Collaborative Multi-Rover Crater Exploration: Concept and Results from the ARCHES Analog Mission

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***Abstract*—Access to extreme terrain, like caves or craters, is a key challenge for future planetary exploration robots. Many experimental robotic systems either use innovative locomotion concepts or elaborate mission designs to explore more challenging terrain. However, this requires a highly-specialized task-specific robot design, limiting the scope of the robot's general application. We investigate an alternative approach, by enabling an existing team of rover systems to crater exploration as an additional opportunistic mission task. The rovers collaborate in a tethered abseiling operation, enhancing the locomotion capabilities of one member of the robotic team. We use our two planetary rover prototypes for crater exploration within the scope of a general multi-purpose multi-robot Moon analog mission. In this paper, we first outline the design of and the modifications to our rover systems and describe the general partial-autonomous setup of the experiment, including the robot collaboration for hooking the tether and the abseiling into the crater. Second, we showcase the feasibility of this concept during a Moon analog campaign on the volcano Mt. Etna, Italy, in 2022. At the site, the rovers successfully access the Cisternazza crater, a crater of approximately 150 m in width and 30 m in depth, featuring steep flanks of partially compacted and partially loose volcanic soil. The experiment showed the feasibility of collaborative manipulation for tethering the two rovers. It additionally demonstrated enhanced rover locomotion capabilities due to the winch, enabling safe crater exploration. We finally discuss the lessons learned from this experiment and the remaining implementation steps to achieve full locally autonomous crater exploration.**

TABLE OF CONTENTS

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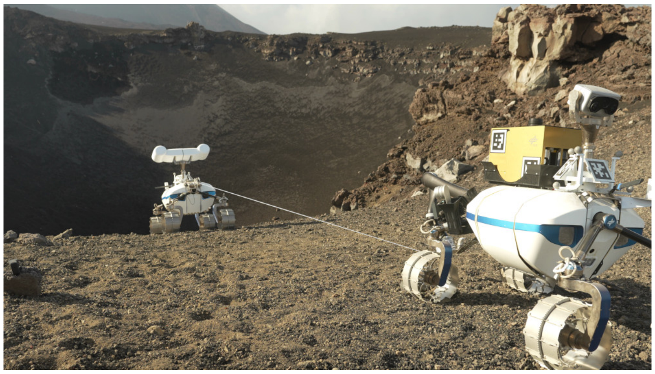

Figure 1: The two LRU rovers on the rim of the Cisternazza crater on Mt. Etna: LRU1 (left) has the winch mechanism mounted on its rear. LRU2 (right) is equipped with a robotic manipulator and connects the end of the tether to a hook on its body.

1. INTRODUCTION

Rover exploration of celestial bodies in our solar system provides astonishing visuals and groundbreaking scientific results. However, most of the exploration is limited to easily accessible terrain, even though locations like craters or caves are deemed to be scientifically most interesting and are additionally valuable targets for in situ resource utilization (ISRU). This limitation is caused by the robotic systems currently in use, as their terrain traversability is constrained by their locomotion design.

There have been many proposals for experimental robotic systems over the last decades, which either use innovative locomotion concepts or an elaborate combination of different robots to explore more challenging terrain. One drawback of most of these approaches is that they require highly specialized systems focusing on the exploration of specific terrains or on specific missions. Such highly specialized robot design usually comes at the cost of reduced versatility to other mission tasks.

In this paper, we investigate an alternative approach, where existing rover systems can be enabled for crater exploration as an additional opportunistic mission task while taking part in a more general robotic exploration mission. We thereby show

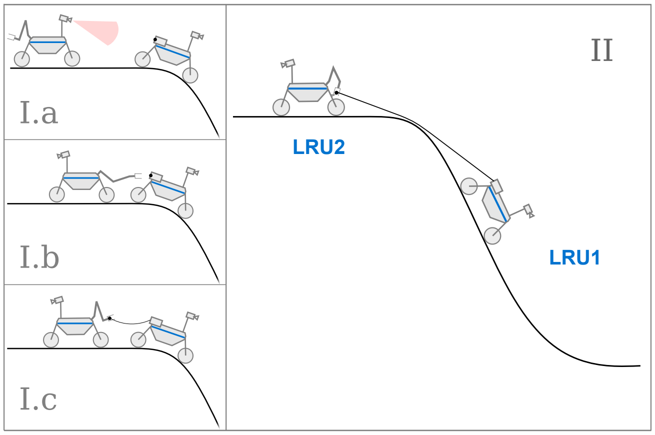

Figure 2: Sketch of the experiment with collaborative tether hooking (I) and the subsequent crater exploration using the winch for abseiling (II). During the first phase, LRU1 is stationed at the crater rim. LRU2 uses its cameras to detect LRU1 and approaches it (I.a). Next, it turns around and grasps the end of the tether on LRU1 (I.b). Finally, LRU2 hooks the end of the tether to its body (I.c) to serve as an anchor during the abseiling process.

that the exploration of challenging terrains can be embedded in a multi-task robotic scenario. The core idea is that robotic teamwork can reduce the requirements on individual robot capabilities, allowing for a more flexible mission and system design. In detail, two robots work as a team to explore a crater, where they first hook each other to a tether and later use the tether for a safe descent into the crater and back. We show that the addition of small auxiliary equipment combined with the robotic teamwork can increase the system's locomotion capabilities without requiring a major redesign of the locomotion concept itself. The design of the mechanical components – the winch, hook, and tether – aims at an easy integration with main system in such a way that there is no interference with the principal system capabilities. Finally, this setup can also serve as an emergency feature: it enables the rovers to rescue each other in case one rover gets stuck – potentially increasing the risks that can be taken during rover operations.

We consider the context of a Moon mission scenario of multiple heterogeneous robots. The mission is centered around a Lunar lander that serves as the communication and infrastructure hub. The concept is a modular, cooperative, and partially even collaborative mission, where the different robotic systems explore the environment around the lander, perform several scientific tasks, or set up infrastructure components.

In such a mission context, exploring nearby craters or other extreme terrain can provide valuable scientific benefits but must not interfere with the main mission. Our approach on crater exploration can therefore only rely on minimal modifications of the systems and instead it has to focus on enhancing the rover's locomotion capability by robotic collaboration.

In this paper, we successfully show a proof-of-concept for collaborative rover abseiling[1] into a crater during a field test in a Moon analog environment. We use our two Lightweight Rover Unit (LRU) systems, which – being connected by a tether and being supported by an on-board winching mechanism – explore a steep volcanic crater as a team. There, one rover system serves as a mobile hook for the tether on the crater rim and the second rover abseils into crater regions that would be impossible to access otherwise. Fig. 1 shows the two rovers at the beginning of the abseiling process, standing at the crater rim. The crater can be seen in the background of the same figure. It features steep flanks of partially compacted and partially loose volcanic soil.

ARCHES and the LRU rovers

Our crater exploration experiment is designed in the context of the ARCHES Moon analog demo mission, a general multi-purpose multi-robot exploration mission. The final of the ARCHES demo mission was a four-week-long field test on the volcano Mt. Etna, Italy, in June and July 2022. The experiment site is located at the volcano's flank at an altitude of approximately 2600 m.

For ARCHES, our two LRUs are among the principal robotic systems for several scientific experiments, exploration assignments, and infrastructure tasks in the Moon analog environment. The focus of ARCHES was on multi-robot exploration and manipulation scenarios. For this, we implemented a wide range of modular autonomous robotic skills that were combined in different ways to achieve the mission tasks. For the crater exploration, we could rely on these proven skills and re-use them to setup the experiment. The demo mission, its key experiments, together with the LRU systems are introduced in Section 3 of this paper.

Many of our technologies used for ARCHES are based on the 2017 ROBEX campaign at the same location at Mt. Etna. This also applies to our 2022 crater exploration experiment, as it is our second attempt after a failed approach during ROBEX five years earlier. The lessons learned from our 2017 crater exploration are also listed in Section 3 and serve for us as guidelines for our current mechatronic and algorithmic design. Additionally, they motivate simplifications to reduce experiment complexity.

The winching experiment

Regarding the crater exploration, we first present an overview on the experiment concept at the end of Section 3 as it is depicted in Fig. 2. Section 4 describes the general system setup of our rovers as far as it concerns the winching experiment. There, we additionally introduce the abseiling-specific enhancements to the LRU systems, both of mechatronic and algorithmic nature.

We present the actual crater exploration in two separate parts. For each part, we first describe the concept in general and second discuss the Mt. Etna experiment results specifically. Part (I) is dedicated to the collaborative hooking of the tether, as outlined in Section 5. This part was executed autonomously and focused on the complex integration of several software components to enable reliable hooking.

We describe part (II) in Section 6, where we detail our descent into the volcanic crater, potential scientific measurements, and the subsequent ascent to the starting location. The rover abseils twice into the crater. There, it overcomes slopes featuring a maximum inclination of 28° thanks to the tether-winch support. This is twice as steep as the rover's stand-alone capability, usually allowing the rover to scale slopes between 10° to 18°, depending on the soil.

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[1] Note that in this work, we use *abseiling* as the loanword of German origin, however many related works use *rappelling* of French origin.

Additional images of the experiments together with the corresponding video are available under `rm.dlr.de/crater-winch-experiment`.

2. RELATED WORK

Research on planetary robotic exploration of extreme terrain has a several decades-long history. It can be divided into works that primarily focus on the locomotion capabilities of the robotic systems and other works, like ours, that rather embed the accessing of challenging terrain in a broader robotic mission concept.

The locomotion designs are generally divided into several groups: legged locomotion, wheeled locomotion, bio-inspired locomotion and flying robots. The latter won't be discussed here further due to their very different characteristics in applicable payload, compared to ground-based mobility systems. All ground-based systems can further increase their locomotion capabilities by relying on auxiliary help like a tether.

A comprehensive overview of legged robotics in the context of general planetary exploration is given in [1]. Example prototype systems are, among others: the ALoF system [2] and Bert [3], both four-legged robot systems or the eight-legged SCORPION [4]. The capabilities of legged robotic systems are tested in the context of space analog missions, for example by [5] during the Space Resources Challenge. Such legged systems can usually scale slopes in the order of 25° to 45°, with literature reporting successful tests on slopes of, e.g., 30° (Bert [3]), 45° (SCORPION [4]), or 25°(within SRC [5]). Note that maximum possible slope values always depend both on selected gait and the soil characteristics, thus complicating a direct comparison.

Regarding concepts for specifically accessing challenging terrains like craters or caves, several related works need mentioning - a number of them rely on tethers for increased locomotion capabilities in rough terrain.

The experiments with the Dante II robotic crater exploration [6] is one of the early works in the field. There, a tethered robot with a "framewalking" locomotion concept explores a volcano in Alaska with slopes up to 90°. Bares and Wettergreen [6] also stress, that the tether for abseiling increases the capabilities of the robot to traverse rough terrain but also limits the range scope, motivating a mobile tether hook.

The TRESSA/Cliffbot System [7] uses two rovers as anchors at the edge of a cliff while a third rover abseils down the cliff, being tethered to both anchors to explore control algorithms for tethered systems on steep slopes. During a planetary-analog field test on Svalbard, Norway, the system was capable to overcome slopes up to 90°.

The Jet Propulsion Laboratory (JPL) used several generations of the legged LEMUR rover [8] to investigate bio-inspired robotic climbing capabilities, leading to a cliff-scaling field test in 2019, where the robot's latest generation climbed steep rocks in Death Valley [9].

JPL also investigated wheel-and-tether-based concepts for the exploration of extreme terrains, featuring the Axel and DuAxel Rover concepts [10]. DuAxel is a four-wheeled rover that can detach one axle on a tether and use this for abseiling into a crater, while the other axle with the main body remains at the crater rim as an anchor. The Axel system is only the axle element that descends the slope and could potentially be attached to other parent anchor platforms. Experimental results showed the traversability of the Axel system for slopes of up to 85° [10]. In this paper, Nesnas *et al.* [10] also make the case for extreme environment exploration using tethered robots – and provide a discussion on different robot systems for extreme terrain exploration. A more detailed look into the DuAxel locomotion system can be found in [11].

Their wheel-and-tether-based concepts culminate in an application study that considers the creation of a crater-based radio telescope on the dark side of the Moon - the CRATER MOON concept [12]. There, they consider using several of the DuAxel robots to abseil into a crater and span cables across the crater that provide a base structure for the telescope.

The DFKI Robotics Innovation Center has seen significant successes in robotic crater exploration, for example, accessing a volcanic crater on Tenerife with the CESAR robot with slopes exceeding 35° [13]. They furthermore showed the successful sample retrieval from a Lunar crater mock-up using a heterogeneous multi-robot team in an indoor Moon analog testbed, featuring crater slopes up to 45° [14]. There, they use a legged system to descent into the crater and collect a sample, which at the crater rim is passed to a wheeled rover that finally hands the sample to a lander system with a robotic arm.

DFKI's efforts culminated in their 2023 multi-robot lava cave exploration on the volcanic island of Lanzarote [15]. There, a small rover for scouting abseils vertically into a cave while being tethered to the large SherpaTT rover [16], and subsequently explores the lava cave.

Finally, the SCOUT rover is a robotic system developed by the German Aerospace Center to explore rough terrain like caves or craters [17]. It features a rugged design to survive drops over cliffs or into lava caves.

Our work differs from the listed related works. It neither considers novel locomotion concepts for extreme environments nor focuses on highly specific mission scenarios. Instead, we focus on increasing the locomotive reach of wheeled rover systems embedded in a broader mission context – to enable opportunistic science capabilities in extreme terrain not by locomotion design but instead by robotic collaboration.

3. CRATER EXPLORATION IN THE SCOPE OF THE ARCHES MOON ANALOG MISSION

We show the collaborative crater exploration with our two LRU rover systems as an opportunistic science part as a side track of the ARCHES Moon analog demo mission. We heavily leverage the multitude of robotic skills that we developed for ARCHES to implement the crater exploration experiment. To provide the necessary context to our experiment, we therefore first describe our rover systems and provide a brief overview of the ARCHES demo mission before introducing the experiment design.

Lightweight Rover Unit - LRU

Two of the core robotic systems of the ARCHES demo mission are our LRUs. The LRUs are small four-wheeled planetary rover exploration prototypes of approximately 40 kg in weight. Both are based on an identical robotic platform of a wheeled rover. They use a stereo vision-based visual-inertial

Figure 3: Abseiling of LRU1 into the Cisternazza crater while being tethered to the LRU2 as its anchor. The tether is visually enhanced for improved visibility. LRU1 carries the winch and it coordinates the unspooling.

navigation (VIN) using their head cameras, enabling locally autonomous rover navigation. The LRU system is described in detail in [18].

The rover's wheels are independently steered and each wheel is actively driven. The resulting locomotion capabilities allow the LRUs to scale slopes with a maximum inclination between 10° to 18°, which is highly dependent on the character of the terrain. For loose soil like gravel or sand, the locomotion capabilities are limited to the lower end of the range, and the upper end of the range applies to compacted ground.

One rover, the LRU1, is equipped with a multitude of cameras in its head, the so-called *science cam*. It features stereo cameras for navigation, a color camera, a thermal camera, a high-resolution narrow field-of-view camera and finally two cameras with hyper-spectral filter wheels for geological analysis. The latter is equivalent to the ExoMars rover's PanCam concerning the concept and the filters used [19]. LRU1 is on the left in Fig. 1 and can be seen in Fig. 8. Its principal purpose is the exploration and mapping of the terrain, and using its sensor suite to identify scientifically interesting locations for measurements or sampling. For our experiment, LRU1 is the rover that carries the winch and abseils into the crater.

The LRU2 is on the front right in Fig. 1 and is carrying a *payload box* on its back. The LRU2 has a Kinova Jaco2 robotic arm mounted on its rear, which enables the rover to manipulate its environment. Using a docking system adapter, the rover can connect to different tools – like a shovel or a robotic hand. Alternatively, it can connect to payload boxes of variable content, e.g., infrastructure elements like radio beacons, scientific instruments, or sampling containers. The manipulation approach of the LRU2 is presented in [20] and the docking system with modular tools and the design of the payload boxes is detailed in [21]. The arm and the docking interface can be seen in Fig. 3 and close up in Fig. 4 as (C) and (D).

Deploying the two rovers in the field together allows for a cooperative robotic exploration mission design, performing a multitude of different tasks. The rovers proved their capabilities on several occasions, most prominently during the 2017 ROBEX Moon analog mission on Mt. Etna [19] and now during ARCHES at the same location.

The ARCHES Moon Analog Demo Mission

We designed our winching experiment with the concept of the ARCHES demo mission in mind and performed it as a final additional science experiment of that mission in 2022. The ARCHES Moon analog demo mission explores the concept of heterogeneous robot cooperation and collaboration in a modular mission design, as a concept study for potential future space missions. The detailed ARCHES concept is described in [22] and we present only the key aspects here.

For ARCHES, the planetary exploration mission is centered around a lander that functions as the logistical hub of the mission providing data transfer, energy, a location reference to the rovers, and serving as the storage for LRU2's payload boxes. The used robotic systems are the two LRU rovers and our multicopter ARDEA. During the main mission, LRU1 and ARDEA have the task to explore the environment around the lander to create a map and identify geological relevant points of interest, which are evaluated by ground station personnel and in turn communicated to LRU2 to gather geological samples [23]. The sampling process of LRU2 allows for either grasping stones or shoveling sand by independently identifying the type of geological sample using deep-learning methods [24].

Furthermore, LRU2 is the manipulation workhorse to set up infrastructure like communication beacons, taking geological measurements with a laser-induced breakdown spectrometer [25], or placing antenna elements for a radio astronomy array [26]. For all these manipulation scenarios, the respective instruments and auxiliary tools are integrated in the modular payload boxes.

One key aspect of ARCHES is our high-level mission control tool ROSMC [27]. The tool is an easy-to-use graphical interface that serves as a high-level abstraction layer to command the robots and monitor the systems' progress. This allows the combination of sending high-level mission commands from human operators together with the execution of locally autonomous tasks by the robots. The idea behind ROSMC is that planetary scientists can directly command the robotic systems instead of relying on robotic experts. When we talk about *local autonomy* in this paper, we have such a setup in mind: the high-level decision-making lies within the hands of the operator but the execution of individual tasks is done by the system autonomously, with direct human interference only for error recovery.

General Winch Experiment Design

Our winch experiment is placed within the context of ARCHES: assuming a planetary mission that contains multiple infrastructure and science tasks, how can our robotic systems be enabled for additional opportunistic science in locations that are challenging to access? More specifically, we consider a mission where – after completing high-priority tasks – free system time can be used for additional science experiments or exploration. Furthermore, being considered only an optional and opportunistic mission task, we specifically consider the constraints that only minimal mechanical and electrical enhancements can be done to the existing systems to not interfere with the main mission. Finally, the execution of the task should consider our concept of local autonomy.

In the context of ARCHES, we therefore select the crater exploration as such an additional opportunistic science task. We consider it a proof-of-concept experiment, thus neither aim at a fully autonomous execution of the navigation nor selecting the most challenging slopes for abseiling. Indeed, we refrain from scaling the areas of the Cisternazza crater with cliff-like structures (as seen in the background of Section 1), We select a location at the crater rim instead, that only features soil close to the *critical angle of repose* – the steepest angle of loose material without sliding off – and individual rocks, which is seen in Fig. 3. Similarly, we specifically do not use our locally autonomous robot waypoint navigation during abseiling into the crater but instead issue short, piecewise driving commands. Both decisions are mainly driven by safety concerns.

Fig. 2 shows the principal elements of the experiment, which we split up into two general parts. Part I includes the robotic teamwork to connect the systems via a tether. Tethered crater exploration usually requires hooking the tether end to some object. In our case, we use one of the rovers as a versatile and mobile anchor that remains at the crater rim. The principal aspect of part I is the robotic collaboration. There, the robots need to detect each other, approach the correct distance, and then work together to hook the tether using the robotic arm.

Part II is the actual abseiling into the crater with the rover. This can be seen in Fig. 3, where LRU1 already started to descend. The main focus of part II is the winch-supported driving of LRU1, its interaction with the soil, and its ability to overcome slopes that are way beyond its regular locomotion capabilities.

Using the 2017 ROBEX Winching Experiment as Baseline

During our first Moon analog campaign (see [19]), we already attempted a winch-based exploration of the Cisternazza crater using LRU1 but failed. Many of the lessons learned from this unsuccessful trial were incorporated into our 2022 experiments.

The 2017 experiment was much simpler in design and considered the LRU1 as a single rover, having a commercial off-the-shelf (COTS) winch mounted on its body. Fiducial markers at the rim of the crater were envisioned to mimic target landmarks for rover navigation during ascent.

Before the actual crater experiment, several dry runs were performed on a moderately steep slope next to the base camp. During one of these dry runs, the spooling mechanism of the winch malfunctioned, causing the tether to interloop on the winch's coil. This led to irrecoverable damage on both the tether and the winch, causing the experiment to fail.

As a result, we incorporated the lessons learned into our 2022 winching experiment design, both for the hardware as well as for the algorithmic and sequencing approach:

- A custom winch has to be designed, that guarantees safe spooling.
- Matching the winching speed of the tether to the (slip adjusted) wheel speed of the rover yielded good results during the dry runs, especially when combined with a speed offset of different signs for both driving directions. This guaranteed tension on the tether for both descent and ascent.
- Using a landmark target concept for autonomous navigation (here mimicked by the fiducial markers), is a promising approach for a real application, but we figured out that it introduces unnecessary additional complexity for our proof-of-concept experiment.
- And finally, even though it might seem obvious, several dry runs of the experiment in a less challenging environment are highly recommended, as our 2017 winch failure within the crater could have resulted in a loss of system.

4. SYSTEM DESIGN

This section introduces the mechatronic and software components needed for our collaborative crater exploration experiment. We detail the specific requirements, considerations, and constraints that had to be taken into account. We briefly describe the well-established and well-tested components that were initially developed for the ARCHES main mission and which we could reuse for the crater exploration. Finally, we present the mechatronic winch design and its algorithmic control.

The underlying requirements for the system design are:

- LRU1 is the exploration entity to enter the crater. It shall be able to directly control the spooling mechanism, to avoid communication issues from relaying the control signal via the other rover. LRU1 therefore shall be the mount of the winch.
- The winch mounting position, its size, and its power consumption must not interfere with the LRU1 core functions of the main mission, for example serving as the landing platform for our multicopter or using its body tilt mechanism for traversing steep slopes sideways.
- LRU2 shall be capable of manipulating the tether. Therefore, both the winch on LRU1 and the hook on LRU2 must safely be reachable by the robotic arm.
- During the manipulation process, the motion of the robotic arm and the spooling of the tether must be harmonized, to avoid entanglement.
- The lessons learned from the 2017 experiment shall be considered.

High-Level Software

We utilize a set of high-level software components to enable the LRUs' local autonomy, especially for manipulating the tether as a team. We developed or improved these multiple software components for the ARCHES demo mission and used them successfully within multiple experiments. This allowed us to quickly design the winching experiment, by reusing existing robot skills and well-tested workflows. We therefore first present our pool of high-level software before we detail the actual winch design.

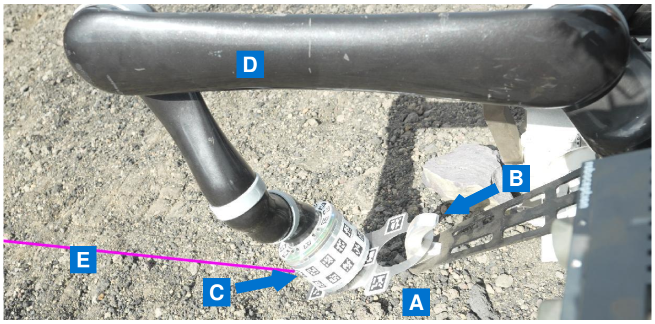

Figure 4: Hooking the tether on LRU2: The end of tether (A) – a metal sheet with the docking adapter mounted on it – is hooked to the LRU2 body. The hook (B) bares the principal load of the tether. The Jaco2 arm (D) grasps the end of the tether using its docking interface (C) during manipulation and holds it in place during the abseiling. (E) shows the tether (colored for visibility).

The *world model* is a knowledge base that centrally maintains the current latest knowledge of the robot about the real world. The world model represents both physical geometries and virtual approach locations for the manipulator, grasp positions, and storages as nodes in a tree structure. There, the nodes represent the real or virtual objects and the edges represent relative transformations between the objects as well as object ownership. The world model interfaces with the other software components which are described in the following paragraphs. For instance, if the robot visually detects objects in the scene, the belief state is updated by adding a new object instance or modifying the pose of an existing object. Furthermore, the action to manipulate an object is represented in the world model by both changing relative transformations as well as changing ownership of the object.

The *object detection and object pose estimation* component relies on fiducial markers, more specifically on the AprilTags library [28]. We use it to detect known objects in the scene, such as the payload boxes or other robots. When compared to non-marker-based approaches, it offers a more precise pose estimation. Furthermore, we apply a multi-marker approach for a robust estimation, where several markers are placed on a single object. Given a marker tree that defines the marker positions relative to each other on the object [29], we conduct a global PnP-based optimization over all detected marker corners to reduce the effect of outliers. The detected ID of the object and its estimated pose are subsequently used to update the world model.

The *motion planner* computes the motions of the manipulator, which in turn move the docking interface and attached tools safely to the relevant poses in the workspace of the robot. Its application to the mobile manipulation with the LRU2 is described in detail in [20]. The planner queries the current geometric state from the world model and ensures that no collision can occur with the robot itself or other close-by obstacles while considering all the kinematic constraints of the manipulator. Additionally, the planner can consider continuous constraints, such as keeping the robotic end-effector within a given orientation margin. This is used here in order not to tangle the tether during the attachment procedure.

The local autonomy is implemented by the *state machine execution software RAFCON* [30]. By orchestrating the other components introduced so far, the hierarchical state machines enable LRUs to make appropriate decisions depending on the current state machine execution state as well as the world state. During ARCHES, we use the hierarchical character of RAFCON to reuse small single-task state machines as *library states* within more complex *skills*, which in turn are used to create the overall mission state machines. For example, the grasping of the end of the tether on LRU1 by LRU2 is – to a high degree – the same state machine as collecting payload boxes from the lander. Thus, we can compose the winching experiment by combining several pre-existing skills that are already thoroughly tested and proven in the field, requiring only minor modifications.

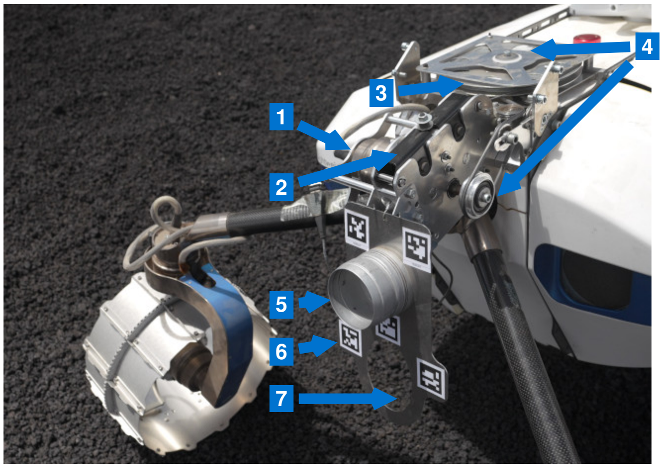

Figure 5: The winch on the back of LRU1. The key mechanical components of the winch are the drive unit (1), the tether-pushing mechanism (2), the coil (3), and the tether tension system (4). The metal sheet end of the tether is marked by (5-7), showing the docking adapter, the fiducial markers, and the tether eye. The multicopter landing platform was dismounted during the winching experiment.

Our mission control framework ROSMC [27] directly interfaces with RAFCON. Even though we were not explicitly using ROSMC during the crater exploration, our underlying design of the state machine allows for simple integration with ROSMC in the future. Here, we stick to the concept of local autonomy with high-level decision-making by the human operator, only without an abstracting graphical interface.

To enable multi-robot cooperation and collaboration, we employ the ROS multi-master setup[2] that allows the sharing of data flows between robots and the calling for the execution of a command on one robot by the other robot. For the winching case, we define LRU2 as having the authority to command LRU1, such that the winding service, which is hosted on LRU1, is available to LRU2.

Geometric Constraints and Winch Placement

The final winch design is shown in Fig. 5, where it is mounted on the back of the LRU1. The principal design elements are numbered accordingly. It is the result of our use-case-oriented mechanical design, which we applied to ensure the correct operation of the winch. The most important considerations for winch placement and design on LRU1 are defined by the grasping and securing operations performed by the LRU2.

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[2] https://github.com/fkie/multimaster_fkie

The LRU2 rover must be able

- to reach the end of the tether with the arm and dock to the tether,
- to detect the end of the tether using either the head or the rear cameras, and
- to securely fasten the tether end on the LRU2 body.

For reliable *docking* to the tether end, the main consideration is kinematic reachability: The tether end must be well accessible for the LRU2 and thus is positioned between the wheels of the LRU1 at approximately the same height as the base of the manipulator of LRU2. In addition, the tether must withstand the force of the LRU2 manipulator pressing on the docking interface, which is important for establishing the correct and precise contact. Fig. 5 shows the end of the end of the tether (5-7) being pressed into its locking position at the base of the winch by fully winding up the winch, which in turn ensures a well-defined contact position. To allow reuse of our modular docking skills for the robotic arm, the end of the tether is outfitted with our standardized docking adapter (5).

The *detection* of the tether must be within the tolerance of the docking interface and the overall precision of the manipulator. For a reliable and precise detection and pose estimation, we decided to integrate several AprilTags (6) on the tether end, allowing us to apply our multi-marker detection. To further increase the precision, the tags are installed closely to and around the docking adapter.

During the *fastening* of the tether on the LRU2 body, both kinematic and precision constraints must be considered. The resulting design is shown in Fig. 4. We decided for an eye-on-hook approach, where the eye (Fig. 5-(7) or Fig. 4-(A)) is located at the end of the tether and the hook (Fig. 4-(B)) is mounted on the LRU2. The hook must be in the reachable workspace, when the manipulator has grasped the tether, thus not only satisfying the arm constraints but also the additional constraints added by the tether. The hook design must additionally ensure that the tether cannot escape during the abseiling process. The eye of the tether must be large enough, such that the tolerance of inserting the tether into the hook matches the manipulator's positioning accuracy.

In the end, these considerations are satisfied by using sheet metal as the end of the tether, where we mount the docking adapter close to the eye and provide several fiducial markers on the remaining surface (see (A) in Fig. 4). We used our motion planner in an offline-mode to thoroughly evaluate possible placements of hook and of the mounting point of the end of the tether, therefore also for the winch, and ensure a high reachability.

Mechatronic Winch Design

The new winch is designed and optimized to fit on the LRU1. The parts of the winch are arranged on the rear side along the shape of the body of the rover. The volume between the body of LRU1 and the landing platform was used and also the area behind the tilt axis of the body of the rover. To ensure free movement for tilting the body of LRU1, the volume of the winch has limitations in its width and in direction to the ground.

The winch components are shown in Fig. 5 and consist of a drive unit (1), tether-pushing mechanism (2), tether coil (3), tether tension system (4), and the metal sheet plate that marks the end of the tether (5-7).

Performance characterization – Note that this design is a proof of concept. The winch is therefore mostly optimized for size and not for weight or power consumption. We nevertheless characterize the winch performance to provide reference values.

The winch weighs approximately 4 kg. Its maximum supported load was experimentally determined to be 500 N. Thus, the winch could potentially bear the full rover weight in Earth gravity but its design rather aims at a *driving support role* during operations.

For our measurements, we use the winch to lift weights from the ground, once attaching 7 kg and once 12 kg. This roughly represents the expected load resulting from fully supporting the rover in the Moon and Mars gravity, respectively. Operating the winch in holding mode, which represents the maximum load during descent, results in a corresponding power consumption of 3.0 W and 3.7 W. Actively lifting the weight at a speed of 0.1 m/s requires 8.5 W and 13.3 W for the two different weights.

Drive unit – We use a drive unit for the winch that is identical to the rover's drive units for steering and traction. This allows us to reduce system complexity and reuse the power and control structure. In addition, these drive units feature integrated gearing, so that the torque requirements to operate the winch are already fulfilled. This way our well-tested robust motor design, gearing, bearing, housing, and sealing can be reused. The drive unit is an ILM38 motor design with a harmonic drive gearbox of a ratio of 1:100, see [31] for details. It is shown in Fig. 5 as (1).

In terms of the connectivity to the rover, the existing communication method and electric infrastructure of the rover are used to operate the winch. Just one more of the used ELMO motion controllers is added to the power and communication line. The LRUs make use of an industrial EtherCAT field bus with a standard DS402 profile specification that defines the functional behavior of the servo drive controller. The physical layer is defined just as it is in Ethernet IEEE. As the EtherCAT network is a ring topology with one master, the winch slave is simply added at the end of the chain of the existing steering, traction, body, and pan-tilt actuator slaves. From a high-level view, we command the winch with a Simulink control model, see the "control" paragraph.

Tether – The tether is made out of braided steel to be robust against the sharp edges of the volcanic soil and to be able to support the weight of LRU1. The design length of the tether is 62 m and it has a diameter of 1 mm.

Tether-pushing mechanism – We use a tether-pushing mechanism that is detached from the winding coil and operates independently. It is marked as (2) in Fig. 5. It has the advantage that the position of transmitting the force to the tether is fixed for all operating states, compared to standard winch systems that actuate the coil of the winch directly. This tether-pushing mechanism consists of two pairs of rollers which are driven simultaneously through gearwheels. The central gearwheel is directly connected to the drive unit. Each of the two roller pairs comprises one roller with a plane surface and the other with a groove for the tether. We use two roller pairs to increase the area to transmit the force of the drive unit to the tether. The two rollers with the plane surface press on the rollers with the groove – including the tether – with the adjustable force of a spring.

Tether coil – The coil for the tether is a flat disc instead of a cylindrical pipe - see (3) in Fig. 5. The coil volume has a height of 4 mm to accommodate the tether. The empty coil has a diameter of 60 mm and reaches 140 mm at the fully winded state housing the complete tether. Our flat disc design provides two crucial benefits: The tether coil fits perfectly into the volume between the body and the landing platform of LRU1. Furthermore, due to the flat disc design, a guided winding mechanism is not necessary and can be neglected.

Tether tension system – Our design decouples the tether-pushing and pulling (i.e., applying the necessary force to the tether) and the spooling of the tether onto the coil. As a result, both elements need to be synchronized. Furthermore, this winch consists of a relatively flat coil compared to standard winches, which results in a high variation of the effective diameter of the coil between the fully wind-up and the unwinded state. The varying diameter of the coil causes a changing spooling velocity for the tether, thus creating a differential rotation between the coil and the drive unit that needs to be compensated.

We apply a new tether tension system (4) that allows matching the coil's (3) rotation speed with the speed of the tether-pushing mechanism (2) while ensuring enough tension between the tether-pushing mechanism and the tether coil to avoid failure during the winding or unwinding operations.

The coil is connected to the drive unit with a belt, thus the rotation of the drive unit will be used to rotate the tether coil. We place two freewheels between the belt and drive unit and the coil and its shaft, respectively. The freewheels lock with respect to opposite rotation directions. This allows to create two different transmission paths of the torque, depending if the winch is currently *unwinding* or *winding* the tether.

In addition, there are two adjustable friction plate pairs. One is placed between the shaft of the coil and the frame of the coil and avoid an unintended unwinding of the tether from the coil due to internal tensions of the tether. The other friction plate pair is mounted for the transmission of the force between the freewheel and the belt wheel on the shaft of the drive unit. If the torque exceeds the adjusted force of these friction plates, a differential rotation of the belt wheel compared to the driving shaft is possible, compensating for the occurring differential rotation. Note that the principal forces of the abseiling are compensated by the tether-pushing mechanism (2), thus for the spooling only low torques have to be considered.

Winch Operating states

The winch has two different operating states for winding and unwinding. Depending on the operation state, the internal torques are guided along different paths.

Unwinding – During the unwinding of the winch, the freewheel connected to the drive unit runs freely, thus no power is transmitted to the belt wheel. Instead, due to the pulling force from the tether-pushing mechanism, the tether coil starts to rotate and unwind. This rotational direction of the coil locks the freewheel next to it and the rotation of the coil will be transmitted to the shaft of the coil. With the friction plates between the structure frame and the shaft, brake resistance is added to the rotation of the coil. As a result, an unintended unwinding of the tether will be avoided and the tether remains under tension within the winch structure.

Winding – The directly driven tether-pushing mechanism moves the tether towards the coil during the winding process. This rotational direction locks the freewheel on the driving shaft beneath the belt wheel so that a force will be transferred to the belt. The movement of the belt generates a rotation of the tether coil, winding up the tether. In this case, the freewheel on the coil runs freely. The changing effective diameter of the coil causes a variable winding speed on the coil. This excessive rotational movement implies a differential rotation at the friction plates on the side of the drive unit. It ensures the needed tether tension towards the coil according to the adjusted force of the friction plates.

As a result, our mechanical design of the winch provides a separation of the two key components of the winch: On one side, it applies sufficient force to the tether for abseiling and ascending using the tether-pushing mechanism (2). On the other side, the tether tension system (4) allows controlled winding and unwinding of the tether, relating to the coil. This separation is a major benefit compared to our 2017 ROBEX winching experiment, as it failed due to the malfunction in the spooling mechanism during the winding of the winch - recall Section 3.

Control

The kinematic mobility controller of the rover maps a desired 2D-velocity command (a longitudinal body velocity together with either a rotational or a lateral velocity) at the body center to the wheels, thus creating a consistent steering configuration in combination with the respective wheel velocity commands. The measured wheel angles and wheel velocities are then used to compute an estimation of the rover speed – the wheel odometry. These measurements allow for synchronization between the spooling speed of the tether and the wheel speed on the software side.

The winch allows for three different operation modes: a) hold, b) externally commanded releasing or tightening the tether, and c) a synchronized motion coupled to the rover's wheel speed.

The hold mode is used during operations that require the robot to stand still, such as the gathering of scientific data within the crater.

The external command is used for the collaborative robotics part. The LRU2 requests a motion of the LRU1 winch for all arm motions while the winch adapter is already attached. This allows our state machine to jointly command a release of the tether while the arm is moving the eye of the tether toward the rover's hook.

Finally, for the abseiling into the crater, the release/tightening of the tether is coupled with the estimated rover speed. We use the wheel odometry measurements including our parameterized slip estimation from [32][3] as the reference signal and synchronize the winch speed accordingly. The slip estimation considers the soil properties, the inclination of the slope and the current driving speed of the rover, among others. The slip-corrected rover reference speed is provided as commanded spooling speed to the winch after it was subjected with a bias to ensure tension of the winch. The winch spooling speed is thus scaled down for descent and scaled up for ascent, respectively. Other approaches to tighten the tether are not available to us due to the currently missing force-torque sensor. The upsides and downsides of this approach are discussed in Section 7.

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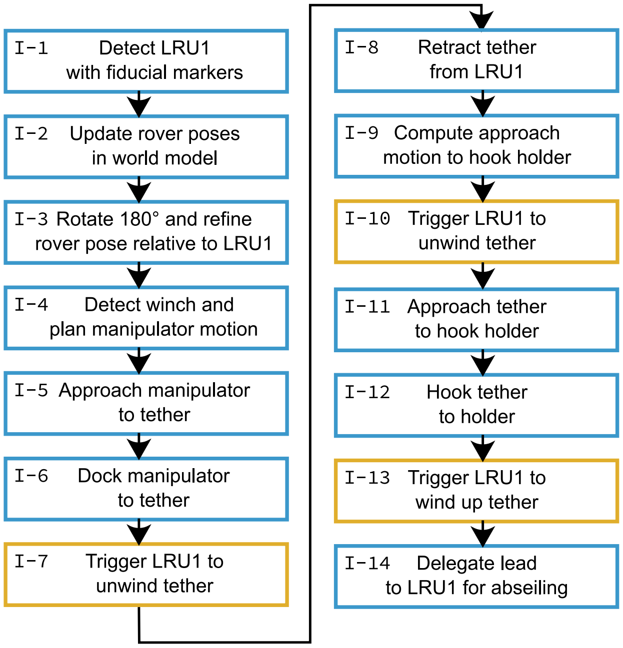

Figure 6: The task sequence of the autonomous collaborative hooking. The sequence execution is done on the LRU2. The "(un)wind tether" skills (in yellow) were triggered by LRU2 and executed on LRU1.

5. EXPERIMENT PART I: COLLABORATIVE HOOKING

We split the crater abseiling into two parts: I) the collaborative hooking of the tether between the two rovers and II) the actual descent into the crater. For each part of the experiment, one rover is selected to take the lead in the task, i.e., to execute the state machine and to command the other rover. In this section, we describe the first part of the experiment, where LRU2 is delegated to take the lead.

As illustrated in the left column of Fig. 2, this experiment consists of three major phases: positioning the rovers (I.a), grasping the tether (I.b), and hooking it (I.c). Figure 6 shows the detailed task sequence as a concept, and Fig. 7 shows selected steps from the real experiment with corresponding numbering. The task sequence is implemented in such a way, that after triggering the start, part I can potentially proceed autonomously.

In the positioning phase (I.a), LRU2 detects LRU1 (task I-1), localizes itself with respect to LRU1 (I-2), and finally approaches it (I-3). The perception software component provides the relative pose of LRU1 to the world model of LRU2, utilizing the fiducial markers on the end of the tether. LRU2 reasons if its drive reached the correct position with respect to LRU1, and, if it remains outside the required precision boundary, it relocates itself using the locomotion system.

For the second phase (I.b), LRU1 resides within the workspace of LRU2 and its collision model is added to the world of the LRU2. LRU2 uses the motion planner component to compute a collision-free motion of the manipulator (I-4), allowing the arm's docking interface to approach the docking adapter of the tether (I-5) using a position-based arm motion. After the approach, the state machine changes the control mode of the manipulator into impedance control to go into soft physical contact. The robot grasps the tether (I-6) by first pressing the docking interface onto the docking adapter and subsequently triggering the locking mechanism.

Figure 7: The collaborative manipulation sequence of the two LRU rovers. The text annotation corresponds to the task sequence shown in Fig. 6 After positioning itself (I-3), LRU2 (on the right) moves the manipulator towards the tether end (I-5) and conducts docking (I-6). LRU2 triggers LRU1 (on the left) to unwind the cable. It then retracts the manipulator (I-8) and hooks the tether to the holder (I-12). Finally, LRU1 is requested to start abseiling (I-14). All the tasks are managed by the on-board computer (OBC) of LRU2.

Finally, for LRU2 to fix the end of the tether on its hook, both rovers need to work together – moving the arm and releasing the tether in an orchestrated manner to avoid entanglement. LRU2 is configured to have the authority to command selected services of LRU1. Thus, the spooling service of the winch is hosted on LRU1 but also available to LRU2. To avoid entanglement, LRU2 iteratively requests LRU1 to unwind the tether (I-7 and I-10) before the manipulator motions take place (I-8 and I-11). After placing the eye of the tether on the hook, the robotic arm stays connected to it to prevent slipping off the hook and switches to a soft impedance control mode (I-12). Finally, LRU2 triggers LRU1 to wind the tether up so that sufficient tension is applied to it (I-13).

The task execution captured in the real experiment on Mt. Etna is shown in Fig. 7. It was executed completely autonomously with the task sequence being implemented in the high-level RAFCON state machine. The hooking was completed within 3 minutes and 20 seconds completely autonomously. Note that for the experiment execution on Etna, we started the experiment after I-3 with the pose refinement to comply with the tight experiment schedule and to reduce task complexity. The left-out steps for robot target detection, approach, and relative pose refinement were already demonstrated successfully multiple times during the other ARCHES experiments.

6. EXPERIMENT PART II: ABSEILING AND CRATER EXPLORATION

After successful completion of the hooking, the LRU2 goes into a passive mode serving as an anchor and using its arm to hold the tether's eye in place. We chose a soft impedance mode of the arm (300 N/m in translation, 15 Nm/rad in orientation) to hold down the tether eye and prevent it from slipping off the hook. The LRU2 furthermore turns its wheels sideways to increase grip on the soil. The remainder of the crater exploration is now commanded from the LRU1.

LRU1 starts to drive slowly towards the crater. For the driving, we use the coupling between wheel speed and the tether release, as outlined in Section 4. Potentially, the LRU1 could abseil into the crater in a locally autonomous fashion with waypoints provided by the human operator, using its existing VIN system, obstacle avoidance, and path planner with minor adaptations. However, for our proof-of-concept experiment, we refrain from it due to safety concerns. Instead, we opt for piece-wise commanded rover motions of approximately 1 m in distance and evaluate the safety of the LRU1 system after each of these steps.

After the rover reaches the desired position, either the bottom of the crater or a scientifically interesting intermediate point on the slope, it uses its cameras to scan and map the area. For the upward motion, the same approach is used: piece-wise motion commands until the LRU1 reaches its start position.

After returning to the start position, the rovers decouple from the tether. First, LRU2 lifts the end of the tether from its hook and places it on the ground. It opens the docking interface and moves the arm away. LRU1 spools up the remaining tether. The end of the tether is automatically aligned correctly on the winch due to its mechanical guides.

Figure 8: LRU1 abseils down the crater on a steep slope.

On Etna

We attempted to descend twice into the Cisternazza crater. We evaluated our recordings of the LRU1's inertial measurement unit (IMU) data to determine the slope of our path from the crater rim to its bottom. The rover's start position is at the crater rim with an initial inclination of approximately 5°. The slope within the crater is generally around 20° to 25°, with a maximum measured inclination of 28°.

The first descent was 23 m in traversed distance. During this attempt, LRU1 stopped mid-way of the slope to scan the crater and take a panoramic picture as a science product, as shown in Fig. 9.

After completing this task, LRU1 was supposed to return to its starting position at the crater rim. However, the stop happened in a steep area with very loose gravel. At the beginning of its drive back, the wheels started to dig into this loose gravel, preventing the successful ascent of the rover. We determined that the cause for this was an insufficient synchronization between the winch speed and the wheel speed at the beginning of the ascent, which is described in detail in our lessons learned in Section 7. As a result, the rover wheels had to be freed by the human operator and it was pushed outside of the zone of loose gravel towards more compacted gravel. Afterward, it returned to its starting position without further complications.

For the second descent, we traveled approximately 40 m into the crater and stopped close to the bottom on a less sloped area with more compacted soil. This, combined with an adapted commanding of the winch allowed LRU1 to ascend successfully back to its starting position, completing its task without any disturbances.

7. LESSONS LEARNED

Thanks to our previous experience with the 2017 winching experiment, we could already rely on valuable lessons learned for our collaborative crater exploration. Especially the improvement of the winch design with a failure-resistant spooling mechanism allowed for a successful proof-of-concept experiment execution. Nevertheless, our 2022 experiment yielded important lessons learned that need to be addressed in the future, to enable even more robust collaborative crater exploration.

Manipulation and Winch Synchronization

During the collaborative manipulation process on Etna, LRU2 commanded the motions of its arm and the winch release of LRU1 in an alternating mode, splitting the whole hooking process into several sub-motions.

This approach was motivated by the fact that the motion planner is not yet capable of considering highly complex constraints like a tether that is within the workspace. Furthermore, having a release mechanism for the tether that reacts to applied forces (e.g. using a force-torque sensor and appropriate force control concepts at the winch) would allow the tether to remain under tension during the entire manipulation

Figure 9: Panoramic scan of the Cisternazza crater by the science cam of LRU1.

sequence. Adding these features would significantly improve future robot collaboration by both increasing the speed of the manipulation as well as decreasing the risk of tether-entanglement with the robot arm.

Slip Parameter and Winch Commanding

Our slip model from [32] assumes homogeneous soil parameters and models the wheel slip depending on the rover motion and the terrain slope. In our case, the slip parameters were determined with compacted soil, with the coarse volcanic grains interlocking – the predominant soil type on our experiment site for ARCHES. However, the Cisternazza crater features a variety of different soil types: besides the previously mentioned compacted soil, there are also areas of basaltic rocks, loose volcanic gravel, or volcanic grain interspersed with rocks, to name a few. Moreover, the slip model was calibrated at moderate slopes up to 15°, whereas the Cisternazza crater features much steeper slopes from 20° to 28°. In theory, the slip model takes different slope angles into account, however, the crater slope is close to the *critical angle of repose* thus potentially exhibiting different material cohesion.

The heterogeneous character of the Cisternazza soil together with the high slopes caused our slip estimation to provide a partially inaccurate assessment of the wheel slip. It therefore commanded the winch inaccurately, causing either too little tension on the tether for the descent or too much reliance on the tether for the ascent.

We assume that this mismatch caused the LRU1 wheels to get stuck during our first attempt to access the crater: In theory, a loose tether on the descent would then be compensated during the ascent. However, at the lowest point of LRU1's descent, the tether was in a loose state due to excess release by the winch. Starting with the ascent, LRU1 had to drive several seconds without any winch support, as the excess tether had to be spooled up first. During this phase, the wheels dug into the soil to such an extent that the LRU1 could not free itself later on, not even with the winch support.

For future experiments, we recommend providing an instantaneous slip computation, i.e., computing the direct difference between the VIN robot motion and the wheel movement.

Alternatively, equipping the winch with a torque sensor would allow control of the spooling mechanism to keep the tether tightened with a specific force. A potential concept would be the combination of torque and velocity control in a switching manner depending on the instantaneous control target. Another interesting control approach could be based on impedance control on velocity level, as described e.g., in [33].

Beyond the control of both spooling speed and torque, a 6DoF force-torque sensor at the winch could even be used to determine the direction of the pulling force. This information could then be used to control the rover's driving direction during ascent to home towards its anchor (i.e., LRU2 at the rim).

Rover Motion Planning

As stated before, we refrained from autonomous long-range navigation due to safety concerns and instead commanded only short local motions to the LRU1 system. Our well-established navigation algorithms can easily be adapted for usage with the crater exploration allowing autonomous navigation for long distances. However, these methods are limited to slopes where no large obstacles are present, as there is no consideration of the tether's properties and potential entanglement. A solution could be the incorporation of motion planning algorithms like [34] into our navigation stack, which allows to consider a tether and the tether's contact with the environment in the motion.

Missing Test Facilities

Conducting a locally autonomous collaborative crater exploration is a complex task. Due to the many experiments planned for the ARCHES demo mission, the available time for the crater exploration was strongly limited. This was sufficient for our proof-of-concept, as we present it here. Especially, as we were able to access and reuse our extensive stack of existing manipulation and navigation skills, that were developed for the main ARCHES mission.

However, introducing more autonomy elements and even a high-level control GUI increases the experiment's complexity to such an extent that it requires extensive testing. This especially holds, if locally autonomous navigation components ought to be used during the abseiling process. The interplay between navigation commands, the resulting driving of the robot (especially while considering obstacles in the path), the wheel slip, and the influence of the winch on the robot motion have to be extensively tested to ensure the safety of the robots.

Testing such a complex experiment requires ”crater analog facilities” or additional field tests, both costly endeavors. For us, missing test facilities were a bottleneck in the past. Fortunately, the German Aerospace Center recently inaugurated the Moon-Mars Test Site, an outdoor test facility for planetary exploration that also features a small Moon-analog crater [35]. This provides us with the possibility to further improve the LRU's crater exploration capabilities in-house.

8. CONCLUSION AND OUTLOOK

Our 2022 crater exploration experiment successfully showed how teamwork allows wheeled rovers to access challenging terrain that is beyond the systems' original locomotion scope.

We demonstrated that the locomotion capabilities of single robotic systems can be enhanced by robotic collaboration and tethering, given minor mechatronic alterations to the existing systems. It was a proof-of-concept experiment that we consider a baseline for our future development of collaborative crater exploration featuring full local autonomy. The more immediate goal is the application of the lessons learned from the previous chapter. Especially the incorporation of a torque/force sensor for the tether would directly improve the manipulation and abseiling capabilities of our systems.

The experiment is also one example that emphasizes the potential of multi-robot missions and underlines the need for further research in this regard, to mature the field. The same holds for opportunistic science in robotic planetary exploration mission scenarios.

We envision a future crater exploration that fully implements our concept from the ARCHES mission, with full local autonomy and having a scientist in the loop. In such a scenario, the scientist selects a starting position for both rovers at the crater rim and defines the exploration targets for LRU1 within the crater, while the rovers can execute all involved tasks independently. This would require only minimal adaptations on the software side, as we can rely on our existing ARCHES setup. However, due to the challenging terrain, extensive tests become necessary to ensure the safety of the system. Crater exploration is a challenging endeavor, primarily due to hard-to-model robot-environment interaction and constantly changing surface properties. This requires a lot of testing to ensure robust operations, especially when aiming at partially autonomous error handling and error resolving.

In this work, we limited the robotic teamwork to collaborative hooking and later used LRU2 as a static hook. In the future, this concept could be further developed, e.g., allowing LRU2 to function as a mobile hook, which in turn extends the exploration range of LRU1 within the crater. Given reliable radio communication between the robotic systems, exploration scenarios become possible, where first LRU1 inspects the bottom of the crater and detects scientifically interesting geological sample locations. After the completed ascent of LRU1 back to the crater rim, both robots could switch sides and LRU2 descents into the crater to sample those geological features initially discovered by LRU1 while commanding the winch remotely.

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