FIELD TESTING OF COOPERATIVE MULTI-ROBOT TECHNOLOGY FOR ACCESSING AND EXPLORING A PLANETARY LAVA TUBE. R. Dominguez[1], T. Vögele[1], J. Ocón[2], T. Germa[3], S. Govindaraj[4], F.B. Haugli[5], E. Törn[5], V. Ciarletti[6], C. J. Perez[7], A. Dettmann[1], A. Berthen[3], L. Lecabec[3], P. Serio [4], F. Polisano [4] and F. Kirchner[1]. [1] DFKI Robotics Innovation Center, Robert-Hooke-Str. 1, 28359 Bremen, Germany (raul.dominguez@dfki.de), [2]GMV Aerospace and Defence, Madrid, Spain, [3]Magellium, Ramonville Saint Agne, France, [4]Space Applications Services NV/SA Leuvensesteenweg 325, 1932 Sint-Stevens-Woluwe (Brussels Area), Belgium (shashank.govindaraj@spaceapplications.com), [5]SINTEF Digital, Mathematics and Cybernetics, Trondheim, Norway, [6]Universite de Versailles Saint-Quentin-en-Yvelines, Versailles, France, [7]Universidad de Málaga, Málaga, Spain

Introduction: The exploration of lava tubes in the surface of planetary objects close to earth is of main importance for the space agencies. The subterranean cavities are considered both relevant from a scientific as well as a logistic perspective. They can shed light on the unknown geological past of the Moon and Mars, keep traces of past life in a more intact status but also be of great practicality for the storage of materials potentially protected from radiation. The human incursion in such environments would nevertheless be extremely risky, thus the current efforts are focused on developing technologies that could allow for the exploration without direct human intervention, through robotic missions.

In this context the European Union research project, *Cooperative Robots for Extreme Environments, CoRob-X* [1], has recently finished. During the project, 3 prototypes for next generation exploration rovers were selected, additional hardware constructed and a software architecture enabling the robotic team to create a 3-dimensional environment reconstruction, including scientific data, of the area around a skylight, its walls and the lava tube underneath was designed and implemented. In the final phase of the project, the mission approach was tested on an analogue environment in the island of Lanzarote (Canary Islands, Spain) where skylights are abundant.

The targeted mission starts with the three robots located on a region at ca. 30 meters distance around the skylight. It is considered concluded when the environment reconstruction of the surface, skylight and cave are received in the Ground Control Station. The mission is divided into 4 Mission Phases (MPs):

- MP1: Cooperative exploration of the skylight region.
- MP2: Mapping of the skylight through the deployment of a sensorics payload.
- MP3: Cooperative rappelling down the skylight.
- MP4: Lava tube autonomous exploration by scout rover.

This paper summarizes the overall architecture for the mission, as well as activities and components of each MP as background. Nevertheless, the main paper focus lies on the field test performed in the last phase on the project. The rationale behind the site selection, the logistics involved, duration of the tests and results yielded are presented.

Architecture: In the cooperative exploration robotic mission three robotic systems are involved: SherpaTT, CoyoteIII and Luvmi-X. From the software side, the components are grouped in 4 main categories: Ground Control Station, Communications, Space Robotics Frameworks and Rover Specific Behavior Control. An overview of the architecture is shown in Figure 1.

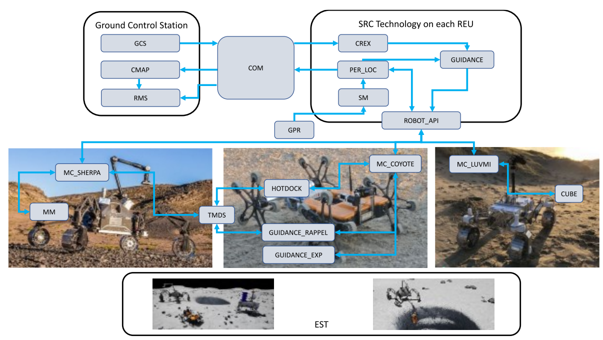


Figure 1 Architecture Overview: Robotic Systems and Software Subsystems

SherpaTT, a hybrid wheel-leg rover equipped with an arm. SherpaTT has 4 wheels located at the end of its articulated legs. The combination of wheels and legs allow the system to move in an energy efficient manner over plain or slightly inclined surfaces and overcome more challenging surfaces or obstacles by using walking behaviors [2]. The arm of SherpaTT is used to support the rappelling of CoyoteIII down the skylight.

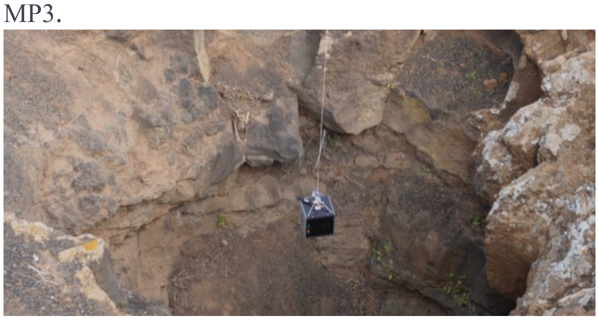
The Coyote III is a small (30x50 cm), light (< 10 kg) and fast scout rover. It features four reinforced wheels and an articulated body to support the challenging navigation over lava crust. Coyote III is also able to handle slopes of more than 30 degrees. Coyote III is be equipped with a tether management and docking system which is used to rappel down the skylight supported by SherpaTT's manipulator in MP3.

In addition, CoyoteIII is equipped with a Ground Penetrating Radar (GPR) to inspect the areas near the skylight.

The LUnar Volatiles Mobile Instrumentation (LUVMI-X) is a medium-sized wheeled rover. It is equipped with four-wheels and an active suspension system, energy sub-system and motors that enable long-distance traverses and to overcome moderate slopes. It holds an ejection mechanism to deploy the sensorics payload in the MP2.

Mission Phases: In the first mission phase, the three rovers explore the area around the skylight and above the lava tube. The objective of this survey is to create a joint 3-D map of the region and to identify the exact location of the lava tube. The rovers use optical sensors (time of flight cameras, stereo cameras, LIDAR) and the WISDOM Ground Penetrating Radar developed for the ExoMars mission.

In the MP2 the mapping of the cave entrance is done through a droppable sensor cube equipped with two depth cameras and one tracking camera. After the cube has descended through the skylight, all the data recorded by the cameras is merged to reconstruct the scene and comprehensive three-dimensional model is provided. Further analysis includes diameters, roughness and tightest hole altitude in preparation for MP3.



In MP3, the data gathered in MP1 and MP2 are used to select the best trajectory to enter the lava tube through the skylight. From the rim of the skylight and supported by largest of the rover team, the small cave exploration rover rappels to the bottom of the cave on a tether.

Once it has reached the bottom of the cave MP4 starts. The exploration rover undocks from the tether and starts to explore the lava cave autonomously.

Field test: To demonstrate all four phases of the lunar mission in an Earth analogue setting, a site in the northern part of the island of Lanzarote, Spain, was selected. The selection of this location was based on a survey of potential lava tube sites in Europe. This survey revealed that lava tubes are a relatively rare phenomenon in Europe and that the Canary Islands are the only region where the environmental conditions necessary for our analogue mission (sparse or no vegetation, dry in winter) could be met.

So, from 21.1. to 10.2.2023, a team of more than 20 researchers from eight organizations out of five EU member states conducted a Lunar analogue mission in the northern region of Lanzarote to demonstrate the four mission phases described above. The success of the mission showed that the exploration of Lunar lava tubes using teams of autonomous robots is well within the realm of what is technically possible today.

The content of this paper describes the set-up, the results, and the lessons learned from the Lunar analogue mission for lava tube exploration on Lanzarote.

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