DLR

Robotics and Mechatronics Center RMC

Knowledge for Tomorrow

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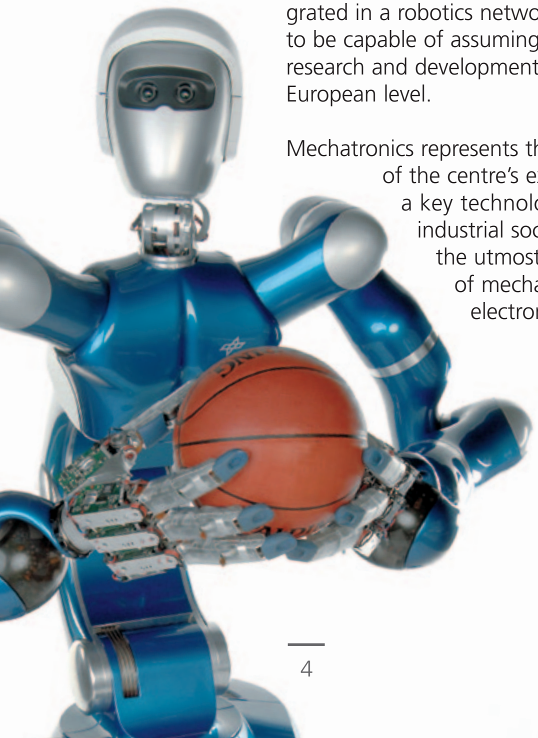
Robotics and Mechatronics Center RMC

Society and industry are not imaginable without robotics. Faster and more reliable robots are not only used in industrial production to maintain international competitiveness. Robots with safe and easy handling are also required in fields where humans are to be protected against special hazardous situations, like, for example, in spaceflight, underwater, or rescue missions. To boost these ideas, the Robotics and Mechatronics Center RMC was founded.

For decades, the DLR site in Oberpfaffenhofen has been the German address for applied robotics research with the highest international reputation. Since 2010, the development of the Institute of Robotics and Mechatronics into this worldwide unique centre has been funded by the Federal Ministry of Economics and Technology (BMWi) in coordination with the Bavarian Ministry for Economic Affairs, Infrastructure, Transport and Technology. Through national and international cooperations, the RMC is integrated in a robotics network. The aim is to be capable of assuming superordinate research and development tasks on a European level.

Mechatronics represents the wide base of the centre’s expertise. As a key technology of our industrial society, it means the utmost integration of mechanics/optics, electronics, and



information technology (software) to create intelligent mechanisms up to autonomous robots. Accordingly, the work of the RMC focuses on interdisciplinary conceptual design and simulations close to reality as well as the implementation of complex mechatronic systems and man-machine interfaces.

The RMC is characterised by its interdisciplinary core competence. This applies, for example, to the close interlocking of space robotics with applications also used on Earth – in industrial robotics, service robotics, automotive engineering, and surgery. The resulting lightweight robotics and the multi-fingered hands have leveraged DLR’s new soft robotics concepts that are important for cooperation with humans. Thus the two-armed JUSTIN on wheels became the flagship of DLR robotics.

The RMC consists of the following departments: Intelligent Robotic Assistive Systems (IRAS) and System Dynamics and Control (SR) at the site in Oberpfaffenhofen, and Optical Information Systems (OS) at the site in Berlin-Adlershof.

RMC Departments

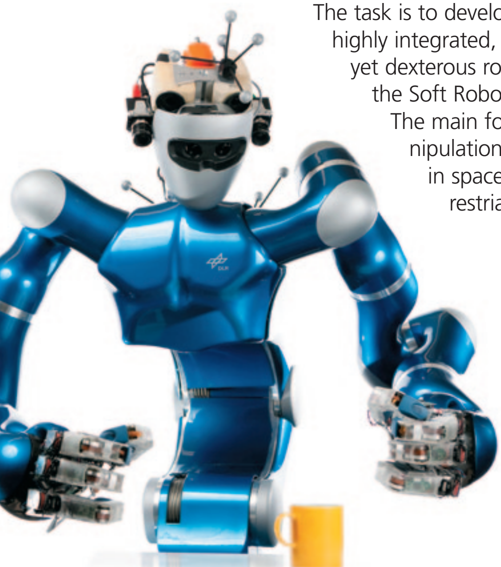
Intelligent Robotic Assistive Systems

The long-term goal of this department is based on the idea of relieving man from inhuman and dangerous tasks and of enabling access to hitherto non-reachable places. Three visionary space scenarios are the starting point for research: the development of orbital service satellites capable of performing maintenance work in space autonomously or telecontrolled, the robonaut as robotic assistant of astronauts for establishing infrastructures in space as well as autonomously flying, driving, and walking robot systems for the exploration of far-off planets.

In interdisciplinary teams, robot systems are developed that constantly define the international state-of-the-art for robots. The foci of integration have considerably shifted from mechanics and control technology to the perception by cameras, force and distance sensors as well as intelligent and autonomous motion and task planning. The DLR light-weight robot and the minimally invasive surgery system MIRO show the great technology transfer potential of these developments.

Mechatronic components and systems

The task is to develop and control highly integrated, high-performance, yet dexterous robots in terms of the Soft Robotics philosophy. The main focus lies on manipulation and locomotion in space flight and terrestrial applications.



The medium and long-term goal is to render operations and exploration in space cost-efficient and to transfer the evolving robot technologies to terrestrial applications.

Perception and cognition
Perception and cognition, important fields in robotics, involve the development of a holistic perception of the environment using the two dominating senses tactility and vision. For teleoperated assistive systems and autonomous robot systems, perception and correct assessment of the sensor signals are elementary components due to the fact that they enable reactive behaviour, attention-based control, and interpretation of situations.

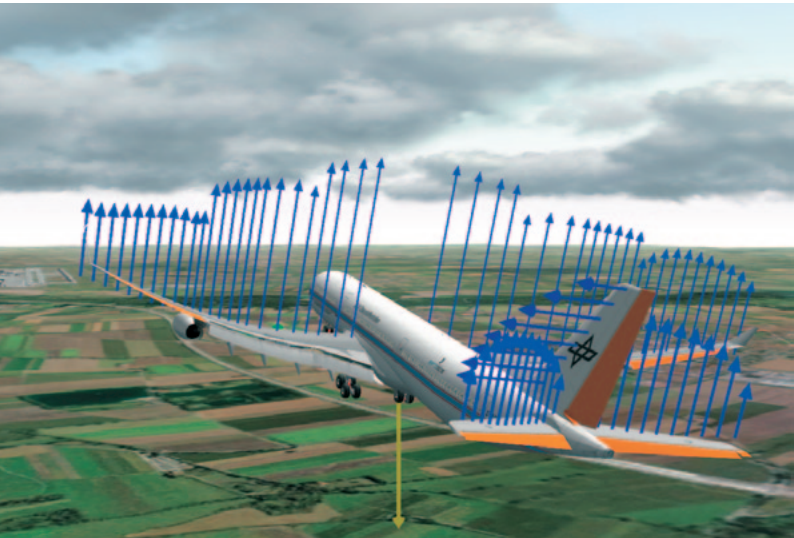
Autonomy and teleoperation
Target-oriented action is an essential feature of an intelligent assistive robot: in the fields of autonomy and teleoperation, there are activities regarding planning and execution of motions on partly multi-armed robots with many degrees of freedom. The tasks range from execution and monitoring of simple motion primitives to the autonomous planning of complex manipulation tasks with robotic hands and arms. A further field of research is the architecture of robot control units for controlling robot motions on flexible, high-performance and distributed calculation platforms under hard real-time conditions.

System Dynamics and Control Technology

The focus of expertise in the fields of system dynamics and control technology lies on requirement-driven, system-dynamic holistic design, optimal and robust control of complex safety-critical systems in spaceflight systems, aircraft, road, rail, and planetary vehicles as well as industrial robots.

To this end, progressive methods and tools for cross-domain physical modelling and identification of systems dynamics, real-time simulation, synthesis and analysis of robust, reliable and fault-tolerant control devices as well as multi-target design and trajectory optimisation are developed and connected to consistent tool chains. Methods and tools represent an independent field of research that is subjected to further cross-application development.

Aerospace system dynamics
Within the framework of the RMC interdisciplinary topics of planetary exploration and on-orbit servicing, essential contributions are made regarding simulation, design optimisation, verification, and control of spaceflight systems



as well as of individual subsystems. Primary tasks are wheel/ground interaction with planetary rovers, mobility of landers on asteroids, and contact dynamics in satellite docking manoeuvres.

Aviation system dynamics
Here, the focus lies on the design of novel flight control and aircraft on-board systems. Novel flight control systems serve for weight reduction by actively reducing the aircraft's structural loads and enhancing the (partly) autonomous operation of manned and unmanned aircraft. To reduce fuel consumption, new electrical board system architectures and components are developed and optimised.

Vehicle system dynamics
In this field, innovative mechatronic undercarriage concepts, integrated driving dynamics control systems and energy management systems are developed both for road and rail vehicles, which serve for reduction of the energy consumption and enhancing comfort. A special focus is placed on electromobility.

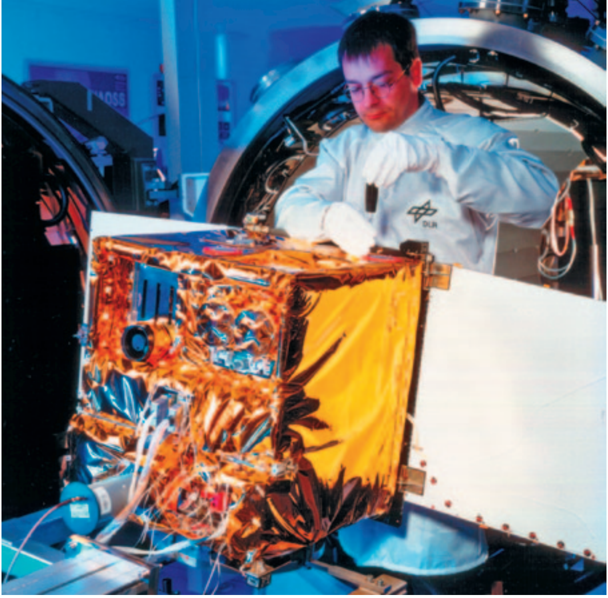
Optical Information Systems

In the field of optical information systems, intelligent sensors and data processing software are being developed to solve industrial, scientific, and official duties. In the focus of these activities are depictive optical systems for use on aircraft and satellites that can be transferred to commercial products in the course of the technology transfer.

Strategic objectives are the development of geometrical and/or spectral high-resolution sensor systems in the visible and infrared range of electromagnetic radiation as well as real-time processing of image data to obtain user-relevant information. Prerequisites for this purpose are autonomous performance of the system and the development of payload platforms.

It is of special importance to pursue systemic approaches that take all optical, mechanical, electronical, and IT-based aspects under consideration during the development of a sensor system. The extreme requirements regarding performance and reliability can only be guaranteed by using high-tech, continuous validation and consistent quality management.

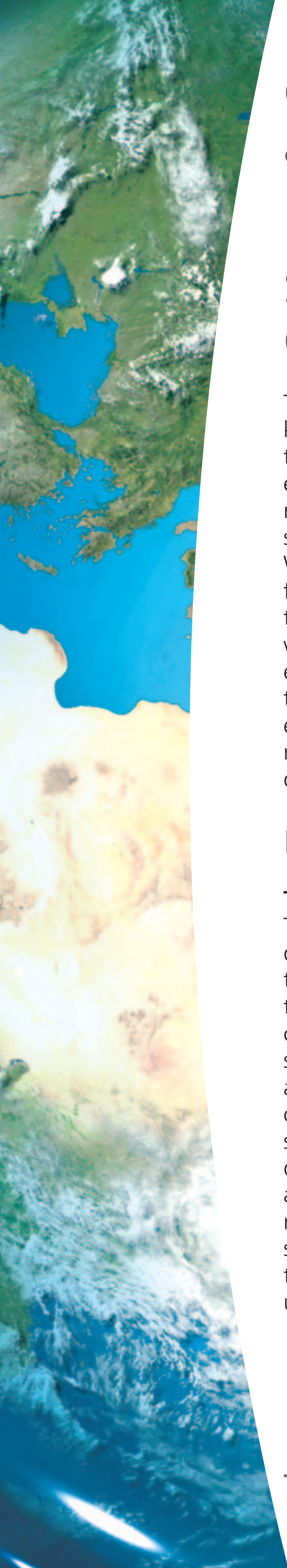
For core products, the complete development cycle is depicted: problem analysis, definition of scientific-technical requirements, modelling and simulation, system design and optimisation, design and development, test and verification as well as data evaluation and information extraction.



Optical sensors and electronics
This field works on the development of electronic system solutions for imaging spectrometers and camera systems. They are used for measurement and assessment of physical parameters in the aerospace industry, in transport, and in industry.

Information processing in optical systems
This field serves for boosting research and development work for creating increasingly intelligent, i.e. autonomously deciding, real-time capable optical information systems. The user is enabled to derive high-quality data products from these information systems.

Sensor concepts and application
The focus is on the definition and development of new camera sensors, verification and validation of aerial image and satellite sensors, processing of the resulting data products as well as the development of corresponding applications.



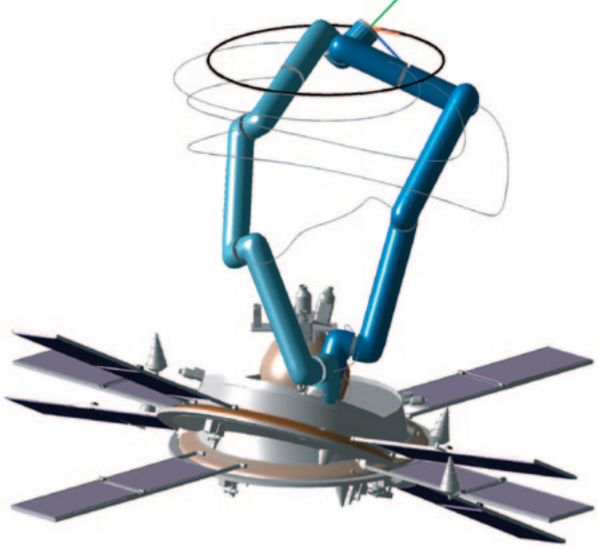
Cross-domain Topics at the RMC

Space Robotics: On-Orbit Servicing

To transport humans into space, to keep them alive there, and to bring them safely back to Earth requires high effort and involves a high risk. Here, robotics that can be well adapted to space conditions can play a leading role. With the help of robots and high-performance teleoperation and telepresence technologies, even more difficult repair work in the near-Earth orbit can be executed from the ground. In the past, the RMC has gained the highest level of experience in this field through its technology missions and is currently further developing this expertise.

Key technologies

Telemanipulation
Telemanipulation of robots in space requires coping with long signal propagation delays (> 1 second). Robust operation can only be achieved by separated control loops for ground control and space robot. For this purpose, concepts are being developed that allow the operator on the ground to work in a simulated environment, generate a sequence of commands from his action and send these commands to the real robot in space. Based on the current sensor information, the robot adapts the commands to the local situation upon execution of the task.



Telepresence and force feedback
For signal propagation delays of less than 1 second, the space robot can be coupled with the operator on the ground in a multimodal way. To this end, special control methods are developed enabling a stable interaction with the distant environment by force feedback. Thus the operator can have a transparent view on the distant environment and act in it as if he were on site: the extended arm of man in space.

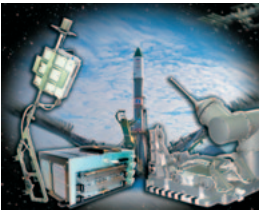
Dynamic motion planning and execution
Maintenance and repair work on satellites require safe catching and stabilising of the wrecked satellite. However, a service robot on a satellite performs dynamic forces in motion that are not simply compensated by a foundation like on Earth. For optimised real-time planning of such approach and stabilisation motions, the RMC is developing and testing methods and prepares them for the mission operation.

Missions

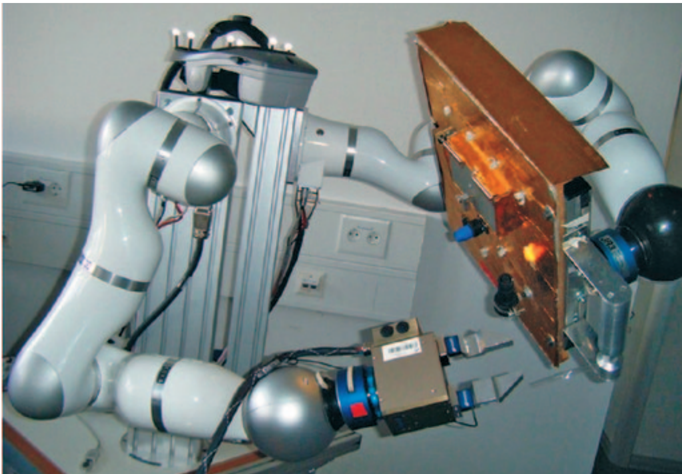
D2 Mission – ROTEX (1993)
The first robot being teleoperated from Earth worldwide: through the integration of distance and force sensors the control loop of the robot could be closed. The user on Earth gives motion commands and controls them in a simulated environment. On site the commands are autonomously adapted to the situation and the simulation is updated. This way, signal propagation delays of more than six seconds could be overcome.

GETEX (1999)
The system having been developed for ROTEX was used for telecontrol of the Japanese robot freely floating in space on the ETS VII satellite. This could be used to examine the interaction of a robot mass performing controlled motion on the position control of the satellite and to determine the satellite dynamics.

ROKVISS (2004 – 2010)
With ROKVISS (Robot Component Verification on the International Space Station ISS), light-weight robotics technology has been successfully tested for six years on the outer shell of the ISS under real conditions. For the first time worldwide, the two joints were operated from Earth through a haptic-visual telepresence channel which means the camera and force data from the robot's sensors were transmitted with minimal delay to the operator on the ground through a force-reflecting joystick and a stereo display.



DEOS (in process of planning)
The German Orbital Servicing Mission will examine how service tasks on a satellite in near-Earth orbit can be performed with the help of a robot arm. This robot arm is being developed at the RMC based on the experience gained with ROKVISS. Technologies of approach, grasping and stabilising and finally also targeted crash (de-orbiting) will be examined and tested. Extensive preparation work for control and dynamic path planning of such systems have already been successfully performed.

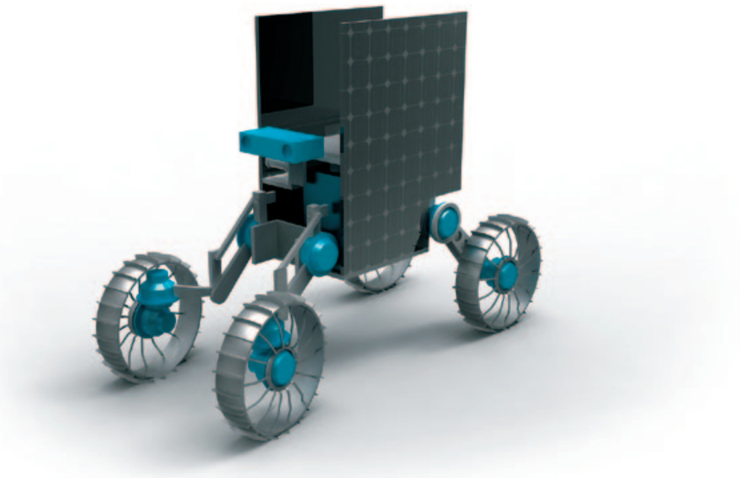


Space Robotics: Exploration

To this day, more distant places like the Moon or Mars are hardly accessible for man and involve high risks to be taken. Previous findings regarding the composition of planets and asteroids are primarily based on non-contact sensorics (optics, spectral analysis). Space robotics can show new ways of gaining cognition in this field through provision of mobility, for example, by rovers and corresponding manipulation arms as carriers for scientific analysis equipment. For this purpose, the robot systems have to work autonomously to a large extent and must be able to react on self-endangering conditions of the environment, like, for example, fluctuations in temperature, state of charge, and special conditions of the soil.

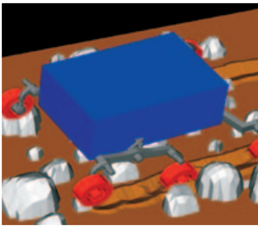
Key technologies

Optimisation of rovers and crawlers
Planning and realisation of space vehicles poses a great challenge due to the special requirements regarding weight, power supply, and desired mobility. Depending on payload and environmental conditions specially adapted concepts have to be developed. The different designs are assessed and optimised by



means of models, like, for example, expected fluctuations in temperature, radiant flux density, day and night phases, and soil conditions in the planned target area.

Terramechanics and surface assessment



The contact to the surface of moons and planets is of decisive importance for the mobility of rovers and crawlers, where the condition of the soil influences the respective locomotion options. To keep the risk for the missions as low as possible, terramechanic contact models are developed, with the help of which the spacecraft concepts are checked. In laboratory tests the simulations are balanced with the driving qualities of real rover models.

Exploration strategies and cooperating robot systems

Redundancy – the multiple availability of functionally identical components – represents an essential approach to minimise risks in spaceflight. Yet this refers mainly to the components of a spaceflight system. For robotic exploration of celestial bodies, however, redundancy could mean several exploration systems that cooperate in exploring the environment. To this end, autonomous cooperation and communication strategies are developed and tested in terrains close to reality.

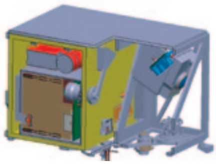
Missions

ExoMars
For the ESA mission ExoMars in 2018, simulations have been conducted regarding the driving qualities of the planned rover on the Martian soil. By means of a vehicle remake, these simulations have been verified in intensive test campaigns in a facility with soils resembling that on Mars.

GLX-Prize (in process of planning)
The goal of the Google Lunar X Prize is to transport a vehicle to the Moon and to send HD video images of a 500-metre route to Earth. Besides other DLR institutes, the RMC supports the team of the Part-Time Scientists. A first prototype, using the propulsion technology

and autonomous navigation developed at the RMC, has emerged from this co-operation.

MASCOT (in process of planning)



For the planned Japanese Hayabusa-2 mission to the asteroid 1999JU3, the mobility system is being developed at the RMC. Gravity on the asteroid is very low, this being the reason for using a mobility concept in the form of an eccentrically attached mass. This mass can be accelerated in a targeted manner and thus imposes momentums on the scientific payload box weighing approximately 10 kilogrammes. This way, for example, the box can be turned over. First tests in parabolic flights show the successful function of this principle.

Terrestrial Assistive Robotics

Many requirements in spaceflight, like, for example, minimal weight, low power consumption, and absolute reliability also apply to robot systems on our Earth. With this proviso, the RMC also develops systems for production and household environments. In this field, the torque control in robot joints is a core technology. It allows for the first time the realisation of programmable and softly reacting arms – features that are indispensable for the work of a robot assistant in human environment. The consistent application of this technology has coined the term Soft Robotics, the compliant and safe behaviour of a robot, and thus also leveraged the light-weight robot (LWR) licensed by the robot manufacturer KUKA.

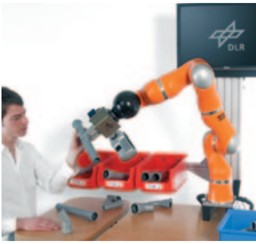
Assistive systems

DLR light-weight robot (LWR)
The LWR is torque-controlled in the third generation. Contrary to the industrial robot it has seven degrees of freedom like the human arm. With a weight of approximately 13 kilogrammes and a power consumption below 150 watts in idle state it is well suited for mobile use in human environments. The arm, which has been awarded a prize several times, is considered to be the most progressive one in terms of technology.

DLR hand
Artificial robot hands as flexible grippers: the first DLR hand of 1998 was already considered the most complex of all robot hands hitherto built. Its second

generation enabled the performance of power and fingertip grips. It had been the paragon for the commercial 4 and 5-fingered hands developed in cooperation with the Harbin Institute of Technology in China.

Rollin‘ Justin
Rollin’ Justin with its two soft-controlled LWR arms and multi-fingered hands is an ideal experiment platform for developing robust control strategies and intelligent action planners for bimanual manipulation.



Robotic CoWorker
One field of application of the LWR is flexible manufacturing in industrial production environments: the robot must cooperate with humans without security fence and it must be possible to program it intuitively and interactively for its tasks. To this end, new concepts have been developed in secure human-robot interaction and interactive robot programming.

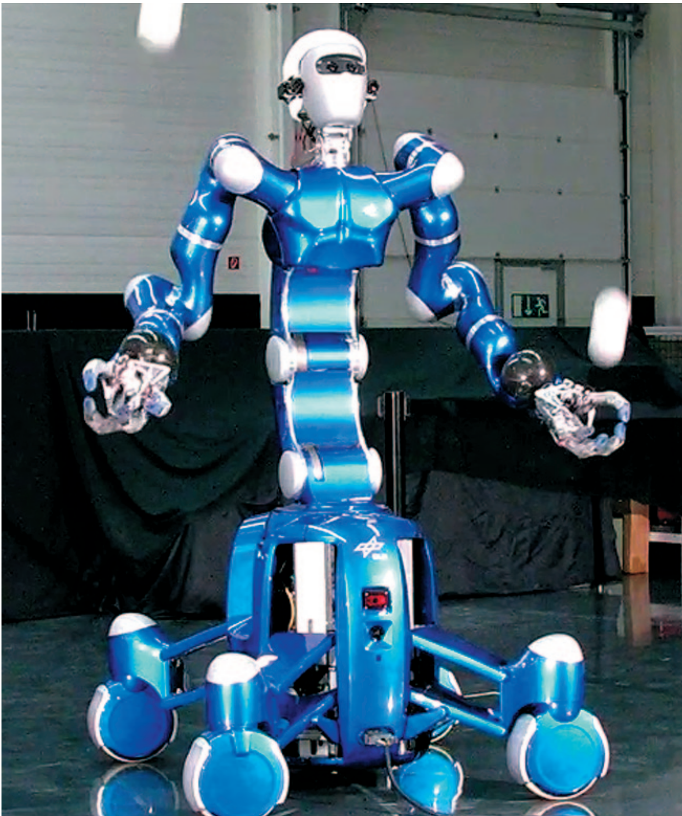
DLR BiPed
Legged robots are particularly favourable in environments with stairs or doorsteps: based on the LWR technology, a walking machine with compliantly controlled legs has been developed, which enables detailed studies of torque-based control methods. The extension of the system by an upper body allows examining the whole-body dynamics with several physical contacts distributed over the body.

DLR hand-arm system
The integrated hand-arm system – a five-fingered hand and an arm with 26 degrees of freedom in total – comes close to human performance. The basic idea is to accept unwanted collisions with the environment and to enhance the dynamics of the system by storing energy in springs. This concept requires highest mechatronic integration, highest power density as well as a control that moves the robot precisely and safely.

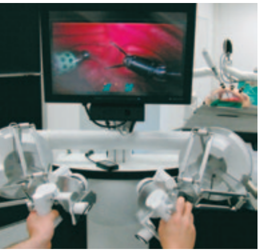
Fields of application

Humans and robots
Robot systems of the future will act in closer contact with humans than they do now, however, the safety of the humans has to be ensured at any time. With robot crash tests potential human injuries are analysed to develop a high-performance robot that is as safe as possible. Sensitive interaction capabilities and the execution of flexible, dynamic motion patterns enable an intuitive and secure coexistence with humans and a considerably more flexible and simpler robot programming.

Learning and planning
Here, flexibility is a special challenge: the basic skills of the systems have to be adapted to the respective conditions. An important issue is the connection of perception and motion planning. The goal is to research on learning as a basic principle of perception, modelling, and action for autonomous systems. Quick learning, planning, and adaptation of tasks and motions through knowledge about its own capabilities as well as intuitive programming of complex actions and interactions shall enable the robot to solve numerous problems and to adapt to new situations.



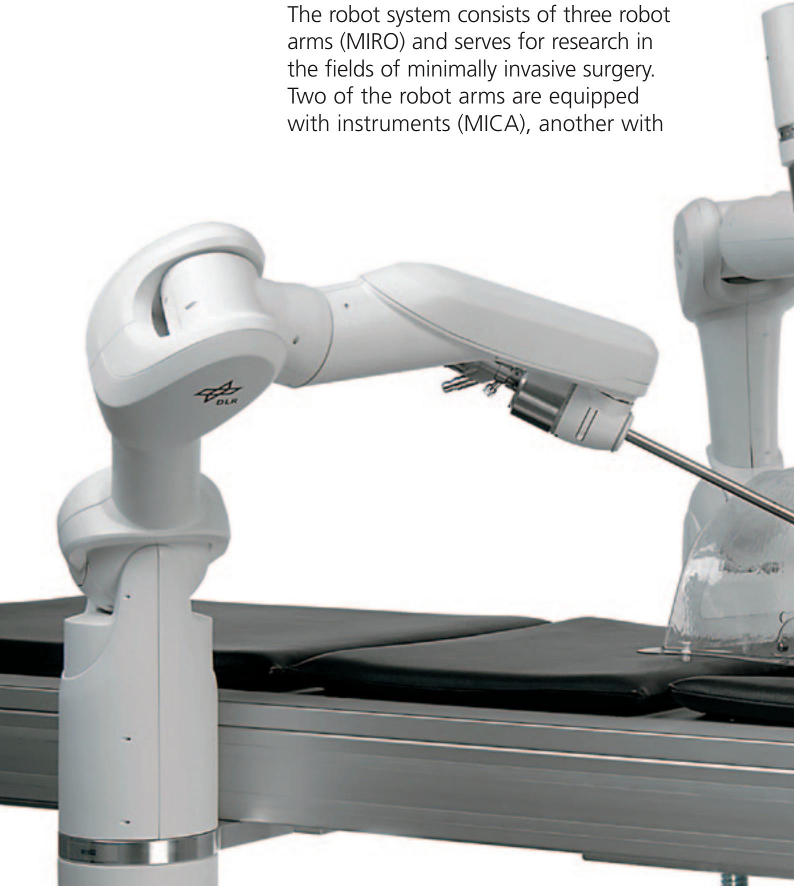
Medical Assistance Systems



In the cross-domain topic of Medical Assistance Systems, findings from space and service robotics are examined regarding medical applications. Core technologies like efficient drives, sensorics, telerobotics, and planning systems are relevant both to space applications and medical systems. These technologies are further developed within the two main topics: medical robotics and active implants.

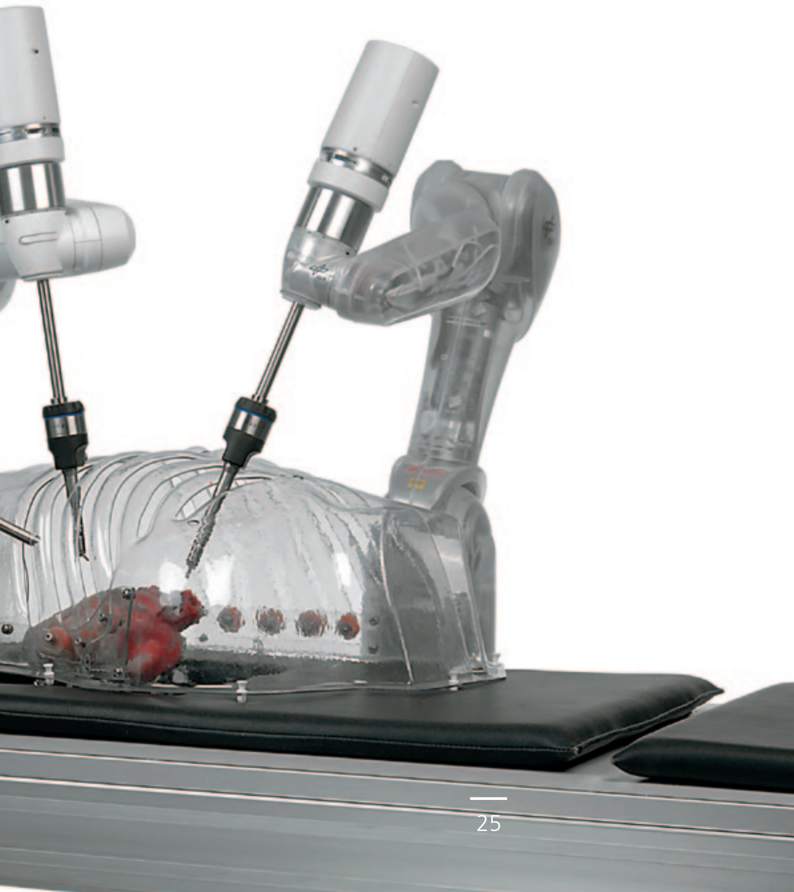
MiroSurge

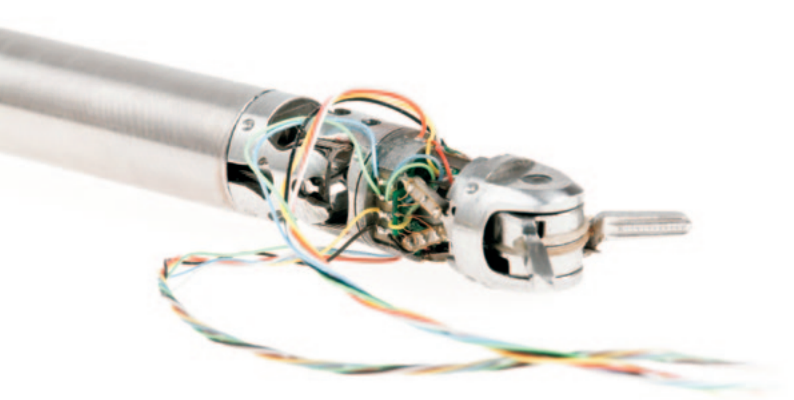
The robot system consists of three robot arms (MIRO) and serves for research in the fields of minimally invasive surgery. Two of the robot arms are equipped with instruments (MICA), another with



a stereo HD endoscopic camera. During the surgery, the surgeon controls the robot from an input panel that enables, besides autostereoscopic video, also a bimanual High Fidelity Force Feedback (1 kilohertz).

MIRO
The light-weight robot MIRO has been specially designed for a variety of surgical tasks. Its low weight and compact dimensions allow for its use also in confined space in the operating theatre. Thanks to the soft robotics properties, the arm can be gently moved through the input panel and also at any time by direct intervention of the surgery staff.



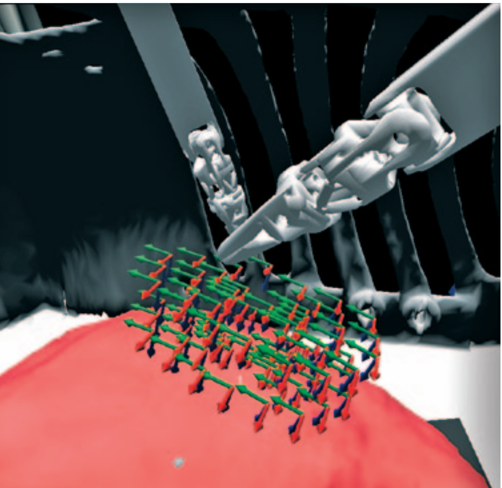


MICA

The instrument extends the robot arm MIRO by three joints in the patient's body. It consists of a universal drive unit with an interface for exchangeable tools built with shaft, wrist, and end effector (gripper, needle holder, and scissors). The additional degrees of freedom directly at the tool extend the well accessible working area of the surgeon considerably. The current configuration also includes a high-resolution force-momentum sensor for sensitive feedback to the physician.

Surgery planning

The flexible fields of application for MiroSurge pose new challenges to the surgery staff. To establish an optimal configuration of the robots on site, the RMC develops interactive planning systems, the operation of which does not require special robotics knowledge.



Based on patient-specific data (CT, MRT) and the planned surgery, the system generates optimised proposals for robot positions and puncture points for instruments that are projected on the patient by means of laser pointers.

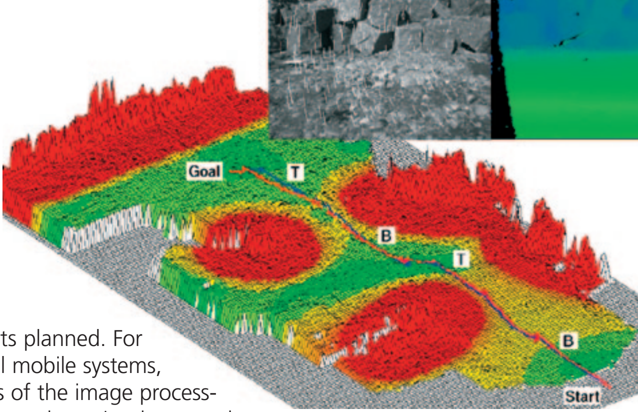
DLR cardiac support system

At present, the artificial heart developed at the RMC using know-how from space is being realised as a product by DUALIS MedTech GmbH. It can be completely implanted with power supply from outside. For this purpose, the RMC has developed a wireless power and data transmission. It is capable of transmitting sensible data from the close range of the patient with high bandwidth in a secured frequency band.

Mobility and Exploration

For exploration in rescue and disaster scenarios and for investigation of celestial bodies mobile systems are developed that move by driving, crawling, and flying. These types of locomotion have different properties: wheels allow for energy-saving load transport, legs are more suitable for difficult terrain. In teamwork the different advantages of the system can be combined. Several robots of the same kind can achieve the redundancy required in space and work faster in parallel operation. The prerequisite for their use is autonomous self-localisation and motion.

Stereo camera based autonomous navigation
For modelling and assessment of unknown terrain, the Semi Global Matching procedure is used that has been developed at the RMC. From stereo camera data a range image is calculated and the proper motion of the system is determined by evaluation of consecutive images. With these data, a 3D topographic map is created, the trafficability assessed and the next way-



points planned. For small mobile systems, parts of the image processing have been implemented directly in the logic of a chip (FPGA). Cooperation partner Daimler Benz also uses this technology for its advanced driver assistance systems.

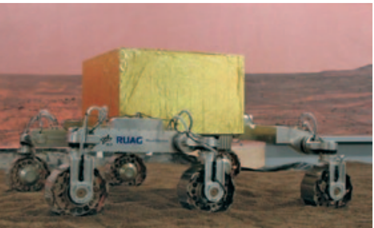
Flying robots

Multicopters equipped with cameras enable a quick overview of an operational area, from which helpers in disaster operation can profit. For this purpose, the flying robot must be capable of determining its location and position also independent from external reference systems, like, for, example, GPS, and autonomously avoiding collisions with buildings or trees. All of these functions and the necessary sensors are directly integrated in the flight systems in a weight-optimised manner.

Robomobil
The electromobile ROMO is designed as robotic vehicle with wheel hub motor and wheel-steering actuators. The extended steering area of all four wheels makes it extremely manoeuvrable and particularly suited for urban environments. It serves for checking driving dynamics control and reliability and fault tolerance concepts. Stereo camera systems enable real-time detection of the vehicle environment and render (partly) autonomous driving possible.

Road-Rail
Intelligent rail vehicles of the future will be operated without driver and networked with a traffic management system in order to optimise operational procedures and to reduce wear and fuel consumption. The RMC examines innovative driving dynamics control concepts with active track guiding on a dynamometer.

Mars rover testbed
Planetary rovers must drive across rough terrain that is hardly known before. Besides optimised mechanics also wheel control can contribute to robust mobility. The replica of the ExoMars rover in the Mars testbed serves for examining sinking depths, torque transmission to the ground, and anti-wheelspin control. Moreover, computer simulations on interaction between the wheels and the hard, or soft, sandlike planet surface are verified.



Flight Robotics and Control

Similar to vehicles, electric drives and electronically controllable systems are more and more used in aviation. Many of the methods used in robotics can be applied. In this field, the RMC pursues the following foci: design and simulation of the entire aircraft's system dynamics and flight control systems, airborne manipulation by means of robot arms and application of sensors and planning systems from robotics to autonomous small aircraft, like, for example, the octocopter.

Solar high-altitude platform ELHASPA
ELHASPA is a solar-driven, extremely light-weight flight platform with a wingspan of 23 metres and a take-off weight of 100 kilogrammes that will be autonomously flying at high altitudes for long periods of time. In the long run, such solar high-altitude platforms could take over application fields of satellites. With the help of this test aircraft, questions on aeroelastics, flight dynamics, and energy management for solar aircraft can be examined.

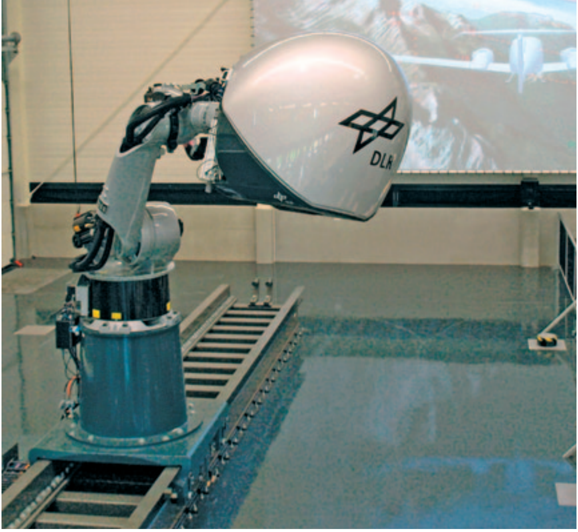
Airborne manipulation
Analogous to the On-Orbit Servicing concepts, where a robot arm is mounted onto a satellite to execute repair work, the RMC intends to use the same concept for helicopters. Similar to satellites, forces act on the aircraft due to arm motions and the contact during gripping that have to be balanced by flight control. To this end, closely connected control loops of robot arm and helicopter are required.

System dynamics/flight control

The design and optimisation of aircraft system dynamics plays a key role in enhancing environmental friendliness, economic efficiency, and safety of future aircraft generations.

Automatic flight control systems enable active stabilisation and reduction of the structural loads of the entire aircraft. So they allow an aerodynamically much more efficient aircraft configuration with considerably lighter structures. Intelligent flight control functions assist the pilot in everyday tasks and emergencies and thus contribute significantly to the security of the entire aircraft.

The RMC gives support in all phases of the development process of future flight control and aircraft on-board systems by a range of computer-based design and analysis tools as consistent as possible. To this end, multi-discipline modelling and simulation plays a key role. In the field of on-board systems, this enables design and optimisation of entire system architectures as regards performance, weight, and reliability. Furthermore, an



energy and thermal management allocating loads, categorising and, in case of fault conditions, reconfiguring energy sources and sinks based on storage effects, can be applied in this context.

DLR Robot Motion Simulator

The DLR Robot Motion Simulator is a novel motion platform that is based on a standard industrial robot. It enables the realisation of any vehicle, aircraft, or helicopter configuration by relatively simple exchange of the instrument module. The prerequisites are a simulation of the vehicle or flight dynamics and a wash-out filter adapted to the robot that undertakes the online path planning. At present, a level-D certified flight simulator for simulating a Diamond DA-42 for pilot training is being built in cooperation with Diamond Aircraft, Diamond Simulation, KUKA, and Grenzebach.

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DLR at a glance

DLR is Germany's national research centre for aeronautics and space. Its extensive research and development work in Aeronautics, Space, Energy, Transport and Security is integrated into national and international cooperative ventures. As Germany's space agency, DLR has been given responsibility for the forward planning and the implementation of the German space programme by the German federal government as well as for the international representation of German interests. Furthermore, Germany's largest project management agency is also part of DLR.

Approximately 7000 people are employed 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 operates offices in Brussels, Paris, and Washington D.C.

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