Towards Heterogeneous Robotic Teams for Collaborative Scientific Sampling in Lunar and Planetary Environments

Martin J. Schuster, Marcus G. Müller, Sebastian G. Brunner, Hannah Lehner, Peter Lehner, Andreas Dömel, Mallikarjuna Vayugundla, Florian Steidle, Philipp Lutz, Ryo Sakagami, Lukas Meyer, Rico Belder, Michal Smisek, Wolfgang Stürzl, Rudolph Triebel and Armin Wedler

***Abstract*— Teams of mobile robots will play a crucial role in future scientific missions to explore the surfaces of extraterrestrial bodies such as Moon or Mars. Taking scientific samples is an expensive task when operating far away in challenging, previously unknown environments, especially in hard-to-reach areas, such as craters, pits, and subterranean caves. In contrast to current single-robot missions, future robotic teams will increase efficiency via increased autonomy and parallelization, improve robustness via functional redundancy, as well as benefit from complementary capabilities of the individual robots. In this work, we present our heterogeneous robotic team consisting of flying and driving robots that we plan to deploy on a scientific sampling demonstration mission in a Moon-analogue environment on Mt. Etna, Sicily, Italy in 2020 as part of the ARCHES project. We first describe the robots' individual capabilities and then highlight their tasks in the joint mission scenario. In addition, we present preliminary experiments on important subtasks: the analysis of volcanic rocks via spectral images, collaborative multi-robot 6D SLAM in a Moon-analogue environment as well as with a rover and a drone in a Mars-like scenario, and demonstrations of autonomous robotic sample-return missions therein.**

I. INTRODUCTION

Mobile robots constitute a crucial element of present and future scientific missions to explore the surfaces of celestial bodies such as Moon and Mars [1], [2]. Compared to current single-robot missions, future teams of robots will improve efficiency via parallelization and robustness via functional redundancy. Furthermore, heterogeneous robotic teams benefit from complementary capabilities of individual agents [3], [4]. Taking scientific samples remains, however, a challenging task: The robots operate in Global Navigation Satellite System (GNSS)-denied environments and thus have to rely on space-suitable on-board sensors such as stereo cameras to navigate, explore, and sample previously unknown areas in rough terrain. Also, the long round-trip times of several seconds (Moon) to many minutes (Mars) can make teleoperation impossible, and autonomy is often required. Thus, the robots need to localize themselves online, model their surroundings, and share information about the environment and their position therein. These capabilities constitute the basis for the local autonomy of each system as well as for any coordinated joint action within the team.

In this work, we present our heterogeneous robotic team that we are going to deploy during a demonstration mission for scientific exploration and sampling in 2020, located in a Moon-analogue environment on Mt. Etna in Sicily, Italy. In Fig. 1, we give an impression from preliminary experiments that we conducted in 2017 at the test site. We describe the composition and capabilities of our heterogeneous robotic team as well as their joint mission scenario for geological exploration and sampling. The mission is part of the Helmholtz Future Project ARCHES [5], [6], [7], with the aim to develop heterogeneous, autonomous, and interconnected robotic systems. While in the ROBEX project [8], [9], we used a single robot to deploy a seismic sensor array, ARCHES focuses on the benefits of cooperation in a heterogeneous team. In contrast to [3], [4], we will test our systems again at a Moon-analogue site. Furthermore, our heterogeneous team includes a flying robot for fast scouting in addition to ground-based robots for close-up analysis and sample-return tasks. This geological exploration of lunar and planetary surfaces aims at understanding the history of our solar system as well as to search for signs of life, exploitable resources or potentially habitable areas. By analyzing soil and rock samples, scientists can, for example, gain insights into the paleohistory, i.e. the time of formation of the rocks, as well as the postformational history, i.e. subsequent climate changes and erosions that affected the rocks on a planet.

The authors are with the German Aerospace Center (DLR), Robotics and Mechatronics Center (RMC), Münchner Str. 20, 82234 Wessling, Germany, {firstname.lastname@dlr.de}

Fig. 1: Preliminary experiments at a Moon-analogue site on the volcano Mt. Etna in 2017: Two Lightweight Rover Units (LRUs) [10] demonstrate their skills for autonomous scientific exploration and sampling.

After describing the robotic team (Sec. II) and its mission (Sec. III), we present results from preliminary experiments on crucial subtasks: the analysis of rocks via spectral cameras (Sec. IV), collaborative multi-robot 6D SLAM in a Moon-analogue environment (Sec. V) and in a Mars-like scenario with a heterogeneous robotic team of flying and driving robots (Sec. VI), as well as demonstrations of autonomous robotic sample-return missions therein (Sec. VII). We successfully showed the latter two types of demonstrations more than 35 times each at the International Astronautical Congress (IAC) 2018, the world's largest annual gathering of space professionals with more than 6500 participants.

II. HETEROGENEOUS ROBOTIC TEAM

In order to tackle the aforementioned challenges imposed by planetary exploration missions, we plan to deploy a heterogeneous team consisting of flying and driving robots as well as static and mobile infrastructure elements such as a lander and multi-purpose payload boxes [9], [13]. We provide an overview of all systems in Table I. The robots have complementary capabilities: Our drone ARDEA [11] acts as a fast scout that can easily reach hard-to-access places such as craters or caves. While flying on Mars [2] or Moon [14] will require different propulsion systems, our hexacopter-based prototype allows us, for example, to implement and test potentially transferable navigation algorithms. Our first planetary exploration rover LRU1 [10] can transport ARDEA and perform close-up inspections with its science camera, whereas our second rover, LRU2 [10], [12], can be deployed to take soil and rock samples as well as to transport and manipulate payload boxes. The latter can be used to transport scientific sensors as well as mobile infrastructure elements to be placed on the planetary surface, for example, to extend the robots' communication range. The lander acts as a base station and global landmark for all robots. In order to enable local autonomy, all robots can localize themselves and each other based on their on-board sensor data. They collaboratively create a dense 3D model of the environment [15], [16] for navigation and mission planning.

For high-level mission control, we employ a prototypical graphical user interface to define the behavior for each agent. It consists of two parts: a 3D interface visualizing the global map, the agents' poses and the positions of interest as well as a separate GUI for the command sequences for each agent. Powerful execution modalities based on hierarchical state machines modeled in RAFCON [17] allow mission control to pause and resume the behaviors of each robot, to modify them, and to exchange the whole command sequence for a rover. On top of that, control can be switched to manual mode in case teleoperation is feasible and required. These features render our mission control software more powerful than many approaches of related work, such as the IMPACT framework [18], which does not allow the parameterization of reactive behavior, and the M2PEM software [19], which does not support heterogeneous teams and does not allow to switch to manual remote control.

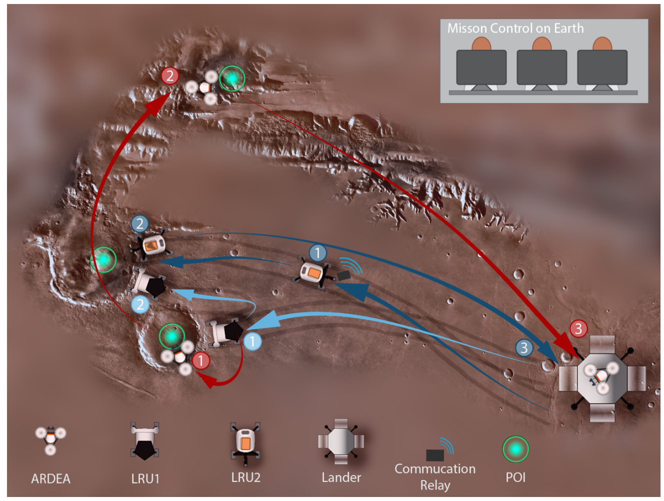


Fig. 2: ARCHES mission scenario with collaborative exploration and sampling. The numbers indicate the sequence of tasks executed in parallel by the individual robotic team members during the mission; The systems are not drawn to scale for improved visibility.

III. SCIENTIFIC EXPLORATION SCENARIO

The goal of the upcoming ARCHES scientific sampling demonstration mission on Mt. Etna in 2020 is the creation of an accurate map of a target region, the spectral analysis of rocks, as well as the collection of sand and rock samples. For this, we will leverage the complementary capabilities of our heterogeneous team of (semi-)autonomous robots. In Fig. 2, we give an overview over the mission scenario. It involves the deployment of our robot systems and infrastructure elements listed in Table I. A landing spot had been selected by a team of scientists and mission operators based on prior knowledge from satellite imagery. It is located near three geologically interesting locations marked as points of interest (POIs) in Fig. 2. As a first step after landing, our rover LRU1 (1) is sent out to explore the closest POI in a nearby crater. It drives towards the target area while autonomously avoiding obstacles on its way. ARDEA, our drone, is carried by the rover on its transport and take-off platform. Upon reaching the target area, the 3D map created by LRU1 shows that the crater slope is too steep for the rover to enter. Therefore, mission control decides to launch the drone ARDEA (1) to further explore and map the crater from inside. At the same time, LRU2 (1) is sent out to place a payload box with a communication relay half way between the lander and the two other, farther-away POIs to ensure radio coverage. In a second step, LRU1 (2) moves towards the next nearby, easier accessible POI and uses its spectral cameras to analyze the rocks there. It identify stones of an unusual type that is worth collecting. Thus, mission control sends LRU2 (2) to take a rock sample and return it to the lander (3) for further analysis. In the meantime, ARDEA (2) reaches the final POI and analyzes the local terrain based on its cameras to estimate the scientific value of close-up inspection. Afterwards, the drone (3) returns to the lander for recharging.

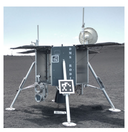
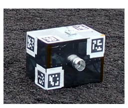
System	System Features	Capabilities
ARDEA [11] 	• Flying system with high maneuverability • Ultra wide-angle stereo camera setup with 240° vertical and 80° horizontal field of view	• Fast scouting for exploration and mapping • Identification of points of interest via semantic analyses • Act as mobile radio communication relay
LRU1 [10], [9] 	• Individually controlled and powered wheels on actuated bogies • Pan/tilt camera head with stereo navigation cameras • Scientific cameras: infrared camera, narrow-angle camera and stereo cameras with spectral filter wheels • Take-off and landing platform for ARDEA	• Autonomous exploration and mapping in rough terrain • Carrier for ARDEA • Scientific analyses of rocks etc. with spectral and thermal cameras
LRU2 [10], [12] 	• Individually controlled and powered wheels on actuated bogies • Pan/tilt camera head with stereo navigation cameras • Manipulator arm with docking interface • Carrier for payload box • Carriers for tools, e.g., robotic hand or shovel	• Autonomous exploration and mapping in rough terrain • Collection of samples (e.g., sand or small rocks) • Deployment of scientific instruments (e.g., seismic sensors or mobile spectrometers) • Deployment of infrastructure (e.g., radio repeaters)
Lander [9] 	• Solar panels and batteries • Computational power • Communication link to Earth • Instruments for scientific analyses	• Perform computationally expensive tasks • Save and aggregate data for downlink to Earth • Recharge robots • Analyze samples (e.g., via breakdown spectroscopy) • Act as artificial landmark for navigation
Payload Box [6], [13] 	Possible content of payload box: • Scientific sensors (e.g., seismic sensor or laser-induced breakdown spectroscopy (LIBS)) • Radio communication relay • Soil or rock sample container Each box has a common docking adapter to be grasped by LRU2.	Depending on content of box: • Take scientific measurements • Analyze rock composition • Extend communication range • Carry multiple soil or rock samples • Act as artificial landmark for navigation

TABLE I: Individual robots and infrastructure systems with their complementary implemented and planned capabilities

IV. Spectral Analysis of Rock Samples

In addition to the three navigation cameras, LRU1 is equipped with a scientific camera first introduced by [9] as ScienceCam, which has a concept similar to the PanCam of the ExoMarsRover presented in [20]. It is composed of two wide angle cameras (WAC) (Manta G-145B NIR) with spectral filter wheels in a stereo setup, a thermal camera (Xenics Serval-640) and a narrow-angle camera (Manta G-505C). The filter wheels for the LWAC and RWAC are each comprised of three colour filters (100 nm bandwidth) and six narrow band (10nm bandwidth) geology filters (*Geo1-Geo12*), across a range of $440 - 660$ nm for LWAC and $720 - 1000$ nm range for RWAC.

By combining several bands, science products can be calculated to distinguish different types of rocks. In Fig. 4, we present a preliminary example of a science product, based on a solely geometrically calibrated camera. It is composed of the *Geo4 (560 nm)* filter image, the normalized difference of the *Geo1 (440 nm)* and *Blue (460 nm)* filter images, and the normalized difference of the *Geo6 (660 nm)* and *Geo1 (440 nm)* filter images. We visualized the resulting three channels for human examination as RGB (Red, Green, Blue) respectively. Rocks that cannot be discriminated in the visible range clearly stand out in the generated science product.

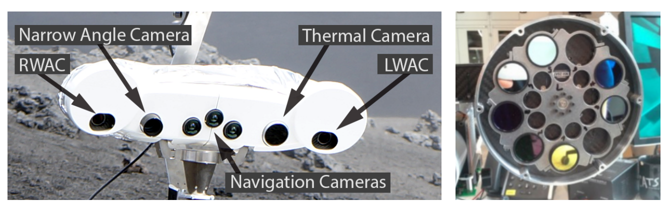


Fig. 3: Left: ScienceCam with LWAC (Manta G-145B NIR), RWAC (Manta G-145B NIR), narrow-angle camera (Manta G-505C) and thermal camera (Xenics Serval-640); Right: Left filter wheel with spectral bandpass filters.

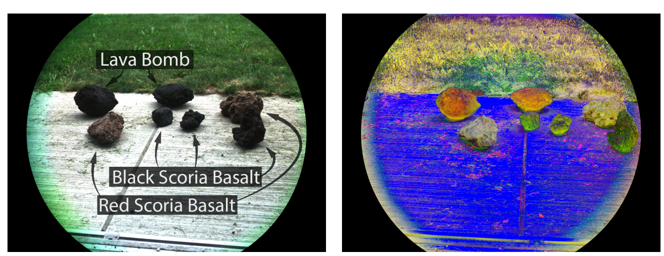
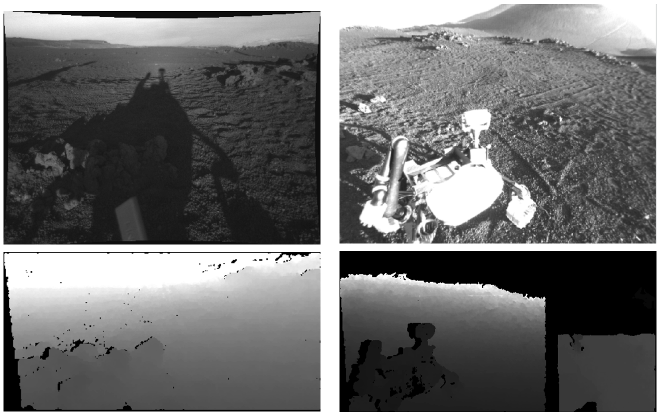


Fig. 4: RGB image of vulcanic rocks from Mt. Etna and generated science product visualized as RGB $= (\text{Geo4}, \frac{\text{Geo1} - \text{Blue}}{\text{Geo1} + \text{Blue}}, \frac{\text{Geo6} - \text{Geo1}}{\text{Geo6} + \text{Geo1}})$. Whereas, e.g. , the lava bomb and the black scoria basalt look similar in the RGB image, they can be clearly distinguished in the science product.



(a) LRU2 (narrow-angle) (b) ARDEA (ultra wide-angle)

Fig. 5: Top: Navigation cameras of LRU2 and ARDEA on Mt. Etna showing challenging conditions with harsh shadows and overexposures due to bright sunlight; Bottom: Dense stereo data (ARDEA: three virtual pinhole cameras: center (left), upward, and downward facing (right, small), see [11]).

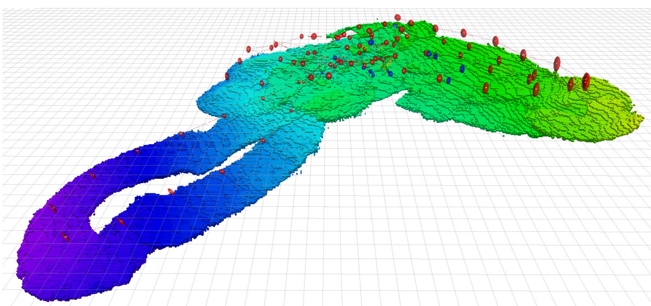


Fig. 6: Height-colored probabilistic multi-robot voxel map created from data acquired in the Moon-analogue environment of Mt. Etna by LRU2 and the ARDEA sensor stack. Blue and red ellipsoids show the respective positional uncertainty of their submap origins (see [15], [16]).

V. NAVIGATION AT MOON-ANALOGUE SITE

During our ROBEX campaign at Mt. Etna in 2017, we collected data in a preliminary experiment, which we evaluated for the ARCHES project: We tested our collaborative 6D SLAM [15], [16] with our LRU2 rover and the sensor stack of our drone ARDEA in a Moon-analogue environment. In Fig. 5, we highlight the challenges both systems face when observing the world with their narrow- and ultra wide-angle stereo navigation cameras – a space-suitable sensor setup, in contrast to rotating laser scanners, which are widely in terrestrial tests of related work, e.g., [3], [4]. LRU2 has visual markers that allow close-range detections from ARDEA. With these, it can act as a moving landmark for the drone, enabling a joint optimization for localization and mapping. We show the resulting dense multi-robot 3D map of the environment on a slope of Mt. Etna in Fig. 6. While we manually controlled LRU2 and carried the sensor stack of ARDEA in this early test, we subsequently used waypoint navigation on both robots, as presented in the next section.

VI. COLLABORATIVE MULTI-ROBOT SLAM

At the IAC 2018, we set up an autonomous planetary exploration scenario in a Mars-like environment in a sandbox of approx. $50\,\mathrm{m}^2$, shown in Fig. 7, featuring a lander mockup and large artificial rocks as navigational and visual obstacles. Therein, we demonstrated collaborative 6D localization and 3D mapping with a heterogeneous team of our rover LRU1 and multicopter ARDEA. We ran our SLAM framework [15], [16] online and on board both robots to locally create partial 3D maps, exchange, connect, and optimize them as a collaboratively built joint map of the environment. Both robots started their mission located in front of the lander, with ARDEA being carried by LRU1. As there is no direct line of sight between the rover and the target area, the operators decided to dispatch ARDEA to take off from LRU1 to explore and map the area with its ultra wide-angle stereo cameras by flying to and rotating $360°$ at several predefined waypoints. At a first waypoint close to LRU1, it was able to observe markers attached to the camera mast of the rover, allowing both robots to connect their coordinate frames and maps. After ARDEA reached and mapped the target area from the air, LRU1 was dispatched to navigate there, avoiding obstacles and mapping its path. In the meantime, ARDEA returned to land near its starting position in front of the lander, which acts as the robots' home base in planetary exploration missions. In Fig. 7, we show the final multi-robot map in its dense 3D point cloud and probabilistic voxel-grid representations. We refer to [16] for further details on the SLAM framework and this demonstration.

VII. AUTONOMOUS SAMPLE-RETURN

The geological analysis of celestial bodies can benefit greatly from rock or sand samples. Autonomous operation would enable scientists to obtain samples from hard-to-access areas. We showcase the capabilities for autonomous sample return in the scenario of Fig. 8, as demonstrated robustly at the IAC 2018 in more than 35 live runs: LRU2 started by retrieving a sample container from the lander using its manipulator arm. It then transported the payload box to a target location at the opposite side of the area and placed it on the ground. The manipulator grasped a shovel and scooped a soil sample into the payload box. Afterwards, the rover returned the payload box to the lander. The robot was able to complete the whole mission with all software running on-board, including task execution, 6D SLAM, navigation and manipulation planning. This allows the robot to take samples even where and when a communication link to its team members and to the ground station on Earth is temporarily unavailable. The autonomous capabilities of LRU2 will be extended for the ARCHES demonstration mission with rock sampling for geological science and infrastructure assembly for the construction of sensor arrays.

VIII. CONCLUSION AND FUTURE WORK

In the upcoming ARCHES demonstration mission, we plan to bring together the individual capabilities of our robots to collaborate in pursuit of a common goal: the exploration

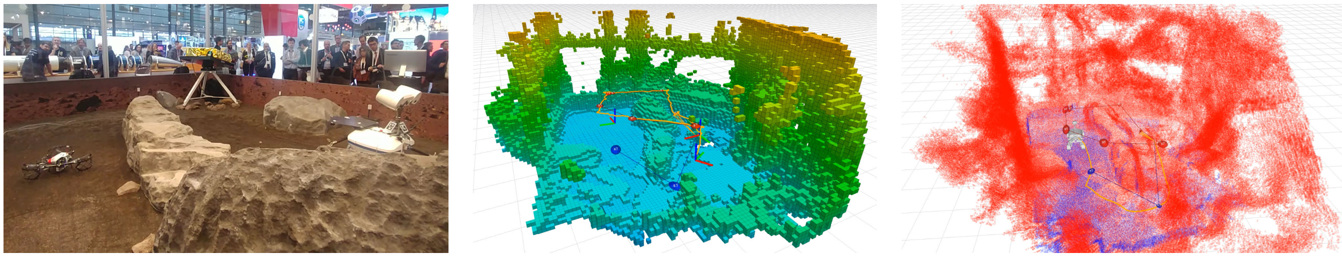


Fig. 7: Impression of our IAC 2018 multi-robot localization and mapping demonstration (left) with the resulting probablistic height-colored voxel-map (center) and robot-colored point cloud (right; red: ARDEA, blue: LRU1), which was computed online and on board the robots. We intentionally excluded the ceiling from our voxel map visualizations for better visibility. The large holes in the walls are due to the transparent glass panes surrounding the sandbox that either were invisible to our stereo sensors or induced noise due to partial reflections. The orange path represent the full trajectories traveled and estimated by ARDEA (center) and LRU1 (right) respectively.

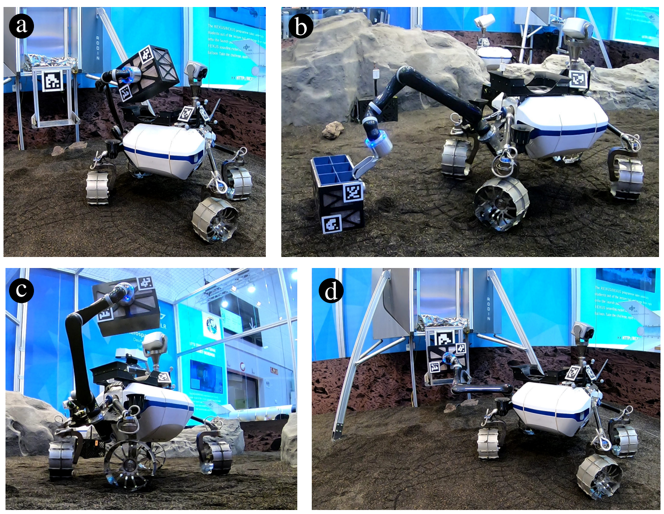


Fig. 8: Sequence of our IAC 2018 autonomous sample-return demonstration: a) pick up container at lander, b) extract sample, c) reclaim container, d) return to lander.

of a challenging extraterrestrial environment, including scientific analyses and autonomous sampling. In addition, we plan to extend the systems' individual autonomous capabilities as well as to increase their operation time and area by developing methods for larger-scale and multi-session mapping. While we solely employ space-suitable types of sensors, most algorithms have been implemented to run on terrestrial computation hardware in order to allow more design freedom and fast iterations during research. Future real planetary exploration missions, however, will require their adaption to space-qualified hardware.

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