Robotic Developments for Extreme Environments – Deep Sea and Earth’s Moon

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Abstract

Robotic Exploration of Extreme Environments (ROBEX) is a nationally funded Helmholtz alliance project. It brings together space and deep-sea research institutions. The project partners are jointly developing technologies for the exploration of highly inaccessible terrain, such as the deep sea and polar regions, as well as the Moon and other planets. In order to increase the science return from robotic systems used for exploration, more sophisticated designs are needed which go beyond the present state-of-the-art. Advanced exploration scenarios are defined that finally will lead to demonstration missions on Earth analogue sites. Both communities expect to highly benefit from each others developments, expertise and maturity of existing robotic systems, and those being under development.

1 Introduction

Since the end of 2012, fifteen institutions distributed all over Germany are jointly developing technologies to improve the exploration of areas with extreme environmental conditions such as the deep sea, polar regions, and Earth's moon surface. This is a real unique endeavour to bring two different worlds together and to benefit from each other’s technological developments. These technologies consider robotic developments and autonomous operations in deep underwater areas and on Moon’s surface. The main idea behind is the development of advanced exploration scenarios and finally its realization by demo-missions on Earth on relevant analogue sites. For that we wish to learn and benefit from the experience and expertise of each of the partners of the two communities. This research alliance is configured to last for at least five years. In the meanwhile, we have learned about the problems, further R&D desires and existing solutions of different maturity levels in the two extreme areas.

Autonomous operations, mobility and manipulability are the three key issues to be covered. Long-range and long-time exploration of both extreme environments, in deep sea and on Earth’s Moon, require advanced mobile systems in combination with skilled robotic arms that operate almost or fully autonomously [1]. In deep-sea applications several mobile systems, Autonomous Underwater Vehicles (AUVs, Figure 1) and Remotely Operated Vehicles (ROVs, Figure 2), are already successfully in operation for many years, although mostly with very limited autonomous capabilities [2,3,4]. In space, the use of mobile systems is very rare, obviously because of minor launch opportunities and high launch and development costs. However, due to lack of direct and immediate in-situ involvement by humans, space robotic systems benefit from their highly developed and redundant components and increased autonomy in order to operate without permanent human interaction [1,5].

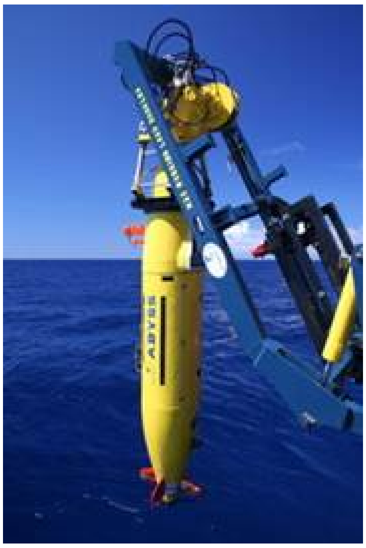

Figure 1. AUV Abyss (GEOMAR)

Figure 2. ROV PHOCA with 2 robotic arms

Having all this in mind, the cooperation of the two extreme exploration areas is expected to identify individual and also common problem areas and to solve them by benefitting from each other. To start the cooperative work, a common and typical exploration scenario has to be established that gives rise to future increase of the existing robotic capabilities. The common scenario will foresee the exploration of larger areas of the seafloor and on the Moon surface, almost autonomously, by specific scientific instruments that are transported by means of vehicles and handled by robotic arms and versatile grippers.

These two scenarios will be described in more detail hereafter. Both Moon and deep-sea scenarios will be studied and developed in two ways in parallel: one envisages an ideal scenario that aims to acquire and realize the overall system more or less in a visionary manner, but with regard to potential hardware and software constraints. The second scenario then will be derived from the ideal one while slimming and reducing visionary ideas in order to achieve a realizable demo-mission here on Earth within the timeframe given for the ROBEX Alliance project. Apart from the work on the specific scenarios, further robotic study topics have been identified that will be investigated within certain design teams consisting of experts from all the topics. Those teams will study relevant robotic and mechatronic problem areas such as: tele-operated handling, camera guided intelligent grappler, docking interfaces, crawler (Figure 3) autonomy, object handling, underwater glider, legged crawler, and underwater navigation.

Figure 3. Deep-sea crawler in operation with data and power umbilical

2 Commonalities and Differences

2.1 General overview

Exploration of deep sea and lunar environments requires un-manned mobile and manipulative systems that are able to be tele-operated or even operated in semi- or fully autonomous modes. By nature, deep-sea applications are much more advanced compared to space applications. However, a limited number of such systems are already operating quite successfully on Mars. High mobility, precise and skilled manipulability and autonomous operations of the robotic systems at very remote sites are therefore important for successful exploration. In today´s world robotic systems already explore the deep sea as ROVs and AUVs, gliders and rovers/crawlers from ships, or even as components of a cabled observatory.

To reach the goal of autonomous robotic exploration in both extreme environments while taking benefit from each other, we have to identify commonalities w.r.t. technological solutions, identify gaps in deep sea and space technology, create operational (pilot) scenarios given the scientific needs, and finally define and develop required sub-components for the specific scenarios. For robotics and mechatronics engineers in space applications, the distinction in the 3 major fields seems obvious: mobility, manipulation and autonomy. However, overlaps are inherent and desired, e.g. in autonomous robotic arm operations. In space, we mostly follow this (smart) distinction. In deep sea, systems often are procured as a whole, whereas mobility, manipulation and some level of autonomy is included in the delivery by the supplier. Moreover, the procured systems mostly allow some flexibility by adding own solutions.

Table 1. Common and different features in deep sea and space exploration missions

Feature	Deep Sea	Earth's Moon
environment physical	high pressure, ~ 600 bar (6 km depth), high drag salty water almost no radiation almost constant temperature around/above zero deg buoyancy visibility poor, only for short range no static environment: moving particles, floating objects, ocean currents terrain unknown, uneven on seafloor	no pressure, no drag (vacuum) no atmosphere solar wind / radiation (high energy radiation, particles, …) extreme temp. differences: -160 … +130 deg vacuum visibility excellent, except shadowed areas and bright sunlight static environment: no dust, no storms, etc. terrain unknown and uneven low gravity (1/6 g) slow Moon rotation (1/28 of Earth rotation)
communication	via cable acoustic waves (sonar) almost no time delay	cables not preferred electromagnetic waves (RF) time delay
power	power cables batteries	solar power (solar panels) secondary batteries (RTGs)
autonomous operations	almost no time delay: tele-operation possible direct intervention possible (from ship) → autonomy less required	large time delay: tele-operation / direct control almost impossible no direct intervention → autonomy required
redundancy	low, due to direct intervention for repair or change	high, due to fail-safe demands and no direct intervention for change
availability of operational systems	high (AUVs, ROVs, else), long tradition of usage	extremely low, due to little launch opportunities and high costs, applications are largely missing
complexity of systems	medium to big	very big
mass	no big issue	light-weight structures etc. a must, due to launch impacts
frame structure	big issue, has to withstand high water pressure	light-weight required, has to withstand launch loads
system intelligence	medium	very high, due to autonomy and self-diagnosis demands

2.2 Common and different features

Due to the very different environmental conditions, it seems that differences are quite more prevailing than commonalities. Communications in deep sea has to rely either on RF via cabling or on sonar waves, whereas on Moon (no acoustic waves) RF is the favourite choice. Specifically, in terms of autonomous vehicle operations video based imaging (visual odometry) is favoured for Moon because of its high precision and resolution and excellent visibility besides shadowed areas, while this is valid only for short range (some ten meters) deep sea operations because of very poor visibility. Here, different techniques have to be applied, such as sonar ones with constrained resolution, however. These and some more important common and different features are listed in Table 1.

2.3 Provision and usability of robotics hardware

One major concern in space applications is the limitation in providing sufficient types and numbers of vehicles and manipulators for their planetary operational use. This is due to the limited launch opportunities for such robotics exploration missions, and vice versa, due to the inherent high development and launch costs. Required high level of system resilience going along with redundant layout of sub-components is the main driver for this constraint. In deep sea applications, since many years a large number of underwater vehicles, also of different type (AUV, ROV, hybrids), are already in operational use. Their big advantage over space applications is there quite easy sub-sea launch from accompanying research vessels, their frequent usability by repeated retrieving and deploying from the ship, and their quite easy maintenance and repair, and even rapid technical modifications of needed. Otherwise, sub-sea vehicles are built on heavy equipment basis. They are particularly cabled for guidance, navigation and communications purposes.

Several of the major vehicles in use and of different operational class are listed in Table 2, also robotic manipulators of common interest. Specific testing and demonstration platforms for space exploration applications are given as well, although not being of use for real operational space missions. Particularly, the mobile robotic system Justin (Figure 4) with its compliant controlled light weight arms and its two four finger hands is an ideal experimental platform for these research issues [6]. Cameras allow the 3D reconstruction of the robot's environment and therefore enable Justin to perform given tasks autonomously. The idea behind these platform provisions is to make use of adequate hardware equipment during the entire ROBEX alliance project for developing and testing reasons. The ROBEX project then will be finalized with the demonstration mission on Earth analogue sites, while putting several of these existing and modified hardware equipments together, or parts of them being developed anew if required during the project lifetime.

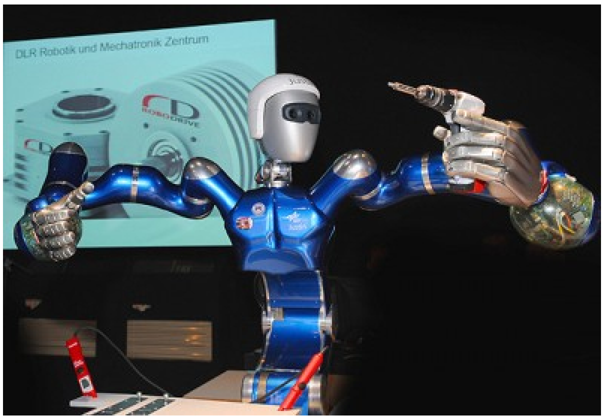

Figure 4. Mobile robotic system 'Justin' (DLR)

2.4 Test facilities to be used

Various test facilities do exist at the ROBEX partners locations. If needed, they will be made available for appropriate testing on component and sub-component level. Table 3 presents a list of the main testing facilities for deep sea and space applications under consideration. Besides facilities with well-defined and somehow repeated environmental conditions (underwater tanks, indoor/outdoor vehicle for driving testing), there exist on-site, in-field facilities that allow in-situ underwater demonstrations and scientific measurements (Hausgarten, Tisler, Neptune Canada).

3 Pilot Scenarios

3.1 Common aspects and needs

Although both communities, deep sea and space, have similar problems of exploring inaccessible extreme environments with different scientific questions, it was agreed to define pilot scenarios being almost common for deep sea and Moon. This project approach is regarded to help identifying the technological gaps and the needs to solve the exploration scenarios successfully. Furthermore, these scenarios then are expected to be worked out in more detail and finally will end up in so-called demonstration missions (i.e. field tests) at analogue sites on Earth at the end of the five years project lifetime.

Table 2. Robotics hardware provided and used by ROBEX partners

System and Type		Partner	Short Description	Site and Type of Operation
Schilling Robotics ROV KIEL6000	ROV	GEOMAR	6000 m rated deep-sea ROV for all kinds of scientific sea floor intervention tasks, including manipulation, sonar and video imaging	Deep sea, sea floor, manipulation
Schilling Robotics ROV QUEST4000	ROV	MARUM	4000 m rated deep-sea ROV for all kinds of scientific sea floor intervention tasks, including manipulation, sonar and video imaging	Deep sea, sea floor, manipulation
Subatlantic ROV PHOCA3000	ROV	GEOMAR	3000 m rated deep-sea ROV for all kinds of scientific sea floor intervention tasks, including manipulation, sonar and video imaging	Deep sea, sea floor, manipulation
Subatlantic ROV CHEROKEE 1000	ROV	MARUM	1000 m rated mid-size ROV for light scientific sea floor intervention tasks, including manipulation, sonar and video imaging	Deep sea, sea floor, manipulation
Hybrid-ROV	H-ROV	MARUM	6000 m rated hybrid, battery powered underwater vehicle, under design and construction at MARUM. Vehicle will be adapted to operate in high-risk areas	Polar seas, under ice, hydrothermal vent fields
Hydroid AUV REMUS 6000	AUV	GEOMAR	named Abyss, 6000 m rated AUV for deep sea mapping, sensing and imaging (multi-beam sonar, side-scan sonar, sub-bottom sonar, camera), manufactured by company Hydroid	Deep sea
I.S.E. AUV SEAL5000	AUV	MARUM	5000 m rated AUV for deep sea mapping and sensing (multi-beam sonar, side-scan sonar, sub-bottom sonar).	Deep sea
Bluefin Robotics AUV3000	AUV	AWI	3000 m rated AUV for deep sea sensing (bio-geochem. sens, water sample, radiation sens.)	Deep sea
4-wheeled crawler MOVE	Crawler	MARUM	Autonomous or remotely controlled deep-sea crawler, as carrier platform for several kinds of scientific applications, e.g. bio-geochemical probing, imaging	Deep sea
Caterpillar-tracked crawler WALLY	Crawler	JUB	2000 m rated, remotely controlled deep-sea crawlers (attached to deep-sea cabled observatory (Neptune Canada), with different sensor packages for bio-geochemical and oceanographic probing, imaging	Deep sea floor, monitoring
AUV Dagon	AUV	DFKI RIC	300m rated holonomic exp. platform for testing of localisation and autonomy algorithms	Autonomy, SLAM
Schilling Robotics ORION 7P	Manipulator	DFKI RIC	Commercial deep-sea manipulator (i.e. used on QUEST 4000), mounted on a motions simulator, used for design and evaluation of semi-autonomous manipulation algorithms	Semi-autonomous manipulation
Sherpa	Rover	DFKI RIC	Rover with adaptive suspension and a manipulator; developed for planetary operations but will be adapted to deep sea environments, used as evaluation vehicle for air-based motion control and manipulation	Autonomy, SLAM, navigation, manipulation
ExoMars BB1	Rover	DLR-RMC	Breadboard for ExoMars rover, fully operational in terrestrial environments	Moons, Planets
Justin	Manipulator	DLR-RMC	Human-like manipulation system consisting of 2 arms, 2 hands and torso	Manipulation in planetary environments
Rollin' Justin	Rover, Manipulator	DLR-RMC	Justin system attached to 4-wheeled basis	Manipulation in planetary environments
DLR Crawler	Crawler	DLR-RMC	Vehicle platform with 6 legs to study autonomous operations and novel mechatronic components	Moon, planetary surface

Table 3. Test facilities at ROBEX partners locations

Testbed	Partner	Short Description
PEL	DLR-RMC	Planetary Exploration Lab; driving performance testing of vehicles on soft/sandy and rocky terrains, with precise camera and infrared based measurement system
Out-door testbed	DLR-RMC	Open air autonomous operations test environment for rovers and crawlers
LAMA	DLR-RY	Landing and Mobility Test Facility (see also Chapter 2.2.2)
HAUSGARTEN	AWI	Long-term deep-sea observatory of (still) stand-alone character covering a depth transect from 1000 - 5500 m; access will be provided during proposed demo missions onboard RV "Polarstern"
Tisler	JUB	Small cabled observatory at 100 m water depth off Norway with internet connection
Neptune Canada	JUB, UVic	Access to the deep-sea cabled observatory node at 900 m water depth, a component of the Neptune Canada infrastructure
Testing Pit	TUKL	Deep testing pit facility for dry/submerged soil with loading apparatus
Underwater Testbed	DFKI RIC	Two test tanks: 20m3 tank, equipped with a 3D Cartesian motion simulator and the capability to change turbidity and prohibit external light; 40m3 tank with glass walls
Out-door test track	DFKI RIC	Outdoor track with various obstacles for testing mobile systems
Underwater test tank	DFKI RIC	Underwater test tank (30m x 20m, 10m deep), for testing and demonstrating underwater equipment and whole scenarios (under construction)

The different scientific questions that we want to answer by the research on the Moon and in the deep sea should be addressed both by a common method, namely seismic surveys, as well as with a common technological solution. To this, it has been agreed in the course of the first year, to develop and build together a combination of a stationary system with one or more mobile elements. The stationary system should provide a central part for energy supply and data exchange and the mobile systems to perform the actual scientific exploration in the deep sea or on the Moon.

3.2 Moon pilot scenario

The Moon scenario (sketched in Figure 5) implies the set-up of an active seismic network (ASN) which means that at least four seismometers and one or more active impactors are to be transported by a rover and deployed on the Moon’s surface by means of a robotic arm and gripper [7]. The seismometers have to be aligned on the surface very precisely w.r.t. the vertical and latitude directions, and specific forces have to be applied to get close contact with the ground. The overall scenario is separated into two individual ones: First, the rover will drive between two lander sites being apart by about 10 km from each other and will deploy the seismic instrument, wait until its measurements are taken, and pick it up again on the rover. Then, the rover will move to the next measurement location and repeat the deployment. The distance between two breakpoints has still to be determined.

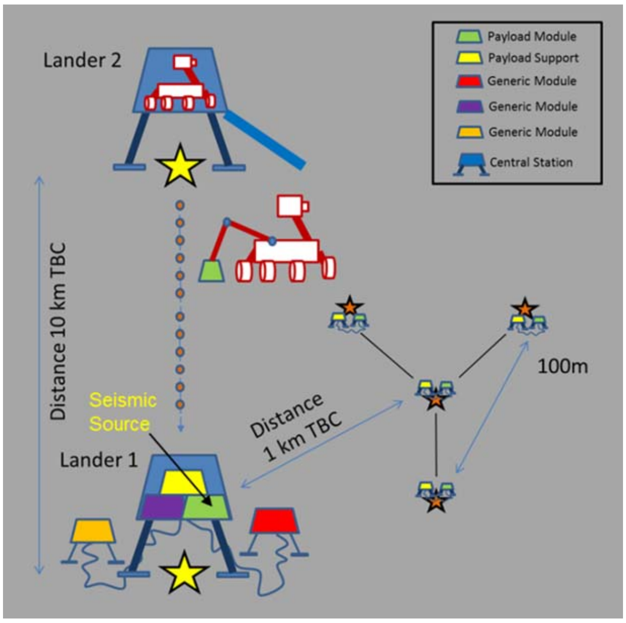

Figure 5. Moon pilot scenario

In a second scenario, located close to one of the two lander sites, the rover has to set up a seismic network consisting of four instruments that are to be arranged at the three corner points of an equilateral triangle of about some 100 meters side length, and one seismometer in the centre of the area. It resembles the ALSEP (Apollo Lunar Surface Experiments Package) experiments performed during several of the Apollo missions on Moon. Both scenarios require high transportation capabilities and driving performance as well as skilled manipulator and gripper devices to place and align the instruments carefully and precisely onto the ground. To be successful, sufficient energy storage and specific docking interfaces for both energy supply and instrumentation accommodation are necessary. Further, the ability to drive through larger shadowed areas is required. Based on these two scenarios, requirements for autonomy, mobility and manipulation have been derived which will be presented. Modelling, simulation and visualization of the two scenarios were performed and will help to decide upon the adequate final scenario and detect any mission failures.

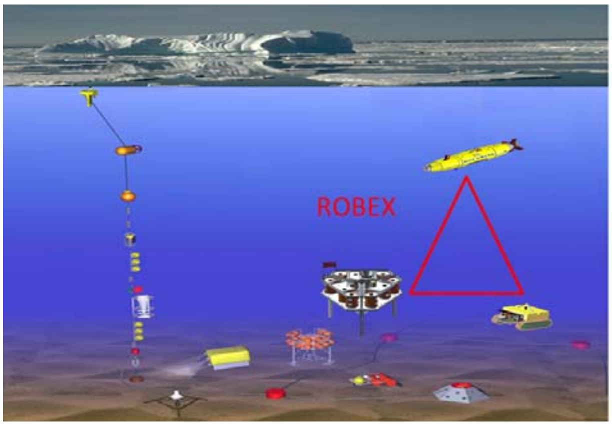

Figure 6. Deep sea pilot scenario

3.3 Deep sea pilot scenario

The deep-sea demo-mission is focusing on an autonomous mobile 4D (3D spatial and 1D for time) observation system. The concept consists of a master lander with power, master computer, central storage and data transfer as well as docking capabilities. Mobile autonomous systems like AUVs and crawlers will explore an area between 100 meters and 1 km (sketched in Figure 6). Such a system combines components for high power capacities, central data storage and transfer with high spatial and temporal flexibility to measure relevant environmental parameters. The major common issue for all deep-sea scenarios (vents, seeps, hypoxia and under sea ice) is to capture the high spatial and temporal variation in environmental parameters, bio-geo-chemical process rates, and biological diversity, which requires repeated measurements over larger areas and tidal or seasonal cycles.

For the deep-sea scenario master lander and crawler systems will be built. The master lander serves as a base for the crawler. When the crawler is docked to the lander, batteries can be recharged, keeping the batteries packs for the crawler small (less weight), and data collected during the mission can be stored to secure them. If a connection (cabled or non-cabled) to a surface-buoy is possible, data can also be transferred via satellite-connection to land. The crawler, as the mobile component, allows repeated measurements over longer time periods, individual measurements of different habitats and measurements over large areas.

Similar to the Moon pilot scenario, the application of seismic methods as described as topics of cross-disciplinary interest is very relevant for detecting and quantifying methane hydrates and free methane gas in the sediment. Up to now, this scenario can only by realized by two ship missions which is extremely costly. Within ROBEX it is planned to design and build an array of bottom crawlers that will allow for placing geophones precisely at predefined positions.

4 First Results

Work started on conceptual design of both pilot scenarios with emphasis on mobility and manipulability increase, as well as to enhance autonomy, specifically in underwater operations. The Moon ASN scenario has been visualized while preparing and generating various modelling and simulation modules. They are based on a powerful software environment (Modelica) and are supported by DLR's visualization library [8]. This library consists of wheel-soil contact models for arbitrarily shaped surfaces, a trajectory (3D) designer, digital elevation models of the operational area, where NASA's LROC satellite remote sensing data could be incorporated. Although, these data were of poor resolution (1/2 to 1 m) for rover driveability needs. Moreover, to advance the work in much more detail, CAD models are needed of lander, rover, robotic arm, gripper, and instruments (seismometer), where all these models will be integrated into the simulation environment.

The existing tool is highly flexible, which means that CAD models of different types of rovers, robotic arms (as DLR's Light-weight Robotic Arm, Figures 7 and 8), terrain topology etc. can be exchanged very easily by more developed ones. This was first shown for different rover types, e.g. the ASN scenario visualization covered rovers with 8-wheels (the early Lunokhod type of year 1970/71), ESA's ExoMars type with 3 bogies and 6 wheels, and a newer concept being developed at DLR-RMC, with the potential to be used in the field tests later, equipped with 4wheels.

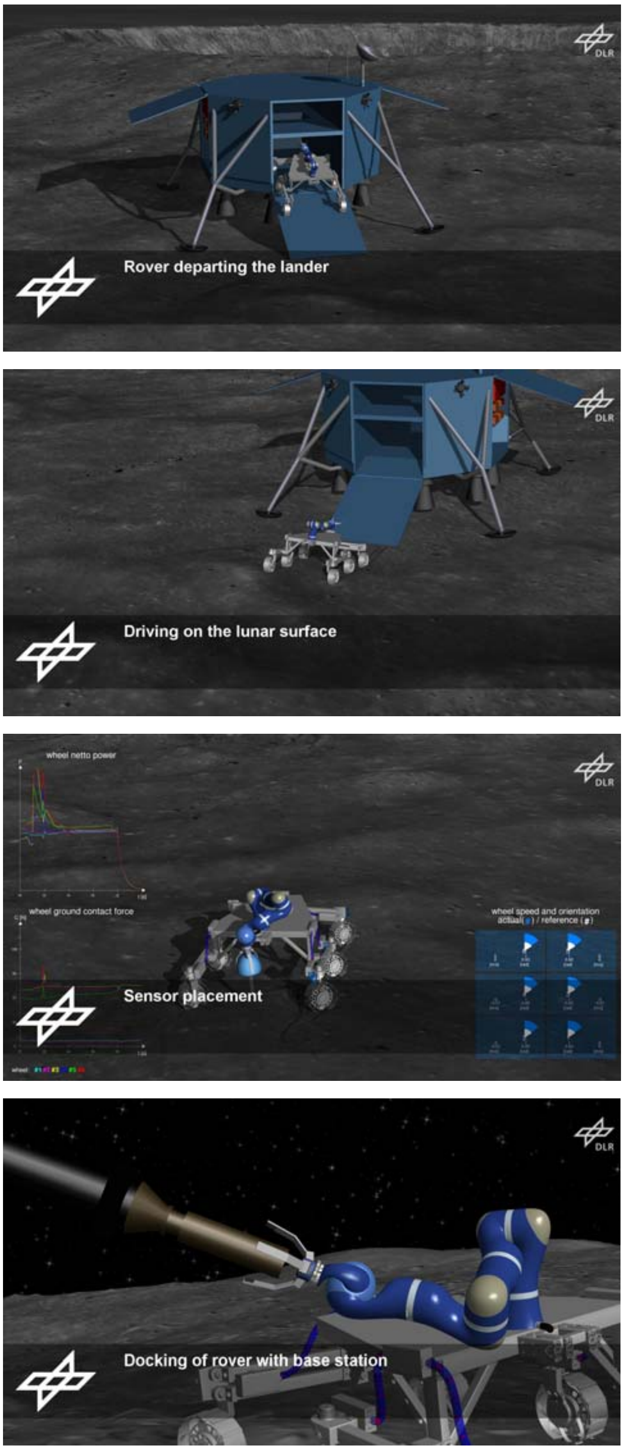

Figure 7. ASN pilot scenario visualized, impressions taken from the movie 'Visualization Moon pilot scenario ASN' [8]

Work on rover conceptual design has started, and a wheeled vehicle will be favourized, having in mind traveling distances in a 10 km range or less, almost beyond horizon, and on moderately shaped surfaces. Power storage, data transfer and communication between rover and lander as well as autonomous navigation were examined in first conceptual design options. The primary interest has been to start working on geometric and rover structural sizing, on proper choice of locomotion suspension and concept (kinematics, motorization, wheel shape, etc.). This is an issue that is to be investigated further. Moreover, it has to go hand in hand with robotic arm design and seismic instruments.

In order to control the interaction forces with the environment, impedance controller is envisioned: this allows to optimize control behaviour w.r.t. position accuracy and provides maximum force interaction (Figure 8). Light-weight arms for space applications are a must: for this purpose DLR-RMC has a large control heritage and we will make use of compensation methods for passive joint compliance to increase end-effector accuracy. To demonstrate advanced control strategies, DLR's Justin platform (Figure 4) will be used to demonstrate controllers to be developed and implemented. Hence, we are able to prove such techniques for ROBEX Moon applications. Considering the docking purpose between manipulator and lander, the kinematic loop is closed and proper control of interaction forces for safe docking manoeuvers are required. Reactive self-collision avoidance algorithms for highly complex robotic systems having many DOFs will be developed in order to comply with physical constraints of robots.

Three different sea-floor crawler designs are identified and will be developed for the deep sea scenario. They will allow different scientific tasks and hence involve modified designs, although being based upon the original Wally crawler construction (Figure 9): AWI's Tramper and Geomar's Viator design with lander connection, both used for biological and geo-bio-chemical measurements and seasonal benthic oxygen gradients and fluxes, and Marum/Geomar's C-MOVE for seismic seafloor measurements. AWI, DFKI, DLR, GEOMAR, JUB and MARUM are cooperating in all of the three crawler types. The existing JUB platform Wally will be modified for autonomous deployment: redesign of front navigation camera has started to allow for development of automated photogrammetrical and mapping systems (relief maps). Such techniques are applicable for both deep sea and Moon extreme environments: for underwater operations manual control at moment is prevailing, but fully autonomous operation will be the final goal.

Synergies between the two communities have been elaborated, at the current project stage with focus on autonomous operations: creating maps and analyzing the map for vehicle traversability, development of path planning and path following strategies, and all kinds of high level planning aspects. Here, deep sea exploration can benefit from space exploration: the control system is the most critical item to be used in non-nominal, specifically in risky operational scenarios, e.g. long travelling distance (several kilometers) under ice operations. Only minor mission tasks are defined currently. Typically, the vehicle is steered remotely, controlled via thin glass-fibre cable by human operator. In case of a broken cable, control has to swap from remote to autonomous mode instantaneously. Also, ultimate rescue pathway under ice is forbidden: no direct dive up and wait at sea level is possible. Hence, new software approaches are under development that bring the vehicle out of such critical operational areas.

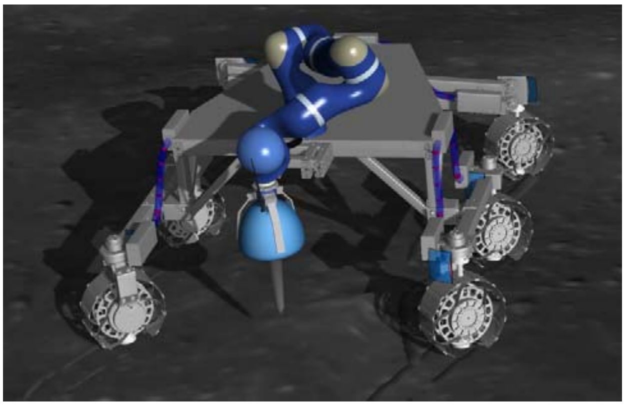

Figure 8. Manipulation by DLR's Light-weight Robotic Arm: ASN Moon seismometer deployment, fine positioning and alignment [8]

Manipulator control on ROVs (like Quest, Kiel 6000, Cherokee) will also benefit: usually, hydraulically actuated and on joint level master-slave control operated, control enhancements are worked on, e.g. based on the CManipulator software stack and upper-body exoskeleton development as developed at DFKI [10] (Figure 10). Enhanced control is to be placed in between master and slave arm: thus extending the capabilities of the hydraulic slave, and allowing for e.g. controlled drilling and swiping operations in tele-operated mode. Further work has started on manipulator family development for use on purely battery driven vehicles like Wally and H-ROV.

The pilot scenarios will end up in field tests (the demonstration mission) at analogue sites on Earth. To prepare for the proper selection of one or two such overall demonstration sites, requirements given by the robotics systems and sub-systems developments and operations have been carefully investigated. They will impact on the proper site selection, together with the desire to find adequate analogue sites in the European region (to hold travelling and operational expenses at a minimum) and to find a common site where both communities can jointly work together and in close vicinity. Indeed, preliminary site selection will favour the Hausgarten / Svalbard area, Mediterranean Sea / Aeolian Islands area, and a few more. Specifically, for the Moon analogue mission, available expertise in site selection will also rely on the expertise described in the excellent CAFE document [9]. Furthermore, there exists very comprehensive experience with ESA's ExoMars rover and instrumentation testing at analogue sites like Svalbard [11].

Figure 9. Deep sea crawler 'Wally'

Figure 10. Manipulation by robotic arm: deep sea scenario for precise geophone placement

5 Conclusions and Outlook

The two research communities, space and marine, are jointly developing technologies to improve the exploration of highly inaccessible and extreme environments, a project lasting over five years, and started 18 months ago. In a first attempt, both communities had met each other while taking part in various workshops, made their respective challenges transparent and agreed on a common solution concept for both research environments. This common concept then will be demonstrated at analogue sites on Earth.

Ongoing work will focus on the detailed elaboration of the pilot scenarios with emphasis on the common challenges and solutions. To support all this, virtual testbed development for Moon rover optimization and entire scenario visualization will be continued, and is expected to impact the detailed design of the deep sea scenario accordingly. Manufacture and demonstration of a first lightweight Moon rover prototype has started already. Advancing of a combined rover/manipulator concept is underway with autonomous driving functions and seismic instrument handling capabilities. Moreover, to advance interactions between the robotic systems and their environment, work on generic docking and interface mechanisms has started for both extreme terrains. This also applies for the handling concepts, for instrument placement and retrieval, for sample acquisition and transfer to a lander station, and for any kind of connecting and disconnecting operations for power and data transfer or for reconfiguration of modules or base station set-up.

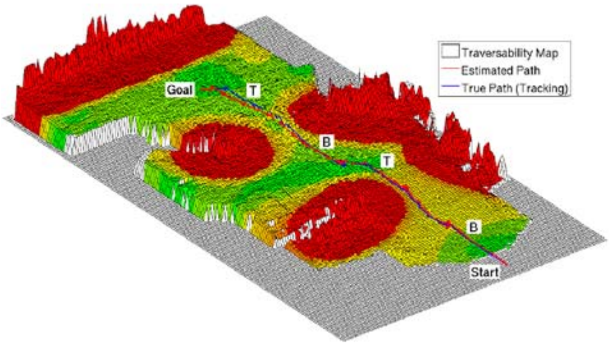

Figure 11. Autonomous vehicle driving using DLR's SGM algorithm [12]: 3D mapping, self-localization and navigation in unknown terrain

In deep sea exploration, the increased desire for certain tasks to switch from tele-operated to more semi- or fully autonomous operations including intelligence enhancement and e.g. logical decision making will be followed. Underwater vehicles need to decide actions on their own, involving path finding and routing strategies as wells as attitude control in unknown environments. SLAM techniques are to be applied as already operational in space vehicle applications (Figure 11) [12]. Visibility is still a challenge for autonomous operations: on Moon, by virtue of excellent lighting conditions in general, camera-based navigation will be further preferred, and more advanced concepts are being further studied and tested. In deep sea, high particle loads reject this approach, and the challenge still exists to find appropriate techniques. Moreover, buoyancy in deep sea is predominant, and no steady position is achievable, vehicles will float up thus losing track. Vehicle control approaches will be studied and tested under such conditions.

Acknowledgment

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