REALMS: Resilient Exploration And Lunar Mapping System

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ABSTRACT

Space resource utilisation is opening a new space era. The scientific proof of the presence of water ice on the south pole of the moon, the recent advances in oxygen extraction from lunar regolith, and its use as a material to build shelters are positioning the moon, again, at the centre of important space programs. These worldwide programs, led by ARTEMIS, expect robotics to be the disrupting technology enabling humankind's next giant leap. However, moon robots require a high level of autonomy to perform lunar exploration tasks more efficiently without being constantly controlled from Earth. Furthermore, having more than one robotic system will increase the resiliency and robustness of the systems, improving the success of such missions, as well as providing additional redundancy. This paper introduces the Resilient Exploration And Lunar Mapping System (REALMS), developed with a scalable architecture for semi-autonomous lunar mapping, it leverages Visual Simultaneous Localisation And Mapping (vSLAM) techniques on multiple rovers to map large lunar environments. Several resilience mechanisms are implemented, such as two-agent redundancy, delay invariant communications, a multi-master architecture different control modes. This study presents the experimental results of REALMS with two robots and its potential to be scaled to a larger number of robots, increasing the map coverage and system redundancy. The system's performance was Verification and Validation (V&V) in a lunar analogue facility, and a larger lunar environment during the European Space Agency (ESA)-European Space Resources Innovation Centre (ESRIC) Space Resources Challenge. The results of the different experiments show the efficiency of REALMS and the benefits of using semi-autonomous systems.

Keywords: resilience, multi-master, delay invariant, mapping, VSLAM, lunar, exploration

COMMENTS TO EDITORS

The authors use British English throughout this manuscript. The word count is 6092 and the manuscript contains 14 figures and 1 table.

1 INTRODUCTION

In recent years, space resources utilisation has become increasingly interesting from both an economic and scientific perspective. The moon can be explored to find different valuable resources for In-Situ Resources Utilisation (ISRU) (Crawford, 2014). Among these, the most important resources are water-ice to generate rocket propellant and oxygen for life sustainability, as well as regolith that can be used as construction material. Given the growing interest, countries are starting to establish legal frameworks (Smith, 2021), allowing for more progress and innovation in space resources utilisation. Luxembourg aims at becoming the leading country in space resources activities (Bloomberg, 2021), establishing a legal framework (Luxembourg Space Agency, 2021) and the European Space Resources Innovation Centre (ESRIC) in coordination with the European Space Agency (ESA) (Naujokaitytė, 2020).

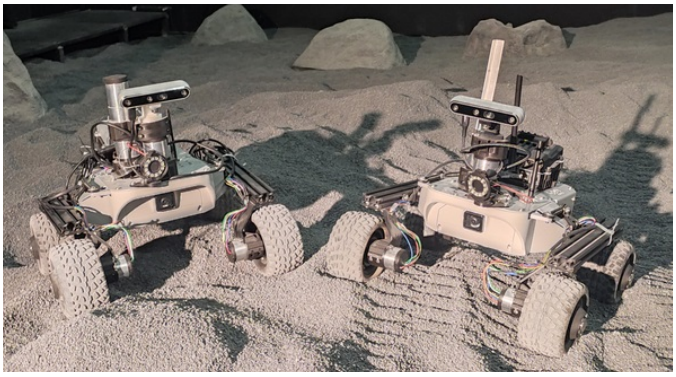

Figure 1. Resilient Exploration And Lunar Mapping System (REALMS) Leo rovers in the LunaLab

The NASA Artemis program (Aeronautics and Administration, 2022a) is leading a set of missions to find water-ice on the lunar surface and perform ISRU allowing astronauts to stay on the Moon for a long time. NASA plans to have the Volatiles Investigating Polar Exploration Rover (VIPER) exploring some Permanent Shadowed Regions (PSR) in the south pole to study the presence of water-ice and to extract samples from them (Aeronautics and Administration, 2022b). The pre-mission planning is based on the maps generated using the Lunar Reconnaissance Orbiter (LRO) data. However, in the best cases, the map resolution in the south-pole is half of the resolution of the maps from the equatorial regions (Delgado-Centeno et al., 2021). In addition, the south-pole regions have large shadows generated by boulders and low incident angles of sun rays that hide potentially hazardous areas. The rover could collide with non-detected small boulders, or the low temperatures in the shadowed regions could damage the robot's electronics. Therefore, the success of this mission will strongly depend on the navigation sub-system of the VIPER rover to generate reliable mapping and localisation estimation in long traverses. Inspired by the VIPER mission, and to drive the innovation in technologies for space resources detection and prospecting, ESRIC and ESA have launched the Space Resources Challenge (ESA - European Space Agency, 2021). This is a lunar prospecting challenge, where each participating team have to explore and map a lunar-analogue facility and analyse specific rocks within a limited time. The facility included boulders, slopes, and low incident angle illumination to replicate the visual appearance of the lunar south-pole. The facility's communication system simulates Earth-Moon-Earth communication with five seconds delay, limited bandwidth, and connection losses. In this work, we present our REALMS approach that led us to be qualified for the final round of this Space Resources Challenge. As part of the LUVMI-XR consortium, REALMS represents the scouting part of the mission, while the scientific analysis was performed by the LUVMI-X rover. This paper shows the REALMS system and performance of the scouting team formed by two LeoRovers (Ideas, 2021) (Fig. 1).

Multi-Robot System (MRS) provide increased coverage and improve the efficiency of specific tasks by executing them in parallel. As a result, the robotic system consists of multiple robots dedicated to a single task, distributing the mission risk across multiple agents and potentially reducing overall mission costs. In a mission focused on exploration and prospecting, MRS are one of the most interesting solutions, especially when mapping and analysing large surfaces in a short amount of time.

This paper proposes our REALMS, a multi-robot, scalable and resilient solution for lunar exploration and prospecting, adaptable to homogeneous and heterogeneous rovers. We summarise the contributions as stated below.

- We changed the communication between the robots and the ground stations to a platform independent protocol to make the system robust to Earth-Moon-Earth communication delay.
- We provide a solution to operate multiple rovers in semi-autonomous and teleoperated modes, which increases the efficiency and reliability.
- We integrate a Visual Simultaneous Localisation And Mapping (vSLAM) solution for a lunar environment.
- We perform the V&V of REALMS with real rovers in two different lunar analogue facilities for short and long traverses within the context of the ESA-ESRIC Space Resources Challenge.
- We present guidelines of using ROS and multi-robot systems in a unique and hybrid approach to overcome problems generated in lunar environments with Earth-Moon-Earth communication such as software timeouts that prevent robots to connect to the ROS Master.

2 RELATED WORKS

Traditional planetary space missions led by space agencies operate single multipurpose robots equipped with several sensors, actuators, and complex algorithms. Their primary goal is to collect as much data as possible about different minerals, rather than explore large areas. Some examples are Lunokhod 2 (Aeronautics and Administration, 2018) and Yutu-2 (Ma et al., 2020) for the Moon, and Sojourner (Heuseler, 1998) and Curiosity (Lakdawalla, 2018) for Mars. The twin rovers Spirit and Opportunity (Arvidson, 2011) were sent to different locations to perform non-coordinated tasks, hence not working together. A similar case are the most recent missions, Perseverance and Ingenuity, in which both robots act as independent systems (Aeronautics and Administration, 2021a). All these rovers were developed with a high level of redundancy and State-of-the-Art sensors. Nonetheless, their missions are strongly constrained by potential mobility issues. Any movement has to be planned precisely. For instance, Perseverance has a maximum speed of 0.042 m/s (Aeronautics and Administration, 2021b) to reduce potential risks. This implies a small-scale coverage, making any exploration mission long and requiring the full supervision of an operator. The coming years are expected to see the first private rover missions on the moon (Lunar Outpost, 2021; ispace, 2021). Limited budgets for these missions will seek for efficiency and resiliency. After an initial test mission, there will be more missions to perform exploration and prospecting using MRS.

The application of MRS has already been extensively studied in many fields such as agriculture (et al, 2021) or search and rescue (Yan et al., 2013). The work described in (Parker, 2008) distinguished four main architectures for MRS: First, a centralised approach to coordinate the fleet from one main computer, assuring a simpler robot design with lower computational requirements. However, this makes the entire fleet dependent on the main computer, causing it to be fault intolerant, as discussed in (Caloud et al., 1990). Second, a hierarchical architecture in which each robot is either a part of a small fleet or a leader of a fleet to control. Each leader will be part of a fleet of leaders controlled by a main unit resulting in a relation tree. This approach is more scalable than the centralised architecture, but highly dependent on tree-top elements(Alur et al., 2001). Third, a decentralised or distributed architecture in which each robot is controlled independently, but making decisions according to the information shared by the other robots. This system is highly fault-tolerant, but less efficient to achieve a global goal. One commonly-used architecture is Alliance (Parker, 1998). Finally, a hybrid architecture combining multiple architectures, where the main computer manages the global goal and can influence small teams of robots. These teams are similar to a decentralised architecture, which allows for an optimised solution while providing a fault-tolerant system. An example of such an architecture is (Parker and Zhang, 2009).

In space, the implementation of MRS solutions has already been studied. The main challenge remains the need for a high level of automation and a reliable handling of the lunar conditions (Alfraheed and Al-Zaghameem, 2013). (Leitner, 2009) showed many use cases of MRS in space, but mostly focusing on satellites constellation. LUNARES (Cordes et al., 2011) presented a solution for heterogeneous multi-robot moon exploration in which tasks are distributed from a ground station to a system of three heterogeneous robots. The variety of the robots allows fulfilling a variety of missions linked to moon exploration, similarly RIMRES is an extended approach that implies more sophisticated robots (German Research Center for Artificial Intelligence GmbH, 2022).

To this end, robotic missions on the Moon and Mars are based on single robots that do not interact or operate with other robots. As a result, their network architecture does not consider multiple robots in the same network, and their level of autonomy is limited despite their complexity. Future MRS will likely require a network architecture that allows multiple agents in the same network. Additionally, operating multiple robots requires coordination between the robots and a higher level of autonomy to handle this coordination efficiently. REALMS aims to address these issues for future lunar missions.

3 SYSTEM DESCRIPTION

The robotic system offers to collaboratively address the challenges of a lunar exploration and prospecting mission.

3.1 Problem Statement

ESA and ESRIC proposed the ESA-ESRIC Space Resources Challenge to motivate the innovation for planetary prospecting technologies focused on the lunar environment. The objective consisted of gathering visual data and generating a 3D map of an unknown environment with illumination and communication delays to be expected during a lunar mission. In the challenge stage, the illumination was set up in a dark hall with black curtains and an array of bright spotlights to replicate sunlight with a low incidence angle, similar to the lunar south pole. The communication delay was achieved using the ESA delay communication system to simulate the delay between the Earth and the Moon at a software level. The round-trip delay consists of five seconds in total. Additionally, it is expected that the proposed system should be able to operate with occasional and eventual communication blackouts. The environment is a flat concrete surface with several obstacles such as rocks and ramps. The goal is to reach a region of interest behind one of the ramps where a crater is constructed filled with small rocks as the soil and larger rocks that are to be analysed by the research teams.

Then, taking into account the challenge description, the following requirements are identified:

1. The system must map as much as possible of the 2500 m² area in 2.5 h.
2. The system must be able to move and explore a lunar surface analogue zone and navigate through rocks and slopes.
3. The system must be impervious to a five seconds delay, unpredictable blackouts and a limited bandwidth.
4. The system must be resilient to partial system failure, allowing to finish the mission even when parts of the system fail.

3.2 Proposed solution

The implemented system consists of two identical rovers controlled by two identical ground stations over a delayed network. This whole system can be extended to any number of rovers and ground stations, depending on the bandwidth allowed. This section explains the whole REALMS architecture composed by n rovers and ground stations, the Lunar-Earth delay simulator and the Lunar testing environment as shown in Fig. 2. First, we will present the hardware and software components of the system. Second, we will explain the ground station setup. Third, we will elaborate the Earth-Moon-Earth delay simulator that adds communication delay in the network.

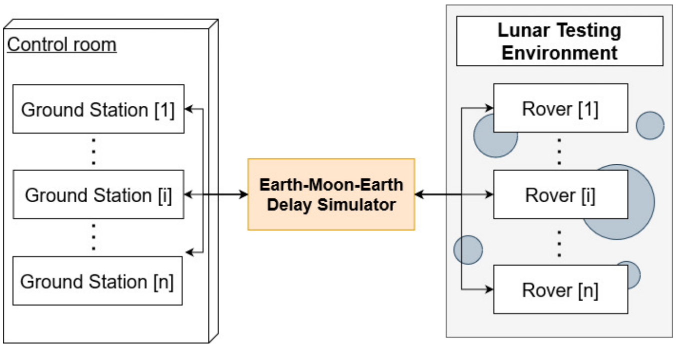

Figure 2. Overview of the REALMS architecture showing how multiple ground stations connect to multiple rovers through the Lunar-Earth Delay Simulator

3.2.1 Rover

The robot architecture of the system used in this work is presented in Fig. 3.

3.2.1.1 Hardware

Each rover is a modified version of a Leo Rover (Ideas, 2021), sold by the company Kell Ideas. It has a mass of 6.5 kg and a footprint of 45×45 cm. The drive system is based on a differential drive mechanism where each of the wheels can turn independently as shown in fig. 4.

The rover is equipped with two different computers. The main embedded computer is a Raspberry Pi $v4B$ using software provided by the Leo Rover manufacturer. This computer runs the ROS Master, the communication to the motor driver, the onboard illumination system, and a dedicated Raspberry Pi camera used for teleoperation. Additionally, the rover has LED rings composed of 12 SK6812-based LEDs. They can illuminate the surface in front of the rover and guarantee sufficient visibility of terrain features,

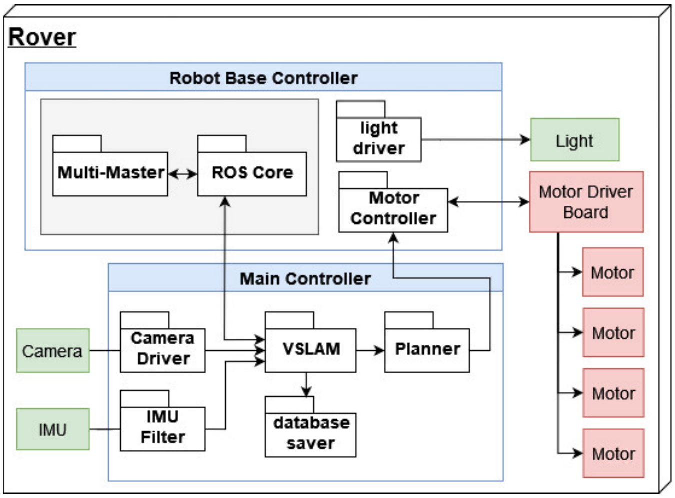

Figure 3. REALMS robot architecture diagram showing the robot base controller hosting the ROS Master, the hardware drivers and the main controller hosting the vSLAM system with the sensor input and the path planner

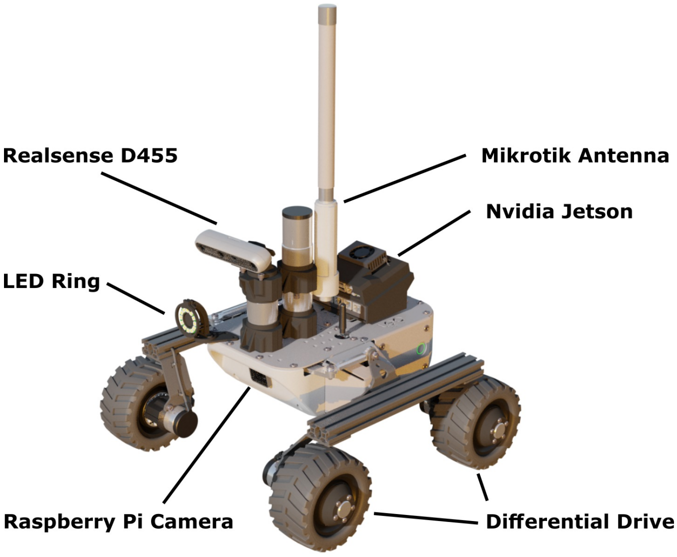

Figure 4. Overview of the REALMS Leo Rover hardware

addressing the mapping requirements. The Raspberry Pi is transferring commands to the motor driver board, a Core2-ROS designed specifically for the Leo Rover. On the other hand, the second computer is an NVidia Jetson Xavier NX running in 15 W power mode. It executes the Real-Time Appearance Based Mapping (RTAB-Map) (Labbe and Michaud, 2019) vSLAM algorithm based on the images and point cloud captured by an RGB-Depth (RGB-D) camera and a path planner. It has sufficient computational power to reliably run the vSLAM software without delays in the mapping process while keeping low power consumption. The Nvidia Jetson Xavier allows to distribute the computational workload while adding redundancy to the system for increased resiliency.

The RGB-D camera used for the vSLAM algorithm is an Intel RealSense D455 with an integrated Inertial Measurement Unit (IMU), which allows navigating in feature-poor environments. The camera uses a resolution of 1280×720 pixels at a frame rate of 5 fps. The RGB-D camera with IMU is the sole input for odometry. Wheel odometry is not used as it is considered unreliable for loose soil as can be found on the lunar surface.

The two embedded computers allow sharing the workload between them. The most computationally expensive programs are ran on the Jetson, leaving all the critical functionality, such as telecommunication and wheel control, to the Raspberry Pi. If the Jetson fails, the Raspberry Pi can still be used for teleoperation, providing additional reliability. As for the networking, the two computers are connected to a MikroTik WLAN router through a network switch, connecting them to the external network.

3.2.1.2 VSLAM

This software component solves the first requirement to map the largest area possible inside the lunar environment. It allows REALMS creating a map of the environment and localisation of the rovers based on visual inputs only, avoiding drift induced by wheel slip (Yang Cheng et al., 2006), a common issue on lunar terrain. For the vSLAM a modified version of RTAB-Map (Labbe and Michaud, 2019) is used. The input data are RGB-D images and data from an IMU. The default version of RTAB-Map generated false obstacles within the 2D local cost-map preventing the optimal navigation of the robot. The false obstacles originate from noise in the 3D point cloud that creates artefacts below the terrain. These are due to the natural reflection of the light on the ground which makes the depth acquisition by the RealSense noisier. To avoid this, the modified algorithm rejects points from the 3D point cloud below a threshold value in the z-axis while generating the 2D map.

3.2.1.3 Path planner and follower

This component focuses on solving the second requirement to navigate inside the environment. It is in charge of producing the necessary manoeuvres to make the rover autonomously drive from one location to another. To do this, the planner calculates a path connecting the rover's location to the target location as the initial step. The path planning algorithm used for REALMS is the Dynamic-Multi-Layered Path Planning (DyMu) (Sánchez-Ibánez et al., 2019) algorithm, which has been developed by ESA. Thereafter, the planner dynamically generates manoeuvres to make the rover follow this path.

The path planning relies on the Fast Marching Method (FMM) (Kimmel and Sethian, 2001). This method numerically solves the propagation of a wave originating from the robot location. The wave expands over a cost map, consisting of a grid where each node has an associated cost value. Depending on this value, the wave expands more or less at the location of the corresponding node. After the wave propagation is calculated, a gradient descent method extracts the path from it. The generated path is optimal in the sense that it is the curve connecting the two locations of interest with the minimal amount of accumulated cost along its way. Each node has an assigned positive non-zero cost value in the grid, ensuring that the calculation of the wave propagation does not degenerate. Unlike other commonly used methods such as A* or D*, this path does not necessarily need to pass through the grid nodes, and hence its shape is not restricted to the grid topology. Path following is based on the Conservative Pursuit (Filip et al., 2017). An improved version of the Pure Pursuit algorithm ensures the rover is always close to the path within a specified threshold. Its performance was already tested in past field tests (Gerdes et al., 2020).

3.2.1.4 Multimaster

The multimaster component focuses on overcoming potential issues with the communication delay and loss as well as increasing the resiliency of the entire system, hence addressing the third and fourth requirements. It allows running one ROS Master on each system element and thus ensures that the topics are only shared between a ground station and its corresponding robot. The ROS Master is a central part of the ROS ecosystem as it handles topics, services and actions, registers which nodes are publishing and subscribing, hold the parameter server and directs the data traffic to the corresponding nodes. By conventional definition, there is only one single ROS Master in a given network of robots to handle all the ROS data traffic within the system. Multiple robots can share a single ROS Master, however this leads to a centralised architecture, more prone to failure, especially when the connection to the ROS Master gets interrupted.

We integrated the FKIE multimaster (Fraunhofer-Institut für Kommunikation, Informationsverarbeitung und Ergonomie FKIE, 2017) in REALMS to prevent communication issues between the ground station and the robots by connecting multiple ROS Master instances and sharing topics between them. It comprises two main components, *discovery* and *sync*. *Discovery* can show all the Master instances available on a network. *Sync* is being used to get the topics and messages from the desired ROS Master.

The two aforementioned components are set up to allow sharing only the correct rover's topic with the desired ground station. This is done by using the option *sync_hosts* filled with the IP address of the robot and the ground station.

3.2.2 Ground stations

The robot is controlled through a computer that serves as a ground station, shown in Fig. 5. RViz is used as a user interface and allows defining a goal position sent to the robot. The FKIE multimaster software allows connecting multiple ROS Masters in the same network so that RViz can be used to control the rovers despite the presence of the network delay. Each robot is unaware of the other robots in the network allowing for easy scaling of the network and reducing interference between the robots. Additionally, the ground station can switch to manual mode for teleoperation of the robot via input devices. The ground stations and the robots are connected through a network with a total communication delay of 5 seconds.

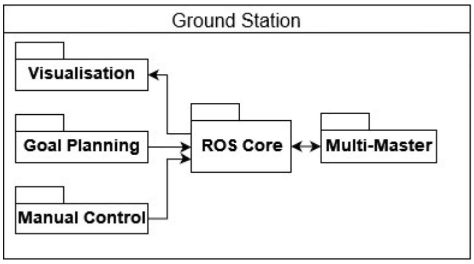

Figure 5. REALMS ground station architecture diagram showing commands sent to the robot and visualisation based on data received by the rover

3.2.3 Earth-Moon-Earth Delay Simulator

Fig. 6 describes the developed network architecture of the lunar delay network (Krueger, 2021) to test the performance of the proposed system. The delay computer has a 3.0 GHz Intel Core $i7$ generation 8 processor, and 8GB of RAM. The operating system that we use is FreeBSD 12.2. The delay computer has two separate network interfaces, $ue0$ and $ue1$, as described in Fig. 6. There are two routers, Delay Router and LunaLab Router, connected to $ue0$ and $ue1$, respectively. All the remote computers to control the navigation and movement of the rovers are connected via Ethernet cable to the Delay Router. Also, the Leo Rover is connected to LunaLab Router via 2.4 GHz Wi-Fi signal. In order to emulate an end-to-end

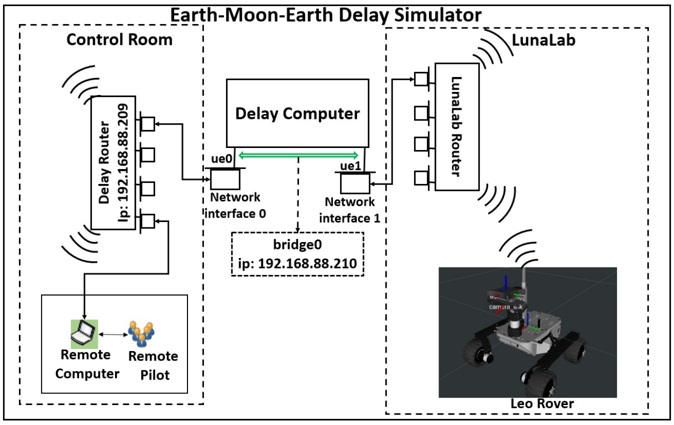

Figure 6. Delay Network Architecture connecting the rovers to the ground stations of REALMS by delaying all network traffic by a pre-defined amount of time

delay between the remote computer and the Leo Rover, there is a bridge, called $bridge0$, between $ue0$ and $ue1$. Therefore, all the traffic passes through the bridge between the control room and the LunaLab. Finally, two rules are set for the outgoing traffic from each network interface that is connoted to the bridge ($ue0$ and $ue1$) using the “ipfw” command to introduce the specific delay.

4 SYSTEM ANALYSIS

Each requirement in subsection 3.1 is analysed and the system designed to meet them accordingly. Table 1 shows how each component addresses each requirement. A component can serve as a key component (K) or supportive component (S). A key component is responsible to meet one of the requirements, while a supportive component contributes partially to meet a requirement in a non-essential way.

Table 1. Components addressing the system requirements

Components	**Requirements** (K: Key Component, S: Supportive Component)			
	Mapping	***Movement***	***Delay***	***Resilience***
Lights	S	S		
Motors	S	K		
Camera	K	S		
IMU	S			
vSLAM	K			
Planner	K			
Multimaster			K	S
Multi robot	S	S		K
Visualisation	S	S		
Dual control mode	S	S	K	K

4.1 Mapping coverage

It is expected that the MRS must cover a large area and create an associated map in 3D within a limited time. In the case of the Space Resources Challenge, the explorable area is specified as 2500 m². The mapping is done with a theoretical maximum movement speed of 0.04 m/s while using the autonomous control by sending goals to the robot. The camera used by the rovers has a field of view allowing to map 4.6 m², in the shape of a trapeze. As shown in Fig. 7, when considering a triangle CNM representing the field of view of the camera, where P is in the centre of NM, the angle $\angle NCM$ is equal to the horizontal field of view FoV_H of the camera and has a value of 87°. The distance NM is the width of the projected field of view on the ground surface that the robot can scan.

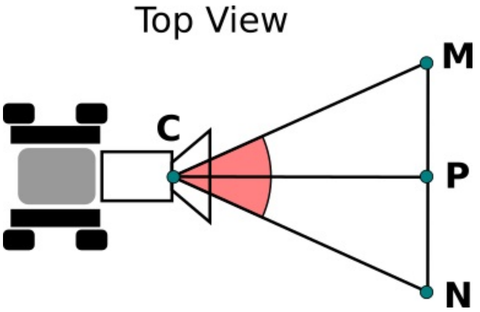

Figure 7. Top view schematic of the camera field of view. NM is the width of the field of view

Z-distances in the camera frame larger than 3 m are assumed to be unreliable due to high noise, so CP is set to 3 m. The distance NM is then 5.69 m, according to (1):

$$NM = 2 \cdot CP \cdot \tan \frac{FoV_H}{2} \tag{1}$$

Assuming each rover is moving at an average speed v of 0.025 m/s in a straight line without encountering any obstacle, each rover can cover an area a of up to 1281.1 m² in 2.5 h, according to: $a = v \cdot NM$. If two robots map simultaneously with a 20% overlap, they can cover an area a_{tot} of up to 2049.8 m² in 2.5 h, according to (2):

$$a_{tot} = 2 \cdot a \cdot 0.8 \tag{2}$$

To verify the coverage an experiment has been carried out to measure the time necessary to cover the LunaLab at Centre for Security, Reliability and Trust (SnT) with a single robot. The laboratory has an area of 88 m². Mapping the entire facility with a single robot took on average 12 min 30 s. As a result, in 2.5 h, a single robot could cover up to 1046.9 m². Based on the mission requirements, the robots must explore an area of 2500 m². As a result, the REALMS rovers can map the target area within 2.5 h.

4.2 Environment constraints

4.2.1 Minimum clearance

A rover needs to operate safely in an unknown terrain for lunar exploration. It needs to keep a safe distance from obstacles in the environment to prevent collisions that could damage the robot. At the same time, the rover needs to traverse between obstacles to access new areas to explore. This is a trade-off between safety and mobility. The path planner is configured to avoid entering into gaps narrower than 92 cm. This value has been defined by the dimensions of the Leo Rovers plus a safety margin of 23.5 cm on each side. This is depicted in Fig. 8. If necessary, the robots can be cautiously teleoperated through narrow spaces.

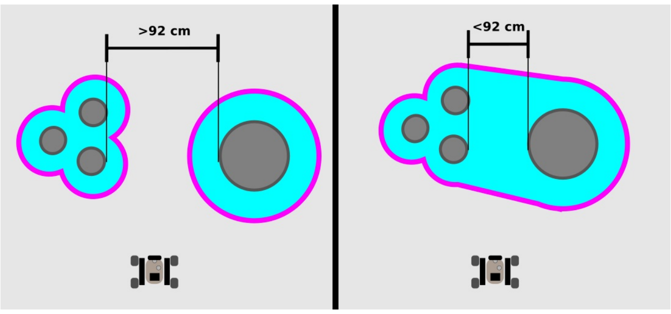

Figure 8. Graphical representation of the minimum clearance of the path planner. Objects closer than 92 cm are considered as too narrow for the planner to traverse in between those objects

4.2.2 Maximum slopes

In the permanently shadowed regions of the Moon, a robot needs to handle slopes of up to 22.1° (Gläser et al., 2018). We measured the maximum inclination angles the REALMS rovers can mount. They traversed a ramp as shown in Fig. 9 multiple times using three different surface materials while gradually increasing the inclination angle. In this way, we discovered the values of the maximum inclination angle the rovers could climb according to these materials. The maximum angle was 30° for loose basalt, 22.5° for a solid wooden surface and 26.6° for an aluminium surface. The friction on basalt is higher than on aluminium which causes the wheels to slip on aluminium.

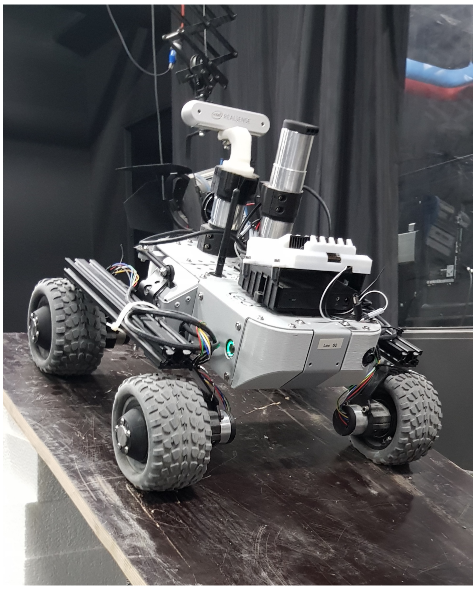

Figure 9. Experiment to determine maximum slope inclination the rovers can traverse

4.3 Delay invariance

Standard software has a timeout function implemented. This function stops the program if no data is received in a certain amount of time. The timeout function prevents communication when there is a communication delay of 5 s as is the case in Lunar-Earth communication. In another scenario, communication blackouts can occur that would also trigger the timeout function to stop the running processes. The visualisation software RViz needs to connect to a ROS Master as otherwise, it returns an error after a timeout of 1 s. For terrestrial applications, it is common to run a single ROS Master in the robotic network where one robot contains the Master, and the ground station is a slave connecting to the Master of the robot. The communication delay will not allow this connection due to the timeout. REALMS overcomes this issue by running a ROS Master on each device involved. That way, RViz and similar software always receive inputs from a ROS Master that runs locally. The FKIE multimaster software is bridging the communication between the individual Master instances, making the system delay invariant as it does not implement a timeout for the communication between the Master.

4.4 Resilience

The resilience of a system is its ability to recover after a partial failure. In the case of this challenge, it is important to see if all the previous requirements can be matched even with a faulty component. REALMS consists of a defined number of rover-ground station pairs. The bandwidth limits the maximum number of pairs. The ROS Master running on each machine make the system more robust as each robot and its corresponding ground station are not interdependent. If one of the two members is faulty, it can still be used to operate another member.

As seen subsection 4.1 and 5.1, it is proven that one robot is enough to map the entire surface. The REALMS used for the challenge is composed of two rover-ground station pairs, providing sufficient capability to map the expected area in the given time. Having more than one pair assures resilience and higher tolerance to potential blackouts. The maps created by each robot are saved locally. Each map can be retrieved by the ground stations and merged on the ground stations, allowing to use an incomplete map to enhance the global map. At this point, the REALMS rovers were ready to face the lunar surface like environmental conditions expected in the challenge.

4.5 Mission Control

REALMS is designed for mapping an unknown environment with multiple rovers in a semi-autonomous approach which is defined by a human-in-the-loop system. A human operator can provide waypoints to the system and the rovers can reach these waypoints autonomously, provided the path planner can find a feasible path.Otherwise, the human operator can take control and teleoperate the robot to cross difficult areas, such as spaces too narrow for the robot to safely navigate autonomously. Fig. 10 shows how the robot is controlled by first using teleoperation until the robot creates the first frame of a map. After this initialisation, the operator can switch to the autonomous mode or keep teleoperating the robots. In the event that the robot cannot plan a path to a given waypoint, the operator can choose a new waypoint or drive manually until it is safe to revert to autonomous mode.

5 EXPERIMENTAL RESULTS

5.1 Testing REALMS in the LunaLab

The LunaLab (Ludivig et al., 2020) is the lunar analogue facility of the University of Luxembourg, a 8×11 m^2 room containing 20 tons of basalt focusing on the optical fidelity with respect to lunar environments (Fig. 11). To test the multi-robot mapping capabilities of REALMS, the two rovers were placed in two different locations inside the LunaLab.

Two scenarios were tested. Scenario one shows the successful mapping a shared area with two robots (Fig. 12 (A)). The light-blue map is made by the first rover, mapping the top side of the LunaLab, while the pink map shows the part mapped solely by the second robot on the bottom side of the lab. In the bottom

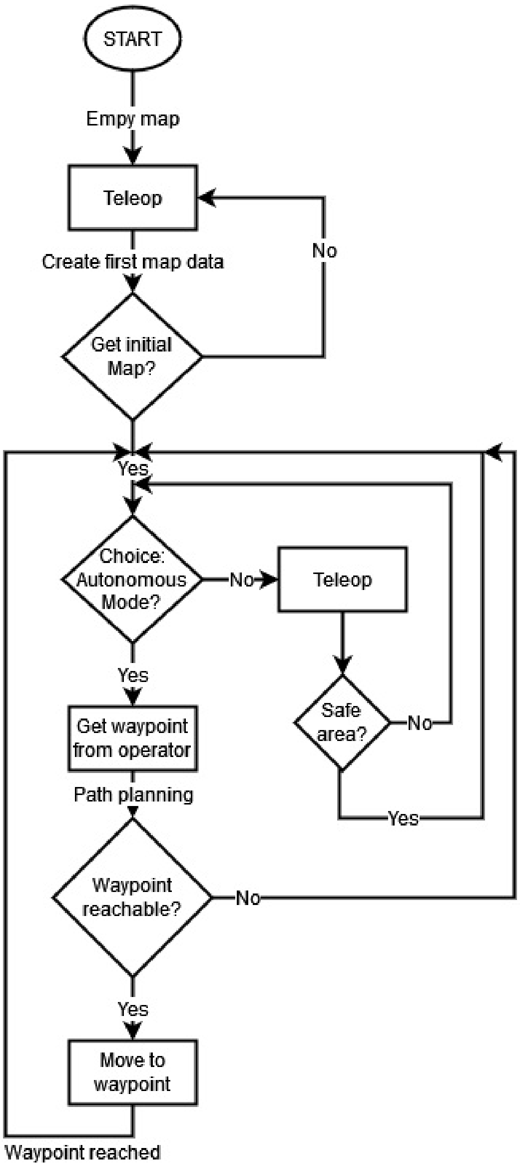

Figure 10. Work flow of the semi-autonomous approach based on receiving waypoints through a human operator and allowing teleoperation.

map, the purple area shows the overlapping part that was mapped by both robots. The entire experiment was realised in 6 min and 48 s. The second scenario simulates the case of a system failure on one of the two rovers where the other rover can cover the missing area so that the mapping can be executed with some coverage limitations or requesting more time to cover the remaining area. Fig. 12 (B) shows a scenario where the second robot experiences an issue after 1 min 30 s and is unable to continue. The first rover can cover the remaining area resulting in less overlap. As a result, the total laboratory area is still covered even in the event of a partial system failure. This experiment was realised in 9 min 2 s.

5.2 Using REALMS during the ESA-ESRIC Space Resources Challenge

The validation experiment of REALMS was the first trial of the ESA-ESRIC Space Resources Challenge. This trial consisted of 6 hours of preparation and 2.5 h to realise the mission. The mission took place in an area of 34×47 m^2. Two-thirds of the area had a concrete surface, while the last part, the region of interest

Figure 11. LunaLab, University of Luxembourg. This facility is equipped with an illumination system that resembles the lighting conditions of the lunar south pole

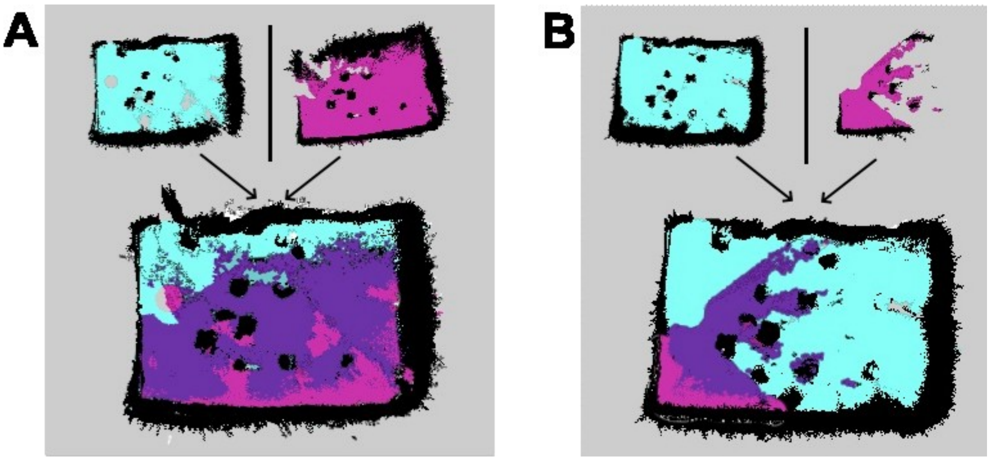

Figure 12. Mapping of the LunaLab done by two REALMS rovers in two different cases. **(A)** Two rovers successfully mapping a shared environment and merging their maps. **(B)** Two rovers mapping a shared environment with one rover failing in the process and the other taking over the area.

(ROI), was made of small rocks of $3 - 5$ cm diameter. The ROI represented the inside of a crater with a rim made out of piled-up rocks. A ramp across the rim allowed the rovers to access the ROI. The first area was filled with rocks, creating a path across two more ramps that led towards the ROI. These obstacles forced larger robots to follow a precise path, passing through the ramps and covering most of the area.

At the beginning of the challenge, the robots were placed in the starting area. Meanwhile, the operators were in a control room with no contact with the outside. In the control room, a network was available to connect to the rovers while adding a delay to the communications with the robots. A hand-drawn map of the lunar area was provided, giving a general idea of the zones to explore. Fig. 13 shows the map handed out to the operators, with the generated map by REALMS overlaid on top of this map.

5.3 Results of the ESA-ESRIC Space Resources Challenge

Despite several communication blackouts, the mission was completed successfully as one rover reached the ROI within the time frame of 2.5 h. The remaining rover was able to get in between the large rocks and go straight to the ROI. Unfortunately, the second rover was lost after a communication blackout at the beginning of the mission, leaving the rover unresponsive to commands. A possible reason for this might have been the limited bandwidth of the network. The second rover was meant to follow the predefined path and increase the map coverage. Fig. 13 shows the area that the first rover has mapped during its traverse to the ROI. As shown in Fig. 13, the ramps in the mission area are clearly represented in the map and also the obstacles in the mission area are mapped as in the provided map. REALMS was able to map some smaller obstacles, close to the last ramp, that were not included in the provided map. The vSLAM algorithm allowed to keep track of the odometry during the entire mission.

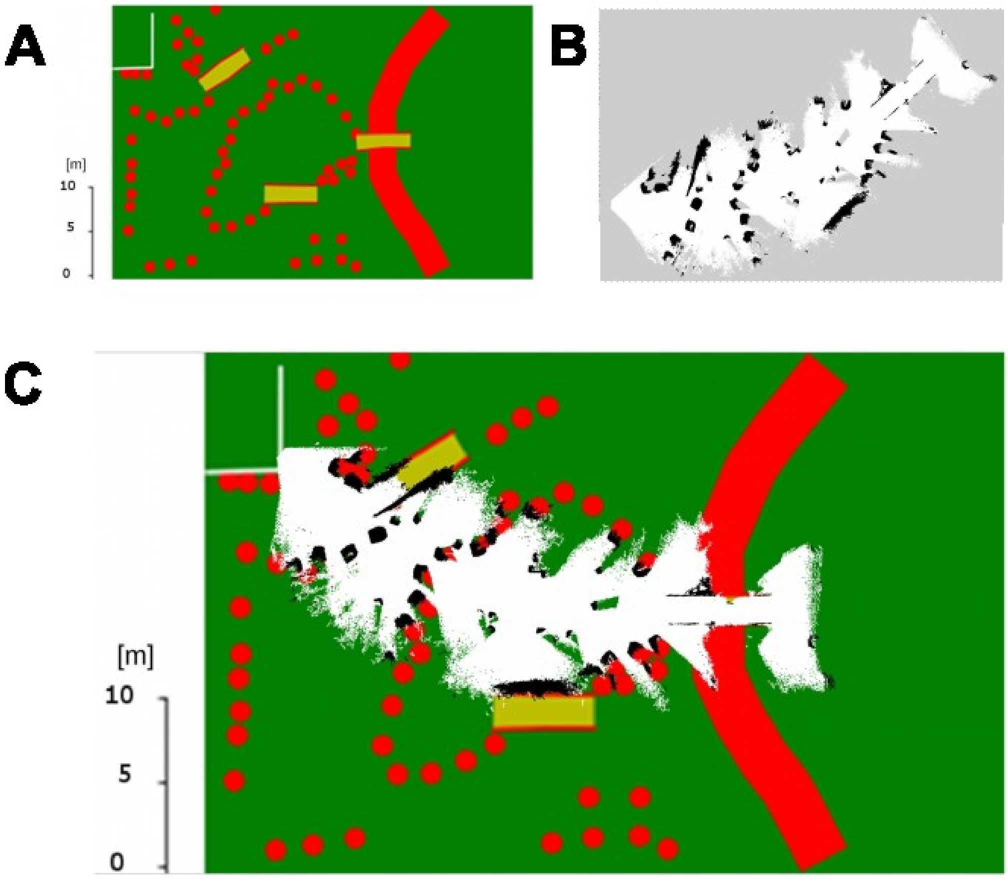

Figure 13. **(A)** Map provided by ESA at the beginning of the mission. **(B)** Map created by one rover during the mission. **(C)** Map of the lunar environment of the challenge overlaid with the map generated by the REALMS rover. The two maps are matching, showing the solution is accurate.

At the end of the mission, the 3D point cloud generated by the vSLAM algorithm is retrieved from the rover, as represented in Fig. 14. The rocks defining the path can be easily recognised in the 3D point cloud as well as the ramp leading to the ROI. Only the descending part of the final ramp is not represented correctly.

The final coverage achieved by REALMS was 310 m^2. Based on our measurements, the entire challenge area was 1598 m^2, REALMS explored 19.4% of the total area. As only one robot was operational and considering the connection outages, it was necessary to pay more attention and to drive more carefully. As a result, the system achieved 24.2% of its experimental capability, which is an encouraging result. This system was selected among 13 teams to continue the challenge and was used for the final trial.

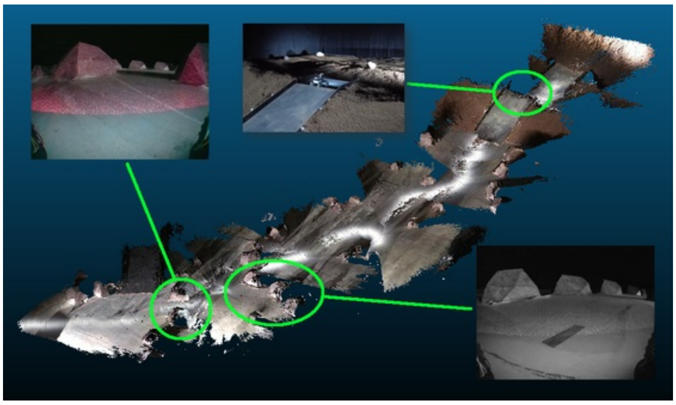

Figure 14. 3D point cloud of the lunar environment of the challenge

6 DISCUSSION AND LESSONS LEARNT

Participating in this challenge taught us valuable lessons regarding the deployment and use of MRSs in extreme environments. In the following, we present a list of lessons learned during the ESA-ESRIC Space Resources Challenge.

1. In ROS, a robotic system has a single ROS Master by default. With the communication delay between the lunar surface and the ground station, the ROS Master on the robot could not be found by some nodes launched on the ground station. This includes RViz for visualisation, and controlling the robot due to a software timeout. Additionally, having two rovers in the field at the same time would require that one ROS Master will handle two robots. With the FKIE multimaster package, it is possible to connect multiple ROS Masters in a single robotic system. This allowed to have a ROS Master on each robot and one on each computer of the ground station, avoiding the software timeout and increasing the independence of the two rovers.
2. The Leo Rovers were not initially designed to use namespaces for their nodes, topics, robot model links and joints. As a result, one robot would respond to the other robot's commands. This was resolved by isolating the two ROS Master through the FKIE multimaster package. Hence, it was reconfigured such that the robots would only listen to their corresponing ground station computer.
3. The default version of RTAB-Map was causing noise. This shows that of-the-shelf components for terrestrial applications have their limitations when being used in extreme environments such as the lunar surface. By customising the code, the mapping results could be improved.

Despite having learned a number of lessons, there are still several challenges that need yet to be addressed:

1. The communication architecture based on ROS 1 using the FKIE multimaster package did not provide the necessary stability to reliably connect to the robots.
2. The inter-robot communication was entirely depending on the provided access point during the challenge. This approach was less reliable and could increase network latency.
3. The resilience of the system was a major contribution to finish the mission to this extent, given that one robot lost the connection to the ground station, the second rover was still able to operate.
4. The user interface easily scales on a system level, but not on a user experience level. Managing multiple robots on multiple operator computers is not feasible for large scale systems.

5. The bandwidth was limited to 100 Mbit/s which caused communication losses when engaging high data traffic, hindering the transfer of data towards the ground station.

7 CONCLUSION AND FUTURE WORKS

Exploring the lunar surface is a difficult task for a single robotic system. REALMS presents a system to increase resilience and coverage for robotic mapping tasks. This is achieved by using multiple small rovers that can work together to overcome challenges like partial system failures and lead the mission to success. The possibility to grow the fleet size with additional rovers allows to increase the mapping capability and system resilience. The system showed its ability to perform during the Space Resources Challenge. It demonstrates the interest in a resilient system designed for lunar exploration.

Future works will take into consideration the lessons learned from the Space Resources Challenge. A major focus point will be the communication structure between the robots with respect of state-of-the-art decentralised network architectures. Such an architecture might increase the overall resilience of the system together with additional robotic agents and sensors used for vSLAM. ROS2 could provide an interesting solution as it is build with MRS in mind and allows connecting multiple robots avoiding the limitation to a single ROS Master per system without the need for external packages. Lastly, the user interface to control multiple robots will be adjusted to simplify the workflow and ease scalability.

CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

DM and LC were implmenting the software on the robots and coding the elements to combine all the modules. AB set up the delay computer simulator. AR and MO contributed to the revision of the manuscript. PS and MO supervised the project. PS worked on the modifications of the vSLAM to filter the noise. JS worked on the setup of the navigation algorithm and writing the specific section for the manuscript.

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