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Finally! Insights into the ARCHES Lunar Planetary Exploration Analogue Campaign on Etna in summer 2022

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Abstract

This paper summarises the first outcomes of the space demonstration mission of the ARCHES project which could have been performed this year from 13 june until 10 july on Italy's Mt. Etna in Sicily. After the second postponement related to COVID from the initially for 2020 planed campaign, we are now very happy to report, that the whole campaign with more than 65 participants for four weeks has been successfully conduced. In this short overview paper, we will refer to all other publication here on IAC22. This paper includes an overview of the performed 4-week campaign and the achieved mission goals and first results but also share our findings on the organisational and planning aspects.

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

1. Introduction

1.1 Scope

The aim 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 fields of deep-sea and space research have been defined as high priority and form the use cases for ARCHES [1] research. The consortium of Helmholtz centres consists of DLR, AWI, GEOMAR and KIT, with the original project duration from 2018 to 2020, which was extended to the end of 2022 due to the pandemic situation.

The technological goal of the project is to develop heterogeneous, autonomous and networked robotic systems. Not only the robots are heterogeneous, but also the future fields of application range from environmental monitoring of the oceans to technical crisis intervention and exploration of the solar system. Especially for the Helmholtz Association's mission to find answers to the essential questions of human society, autonomous robot networks are becoming a key technology.

In particular, solving problems such as monitoring and understanding the marine environment or exploring the solar system will depend heavily on the use of autonomous and networked robotic systems.

They will provide the necessary capabilities for continuous, long-term and large-scale data recording, as well as for manipulation and direct interaction with the environment. Robots enable the monitoring and manipulation of objects on a large scale in harsh and extensive environments.

The next decade will see an increasing global commitment to lunar exploration, with humans arriving back on the lunar surface, the ISS station reaching its end of life and its successor, the Lunar Gateway, being established in lunar orbit to pave the way for manned Mars exploration missions after 2030. The ARCHES demonstration missions thus 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 (see following related mission publications: [2], [3], [4],[5], [6] and [7])

2. High-level mission description

Since the publication at IAC 2021 [8] describes already very detailed the overall mission descriptions, this section here just gives a brief overview on the planned three missions.

In general, the idea of the ARCHES mission is related to the idea, that a scientifically related geological mission is planed as precursor, when not yet a lunar gateway is operational and robots are mainly operated from earth (Mission I – GEO I), following from a geological second mission (Mission II – GEO II) where samples from the prior mission are picked up, and already explored sites and positions are explored further. The last mission is dedicated to the fact that a permanent base and installation on the surface of the moon shall be established and therefore the scientific idea of the robotically installation of a LoFar telescope for the far side of the moon has be the motivation for the Mission III – LoFar (see Fig. 1).

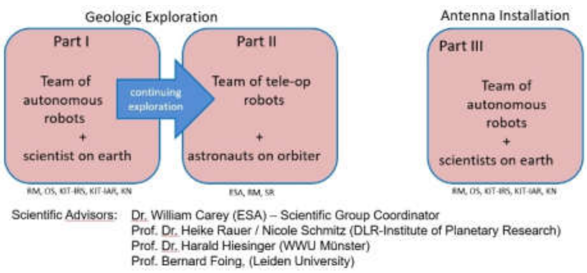

Fig. 1: The three mission sequences

This is because the three mission sequences were planned in detail from the operational side through mission pre-planning. The basis of this planning was aligned with real missions and based on non-detailed overview images, such as satellite and pre-collected other data. These planning scenarios are then executed in a joint autonomous manner, and the operators and scientists observing mission results in the catacombs and ESOC control room have the opportunity to intervene and interact with the joint autonomous mission execution management. It has always been possible as a scientist and/or mission operator to intervene in the autonomy and shared autonomous functions, as described in Section 4, while observing the general outcome of the mission executed by an intelligent network of robots.

2.1 ARCHES Summerschool on Vulcano

After a break of two years, the two-week summer school in Vulcano, Sicily, in June 2022 again brought together scientists, researchers, students and technicians for another field campaign covering topics such as geology, robotic environmental exploration, astrobiology and the study of planetary analogues. A number of successful experiments (planned and unplanned) and sampling campaigns have been conducted on the island and in the coastal waters around Vulcano. Vulcano is the third largest and southernmost island of the Aeolian Archipelago in the Tyrrhenian Sea. The central fossa crater on Vulcano has a surface morphology similar to lunar and Martian regions with extremely dry, arid conditions, little or no vegetation, angular grains over a range of grain sizes. The diverse and extreme (hostile) environments on Vulcan are an important training ground for testing instruments and techniques needed for future robotic missions to Mars and other bodies with a particular focus on astrobiology. This year, as in previous campaigns a variety of spectral instruments ranging from visible and near infrared (VNIR) reflectance to Raman spectroscopy were deployed at various sites for mineralogical, biological and elemental analysis. The in situ survey, and its comparison with laboratory standards and instrumentation, will provide an assessment of the usability of these techniques to characterise extraterrestrial environments and guide our search for life in the solar system (e.g. by assessing the detectability of biosignatures). Drone photogrammetry surveys provide regional context, mapping areas of interest such as potential hazards, while an integrated positioning system (IPS) combined with infrared thermal imagery is used for future mapping and analysis of thermal stability at various volcanoes. In addition, geophysical techniques such as TEM and IP electrometry measurements of fumaroles and their 3D structure will be investigated. Last but not least, robotic missions will be carried out for terrain analysis, locomotion and mapping on different lunar and Mars analogue terrains.

3. Infrastructure and network concept

As during the ROBEX mission in 2017 [9],[10], 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 1000 x 1000 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 (see Fig. 2).

Fig. 2: Field Side of ARCHES demo mission

A communication link was established from the control center near the city of Catania to the mountain site. This was implemented by a directional radio link referred to as *Link CC – BC* in Fig. 3. The control center of the analogue mission was located in a hotel near Catania where the crew and equipment were accommodated but also a mission control room, and a scientific operations room have been established.

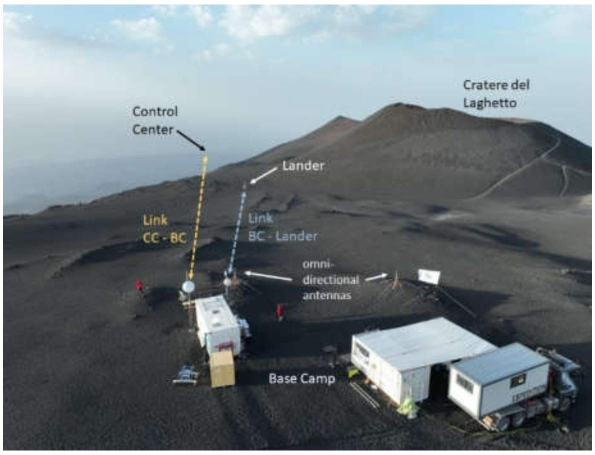

Fig. 3: Field site of the ARCHES demo mission. View from the Base Camp towards Control Center near Catania.

A similar setup for the directional radio links as for the ROBEX demonstration mission was implemented [11]. The air-line distance between the control center and the field base camp was about 23 km.

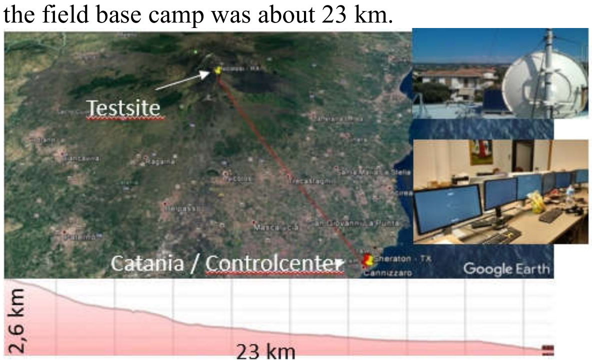

Fig. 4: Control room and field side link

The directional antennas of the control center have been mounted on the roof top of the hotel and the directional antennas of the field base have been installed on one of the four 20 feet containers shown on the left-hand side in Fig. 3. From this container, network cables established connections to the other containers of the base camp.

Furthermore, from the base camp, several antennas distributed the communication network. There was a directional link from the base camp to the lander referred to as *Link BC – Lander* in Fig. 3. From the lander, the network was further distributed. Moreover, the network comprised several omni-directional and sector antennas providing network coverage to several spots on the side. Some of these antennes have been mounted on movable tripods offering maximum operational flexibiliy. 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 was not only located in the Catania ground segment (see Fig. 4), 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 was established, where mission control for some of the experiments inside the geological II mission was planned and supervised.

3.1 Modular Approach:

The activities in ARCHES follow a modular approach which has been already described well during [13] and updates will be reported in [14] and the summary in section 5.

With the intention of adding flexibility and versatility to the mission, several standardised modular payload carriers and special robotic tools were developed. While the former house various scientific instruments and infrastructure facilities inside, the latter are attached to the LRU2 body and can be quickly accessed at any time. All these elements have a common interface that can be docked by the active docking partner of the ENVICON docking interface system [15].

This active interface is the end effector of the LRU2 robotic arm, allowing the rover to manipulate payloads, exchange tools and perform scientific tasks in the field. With this strategy, the robots become multi-functional, highlighting the heterogeneous capabilities of the ARCHES robot team and its ability to adapt to the needs of the mission.

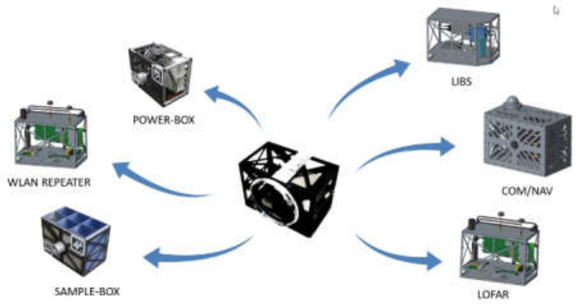

Fig. 5: Modular Payload Carriers in the ARCHES scenario

For the ARCHES demonstration mission, 21 different payload carriers (Fig. 5) 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.

Furthermore, during the ARCHES mission, the LRU2 rover can not only manipulate several payload modules (e.g. LIBS payload module or soil sample container) using its robotic arm and modular docking interface, but also connect three different tools (Fig. 10) in accessible holders on the rover body.

Fig. 6: 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 [16]. 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

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. 7: 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.

Since the individual systems itself has been already described in the publication [8] on IAC 2021, to not repeat this here, the overview summary shall be enough (see also [12]).

4. Results and achievements

4.1 Mission Part I - Geo I:

The Geological Mission I (GEO I) took place the 29th of June 2022, and saw the LRU1 and LRU2 rovers operating in semi-autonomy to reach, inspect, and collect targets of scientific relevance, located in an area at a maximum distance of 50 meters from the Lander. The GEO I demonstration mission started officially at 11:00, when the rovers started to navigate towards the first targets, and ended at 14:00, when the robots were driven back to the base camp, leaving the Lander site. The demo, therefore, was successfully executed for a total duration of 3 hours, in which the rovers autonomously navigated and manipulated without interruptions, demonstrating outstanding robustness for all the software and hardware components involved in the process. Compared to the original plans for the execution of the demo, the extreme wind conditions, with speeds exceeding 25m/s, were prohibiting for the autonomous flights of ARDEA for reasons of safety of the system as well as of the operators monitoring the robots from the mission site.

The GEO-I mission started with Mission Control imparting high-level commands to the robotic team. The mission control tool named ROSMC was utilized throughout the mission. With the easy-to-use graphical interfaces, the framework enabled the intuitive mission specification and monitoring throughout the mission. Mission Control operated from the control room located in the hotel in Catania, sharing with the robots at the lander skills to be executed and receiving updates on their status, e.g., high-level updates on the actions performed, as well as the output of the mapping pipeline. With these, the remote operators were aware at all times of the location of the robots with respect to the Lander, the spatial conformation of the environment, unknown at the start and continuously mapped, and their readiness to accept further commands. ROSMC allowed the operators to flexibly adapt the mission based on the in-situ discovery on site as the mission progresses.

Fig. 8: Mission OPS with ROSMC in Catania

LRU1, equipped with a suite of scientific cameras in its pan-tilt unit, navigated towards 3 different locations with the aim of collecting panoramic scans (see Fig. 8). All 3 targets were placed in hazardous and hard to reach locations, due to the presence of isolated stones or regions where the emerging rocky features could harm the wheels of the robots. Safe navigation has, however, been achieved with a combination of accurate and efficient detection of geometrically non-traversable areas and the autonomous detection of unknown objects, implemented though a state-of-the-art deep learning approach.

LRU2, which has a robot arm mounted at the rear, successfully picked up a sample box from the Lander, put the box on its back, and navigated to the relevant sampling sites. After reaching the target locations, the operator was able to adjust the final rover position via a GUI. The same interface was then used to determine which sample should be collected. To further reduce expert knowledge, rocks within the field of view were visually detected and filtered by size for the robot hand graspable instances. The operator was able to either select a rock instance or to choose a location to sample soil. Based on the selection, whether rock sample or soil, LRU2 automatically attached the robot hand or shovel respectively and executed the sampling process. After the sample was stored in the sample box, the operator could decide to collect another sample or proceed in the mission. The mission finished by the rover placing the box containing the collected samples at a predefined location. During the demonstration our collect sample approach was successfully triggered 7 times resulting in 4 rock and 3 soil samples.

Similar to the sample collect task, for geochemical in-situ analysis, LRU2 collected the LIBS payload module from the Lander, placed it into the frame on its back, and drove to the target of interest. Again, the final rover position was adjusted by the operator via the GUI. Once positioned in the appropriate distance the operator selected a target of interest detected by the same machine learning based rock segmentation approach applied for the sample collect task. Given the target of interest a suitable surface was automatically determined. Next the LRU2 coupled its robotic arm to the LIBS module stored on its back and placed it onto the target. To ensure a suitable working distance for the integrated laser that ablates and vaporizes a small amount of sample material and turns it into a micro plasma, a baffle is mounted to the front of the LIBS module. When performing a LIBS measurement, the laser is triggered and the emission from the induced plasma is collected and spectrally analysed to obtain information about the elemental composition of the sample. A movable mirror allows for small scans along an arc inside the baffle and, therefore, to obtain LIBS data from several positions on the target. In the framework of the GEO-1 mission, three separate sampling procedures were executed as expected on three different rocks and the collected LIBS data was transferred to mission control, where it was visualized in a dedicated GUI, successfully demonstrating every step from the sampling process to data analysis.

Our localization and mapping approach (SLAM) allowed us to track and optimize the history of positions of the two robots for the whole duration of the mission, without any interruption, and continuously create an optimized representation of the explored environment in form of point clouds and elevation maps. To this end, a SLAM graph included positions and measurements from the robotic team, including the Lander, LRU1 and LRU2, and utilized multi-robot detections as well as loop closure constraints, through re-detection of previously observed scenes, to ultimately reduce the pose estimation drifts. With a total of more than 200 submaps, where each submap represents a mapped area of about 10 m^2, our distributed multi-robot mapping pipeline produced a map covering about 350 m^2 of the volcanic slope around the Lander site, see Fig. 9.

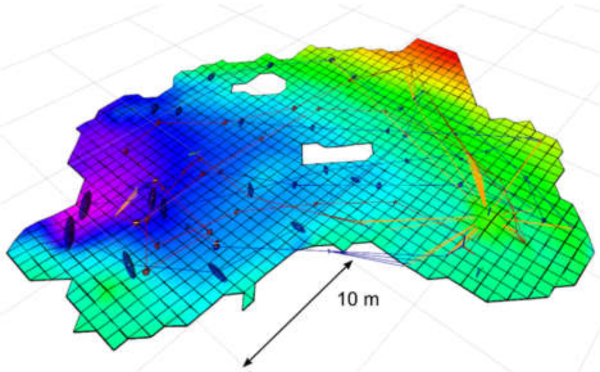

Fig. 9: SLAM graph and elevation map collaboratively created by the robotic team during the GEO1 mission.

4.2 Mission Part II - Geo II:

The Geological Mission II (GEO II) took place on the four consecutive days from 27th to 30th of June 2022. Real-time operations started each day at 12:00 and lasted four hours. The INTERACT and Scout rovers explored the area around the lander after a predetermined plan laid out by the scientists and navigation (rover control) team. During the first two days of operations seven points/regions of interest were surveyed. An experienced ESA astronaut (Thomas Reiter) joined the team for the third day of Geo II operations. This third day was utilized for the in-scenario team to assess the data collected from the first two days scouting, and for the astronaut to do some rover driving and robot arm operations to refresh himself with operation of the ACTOR control station. On the last day of operations, samples were taken from some of these points and brought back to the lander.

Fig. 10: The INTERACT rover (with dimensions)

The INTERACT rover is built around a two-wheel drive platform with cameras and two robotic arms. The camera located on the tip of the Kuka LWR arm mounted on top of the rover can be moved to any angle or position by the operator of the ACTOR control station. When operated from the ground, this top arm behaves similarly to a pan/tilt unit. The other robotic arm mounted on the front of the rover is equipped with a gripper capable of dexterous manipulation through direct teleoperation. This camera was used primarily for navigation and to provide contextual images.

A second camera is mounted at the tip of the sampling arm mounted on the front of the rover to assist in the selection and collection of samples. This collection of samples was performed by the astronaut (in consultation with the in-scenario science team members on the ground). The astronaut was in one control room located at the hotel in Catania (essentially playing the role of the Lunar Gateway in this mission scenario), and the in-scenario science team in another separate control room (with limited access to maintain the realism of the simulation).

Scout was solely equipped with one camera which was fixed on the front of the first segment. The INTERACT rover visited three additional points of interest which were not further investigated by the rover. Since the camera is fixed to the housing, the Scout rover was commanded to conduct 360° point turns on spot to survey the environmental setting. The camera capture was additionally used to assess the traversability for the INTERACT rover. The Scout rover further assumed its role as communication relay for the INTERACT rover when both operated far away from the lander. The terrain proved to be rather benign for the Scout rover.

Fig. 11: The KIT HMI in use during the GEO II mission

An important goal of GEO II was the successful demonstration of a cooperative rover mission. This requires close cooperation and coordination between the different rovers and their teams at many levels. More precisely, the collaboration between mission control, the engineering and science teams of the rovers as well as the navigators and operators is key to the success of the overall mission. The operational processes need to be flexible to react and adapt the mission plan to unforeseen circumstances, e.g., obstacles, and events; discovery of additional points of interest. Mission control was split across two operation centers: the operation managers and INTERACT engineering team were located in Darmstadt; the Scout engineering team and the science team were in Catania together with mission control of the GEO I mission.

A second goal of Geo II was to drive the rovers and the robotic arms of INTERACT using a high-fidelity tele-operative haptic control devices with visual feedback. These devices made the control more intuitive and supported the operators with direct feedback from the robotic systems (i.e., a sense of touch). Full haptic feedback was transmitted to the operator. For the Geo-2 mission the end-effector utilized was a two-finger gripper.

For the command of scout rover, a novel and generic haptic human-machine interface (HMI) based on a KUKA LBR iiwa14 was applied. It allows for a versatile mapping of its 6DoF according to the use case; while commanding Scout rover, a relatively large input workspace of 40 cm by 30 cm in x- and y-direction was directly mapped to the two DoF of the rover. As the focus of the mission was to either move Scout rover straight or perform point-turns, the operator was haptically assisted to achieve this goal. Additionally, an adaptable automation exerting supporting forces on the HMI was successfully applied. Using this automation, the operator was able to choose between three degrees of automation [39]: (i) commanding in a fully autonomous mode where the automation received continuously updated paths provided by the navigator and controlled Scout rover automatically, (ii) commanding in collaboration with the path-following automation , or (iii) a fully manual mode. The operator used each of these modes during the mission to optimally balance workload, situational awareness and performance.

For the fourth and last day of the Geo II mission, the astronaut had no time delay to the rovers but when communicating with the rest of the team in mission control a five-second delay was introduced in the communications system to mimic the Round Trip Time (RTT) to the Moon and back. This changed the dynamics of operation more than expected. Whereas the planning was fast and the driving took long without the astronaut in the loop (because of the time delay between mission control and the field), now planning took longer, because of the time delay between mission control and the astronaut, while the driving was fast. The astronaut in the loop also provided valuable insight into the requirements and use cases for control devices and operational processes This will be for the benefit of the further development.

<u>Preliminary Results:</u>

Preliminary results from Geo II are summarized in [17], [18]. Those objectives remaining incomplete following the Analog-1 ISS part of Analog-1 were all fully addressed and even included a 'surprise' task requested to the astronaut for the collection of a sample container and to return it to the lander which was carried out efficiently and effectively by the crew member. [18] reports the reults more fully, but in short:

- Robotic asset cooperation proved very viable and effective.
- Orbital control (via astronaut) and ground control (via ESA ESOC) was fully exercised (including traversing and sample collection).
- The GUI used for rover/robot control (of INTERACT) was assessed via a questionnaire to the astronaut.
- The advantage of having a geologically trained astronaut to increase the efficiency and effectiveness of sample selection and collection was (again) demonstrated.
- The detailed analyses are still ongoing.

4.3 Mission Part III - LoFar:

The Antenna Installation of the LoFar Array (LoFar) took place on the 1st of July 2022. The missions main goals were:

1. Demonstrate that the heterogenous team of robots can complete an infrastructure installation, which is able to gather scientifc relevant results for space exploration.
2. Demonstrate that the robots operate independent and autonomous where all mission critical computations are executed on the systems computation stack.
3. Demonstrate that the modular payload concept allows to construct complex infrastructure in an analogue site.
4. Demonstrate a real-time decentralized radio-navigation system to accurate localize payload-boxes for array operation
5. Proof-of-concept array operation such as beam-forming and signal direction of arrival estimation

To ensure all important parts of the mission could be tested in one day, part of the LoFar array was prepositioned in the field and the task of the autonomous systems was to increase the size of the array by placing one more functioning setup.

The most important milestones of the LoFar mission are detailed in Figure 12. The mission started with both rovers located at the lander site. The rovers registered with the lander to obtain a common coordinate system. LRU2 approached the lander and picked up the power payload box with the manipulator (A). Once the power box was in the transport position, LRU2 drove to the deploy location of the installation. At the location the rover deployed the power box in the field with the manipulator (B).

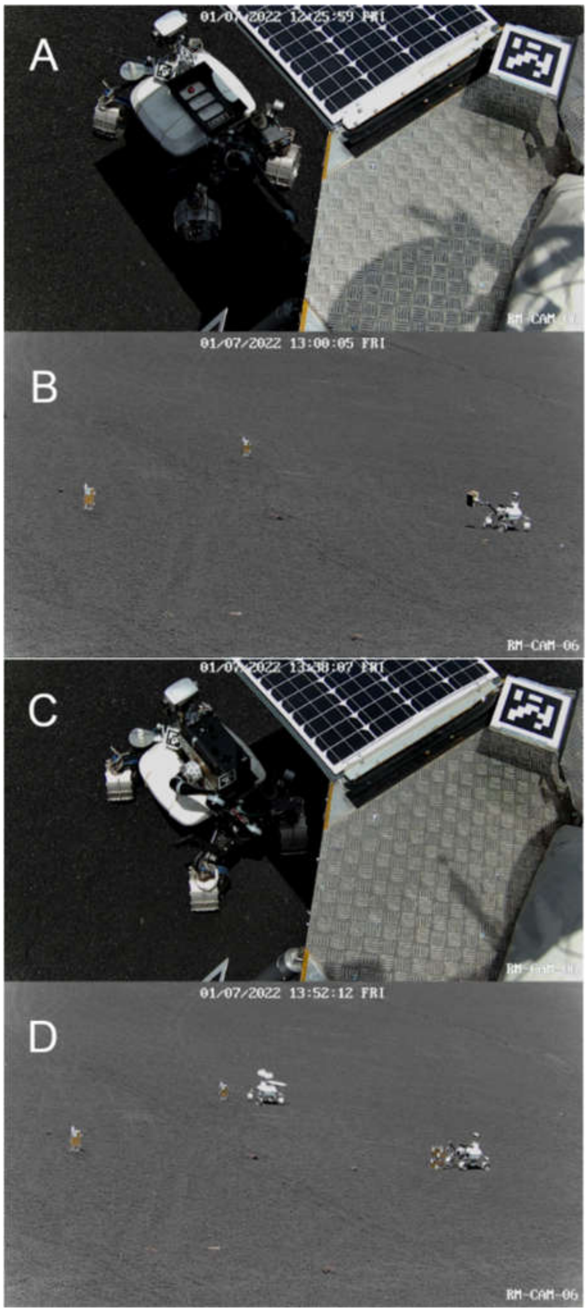

Figure 12: Pictures captures with the Mast Camera of the Lander during the infrastructure installation.

To ensure correct positioning the LRU rover drove through the array, detected the placed payload boxes and updated the information in the central world model, shared by all systems. LRU2 drove back to the lander to pick up the LoFar payload box equipped with antenna (C). With the instrument safely stored on the back of the rover, LRU2 drove back to the previously positioned power box. At the deployment location, LRU2 initiated the most critical mission phase: stacking the LoFar payload onto the power payload to create a functional element of the array. The rover detected the power payload with the rear stereo camera array and computed the approach coordinates as well as a joint motion to position the instrument. During the stacking motion the manipulator switched into an active force-controlled mode to ensure smooth docking of the two payloads (D). After successful stacking of the payload, both rovers drove a final measurement cycle to capture the array coordinates and returned to the lander to complete the autonomous part of the mission.

In the mission the team of rovers was able to achieve all goals:

1. LRU2 completed the setup of one functional unit of hardware in the LoFaR array, which after the autonomous part captured scientific data.
2. All operation of the rover systems was based on the decisions of their on-board computation stack – mission control only provided high level goals.
3. Stacking the two payloads to created a functional unit in the LoFaR array and allowed to install an element consisting of modular payload.

Once the robots cleared the LOFAR experiment field, our developed decentralized radio-navigation system is used, to determine the final payload box positions accurately. The estimated payload box positions are then used to determine the final array geometry which serves as input for the array operation. As proof-of-concept array operation we chose two use-cases: signal direction of arrival (DoA) estimation and beamforming. We successfully demonstrated DoA estimation of a low-frequency radio-beacon of unknown position placed in the experiment area. Additionally, we successfully demonstrated the array's beam-forming capability.

4.4 Science Findings:

The success of the ARCHES campaign demonstrates the potential inherent in robotic space missions and the deployment of even larger groups of heterogeneous robots in future campaigns seems promising. The challenge of expediently and effectively coordinating the robotic team however, rises with the number of robots and tasks. To address this challenge, a task planner was developed and implemented. The coordination algorithm [36] is capable of handling the heterogeneity of the robotic team as well as temporal constraints arising from precedence constraints or cooperative tasks which require the direct interaction between several robots. The envisioned approach, which was implemented and demonstrated by an associated control centre, still involves the expertise of the scientist who defines the tasks to be performed by the robotic team, but reduces the mental load for the scientist by outsourcing the coordination to the task planner. This approach was successfully demonstrated in association with a simulation environment including eight fully autonomous robots and an extended pool of simulated tasks including, besides several tasks inspired by the Geo I mission, also some cooperative task like the mutual rappelling into a crater.

5. Other relevant papers here at IAC in Paris

Since this overview paper is just introducing the section of the ARCHES results, we are looking in a future of several papers, journals and phds, thus this section is just referring to the other papers in the 2022 IAC Paris:

IAC-22,D3,3,4,x73713: **"Modular Mechatronics Infrastructure for Robotic Planetary Exploration Assets in a Field Operation Scenario"**

Abstract: In 2021 the Modular Mechatronics Infrastructure (MMI) was introduced as a solution to reduce weight, costs, and development time in robotic planetary missions. With standardized interfaces and multi-functional elements, this modular approach is planned to be used more often in sustainable exploration activities on the Moon and Mars. The German multi-robot research project "Autonomous Robotic Networks to Help Modern Societies (ARCHES)" has explored this concept with the use of various collaborative robotic assets which have their capabilities extended by the MMI. Different scientific payloads, engineering infrastructure modules, and specific purpose tools can be integrated to and manipulated by a robotic arm and a standardized electromechanical docking-interface. Throughout the MMI's design and implementation phase the performed preliminary tests confirmed that the different systems of the robotic cooperative team such as the Docking Interface System (DIS), the Power Management System (PMS), and the Data Communication System (DCS) functioned successfully. During the summer of 2022 a Demonstration Mission on Mount Etna (Sicily, Italy) was carried out as part of the ARCHES Project. This field scenario allowed the validation of the robotics systems in an analogue harsh environment and the confirmation of enhanced operations with the application of this modular method. Among the numerous activities performed in this volcanic terrain there are the efficient assembling of the Low Frequency Array (LOFAR) network, the energy-saving and reduced complexity of a detached Laser Induced Breakdown Spectroscopy (LIBS) module, and the uninterrupted powered operation between modules when switching between different power sources. The field data collected during this analogue campaign provided important outcomes for the modular robotics application. Modular and autonomous robots certainly benefit from their versatility, reusability, less complex systems, reduced requirements for space qualification, and lower risks for the mission. These characteristics will ensure that long duration and complex robotic planetary endeavours are not as challenging as they used to be in the past.

IAC-22,B3,6-A5.3,4,x73187: **"Introduction to Surface Avatar: the First Heterogeneous Robotic Team to be Commanded with Scalable Autonomy from the ISS"**

Abstract: Robotics is vital to the continued development toward Lunar and Martian exploration, in-situ resource utilization, and surface infrastructure construction. Large-scale extra-terrestrial missions will require teams of robots with different, complementary capabilities, together with a powerful, intuitive user interface for effective commanding. We introduce Surface Avatar, the newest ISS-to-Earth telerobotic experiment series, to be conducted in 2022-2024. Spear-headed by DLR, together with ESA, Surface Avatar builds on expertise on commanding robots with different levels of autonomy from our past telerobotic experiments: Kontur-2, Haptics, Interact, SUPVIS Justin, and Analog-1. A team of four heterogeneous robots in a multi-site analog environment at DLR are at the command of a crew member on the ISS. The team has a humanoid robot for dexterous object handling, construction and maintenance; a rover for long traverses and sample acquisition; a quadrupedal robot for scouting and exploring difficult terrains; and a lander with robotic arm for component delivery and sample stowage. The crew's command terminal is multimodal, with an intuitive graphical user interface, 3-DOF joystick, and 7-DOF input device with force-feedback. The autonomy of any robot can be scaled up and down depending on the task and the astronaut's preference: acting as an avatar of the crew in haptically-coupled telepresence, or receiving task-level commands like an intelligent co-worker. Through crew performing collaborative tasks in exploration and construction scenarios, we hope to gain insight into how to optimally command robots in a future space mission. This paper presents findings from the first preliminary session in June 2022, and discusses the way forward in the planned experiment sessions.

IAC-22,A3,IPB,31,x69374: **"Robust place recognition with Gaussian Process Gradient Maps for teams of robotic explorers in challenging lunar environments"**

Abstract: Teams of mobile robots will play a key role towards future planetary exploration missions. In fact, plans for upcoming lunar exploration, and other extraterrestrial bodies, foresee an extensive usage of robots for the purposes of in-situ analysis, building infrastructure and realizing maps of the environment for its exploitation. To enable prolonged robotic autonomy, however, it is critical for the robotic agents to be able to robustly localize themselves during their motion and, concurrently, to produce maps of the environment. To this end, visual SLAM (Simultaneous Localization and Mapping) techniques have been developed during the years and found successful application in several terrestrial fields, such as autonomous driving, automated construction and agricultural robotics. To this day, autonomous navigation has been demonstrated in various robotic missions to Mars, e.g., from NASA's Mars Exploration Rover (MER) Missions, to NASA's Mars Science Laboratory (Curiosity) and the current Mars2020 Perseverance, thanks to the implementation of Visual Odometry, using cameras to robustly estimate the rover's ego-motion. While VO techniques enable the traversal of large distances from one scientific target to the other, future operations, e.g., for building or maintenance of infrastructure, will require robotic agents to repeatedly visit the same environment. In this case, the ability to re-localize themselves with respect to previously visited places, and therefore the ability to create consistent maps of the environment, is paramount to achieve localization accuracies, that are far above what is achievable from global localization approaches. The planetary environment, however, poses significant challenges to this goal, due to extreme lighting conditions, severe visual aliasing and a lack of uniquely identifiable natural "features". For this reason, we developed an approach for re localization and place recognition, that relies on Gaussian Processes, to efficiently represent portions of the local terrain elevation, named "GPGMaps" (Gaussian Process Gradient Maps), and to use its gradient in conjunction with traditional visual matching techniques. In this paper, we demonstrate, analyze and report the performances of our SLAM approach, based on GPGMaps, during the 2022 ARCHES (Autonomous Robotic Networks to Help Modern Societies) mission, that took place on the volcanic ash slopes of Mt. Etna, Sicily, a designated planetary analogous environment. The proposed SLAM system has been deployed for real-time usage on a robotic team that includes the LRU (Lightweight Rover Unit), a planetary-like rover with high autonomy, perceptual and locomotion capabilities, to demonstrate enabling technologies for future lunar applications.

IAC-22,B3,6-A5.3,6,x69166: **"Towards Real-Time Communication Coverage Prediction for Cooperative Networked Robots: Results from a Space-Analogue Campaign on Mt. Etna"**

Abstract: Future planetary space exploration is expected to use a plethora of robotic entities: be it a swarm of homogeneous robots forming sensing arrays, or heterogeneous teams of robots collaboratively solving complex tasks. The level of autonomy for in-situ instrumentation ranges from remotely controlled robots to semi-autonomous systems. For all of them, a key element is communication. Remotely controlled robots have strong communication demands in terms of connectivity among the robots and to a lander platform. Semi-autonomous systems require communication to share information: they compose a selforganized network and can support each other to enhance communication where needed. Connectivity and communication coverage for networked robots depend on a variety of factors, including knowledge of the terrain and a deep understanding of radio-propagation.

Thus, communication quality prediction is a challenging problem, which is not yet solved. In the ARCHES (Autonomous Robotic Networks to Help Modern Societies) project we particularly have a look at predicting the communication coverage for such robotic networks. In an intra-disciplinary team, we have developed a framework that supports an operator at the ground control. This framework predicts the communication coverage for the targeted exploration areas and points of interest for in-situ instrumentation and provides a graphical user interface.

In our novel approach, we combine real-time robotic terrain mapping with radio-propagation modeling. With the help of the predicted communication coverage map, an operator can intuitively make sound decisions on where robots can move for in-situ instrumentation while preserving communication connectivity. In addition, the operator can view areas where robots acting as communication relays should optimally be placed. Besides showing details of our framework, we present results from a space-analogue in-situ instrumentation campaign on the volcano Mt. Etna, Sicily, Italy. In this campaign taking place in June 2022, a team of heterogenous robots, partly remotely controlled and partly (semi-)autonomous, explores and maps an

unknown rough terrain. Our framework predicts communication coverage for the operator at the ground control in near real-time. We show details of this campaign, and provide an outlook on the extension of our framework.

IAC-22,A3,IPB,32,x69159: **"Radio-Localization and Multi-Robot Technologies for Low-Frequency Radio Arrays: Results from a Space Analogue Campaign on Mt. Etna"**

Abstract: A forward-looking vision of astronomers worldwide is the operation of a large-scale radio-telescope onthe far side of the Moon to observe the sky in the radio-frequency (RF) range of few Megahertz with unprecedented quality. Observations in this frequency range, free of interference from Earth's ionosphere and human-made RF sources, enable insights into the dark ages of the universe, the magnetospheres, and space environments of possibly habitable exoplanets and our solar system. Numerous concepts for lunar radio-telescopes have been proposed, and are mostly involving tethered antennas robotically deployed around a lander. In contrast to these concepts, we propose a distributed untethered array to potentially span the array over a larger area, and to reconfigure array geometry. Key technologies to achieve this goal are precise localization and synchronization of array antennas and robotic manipulation capabilities for autonomous deployments and reconfiguration. The ARCHES (Autonomous Robotic Networks to Help Modern Societies) project focuses on the development and validation of these technologies.

In this work, we present our radio-localization system providing precise relative localization of array antennas as well as multi-robot technologies for array deployment. The array is referred to as lowfrequency radio arrays, and comprises multiple distributed antennas realized in payload boxes. These shoe box sized payload boxes can be transported and manipulated by our Lightweight Rover Units (LRUs), prototypes of small and agile exploration rovers featuring a high degree of on-board autonomy. These technologies will be demonstrated in a space-analogue field campaign on the volcano Mt. Etna, Sicily, Italy, in June 2022. We give insights into this field campaign with this experiment, and show results and performance comparisons of our demonstrated technologies. Furthermore, we give an outlook on future developments and future usage of these technologies.

IAC-22,A3,2B,4,x68357: **"Analog-1: A Touch Remote"**

Abstract: The METERON project (Multipurpose End-To-End Robotics Operations Network) was implemented by the European Space Agency as an initiative to prepare Europe for future human-robotic exploration scenarios that in particular, focused on examination of the human-robotic partnership, and how this partnership could be optimized through an evaluation of the tools and methodologies utilized in the experiments in the domains of operations, communications and robotics (specifically with respect to control strategies).

Implemented through series of experiments of gradually increasing complexity, the project was originally conceived to culminate in the control of a rover-robot located at a terrestrial analogue site. Being operated by a geology-trained astronaut from the International Space Station (ISS), such a test would enable a reasonably high-fidelity examination of how crew on an orbiting vehicle around the Moon or Mars could remotely perform exploration tasks in an unstructured environment in close collaboration with operations teams at various centres on Earth.

In early 2019, Lanzarote was selected as the terrestrial analogue site due to its lunar-like terrain coupled with the fact that the Tinguaton area had been used by the European Astronaut Centre's PANGAEA astronaut training course in 2017. Alignment of ISS planning with the unpredictable constraints of an outdoor planning drove the team to decide to split METERON Analog-1 into two segments: control of the rover/robot from the ISS as an excellent analogue of the Lunar Gateway, together with a more realistic ground analogue campaign - Mount Etna in this instance – where the Gateway analogue was simplified to a room in a nearby hotel.

The Mount Etna test was performed in cooperation with the DLR ARCHES campaign in June-July 2022 through implementation of a joint 'space demo mission' – described in detail in a companion paper in this Congress – addressing geology and radio astronomy [1].

The first part of Analog-1 was successfully accomplished in November 2019 by the astronaut who drove the rover at an 'indoor' analogue site in the Netherlands and operated the rover's robotic arm using a novel haptic control station (Sigma-7) that allowed the astronaut to 'feel' the forces experienced by the robotic arm as he collected selected samples.

This paper will report on the results of the Mount Etna 2022 campaign and contrast with the results from the ISS experiment obtained in 2019, with a particular focus on the interaction between the 'Science Backroom', the rover operations centre at ESOC, and the subject astronaut, who for the Mount Etna testing was retired ESA astronaut Thomas Reiter.

6. Conclusions

A foreign campaign of this scale, involving several institutions, partners and nations, is a big challenge in COVID time, especially as it was postponed twice because of the pandemic. In the end, we are very happy to have been able to complete it so successfully despite all these challenges. It was possible to demonstrate the full campaign with the originally planned experiments. Only through the strongly supporting and motivated team, the clear agreements and also rules, such as the Corona rules of conduct within the team but also externally, have shown that with discipline and a sense of responsibility such a campaign can also be implemented at our time.

Especially the teamwork and the cooperation of the different disciplines, the different institutions, the different characters worked very well under these conditions, because a common "we" feeling was formed among the core participants. This was also reflected in the very harmoniously executed three demonstration tragedies in the third week, where the three missions were successfully carried out and accompanied from Catania with "live circuits" and a small conference programme.

The technical demonstration, accompanied by a planetary science team, and defined mission procedures have shown that today's robotic systems at ESA, DLR, and KIT can be remotely controlled to the extent that they can perform intelligent mission-relevant tasks. As is often the case with such experiments, there is of course a need for optimisation of the systems, but also of some of the methods and technologies, which is particularly noticeable in the joint use of these technologies in such analogue campaigns. In particular, the cross-domain work on a common mission strongly promotes common understanding and draws attention to the challenges and difficulties of the other, which greatly improves understanding among each other.

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