

# ROBEX – Robotic Exploration of Extreme Environments

## An Alliance of the Helmholtz Association of German Research Centres

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**Abstract**—The Helmholtz Alliance ROBEX is developing innovative technologies and procedures for the exploration of extreme environments and the operation in the deep sea and on the Moon or other celestial bodies. This paper provides an overview on the overall project structure and key robotic developments are described exemplary. The use of new technologies will improve the capabilities to enhance our knowledge in both fields. These developments will be demonstrated and tested in representative deep sea and Moon environments during demonstration missions in 2017.

**Keywords**—Extreme environments, robotic exploration, autonomous operation, navigation, mobility, manipulation.

### I. INTRODUCTION

THE ROBEX (Robotic Exploration of Extreme Environments) Helmholtz Alliance [1] serves for the first time in Europe as a co-operation platform between explorers from two different worlds – space and deep-sea research. Despite the obviously different physical boundary conditions with respect to pressure, light, gravity, etc., both environments are facing similar challenges for their exploration technologies. Both need solutions for energy management, autonomy, navigation and communication. The scientific and operational crews, which are controlling and operating the remote robots in its space and underwater environments, are facing similar goals, tasks and challenges. Therefore, both communities benefit from the collaboration regarding the ability of inspection, probe extraction, probe handling, *in situ* analysis and robot manipulation.

In ROBEX, three Helmholtz Centers (Alfred Wegener Institute Helmholtz Center for Polar and Marine Research (AWI), German Aerospace Center (DLR) and GEOMAR Helmholtz Center for Ocean Research Kiel), MARUM Center of Marine Environmental Life, six universities (Technical University Berlin, Kaiserslautern, Munich, Dresden, Jacobs University Bremen, University Würzburg), the German Research Center for Artificial Intelligence (DFKI) as well as AIRBUS Defence and Space (D&S) are involved. The last two institutions participate as associated partners. The major goal of this co-operation is the mutual exchange of information, experiences and joint developments concerning the exploration of extreme environments such as deep sea or planetary surfaces.

The research of the Alliance is organized in four topics: the first addresses the central research questions that are specific for the two environments considered in this Alliance (1000), the second topic focuses on the development of the system design (2000), the third topic addresses the development of robotics (4000) and the fourth topic covers payload instrumentation (4000). For each topic, three work packages were identified for the main tasks and activities (**Figure 1**).

Cross cutting interdisciplinary activities are established through 12 design team projects where researchers and engineers work together and develop technological solutions so that both sides with their respective expertise benefit from each other (**Figure 2**).

At the end of project and a part of these activities, demonstration missions, both underwater and on terrestrial analogue sites for planetary surfaces, will be conducted to demonstrate interdisciplinary teamwork of both communities and the capabilities of the new and innovative technologies.

An extensive training and educational program accompanies the ROBEX Helmholtz Alliance for doctoral students and technicians. Public outreach programs inform teachers and students, as well as young scientists in the progress of this new synergy between previously separate research communities.

### II. ROBEX DESIGN TEAMS

After an initial period of adaptation between the two different scientific communities, all partners of the ROBEX Alliance are working very close together on the identified scientific and technological challenges. Twelve interdisciplinary design team projects (**Figure 2**) have specific goals and the synergies between underwater and space communities are used in various ways. Examples are the *Glider* and *MOVE-Seismic* design teams (**Figure 3**) where the competences of both communities lead to new robotic hardware and concepts mainly for underwater applications.

The *Glider* design team works on a new design approach for an underwater glider based on the so called flying wing design. Although the benefit of such type of design is well known for aircrafts practical realizations have only been seen in military applications. In the underwater world, gliders have been built based on Autonomous Underwater Vehicles (AUVs) design that was derived from torpedo shapes. There are good reasons for such type of design that are related to the housing of power,

electronics and sensors. However, with today's technical capabilities in regard to battery systems, electronic boards, and the availability of lightweight, high strength construction material it is worth evaluating a new approach that offer new opportunities for sensor integration and flight behavior and consequently new scientific applications. Design team work take advantage of work carried out by AIRBUS D&S on space glider systems, the experience of DLR Robotic and Mechatronic Center in the domain of aircraft design and control, the consideration of functional integration and the use of light-weight material for the vehicle hull (DLR Inst. of Composite Structures and Adaptive Systems), the expertise in flight robotics at the University of Würzburg, and the experience in underwater vehicle design, construction and operation of MARUM.

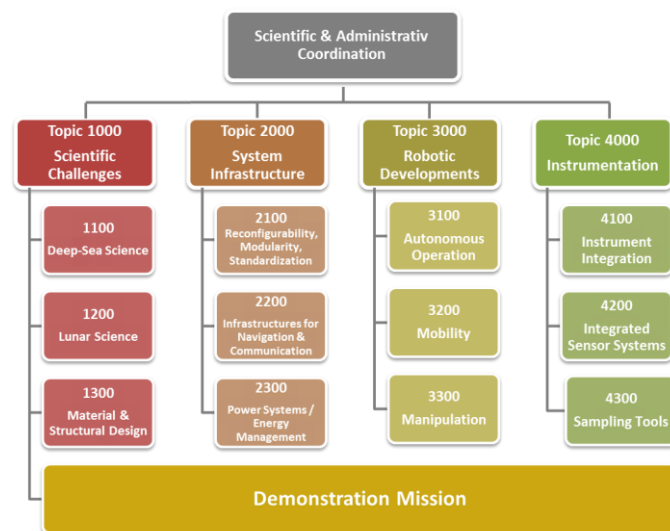


Figure 1 Overview ROBEX Work Breakdown Structure (WBS)

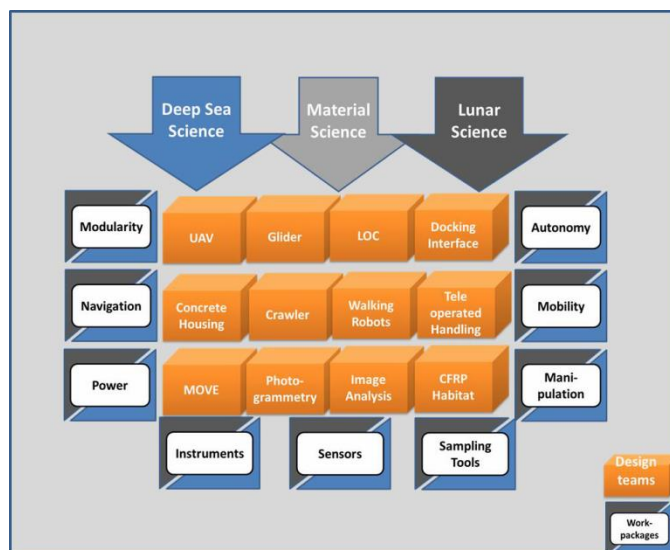


Figure 2 Integration of ROBEX design teams into the WBS

The main issue of the *MOVE-Seismic* design team is to develop a multi-vehicle-system where several carrying

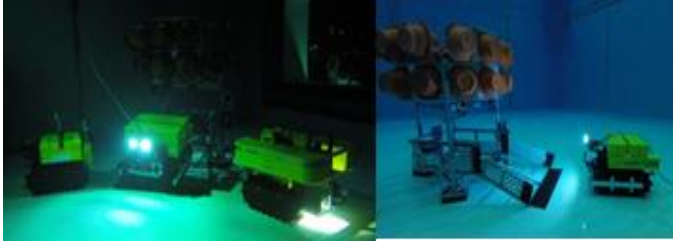
platforms are coupled to conduct coordinated seismic measurements at the seafloor. This allows performing multiple measurements at the same time at different spots along the vehicle chain which can be precisely relocated covering a definite region. As this application scenario is very similar to the lunar concept the design team has been formed to allow for close interaction between the scientist and engineers to develop a technical requirement profile addressing the optimal observing strategy. As one challenge, the mobility of the deep-sea vehicles has to be enhanced to avoid the vehicles getting stuck in changing sediments. As similar issues exist for planetary missions a mobility concept developed by DLR Robotic and Mechatronic Center has been used as the base for the deep-sea vehicle *MOVE-Seismic*.



Figure 3 Underwater glider for deep-sea application (left). Underwater crawler from MOVES-Seismic design team for seismic and electromagnetic measurements at the seafloor (right)

Substantial progress has also been achieved in the *Crawler* design team where three different adaptations of one basic caterpillar driven robot frame (Figure 4) have improved the capabilities for mobile underwater robotics. One new development describes a fully autonomous crawler system (VIATOR) for long-term deployments including a hangar/lander system (MANSIO) for energy and data transfer (Figure 4, right). This is an analogue to Moon missions with masterlander and cooperating autonomous rover. The second approach focuses on a fully autonomous long-term deep-sea crawler for biogeochemical studies at remote areas of the seafloor (TRAMPER). Here, the mission objective is to perform repeated measurements of oxygen profiles in Arctic deep-sea sediments over a period of 12 month. The third system, iWALLY, is developed to design and build a crawler which is capable of automatic photogrammetry, generating 3D maps of the area through which it traverses. Automated operations within the mapped area are then intended. The three deep-sea crawler projects benefit from the expertise of partners from the space and deep-sea community regarding autonomy and navigation (near- and far field) of the crawler systems. In case of VIATOR and TRAMPER, the DFKI and AIRBUS D&S closely work together to develop joint hard- and software solutions. Based on the ROCK software package of the DFKI, all additional camera and sensor systems are implemented into the various platforms. This includes mission planning, as well as navigation (both AIRBUS D&S) and control of the scientific payload. The inductive coupling and energy transfer are developed and tested in collaboration with the DLR. The creation of a modular robotic infrastructure environment, both in hardware (for lunar/deep-sea application, networking of system components, mobility, autonomy etc.) and in software

(modular approach in order to cope with re- configurability) is the major synergetic effect of ROBEX. The integration of ROBEX community members into the design of the three crawlers has allowed automation in movement and mapping, improved imaging techniques and onboard processing of image data to be incorporated into this next generation of cabled and uncabled research crawlers.



**Figure 4** The three ROBEX underwater crawler iWALLY (l) from Jacobs University, VIATOR (m) from GEOMAR and TRAMPER (r) from the AWI (left). MANSIO-VIATOR system from GEOMAR

Another example for the benefit from collaboration regarding the ability of situational awareness, probe extraction, probe handling, *in situ* analysis and robotic manipulation is the design team *Lab-on-chip* (LOC, **Figure 5** left). Although it has initially been developed for underwater applications, investigates on its applicability for space missions on the International Space Station (ISS) have been initiated. In medical and biosciences the LOC technology is an emerging technique that miniaturizes standard laboratory procedures down to chip-size. In marine and space sciences, however, this technology still remains largely unexplored [2-3]. Aim of the LOC design team is to develop and integrate LOC technology on different underwater vehicles such as glider, AUV, lander or crawler as well as for *in situ* measurements on the ISS. Further aim is to explore LOC technology as ready to use experimental platforms for both marine and space applications. Introducing LOC into ocean and space sciences meets many technical demands that are outlined in ROBEX for the successful operation of exploring platforms and associated vehicles. This includes low energy demand, low demand of reagents, small size as well as small weight, and long-term sensor stability, which renders LOC sensors especially suitable for operation on gliders or AUV's. Low costs of production, enables mass manufacturing that will potentially allow the establishment of sensor networks. Exploring the suitability of LOC technology for both scientific communities lead to the joint proposal BIOSIGN that was submitted to the European Space Agency (ESA).

Requirements of an underwater and space docking interface lead to the establishment of an appropriate design team. A review about the state of the art for docking and interface systems in space has revealed a multitude of different designs. Almost each user group has its own solution for their application. Functionality and realization differ significantly for similar tasks. Up to now, there is no standard docking and interface system so that the goal of this design team is to develop a modular standard docking and interface system for the needed applications justifies. Depending on the pressure,

respectively the depth, deep-sea docking and interface systems can be tested in less time and more often under real conditions compared to space applications. Nevertheless interface systems for scientific tools and research groups in the deep sea are only available for few requirements. The different specification of the oil and gas industry to the research groups lead to this situation. The design team *Docking and Interfaces* elaborated the requirements for the design approaches. Especially the wide range of available deep-sea connectors and the experience inside the long-term developed products leads towards a design of a possible deep sea as well as space usable copper connector configuration inside the docking interface.



**Figure 5** Lab-on-chip (LOC) technology (left). Concrete housing for underwater application (right)

The design team *Concrete Housing* (**Figure 5** right) is a result of ideas that developed during one of the first Alliance workshops. The initial plan of the Technical University Dresden as Alliance partner was to investigate the applicability of lunar concrete for building structures for future manned habitats on the Moon [4]. However, exchange of information during first meetings between experts from deep-sea, space and materials research led to the formation of this design team composed of representatives from space (DLR), deep-sea (AWI, GEOMAR, Jacobs University) and material science (Technical University Dresden). For deep-sea research, expensive housings and constructions made of titanium are used to avoid corrosion in the maritime environment and to guarantee long-term deployments. The suitability of high-strength concrete for underwater pressure housings and constructions is examined to provide a low cost and durable alternative. The good cooperation and support e.g. in manufacturing of different parts (AWI) as well as the provision of testing facilities (GEOMAR and DFKI) led to successful research work. The first prototypes were developed, manufactured and tested within one year. The expansion of the network of contacts resulted in the unique possibility of *in situ* testing at the Arctic deep-sea HAUSGARTEN site [7] as well as NEPTUN Canada, a long-term deep-sea observatory at 3000m water depth off the West Coast of Canada [5].

### III. ROBEX DEMONSTRATION MISSIONS

The different scientific questions which should be answered by the research on the Moon and in the deep sea will be addressed with a common technological solution. During the project a representative exploration scenario has been defined for both fields of applications which shall demonstrate the fundamental required capabilities of typical exploration missions namely mobility, manipulability and autonomy. It has been agreed, to jointly develop and build a combination of a stationary system with one or more mobile elements. The

stationary system should serve as a central part for energy supply and data exchange, the mobile systems as units to perform the actual scientific exploration in the deep sea or on the Moon.

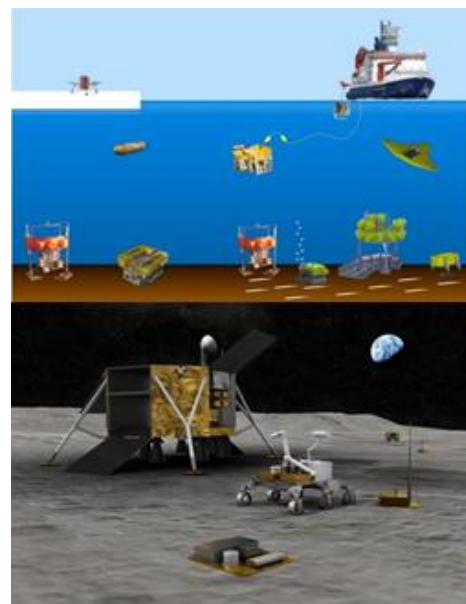
The deep-sea demonstration mission is focusing on an autonomous mobile observation system based on a master lander in combination with mobile vehicles. The MANSIO-VIATOR crawler system excellently represents the scenario of the deep-sea demonstration with a stationary system (lander) and a mobile unit (crawler) for scientific exploration. The overall aim is to demonstrate the applicability of the new and innovative underwater-platforms and sensors for investigating different scientific questions. The ability to address questions concerning ocean change is fundamentally limited by the lack of key technologies for enabling *in situ* experimentation, conducting targeted sampling, and performing persistent sensor measurements in the ocean. Although there are different needs and strategies for deep-sea missions to investigate the defined research and working areas (e.g. fluid seepage from the seafloor and related slope stability investigations, detection of hydrothermal vents and assessment of biological processes, effects of hypoxia on the ocean ecosystem, dynamics of the under ice environment), a common mobile benthic robotic-system was identified as the central technology for the deep-sea demonstration mission, which can be used at all sites. As demonstration mission sites two scientific areas, the gas hydrate site of Svalbard [6] and the Arctic deep-sea HAUSGARTEN site, were chosen. The deep-sea demonstration mission carried out in 2017 during a proposed expedition on board *RV Polarstern* will test the capability of new and innovative technologies developed within topic 2000, 3000 and 4000 and different design teams (e.g. *Crawler*, *Glider*, *LOC*). Investigations will include Arctic ecosystems that are strongly influenced by climate change, such as marine arctic sediments hosting gas hydrates and Arctic deep-sea benthic communities (topic 1000) [8]. At the gas hydrate stability zone, gas hydrate deposits as well as water column gas concentrations at different spatial and temporal scales will be quantified. At the HAUSGARTEN deep-sea observatory, studies on the pelagic-benthic coupling will be performed, to investigate how benthic life is governed by the food supply from surface waters. The use of new underwater technologies will thereby improve the capabilities to deepen our knowledge on the effects of climate change on the Arctic ecosystem.

Contrary to the deep-sea demonstration mission, colleagues from space obviously cannot perform a real space mission in the foreseen lunar environment, hence this is a known constrain for space science and engineering while demonstration mission in analogue environment are planned. The scientific motivations by the foreseen lunar mission are investigation in sub-surface properties and seismic activity of extraterrestrial environments, while a seismic network has to be deployed on the surface of the celestial body to reconstruct crust and sub-surface models of the moon [9]. Hence, since this activity cannot be performed within ROBEX in the lunar environment, an analogue demonstration site has been identified on Italian

Aeolian islands and Etna regions, since this seismic active area and Moon like environment is ideal as test environment. Hence, the first task was to translate and downscale a “real” Moon mission concept into a Moon-analogue scenario, which includes the demonstration of the main scientific and technical challenges, which will be faced on the Moon. During this Moon-analogue demonstration mission, all key elements of the mission shall be demonstrated, both from the science side and the technological point of view, i.e. mobility and navigation, communication, deployment, positioning and manipulation of the seismic packages. The major objective of the tests will be to demonstrate that the intended science objectives can be met using the developed technology, and that the level of implemented autonomy, together with limited human intervention only for science decisions, is suitable (and flexible enough) for high-quality science results. For this purpose, at least one lander and one fully equipped rover (LRU; Light Remote Unit) [10] are needed, including a navigations system, a GeoCam (Geological Context Imager), and a robotic arm to deploy the so-called modular remote units, which will house in this experiment the seismometer and provide all essential services for its operation, such as data management, provision of power or sensor levelling. Key parts of the demonstration mission scenario will be

- a) a reduced active profile experiment, and
- b) the set-up and operations of a fully functional Y-shaped passive seismic array, which will have a smaller diameter than the lunar one.

For all measurements, a rover will pick up the remote units from a lander and transport them to the measurement site(s) for final deployment in an autonomous manner. The docking interface, as interface between the modular remote units, developed within ROBEX will play a key role during the technological tests [11].



**Figure 6** Deep-sea scenarios for demonstration mission (above). Scenario for Moon-analogue mission (below)

For the deep-sea demonstration mission new mobility concepts are developed, while for the Moon-analogue demonstration mission, the focus is on technical qualification and system readiness for the overall setup and especially autonomous capabilities, rather than developing new mobility concepts. 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 focused on scientific applications and less on the development of new hardware components and robotic modules. This is in contrast to space exploration, where every system is a prototype that is designed for a specific mission. The underwater community sees the advantages of special developments for targeting specific research goals, where existing components are not sufficient, e.g. autonomous navigation. Vice versa, the space community sees that special developments are very time-consuming and resource-demanding and that a reuse of components is beneficial. The underwater community shows how fast developments can be achieved using off-the-shelf-components that are reliable and safe. Test-orientated qualification and more practical developments are often lacking in the space community. This is mainly due to the limited and expensive flight opportunities resulting historically in a very conservative and slow process for space system developments with strong standards.

A general and clear trend in ROBEX is that the deep-sea research profits more from the space community than vice versa. Autonomous systems were from the beginning required for space exploration (power generation onboard, radio communication, autonomous control systems for flight and vehicle management). New autonomous underwater systems require this as well. Mainly through its demonstrations missions ROBEX will verify a set of prototype robotic systems by a deep-sea demonstration mission in real environments with strong space community involvement and by a space demonstration mission in a Moon-analogue environment on Earth. In summary, the deep-sea community profits from historical development of autonomous space systems and provides opportunity to apply or test space technologies lacking sufficient own missions. The space community profits from the deep-sea research by implementing more pragmatic mission oriented approaches and having a test bed for faster technology demonstration in another extreme environment. Mission orientation not only depends on launch costs. There is a lot about mindset to learn from the deep sea.

#### IV. ROBEX TRAINING AND EDUCATION

The training of graduates and post graduates was set as an important goal of the ROBEX Alliance, which is seriously committed to accomplish two complementary goals: professional development of scientists and young engineers, and assistance to the full-time and part-time staff. During the last 2.5 years, 3 Training Workshops (TW) were carried out by different lectures from the ROBEX partner institutions. The first TW consisted of theoretical introductions to the space and ocean sciences, where the main technological challenges were presented to the audience. Interdisciplinary sharing and

brainstorming as well as discussion of the main scientific questions and identification of technological challenges faced in ROBEX are example activities. The trainees were exposed to this dual perspective on systems engineering and power management; simulations, visualization and interfaces; autonomy; and sensors and instrumentation. A demand for a more practical approach to the training was identified, while staying very close to the stated objectives of the Alliance to inspire a diversity of discussion and cross-fertilization of ideas. Hence, trainees carried out e.g. small missions with mobile robots from Alliance partners during the following TW and were introduced into the interpretation of Moon and deep-sea video transects for later statistical analysis. In this context, the Jacobs University, in collaboration with DLR and educational experts from outside of the ROBEX community (from the University of Edinburgh and the American University of London), as well as researchers from CSIC, Barcelona have produced a fully online training course. The training course is available to anyone interested, with all teaching materials provided online, and is designed to be taken over a 10-week period. The training course was envisioned as something which should be useful to undergrads, master students and early course PhD students with an interest in spatial statistics and/or image analysis (<http://imageanalysis.weebly.com/>). These topics were chosen as these aspects of extreme environment research are analyzed by both marine and planetary researchers, thus, are ideal foci for materials generated by the ROBEX community and ROBEX research. During a field trip to the island of Volcano (SW Italy), ROBEX students had the possibility to carry out small demonstration missions with various mobile underwater and terrestrial vehicles (rover, crawler, AUV) from the ROBEX community. Training workshops, the online training course as well as additional activities like field trips clearly contribute to a new young scientific ROBEX generation consisted of prospective experts for the exploration of extreme environments.

#### ACKNOWLEDGMENT

This work was supported by the Helmholtz Association for German Research Centers; project Alliance ROBEX, under contract number HA-304.

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