COROB-X: DEMONSTRATION OF A COOPERATIVE ROBOT TEAM IN EXTENSIVE FIELD TESTS

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1 ABSTRACT

The EU-funded project CoRob-X showcased how hard-to-reach areas on planetary surfaces, such as lava tubes on the moon and mining tunnels on Earth, can be explored with teams of cooperating autonomous robots. Building on technologies funded by the European Commission in a series of R&D projects under the Horizon 2020 Space Strategic Research Cluster, a Lunar Analogue Mission on Lanzarote demonstrated the exploration of a lava tube with a collaborative team of three autonomous rovers. In another field test, the inspection of a mine shaft after an explosion with a rover and a drone was shown. This paper summarizes the objectives and results of the field tests conducted in early 2023 on the Canary Islands and on the Spanish Peninsula.

Key words: Planetary Exploration, Lava Tubes, Skylight, Multi-Robot Collaboration, Lunar Analogue Mission, Rappelling, Field Tests, Autonomous Control, Tether Management

2 INTRODUCTION

The CoRob-X project evaluated space robotics technologies for planetary exploration in large-scale field tests that were developed within the framework of the EU Strategic Research Cluster (SRC)[1] since 2016. The building blocks were adapted, modified, and improved to implement the CoRob-X software architecture (Figure 2) with the objective to enable a Lunar Analogue Mission and a Terrestrial Demonstrator. The Lunar Analogue Mission covered the exploration of a subsurface lava tube with a cooperating team of three autonomous rovers (Figure 1). The Terrestrial Demonstrator included the inspection of a mine shaft after an explosion with a rover and a drone. This paper summarizes the objectives and results of these two large-scale field tests. In this paper, we describe the outcome of the field trials, including problems and challenges encountered during system development and system validation in the field.

We also discuss the field trial findings regarding the applicability of the Space Robotics Technologies in future space missions and terrestrial contexts that require a high level of robotic autonomy.

Figure 1 All three robotic explorer units involved in the field tests in Lanzarote surrounding the entrance to the subsurface lava tube, namely CoyoteIII, SherpaTT and LUVMI-X from left to right.

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[1] https://cordis.europa.eu/programme/1d/H2020_SPACE-12-TEC-2018

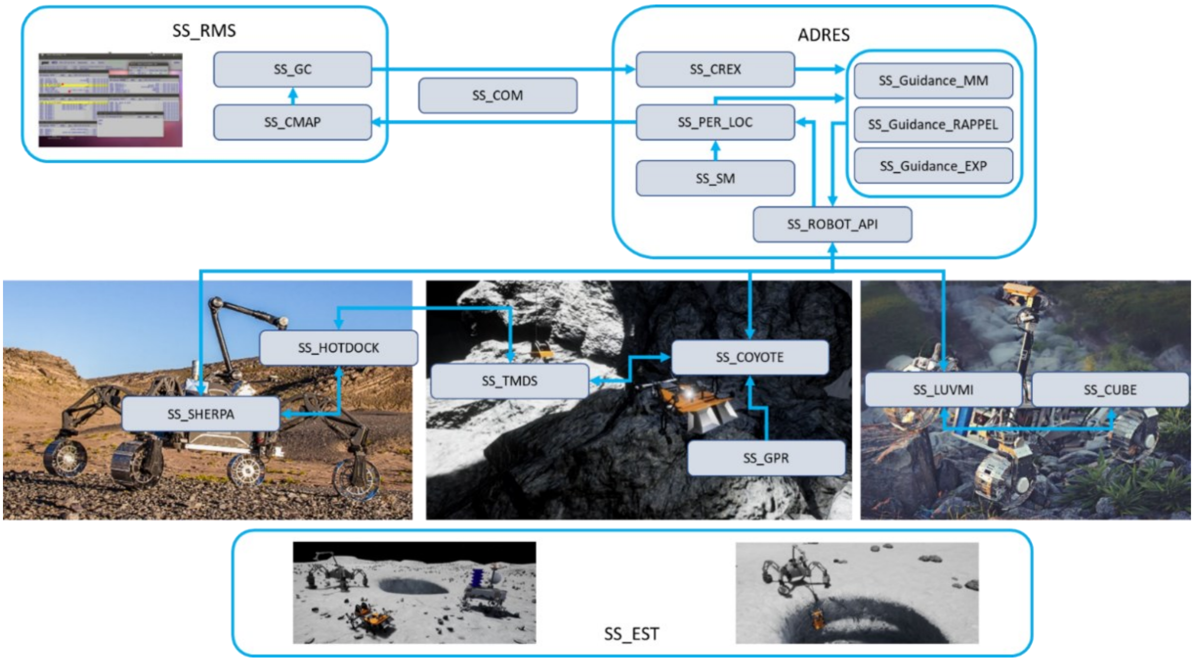

Figure 2 Software subsystems used to perform all 4 mission phases of the CoRob-X project.

3 LUNAR ANALOGUE MISSION

3.1 Mission Overview

The Lunar Analogue Mission simulated a lava tube exploration scenario in the Marius Hills area on the Moon through a hole (skylight) in the ceiling of the cave. The pre-condition for the scenario was that the three REUs (Robotic Explorer Units) had already been transported to the Moon and had safely reached the target area. The mission comprised four consecutive, but independently initialized, mission phases (MPs). The main objective was to use three rovers with different capabilities, DFKIs SherpaTT (REU-1) [1] and CoyoteIII (REU-2) [2], as well as LUVMI-X from Space Applications Services (REU-3) to cooperatively and autonomously enter and explore the lava tube.

The procedures for the Lunar Analogue Mission were defined based on the constraints and assumptions of a real lunar mission scenario. The four-phase mission scenario included the collaborative exploration of the lunar surface in the vicinity of the lava tube and skylight (phase 1), the exploration of the cave walls and floor with a deployable ballistic probe (phase 2), as well as the entry and autonomous exploration of the lava tube by a scout rover (phases 3 and 4).

The Lunar Analogue Mission was organized as a three-week field test in January/February 2023 on Lanzarote, Spain.

3.2 Analogue Site Selection

The site for the Analogue Mission was selected based on a set of scientific, technical, logistical, and regulatory requirements. Traversability of the surface terrain and the floor of the lava tube was one of the most relevant selection criteria. The terrain around the skylight needed to be traversable by REUs, with characteristics similar to those of the lunar surface.

For the skylight exploration, an entry hole with the right dimensions and an overhanging section was required. For the cave exploration, an unstructured, rough surface without large obstacles was needed.

After an extensive trade-off analysis based on literature research, interviews with experts, and a one-week site scouting mission, a cave located near the town of Maguez, part of the *La Corona Lava Tube System* on Lanzarote, Spain, was selected (Figure 3). This site not only fulfilled all technical requirements but was also feasible with respect to logistical accessibility and the possibility to obtain the necessary permits.

The site was on private property and not within an environmentally protected zone, which made it possible to properly prepare (e.g., remove unwanted vegetation) the terrain and operate a large field camp with more than 25 people for more than 3 weeks (Figure 4).

Figure 3 Location for Lunar Analogue Mission (before site preparation).

4 MISSION RESULTS

4.1 Mission Phase 1

In Mission Phase 1 (MP1), the 3 REUs cooperatively explored the area around the skylight. REU-1 and REU-3 autonomously explored and mapped a pre-defined area, while REU-2 used a Ground Penetrating Radar (GPR) to acquire data on the characteristics of the soil above the lava tunnel. The result was a comprehensive 3D map of the area in the vicinity of the skylight.

REU-1 and REU-3 performed as expected, except for unstable mesh communication at the beginning of the tests due to line-of-sight effects. The communication issue could be solved by placing the antenna at the top of the REUs in an improved 360°-viewable position.

REU-2 generated 3D data of the surface with its two Time-of-Flight (ToF) cameras. The GPR recorded cross-sectional radar grams of the subsurface. Since the field of view of the ToF cameras was small compared to that of the sensors on REU-1 and REU-3, and because the GPR readings required a stop of several seconds every 10 cm, REU-2 could explore only a straight line of a few meters above the lava tunnel instead of analyzing several possible lava tube directions.

The collaborative exploration was enabled by a multi-agent decision-making subsystem [3] and [4]. It planned, executed, and monitored the activities of the REUs and ensured their collaboration in space and time by exchanging timely information on their status and activities. The multi-agent system was the entry point for commands from the ground control station and scheduled each REU to do a specific task. Each REU was equipped with an agent component of the multi-agent system. Hence, each REU was able to autonomously compute a sequence of waypoints and to perform the navigation based on data delivered by other subsystems.

The multi-agent subsystem performed nominally during MP1, which lasted approx. 30 min (Figure 1). In this time, REU-1 and REU-3 explored an area of roughly 2x50 m^2, following 5 and 7 waypoints, respectively (the waypoints are computed based on the physical capabilities of each REU). In the same time interval, REU-2 explored a trajectory of only 3m, due to the frequent GPR readings.

The subsystem for perception and localization computed a 2.5D Digital Elevation Map (DEM) that included the position of the rovers. It used various proprioceptive and exteroceptive sensors, depending on the available hardware (rover, sensors). Accurate timely rover-pose estimates were achieved by online fusion of visual odometry poses, wheel odometry, and IMU measurements. For REU-1 and REU-3, both equipped with two stereo cameras, the subsystem provided an accurate localization with an absolute error over 50m of less than 1.5% for REU-3 and less than 4.5% for REU-1. Figure 5-left depicts real (red) and estimated (blue) trajectories for the two rovers.

Figure 4 Overview of the field test camp and surface test area.

The guidance subsystem enabled the REUs to autonomously navigate and explore an area. An integrated path planner analyzed the DEM generated by

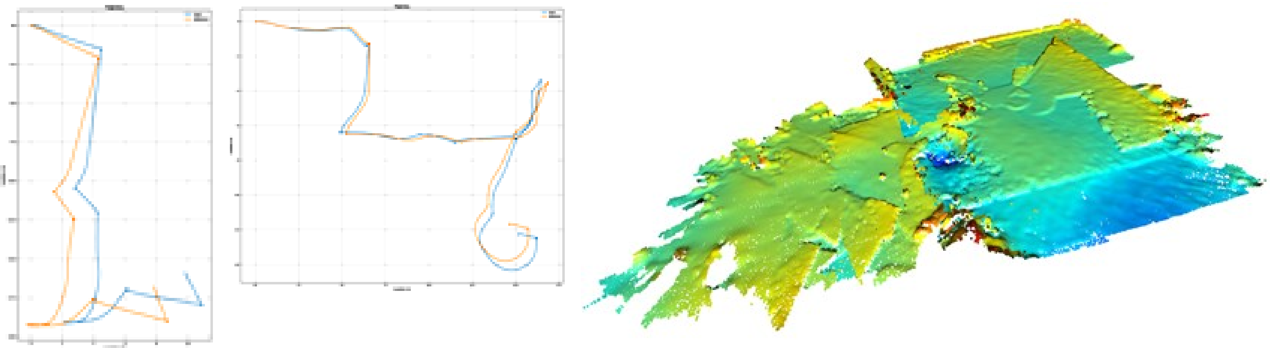

Figure 5 Trajectory estimation REU-1 (left), REU-3 (center) and Elevation map created with cooperative mapping (right)

the perception and localization subsystem to differentiate traversable areas from obstacles and computed the optimal path to reach a target position. A trajectory follower then generated the respective REU motion commands (i.e., translational and rotational speeds).

In MP1, the guidance subsystem successfully empowered REU-1 and REU-3 to autonomously explore the area surrounding the skylight and to reach their target locations while avoiding obstacles and impassable zones (such as the skylight).

The subsystem for cooperative mapping [5] transformed the local maps and trajectories produced by the perception and localization module into a global map of the environment. This global map enabled the operators in the command-and-control centre to identify the best access point for entering the lava tube. In MP1, the cooperative mapping performed as expected, refining offline the data from the REU-1 and REU-3. Only some biases in the initialization of the REUs pose introduced a constant offset, which had to be eliminated to generate the final map (Figure 5).

The I3DS framework[2] provided a unified sensor interface and was used to manage the dual ToF cameras and GPR on REU-2, as well as the high-resolution cameras and IMU on REU-1. With this framework, the robotic software can be sensor-agnostic and use an I3DS service to obtain camera data, for example. I3DS services establish interfaces to specific sensors using a plugin concept. For CoRob-X, the framework was improved with respect to bandwidth consumption and responsiveness and new drivers for new sensors (e.g., GPR) were implemented.

The improved I3DS worked well during the analogue mission. However, the chosen ToF depth camera (Vzense DCAM710) performed suboptimally in three areas: depth range, lack of ability to synchronize two cameras, and sensitivity to noise because of dust and air particles (such as within the cave).

The lightweight GPR installed on REU-2 was a copy of the WISDOM radar designed for the ExoMars planetary mission. Although no significant changes were made to the GPR HW, control of the WISDOM radar was achieved via the I3DS library, which enabled TM/TC exchange between the instrument and the rover. Surveys were triggered every 10 cm in full polarimetric mode to map the subsurface along the rover's trajectory to the surface.

Tests to study the impact of the rover's body and wheels on the radar signal showed multiple reflections from parts of the rover, depending on the rotation angles of the wheels. An algorithm to account for these reflections was developed and successfully implemented. Radargrams acquired by REU-2 clearly show the thin layering of the very shallow subsurface (~15 cm). This demonstrated that the GPR exploration was successful and that operating a GPR with a small rover is possible.

4.2 Mission Phase 2

The objective of MP2 was to explore the lava tube skylight with a payload cube deployed by REU-3 in a ballistic trajectory. Under lunar gravity conditions, the slow descent of the cube would give the sensors integrated in the cube sufficient time to record the characteristics of the skylight. This does not work under terrestrial conditions, hence the MP2 simulation was implemented in two sub-phases:

First, REU-3 approached the rim of the skylight and shot a mock-up of the cube into the skylight. This proved the feasibility of the ejection mechanism. In a second step, a fully integrated version of the payload cube was lowered into the skylight using a pulley system. This set-up allowed to simulate realistic accelerations and speeds for the descent and to verify the functioning of the sensors in the cube.

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[2] https://github.com/I3DS

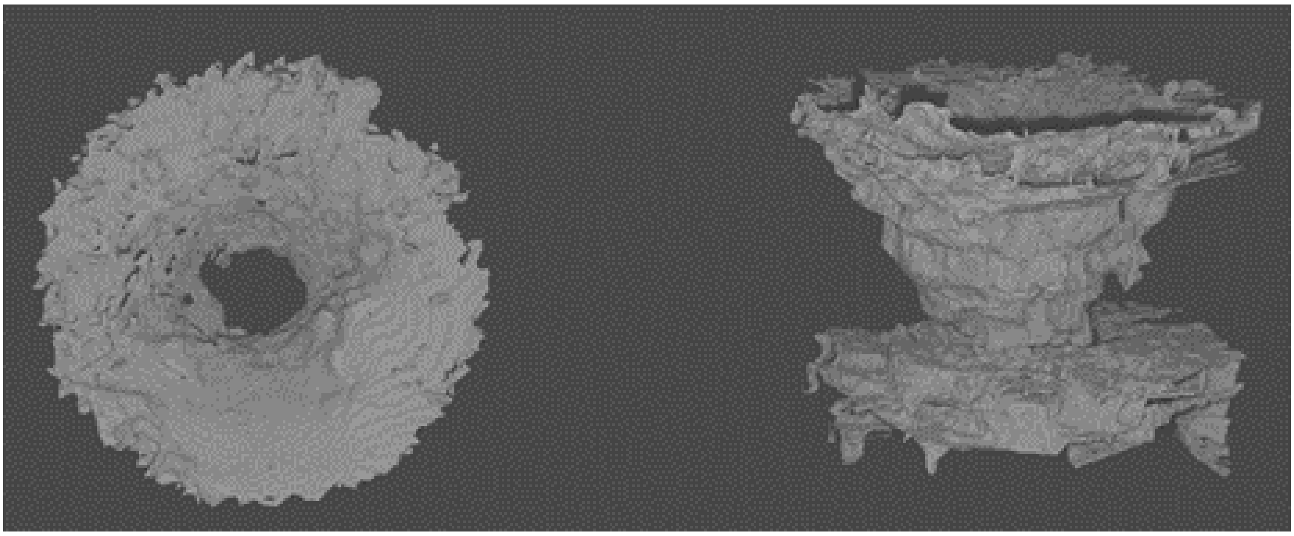

Figure 6 3D map reconstruction of the skylight from point clouds captured with the payload cube's on-board sensors during the descent into the lava tube.

The ejection mechanism worked as expected and during the controlled abseiling into the skylight, the payload cube was able to produce continuous point clouds with its two RGB-D cameras plus an odometry estimation from a tracking camera. The data processing was done offline due to the limited bandwidth between the cube and the remote monitoring station, as well as the computational limitations of the CPU on-board the cube. The result was a reconstruction map of the skylight in the form of point clouds and mesh (Figure 6), together with an estimation of roughness, bottleneck area, and diameter. The latter resulted in a computed value of ~1.85 m, against a measured value of ~1.65 m.

4.3 Mission Phase 3

In MP3, the rappel of a scout rover (REU-2) into a lava tube through a skylight was performed. To achieve this goal, REU-2 carried a tether that was self-contained in a tether management and docking system (TMDS) and attached to REU-1. Thus, grounded on the surface, REU-2 used the tether to rappel from the rim of the skylight to the floor of the lava tube, approximately 5 m below (Figure 7).

At the start of MP3, REU-1 deployed the TMDS with its 6-DoF manipulator to the ground in the vicinity of the skylight. The TMDS was attached to the active electro-mechanical interface (EMI) [6] at the tip of SherpaTT's manipulator with a passive EMI counterpart at the end of the tether during the complete mission phase. In this way, a solid mechanical connection as well as the transfer of data and power between REU-1 and the TMDS were ensured. In order to lower the TDMS to the ground, the manipulator followed the waypoints of a pre-defined deployment trajectory in synchronization with lateral drive motions for REU-1 and commands for the winch inside the TMDS to unwind the tether with the desired velocity.

After the TMDS had been positioned on the ground (Figure 7, left), REU-2 semi-autonomously docked to the TMDS. Images of a backward-facing camera were used to detect ArUco [7] markers placed on the TMDS, thus creating a closed-loop control feedback to follow the pre-planned docking trajectory. As the internal wheel odometry was not accurate enough due to wheel slip in the loose sand, manual steering was required to align REU-2 with the TMDS. Once in position, all subsequent steps were executed without intervention by the operators.

A HotDock interface [8] was used to connect REU-2 to the TMDS, where the active interface was positioned on the underside of REU-2 and its passive counterpart on the top of the TMDS. The docking procedure used a short-distance Wi-Fi connection between REU-2 and the TMDS. After docking, a communication chain between REU-2 and REU-1 via the TMDS and both interfaces EMI and HotDock was established.

The descent of REU-2 into the skylight (Figure 7, centre-left) was initiated and controlled by the rappelling guidance subsystem. Meanwhile, the TMDS control subsystem commanded the winding and unwinding of the tether according to force-torque sensor data from the tip of the manipulator measuring the tension on the tether. The objective was to allow unwinding only under tension and thus prevent entanglement of the tether. REU-1 supported this process by autonomously synchronizing its position and the movements of the robotic manipulator to the movements of REU-2 with the help of the mobile manipulation control subsystem.

Figure 7 Several steps of Mission Phase 3 are depicted: Semi-autonomous docking between Coyote3 and the TMDS (left), descent of Coyote3 into the skylight (center-left), rappelling along the vertical walls (center-right) and touchdown at the bottom of the lava tube (right).

During the rappel, REU-2 used its on-board sensors to create a vertical visual profile of the skylight walls and a 3D reconstruction of the traversed area (Figure 7, centre-right). The descent continued until the rappelling guidance subsystem detected the touchdown. During the landing phase, the front wheels of REU-2 were spinning slowly in a forward motion, which steadied the rover in the right position at touchdown and enabled a very smooth landing (Figure 7, right). Once landed, the undocking sequence was initiated, and REU-2 disconnected from the TMDS.

The TMDS was a core component in MP3. It provided a wired (through the tether) and a wireless communication channel. The first was used by REU-1 to control the TMDS and the winch mechanism during deployment. The latter was used by REU-2 to control docking and undocking as well as the winch mechanism during rappelling. Both, the communication channels and the winch mechanism, worked reliably during the mission.

The capability to release tether only when the expected force is applied proved to be a very important to prevent entanglement of the tether.

A lifting mechanism was used to change the height of the TMDS to facilitate docking between REU-2 and the TMDS. The lifting mechanism had to be cleaned during the field tests as dust and sand caused it to block. Other on-site improvements included the contact zone between the TMDS and the REU-2 wheels. Material was removed from the inner sides of the wheels to allow for a better alignment of TMDS and REU-2.

The HotDock interface was extensively tested during the analogue mission. Designed mainly for on-orbit applications, the dusty environment of the analogue mission proved to be a challenge. After many successful test runs, fine dust found its way into the system and blocked the mechanism. However, after some serious cleaning, the interface was operational again and performed as expected in MP3.

On the software side, the same multi-agent subsystem as in MP1 controlled the rovers. It enforced a very stringent collaboration between REU-1 and REU-2 to ensure the success of the rappelling. After some troubleshooting due to last-minute interface changes, the subsystem worked nominally during the MP3 demonstration, with the entire sequence being executed timely and in synchronization.

4.4 Mission Phase 4

In MP4, the lava tube was autonomously explored by REU-2. This included the autonomous selection of target goal points and the construction of a 3D environment representation. The target points were validated internally on two conditions: remaining energy and the safety of the trajectory.

The latter was determined based on the result of an internal physics simulation and used to optimize the behavior of the rover. Scientific data from the safest areas was collected first, and only after the data had been sent to the ground control station, further explorations in less safe areas were allowed.

To assess the performance of the cave-navigation algorithm, two sets of experiments were conducted. The first verified outdoor software module integration, while the second quantified autonomous navigation under representative cave conditions. The performance targets included successful undocking and docking during exploration (1), successful exploration in HIGH safety mode (2) and successful exploration in LOW safety mode (3).

REU-2 underwent initial testing in the cave with direct remote control to evaluate its basic traversal abilities. It successfully navigated most areas of the cave, except for spots where large lava crust layers had collapsed from the ceiling. However, during the autonomous mission, the ToF cameras did not work very well because of random interferences between the two cameras (Figure 8). This introduced errors in the depth maps, such as fake cavities and holes, which disturbed the pose estimate and localization by the visual odometry subsystem. Nevertheless, despite the ToF interferences, the 3D mapper was able to deliver a 3-D map based on fused ToF point clouds to the path planner subsystem (Figure 9).

In MP4, the multi-agent subsystem was inactive and REU-2 was controlled mainly by its on-board agent, which used a guidance subsystem specialized on cave exploration. The agent worked nominally, but some actions, such as the return to the docking station, could not be validated during the field tests.

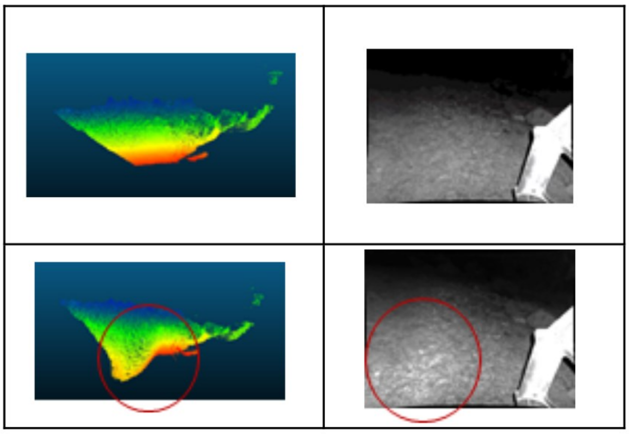

Figure 8 Example of correct (first row) and interfered (second row) TOF data from REU-2.

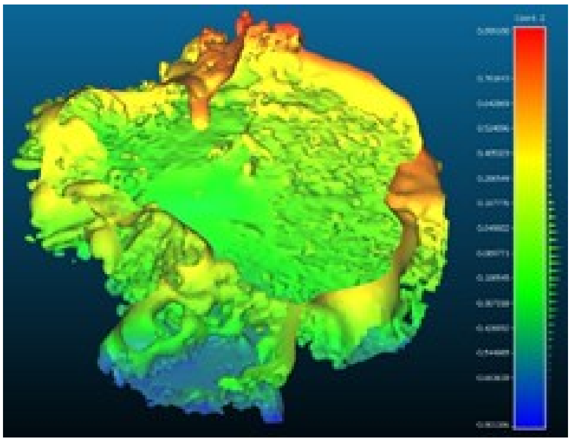

Figure 9 Mesh of the skylight generated from 3D Mapper merged point clouds (right).

5 TERRESTRIAL DEMONSTRATOR

In an additional terrestrial demonstration that made use of selected components of the CoRob-X software, a rover and a UAV collaborated to explore a mine shaft after a blast. This Terrestrial Demonstrator proved that the technologies developed in the SRC do not only pave the way for the robotic exploration of planetary surfaces but can also be used to enhance terrestrial robots and enable new economically relevant applications on Earth.

The final demonstration was conducted in a 500 m long mining tunnel located in León (Spain). The facilities were provided by CoRob-X beneficiary Fundación Santa Bárbara, an institution devoted to teaching mining and underground construction to companies from all over the world.

The goal for the terrestrial demonstrator was to showcase the usability of CoRob-X technology and SRC building blocks in terrestrial markets and to integrate existing terrestrial standards (e.g., the ROS operating system) with the technology of the SRC building blocks. Since the limitations from the space arena (in hardware and software) did not apply, we developed a specific use case with different, dedicated REUs. On the other hand, core parts of the CoRob-X software framework (e.g., the ground station, the multi-agent subsystem and the I3DS framework for sensors) were shared between both use cases.

5.1Test Site and Mission Overview

The use case for the terrestrial scenario focused on the inspection of a mining tunnel after the use of explosives. This is a common and frequent task (blasts are performed daily in mining operations) and requires the inspection of the tunnel for structural safety and unexploded explosives. For mining companies, it is very relevant to be able to automate this task since it will increase safety and reduce the timing for daily operations. In this task, we foresaw the collaboration of a mother rover (REU-4) carrying a drone (REU-5) (Figure 10).

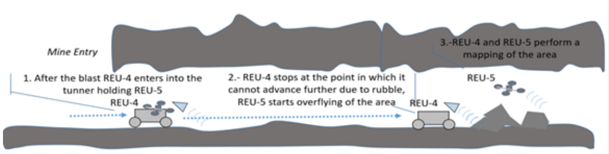

Figure 10 The scenario for the terrestrial demonstrator

The Terrestrial Demonstrator consisted of three phases:

In Phase 1, the mother rover (REU-4) traversed the tunnel after the blast, carrying the UAV (REU-5) to the point at which obstacles prevent the rover from advancing. Once REU-4 and REU-5 reach the blast area, Phase 2 begins, and REU-5 performed a fly-over of the site for a full mapping of the blast area. It finally landed on top of the rover. In the final Phase 3, REU-4 returned to its initial position, carrying REU-5 on top again. Both robots performed a mapping of the area, combining their capabilities to retrieve a 3D mapping surface.

5.2 Logistical Challenges and Solutions

From the logistical point of view, the facilities of FSB provided the ideal test environment, including a tunnel of around 500 m length. The team was located at the end

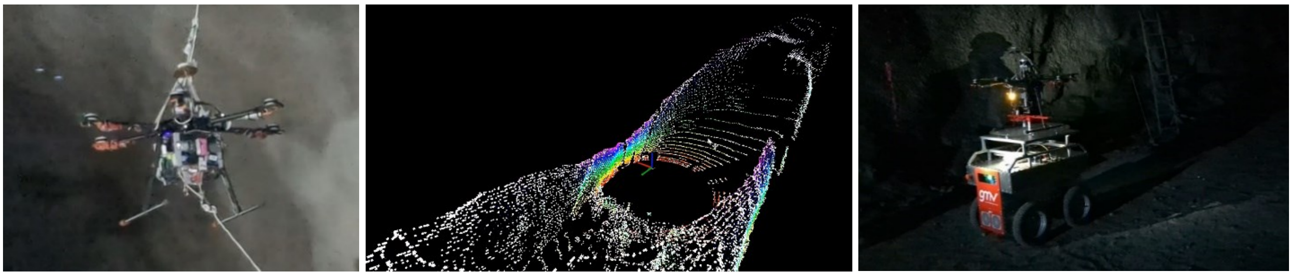

Figure 11 REU-5 UAV (left) exploring the tunnel. A DEM of tunnel (center) generated by REU-5. REU-4 (mother rover) carrying REU-5 (drone) (right).

of the tunnel (where the blasts are usually initiated to advance in the construction).

6 RESULTS OF TERRESTRIAL DEMONSTRATOR

6.1 Phase 1

Phase 1 started at a safe distance of 30 m from the blast area. From that initial point, REU-4 using autonomous guidance identified the path to reach the blast area and drove to a designated point from which REU-5 started its flight. During this traverse, REU-4 performed a 3D mapping of the area using its LIDAR sensor and an analysis of the gases inside the tunnel. REU-5 was attached to the top of REU-4 by a locking system. The locking system was released when the rover reached the final position. In addition, the rover's cameras were able to take images of the tunnel during the whole traverse.

The main problems found during the execution of Phase 1 were related to the need of fine-tuning LIDAR parameters for smooth guidance and to the robustness of the locking system (vibrations due to obstacles). Minor fixes were required to the multi-agent subsystem in order to cope with non-nominal circumstances. The final distance travelled inside the tunnel was 30 m, where both the 3D map and the gas analysis performed as expected.

6.2 Phase 2

Phase 2 was the most challenging for the use case since it involved the overfly of the area by REU-5 (Figure 11 left). REU-5 was a drone developed from scratch specifically for this project. It includes a LIDAR, an IMU, a camera for landing and a Ubiquity link used to communicate with REU-4.

The area covered during the flight by the drone was a square of 4x4 meters at an approximate height of 3m. This is a small area, but due to the high position of the LIDAR in the tunnel, the UAV was able to create a full 3D map to the end of the tunnel, which is located 20 m away from the position where the UAV started its flight (Figure 11 centre). The whole process of taking off, overflying the area, and landing was performed in less than 3 minutes.

The landing was based on markers located on top of the REU-4 platform. For safety reasons and due to problems locating the rover in the tunnel (it was a very muddy area), it was not possible to land the drone on top of the rover. This maneuver had to be simulated on a separate platform.

6.3 Phase 3

In Phase 3, the rover returned to the starting point. It first locked the UAV after the landing, performed a 180-degree point turn, and returned using its autonomous guidance system, reaching the safety area with the UAV on top (Figure 11 right).

7 CONCLUSIONS AND LESSONS LEARNED

The Lunar Analogue Mission and Terrestrial Demonstrator in CoRob-X successfully showcased the capabilities of cooperative autonomous robot teams in tackling complex exploration tasks, yielding valuable insights and challenges:

- Field Testing: Thorough field tests were essential to identify weaknesses in newly developed hardware.
- Dust Issues: Dust posed a significant problem, leading to several issues like burned electronics and a jammed HotDock interface. This problem is likely to affect real planetary missions as well.
- Spare Parts: It is advisable to bring spare parts for all electronic and hardware components during field trials to ensure quick repairs.
- Component Breakages: Several electrical and mechanical components broke during the tests. They could be repaired due to the availability of tools and spare materials.
- Camera Sensor Sensitivity: Camera sensors used in the field tests were sensitive to changing lighting conditions and required manual recalibration.
- Payload Cube Ejection System: The spring-based ejection system of the Payload Cube was challenging to reproduce accurately on Earth, especially regarding tumbling effects.
- Experiment Replicability: Due to its single-shot modality, the experiment was not easily replicable, imposing limitations on data collection.

- Communication Network Setup: Careful planning of the dynamic network setup was necessary to prevent network loops.

In the Lunar Analogue, all four mission phases could be accomplished. This included demonstrating cooperative mapping around the skylight, detailed prior knowledge acquisition of the entry with a sensor cube, rappelling of a scout rover using an active TMDS, and autonomous exploration of the lava tube.

The Terrestrial Demonstrator proved that the CoRob-X software can be successfully transferred to another use-case and other robotic systems. Among the specific insights gained in the Terrestrial Demonstrator are:

- Design Flaws: Some design flaws (e.g., the locking system, which was too weak and markers for the landing site that had to be illuminated) could only be identified in the field tests.
- Locomotion capabilities: The all-terrain capabilities of REU-4 for navigating inside a tunnel have to be improved.
- Autonomous Guidance: The autonomous guidance system provided good results from the start, but further refinement was needed for the scenario.
- System Robustness: The need to increase the robustness of the whole system to hard environmental conditions (e.g., IP68) was identified.

In summary, the primary objective of the field trials, which was to assess the usability of the outcomes of the SRC Space Robotics Technologies for applications in space and on Earth, was achieved.

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