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Preliminary Results for the Multi-Robot, Multi-Partner, Multi-Mission, Planetary Exploration Analogue Campaign on Mount Etna

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Abstract

This paper was initially intended to report on the outcome of the twice postponed demonstration mission of the ARCHES project. Due to the global COVID pandemic, it has been postponed from 2020, then 2021, to 2022. Nevertheless, the development of our concepts and integration has progressed rapidly, and some of the preliminary results are worthwhile to share with the community to drive the dialog on robotics planetary exploration strategies. This paper includes an overview of the planned 4-week campaign, as well as the vision and relevance of the mission towards the planned official space missions. Furthermore, the cooperative aspect of the robotic teams, the scientific motivation, the sub task achievements are summarised.

Keywords: robotic, exploration, mobile robotics, rover, human robotic exploration, teleoperation, in-situ science

1. Introduction

1.1 Scope

The intention of the "*HELMHOLTZ Future Project"* ARCHES, is to establish and strengthen cooperation in the German HELMHOLTZ research centres in the field of robotics. The two-application field of deep sea and space exploration has been defined as high priority and builds the use cases for the ARCHES [1] research. The consortium of the Helmholtz Centres consists of DLR, AWI, GEOMAR and KIT, while the initial project period has been foreseen from 2018 to 2020.

The technology goal of the Project is the development of heterogeneous, autonomous and interconnected robotic systems. Not only the robots are heterogeneous, the future fields of application span from the environmental monitoring of the oceans over technical crisis intervention to the exploration of the solar system. Especially for the Helmholtz Association mission of finding answers for the essential questions of the human society, autonomous robot networks will become a key technology.

In particular, solving tasks like monitoring and understanding the ocean environment or exploration of the solar system will strongly depend on the deployment of autonomous and networked robotic systems. They will provide the required capabilities for continuous, long-term, and large-scale data recording as well as for manipulation and direct interaction with the surroundings. Robots allow monitoring and object manipulation on a large scale in harsh and vast environments. Accordingly, a robot network will be created within this project, which acts as an enhancement of human perception and as an extended arm for human manipulation.

Since the beginning of the project, besides the new technology and method developments an increase of the technology readiness of the systems and methods has been defined as high priority. Especially the usability for the application cases has been in focus.

This work plan was implemented as a continuous and iterative process in the project, culminating in a joint and final demonstration validation. Thus, a space and a deep see demonstration has been planned. The space demonstration mission initially for summer 2020 planned on Mt. Etna is the focus of this paper. This mission has been postponed to 2021, and just in the first half of this year again postponed to 2022, due to the COVID situation.

1.2 Robotic space exploration goals and ambitions of the near future

The next decade will experience an increasing global commitment to exploration, where humans will arrive again on the lunar surface, where the ISS station will be reach EOL, and its successor, the Lunar Gateway will be established in the lunar orbit to path the way for human mars exploration missions after 2030. Several lunar exploration programs, traditionally established by agencies and countries, but also commercial activities like the US CLIPs program and the commercially available launches, e.g. Space X, Blue Origin and Virgin will decrease the cost of exploration and enhance and increase the amount of missions [2].

Thus, also the German and other European space agencies have foreseen several activities in this direction. The DLR research institutions are involved in the JAXA-MMX (Martian Moons eXploration) mission [3], where CNES and DLR together build a 30kg rover for the Marian moon Phobos, to be launched in 2024. This mission is a successor of the 2018 landed MASCOT [4],[5] payload on the Asteroid Ryugu, which has been launched as payload with the Hayabusa II mission of JAXA. The current activities at ESA to access the lunar surfaces have been initially started with the next lunar lander (NLL), continued with the HERACLES [6] mission concepts where a lunar lander with approx. 150 kg landing payload should have been landed on the lunar surface. Finally, since 2019, in agreement with the US and the ARTEMIS program, ESA has turned the development into the direction of the EL3 (European Large Logistics Lander), where an approx.1.5-t landing mass for the lunar south pole is planned. In this scenario, the EL3 lander was to serve as a system for repeated reuse with several missions in succession [7].

The ARCHES demonstration missions serve to test and validate scientifically relevant mission scenarios; in particular, the validation of technology and method developments for the use of robots in such missions is a central element of the joint mission.

2. High-level mission description

The high-level demo mission concept and idea is explained and illustrated in this section.

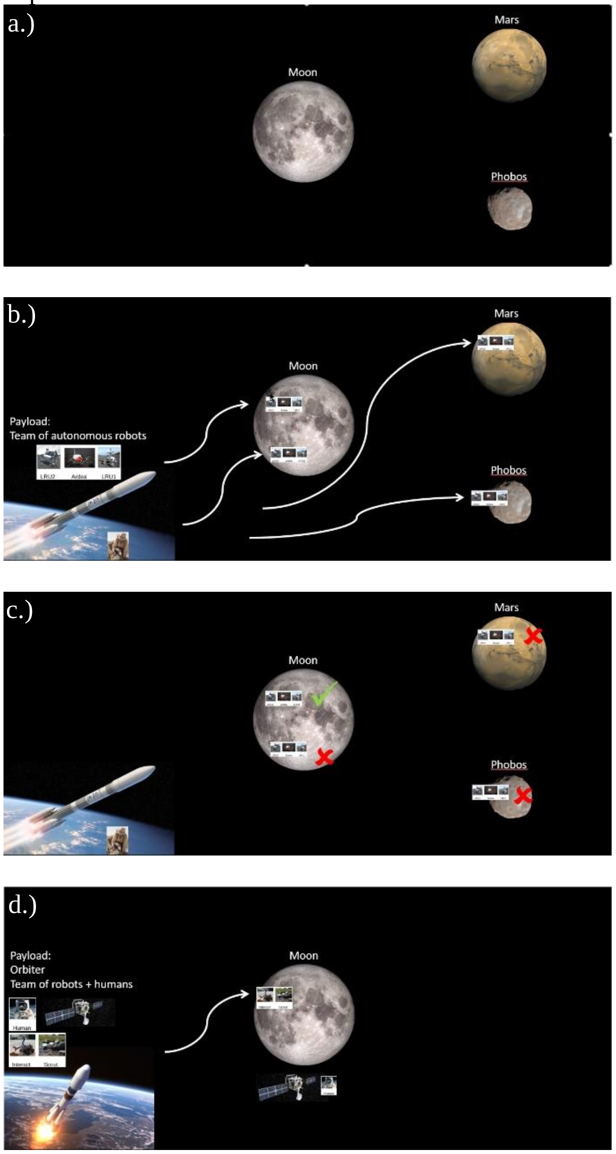

Fig. 1: High-level Mission Timeline

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The overall mission time line underlays a story, that prior to the agency's exploration goals, the three planetary targets, which beside are from high importance for DLR research, are evaluated as possible earth moon, mars or the Martian moon Phobos, has been evaluated as future top goals and need to be analysed further (Fig. 1a). As a precursor missions to all three targets (Fig. 1b), the moon has been chosen as primary target of interest for the first mission (Fig. 1c - Part I: Geo Mission I). A while later, some more exploration missions are foreseen to take place (Fig. 1d - Part II: Geo Mission II) and establish permanent bases and infrastructure on the lunar surface e.g. a Low Frequency Antenna Array (Part III: LoFar Mission), or a seismic network (ROBEX [8], [9]).

At any time of the developments in ARCHES, which aims to enhance the operational aspect of team and cooperative robotic assets in harsh environments, the focus of this demo mission is to consider the aspect, of how cooperative assets of robots will be operated in a direct tele-operation aspect, in a shared autonomy paradigm and with a high degree of autonomy.

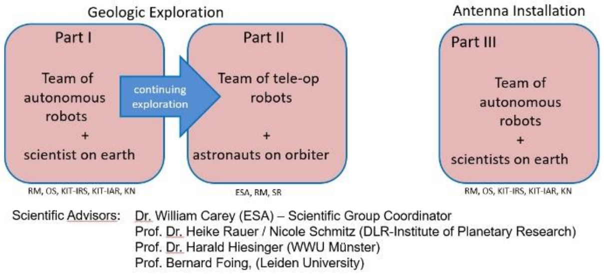


Fig. 2: The three mission sequences

Regarding the upcoming robotic lunar exploration plans of US (ARTEMIS), ESA (EL3), JAXA (MMX) and several other nations, the operational aspects of robotics are a key to future developments.

2.1 Part I: The Geological Mission I

Therefore, the geological mission I is representative for the period where no Lunar Gateway is in existence. Therefore, the mission could be considered as robotic pre-cursor mission, where the robots are operated from earth and a certain number of autonomous functionalities are needed to obtain speedy and efficient operations of the robotic network deployed on the lunar surface. In particular, a shared autonomous mode, where the interaction between the operators/scientist on the ground, is in focus of this mission segment, since simple machine-based decision, (e.g. navigate left, or right passing an obstacle) will be decided locally on the machines. In contrast, definitions of scientifically interesting POIs or targets and, mission crucial decisions are envisioned to be taken in the control center at earth. The geological mission I takes place in the period before the lunar Gateway and is therefore the robotic pre-cursor mission. The robots are used to explore the previously unknown environment and extract geological samples.

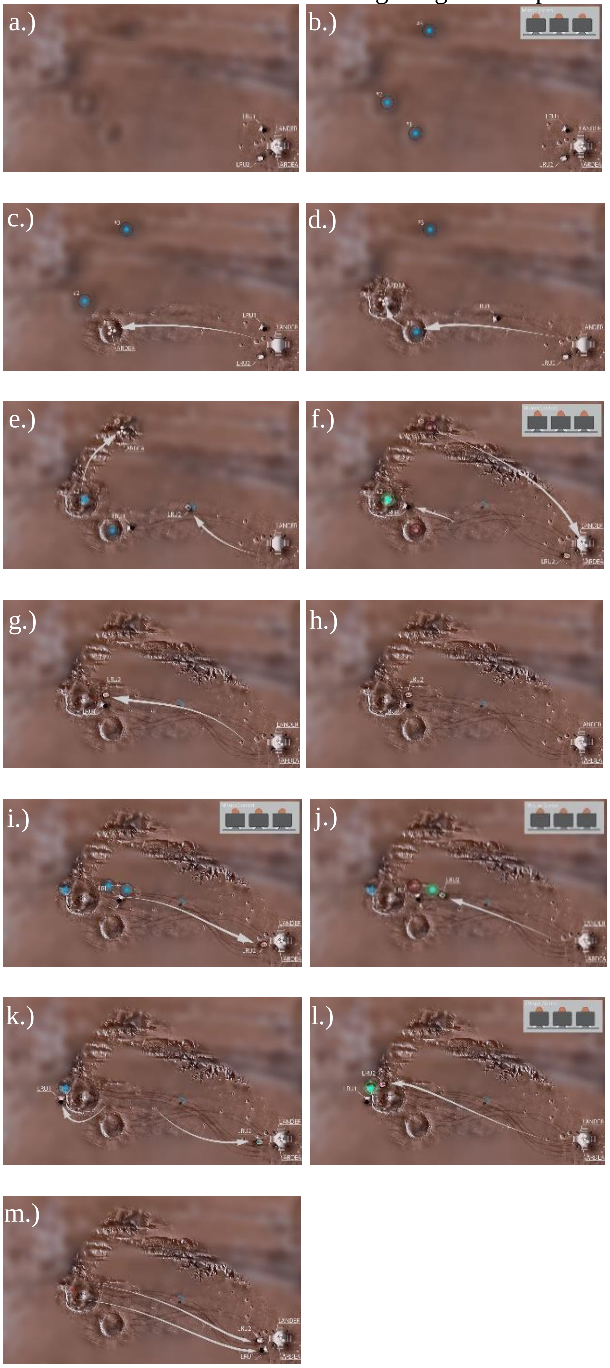


Fig. 3: High level, geological Mission I hidden object scene timeline

In order to perform these tasks in an efficient manner, the robots have multiple autonomous functionalities to provide the operators on Earth an easy interface to guide the sample extraction. The idea here is that lower level mission tasks, like reaching a certain location are autonomously performed by the robot, whereas higher level tasks, e.g. decide which geological location should be investigated or which samples should be extracted, are directly controlled by the operating team on Earth. Fig. 3 depicts the mission sequence for this mission. For the geological mission three robots and the landing system are deployed. In the beginning the three robots start their mission next to the landing system, as it would be also the case for an actual mission (Fig. 3a). At this stage, the surroundings is only mapped with a coarse resolution based on satellite imagery or not known at all. Operators on Earth select multiple Point of Interests (POI) based on this map (Fig. 3b). These POI are potential scientific interesting regions, which shall be explored by the robotic team. Instead of sending the entire robotic team directly to all POIs, the flying system, ARDEA, will be send to them first (Fig. 3c). This is a more efficient and faster way to investigate the given POIs instead of sending a roving unit. Once a POI is classified as scientific interesting based on the data obtained by ARDEA, the rover, LRU 1, is send to its position (Fig 3d). Meanwhile, ARDEA is flying to the rest of the POIs. Depending how far apart the selected POI is from the landing system, the second rover, LRU 2, will be send out to place a communication repeater box at a strategic point to ensure communication coverage (Fig. 3e). Whenever LRU 1 reaches the selected POI, it sends further scientific data back to the operations team on Earth. LRU 1 has more scientific sensors on board in order to make further investigations compared to ARDEA. If the scientific team decides against a sample extraction from the current reached POI, LRU 1 drives to the next one in the list, which was created by the data recorded from the flying system (Fig. 3 f). Meanwhile, ARDEA is flying back to the landing system, once it reached all initial POIs. Once LRU 1 reached a POI, which is classified as scientifically interesting by the scientists on Earth, LRU 2 will be send to it (Fig. 3 g) for sample extraction (Fig. 3 h). While LRU 2 is returning the collected samples to the landing system, LRU 1 keeps on exploring the surroundings for more potential samples (Fig. 3 i). Once it finds samples for extraction, LRU 2 is send to collect them. This process is repeated until the operation team on Earth commands otherwise (Fig. 3 j-l). Once the sample extraction is completed, all robotic systems are traversing back to the landing system (Fig. 3 m).

2.2 Part II: The Geological Mission II

The geological mission II is focused on the aspects of a later mission, a follow up mission to the lunar surface in a time phase, where a gateway and human presence in the lunar orbit are established and thus, advanced telerobotic concepts such as high fidelity tele-operative control with visual and haptic feedback are to be established over short latency communications. Furthermore, here the aspect of shared autonomy will play a key role in operating the robotic network, to save astronauts time and focus the attention to important tasks.

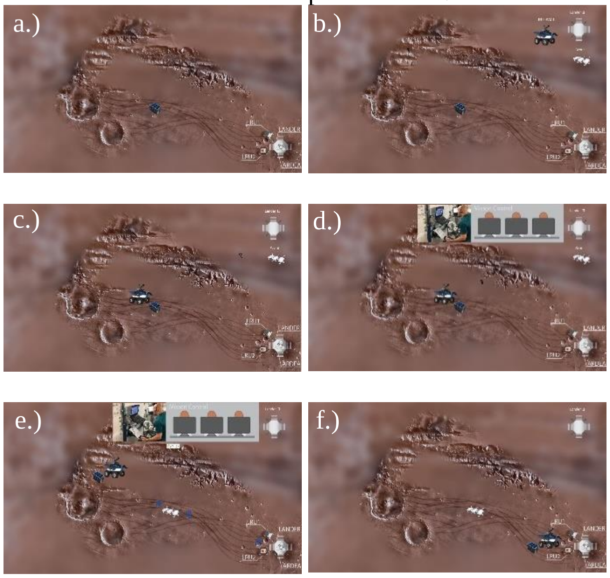
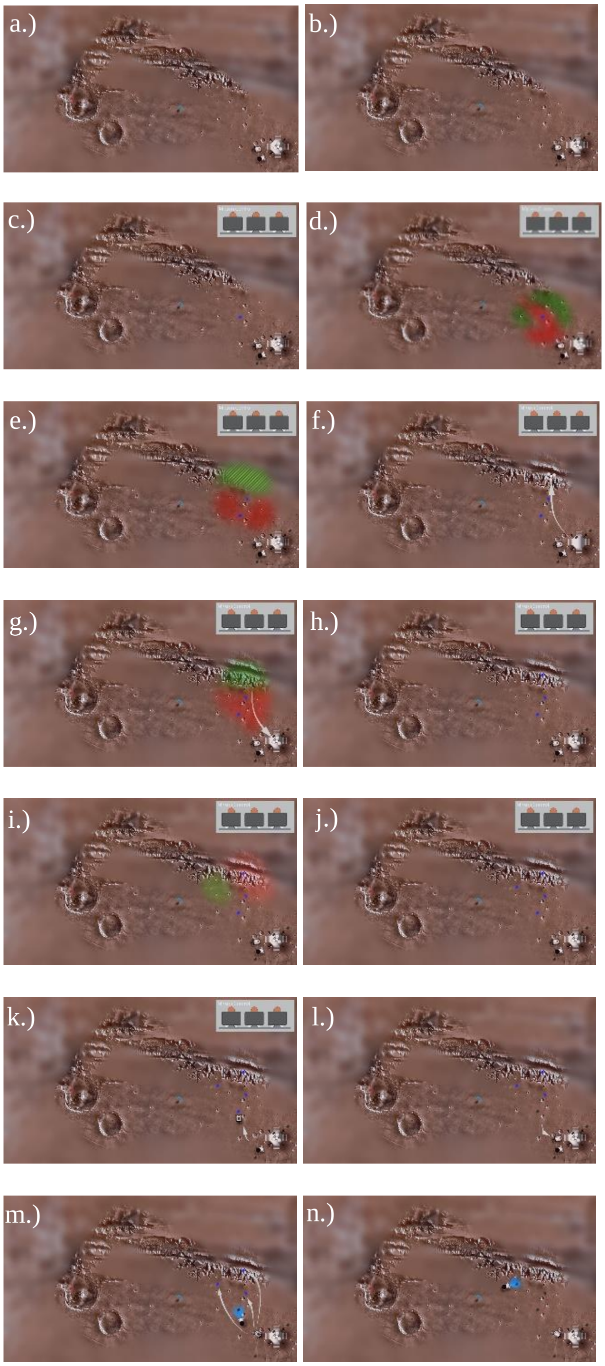


Fig. 4: High level, geological Mission II hidden object scene timeline

The cooperative concept of this mission scenario is roughly visualized in the Fig. 4. The scenario starts in Fig. 4a, where the sample container from the ARCHES Geo Mission I is left behind, and the lander of the Geo-mission I is still in place to provide power and communication. After the landing of the second lander Fig. 4b, the Interact and the Scout Rovers are delivered to the planetary surface to proceed with their tasks. First, the Interact Rover drives to the sample container left behind from the previous mission (Fig. 4c). Since the pickup and handling process of the container is complex, mission control located in the lunar orbit (e.g. gateway), during this period, would be switched to teleoperation mode, with haptic and visual feedback, to proceed with the collection phase (Fig. 4d). In the following period, the Interact and Scout Rovers proceed to explore the environment together, to find new points of interest. Should a point of interest be located outside the communication connection range between the lander and the Interact rover, the Scout rover can serve as communication relay for the Interact rover. This enables the collection of samples from locations farther away from the lander (Fig. 4e), while still providing high fidelity force and visual feedback (with connection latency below 800 ms). In contrast with the Geo I mission scenario, where the sample collection process are carried out with autonomous operations, and shared autonomy, using high level commands from the control center on Earth over multi-second latencies. Finally, the Interact Rover returns the collected samples back to the lander from mission I (Fig. 4f), ready for a sample return demonstration.

2.3 Part III: The Antenna Installation / Operations

To scope also the robotic aspect of installation and maintenance, this mission section is considering the scientific high rated ambition, to install a low frequency radio antenna array on the lunar surface, to explore the deep of the universe.



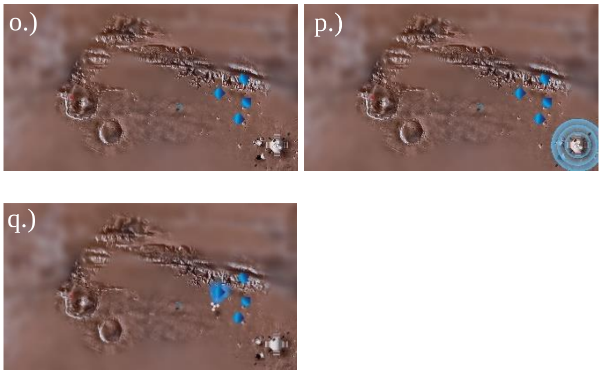


Fig. 5: High level, Antenna Installation hidden object scene timeline

The third mission aims to build up and operate infrastructure and to take care of its maintenance with robotic units. For that a low frequency radio antenna array is supposed to be installed on the lunar surface. This is of high scientific interest in order to study the universe. Each antenna of the array is capsuled in a payload box, which will be deployed by the robotic team. For the mission the systems of mission I are used again. For this mission, the map, which was gained by the previous missions, is used again (Fig. 5a). Based on this map the control team on Earth picks the first location for an antenna box (Fig. 5b). According to the hypothetical placement of the first box, positions are evaluated for the next placement position (Fig. 5c). In this case red indicates a rather bad location, whereas green a good location. Once another box is virtually placed, the map is updated (Fig. 5d). If a potential good location lays in a region, which is unexplored (Fig. 5e), the control team can make the decision to further explore that region with ARDEA (Fig. 5f). Based on the updated map information, the control team can make further decisions (Fig. 5g-h). This procedure is continued until all boxes are virtually laid out (Fig. 5i-j). Next the actual boxes with the antennas can be placed on the field with the LRU 2 (Fig. 5k-m). Meanwhile LRU1 is driving to three reference boxes of the array to measure the precise location of them (Fig. 5n). Those three reference boxes serve as anchors for precise radio-localization in the next step. After all boxes were deployed, the antennas can be unfolded (Fig. 5o) and the calibration procedure can be started (Fig. 5p). This calibration procedure uses a novel developed radio-localization system to precisely determine the position of all array elements (payload boxes), and dedicated low-frequency transmitters for phase calibration. The antenna array is now ready for operation. ARDEA is flying to the boxes first also perform a visual localisation, additional to the radio localisation, further on ARDEA performs inspection and maintenance on the antenna array (Fig. 5q). Detail scientific and operational aspects on the deployment of a low frequency antenna array on the lunar surface has been discussed in [11].

3. Infrastructure and network concept

As it was already executed during the ROBEX mission in 2017, the site is located on the Mt. Etna "Piano di Lageto" area at an altitude of 2600 m. The site includes an experiment area of more than 500 x 500 meters, while the core experiment will take place on a smaller spot. Furthermore, the area chosen is feature rich for scientific analyses, but also for different terrains, slopes and e.g. the 70 m diameter Cisternazza crater with geological visible geological layers.

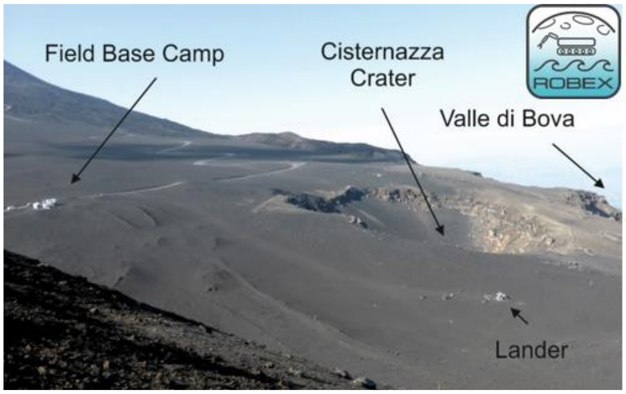


Fig. 6: Field Side of ARCHES demo mission

A network infrastructure will be established from the city of Catania to the mountain side. The ground segment of the analogue mission will be located in a hotel in Catania where the crew and equipment will be accommodated but also a mission control room, and a scientific operations room will be established [10], [9]. A similar setup for the directional radio links as for the ROBEX demonstration mission will be implemented. The air-line distance between the ground segment and the filed base camp is about 23 km. Instead of one radio link, it is planned to install a second radio link and use link aggregation in order to further increase the data throughput.

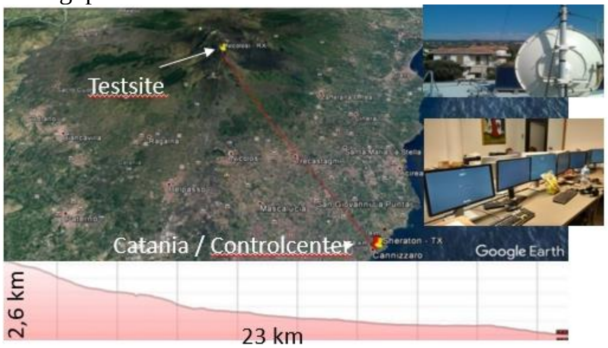


Fig. 7: Control room and field side link

The directional antennas of the ground segment will be located on the roof top of the hotel and the directional antennas of the field base camp will be installed on one of the four 20 feet containers which are part of the base camp setup.

Furthermore, from the upper side of the mountain, several antennas will distribute the communication network. There will be a directional link from the base camp to the lander where the network is further distributed. Moreover, the network comprises several access points and two movable sector antennas providing network coverage to several spots on the side. For mission demonstrations reasons, also WIFI repeater boxes (3) can be individually replaced in the field by the light weight 2 robot and can enlarge either the Lander network or the field base camp network.

Since the mission control is not only located in the Catania ground segment, regarding the story line of the second geological mission, the Catania control room would be inside the Gateway, a supervised connection to the ESOC in Darmstadt from ESA is established, where mission control for some of the experiments inside the geological II mission will be planned and supervised.

3.1 Modular Approach:

The activities in ARCHES also follow a modular approach [12]. With the intention to provide flexibility and versatility to the mission, several standardized modular payload carriers and specific-purpose robotic tools were developed. While the former encapsulates different scientific instruments and infrastructure equipment in its interior, the latter are attached to the LRU2 body and can be quickly accessed at any time. All of these elements have a common interface which can be docked by the active coupling partner of the ENVICON docking interface system [13]. This active interface is the end-effector of the LRU2 robotic arm which allows the rover to manipulate payloads, exchange tools, and perform scientific tasks in the terrain. With this strategy, the robots become multi-function, which underlines the heterogeneous capabilities of the ARCHES robotic team and their ability to be adapted to the needs of the mission.

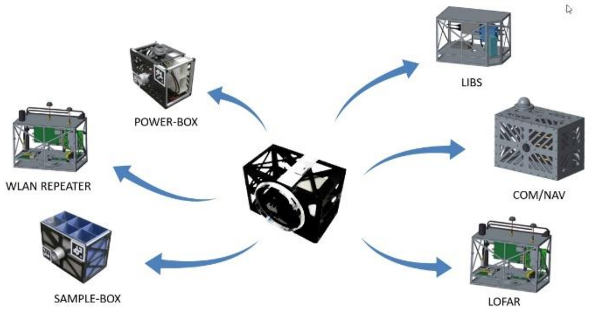


Fig. 8: Modular Payload Carriers in the ARCHES scenario

For the ARCHES demonstration mission, 21 different payload carriers (Fig. 8) have been manufactured: 2 sample containers, 2 Wi-Fi-repeater modules, 1 LIBS module, 3 Radio Communication and Navigation modules, 4 LOFAR modules, and 9 Power Supply modules.

3.2 ARCHES Team Members

The following robots are used in the ARCHES demo mission team:

- The autonomous Drone ARDEA
- The Scout Rover
- The Interact Rover
- The LRU 1
- The LRU 2
- The Rodin Lander

Fig. 9: Team of Robots in the ARCHES Scenario

Since the aspect of ARCHES is the cooperation/interaction and cooperative exploration of heterogeneous robotic assets, to succeed much faster with their work task than single assets would do, the complementary capabilities are key aspects of the team:

ARDEA is a 2.7 kg aerial hexacopter, which is designed for autonomous scouting [14]. Due to its frame and stack design, the propulsion system can be exchanged based on the mission objectives. With that it is also possible to adjust it for a lunar mission. The flying robot is equipped two stereo camera systems, which cover a wide field of view (240° vertical and 80° horizontal) [15]. With that ARDEA is not just able to navigate robustly without any GNNS, but also able to perceive its environment in an efficient manner. As a result, the drone can create dense 3D maps onboard the system and online. Furthermore, it provides valuable information about the underlying terrain. In order to achieve high resolution maps, ARDEA flies between 3 to 5 meters over the surface. Since the drone cannot be manual piloted in an actual space mission, due to communication delays and also to ensure an efficient action execution, ARDEA has multiple autonomous skills [14][16].

The Scout rover is a highly agile 18 kg robotic system with a novel compliant rimless wheel to step over obstacles. The simple system uses one fully rotational actuator per wheel. Together with the compliant spokes and spine, the rover can achieve energy efficient, dynamic, and robust locomotion in highly unstructured terrains. The main goal of the "Scout" rover is to access areas on extra-terrestrial planets that are inaccessible for current rovers, e.g. crater walls and planetary caves. The system is not only capable to traverse rocky obstacles, but also to "paddle" through soft sand pits, which could entrap conventional wheeled systems. On Earth, the robust system can be used in agricultural robotics, or to help rescue people from hazardous areas. In the geological mission II, it explores the area and also works as a WIFI relay for the ESA Interact Rover.

Developed at the ESA Human-Robot Interaction (HRI) Laboratory, the Interact Centaur Rover is a 4x4 wheeled rover combining a camera head on a multi-DOF robotic neck system, a pair of highly advanced force sensitive robotic arms designed for remote force-feedback-based operation and a suite of proximity and localisation sensors. The ESA Interact Rover will be used in the second geological scenario, and will be operated in a teloperated manner, collecting the sample container from the geo-science I mission part, further more Interact will collect additional samples.

The Lightweight Rover Unit (LRU) is the prototype of a mobile robot for exploration in unknown, rough and difficult-to-access terrain. The LRU combines a variety of state-of-the-art technologies developed at the DLR Institute of Robotics and Mechatronics, such as the drive and steering units, whose motors were showcased in in the ROKVISS experiment on the ISS from 2005 to 2010 [17],[18]. A stereo camera and the multi-award-winning semi-global matching stereo method (SGM) give the robot the ability to perceive its surroundings in 3D. From this, the rover calculates maps of its surroundings and then autonomously [19] navigates to pre-defined destinations in unknown and uneven terrain. This autonomous navigation (long distance navigation dataset: [20]) is essential, as signals from Earth take seconds or minutes, making direct remote control difficult. The addition of a robotic arm mounted on the system allows the LRU to manipulate known and unknown objects. In the ARCHES Scenario the LRU1 is equipped with a scientific spectral imager and a landing platform for the drone ARDEA. The LRU2 is equipped with a payload carrier and a robotic arm to handle the payload boxes and the tools.

In this scenario, the lander RODIN is the stationary unit that is used as a communication node, payload carrier, power supply or battery charging, Wi-Fi distribution and for pre-processing, storage of data.

RODIN has been initially developed as a prototype for a lunar lander (ESA-NLL) by DLR Institute of Space System and modified for ARCHES.

3.3 ARCHES / LRU2 Tools

During the ARCHES mission, the LRU2 rover with the use of its robotic arm and modular docking interface not only can manipulate several payload modules (e.g. LIBs payload module or Soil Sample container), but also connect to three different tools (Fig. 10) in reachable holders mounted on the rover's body.

Fig. 10: Manipulation tools on the LRU 2 for the ARCHES scenario

The Karlsruhe Institute of Technology (KIT) Hand tool is a five-finger hand utilized for grasping rocks. With two motors actuating ten degrees of freedom, it has cylindrical grasp force of 24.2 N, hook grasp of 120 N, and closing time of 1.3 s [21]. The Segregation tool is used to separate one rock from another when they are all gathered in the same place. This facilitates the grasping task to be performed by the KIT hand. The Scoop is an aluminium tool which is able to collect soil samples from the terrain and store them in the Sample Soil container.

4. Scientific background and Operations concept

The first part of the ANALOG-1 campaign was first reported in [22], where ESA astronaut Luca Parmitano, on board the ISS, controlled a rover at an analogue site close to ESTEC in November 2019, to simulate a surface mission scenario segment of a notional European Large Logistic Lander (EL3) sample return mission. Further insights on ANALOG-1are also detailed in [22]. It is a part of the Multi-purpose End-To-End Robotic Operations Network (METERON) initiative - which since 2009 through 12 ISS-to-Ground experiments exemplified by haptically coupled telepresence in INTERACT [22], and supervised autonomy in SUPVIS Justin [22].

For the second part of the ANALOG-1 campaign, the following objectives still remained open following the successful implementation of the first part in the 2019 experiment. Specifically, these objectives were:

1. To obtain data on the task duration (navigation, hazard avoidance, sampling, site survey) during a lunar/geology exploration mission, following different strategies and evaluate the differences, especially in terms of speed of execution/reactivity (*addressed but with reduced representativeness*).
2. To evaluate the benefits for orbital control vs ground control, by comparing qualitatively efficiency vs time to complete activities as well as qualitatively the operations efficiency (*ground control was not included so comparison not feasible*).
3. To demonstrate and evaluate the versatility of the developed tools and techniques on rover/orbital control station side by performing tasks in unstructured (geology) and structured (system maintenance) environments (*structured tasks not addressed and unstructured tasks with reduced representativeness*).
4. To further evaluate efficiency of having a geology-trained astronaut (*addressed, but with reduced representativeness).*

In December 2019 an agreement was concluded to integrate the ground test campaign of ANALOG-1 as part of the ARCHES activity. As mentioned previously, the ARCHES analogue demonstration on Mt. Etna consists of three distinct exploration demonstration missions which are however, linked: a geological exploration scenario involving in-situ analysis, termed Geo I and sample return scenario termed Geo II, and a third scenario, an antenna installation. The Geo I and Geo II demonstration mission scenarios of the ARCHES campaign are the focus of this section of the paper and provide the opportunity to address certain aspects of the four objectives of ANALOG-1 presented above, through the theme of a symbiotic partnership between rovers and humans. All of the demonstration missions are foreseen to be performed in the third week of the overall mission timeline.

4.1 Geo I - In-Situ Analysis:

The first geological scenario focuses on a cooperative heterogeneous team of robots, consisting of two wheeled rovers (LRU1 and LRU2) with a flying drone (ARDEA) – three robotic assets – which will fully autonomously and in a shared autonomy approach explore the site of interest and perform scientifically triggered remote spectral imagery, LIBS (Laser Induced Breakdown Spectroscopy) measurements including complex sample selection, analyses and collection with various robotic tools. The primary focus of Geo I is on the technical demonstration of cooperating autonomous robotic assets, with the secondary objective to demonstrate the end-to-end scientific process of sample selection including the verification of a ground control room with mission control and scientists, to verify and high-level command in a shared autonomous manner, sub-mission sequences. This includes online review and reactions on scientific data, acquired in the field and send back to the control station.

Geo II - Sample Return:

The second geological scenario will implement the MIRACLES mission and will focus on the control and coordination of the mission from the Mission Operations Centre (MOC) as well as the interaction and involvement of a geologically trained astronaut to teleoperate a highly dexterous rover with robotic arm while interacting with an operations team and science team on Earth. A fourth robotic asset, the INTERACT Rover will also perform site surveying through supervisory control from a control room at the European Space Operations Centre (ESOC), with the interaction of a team of scientists. A fifth robotic asset, a Scout Rover, will enable an extension of the range of the INTERACT Rover through a coordinated positioning of a wireless repeater. This sample return scenario will address the following:

- Several aspects of visual and haptic feedback, including shared autonomy, to enhance the capabilities of the astronaut's actions to operate the INTERACT rover.
- Demonstration and validation of operational concepts.
- Demonstration of cooperating robotic assets.

4.2 Preparation Activities:

Prior to the campaign itself for both the geological exploration and antenna installation, the field-test site has to be surveyed in order to obtain a good understanding of the environment, specifically the geological context, together with the identification of Points Of Interest (POIs) and Keep-Out Zones (KOZs).

4.3 Out-of-Scenario and In-Scenario Teams:

The Out-of-Scenario team consists of a number of ARCHES team members that are involved in preparation and implementation of the Geo I and Geo II missions. The In-Scenario team consists of a number of ARCHES team members that are only made aware of sufficient data and resources to enable them to view their activity as executing a real lunar exploration mission, i.e., their situational awareness will be limited to providing them with surface imagery from the Interact rover, interaction with the Mission Operations Centre and astronaut operator. The In-Scenario team (or Science Backroom) will perform what is referred to as the 'MIRACLES' mission, which has the overarching mission objective to explore, collect and return a suite of samples to Earth, using in-situ instruments to assist the selection of samples.

4.4 Science Backroom Procedure:

The Science Backroom team will begin with the orbital imagery of the field test site identifying the POIs and KOZs defined from the site survey completed several months prior. The KOZs will show those areas where the Interact rover should not go, and the POIs those scientifically interesting regions which could be explored further to look for rock or soil (regolith) samples to collect. The Surface Operations team and the Science Backroom will work together to define safe traverses to provide a 'ground-truth' data to explore as many of the POIs as feasible within the time available. The traverses need to be closely coordinated with the KIT Scout Rover robotic asset (i.e., performs a wifi repeater function) to ensure continuous communication. See section 2.1 for a detailed sequence of activities. The data collected from this activity could in principle provide for example 10-15 potential sampling sites from the originally defined POIs from the orbital imagery.

The 'ground truth' data collected during the Geo I activity is analysed offline by the Science Backroom team to prepare for the sampling activities of Geo II (the MIRACLES mission), reducing the 10-15 sampling sites to for example 5-6. Based on this assessment the Surface Operations team will then plan the rover traverses based on the inputs received from the Science Backroom.

4.5 Sampling Activity:

The In-Scenario science team will support the astronaut operator in the sampling process, and the Surface Operations team will support the astronaut operator in carrying out a safe traversing of the terrain. A TBD number of samples will be collected following discussions between the astronaut operator and the in-Scenario science team.

5. Preparation achievements for now:

Since the pandemic situation has also influenced the lab access and all the preparation activities for this mission, the overall tasks, especially when hardware implementation is involved are barely delayed. Nevertheless, many achievements and probably more solid developments could be tackled and are currently in the final fine-tuning for the mission.

5.1 LIBS test achievements

With the laser-induced breakdown spectroscopy (LIBS) module, elemental analysis of rocks and soils can be performed. It is built from commercial components (laser, spectrometer, micro-controller), weighs about 1 kg and fills only a small part of the volume of the standardized payload carrier. A Nd:YAG laser with 8 mJ and 6 ns pulses at 1064 nm is used to create the micro plasma. The spectrometer covers a range of wavelengths of 550−770 nm with a resolution of 0.7 nm. An integrated scanning mirror allows for the spectra being acquired along a curved line on the sample's surface. Data acquisition and work flow control is managed by a single board computer which also transfers housekeeping and scientific data to the rover network. The scientific data is then forwarded to the operation center where it is visualized and analysed with a dedicated GUI.

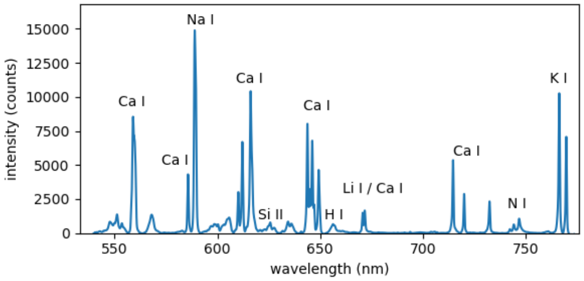


Fig. 11: LIBS spectrum measured by the LRU2

The first LIBS spectrum measured by the LRU2 with the LIBS module is shown in Fig. 11. Major rock-forming elements such as silicon, calcium, sodium, and potassium can be seen as well as minor and trace elements such as hydrogen and lithium. The emission of nitrogen is a result of the breakdown of the ambient atmosphere. The iteration of the instrument and the final manipulation of the LRU2, when placing the LIBS instrument on a stone is shown in Fig. 12.

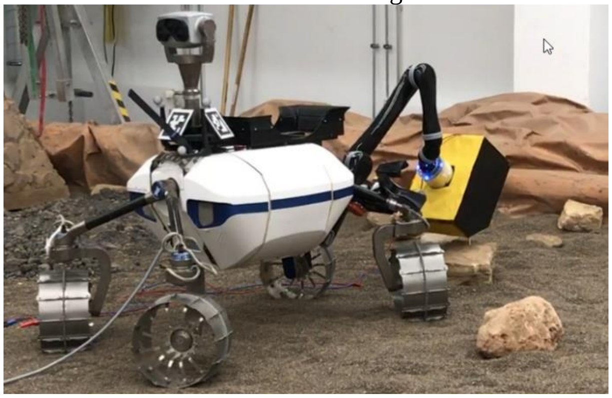


Fig. 12: LRU2 places the LIBS Payload Instrument on stone in the lab

5.2 Object detection / Navigation achievements

Besides the rough localisation for navigation purposes, a second, more precise method is required for manipulation tasks.

The visual perception in a planetary exploration scenario can be divided into two cases. One the one hand introduced object instances from Earth, such as the lander, the payload carriers, or the different robots (see Fig. 8 and Fig. 9) are well known. On the other hand, the local environment is unpredictable and thus unknown. Therefore, separate methods addressing the attributes of both applications are required.

In the case of known objects it further can be divided between roughly localising an object from far away to approach it or a precise estimation for manipulation purposes. Detecting familiar objects from far away mainly applies for the flying system, since it is meant to fly further away to explore the environment.

Crucial navigation capabilities of the flying system are finding its way back to a landing spot. If the localization algorithm has accumulated drift or if the roving unit has moved, it is desired for the flying system to find these landing spots again. Yet, it is not just enough, to detect the objects, but it is also mission critical, that the object detector outputs a confidence measure. This is crucial, since the system should just attempt a landing, if it is confident enough to have detect the desired landing systems. To this end, another navigation achievement is the development of a probabilistic object detector. By utilizing Gaussian Processes regression model for uncertainty estimates, the developed probabilistic object detector not only classifies objects in an image along with their 2D location, but also delivers confidence estimates of the predictions from deep neural networks [23].

The main focus herein is both reliability and efficiency of the algorithm – the aspects that existing methodologies had difficulties in [24] including our previous works [25]. The results are depicted in Fig. 13. As we can see, the flying system detects both the landing targets, e.g. rovers and landers with confidence estimates. Our plan is to use these confidence measures for decision making under uncertainty.

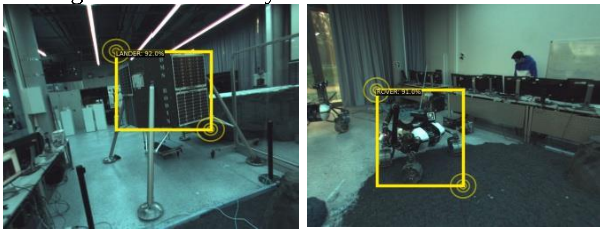


Fig. 13: Navigation achievement in developing probabilistic object detection. A method is developed to classify and locate the landing targets, e.g. rover or lander. The confidence estimates are also depicted both for classification and regression. The circles indicate standard deviation of the target location up to three.

Besides the rough localisation for navigation purposes, a second, more precise method is required for manipulation tasks. Similar to already conducted space missions this method is based on visual markers. Here, visual fiducial system April Tags [26] are applied. In comparison to non-marker-based approaches, it enables a robust and highly precise detection as well as pose estimation. Given the marker positions relative to each other on an object, the pose of the object can be determined by detecting one or multiple markers. To further improve the performance a PnP-based multi-marker optimisation is additionally applied [27].

For both presented methods, an existing model is assumed. This can be either the real object to obtain training data or a 3D model to generate synthetic training images. However, this assumption only holds for artificial objects and not for the ones encountered in the unstructured environment during exploration. For instance, the variations of natural rocks, especially the shape, are almost infinite. Hence, a specific 3D model to train the mentioned detector cannot be generated. To overcome this issue, an unknown object segmentation approach called Instance Stereo Transformer (INSTR) [28] is used. Instead of focusing only on known objects, it is trained to understand the concept of *objectness* and thus can detect any object instance. In contrast to other approaches in this field, this method does not rely on high-quality depth data. Instead, it directly takes a stereo image pair as input (which is given for the head cameras as well as the manipulation cameras), to implicitly fuse RGB and disparity information. Originally, the method is trained on synthetic data to segment unknown object instances on dominant horizontal surfaces (e.g. tables) in indoor environments. Since rocks on a planar surface state a similar problem, the pre-trained INSTR is already able to partially segment instances. To further improve, the general problem statement is directed towards the underlying use-case [29]. Therefore, INSTR is fine-tuned with photo-realistic synthetic data of rock instances generated by OAISYS (Outdoor Artificial Intelligent SYstems Simulator) [30].

Fig. 14: Example images of synthetic training data generated by OAISYS

As can be exemplarily seen in Fig. 14, this simulator enables the generation of photo-realistic images and is specifically designed to meet the requirements of unstructured outdoor environments for planetary robotics. Qualitative results of the fine-tuned method on recorded image samples from Mt. Etna can be seen in Fig. 15.

Fig. 15: Qualitative results on of the rock segmentation approach. Colours are assigned randomly.

5.3 *Grasping*

For sampling, different approaches have been developed to accommodate different types of samples. The Docking Interface [12] allows us, besides docking the payload boxes, to mount different tools to the manipulator, as described in section 3.3.

When the scientist selects a sample, the system automatically decides which tool is best based on sensor information. If it is a fine granular structure, the scoop is selected. If individual stones can be identified, the system will use the robotic hand [21]. The corresponding tool is then automatically connected to the manipulator via the docking interface and, if necessary, supplied with energy.

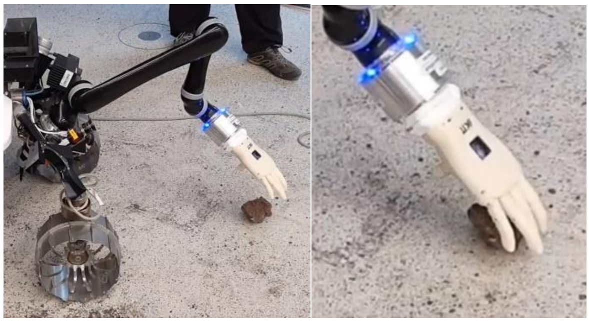


Fig. 16: Sub Sequence of the mission State machine

For the manipulation process itself, a combination of motion planning [13] and stored manipulation strategies is used. The motion planning ensures that the sample can be reached without collision and that the kinematic constraints of the system are considered. The manipulation strategies, in turn, allow a safe contact with the environment, they compensate local uncertainties, and make the manipulation process observable. This, in combination with the compliance of the hand, allows to reliably and safely grasp even unknown stones. Due to the observability, possible errors, e.g. an unexpected contact, can be detected early and corrected automatically. For example, the tool can be switched to the separation tool, which can be used to improve the manipulability of the selected sample rock. This is done by either pushing the sample itself to a better position or by removing the obstacles close by the sample.

After gripping the sample, it is automatically stored in a sample box

5.4 *Task Planning / State machine, /Autonomous navigation and Grasping*

To achieve autonomous navigation and grasping, skills are modelled as hierarchical state machines by our open-source framework RAFCON [33] [33]. RAFCON provides powerful execution modalities to achieve local autonomy of each robot, allowing to pause, modify, and resume robots' behaviours (Use case in ROBEX [19]). The robots' entire command can be implemented or exchanged by the intuitive graphical editor, even during execution. Fig. 17 shows the implementation of the RAFCON state machines of the LRU2, containing all the high-level skills.

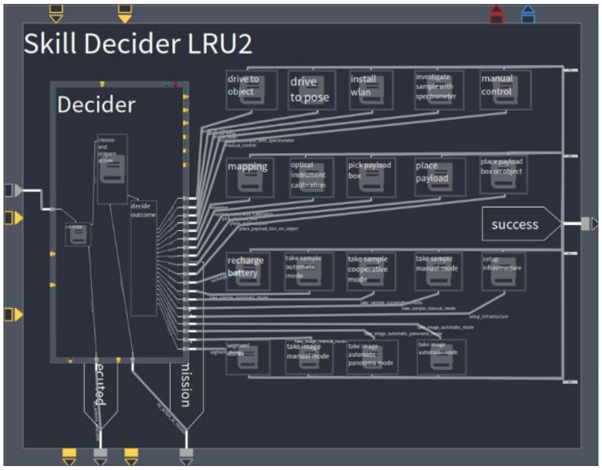


Fig. 17: RAFCON state machines implementing the LRU2's skills to achieve autonomy

To coordinate the team of the heterogeneous robots for achieving the goals of the missions, we developed a framework ROSMC [32] for high-level mission control as well as for interaction with the scientists. ROSMC allows users to define the sequence of the skills of different robots, and thus to compose the entire mission in a goal-driven manner. ROSMC is hosted on the lander and distributes the mission to each robot. During mission execution, ROSMC coordinates the mission progress and task synchronization if required. Fig. 18 shows the screenshot of the 3D GUI of ROSMC, with which users can intuitively define POIs and ROIs at the planning phase and monitor the mission progress at the execution phase.

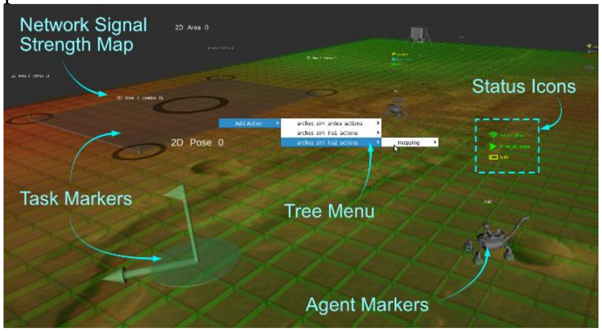


Fig. 18: Screenshot of the 3D GUI of the ROSMC high-level mission control framework

The overall mission sequence of the Mission-I is shown in Figure 3. Each rectangle block represents a skill implemented by RAFCON and transitions between them are managed by ROSMC.

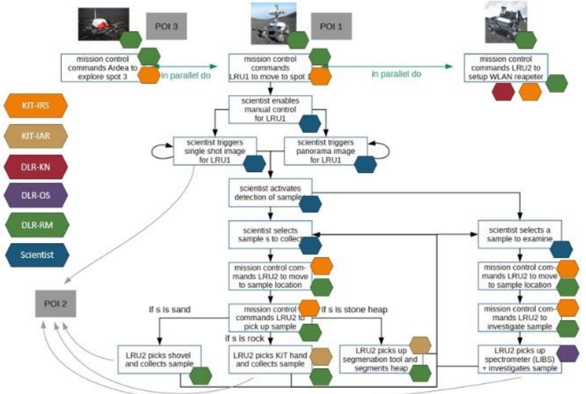


Fig. 19: Mission sequence of the Mission-I, orchestrated by ROSMC and RAFCON

5.5 *Simulation and autonomous coordination achievements*

The promising preliminary results motivate the deployment of even larger groups of autonomous robots in future campaigns. In order to gain first insight into such an increased scope, a simulation environment including eight fully autonomous robots has been developed. It combines loosely coupled, distributed and partitioned simulations. This allows for the implementation of simulations which, if solved as one, would be too computationally expensive. In addition to the tasks of taking scientific samples and different kinds of scientific photographic images, the pool of simulated tasks also contains tasks requiring the direct cooperation between two robots, such as the mutual rappelling into the crater.

With the number of robots and tasks growing, the effective coordination of the robots becomes increasingly challenging. Therefore, a task planner based on a coordination algorithm [35], which is capable of mastering the challenges arising from the heterogeneity of tasks and robots as well as due to the consideration of cooperative tasks, has been developed and implemented. An associated control centre allows the scientist to define and situate the tasks for the mission. The tasks are sent to and coordinated by the task planner and the resulting mission plan is transferred to the simulation for mission execution. A virtual demonstration in July 2021 presented the successful combination of the planner and the simulation in a decentralized solution, with the control centre and coordination algorithm being located on KIT premises in Karlsruhe and the simulation running on the DLR site in Oberpfaffenhofen.

5.6 MIRACLES first Mission success

A total of three days were spent on simulated experiment operations with several ground teams in ESOC, DLR and Academia. Throughout the experiment, an in-scenario concept for the experiment participants was applied. The in-scenario participants were immersed in a lunar mission scenario, conducting operations planning from project start, and performing the planned lunar operations in a realistic setting, as part of the geological Mission II with the focus on exercising operations of relevance to future lunar exploration missions.

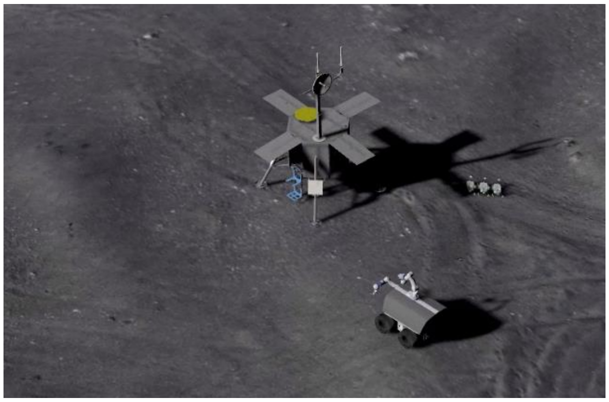


Fig. 20: DLR lander and robotic assets included in the MIRACLES analogue simulation: DLR's Scout rover (right), ESA's Interact rover (bottom).

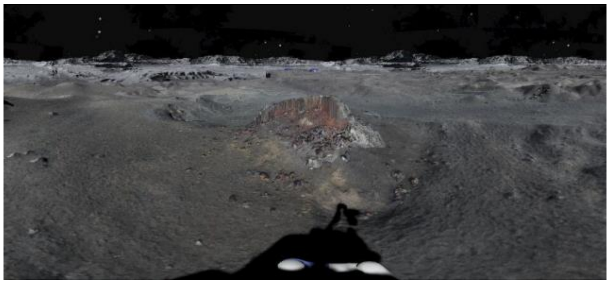


Fig. 21: Panorama image of a science target as acquired by ESA's Interact rover during MIRACLES operations.

The simulated mission was called MIRACLES and comprised about 13 hours of net operations time. The simulation successfully demonstrated the readiness for Mt. Etna field operations in 2022. The operators were able to drive a distance of approximately 1400 meters and perform the required scientific operations, including the collection of 3 rock and regolith samples.

5.7 Interact Preparations

The rover has demonstrated its capabilities in the ANALOG-1 experiment being controlled from the ISS in an aircraft hangar [22]. However, operating in the conditions of the peak of a volcano is very different.

Fig. 22: INTERACT rover with covers and sleeves for dust protection

On first sight obvious factors are dust and water protection of a system that has been operated mostly indoors. In technical terms the first requirement is to increase the IP rating. Although the rover body already has basic protection, we devised additional sleeves from polyurethane laminate fabric (PUL) for the robotic arms. The design choices are a trade-off between proper dust/water protection, against mounting effort, maintainability and a little bit of fashion sense and optics. The most consideration was given to condensation inside, overheating protection issues and how not to constrain a force controlled and compliant robotic arm with too tight sleeves. First tests show good results and the rover can be seen in Fig. 22.

Another challenge is the terrain and the ground properties. The rover with a mass of approximately. 300 will have like any other car different driving behaviour than gravel or sand. In the most extreme case sand or loose gravel could cause sinkage and even with the powerful drivetrain the rover could get stuck – a situation to be avoided at all costs. Similar to car racing or rally sports we believe that tires will make the difference. Thus, we have prepared different sets of tires – see Fig. 23.

Fig. 23: Tire options for Mt. Etna (left: road tire, mid: contenders, right: the choice for Mt. Etna)

Even though we could not go for a scouting trip due to the pandemic we believe that a wider tire with profile that is in the mid of sand and hard underground and reduce pressure will fit best. The internal control algorithms and the configurations to for wheel odometry and auto-navigation have been updated and we are testing further.

Another new aspect on rough terrain compared to flat surfaces are dynamic loads, torsion of the chassis and larger/faster attitude changes. As compensation, on the pure mechanical side, we decoupled the locomotion unit and the very stiff payload container with wire spring dampers. This solution allows the bending to its specifications on the locomotion unit and in addition, the wire spring dampers protect the payload body from hard jerks in case of collisions.

Fig. 24: A wire spring damper to decouple the stiff payload container from the locomotion unit

For the control of the arms, adjustments on the control must be made. Force controlled robots that behave like compliant human arms are not only ideal for teleoperation, safe in human vicinity but also will not take damage when driving over bumpy terrain. However, for the robot to hold its position it needs to know the gravity vector. On flat terrain this is straight down but on slopes like on Mt. Etna this can vary a lot. To compensate for this effect, we integrated the IMUs sensing of accelerations and gravity vector as feed forward into to the robot control. This is currently tested and thus the robot can be in impedance mode while driving over rough terrain and is able to operate on any slope.

Even though that the control software was stable in previous experiments the pandemic with home offices and a lot of different internet connections with huge variations in quality and bandwidth made showed us new points for improvements and other use cases which we incorporated for better remote operations.

5.8 Scout Preparations

The Scout rover is a well tested, harsh terrain specialist with an IP67 rating. Primarily being a cave exploration rover [37], Scout is also well suited against condensation and cold conditions. However, measures to prevent overheating in excessive sunlight 2500m above sea level has been one of the preparation tasks undertaking for ARCHES Geo-II mission. Furthermore, to assist above ground positioning a GPS-IMU module has been added to the rover in order to provide operation and navigation, as well as INTERACT with precise information on position and heading of the Scout.

In order to make sure the Scout rover is well prepared for the terrain on Mt. Etna, tests in the DLR harsh terrain testbed have been performed on a regular basis. These tests also included situations of rockfall, drops of the rover and negotiation of large debris fields. The latter can be seen in Fig. 25.

Even though the pandemic caused a large amount of issues and overhead, it certainly pushed the Scout rovers telecommand capabilities. Due to strict regulations, GEO II scenario tests have been performed in a telecommanded manner from different sites in Europe. Thereby the rover was physically driving in Oberpfaffenhofen while being commanded from Karlsruhe. These tests pose a worst case scenario compared to the Mt. Etna communication and were thus well suited to identify issue in communication and camera streaming while driving.

All this preparation work also assists to adapt the Scout rover for its first in cave tests in 2022.

Fig. 25: The Scout rover making its way up a 30 degrees sloped boulder field

5.9 Haptic Human-Machine-Interface for Shared Control

A generic haptic human-machine interface (HHMI) is implemented based on a serial robot kinematic with seven degrees of freedom (DoF). It features a large workspace of 40 cm by 30 cm and is able to exert forces and torques in six DoF, thus allowing for haptic shared control in all six DoF. The HHMI was successfully applied during the MIRACLES mission in July 2021. In this scenario, the HHMI was utilized to enable the cooperation between a DLR robot navigator planning paths for a simulated robotic asset on the moon surface, and a KIT robot operator commanding this robotic asset through an adaptable automation with three levels of automation [38]. The operator was able to choose from (i) commanding the robotic asset manually, (ii) in cooperation with a path following automation executing the path planned by the robot navigator, or (iii) a fully autonomous mode.

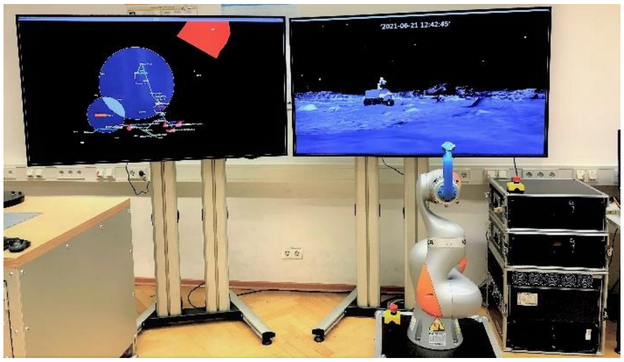
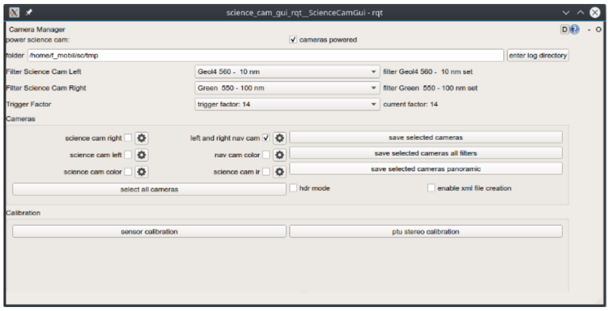


Fig. 26: KIT Telerobotic interface connected to the simulation

5.10 Science Cam interface

To help the scientists on Earth with the decision if a POI is scientifically relevant, and to analyse the POI in detail, LRU 1 is equipped with additional cameras (Fig. 28). In addition to the three cameras mainly used for navigation, an infrared camera, a camera with a telephoto lens and two cameras with high sensitivity in the near-infrared spectrum are mounted on the pan/tilt unit. In front of the two cameras with high sensitivity in the near infrared spectrum, filter wheels with a total of 18 band-pass filters in the range from 460 nm to 1000 nm are mounted.

Fig. 27: LRU 2 equipped with cameras mainly used for navigation and manipulation, right: LRU 1 equipped with additional cameras supporting scientific analyses



power science cam: ☑ cameras powered
folder /home/f_mobil/sc/tmp
Filter Science Cam Left: Geol4 560 - 10 nm — filter Geol4 560 - 10 nm set
Filter Science Cam Right: Green 550 - 100 nm — filter Green 550 - 100 nm set
Trigger Factor: trigger factor: 14 — current factor: 14
science cam right ☐
science cam left ☐
science cam color ☐
left and right nav cam ☑
nav cam color ☐
science cam ir ☐
☐ hdr mode
☐ enable xml file creation

Fig. 28: Screenshot of the graphical user interface used to control the Science Cam

A graphical user interface to remotely control the cameras was developed. It allows to switch off cameras currently not needed, to reduce energy consumption of the overall system. The frequency of the cameras mainly needed for navigation is fixed. The four additional cameras are triggered synchronously to the navigation cameras, but the frequency can be adjusted to save bandwidth and reduce system load. In addition, general camera parameters like exposure mode, exposure time or exposure value can be set, a high-dynamic range mode can be activated and the filters for the two cameras can be selected in the GUI.

The GUI also allows the user to execute routines to automate special tasks. For the preparation of the demo mission, two routines to support the collection of images needed for the calibration of the cameras and the pan/tilt unit are implemented. During the mission scientists can call routines to record images of selected cameras and filters with a fixed pose of the robot and fixed pan/tilt angles or decide to collect data of a full panoramic scan.

The LRU1 Science Cam is a copy of the following described PanCam emulator.

5.11 The PanCam Geometric Emulator (GEPE)

The Geometric PanCam Emulator (GEPE; Fig. **29**) developed by JOANNEUM RESEARCH is a breadboard to simulate the geometric specifications of the ExoMars PanCam and NavCam instruments. It is designed to test ExoMars PanCam and NavCam operations in terms of representative data capture in the field for the testing and validation of stereovision-based 3D & panorama processing. Within ARCHES, GEPE will be used to capture close- to medium-range (2m – 100m) stereo panoramas and generate digital elevation models / textured point clouds therefrom, using the ExoMars 3D vision processing suite PRoViP as currently under test for ExoMars ground operations. The site crew will be equipped with the Planetary Robotics 3D viewer PRo3D[*] to support the interpretation of the mapping result, conduct quantitative tactical planning, and in almost real-time help perform a geologic assessment of the site patch addressed.

Fig. 29: Geometric PanCam Emulator GEPE

6. New analogue mission time line

Due to constraints posed by the COVID pandemic of limited travel for health and safety considerations for the team, we twice postponed the demo mission from the originally planned year 2020, first to 2021, and now finally to 2022.

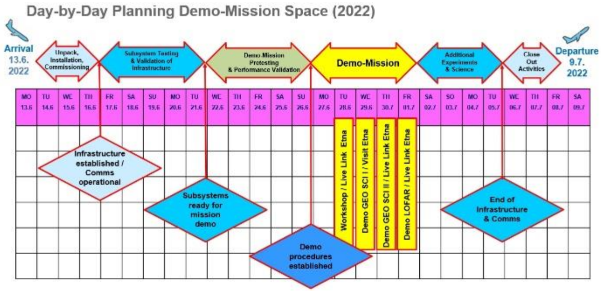


Fig. 30: ARCHES demo mission timeline

A team of approximately 50 experts from Germany, Austria and, the Netherlands are currently foreseen to travel to Catania for four weeks to carry out this mission.

The weekly planning starts with the common arrival on Monday June 13, 2022 to Catania, where logistics and setup of the infrastructure is occupying the first week's schedule until approximately Friday 17th. The second section from Sat. 18th until 25th is dedicated to sub system validation tests, inspections, repairs after shipping and verification of the installed infrastructure. From Mo. 26th on until Mo. 27th, the demo mission test for each three sections, Part I, Part II, and Part III will be trained, optimised and verified.

Each demo mission is planned to be executed in one Etna mission day, which is defined as 6 hours mission operations, including morning start-up phase and execution phase and evening shutdown phase.

During the demonstration week, the three mission sequences will be demonstrated:

- Tue.: 28.6 Welcome in Catania
  Live Chat on Etna
- Wed.: 29.6 - Mission Part I: Geo I
  Visit on Etna – Organized Bus Trip
- Thu.: 30.6 - Mission Part II: Geo II
  Conference in Catania - Live Chat on Etna
- Fri.: 1.7 - Mission Part III: Geo II
  Conference in Catania - Live Chat on Etna

In the final phase, from 2nd July till 5th July, the high-risk additional experiments will be performed.

Additionally, to help inform students and the public about the mission and advancements in robotics for space exploration, a summer school shall be held one week before the mission on the Aeolian Islands, on the volcano [39].

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[*] https://github.com/pro3d-space/PRo3D

7. Conclusions

A campaign of this size, with several institutions, partners and nations, poses great challenges, when coupled with two postponements, an assortment of uncertainties related to the COVID pandemic. One of the main challenges is keeping the tasks and teams continuously up to date, as well as shifting work tasks to cope with the realities of financial constraints. It is no small feat to maintain and develop hardware and software systems with strict limitations of access to lab and office locations. Adapting to communication over video calls has ironically given the team some unexpected "training", and tangible understanding of the skills and process needed for space operations, and an even greater respect for our space ops colleagues.

Finally, as the date of the eventual ARCHES mission moves closer, we owe a great deal of thanks to the entire team for persevering through these unusually difficult times. We believe that the long preparation will finally give way fruitful results to help the quest to achieving human-robot collaborative team in space exploration.

Acknowledgements

We would like to thank especially the Helmholtz association for understanding and supporting the postponement of the project twice in a row. Furthermore, we would also like to thank the local entities in Italy for understanding our proponent and supporting the missions with logistics, accommodations and licences. The "Parco di Etna", "INGV Catania", "Funevia di Etna", "Giro Calabria", "Glasser Sondertransporte" and the "Baia Verde Hotel" are given credits as well.

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