COROB-X: A COOPERATIVE ROBOT TEAM FOR THE EXPLORATION OF LUNAR SKYLIGHTS

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ABSTRACT

The project CoRob-X develops and demonstrates enabling technologies for multi-agent robotic teams to explore planetary surfaces with a focus on hard-to-reach areas where a collaborative scheme is required to efficiently explore complex environments. Exploring lava tubes is such a challenging environment and requires a team of robots able to collaborate in an autonomous way to find their way to the subsurface tube system, descend through a natural entry hole (the so-called skylight), and explore the interior with payload instruments to provide scientific data. The developed robotic exploration system that will tackle the ambitious goal is composed of three rovers with substantially different technical characteristics. The paper presents the overall approach, i.e., the control architecture, the robotic systems, and the software to be used. It also showcases the selected mission phases that will be demonstrated in a field-test campaign. In addition, a terrestrial mining use case is presented that demonstrates how the developed autonomy-enabling software can be transferred to terrestrial applications.

Key words: **Planetary Robotics, Multi-Robot Exploration, Autonomous Control** .

1. INTRODUCTION

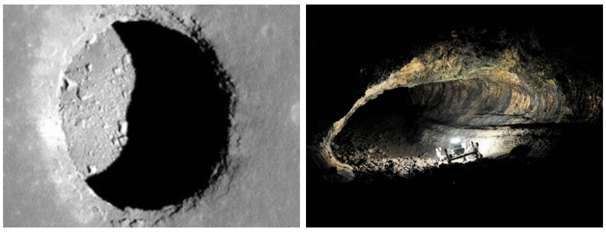
Subsurface lava tubes on Moon are of great interest to space scientists because they can contain pristine rocks that allow a better understanding of the origin of the Earth-Moon system. But also from the ecological point of view, they are excellent places for human long-term habitats as they provide shelter from radiation [6]. However, they are out of reach for current exploration rovers as they can only be accessed through entry holes, so-called skylights, with nearly vertical walls. CoRob-X is taking the challenge to develop demanded advanced robotic concepts that would allow the exploration of such demanding terrain. CoRob-X builds on robotic hardware provided by the project consortium and the software building blocks developed within the framework of the Strategic Research Cluster on Space Robotics Technologies[1]. These building blocks are reused and significantly enhanced to support a multi-agent exploration team of robots. This paper provides an overview on the robotic approach that is followed in the project.

The paper is structured as follows: Section 2 describes in detail the Lunar reference mission and the executed mission phases that are planned to be demonstrated in a field-test campaign on Earth. It provides an overview on the utilized robotic systems and presents the selected test-site for the experiments. Section 3 presents details on the developed subsystems that provide the required functionalities and level of autonomy to form a cooperative robotic team out of single rovers. Section 4 briefly summarizes a terrestrial use case scenario that demonstrates how other industry sectors can also benefit from the developed and advanced software components. The final section will conclude the results and provides an outlook on future activities.

2. LUNAR ANALOGUE MISSION

The goal of CoRob-X is to demonstrate the developed technologies in a lunar analogue mission. This section introduces the envisioned lunar reference mission, then details the phases to be demonstrated within the project, and provides information on the utilized robotic exploration units (REUs) as well as on the selected test site.

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



(a) Marius Hills skylight [credit:NASA] (b) Exploration of a terrestrial lava tube on Teneriffe

Figure 1: Skylight and lava tube exploration

2.1. Lunar Reference Mission

A realistic scenario of a future lunar exploration mission serves as a reference for the project; it uses one of the many suitable skylights detected on the Moon from orbit to access the underlying lava tube and explore the lunar subsurface. The mission would land in the area of Marius Hills and target the Marius Hills pit (Figure 1a). This skylight (60 m in diameter, 45 m in depth [10]) is likely to provide an ideal access to a network of large lava tubes, the width of which can reach several hundreds of meters and, thus, ensure that the collapsed roof that created the skylight is not totally obstructing the way down to the lava tube. In order to reduce the constraints on the rovers which would be raised by surviving the Lunar light, it is envisaged to limit the mission to one lunar day at the chosen location; therefore, the mission needs to be completed within 10 Earth days. Further details of the envisaged mission can be found in [19].

2.2. Executed Mission Phases

The reference mission described above will partially be demonstrated within extensive field trials. The lunar analogue scenario assumes that the REUs have been transported to Moon, egressed the lander, and traveled to the target skylight. The following executed mission is then composed of several consecutive *mission phases* (MP). These phases can be executed in an end-to-end autonomous demonstration of the system's capabilities, but also independently for validation. Hence, it is assumed that for each MP, the REUs are already in the initial poses, software and hardware errors-free, and they are aware of the area in which the tasks are performed (i.e., preliminary 3D orbital map or local map built during the execution). Three REUs are involved in the MP: SherpaTT, Coyote III, and LUVMI-X (all described Section 2.3). Figure 2 depicts the single mission phases.

MP1 – Cooperative Exploration of the Area

The first mission phase (Figure 2a) involves all three REUs that collaboratively explore the area around the lava tube skylight and gather science on the surface. More specifically, the operator requests the execution of MP1 by indicating the area to be explored by each REU given their locomotion capabilities and the overall duration of the task. Then, SherpaTT and LUVMI-X autonomously and exhaustively explore the area indicated and build the associated 3D map. As Coyote III is equipped with a Ground Penetrating radar (GPR), besides executing the exploration task, it also autonomously takes subsurface measurements at different poses. The aim of Coyote III is to provide at the end of MP-1 an overview of the lava tunnel obtained with the GPR. Once the exploration has finished, the complete 3D map of the skylight is obtained offline from fused information from all the REUs.

MP2 – Sensor Cube Deployment

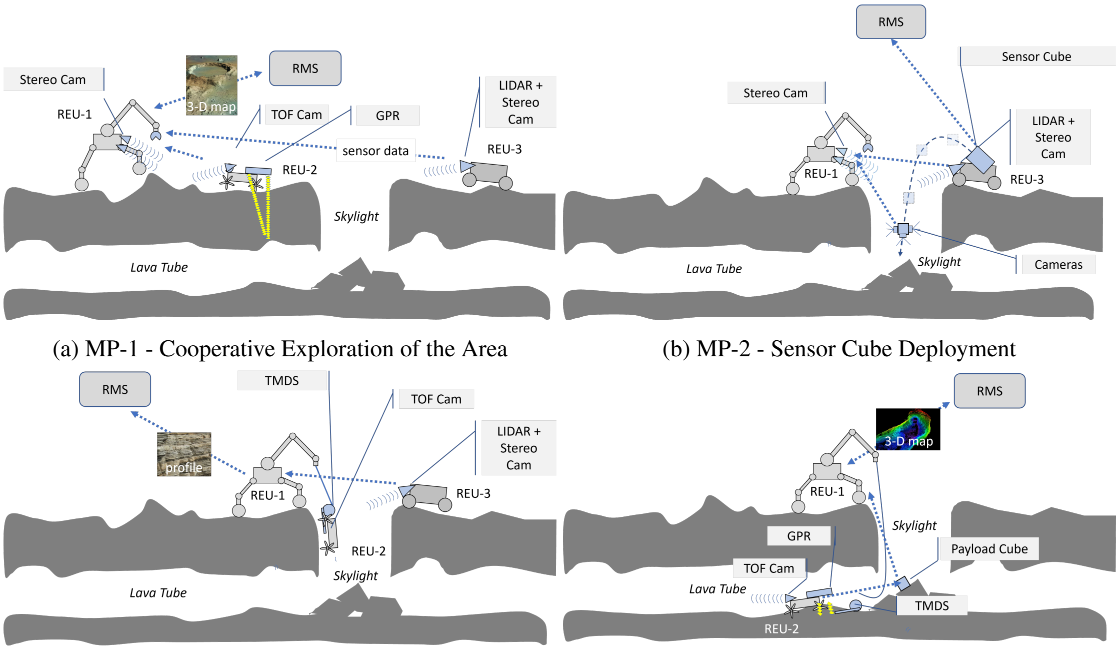
In MP-2, LUVMI-X ejects a sensor cube (Section 3.6) into the skylight (Figure 2b). During the flight, the cube collects data about the skylight walls, and finally from its landing sides. The gathered information are then sent wirelessly to the surface to provide as many information as possible for the upcoming phases. The operator initiates this tasks and also indicates its duration. It is finished once the cube reaches the lava tube soil and telemetry is received from it.

MP3 – Tethered Descent

The third mission phase (Figure 2c) involves the descent of Coyote III into the skylight, with a tether system supported by SherpaTT. As above, the task is initiated by the operator with the specification of the duration. It is assumed that all REUs are in position, with SherpaTT and Coyote III close to the skylight rim in poses from which the descent can start. LUVMI-X will be located in opposite position of the skylight to be able to track the descent. At the beginning, SherpaTT connects with its robotic arm to the *tether management and docking system* (TMDS) that it carries and deploys it on the ground. Then, Coyote III connects to the TMDS and performs the descent. This activity is supported by the TMDS through winding/unwinding and by SherpaTT through arm and lateral base movements, and is being tracked by LUVMI-X. During the descent, Coyote III also gathers data for a 3D reconstruction of the cliffs. This phase finishes once Coyote III reaches reasonably even ground within the lava tube entrance area.

MP4 – Lava Tube Exploration

The last phase is the exploration of the lava tunnel by Coyote III (Figure 2d). An iterative exploration scheme of consecutive autonomous runs is foreseen. The task is also initiated by the operator that indicates the risks the REU can take during the exploration (i.e., what terrain difficulty it tries to traverse), and the moment at which Coyote III should return to the TMDS for charging and transferring data, modelled as battery level threshold and task duration. Then, Coyote III undocks from TMDS and performs the exploration. The GPR is also used during this exploration in order to gather science on the lava tunnel structure. Coyote III returns to the TMDS either when the exploration has finished, or the task duration or battery level constraints are satisfied. Finally, Coyote III docks to the TMDS to recharge batteries from energy that



(a) MP-1 - Cooperative Exploration of the Area

(b) MP-2 - Sensor Cube Deployment

(c) MP-3 - Tethered Descent

(d) MP-4 - Lava Tube Exploration

Figure 2: Mission Phases of Lunar analogue mission

is provided by SherpaTT. In addition, the cable-bounded connection can be used to transfer large data files to the surface. A new exploration with different parameters can then be issued by the operator to iteratively explore more of the lava tube system whereas the safety level can be adjusted to enlarge the possible exploration area within the remaining time before lunar night occurs.

2.3. Utilized Robotic Exploration Units

The CoRob-X projects focusses on the development and testing of software components. Thus, existing hardware systems are used and advanced to be integrated into the robotic team and to be prepared for the field experiments.

REU-1 – SherpaTT

SherpaTT [5] (left rover of Figure 3) is a four wheeled rover weighing around 230 kg when being equipped with a fuelled power generator and the AvionicsBox in front that houses two stereo cameras systems, an inertia measurement unit (IMU), and an additional on-board computer. The rover can transport heavy payloads and small rovers over long distances. A key feature of the rover is its active suspension system: The four wheels that can separately drive and steer are mounted at the end of actively actuated legs or suspension units with additional three degrees of freedom (DoF). Furthermore, the rover is equipped with a six DoF manipulation arm and a DGPS system for ground truthing purposes. The system was already used in precursor projects, such as Facilitators and ADE [14], and proved reliable autonomous driving capabilities in several outdoor field tests.

REU-2 – Coyote III

The micro rover Coyote III [18] (middle rover of Figure 3) serves as REU-2 in the context of CoRob-X. Coyote III was already employed in cooperative scenarios with SherpaTT and complements the relatively large and heavy SherpaTT with its high mobility, speed, low mass, and small size. Moreover, it was developed and deployed together with SherpaTT in a multi-robot exploration scenario comprising an extensive analogue field test in the desert of Utah, USA. It's star wheels provide high mobility in unstructured environment. However, the design of the rover is being reiterated including new wheels to cope with the projects requirements, i.e. to carry the GPR and to be able to connect and carry the TMDS.

REU-3 – LUVMI-X

REU-3, the LUVMI-X rover [12] (right rover of Figure 3) brings complementary capabilities, as a mid-size rover platform equipped with a relevant selection of sensors. LUVMI-X was developed during the H2020 LUVMI and then LUVMI-X projects to be a lightweight 4-wheeled rover capable of carrying a vast and customizable array of payloads and sensors. The main tasks of this rover are to contribute to the exploration and mapping in MP-1, and then the deployment of the Sensor Cube in MP-2 to provide preliminary data of the lava tube skylight for the descent of Coyote III.

2.4. Analogue Test Site

Finding the right location for the Lunar Analogue Mission is not a trivial task due to many operational, physical, mission phase-specific, and general project-related constraints. The occurrences of lava tubes in Europe are limited and confined to areas with volcanic activity. Theoretically, there are lava tubes on Iceland, on the flanks of the Italian volcanoes (Aetna, Vesuvius), and on volcanic islands such as Madeira and the Canary Islands. Practically, however, the suitability of a site is also determined by climatic conditions (due to the project schedule, the field trials have to take place in winter), logistics (the sites have to be accessible and support a large team of researchers), and legal constraints (many volcanic areas are in national parks and thus under environmental protection). After a thorough trade-off of different potential sites, the Island of Lanzarote emerged as the most promising candidate for the field tests. On Lanzarote, the Corona volcano in the north-eastern section of the island has formed a large network of lava tubes. The main system consists of large caves with a height of 10 m and more, which extend for more than 20 km from the volcano down to the sea. After a site visit in fall 2021 and a thorough trade-off of different options, the CoRob-X team decided to use a cave system on the southern periphery of the Cuevas de Corona. The selected Cueva de Maguez is in an area that is accessible by both robots and crew, and the skylights to the caves are on privately owned land without significant legal access restrictions. Also, the selected caves are less deep and wide as those of the main system, which makes them better suited for robotic exploration and significantly reduces the risks of accidents.

3. DEVELOPED SYSTEM COMPONENTS

CoRob-X builds on robotic hardware provided by the project consortium and the software building blocks developed within the framework of the EU-funded Strategic Research Cluster on Space Robotics Technologies that were developed in the previous operational grants. Figure 3 provides an overview of the main subsystems. The ground control station provides a control and data visualization interface to each REU and communicates though a wireless mesh communication (*COM*). The software of every REU is distributed on two main computers. The first is running the ESROCOS [1] operating system an with it the advanced version of the previously developed software building blocks that provide sensor measurement processing (*SM*), perception and localization (*PER_LOC*), trajectory generation and control (*GUIDANCE*), and autonomous collaborative capabilities (*CRE-X*). The second computer is running the usual robot operating system to drive the sensors and actuators and the respective motion controller (MC_SHERPA, MC_COYOTE, and MC_LUVMI, respectively). In addition, robot-specific subsystems are running on this computer to provide additional function-

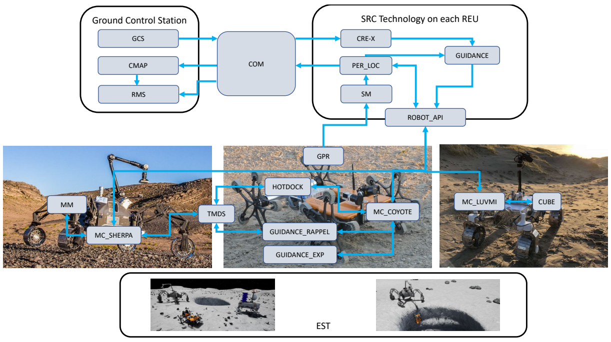


Figure 3: Overview of newly developed and advanced subsystems

alities. Due to the fact, that SherpaTT and Coyote III are running ROCK[2] and LUVMI-X ROS2[3], a lightweight framework-independent communication library is introduced to connect the software components across both computers (*ROBOT_API*). In addition, an environment and simulation tool (*EST*) with the same interfaces is provided to allow early integration testing with partners that are located across Europe. The single subsystems are explained in more detail in the following.

3.1. Ground Control Station

The collaborative system is commanded and monitored with two dedicated components: Ground Control (*GCS*) and Remote Monitoring (*RMS*) Stations, respectively. *GCS* provides two main features: (i) to prepare and send commands to the system in all autonomy modes from E1 to E4, as described in [16], where collaborative tasks are considered an extension of E4, and (ii) to receive and monitor basic telemetry on the system health. These features are provided in a Graphical User Interface environment, that uplinks to the on-board system commands, stored as files, and downlinks the telemetry in a similar approach. The main objective of the *RMS* is to monitor the ongoing mission by displaying the progress and the status of the involved robots. Raw and processed data will be displayed such as poses, maps, obstacles, trajectories, and status information. To receive data from REUs and display them on a graphical user interface, the RMS will interface with the robot's communication system and serve the data in real time while also keeping a history of it for post processing. To efficiently visualize positions and processed data, RMS will provide 2D and 3D displays. The RMS is based on browser Nasa Open MCT user interface with custom visualization plugins and backend data base providing data handling services. *RMS* will also include the Collaborative Mapping (*CMAP*) component. *CMAP* is a multi-robot SLAM pipeline developed during the CoRob-X project to receive various sensors data (such as poses, maps and frames) from all the REUs. It will then generate refined trajecto-

[2] https://www.rock-robotics.org/
[3] https://docs.ros.org/en/foxy/index.html

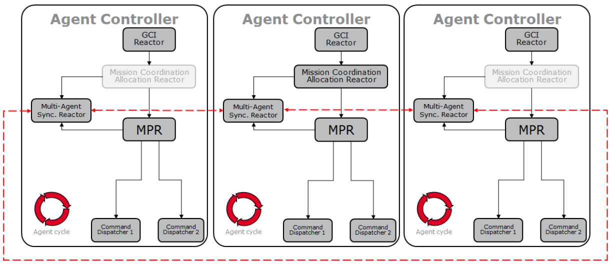


Figure 4: Architeture of the high-level collaborative system *CRE-X*.

ries of the REUs and a global map from the local maps of all the robots.

3.2. CRE-X

The autonomous collaborative capabilities are provided by the multi-agent system, *CRE-X*. This system is composed of a set of ERGO Agent instances [13], one per each REU. The overall architecture of *CRE-X* is provided in Figure 4. An Agent provides the high-level autonomous capabilities, including mission planning, scientific detection and communication with *GCS*. These capabilities are enabled by a dedicated architecture consisting of a controller in charge of coordinating different execution loops, and several reactors in charge of executing specific control loops. Types of reactors include Ground Control Interface (GCI) for the file-based communication with ground and processing of commands and telemetry, Command Dispatcher Reactor for forwarding goals and observations between the deliberative/executive and functional layers, and Mission Planner Reactor (MPR) for decomposing high-level goals into low-level activities by invoking the Stellar planner [3] and scheduling and monitoring their execution.

The collaborative capabilities are achieved by a set of Agents through available reactors such as Mission Configuration and Allocation Reactor for decomposing multi-agent mission goals into individual agent goals, and Multi-Agent Synchronization Reactor for transferring goals and observations between the different agents. These capabilities are available at a single entry point, configurable through a roles system management. Additionally, a watchdog handles the possible disconnections between the Agents, such that a consistent and coherent status is achieved in the system.

3.3. Guidance

The guidance component objective is to provide a path, and the required speed commands to follow it, depending on the rover and the goal poses and the environment information from *PER_LOC*. In CoRob-X, three different guidance modules are exclusively used.

GUIDANCE is in charge of providing for each REU the capability to navigate around the skylight during MP-1. Guidance is divided into the Path Planner [15] and the Trajectory Follower [9]. On the one hand, the Path Planner generates a cost map for the provided digital elevation map and computes an optimal and safe path to get the rover from its initial position to a final goal position, accounting for obstacle and slope information. The Fast Marching Method is used to generate smooth, continuous, and optimal trajectories. On the other hand, the Trajectory Follower computes speed motion commands for the rover based on target and current positions to reach each way point of the newly generated trajectory. Whenever the rover reaches the final goal position, it stops and waits for a new digital elevation map and a new goal.

GUIDANCE_RAPPEL is implemented on the ROCK side and replaces the nominal *GUIDANCE* during the descent of Coyote III in MP-3. Besides generating motion commands for the rover, it also sends winding and unwinding commands to *TMDS* to synchronize the robe length with the rovers motion.

GUIDANCE_EXP is also deployed on Coyote and is being activated to autonomously explore the lava tube during MP-4. Besides generating a path and controlling the trajectory, it also introduces advanced exploration techniques: (i) the map generation and path planning is in 3D, (ii) new exploration targets are iteratively generated and adapted according to the newly received map information, (iii) the exploration is monitored with respect to battery and time constraints that might trigger an intermediate return to recharge batteries before starting a new exploration run, and (iv) before following a path on the real system, the current environment information is transferred to an internal simulation which is then used to test the expected motions beforehand to increase safety.

3.4. Environment Representation and Rover Localisation

The Perception and Localization (*PER_LOC*) subsystem is one of the core rover components enabling safe autonomous traverses. It consumes proprioceptive and exteroceptive sensor data to generate the specific data products required by other autonomy-related subsystems. As the sensor suites embedded in the three REUs are different, *PER_LOC* is specifically designed to be highly configurable and capable of handling inputs from various types of sensors such as stereo-cameras (LocCams and NavCams), Time-of-Flight (ToF) cameras, IMUs, wheel odometry, etc.

Among its primary functions is the generation of a digital representation of the environment upon request by the Guidance component, used to plan a safe path towards a goal position. The nature of this environment representation varies depending on the mission phase. During MP-1, as the REUs navigate on the surface, a 2.5D Digital Elevation Map is sufficient to safely perform the navigation task. In MP-3, 3D point clouds are produced throughout the descent of Coyote III and fused offline to map the cliffs. Finally, the 3D constraint of MP-4 requires the production of a 3D map that accurately represents the lava tube's floor, walls, and ceiling.

Providing timely rover pose estimates in the mission reference frame at a constant frequency to the other GNC subsystems is the second primary function of this component. It is achieved by online fusion of visual odometry measurements from LocCams or ToF cameras with wheel odometry and IMU data through a graph-based optimization engine.

3.5. Ground Penetrating Radar

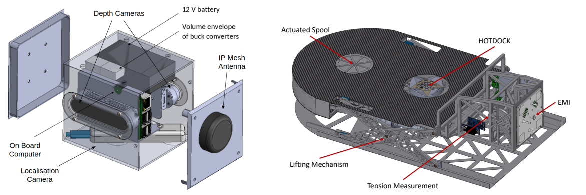
The GPR used in the CoRob-X project is a copy of the WISDOM GPR [4] designed for the Rover of the ExoMars mission to probe the shallow Martian subsoil. Because of its lightness (less than 1.7 kg), the GPR can be embarked on various rovers operated either on Mars or on Moon. The instrument consists of two main subsystems: the electronics unit and the antenna system which must be housed outside the rover body and facing down. The GPR operated along the rover's path provides high-resolution radargrams of shallow subsurface that extend to depths ranging from 2 m to 10 m with a vertical resolution of a few centimeters, depending on the characteristics of the sounded materials. In addition to detecting buried structures such as layers, embedded rocks, voids, and thus shallow lava tubes, the instrument also provides constraints on the porosity and composition of the upper layer. Finally, which could be an essential asset for a lunar mission, the GPR is capable of detecting segregated units in the subsurface and of estimating their thickness.

3.6. Sensor Cube

Cube is a sensor system that is ejected from a launcher on the LUVMI-X rover to provide data from otherwise inaccessible regions. In the scope of the CoRob-X project, *Cube* is deployed inside the skylight of the lava tube during MP-2. During its fall, it will collect visual and depth data of the walls and floor of the skylight. This data is then transmitted back to *RMS* to be processed into a trajectory and a 3D Map, with the final objective of providing preliminary information for the descent of Coyote III in MP-3. Lastly, once *CUBE* has landed, it will serve as a communication relay between Coyote III and the other REUs still on the surface.

The Payload Cube contains the following components in its 1U form factor, as shown in the rendering in Figure 5a:

- two Intel Realsense D435 cameras mounted on the sides that will provide depth data of the walls,
- an Intel Realsense T265 camera facing downwards to provide both visual and localisation data,
- a concealed IP-Mesh system to ensure communication after the deployment,
- a Jetson Nano to log the sensors data, and



(a) deployable sensor cube (b) tether management and docking system

Figure 5: Renderings of the newly developed hardware components

- various electronics and a battery to ensure about 60 min of operation.

3.7. Tether Management and Docking System

The TMDS subsystem (Figure 5b) is the key technology that aids a robotic system in traversing very steep terrain, though using a rappeling approach. Docking can be achieved by either lifting *TMDS* to establish contact between its topside interconnect and an interconnect on the bottom side of the rappelling system or by actively grasping the rear-side interconnect which is directly connected to the tether. In CoRob-X, Coyote III uses the *HOTDOCK* interconnect [11] of the center body to connect from the top while SherpaTT uses the electromechanical interface (EMI) [8] of the end effector of its manipulation arm to connect from the back. While Coyote III will be rigidly connected during the tethered decent, SherpaTT is connected to the loose part that can be winded and unwinded by an actuated spool. The TMDS is controlled in MP-3 by the rappelling rover to synchronize its movements with that of the rappelling rovers locomotion system. To allow a controlled descent, *TMDS* features a mechanism for sensing the tension in the tether. To enhance the functionality of the rappelling rover team, *TMDS* also supplies a power and data connection between the docked systems and features a WiFi access point to remotely trigger the lifting mechanism for docking.

3.8. Mobile Manipulation

During MP-3, SherpaTT will support the rappel of Coyote III into the skylight. The goal is to increase the safety of the mission, i.e. reduce to the minimum the tension that the tether is suffering while Coyote III is descending into the lava tube. For that purpose, depending on the measured forces and torques on SherpaTT's end effector, this rover will perform whole body movements using its full kinematic chain (mobile base and robotic arm) to control the TMDS anchor pose, which will be located in the manipulator end effector.

To do so, SherpaTT will make use of the Mobile Manipulation component (*MM*), which is able of planning and controlling the movements of a mobile base and its robotic arm in a coordinated, coupled, and efficient way, in order to place the manipulator end effector in a particular pose. It uses a Model Predictive Control [2] approach to continuously plan and control the motion of the whole system's actuators with an optimal motion planner, based on a Sequential Linear Quadratic optimization solver [17]. The motion planner is able to generate partially-optimal motion plans, obtaining energy and time efficient solutions while handling non-linearities, such as collision avoidance, non-holonomic constraints of the mobile base, system limitations, and actuation constraints.

Therefore, the MM component control workflow is as follows: SherpaTT will measure continuously the force/torque on its end effector while Coyote III is descending, which is directly related to the tension on the tether. This force/torque will be translated into a reference pose and speed for the manipulator end effector, in order to reduce the tension on the tether. The reference pose and speed will be fed to the MPC, which will decide to use the mobile base and/or manipulator joints to continuously reach that reference, until Coyote III reaches the lava tube floor.

3.9. ROBOT-API

In projects with multiple partners involved, combining different software stacks is a common problem that complicates the joint integration into one working software stack. This is especially true for CoRob-X where partners across Europe work on a software that runs on multiple robots that feature the operating systems ESROCOS, ROS2, and ROCK. Thus, the goal of *ROBOT_API* is to provide a generic interface to connect and communicate across different robots and software components that feature different operating systems, robot frameworks, and data types. It uses the light-weight and framework-independent communication robot remote control library [7], which serializes and deserializes data with Googles protobuf and transmits it via ZeroMQ over ethernet. The latter is also adjustable, e.g., to use shared memory access on one CPU or TCP/IP for communication across networks. It uses separate channels for commands to the robot as well as sensor data and states coming from the robot to account for different requirements in terms of frequencies and quality of service. In CoRob-X, *ROBOT_API* is used to connect the ESROCOS-based software modules with the robot-specific implementations in ROCK (in case of SherpaTT and Coyote III) and ROS2 (in case of LUVMI-X).

3.10. Environment and Simulation Tool

The environment and simulation tool (*EST*) is used (i) to support testing in early development stages and (ii) headless within the autonomous exploration of the lava tube in MP-4 to evaluate derived paths prior to their execution on the real system. For the former, the simulations shall cover both, the activities of the individual REUs and the cooperative interaction of the REUs in the application scenarios. It will be used to verify the functionality of the CoRob-X software and to identify errors and shortcomings in the software early in the development process. *EST* is based on the physical simulator MARS[4]. It provides the target skylight and lava tube as a scene that was created based on collected image and point cloud data. The robots with their respective motion controller are modelled and can be interfaces through *ROBOT_API* in the same manner as their real counterparts.

4. TERRESTRIAL USE CASE

The capabilities developed in the CoRob-X project are also showcased in a terrestrial exploration mission that addresses the inspection of a minning tunnel after blast. This inspection is done by two REUs from GMV: Foxizirc, a 4-wheeled rover, and a UAV. Foxizirc acts as the master REU performing the main operations of traversing the mine and gathering science about the blast effects. The UAV acts as the scout REU mapping the explosion site that Foxizirc cannot reach.

The mission to be demonstrated consists of three phases: (i) approach of Foxizirc with the UAV locked on top to the blast area and characterization of the tunnel during the traverse (i.e., building the 3D map), (ii) flight characterization of the blast area by the UAV and identification of unexploded cartridges, (iii) return to the safe area by Foxizirc with the UAV once the flight mission is finished, and (iv) characterization of the tunnel and the gases present in the tunnel during the return traverse. Once the safe area is reached, the data is transferred to mission control.

The demonstrator consists of already existing systems, e.g., the Foxizirc's software, systems developed for the lunar analogue mission and tailored to this scenario, e.g., GCS, CRE-X, and new development, e.g., the UAV GNC. The demonstration will be carried at the mining facilities of Fundacion Santa Barbara in Spain.

5. CONCLUSION AND OUTLOOK

The proposed multi-robot exploration system is being developed to demonstrate that hard to reach areas can be explored with a high degree of autonomy. SherpaTT, Coyote III, and LUVMI-X will show in an lunar analogue mission, that they can cooperatively explore the area around the skylight. In addition, a sensor cube will be deployed to gather further information of the skylight walls and its subsurface lava tubes. A tethered descent of Coyote III will show, that the lava tube can be entered through the vertical entrance without human intervention and, eventually, explored in an autonomous manner.

[4] `https://github.com/rock-simulation/mars`

The developments of the presented hardware and software components is nearly completed and first integration and functionality tests are being performed in simulation. In late summer 2022, a joint integration and test workshop at DFKI's premises in Bremen is planned. The conducted experiments with all systems and partners at one place will speed up the integration and reveal issues to be solved before starting the field trials on Lanzarote.

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