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# FIRST RESULTS OF THE ROBEX ANALOG MISSION CAMPAIGN: ROBOTIC DEPLOYMENT OF SEISMIC NETWORKS FOR FUTURE LUNAR MISSIONS

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## INTRODUCTION

This paper presents first results of the analog mission campaign which was performed between the 12th of June and the 10th of July 2017 on Mount Etna in Europe, Italy. The aim of the ROBEX demonstration mission is to test and validate a complex robotic mission. This includes highly autonomous tasks with supervision from scientists to guarantee measurement of real and scientifically relevant data. The main scientific objective of the ROBEX mission, the detailed analysis of the lunar crust layers, that is replaced by the analysis of Etna lava layers in the demo mission, has been guiding the developments of the last four years.

As key missions, a seismic network has been deployed and a seismic profile measurement has been conducted using only robots on the landing site. Additional experiments consisted of long term autonomous navigation, multi-robot mapping and exploration of craters as well as experiments with the aim of geological analyses and probe selection. During the one month analog campaign, a realistic mission scenario has been built up, including a control station approximately 30 km from the remote site.

### The ROBEX Project

The Helmholtz Alliance “Robotic Exploration of Extreme Environments – ROBEX” is the world’s first integrated space and deep-sea research community. It brings together researchers of 16 institutions from all over Germany, jointly developing technologies to improve the exploration of environments such as deep sea, polar regions, the Earth’s moon and other celestial bodies. These all have in common their extreme conditions, under which robots face similar problems concerning navigation, power supply, and communication.

The different scientific questions and technological challenges with respect to exploration on the Moon and of the deep sea are addressed by the ROBEX community with common methods and technological solutions. As project goal for ROBEX it was decided to build and deploy a combination of a stationary system and one or more mobile elements. The stationary system (a lander system) should serve as a central node for energy supply and data exchange, with the mobile elements performing the actual scientific exploration in the deep sea or on the Moon.

The complex interaction between these elements in the deep sea as well as in a “Moon-analogue site” has been demonstrated during the demo missions in the final year of the project. This paper will describe the first results of the space demo mission.

Within the project, two demonstration missions and nine design team projects were realized. Within these design teams, researchers and engineers work together interdisciplinary and develop technological solutions for both marine and space partners using their respective expertise to benefit from each other.

### The Mission Setup on Mt. Etna

For the demonstration mission space, a dedicated scenario was chosen by the ROBEX lunar scientists. The scenario describes the installation of an active seismic network (ASN) on the Moon’s surface. Main focus here is the measurement of the internal structure and the composition of the upper layer, the lunar regolith. In addition, the natural seismic activity shall be monitored, including meteorite impacts, which can serve as semi-controlled sources if impact flashes are observed from Earth. The seismometers are planned to be transported by a rover and put down on the surface by means of a robotic arm.

The analog mission on Mt. Etna mainly consists of two individual experiments: First, the rover will traverse from the lander site, deploys the seismic instrument, wait until one measurement cycle is done

(i.e. signals from an active seismic source are recorded), pick it up again and repeats the measurement on several points on its trail
(see Fig. 1).

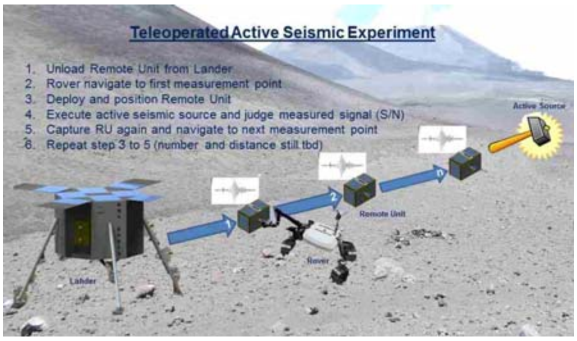

Fig. 1: Teleoperated active seismic experiment placing the sensor boxes along a line

In a second scenario, located close to the lander site, the rover sets up a seismic network consisting of four instruments that are to be arranged, three at the corner points of an equilateral triangle of about 50 m and one in the center of the triangle (see Fig. 2). Both scenarios require high transportation capabilities and driving performance as well as advanced manipulation capabilities to place and align the instruments carefully and precisely onto the ground. The other technological challenge is to allow for both tele-controlled and for certain parts of the mission, fully autonomous operation of the system.

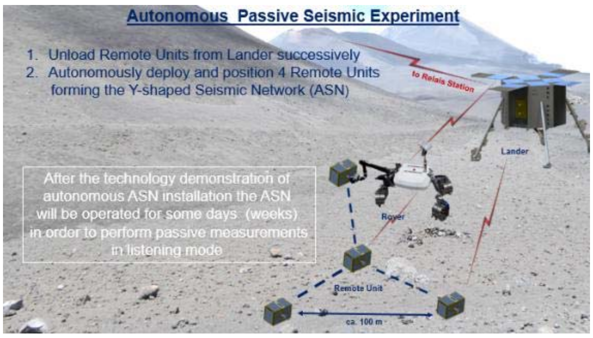

Fig. 2: Autonomous passive seismic experiment using 4 remote units in a Y-shaped configuration

The Mt. Etna site has been chosen due to its natural seismic activity, which has a focal depth of up to 600 km, similar to lunar deep quakes (700 to 1100 km). Furthermore the region is seismically highly active, probably three to four events per day, which means that scientifically relevant data will be acquired within the one month duration of the mission. In addition, the site fulfills important criteria for an analog mission which are:

- shall be of volcanic origin and reveal natural seismic activity
- fulfil criteria of Moon-analog regarding the geologic context and shape
- the topography and morphology shall be representative of lunar surfaces
- shall enable building up the necessary logistic and operational infrastructure

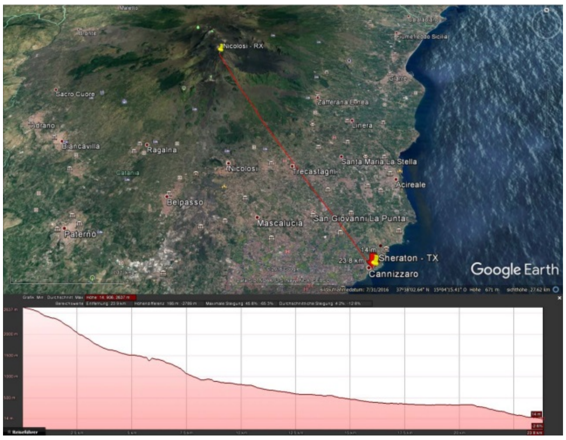

Fig. 3: Location of test site and control center. Inlet: topographic profile

For the Demonstration Mission Space, a dedicated network infrastructure and a ground segment have been installed. The ground segment included a Control Center which was based in Catania, Italy. Various terminals allowed for controlling a lander, a robotic rover and several scientific payload carriers which have been placed in 23 km air-line distance on Mt. Etna (see Fig 3). This distance was bridged by a radio link between the Control Center and a base camp at the demo site. From the base camp, a shorter radio link of several hundreds of meters to the Lander was established, and from there, the signal was distributed using several Access Points.

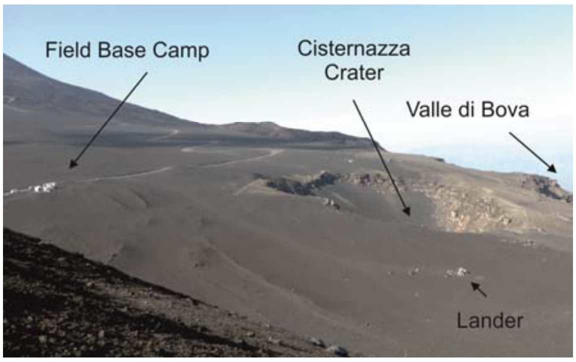

Fig. 4: Photo of the test area on Mt. Etna where all tests and demonstrations took place, as seen from the Laghetto cone

## THE TECHNOLOGICAL ELEMETS

### The LRU Rover

During the ROBEX project, we extended the capabilities of the Light Weight Rover Unit (LRU) [1][2][3], our rover prototype for planetary exploration missions. This area of application poses many challenges to the design of a robot. It has to be light-weight to allow economic transportation to another planet. After its arrival on the planet's surface, all sensors and actuators are required to work under these alien conditions. Heavy communication delays and blackouts between the robot and operators on Earth are to be expected. A ground station team thus must be able to interact with the rover on a high level. As large communication delays render teleoperation inefficient, the rover has to solve most tasks autonomously. It needs to navigate previously unknown, rough terrain in order to explore the area and arrive at scientifically relevant locations. There, the rover can employ its manipulator to take samples or to assemble technical equipment.

We considered these challenges during the design of the LRU: Its unique construction is light weight (approx. 40 kg) and thus economic to transport into space. Further, the LRU solely relies on sensors (stereo cameras, inertial measurement units) that work in alien conditions and are used in current space missions [4]. We designed its locomotion system for rough terrain and high manoeuvrability with four independent wheels, each being equipped with individual steering and driving motors. A force-controlled manipulator on the back of the rover can be used for pick and place tasks and to assemble objects. The autonomous capabilities of the LRU stem from a variety of software components. We developed and integrated modules for on-board self-localization in GPS-denied environments, local and global mapping, fast obstacle avoidance, path planning, object detection and pose estimation, manipulation, inter-process communication, high-level autonomous task control as well as a ground station mission control to overview and control the processes, and interact if necessary.

### The Docking-Interface between Manipulator and Payload Carrier

The leading aim of the design team "Docking & Interfaces" is the definition and development of reliable docking interface systems with the capability of defining a new interface standard. With respect to the requirements of the deep sea- and space domain, corresponding prototypes have been constructed and validated during laboratory and analog field tests. The various mission tasks conducted autonomously by the LRU during the space analogue mission required an extension of the rover's capabilities by a modular robotic docking interface and a payload carrier to enclose scientific mission equipment that could be docked by the interface.

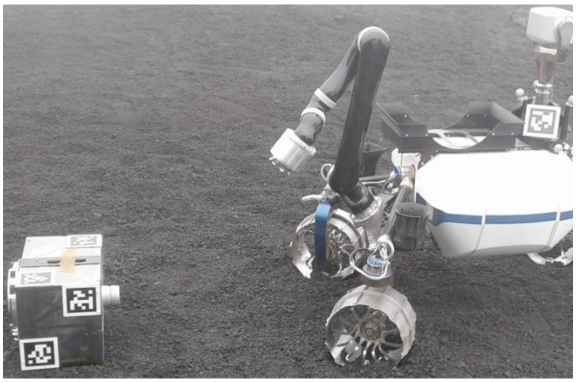

Fig. 5: The scientific payload carrier (left) with the passive coupling partner. LRU rover with the robotic arm and the Docking Interface (right).

To this end, the docking interface was designed for autonomous or tele-operated docking procedures with the aim of enabling mechanical connection, the transfer of electrical power, data communication and fluid transport among the docked systems.

However, during the analogue mission campaign the docking requirements have been reduced to connect mechanical loads with a high degree of reliability. To enable mobile measurement capabilities, the scientific carriers have been equipped with durable internal batteries and a COTS-based wireless LAN communication device.

In order to increase the safety of the mission in such extreme environment, a dedicated, robust docking process has been thoroughly designed that enables a high degree of repeatability and high docking success rate. The process' reliability is complemented by the simple geometry of the coupling components as well as the modular and scalable design. With respect to the design, the rotational symmetrically shape of the passive coupling partner and the mechanical mating mechanism provides high misalignment tolerance.

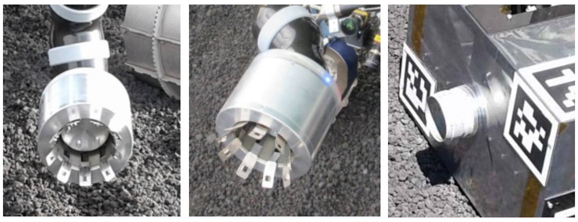

Fig. 6: The mechanical module of the Docking-Interface. The active interface part (left and middle), the passive side mounted on the payload carrier (right).

**The Scientific Payload Carrier**
The scientific payload carrier is based on modular design and equipped with three-component seismometers. The concept for this carrier is inherited from DLR's Mobile Asteroid Surface Scout (MASCOT), currently en route to its target asteroid on-board JAXA's Hayabusa 2 mission [5,6].

The monitoring stations are shown in Fig. 7, including antennas for communication, docking interfaces to lander and the robot arm side. The fully equipped version (left side of Fig. 7) includes also a deployable solar array, a bus compartment and an instrument compartment with a self-levelling seismometer. The sensor is a modified Lennartz LE3Dlite Mark III short period seismometer, from which we use the three geophones and the internal feed-back electronics board. Two variants of seismometer integration are realized for development and test purposes: (i) a more lightweight but fixed installation (right side of Fig. 7) and (ii) a heavier, more complex but self-levelling housing (left side of Fig. 7).

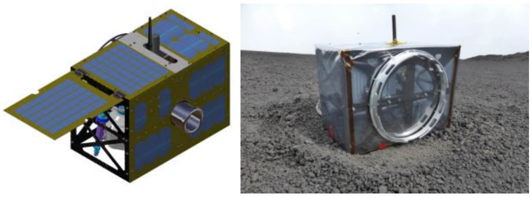

Fig. 7: Model of the fully equipped monitoring station (left). Deployed station, a test article w/o solar arrays and with fixed seismometer assembly (right)

**The Lander**
The RODIN lander is a size-scaled equivalent mockup of the European lunar lander module. In the ROBEX demo mission the lander hosts four of the modular payload containers, which are lowered to the ground to be reachable by the mobile system. The lander provides the communication link to the subsystems. The lander module (see Fig. 8), also comprise energy systems such as solar arrays and connectors.

Fig. 8: The Lander RODIN

**METHODS**

To drive, navigate and manipulate at a high level of autonomy, the LRU requires software components for the perception and mapping of its environment as well as for planning and for autonomous task control.

**Perception**
The LRU's perception of the environment is based on cameras in its pan/tilt head as well as at the back of the rover. For visual odometry, obstacle avoidance and 3D environment mapping, we employ a pair of stereo cameras and perform dense reconstruction through Semi-Global Matching (SGM) [7], which runs on an on-board Spartan 6 LX75 FPGA with a resolution of 1024 x 508 px at 14 Hz. The rear-facing color cameras are only triggered on-demand for close-range precise 6D object pose estimation during manipulation tasks. We use AprilTags [8] as artificial visual markers to reliably detect and localize known objects as well as other rovers in multi-robot setups.

**The ScienceCam**
The ROBEX field test was the first opportunity to test the newly assembled sensor suite, DLR ScienceCam. For an image of the ScienceCam hardware setup, see Fig. 9. Its first purpose is to serve as a new backwards-compatible iteration of the original LRU's PanTilt Unit[9], performing the tasks of 3D-reconstruction, localization, mapping, navigation and exploration. For this purpose, the ScienceCam has an optical bench of three 1292x964 px cameras, two grayscale and one RGB. The baseline of the two grayscale cameras is 9cm, while the RGB camera is located 2cm above them. The ScienceCam's second purpose is to allow for greater yield in scientific data collection and subsequent analysis. This is achieved by carrying an additional

suite of sensors relevant to planetary geology and biology: A second optical stereo bench of a 50cm baseline, containing two hyper-spectral cameras, a high-resolution camera and a thermal camera. This optical bench is  equivalent to the ExoMars' PanCam [10]. Each hyper-spectral camera consists of a camera sensitive to visible and near infra red light and a rotating barrel of 9 optical band-pass filters. Three of the filters in the motorized filter wheels are filters with center wavelenghts of 460nm (blue), 550nm (green), 660 nm(red). The remaining 2x6 are narrow-band filters chosen to comply with the FERRIC filter set, optimized for analysis of Mars-like geological compositions [11]. The high-resolution camera has a narrow FOV and can be used for detailed inspection of objects of interest. The infrared camera serves for thermal inspection. The ScienceCam was designed and integrated in-house [12].

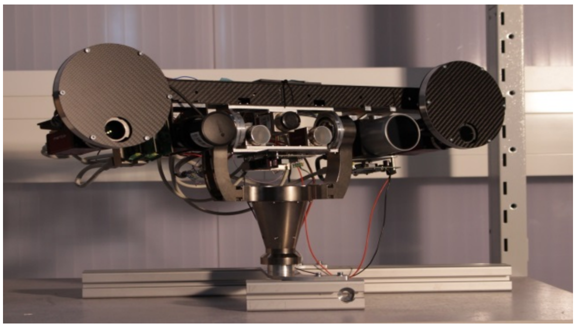

Fig. 9: ScienceCam hardware setup

During Etna field test, ScienceCam was used to capture panoramic image on the rim of Cisternazza crater which is the pit crater from the explosion in 1792. For a static scene capture, one shot consists of 23 images. To capture the panoramic image, 20x3 shots are captured, which amounts to 1380 images in total. The panoramic image set was captured fully automatically. To see images of a few shots from selected cameras, refer to Fig. 10. The data is still being analyzed for scientific yield.

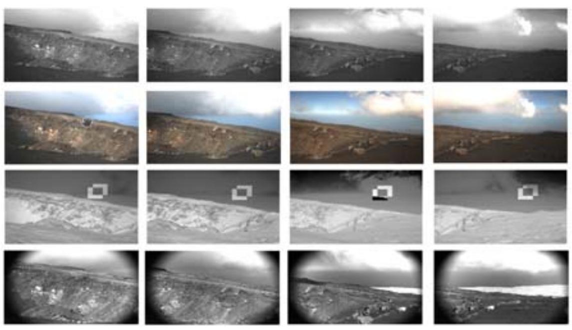

Fig. 10: ScienceCam data, from top to bottom: left navigation camera, wide-angle color camera, infrared camera, hyper-spectral camera (filter wavelength of 440nm)

**Autonomous Navigation, Search and Exploration**

During planetary exploration missions, the LRU needs to operate autonomously in GPS-denied unstructured outdoor environments. We combine fast local state estimation with global optimization to satisfy the requirement of having up-to-date 6D pose and 3D map estimates available on board the rover at all times. For robust, real-time local pose estimation, we compute key frame-based visual odometry estimates and fuse them in an Extended Kalman Filter (EKF) [13] with IMU data and wheel odometry. We perform a stereo error-adaptive traversability classification of the local terrain [14] and aggregate these estimates along the filter trajectories. The resulting cost maps can then directly be used for local path planning and fast obstacle avoidance between waypoints. In order to compute a globally consistent map, we integrate the local data into so-called submaps of limited size, which we can also exchange within multi-robot setups. They are connected via a single- or multi-robot SLAM graph [15]. Incremental graph optimization allows us to compute global joint pose and map estimates online. The LRU can recognize objects like the ROBEX lander and payload boxes via markers as static landmarks, as shown in Fig. 11. We further integrate the detections of other robots as moving landmarks to create further loop closures between robots. In addition, the LRUs can recognize already visited terrain by matching the 3D geometry represented in its submaps to create intra- and inter-robot loop closures [16].

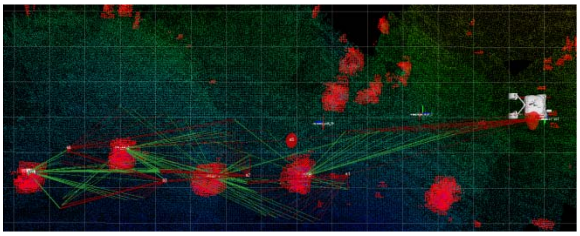

Fig. 11: Top-down view (1m grid size) of 3D point cloud map (5cm resolution, height-colored, obstacles in red) with SLAM graph (red covariance ellipsoids at submap locations, red and green edges for filter and object pose estimates respectively). In this experiment on Mt. Etna, the LRU detected four ROBEX payload boxes (red obstacles connected via the green observation edges) in order to improve its localization and map.

In order to map previously unknown terrain, we employ a frontier-based exploration algorithm. We thereby compute the expected information gain at the frontiers between known und unknown space in our global map. A 3D probabilistic voxel-grid representation of the map allows us to simulate the expected information gain at potential goal locations. We then select goals based on a trade-off between the expected information gain and the expected costs to reach them. In addition, we employ active loop closing, taking into account the costs and benefits of revisiting known locations in order to generate loop closures and thus improve the localization and map quality [17].

**Mapping and Exploration Experiments**

We tested and evaluated our localization and mapping pipeline as part of the ROBEX main experiments as well as in additional tests to validate its accuracy, to build maps in difficult terrain and to create multi-robot maps. In Fig. 12, we show the image of one of LRU's navigation cameras with our terrain traversability map as a color-coded overlay. During our experiments, we learned that in the rough terrain on Mt. Etna, it was difficult for our depth-based traversability classification algorithm to correctly distinguish between stones above a certain size and mounds or cavities in the soft sand. While the stones should not be traversed at all, the sand could easily be crossed. For future work, our traversability assessment could thus be improved by taking material properties into account, which could for example be inferred as a semantic labelling from image-based classification.

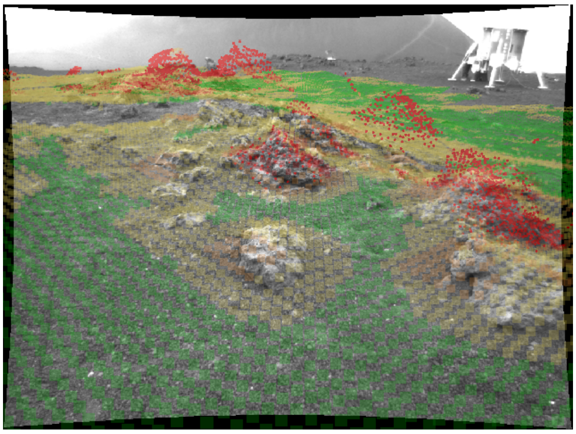

Fig. 12: Pan/tilt camera image on Mt. Etna from a navigation experiment. The colors show our 2.5D terrain classification map as an overlay (red: obstacles, orange and yellow: difficult to traverse, green: safe to traverse).

Further, we conducted single- and multi-robot exploration experiments, in which one or two LRU rovers had to autonomously explore a pre-defined area of approx. 20m x 20m. In Fig. 13, we present a map generated during such an autonomous exploration experiment on Mt. Etna.

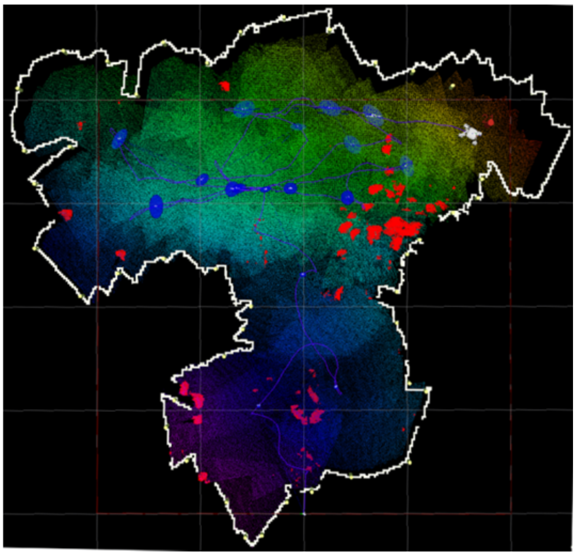

Fig. 13: Autonomous exploration experiment on Mt. Etna: Top-down view (5m grid size) of 3D point cloud map (height-colored, obstacles in red) with SLAM graph (blue covariance ellipsoids at submap locations) and exploration frontiers (white).

In order to evaluate the localization accuracy, we employed DGPS on the LRUs to record ground truth for their trajectories. The quantitative analysis of the experimental data gathered on Mt. Etna is still work in progress.

**Long-range Navigation Experiments**

In addition to the experiments relevant to the ROBEX demo mission and autonomous mapping and exploration experiments, we made use of the test site to perform some long range experiments. The motivation for these long range tests is to record datasets for the evaluation of our system performance over large areas. We collected two such datasets where the rover covered a distance of 796m and 1184m respectively as shown in Fig. 14. These datasets are useful for us in two ways: 1. To evaluate the performance of the current pose estimation and its components which are the wheel odometry, visual odometry and IMU (inertial measurement unit); 2. As a test dataset for evaluating the improved pose estimation pipeline in the future. The preliminary plots illustrating the performance of the pose estimation with respect to ground truth is shown in Fig. 15. The detailed data analysis is ongoing work.

Fig. 14: Google earth view of the two tracks extracted from the DGPS data collected as ground truth (top: 796m and bottom: 1184m )

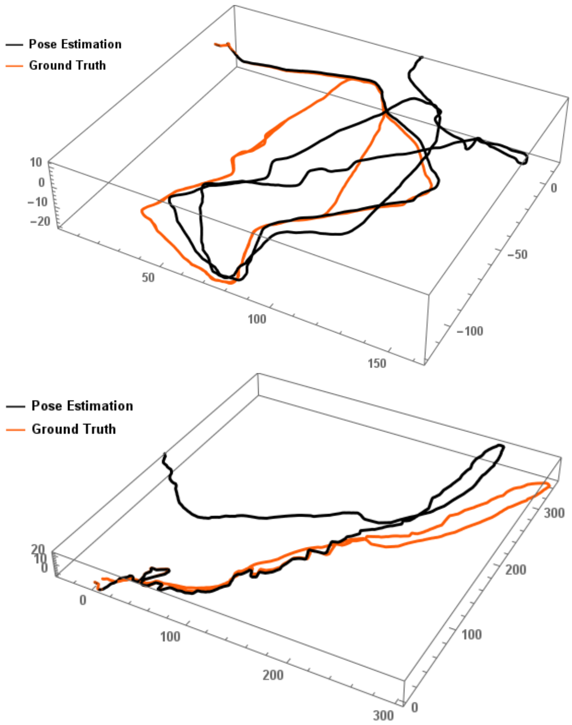

Fig. 15: Preliminary results of the pose estimation analysis showing the results of the robot's pose estimation in black with the ground truth obtained using DGPS in orange

**Placement of Scientific Instrument**

During the ROBEX demo mission, the rover must place the seismograph at a specified location. The scientific evaluation defined three major constraints for the placement process: 1) The seismograph must be aligned to the gravity vector to allow the internal pendula to function correctly, 2) the seismograph must be in full contact with the soil and 3) the seismograph contact has to be verified with an immediate test impulse.

We designed a custom manipulation approach for each of the constraints. To align the instrument with the gravity vector we implemented a strategy which uses the manipulator to iteratively flatten the ground with the instrument and queries the new orientation from an accelerometer within the payload carrier. To optimize the contact with the soil we use a compliant manipulator controller to press the seismograph onto the ground and perform a rotary motion. To verify the ground contact the rover hits the ground next to the instrument with the manipulator wrist in a compliant control mode.

The possibility to interactively design individual behaviours to fulfil the scientific constraints showcases the advantages of a multipurpose robotic manipulator on the rover. The integration of autonomous task oriented motion planning and execution for the manipulator eases the implementation of new strategies for unforeseen scientific or technical constraints.


Fig. 16: The LRU rover during the deployment of the seismic instrument on Mt. Etna, Sicily.

**Autonomous Task Control**

To orchestrate all software components of the LRU in order to create a robust, autonomous behavior we employed RAFCON. Developed at DLR-RMC since three years, RAFCON represents a powerful flow control programming framework. It is based on hierarchical state machines and features an elaborate visual programming environment. All navigation, manipulation, object localization and world model actions are controlled by RAFCON in a centralized manner. Easy collaboration between several developers is enabled via library states, which represent modular components designed for easy reusability and versioning. Fig. 17 schematically shows the layout of a subtask, programmed for the ROBEX mission.

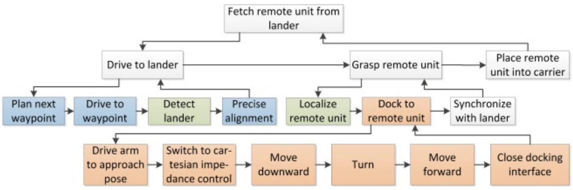


Fig. 17: Example hierarchical, action sequence for fetching a remote unit object from the lander. Each row represents another hierarchical level. Horizontal arrows define successor states and vertical arrow represent the hierarchical boundaries. The different colors classify actions into several categories. Blue actions refer to navigation states, red to manipulation states and green to computer vision states.

**Controller for the Locomotion on Volcanic Soil**

To cope with the rough terrain on Mt. Etna, the platform controller was adjusted to improve the locomotion capabilities of the rover on volcanic soil. Basing on the concepts introduced in [18], a parameterized slip model was identified experimentally. The resulting online slip estimation was used to implement a traction controller that is acting on the desired body velocities, serving as input for the underlying kinematic controller. Additionally, the slip estimation was used to improve the wheel odometry measurements, that are adopted by the pose estimation algorithm. Vibrations introduced to the elastic rover structure by wheel-ground contact were detected by a Fourier transformation of the IMU signals and also accounted for by the kinematic controller.

## SUMMARY

We described and presented results of the one month long ROBEX analogue mission campaign on Mt Etna. The focus was on the operational aspects, the interaction between engineers, scientists and the operational crew. The technologies and methods especially developed for autonomous operation of robots was validated and tested in relevant environment. The scientific data acquired will be discussed in dedicated publications. Experiences made in the interdisciplinary team will feed back into upcoming design and planning periods as well as possible future field campaigns. One main aspect of this analog mission campaign was to gain experience on the operation of robotic assets on planetary surfaces, using both autonomous and teleoperated techniques, which has been shown during the execution of the ROBEX main tasks with the active and passive network. The experience generated during this field trip has shown, that the scientists would need more time to acquire data in the field with the robots, furthermore the technology elements needed to be adapted to the surroundings, which was a delaying aspect. Meanwhile, long-term autonomous navigation, autonomous task execution, autonomous exploration of unknown terrain and many high demanding methods and technologies could be demonstrated during the ROBEX field campaign. The generated outcome will be used to further improve the concepts, systems and methods, be partly published to the community.

**Acknowledgements**

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