

# ROBEX – COMPONENTS AND METHODS FOR THE PLANETARY EXPLORATION DEMONSTRATION MISSION

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## ABSTRACT

This paper presents the current activities of the ROBEX alliance. ROBEX is developing innovative technologies and procedures for the exploration within extreme environments and also systems operating in the deep sea, on the moon or other celestial bodies. This paper gives a brief overview on the project's aims and the core development activities, as well as robotic key components. It is planned to demonstrate and test those developments in a representative environment. Therefore a demo mission is scheduled in 2017. Within this paper, the planned "Demo Mission Space", that covers the challenge of fully autonomous performance of complex robotic manipulation as well as the acquisition of scientific data in a space relevant environment is described in detail. Finally a novel rover simulation toolkit is presented which strongly supports the overall design process of planetary rovers and facilitates mission planning.

## 1. GENERAL SPECIFICATIONS INTRODUCTION TO ROBEX

The ROBEX (Robotic Exploration of Extreme Environments) Helmholtz Alliance [1] is a co-operation between 16 research institutes, companies and universities, operating either in the field of deep sea or space exploration. The major goal of this co-operation is the mutual exchange of information, experience and joint developments concerning the exploration of extreme environments such as the deep-sea or Extra terrestrial surfaces. As a part of these activities, demonstration missions will be conducted in the near future, covering both underwater and planetary surface analogue sites.

This paper introduces the development of the robotic systems, components and methods used for the realisation of said exploration missions. During the project a representative scenario has been defined for

both fields of applications which shall demonstrate the fundamental capabilities typically required for such exploration missions namely mobility, manipulability and autonomy. Both scenarios, but exploration in extreme environment in general, often require a central fixed base system with one or more mobile elements. Several robotic developments have been initiated within the ROBEX team for both scenarios. Especially the common developments and technologies applied in both fields of applications will be presented in this paper. The deep-sea demo mission (see Figure 1) is focusing on an autonomous mobile observation system based on a master lander in combination with mobile Autonomous Underwater Vehicles (AUV). The main objective of the selected lunar demonstration mission is the installation of a seismic sensor network. The used sensor probes shall be extracted from a lander payload, be transported to a designated area of interest and be placed in a predefined pattern.

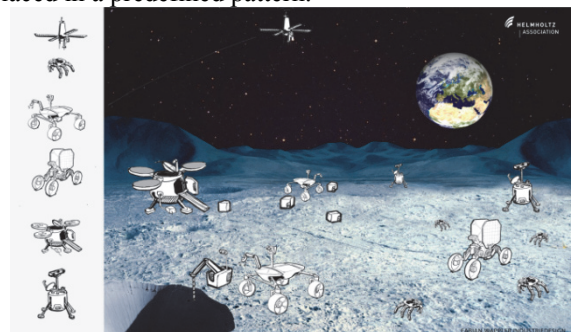


Figure 1 Sketch of future lunar scenario

During the project several mobile systems have been developed including the Lightweight Rover Unit LRU [2]. Moreover, to advance interactions between the base system, the mobile systems and their environment, work on a universal docking interface mechanism has been initiated for both extreme environments which allows mechanical coupling as well as data and energy transfer. In order to further increase the scientific return of such

robotic systems, the docking interface is also designed to allow an easy exchange of data and energy and to furthermore employ a wide variety of tools and scientific instruments. During the demonstration missions, the overall operational concept will be a key aspect. In order to operate robotic systems in extreme and very remote environments reliably, operational concepts are strongly recommended. Used algorithms have to face various challenges, including time delays or managing very complex tasks and situations that emerge on-site. Several control strategies suitable for both communities, i.e. under water as well as for space exploration, have been developed and analysed. This includes tele-robotic control, characterised by a human operator as part of the control loop, as well as robotic systems that operate and navigate fully autonomously in an unknown environment. The design of the rover and rover/arm combination, as well as the development and optimisation of the autonomous navigation system for the demonstration mission have been supported by computer simulation. Therefore pure computer and software in the loop (SIL) simulations have been performed utilising the new DLR Rover Simulation Toolkit (RST) for Modelica. The RST is a multi-physics toolkit that includes models for all rover components as well as different contact models. Standardising interfaces between the components, as well as using a common base layout for each class allows an easy replacement of single modules and the setup of HIL simulations.

## 2. ROBEX: DEEP-ASEA AND SPACE EXPLORATION IN EXTREME ENVIRONMENTS

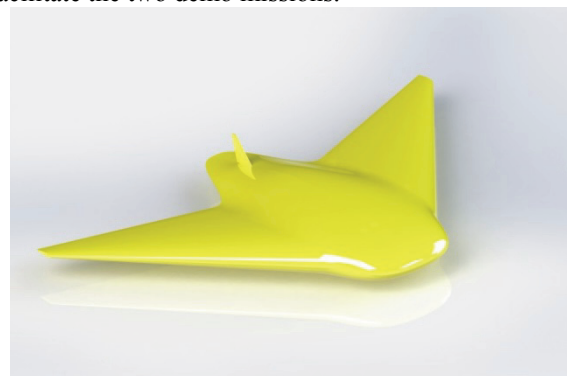
Robotic exploration of extreme environments, like the deep-sea or Earth's Moon, requires an advanced robotic development that focuses on reliable systems and components. The operation of such complex robots in their individual environments demands advanced operational concepts and operational architectures. Suitable control strategies range from tele-robotics, where a human operator is always part of the control loop with the robot, to fully autonomously operating robotic systems. Solutions in between include shared autonomy with partly autonomous sub-task execution or way point navigation. All of these technological developments are common in both communities. The scientific and operational crews, which are controlling and operating the remote robots in their space or underwater environments, respectively, are facing similar goals, tasks and challenges. Therefore, both communities benefit from the collaboration regarding the ability of inspection, sample extraction and handling, in-situ specimen analysis and robotic manipulation. Examples are MOVE-Seismic (see Figure 2) and the deep-sea glider (see Figure 3) where the competences of both communities lead to new robotic

concepts and hardware. Joint task oriented design teams develop new technologies for both communities which are finally tailored and applied to the related demonstration mission scenario.



*Figure 2: MOVE-Seismic- Underwater Rover: design inspired by the space rovers for active seismic payload*

Within ROBEX, it is the inspiring synergy between the underwater and space communities that will sustainably facilitate the two demo missions.



*Figure 3: Deep-Sea Glider*

In contrary to the very limited space missions, suitable underwater applications are numerous available. They demand innovative robotic systems and allow their testing and operation by means of realistic practical purposes and underwater missions. The “Demo Mission Deep-Sea” will take place in the HAUSGARTEN area near Svalbard in the eastern Fram Strait which offers all scientific relevant conditions. The “Demo Mission Space” will focus on a fully autonomous demonstration of a complex robotic interaction in a relevant scientific analogue environment, i.e. a seismic active region in southern Italy. For the “Demo Mission Deep-Sea” new mobility concepts are developed from scratch, as for the “Demo Mission Space”, the focus is on technical qualification and system readiness for the overall setup, especially autonomous capabilities, rather than the development of new mobility concepts. Several developments of sub-systems like the modular scientific experiment box or the common docking interface are expected to be beneficial for future missions of both

communities. A successful demonstration of the combined underwater lander/crawler system MANSIO-VIATOR (see Figure 4), including the first marine operation of an underwater crawler with a lander and a contactless charging interface, has already been performed.

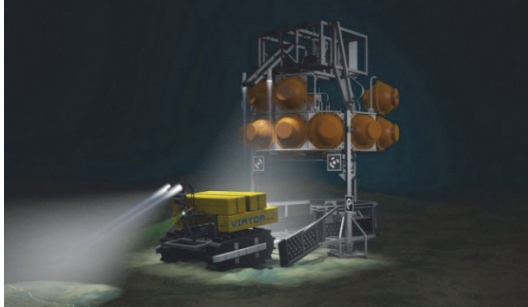


Figure 4 MANSIO-VIATOR

Nevertheless the desired testing environment and conditions differ significantly for the two scenarios and therefore two separate demo missions will be performed. The deep sea mission is not only a technical demonstration mission; it also forms a real scientific mission in an authentic environment. Since a real space mission is out of the scope of ROBEX, a virtual lunar mission is defined only for reference, and the relevant space technologies will be demonstrated in an appropriate analogue environment. The following chapter 2.1 will describe the real aimed on reference lunar scenario, while chapter 2.2 describes the related space demonstration mission in a terrestrial environment.

## 2.1. ROBEX Lunar reference mission concept for Active Seismic Network

To investigate sub-surface properties and seismic activity of extraterrestrial environments, such as the Moon, a seismic network has to be deployed on the surface of the celestial body. However, the manual installation of extraterrestrial seismic networks, i.e. geophones, is risky, expensive and error-prone. Evidence for this can be found in the reports of the Active Seismic Experiment (ASE) conducted during the Apollo missions [3]. During the Apollo 14 mission, the astronauts emplaced the so-called Apollo Lunar Surface Experiments Package (ALSEP), which constitutes a seismic network consisting of a seismometer and a string of three spiked geophones. In [4] the force driven positioning of a geophone in regolith-natured ground is discussed. Moreover, The Lunar Reconnaissance Orbiter (LRO) recently captured images of additional seismic instruments deployed during the Apollo 17 mission. These images revealed significant differences between previously published and LRO based source-receiver distances of up to 40m resulting in inaccurate assumptions of the lunar sub-surface properties [5].

## 2.2. “Demo Mission Space” and analogue scenario

The major objective of the test campaign is to validate the mission concept and architecture and to demonstrate that the intended scientific objectives can be achieved using the developed technology and implemented level of autonomy. This approach requires very limited human intervention, which is mainly required for scientific decisions. During the “Demo Mission Space” all technical and scientific key elements of the lunar reference mission shall be demonstrated i.e. mobility and navigation, communication, deployment, positioning and manipulation of the seismic packages and drive-by-geology. Furthermore, some key elements of the robotic equipment, such as the locomotion sub system of the rover shall also be tested with respect to defined technological requirements. It is out of the scope of this project to fully develop all key mission elements for a lunar mission. The focus is a proof-of-concept of space-qualifiable components and systems, which allow a future upgrade for space applications. Hence, the first task was to adapt the ROBEX Moon Mission concept – Active Seismic Network (ASN) – to a feasible representative terrestrial scenario, which includes the demonstration of all main scientific and technical challenges. An overview of the Demo Mission Space is given in Figure 5. The main elements will be a rover system including a manipulator arm and a scientific multispectral stereo camera system (GeoCam), a lander serving as payload carrier, and several payload boxes, equipped with seismic sensors. These boxes will autonomously be deployed and positioned by the rover during the demo mission in order to collect seismic data at the demo mission site. Furthermore, the rover will be equipped with additional scientific instruments. One concept is to use the GeoCam (Geological Context Imager) in addition to the navigation camera. The GeoCam is based on the Moonrise Context Imager (MCI) and ExoMars Panoramic Camera System (PanCam). Key part of the demo mission scenario will be

- a) a reduced active profile experiment, to perform active seismic measurements by using a lander-based seismic source and mobile (rover-carried) sensor
- b) the set-up and operation of a fully functional Y-shaped passive seismic array, which will perform passive seismic measurements in a “listening mode”, impact registration and event location.

For the active profile measurement, a combination of a lander, one mobile element (a rover equipped with a seismic sensor), and one stationary seismic source is required. To build up the seismic profile, after egressing from the lander, the rover will pick up the seismic receiver from the lander and start traversing



towards the seismic source. At predefined profile points along the traverse, the rover will deploy the seismic receiver in order to listen to the fired seismic source, then pick it up again, and to drive to the next profile point.

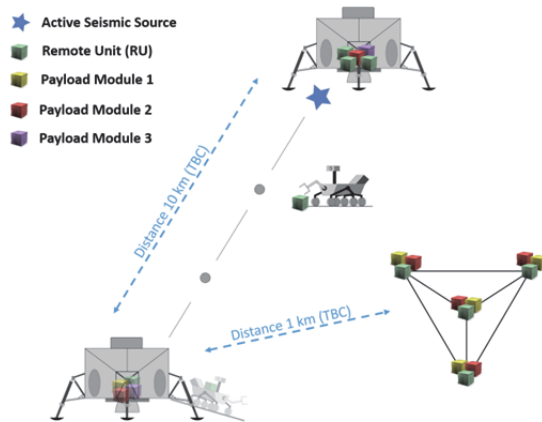


Figure 5 Scenario "Demo Mission Space"

In order to complement seismic measurements with surface geologic context, the GeoCam mounted on top of the rover, will perform „drive-by geology“, i.e. 3D mapping and multispectral analysis of the surface along the rover traverse. The entire process will be repeated several times. After completion of the active seismic survey, a Y-shaped array of four remote units for the passive seismic experiment will be deployed. The rover will autonomously deploy at least one of the four units, and the seismometer will be autonomously levelled by an internal leveling mechanism, which will be situated within the package. In order to increase the likelihood to record not only local microseismicity, but also a seismic event, the network will operate on-site a couple of weeks or months beyond the demo mission duration. It is also planned to compare the measurements with those of seismic stations (operated by terrestrial survey institutes) in the area. The terrestrial analogue site for the "Demo Mission Space" has not been selected yet. For the purpose of this study, we focus on operational and scientific field activities that are connected to lunar surface activities. Evaluation criteria include the site geology and geophysics (moon-analogue regarding seismic studies of a Mare region), but also rover traversability and logistics issues. Since the ROBEX lunar mission aims at seismic measurements in a Mare region on the Moon, the site shall be of volcanic origin, furthermore shall possess natural seismicity/microseismicity and would at best experience a few (low-magnitude) quakes each year. Further criteria include a Moon-analogue overall geologic context and shape, soil physical properties and lithostratigraphy for the seismic measurements of the subsurface structure. The topography, morphology, and rock-size frequency distribution shall be compatible with the rover's traversing capabilities. For the active seismic profiling,

as well as for the set-up of the Y-shaped seismic array, an available rover traverse range of approximately a couple of 100 meters is required. Based on these evaluations, the currently top-ranked regions are Mt. Etna (Sicily) and the Aeolian Islands region, with the preferred site being the "Grand Crater" on Vulcano. The Aeolian Islands formed as a result of the African Plate being subducted beneath the Apulian Plate. The region around Vulcano Island is characterized by a constant microseismicity induced by volcanic and fumarolic activity. Furthermore, the southern part of the Tyrrhenian Sea shows a concentration of subcrustal and deep earthquakes with focal depths between 200 - 600 km. These correspond to the depths expected for deep lunar quakes.

### 3. ROBOTIC SYSTEMS AND COMPONENTS

During the ROBEX project small research groups have been formed to work and handle specific topics and mission elements. These so-called design teams (see [1] for a detail list) are developing key technologies for deep-sea and space based applications. For the sake of brevity only the space related technologies and the corresponding demo mission relevant key robotic assets are described in the following sections.

#### 3.1. Common Docking Interface for robots

A review about the state of the art for the docking and interface systems in space has revealed a multitude of different designs of interfaces. Almost each user group has developed its own solution for their application. Functionality and realization differ significantly for similar tasks. Up till now, there is no standard docking and interface system available leading to the motivation of developing a modular standardized docking and interface system for a broad bandwidth of applications and user groups.

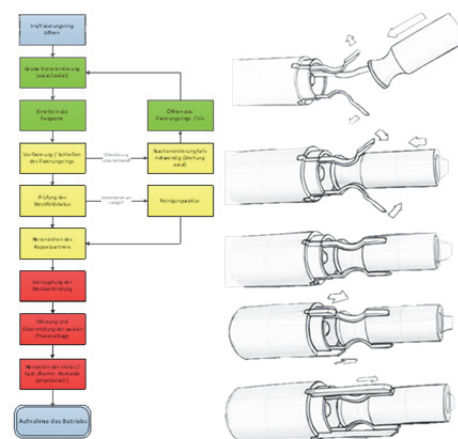


Figure 6 New docking process and design idea of the common docking interface.

To enable the operation of a variety of tools and scientific instruments, the requirements for the docking interface like power consumption, data transfer method,

additional fluid transfer, geometric dimensions and weight have been collected. With this information three scalable sizes of docking interfaces for robotic arms have been defined.

In extreme environments reliability and robustness of a robotic system and its components are the key aspects for the development of a docking interface. Therefore and due to the fact, that no standard system is available that matches the requirements of said tools and scientific instruments, a novel docking process has been developed in cooperation with the TokyoTech. In Figure 6 the docking process and the design idea is depicted. The basic principle is, that the robotic arm, instead of pushing the coupling partner against different undefined structures or using the environment, the line of the mating force will be closed within the docking interface by retracting the coupling partner. The retraction will be accomplished by form closure with a clamp and a groove system.

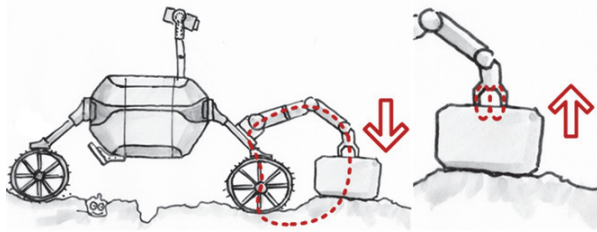


Figure 7 Closed force flux concept (right) compared with conventional method (left).

To increase the robustness of the plugging procedure, the passive coupling partner will be caught and aligned by the active side of the docking interface along with a rotationally symmetric electrical plug.

To reduce the complexity and increase the robustness while fulfilling the functionality of the process, the current detailed design foresees only one driving unit.

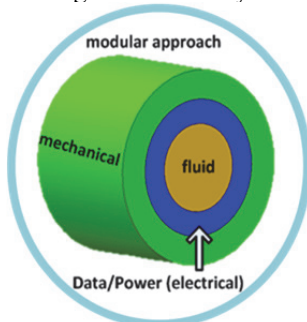


Figure 8 Modular adaptable design

The different requirements by the tools, the scientific instruments and the different environmental conditions in space and in the deep sea lead to a modular design of the docking interface. The pursued construction is depicted in Figure 8. To gain a high mechanical stability with regard to the dimensions, the mechanical connection is located at the outside ring. The volume of the middle ring illustrates the location of the electrical plugs, like power and data transfer. In the center a fluid

transfer for the thermal management or hydraulic applications can be integrated in the next steps.

The modular elements can be replaced with each other. There can be different types of modules for the data and power transfer. Depending on the application and the environmental condition it should be possible to use a copper connector or a wireless power and data transfer system. In Figure 9 an electrical module for wireless power transfer was tested with the MANSIO-VIATOR system under water.

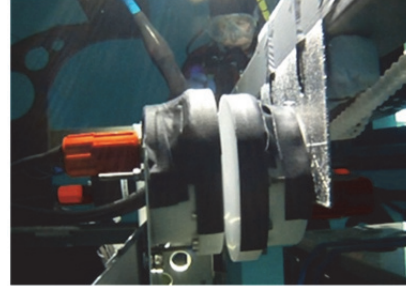


Figure 9 Testing of the inductive power transfer system with the MANSIO-VIATOR system

Due to the large industry of gas and oil extraction in the deep sea, a lot of components and products are available suitable for the use together with the docking interface. The reconfigurable interface can be equipped with different plugs for various applications and environments. Especially the wide range of available deep sea connectors and the experience with long term developed products lead towards a design of a possible deep sea as well as space usable copper connector configuration inside the docking interface.

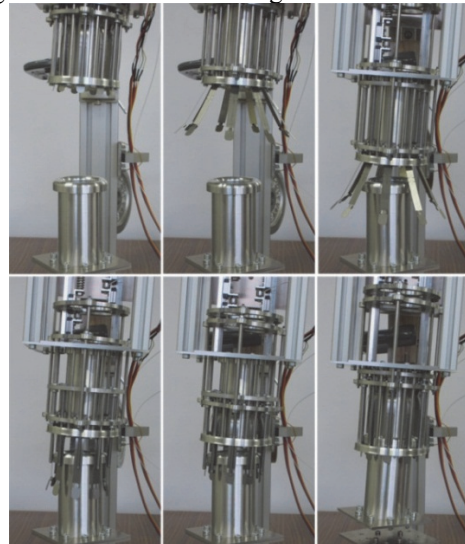


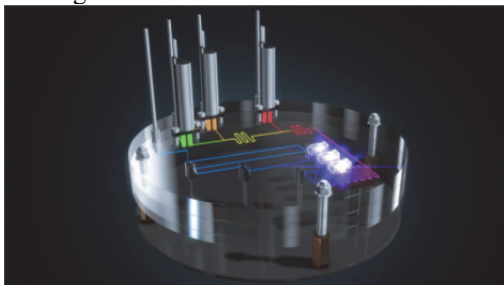
Figure 10: Function test at Tokyo Institute of Technology.

At the Department of Mechanical and Aerospace Engineering at the Tokyo Institute of Technology, the first laboratory prototype of the docking interface has been tested within a test apparatus of ToykoTech. With this test setup it was possible to measure the required

load to extend and retract the spring- as well as the pin elements, which are responsible for catching and locking during the docking process,. Together with the test apparatus, functional docking tests with a certain misalignment have been performed. In Figure 9 a first docking test is demonstrated. The initial test results of the clamp-groove system, i.e. the amount of required forces and further parameters will lead to a first, completely integrated prototype design. This prototype will have the smallest one of three sizes defined for ROBEX and will be used together with the robotic arm in the “Demo Mission Space”. In that mission, the rover will use the manipulator arm and the docking interface to pick up and transport previously described remote units.

### 3.2. Lab-on-Chip

While Lab on a chip technology (LOC) is rapidly expanding in medicine and pharmaceutical industries it's still in its infancies in space- and marine sciences. Within ROBEX the enormous potential of LOC technology for planetary and oceanic missions is explored and tested. LOC technology offers a broad bandwidth of applications ranging from miniaturized bioreactors for the synthesis of biomolecules, all kind of analytics to cellular assays and experiments. Obvious advantages of LOCs include small size, low weight, low energy demand, low sample and reagent volumes, fast processing times and high degree of autonomy, which render them particularly suitable for their deployment on a variety of different vehicles such as rovers, lander systems or gliders.



*Figure 11: Scheme of a photometrical Lab on a Chip*

Due to the various applications the complexity of LOC varies from simple test stripes to highly complex, autonomous system architectures for the continuous and simultaneous measurements of multiple parameters. In cooperation with the National Oceanography Centre Southampton first nutrient (nitrate, nitrite) time series measurements close to the seafloor in 170 m water depth using self-calibrating LOCs offshore Mauritania has proven this technology to be a robust and reliable tool for under water deployments [6]. Further test will be conducted during the demo-mission in 2017.

### 3.3. Lightweight Rover Unit LRU

The Lightweight Rover Unit LRU from DLR–RMC is a new innovative mobility device tailored to the needs of

planetary exploration and terrestrial search and rescue applications: It is designed to operate reliably on moderate to challenging terrain and allows the exploration of large areas in a fast and efficient manner. Due to its lightweight design and total mass of less than 30kg, it is a promising additional payload candidate for future lunar missions. The LRU is perfectly suited for fetching and handling tools and samples. The rover concept is strongly inspired by the Lunar Lander Mobile Payload Element and is in line with similar intended international planetary exploration missions. The design of the rover system is based on DLR's long experience in designing lightweight actuator units and robotic systems. The overall design process is continuously supported by simulation and a detailed evaluation of the performance even before the hardware becomes available.



*Figure 12 LRU (Lightweight Rover Unit) with manipulator – visualization of the DLR Rover*

## 4. THE ROVER SIMULATION TOOLKIT WITHIN ROBEX

The design of the rover and rover/arm combination as well as the development and optimization of the autonomous navigation system for the demonstration mission have been supported by numerical simulation. Therefore pure computer and software in the Loop (SIL) simulations have been performed utilizing the novel DLR Rover Simulation Toolkit (RST) for Modelica. The RST is a multi-physics toolkit that includes models for all rover components as well as different contact models. Standardising interfaces between the components as well as using a common base layout for each class allows for an easy replacement of single modules and the setup of SIL simulations. This simulation environment and modelling approach is continuously applied during the project and the overall design process strongly benefits from the concurrent engineering. Above that, mission planning and the development of software algorithms also benefit from the toolkit.

### 4.1. Language and framework

The DLR Rover Simulation Toolkit is a multi-physics toolkit that utilizes the object-oriented and equation-based Modelica modelling language [7]; an open standard designed for the simulation of multi-domain

physics models. Such complex models can consist of interconnected sub-models, which in turn are defined by component equations and algebraic sections. Using Modelica allows us to benefit from a large selection of preexisting custom libraries as well as a variety of commercial libraries. E.g. the DLR Optimization library [8] allows multi criteria optimization of model parameters and a Manipulator library enables the user to simulate rigid and flexible robot manipulators. The compliance of robots and other parts can be accurately simulated with the DLR Flexible Bodies Library [9]. Utilizing the open source Modelica\_DeviceDrivers Library [10] and the DLR Links and Nodes framework, communication with hardware components in real-time becomes possible. The DLR Visualization library [11] is used to generate graphical representations of the simulations as well as to obtain physically relevant information. Currently, the latter comprises collision detection, sensor simulation and virtual camera data, usable for the development of mapping and localization algorithms.

#### **4.2. Principles of the toolkit**

The basic principle of the toolkit is not to provide merely physical subcomponents, for example rover kinematics, drivetrains, manipulators and wheel-ground contact models but also standardized interfaces connecting them. Modelica provides so-called replaceable models, allowing the user to switch between different sub-models derived from the same base class. Via base classes, interfaces like mechanical or electrical connectors as well as basic parameters can be defined. Sub-models that share these basic properties can subsequently be derived from their base class. This results in a flexible, yet well-organized structure of the rover models and allows the mixture of components with different levels of detail in the same model. It also enables the reusability of sub-components in different rover models.

#### **4.3. Content of the toolkit**

The DLR Rover Simulation Toolkit covers all relevant aspects for the locomotion of planetary rovers. Classical multibody methods are used to simulate the dynamics of the rover system. The DLR Rover Simulation Toolkit contains a large selection of components, typically found in planetary rovers, like linkages, gears, drives, bogies and rockers. The wheels represent the final link of the rover's kinematic chain, at which forces and torques are calculated by the wheel-ground contact model. An interface for replaceable contact models allows for an easy adaption of the model to the demanded level of detail and desired simulation speed. Utilizing the DLR Visualization library for Modelica, it is possible to calculate the contact points between manipulators and objects or wheels and arbitrary ground surfaces via their CAD description. For approximating

hard contacts such as manipulator-payload contacts, a virtual spring damper element including frictional effects is introduced. For real-time simulations of wheel-ground contact, a BEKKER/WONG [12] based model is used. With semi-empirical equations, these models take forces exerted by the grouser and the force distribution due to sinkage into account. For more detailed simulations of effects, like deformation of the ground or land-slides, as well as material displacement, the DLR soft soil contact model (SCM) [13] is used. Particle-based soil contact models like the DLR DEMETRIA DEM framework [14] are used for in-depth simulations of terramechanics effects, as well as for the validation of the faster methods [15]. The toolkit provides a hierarchical structured control system. In this structure a high-level controller, for example a navigation algorithm may be implemented independently from both the rover's physical structure and its lower-level controllers like servo drives. By combining the mentioned subsystems such as locomotion components, wheel-ground contacts, controllers and manipulators, parameterized models of rovers can be designed. A parametrized model has a given structure while nominal values may easily be adjusted. This is commonly used for the evaluation and comparison of different designs. The toolkit currently contains three such parametrized rovers, which show how differently structured rovers can be implemented: Besides the LRU rover described above, a model of the Exomars BB2 Breadboard and a simplified model are comprised. These demonstrate the toolkit's structure and functionality and reflect our current research focus. However they may be used as a basis for further developments as well.

#### **4.4. Contributions to ROBEX**

During the preparation of the ROBEX Demo Mission, several simulation scenarios using the DLR Rover Simulation Toolkit were developed.

The first system is a mission simulator which demonstrates single ROBEX mission tasks such as payload pickup, navigation and payload deployment. While the simulation is still a central part of this demonstrator, its focus is on education of pupils and interested visitors.

Furthermore, within the toolkit a validated model of the JACO2 arm has been used to analyze the loads generated by the manipulator and the seismometer payload as well as their influence on the locomotion system in terms of mechanical stability.

The RMC Rover Sim simulates the physical structure of the LRU rover, its drivetrain, key sensors, its environment and its interaction with the latter, in particular the wheel-ground interaction. The simulation communicates in real-time with the control algorithms via the Links-and-Nodes framework. The decisive point is, that this allows us to transparently replace single



components or the entire rover by simulations without making any adjustment to the control algorithms.

## 5. CONCLUSION

During the current ROBEX activities the space and underwater communities worked out overlapping scientific and technological questions present within both communities. Underwater research has the advantage of access to a big market of components and robotic modules due to high industrial interests, e.g. oil and gas industry. The marine partners are therefore more task-oriented and focussed on scientific research and less on the development of new hardware components or robotic modules. This is contrary to space exploration, where every system is an exceptional product that is designed for a specific mission. In ROBEX, both communities benefit from the differing approach of the counterpart. The space community recognizes, that the fast forward approach of the underwater community maybe sufficient for certain space topics and applications. Especially the rich experience and expertise in implementing scientific missions and the lessons-learned from a large number of successful deep sea missions form a valuable enrichment to the space community. Vice versa, the deep sea community also benefits from the concentrated experience of the space community by developing customized technologies and algorithms for extreme environments and operating in remote terrain. Thus, e.g. autonomous navigation may play a more dominant role for future under water applications. Furthermore concurrent engineering and simulation support is beneficial for the marine community. The “Demo Mission Space” aims on providing and demonstrating key technologies needed for future robotic missions on planetary surfaces. Furthermore the presented concept of setting up a lunar seismic network is evidently scientifically relevant. From a technical point of view the developed systems as well as the presented planning and high level control algorithms for autonomous robotic systems mastered a challenging step towards real applied missions and the TRL of selected sub-components has been successfully increased.

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