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From single autonomous robots toward cooperative robotic interactions for future planetary exploration missions

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Abstract

Mobile robotics will play a key role in future space, ocean and deep sea exploration activities. Besides the actual development of the robotic systems, the different ways of commanding those systems, using technologies varying from teleoperation with the human in the loop, through shared autonomy towards highly autonomous systems, will be the main challenges of these missions. This paper describes the robotic activities of the DLR institutions within the Helmholtz projects ROBEX and ARCHES, dealing with robots for autonomous space and ocean exploration applications. Furthermore, it describes the challenges, the overlap and the synergies of those domains, the different approaches of operating robots from far distances in extreme environments and gives an outlook on future mission possibilities.

Keywords: robotics, autonomy, exploration, shared autonomy, teleoperation

1. Introduction

This paper describes the continuous development of mobile autonomous exploration robots that finally are able to cooperate and solve tasks of higher complexity given by high level commands. Right from the beginning, the idea was to have robots assisting the human operator in dangerous or inaccessible environments. The scenario may be operation in deep-sea, planetary exploration or search and rescue in disaster areas. The communication to the robot may be interrupted or delayed, therefore the robot must be able to perceive hazardous situations on its own and deal with it without user intervention. This is the first level of autonomy that is mandatory to exploration systems. When thinking of delayed communication, the robot operation is either to be slowed down tremendously or the robot skills need higher level of autonomy. This scenario leads to the idea of robots performing autonomous tasks with only high level commands given by the human operator. When several robots are envisaged to collaborate and add their skills to one powerful worker the level of autonomy needs to be increased even further.

The first rover platform with perception and autonomy skills able to explore in unknown environment was shown at the SpaceBotCamp [4]. The platform is called LRU (Light Weight Rover Unit). In this scenario, one autonomous rover should explore unknown terrain and search for two objects that were known before. These objects had to be brought back to the start position. Additionally, the objects needed to be assembled at a base station near the start position. All these tasks were executed without user intervention.

In the ROBEX (Robotic Exploration for Extreme Environments) moon analogue mission, performed on Mt. Etna, Italy in 2017, the goal was to install a seismic network on the volcano [7]. Again, objects needed to be picked up, transported to defined locations and be placed on the soil. To gain a maximum of experience from this project two rovers were used and controlled from a remote control center in Catania at the foot of the volcano. These two rovers were working in parallel but were not collaborating. However, still the grasping and placing of seismometers needed to be performed as an autonomous task as this would be very challenging to be tele-operated.

These findings will be transferred to the project ARCHES (Autonomous Robotic Networks to Help Modern Societies), which started in 2018. Its main focus is on cooperative aspects of heterogeneous robotic teams. In contrast to ROBEX, the robots shall now work together to explore, deploy, and maintain infrastructure and scientific instrumentations on planetary surfaces or the marine environment. The developed algorithms and methods will be strongly relevant for the robotic support and operation of permanent installations and bases (e.g. the Lunar Village concept, or large scientific observatories, such as interferometers). This paper discusses the different conceptual modes of operating robots in such scenarios, starting from teleoperation and shared autonomy to highly autonomous behaviors that even include collaborating systems. The aim of ARCHES is to develop approaches that allow robots to acquire, analyze, and interpret measurement data autonomously, covering large areas and long periods of time. The project thereby focuses on the key technological challenges required for robot autonomy as well as for high-level human supervision of the robotic teams operating at remote sites. In order to cope with the challenges addressed in the project, the evolution from single robotic systems to cooperating autonomous robotic networks is essential. The focus thereby is not only on the ability to monitor large-scale processes, but also on the autonomous assessment of the recorded situation and the resulting on-site intervention. This is particularly important for exploration and manipulation tasks in extreme, inaccessible and dangerous environments.

2. Autonomous robots to explore universe and deep-sea

Regarding space applications, especially spin in and spin out potentials are always of high value. Due to the fact, that development for space is especially challenging in reliability, reachability/communications and energy consumptions the technologies are on intensive research. Often space technology developments show also a high potential for the use in terrestrial environments and fields of application such as medical, transportation, industry, agriculture, search and rescue and deep sea. Also often technologies or methods from these applications domains are foundations for next level space developments. Thus, the exchange between application domains can be highly beneficial, in technological, ecological, humanitarian or economical ways.

Especially in deep sea and space robotics, the application domains from our past ROBEX and active ARCHES projects have a common overlap in the environmental and operational fields of application, but also with future use cases and application scenarios.

In both application domains, the intention and the demand to operate robots, even teams and swarms of such are agreed. In theses extreme environments, where no services like GPS are available, challenging atmosphere and temperatures are evident, the aim of increasing autonomous functionalities to enlarge the area of operation and to extend the time of the missions is of great relevance.

Not only the projects ROBEX and ARCHES but especially space and deep sea share the following key technological requirements for their exploration:

- Mobile robots that can explore demanding rough terrain with a high degree of autonomy
- Dedicated sensor and communication systems
- Tools for manipulation and acquisition of samples
- Methodologies for cooperation among robots as well as between robots and human operators
- Different robotic systems, which provide complementary capabilities, for example flying explorers, transport rovers, and small cave crawlers
- Reconfigurable robotic systems to deploy scientific and infrastructure elements

All of these mission and operational concepts are in line with the Global Exploration Strategy, that aims toward human robot cooperation, partly autonomous robotic systems, and the installation of permanent bases, e.g. the Lunar Village, and the Cis-Lunar Habitat or the Deep Space Gateway. Finally, a robotic strategy will be presented in this paper

The search for extraterrestrial life on planets and moons of our solar system is one of the most exciting tasks of space. According to current knowledge, some places can already be considered as fluid and potentially life-supporting. For this purpose, only mature and fully autonomous designed systems come into question. The development of absolutely necessary key technologies is essential for the realization of such space missions: Addressed issues are artificial intelligence, navigation, robotics, energy, communication, sampling and sample analysis procedures, mission planning and of cause astrobiology.

Space missions to explore the extra-terrestrial oceans on some moons in the solar system will be only realized in the later course of the next decade. But the shared experiences that were made in the context of the Helmholtz alliance ROBEX and the project ARCHES for the exploration under extreme, environmental conditions will definitely influence the concepts for such future missions.

3. ROBEX

This section presents results of the analogue mission campaign, which was performed as part of the final demonstration of the results of the ROBEX project. The analogue mission took place between the 12nd of June and the 10th of July 2017 on Mount Etna in Italy. ROBEX is a Helmholtz Alliance and is a collaboration of 16 institutes performing space and marine research. As the goal of the project was to develop technologies and tools that help in exploring the deep sea and extra-planetary surfaces, two demo-missions, one for space and one for deep sea exploration were performed. Both these missions used advanced and complex robotic systems to perform the missions.

Demo Mission Space: The scientific objective of the space related demo-mission was to analyse the lunar crust layers. As an actual moon mission is outside the scope of the project, an analogue mission was performed on Mt. Etna, Italy. The mission was to deploy a seismic network using a robot to study the surface layers composition by studying the seismic profile. This was accomplished using an autonomous mobile robot with supervision from scientists from the control center.

The Mission Setup on Mt. Etna: Mt. Etna, Italy was chosen as the analogue site for the demo mission due to the surface composition, which resembles the lunar surface, as well as due to presence of seismic activity. The actual test site is next to the crater Cisternazza located at a height of about 2600 m. A photo of the site is shown in Fig. 1.

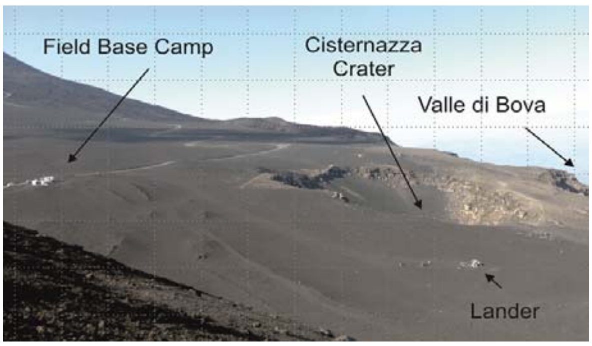

Fig. 1: Photo of the test area on Mt. Etna where all tests and demonstrations took place

The analogue mission consisted of two parts. One was to measure the seismic profile by placing the sensor box in a straight line at intermediate points and using an active seismic source. Fig. 2 gives a pictorial representation of this experiment. The mission included three main technical components which where the lander, the LRU rover and the seismometer sensor box. The lander held the sensor box at the start of the mission and also acted as the communication interface between the LRU rover and the control center. As, the mission started, the rover localized the sensor box on the lander and grasped it using a docking interface located at the end of the manipulator. It then navigates to different locations where it repeats the actions of placing the remote unit, waiting for the measurements to be taken and picking up the box to navigate to the next location. The whole mission was performed autonomously giving room for scientists to look at measurement data and intervene when necessary. The whole process of task design and mission control was done using a intuitive and graphical state machine editor called RAFCON developed at the Institute of Robotics and Mechatronics, DLR and is explained in detail in [14].

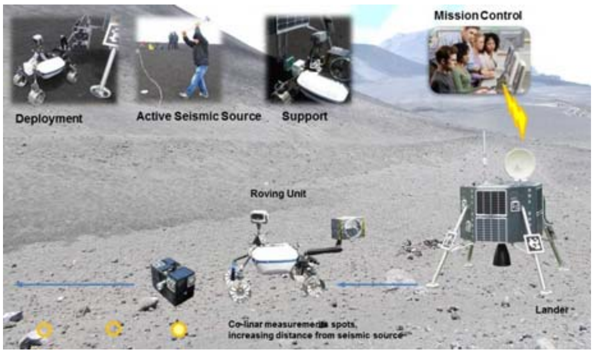

Fig. 2: Tele-operated active seismic experiment placing the sensor boxes along a line

The second experiment was to build a Y-shaped sensor array and measure the seismic profile using the natural seismic activity that happens at Mt. Etna over a period of few days. Fig. 3 gives a pictorial representation of this experiment.

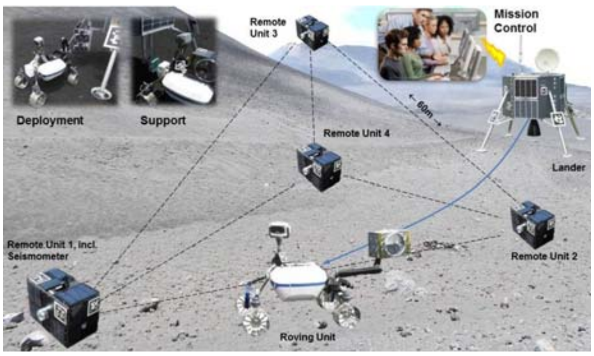

Fig. 3: Autonomous passive seismic experiment using four remote units in a Y-shaped configuration

For both these experiments, an effort was made to simulate an actual lunar mission as much as possible. The whole operation was done and monitored from a control centre in Catania. An image showing the approximate locations of the test site and the control centre using google earth is shown in Fig. 4.

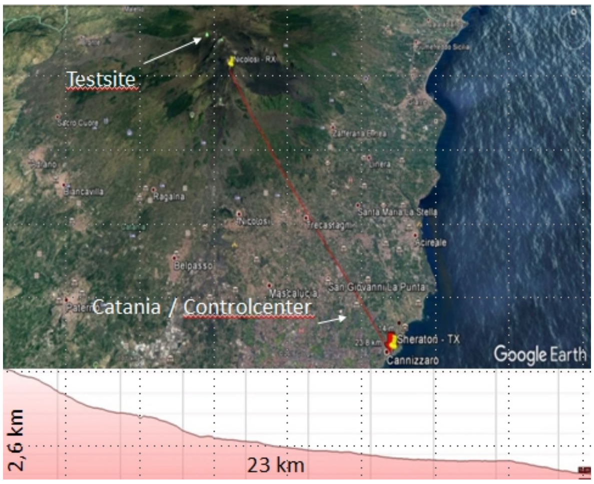

Fig. 4: Location of test site and control centre. Inlet: topographic profile

In addition to these main missions, we performed additional experiments during the campaign. These experiments comprised of Long Range Navigation Tests [13], Multi-Robot Mapping and Exploration as well as Sample Collection and Return Experiments.

4. ARCHES

The ARCHES project focuses on a heterogeneous robotic team[*] as a key technology for missions to address essential questions of human society. The overall objective of ARCHES is to provide solutions for autonomous and human-guided cooperative action of robots in human-unfriendly environments. The technologies developed in the project will be demonstrated for two application domains featuring harsh environments, namely the ocean and planetary surfaces. The key challenges therein are the

- Autonomous exploration, monitoring and assessment of the marine environment with underwater robots, featuring high-resolution observations in space and time (see Fig. 5)
- Long-term and large-scale in-situ exploration of extra-terrestrial environments in our solar system (see Fig. 6)

[*] Heterogeneous robotic teams: the term describes the combination of different capabilities of robots within one group, e.g. flying, rolling, and crawling with complementary sensor equipment.

Both the monitoring and understanding of ocean environments as well the exploration of planetary surfaces will strongly benefit from the deployment of autonomous and networked robotic systems. Robotic teams can provide the capabilities required for continuous, long-term, and large-scale data recording in these harsh and vast environments as well as for manipulation and direct interaction with the surroundings.

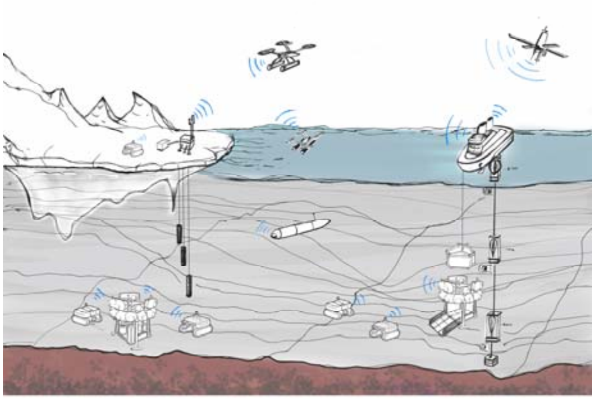
Fig. 5: Sketch of ocean exploration scenario with a heterogeneous team of robots

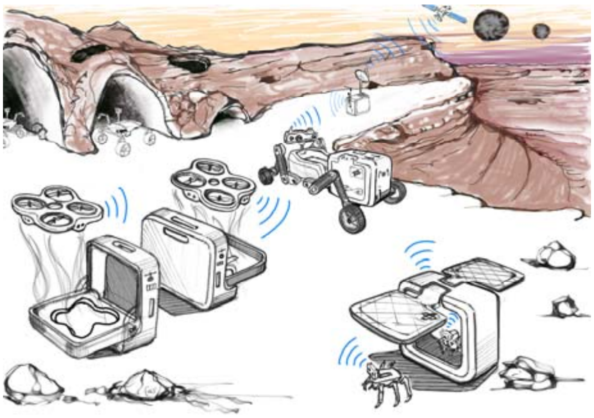
Fig. 6: Sketch of planetary exploration with a heterogeneous team of robots

Through ARCHES, networks of robotic systems will be developed that fulfill the requirements for robustness and reliability characteristic for both application domains. Existing hardware platforms consist of configurable carrier systems featuring modules for sensors and manipulators. Their configuration can be adapted to specific applications on different systems and across domains. The aim of the project is to develop approaches that allow robots to acquire, analyze, and interpret measurement data in an autonomous way. This requires concepts for autonomous navigation in unknown areas, interaction and manipulation in these environments, energy management systems and selforganizing communication systems, which allow communication between the individual robots as well as between the robotic network and mission control. Furthermore, a seamless interaction of robots and humans requires an interface that allows coordinating the robot team almost as intuitively as one would coordinate a team of humans. This way, non-robotics experts can efficiently participate in the mission planning procedure. The ARCHES project aims to develop common solutions for the aforementioned challenges and will establish cross-domain interfaces.

The goal of ARCHES is to improve the efficiency and effectiveness of multi-robot cooperation by moving the exchanged information from the raw data level to the semantic one. This requires high levels of introspection and autonomy from each team member, and an intelligent distributed reasoning mechanism with one or multiple humans in the loop. High-level commands do not have to be broken down into low-level actions, involving for example pixels and coordinate frames, but can be "affordance-" or "skill-based". In ARCHES, robots will collaboratively generate and exchange compact maps for autonomous navigation but also application-specific thematic maps.

The key scientific and technical objectives are the

- Collaborative long-term mapping by a heterogeneous team of robots, including the efficient generation and exchange of maps based on metric and semantic representation
- Relieve of human operators by enabling high-level control and supervision of robotic systems through interaction with the robots on a semantic level
- Exploitation of prior knowledge and synchronization of on-board local representations with off-board models to achieve high-level situational awareness of human mission control
- Substantial advancement of autonomous on-board robot capabilities for navigation, manipulation, decision making, energy management and communication
- Development of novel standardized modular interfaces
- Increase of the "Technology Readiness Level" of robotic technology for our key challenges and its evaluation through real missions or demonstration campaigns

In ARCHES, sensor data processing will be partitioned into onboard and online sensor data processing and off-board and offline processing, as visualized in Fig. 7. For highly dynamic systems (e.g. fast rovers, aerial robots, etc.), the onboard processing is further split into a real-time part for control and fast obstacle avoidance and an online part for all other, less critical, processing steps. Therefore, the following design principles will be applied to sensor data processing for heterogeneous multi-robot teams in both application domains:

- Local, onboard processing and aggregation of high-frequency and high-bandwidth data
- Online and onboard processing as far as needed to support local, online decision making for autonomous behavior of individual robots (communication links cannot be guaranteed at all times)
- Exchange of aggregated, low-bandwidth data (limited communication links, scalability)
- Local robot autonomy: Not every robot needs to have all raw data

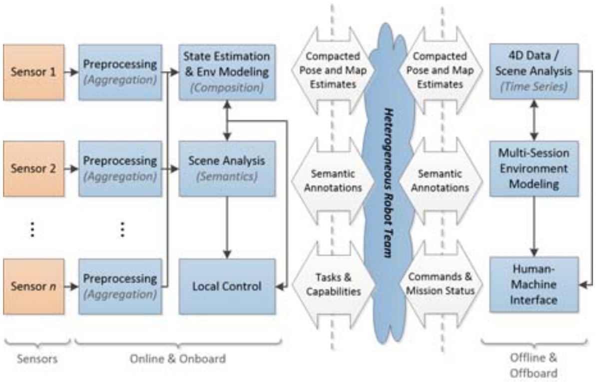

Fig. 7: General sensor data processing architecture

A first step in ARCHES towards autonomous multi-robot coordinated action was taken by analyzing data gathered by two of our LRU rovers during the final ROBEX demonstration mission on Mt. Etna in 2017. Both robots autonomously explored a target area while localizing themselves and creating a 3D map of the area, all sensor data being processed on-board the systems. For exploration, they employed an extended version of a frontier-based exploration approach [6]. The resulting datasets allow the evaluation of our methods for localization and mapping in a relevant space-analogue environment. More details on our methods and first results can be found in our upcoming publication [3].

5. Operational Aspects: from teleoperation to autonomy

In all fields of automation engineering the user interface is a crucial component that needs to be solved for broad acceptance. The usefulness of robotic systems is always strongly combined with the usability. This is why the first approach is to increase the user's immersion. Thinking this way the user interface for tele-manipulating a humanoid robot like Justin HUG was developed and demonstrated for different scenarios [9]. The user can see through the “eyes” of the robot and feel the real torques in the robotic arms. The user gets virtually connected to the robot and becomes strongly involved to the environment of the robot. A similar approach was the development of the MIRO surge robot [2]. The robot is used for minimal invasive surgery by the surgeon who can see a 3D image from the inside of a patient and feel the forces applied to the used instruments. Again, the operator can be separated from the robot and long distances may be bridged with this kind of system.

As the communication delays and disturbances increase with the distance that needs to be bridged, the level of commanding needs to be abstracted. First teleoperation from earth to an orbiting space shuttle with large time delays was conducted within the ROTEX experiment in 1993 [1] A direct teleoperation with closed loop feedback was tested in the space context in the frame of ROKVISS experiment in 2005 [10]. From January 2005 until November 2010 a 2-DoF robotic arm was mounted to the outside of the Zvezda-Module of the International Space Station ISS. By use of a force-feedback joystick at ground control the user could feel the robotic arm’s contact forces within a metal contour or could feel the force that is needed to apply to expand a spring. In that experiment it could be observed in practice how seriously the closed feedback loop suffers from signal delays. Even relative short delays of 20 ms cause challenges to the control algorithm. For human operators this delay poses also a big challenge. To investigate on the astronauts’ ability to command robotic systems with a force feedback joystick at ISS and a robotic system down at earth with Kontur an additional experiment was conducted [11]. Due to bandwidth limitations and signal quality, the level of connection from astronaut and robotic system needs to be optimized. Force feedback needs to be focussed on applications that profit the most from its features. This is typically the case when dexterous manipulation is needed or force feedback is used to assess situations.

To investigate further on that idea a robotic arm was set-up and equipped with a shovel. When taking a soil sample the reflection of the contact force of shovel and ground may be helpful to solve the task. Again, the signal delay is the bottleneck of the quality that can be achieved.

When thinking of a scientific observatory on moon that is setup and maintained by robots, much higher complexity needs to be solved. As shown in the METERON experiment a tablet computer could replace the HUG system and command the same humanoid robot Justin [12]. In that experiment the robot is working at the robotics institute and is commanded by an astronaut from the orbiting international space station ISS. Depending on the perception results of the robot different types of actions are offered to the operator. These actions are then initiated by the astronaut and the robot carry out the task on its own. Even when communication signal gets lost completely the task can be completed safely. The working speed and also the safety is increased dramatically by that advantage.

In future, all results of these experiments need to be used to develop an ideal way of commanding for every kind of application. The goal is to use as much immersion as possible and still be able to handle signal delay and disturbance in the communication channel. As a result, the immersion needs to be cut back to a level that is comfortable for operating astronauts in orbit and technically feasible in terms of bandwidth and signal delay. The most robust way of operation is a robotic system that is able to perceive its environment and rating different actions that could be taken as a next step. A fully autonomous robot would mean to replace the skills of a scientist by an algorithm. This is not recommended as the decision taking of human operators always involves a lot more parameters than only the factors bound to the task itself. Considering the consequences of each task execution is one of the things a human is in advantage of each robotic system.

6. Future Mission Concepts and Opportunities

The next future robotic missions will focus on the exploration of moon, mars and minor celestial bodies. Meanwhile the Global Exploration Roadmap GER3 [8] foresees three steps in the next decade, starting from earth orbit to the moon orbit, continuing with moon surface operations and applying these approaches later on to the martian environment (see Fig. 8).

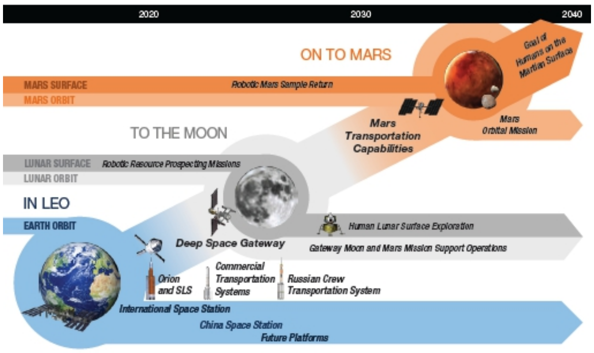

Fig. 8: The global exploration roadmap [8]

As described in the GER3 [8] the first robotic mission on moon might be a precursor mission with the objective of operating robots to install, maintain and operate permanent bases. ISRU (In-Situ Resource Utilization) is a key aspect of permanent operated bases on foreign planets, therefore many precursor missions, also planned by ESA for the near future, include these activities. In general, initially starting with full robotic driven missions while later resuming with human/astronaut cooperative mission is the common roadmap. Robotic precursor mission my focus on enabling the operation of single robotic assets to demonstrate the achieved capabilities. Subsequently, cooperative robotic systems comprising heterogeneous capabilities will be the next step to complementarily solve the challenges necessary for permanent operated installations, such as energy farms, oxygen generators scientific bases or even the visionary lunar village coming from ESA.

Furthermore, a lot of scientific questions concerning moon or mars are still under investigations. The overall search for live, the understanding of the composition and distribution of materials on and inside the planets, their overall origin and evolution, and of cause the question of how the universe has been formed and evolve itself. Sampling collection, inspection, in situ analyses and sample return will be robotic tasks of the next science missions. The robotic challenge common with all these tasks will be the mode of operation from a distance but also from orbiting and surface based stations. However the mode of operation can vary from the tele-operated case, with the human in the direct loop with the robot's controller through supervised autonomy towards the common goal of highly autonomous robotic systems (see section 5 operational aspects).

The robotic systems therefore will start with surface missions, as scientists have high interests in lower areas such as gullies, lava tubes and craters, as well as to reach permanently shaded areas and meteorite unchanged environments. For the establishment of permanent bases, the aspect of shielding and covering the bases against cosmic radiation inside these natural structures and shelters looks promising.

Currently several European activities focus on the development and enhancement of technologies for such missions. The H2020 space activities in the Peraspera framework (Compet-4) seek for the common development of base technologies for orbital space robotics but as well planetary exploration with the common goal of serious demonstration missions in relevant environment. In the ESA METERON (Multi-Purpose End-To-End Robotic Operation Network) framework, several sub projects are and will be established as experiments addressing validation of technologies needed to operate robotic assets on the surface of the Moon or Mars from a Lunar/Martian orbital station. The experiments in METERON will also serve as baselines for the HERACLES scenario which has the target to use the Deep Space Gateway (DSG) to deliver samples to scientists on Earth

Meanwhile ESA, DLR and its partner Agencies look for Mission opportunities with e.g. the Japanese space agency JAXA and the Russian ROSKOSMOS for common activities. Within the DLR cooperation with JAXA the flight opportunity during the HAYABUSA-2 mission has enabled the DLR to contribute the small MASCOT lander to this interesting Mission of the Japanese to the Asteroid RU-1999. A possible follow-up cooperation probably combined with the French space Agency CNES will allow DLR and CNES to contribute a small landing element to JAXA's MMX Mission which aims the research on the mars moon Phobos.

During the ARCHES project the scientific question of the deploying and maintaining a radio telescope infrastructure on the planetary surface will be in focus as well as scientific relevant surface exploration, sample selection and collection. The aspect of in-situ inspection and analyses will be furthermore a new aspect in this research project. To achieve this objective for a more widespread area and a longer period autonomous cooperative robotic assets will be used and heterogeneous robotic systems will cooperate together (see section 4). With the probably biggest robotic ESA Mission coming up, EXOMARS will underline Europeans role in planetary exploration with the landing of the rover element in 2020.

7. Conclusion and Outlook

As robotic systems become present in an increasing number of applications the interface presented to the human operator becomes more and more important. In industrial applications the focus for command interfaces is mainly set on flexibility, usability and cost. Other fields of application require concepts where the focus lies on reliability and safety even with delayed or interrupted communication. Within the ROBEX project the analogy between space and deep sea applications became clear. Both disciplines demand for semi-autonomous systems that are able to perform hazard avoidance tasks without additional user input. Furthermore, with growing complexity of robotic tasks in both fields of application, a collaborative team of robots seems to be promising to achieve the envisaged mission objectives. The tools that were developed to operate a single robotic system still need to be extended to the operation of several robots with different skills and a high level of versatility. For every aspect like communication delay, semantic scene analysis, tele-commanding and robust and safe system performance dedicated concepts have been developed in recent years. Nevertheless, all these concepts need to be integrated into one solution that leads to a demonstration of the described scenarios. Within the project ARCHES this challenging objective is envisaged in order to extend the cooperative heterogeneous teams of robots to operate in larger scales and longer time frames without any user input.

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