models. As the microgravity field and the asteroid surface properties feature a high variability, robust solutions are determined by model-based optimisation approaches.



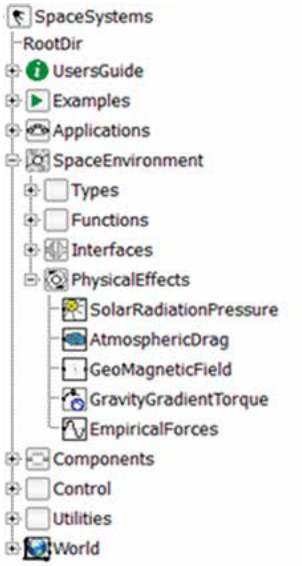
Satellite systems

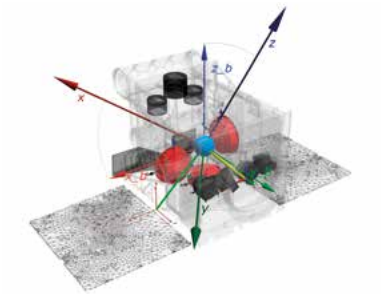
For current and future space missions involving on-orbit servicing and Earth observation, multidisciplinary modelling environments are developed to assist the specification, design, and assessment of satellite systems and their dynamics, including their control system and their interaction with the space environment.

The satellite platform BIROS is a technology demonstrator for the DLR FireBIRD space mission. To demonstrate an attitude control system for fast rotational manoeuvres, the platform is equipped with "High-Torque-Wheels (HTW)". The satellite dynamics model including structural flexibilities and an attitude control system was developed at the SR institute using the DLR Space Systems Library based on Modelica.

The library also contains modules to represent a realistic space environment. To this end, gravity models and modules for typical parasitic effects acting on spacecraft are modelled. Extensive graphical options are also available to visualise these space missions.

Special attention is given to the modelling of elastic components like satellites´ solar module structure and the consideration of these models for the control systems design.





Launcher systems

The European launcher systems Ariane and Vega are being continuously improved. Within this framework and based on experience in systems simulation, the SR institute contributes to the preliminary design, evaluation, and optimisation of current and future reusable launcher systems.

To this end, the SR institute performs detailed studies on optimal flight trajectories, physical modelling, and "Guidance, Navigation and Control" (GNC) for controllability and stability considerations during all relevant flight phases of launcher systems. Optimal flight trajectories are most relevant because of their influence in the design of reusable launcher systems.

Based on the modelling language Modelica, a framework within the DLR Space Systems Library provides methods and tools for modelling of rigid and flexible launch vehicles considering structural elastic effects, which have a significant impact on the launcher performance.

Aeronautics

Aeronautical research at the SR institute focuses on the design of novel flight control systems and aircraft systems. We aim to reduce the aircraft's weight by actively alleviating structural loads and by improving the (partly) autonomous operation of manned and unmanned aircraft. In order to reduce fuel consumption, the institute also develops, assesses and optimises advanced energy systems for future aircraft.

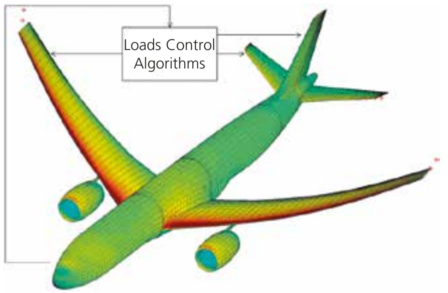
Flight control

The design and optimisation of aircraft control systems has a key impact on improving environmental friendliness, economic viability and safety of future aircraft generations. Automatic flight control systems allow for active stabilisation of the aircraft and for reduction of loads on the structure, and in this way facilitate the design of aerodynamically more efficient aircraft configurations. Modern fault-tolerant and adaptive control methods additionally guarantee full functionality of the control systems even in severe failure cases and thus improve the safety of the aircraft.

Researchers at the SR institute develop novel flight control systems and support the design process with versatile computational design and analysis tools. In flight experiments with DLR's research aircraft, such efficient control algorithms are validated and airport approach trajectories with minimised emissions are demonstrated.

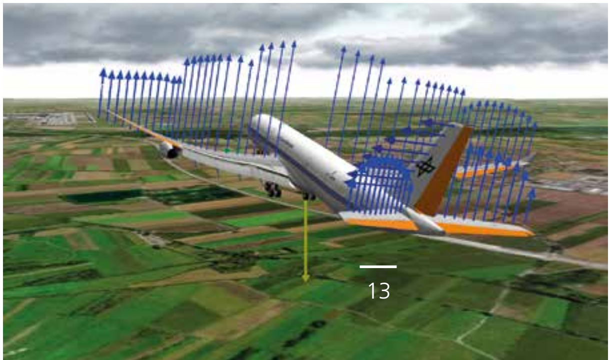
For the automatic simulation of complete flight missions, of e.g. solar high-altitude platforms, the institute develops novel methods for mission planning and trajectory optimisation.

ATTAS Test 1134
Control law experiment SR, 2011



Flight dynamics and structural loads

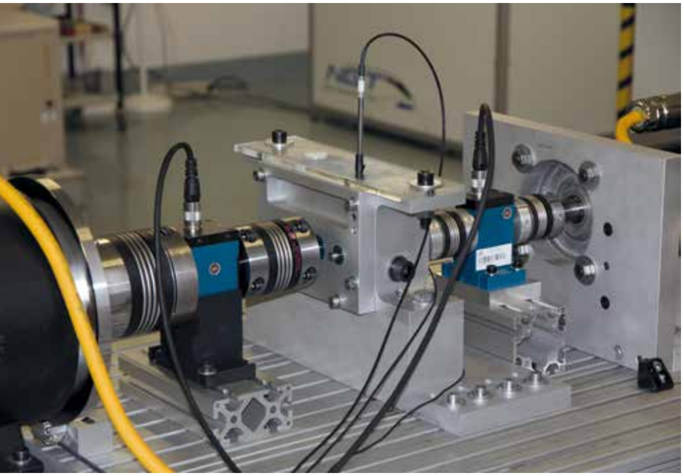
The analysis of flight dynamics and structural loads is a key aspect in the design optimisation for environmentally friendly and highly efficient aircraft configurations as well as for the design of their flight control systems. The institute develops automated processes and tools for multidisciplinary modelling, simulation, and efficient analysis of closed-loop controlled, flexible aircraft. Research focuses on novel analysis methods and on improved accuracy and numerical efficiency of the simulation models, in order to reliably address the complete flight domain and to guarantee short development cycles. Another focus is modelling and analysis of challenging scenarios including complex manoeuvres and atmospheric distortions such as gusts and turbulence. Prominent examples are wake vortices and their influence on following aircraft. Our automated modelling and analysis processes for closed-loop controlled aircraft allow us to directly integrate them in the highly multidisciplinary optimisation of the overall aircraft system.



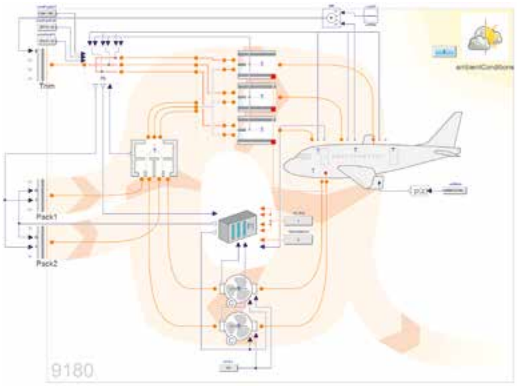
Aircraft energy systems

In today's aircraft, all on-board systems are supplied by hydraulic, pneumatic, or electric energy. For decades, however, there has been a development trend leading towards "More Electric Aircraft". This term refers to architectures, where hydraulically or pneumatically driven on-board systems are replaced by electrically driven systems. The SR institute develops methods and tools for the model-based design, optimisation, assessment, and control of such systems.

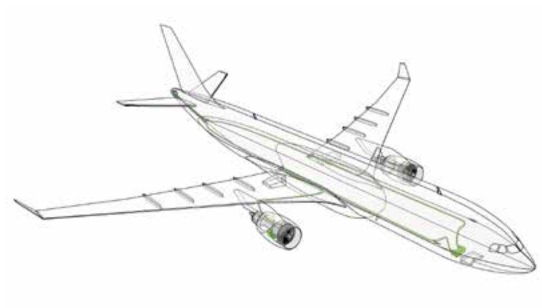
Actuation systems
The use of electro-mechanical and electro-hydraulic actuation systems in flight control calls for very reliable detection of potential faults. To this end, fault-detection algorithms are developed that are based on versatile models of faulty components. These models and algorithms are validated using a corresponding test rig.



Thermal systems
The thermal system of an aircraft comprises the environmental control system, the bleed air system, the ram-air channel as well as the air distribution. With a higher degree of electrification, the cooling of the avionics also takes on increasing importance. For this purpose, in cooperation with Airbus, a set of pre-design tools is being developed and continuously enhanced.



Electrical systems
Given the higher degree of electrification, weight and reliability of the electrical components is of increasing importance. To this end, the SR institute developed tools for modelling and optimisation of electrical architectures as well as for safety and reliability analysis of these systems. Furthermore, model libraries are being created for the detailed design, test, and integration of electrical components.



Assessment of technologies from the perspective of flight dynamics
The assessment of new technologies at aircraft level, especially regarding the quantification of economic and ecological benefits, is of high relevance. The institute develops multi-physical model libraries and methods to get tools for comprehensive gate-to-gate mission simulations. In this way, novel technologies such as an electrified landing gear or a hybrid-electric power train can be assessed and optimised under realistic conditions at an early stage of the design process.

Energy management
Optimal control strategies are of particular importance for high energy efficiency and the sizing of aircraft systems. Hence, energy management algorithms increase efficiency at each operating point by optimally distributing the sources of thermal or electric power. In addition, the energy management enables sizing of system components with realistic load profiles. This leads to a significant reduction of system weight.

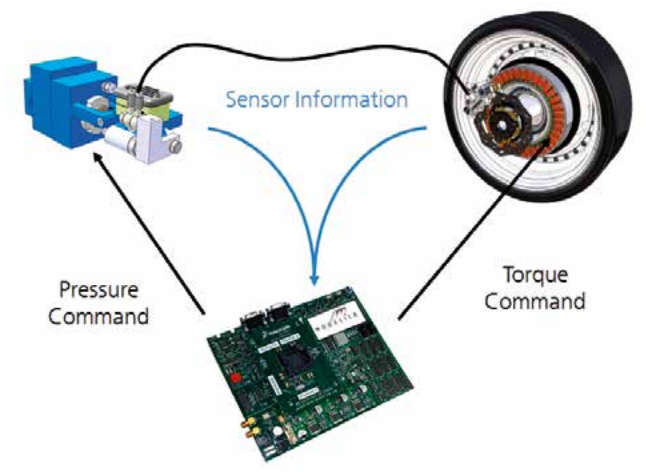
Transport

Safety, comfort, and responsible use of natural resources are in the focus of the work regarding road and railway vehicles. In both, the research topics of energy management, vehicle dynamics and vehicle intelligence are addressed. These activities shall in particular exploit the opportunities offered by electromobility as well as support its establishment as a mainstream technology. The development of modular, mechatronic, and highly integrated chassis and propulsion systems benefits from an integrated approach based on common vehicle concepts. This idea serves as a framework across the DLR for the coordinated development of concepts, methods, and technologies in the Next Generation Car and Next Generation Train projects.

Automotive

Innovative approaches for mechatronic chassis are being developed in the automotive area. The main goal is the simultaneous improvement of energy efficiency, safety, and driving comfort.

Rigid mechanical connections are still common in today's vehicles, in particular within the steering system. These are being replaced to an increasing amount by "X-by-Wire" technologies. As a result, the methods and tools for ensuring functional safety have become highly significant. Model-based development processes and toolchains play a crucial



role for this purpose, as well as for the development of integrated chassis control and vehicle state estimation. Therefore, the technologies for multidisciplinary modelling, simulation, and evaluation form a significant foundation that is being advanced at the SR institute. These technologies enable the investigation of complex interactions between the chassis, the road, and the complete vehicle in the domains of multi-body dynamics, electrical energy flows, and discrete control algorithms.

One research focus is braking control for electric vehicles using electric motors in combination with friction brakes, in order to recuperate the highest possible energy into the batteries while minimising the braking distance. A further focus area concerns strategies for the control of vertical dynamics using highly dynamic semi-active dampers, which are designed to mitigate the effects of the higher unsprung mass introduced by the in-wheel electric motors. Moreover, novel toolchains are developed at the institute, which aim to automatically generate code for close-to-production ECUs from control algorithms synthesised in Modelica.

Railway vehicles

Active control of railway vehicle dynamics offers an enormous and so far unexploited potential for enhancements regarding safety and comfort. It additionally allows for reducing energy consumption, noise emission and wear as well as life cycle costs.

This potential motivates research and development of a mechatronic low-floor running gear with independently rotating wheels, for which an experimental design study is tested and validated at our scale 1:5 roller rig.

These activities contribute to the DLR research project Next Generation Train, which deals with concepts, methods, and technologies for a very high speed train in double deck configuration and lightweight design. The concept is targeted on sustainability and protection of natural resources. These key features impose major challenges only to be met by elaborate dynamical design studies, which intensively utilise simulation and optimisation, and by relying on the application of mechatronic vehicle systems.

Our goal is the feedback control of all running gear functions such as track guidance, primary and secondary suspensions, traction drives, and brakes on the basis of an integrated strategy. In addition, all subsystems of the trainset will be crosslinked in order to gain further synergy effects. Therefore, we are developing appropriate tools to support the analysis, the design, and the implementation of such systems.

Research synergies

In the context of our multidisciplinary research, we are investigating and developing a diverse range of research subjects and systems, which explicitly exploit synergies between the different DLR research areas. In this way, knowledge from the aeronautics, space, transport, and energy sectors is optimally combined and reused for tomorrow's products.

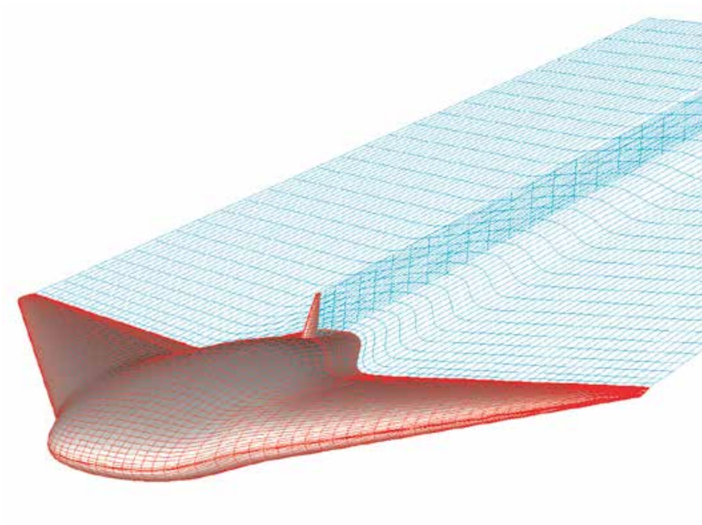
ROboMObil – space and transport

The ROboMObil is DLR's space-robotics driven-by-wire electro-mobile research platform for mechatronic actuators, vehicle dynamics control, human machine interfaces, connected mobility (Car2X) and autonomous driving. Due to its four identical, highly integrated wheel robots, the ROboMObil exhibits an extraordinary manoeuvrability even allowing for driving sideward or rotating on the spot. As both a research platform and a demonstrator, it forms an interdisciplinary topic within the RMC. The SR institute is responsible for project management, conception, and operation of the platform, while the research on the topics of autonomy and human-machine-interface is supported by the RM institute.

Wind energy – aviation and energy

Virtual wind fields, aerodynamics of rotors, flexible bodies, models of gears, and power electronics – all these different domains are required to form a complete model of a modern wind turbine. The Modelica technology is perfectly suited to fit these multi-physical set of demands. Hence, a new modelling library developed by our institute will help to conduct research and development for topics addressing the complete system of a wind turbine.

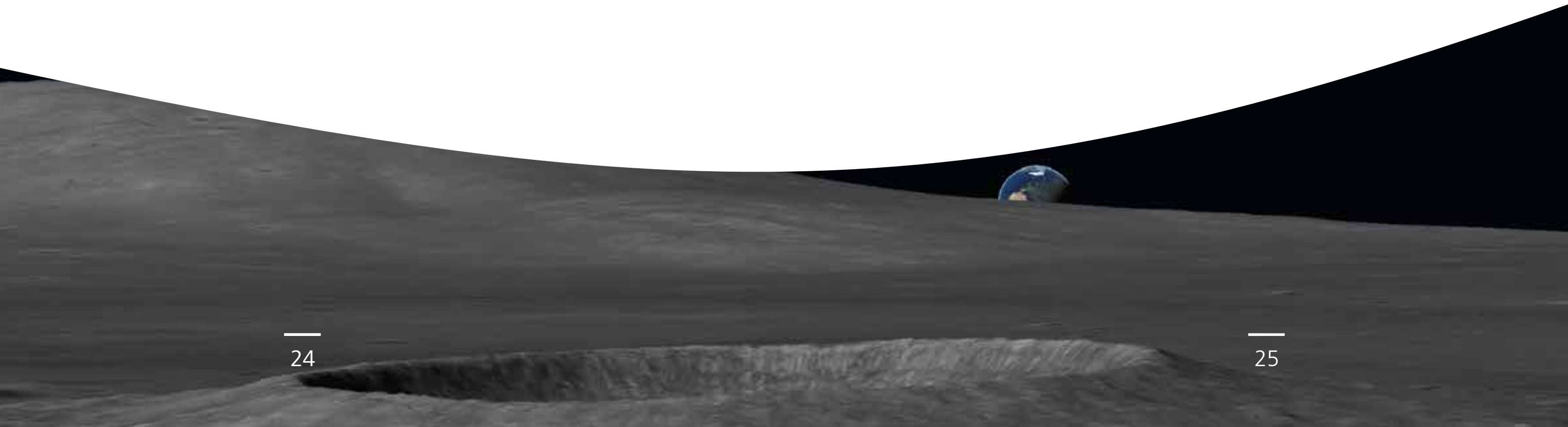
Application examples are the optimal non-linear control of the system and its safe integration into the European energy network. Within the frame of these applications, valuable synergies arise with respect to related problems in aviation. One common research task is, for instance, the use of LIDAR-based wind measurement systems for gust detection and actively controlled gust load reduction.



ROBEX – deep sea meets space

The Helmholtz-Alliance "ROBEX – Robotic Exploration of Extreme Environments" represents the joint effort of space and deep sea researchers to collectively develop new technologies for the exploration of difficult-to-reach areas such as planetary surfaces and the deep sea. Naturally, tests under these conditions are extremely complex. The SR institute utilises synergies with automotive and aircraft research to simulate mobile platforms such as the "Lightweight Rover Unit" (LRU) designed at the RM institute for lunar applications. Detailed models of the suspension and wheel-ground contact make it possible to evaluate new mobility concepts for rovers.

For the maritime application, hydrodynamics calculations contribute significantly to the design of a new deep sea glider. Furthermore, the simulation models facilitate the testing of new navigation and control concepts under realistic conditions, with an interface that allows for transparent switching between the real and simulated systems.



Technology transfer

The methods and technologies developed at the institute are used in tight collaboration with the industry to design and improve new innovative products. Especially the time-proven cooperation with Germany's leading industrial robotics company KUKA allows the integration of SR technologies into market-ready industrial products.

Industrial robots

New areas of application and the steady pressure of competition in the robotics industry demand continuous improvement of industrial robots in terms of speed and accuracy. The Institute of System Dynamics and Control contributes to this improvement by developing advanced model-based control methods. The goal is a significant improvement in the performance of the machines, purely based on new software algorithms. Many algorithms developed during the long-standing cooperation with our industry partner KUKA are today part of commercial KUKA robot controllers. The success of this technology transfer continues until today.

Our research focuses on optimal trajectory planning, compensation of elastic effects by calculating the inverse dynamics, robust and adaptive control methods for position and force control as well as model-based disturbance compensation.

Lightweight production technology

Manufacturing carbon fibre reinforced parts requires a high level of accuracy. If the manufacturing processes are automated by utilising multi-robot production cells, elastic deformations of the robot components and their supporting frame lead to negative effects, including positioning errors. At the Institute of System Dynamics and Control, methods are developed to compensate these elastic effects. This is realised with detailed simulation models, high-precision measurement equipment, and real-time control algorithms, which are implemented and tested at DLR's Center for Lightweight-Production-Technology.

DLR Robotic Motion Simulator

The DLR Robotic Motion Simulator developed at the RMC is a new type of motion simulation platform based on a standard industrial robot. By changing its modular input instruments, it is possible to implement different flight and driving simulations. This requires a dynamic simulation of the vehicle dynamics and a “washout” filter adapted to the robots dynamics. The filter is responsible for the real-time path planning of the system. Equipped with two endless rotating axes, the simulator is able to reproduce inverted flights, barrel rolls, and skidding manoeuvres.

Additionally, the institute maintains a second robot-based flight simulator equipped with an original DA42 cockpit and a 220° visualisation dome. These systems are being used for research in human-machine interfaces, development and testing of vehicle and flight control algorithms, and psychological studies.

Method and tool development

The various research activities of the institute are based on the key technologies modelling, optimisation, and control. The SR institute develops new methods and technologies in these areas and implements them with specialised software tools. Many of these tools are provided to the research community in form of open source or commercial software.

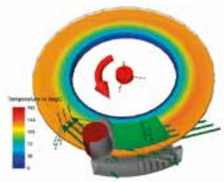
Modelling

Modelica

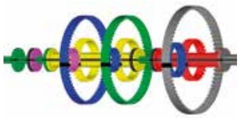
The SR institute has been developing, together with other partners, the modelling language Modelica since 1996. This language is supported by many simulation environments including Dymola, Maplesim, SimulationX and OpenModelica. Modelica is used in the research activities of the institute to describe multi-domain plant models – from architecture models to detailed system models. These models are also used directly in non-linear control systems, usually after simplification and (automatic) inversion.

For this purpose, a multitude of Modelica modelling libraries are developed at SR that are also utilised outside the institute.

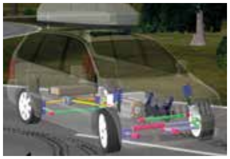
Flight dynamics



Flexible bodies

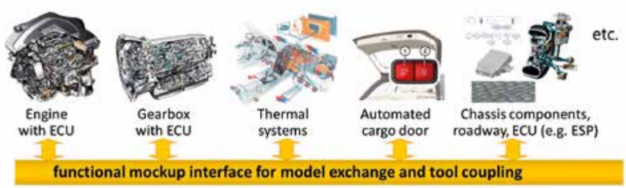


Power train



Visualisation

Functional Mockup Interface
The SR institute and its partners have also been developing the Functional Mockup Interface (FMI) since 2008. FMI is now established as world-wide standard for the exchange of models and is supported by more than 80 software tools. For example, this makes it possible to develop Modelica models in Dymola, export them in FMI format and execute the models directly on a dSPACE rapid prototyping hardware supporting FMI.



courtesy Daimler

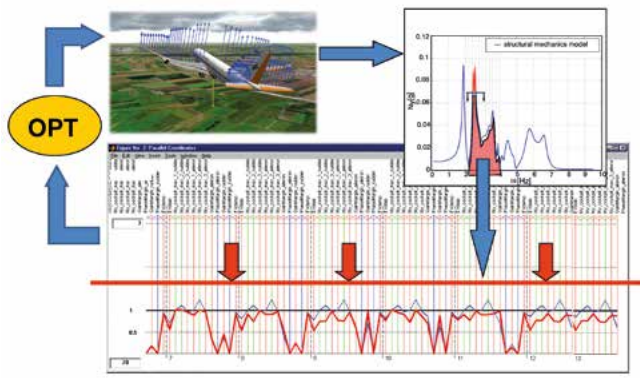
Standardisation
The SR institute leads the international Modelica Association that develops standards such as Modelica and FMI, as well as supporting open source software such as the FMI Compliance Checker.

Optimisation

The quality assessment of complex systems is carried out with different criteria, such as performance behaviour, energy consumption, or reliability. With a model-based design optimisation, the different objectives can be included directly into the system design at an early stage. Optimisation strategies can then be applied to find the best possible compromise solutions satisfying the design demands.

Not only design but also system validation can be formulated as an optimisation task by formulating the design requirements as criteria. By means of optimisation strategies, it is then possible to find the worst case with respect to all admissible parameter variations. The system is verified, if all criteria values remain within a specified range expressing the design demands.

The optimisation tools developed in the SR institute are universally applicable and integrated in general computer-aided environments for design, modelling and simulation, such as Matlab or Modelica. Real-time variants of these methods are applied directly for online optimal control applications.

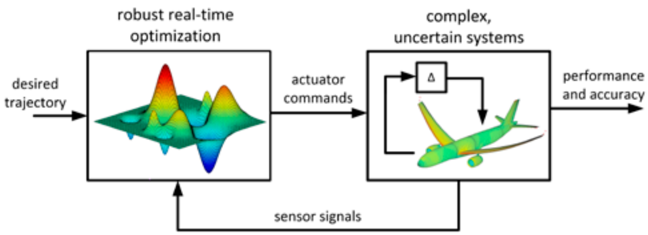


Control

One focus of the SR institute is the development and implementation of modern model-based control methods. These approaches use a mathematical model of the controlled system in order to explicitly predict and improve its behaviour.

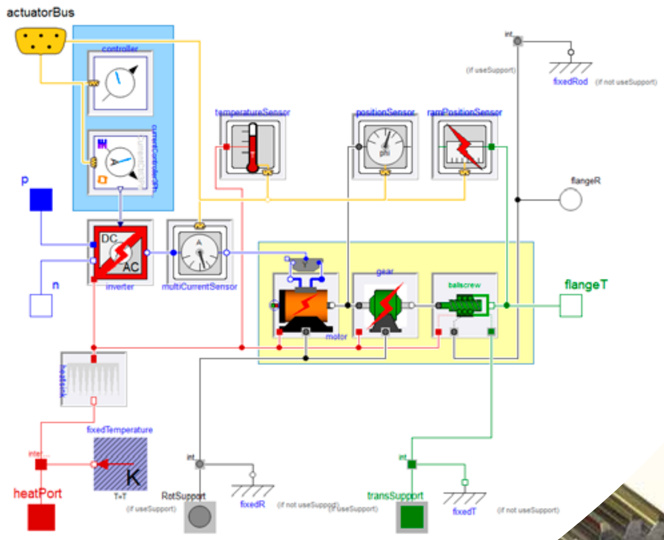
Using inverse dynamical models in control algorithms allows, for example, to compensate undesired elastic effects. By using robust control techniques it is additionally possible to directly account for the unmodelled uncertainty of the systems. Optimisation-based methods make it possible to further manage overactuated systems and to follow trajectories with highest accuracy. Adaptive and fault-tolerant control methods react flexibly to the system's state and reconfigure the system in case of a failure.

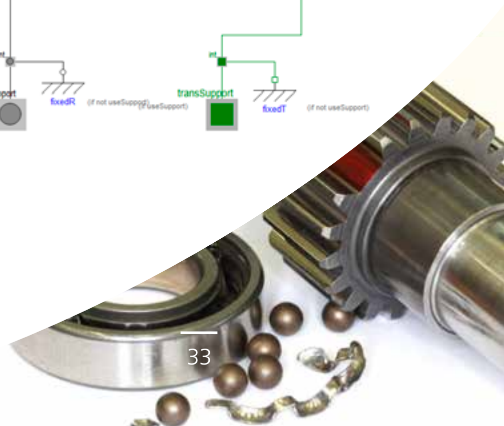
By consistently applying modern control methods, more lightweight systems can be designed and their efficiency can be improved considerably. The tight integration of modelling, optimisation, and control additionally allows the holistic design of the controlled system with regard to its system dynamics within the framework of a multidisciplinary design optimisation.



Fault diagnosis and fault-tolerant control
Development of robust fault diagnosis methods is a prerequisite for the design of advanced fault-tolerant control laws with event-driven reconfiguration capabilities. Main applications are safety, reliability, and performance in automatisation of ground and air vehicles.

The competences of the SR institute in the field of design of robust fault diagnosis systems as well as design of fault-tolerant control laws have been successfully applied in several EU projects and in close cooperation with industry (e.g. Airbus). Efficient methods and tools for design and implementation of model and signal-based fault diagnosis systems have been developed at the institute.





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DLR at a glance

DLR is the national aeronautics and space research center of the Federal Republic of Germany. Its extensive research and development work in aeronautics, space, energy, transport and security is integrated into national and international cooperative ventures. In addition to its own research, as Germany's space agency, DLR has been given responsibility by the federal government for the planning and implementation of the German space programme. DLR is also the umbrella organisation for the nation's largest project management agency.

DLR has approximately 8000 employees at 16 locations in Germany: Cologne (headquarters), Augsburg, Berlin, Bonn, Braunschweig, Bremen, Goettingen, Hamburg, Juelich, Lampoldshausen, Neustrelitz, Oberpfaffenhofen, Stade, Stuttgart, Trauen, and Weilheim. DLR also has offices in Brussels, Paris, Tokyo and Washington D.C.

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