# THE DLR SCOUT ROVER DURING THE 2022 ARCHES DEMOMISSION SPACE ON MOUNT ETNA: OPERATING THE ROVER OUTSIDE OF ITS COMFORT ZONE

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## Abstract

We report about tasks, results and lessons learned driving the DLR Scout rover during the ARCHES Demomission Space in 2022 on Etna. The rover investigated trafficability and relayed signals for an ESA rover, was platform for an HMI, carried transceivers and demonstrated its robustness in a survival test. Scout fulfilled all tasks and gained maturity for a space mission ~2030. Lessons were learned in thermal management, power supply and wiring, as well as operational procedures.

## Keywords

Planetary exploration, Robotic surface operations, Analog rover campaigns, Heterogeneous rover swarm operations, Human machine haptic control interface, Rover robustness test

## 1. INTRODUCTION

### 1.1. ARCHES

**A**utonomous **R**oboti**c** Networks to **He**lp Modern **S**ocieties, *ARCHES*, [1], is a project funded by the Helmholtz Association involving the German robotics research centers DLR, KIT, GEOMAR and AWI. Heterogeneous robots, in terms of size, capabilities and area of operations, network together to accomplish advanced scenarios about future challenges. In focus are deep sea and space, domains difficult to access for human beings. Tasks are done mostly autonomously or in partial autonomy with the operators being far away. A simulator that handles many different agents in the same scenario at the same time complements the project. Originally, the project time was from 2018 to 2020. This was extended to 2022 because of the COVID-19 pandemic.

### 1.2. ARCHES Demomission Space

The culmination point of the ARCHES space segment was the Demomission from 13 June to 8 July 2022 on Mount Etna in Sicily [2–4], postponed from the original 2020 date. Under the leadership of the DLR Institute of Robotics and Mechatronics *RM*, five DLR institutes (RM, System Dynamics and Control *SR*, Communication and Navigation *KN*, Optical Sensor Systems *OS* and Planetary Research *PF*), the DLR Mobile Rocket Range *MORABA*, the Karlsruhe Institute of Technology *KIT* and the European Space Agency *ESA* set up a Moon analog base on the slopes of the volcano and a control center in Catania. Six entities were part of the heterogeneous core robot team: the *Rodin*[1] lander, the *Ardea*[2] drone and the four rovers *LRU*[3] 1 and 2, *Interact*[4] and *Scout*[5].

The Demomission was divided into smaller sub-scenarios. The Scout rover, which this publication is centered on, was part of the Geological Mission II *GEO II* along with Interact[6]. In there, it scouted the terrain and acted as communication relay station for Interact and investigated **r**egions **o**f scientific **i**nterest *ROI* that were not visited by the Interact rover because of too rough terrain or time constraints. This will be further elaborated in section 4.

The rover also served as a research platform for the cooperation partners. In a first example mentioned in this text, for the large test campaign conducted by KIT for their novel remote-control **h**uman-**m**achine **i**nterface *HMI* and automation services. Trained experts (for the GEO II mission) as well as laypersons operated the rover from the control center using a 6 **d**egrees **o**f **f**reedom *DOF* robotic arm with visual and force feedback. The laypersons, most notably former ESA astronaut Thomas Reiter, reported on their experiences in terms of usability and intuitivity, see Figure 1. This will be further elaborated in subsection 6.1.

In the second example, the Scout rover took part in a swarm navigation experiment for DLR KN as one robot carrying sensors. This will be further elaborated in subsection 6.2.

The Scout team also had opportunity to pursue own research goals. Next to assessing the limits on one battery pack and reactions to relatively high temperature intervals, driving on a new site and especially coping with the sharp, coarse underground permitted the collection of large amounts of engineering data. The most extreme and exciting example was to enter and (try to) exit the Cisternazza crater. This will be further elaborated in subsection 5.2.

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[1] https://www.dlr.de/content/de/bilder/2022/02/lander-rodin-und-rover-lru1-am-aetna.html, all URLs accessed September 11, 2023

[2] https://www.dlr.de/rm/desktopdefault.aspx/tabid-11715/#gallery/29283

[3] https://www.dlr.de/rm/desktopdefault.aspx/tabid-11431/#gallery/32387

[4] https://www.esa.int/ESA_Multimedia/Images/2022/07/Interact_rover_by_lunar_lander

[5] https://www.dlr.de/sr/desktopdefault.aspx/tabid-13261/23182_read-53800/

[6] https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Rover_plus_astronaut_complete_Mount_Etna_challenge

FIG 1. Former ESA astronaut Thomas Reiter driving Scout using the KIT control device. Photos: Florian Voggeneder/DLR

Finally, the text ends with some more general lessons learned in section 7, and concluding as well as forward-looking remarks in section 8.
While such a mission is not unprecedented, see subsection 2.1, we still think it worth publishing our experiences and lessons learned. We hope that it will inspire other teams currently in development processes of mobile robotics about the preparation and execution of large-scale test campaigns and that the lessons learned mentioned here will prevent them to repeat mistakes we made.

### 1.3. The Scout Rover

The Scout rover developed at DLR's institute SR is inspired by biological locomotion. Along a segmented backbone with compliant *vertebrae*, a few *modules* with two individually actuated *rimless wheels* each are aligned. One module acts as the main module and carries the power supply and distribution unit, the on-board computer and the communication devices. The other modules are auxiliary and have about $2.5\,\mathrm{dm}^3$ volume to carry up to $3\,\mathrm{kg}$ payload each. The "nominal" configuration of the Scout rover has two auxiliary modules, in the front with a camera and in the back with a GNSS sensor and an **i**nertial **m**easurement **u**nit *IMU*. The main module is in the middle. All rimless wheels are the same with three curved, compliant spokes and flexible feet at the end with grousers for higher traction. Figure 2 shows the nominal rover on the test facility outside the Scout rover lab before the ARCHES Project.

FIG 2. Scout before the ARCHES Demomission Space

The design driver for the Scout rover is to explore caves and lava tubes on Moon or Mars [5]. There is evidence from orbiter data that these exist. Possible traces of past life might still be discoverable in there and they are prime candidates for habitats for crewed missions. Current wheeled rovers, as successfully operated by China and the United States, unfortunately are not able to explore them. The access is too difficult (steep slopes, cliffs and big rocks), they would possibly not survive drop in and the inside is likely very narrow. The Scout locomotion system is designed to face these challenges. The rimless wheel permits crossing of relatively high obstacles in narrow places, "swimming" through very soft soil and climbing steep slopes, all this with minimal energy requirement [6]. Further, the compliance of spokes and vertebra greatly increases the ability to survive high drops and finally the design is symmetric for upside down driving. The development of the Scout rover follows a "simulation driven" approach and uses a toolchain with elements from rapid control prototyping and model-based development [7, 8]. Prior to the assembly of the first prototype [9, 10], the rimless wheel was extensively studied [11, 12]. This development approach has proven itself and the current state of the Scout rover is already exceeding expectations. Still, extensive analog test campaigns in relevant environment can't be replaced, hence the participation in ARCHES.

## 2. STATE OF THE ART

"State of the art" in the scope of this text is about analog campaigns for planetary exploration rovers on Earth, with a focus on the locomotion subsystem against payload and science. Prior work about operations with heterogeneous robot teams and their control devices will also be reviewed. Of course, any robotic space exploration mission has gone through numerous and long test phases which will not be reviewed here, refer for example to [13–18]. Similarly, system presentations and analyses of rovers with rimless wheels will not be reviewed here, refer for example to [19–24].

### 2.1. Analog Rover Campaigns

The ARCHES project is a direct follower of the ROBEX project (**Robo**tic Exploration of **Ex**treme Environments) involving essentially the same institutions as ARCHES [25]. The culminating point was also an analog mission on Mount Etna [26]. A major difference of ARCHES to ROBEX is the inclusion of additional robots (Ardea, Interact and Scout) to the two LRUs, creating a team of rovers complementary to each other. Remote operation of the rovers from the control center at the foot of the volcano, online inclusion of scientists and robustness tests in the Cisternazza crater are other new activities, all of them building up on the experience gained during the ROBEX analog mission.

In an exemplary series of field campaigns in relevant Earth environments in New Mexico [27], Alaska [28] and Utah [29,30] spanning many years, NASA teams of scientists and engineers have conducted assessments of Mars rover protocols for sampling, habitability inspection and other science activities. Unlike ARCHES or ROBEX, no robotic rover was operated, instead a “rover team” of humans were equipped with the instruments and performed the experiments following the instructions of the science team leading the campaign. While this “roverless roving” is

> « low-fidelity in terms of engineering . . . (it) is high-fidelity in terms of the data acquired and . . . focus on decision-making protocols used by the science team. » [30]

ARCHES followed a similar strategy with campaign preparations on Etna without rovers and protocols preparations in simulation sessions at home before the Demomission.

A second aspect of this series is interesting to mention in the scope of this text. The teams were divided in two and followed two different general strategies throughout the mission. In [30], the “linear team” performed walking and science operations in sequence for each site while the “walk-about team” first investigated the whole area using only remote sensing and visual information before returning to the most interesting places for sampling. Overall, the walk-about strategy performed better and did not discard sub-optimal samples, suggesting higher efficiency. Additionally, having a broader view of the area, before going into precision and details, is recommended by the authors. This is achieved faster by the “walk-about team”, although in the end results about which team provided more and better science are mixed. The division for [27–29] was a little different, with the “rover team” strictly following protocols implemented for the MER mission (which also allows walk-abouts although only rarely applied [31]) while the “tiger team” had no recommendation of that sort. Note however, that members of both teams always had no prior knowledge of the analog site, just like the rovers on Mars. The “tiger teams” thus provided a baseline of a human mission at which the efficiency of the “rover team” could be compared to, thus giving an evaluation of the MER guidelines. Although the ARCHES GEO II generally followed established protocols, these allowed for variation based on terrain and current state of the rovers for maximum final output.

[32] reports about the extensive field testing of the *SherpaTT* rover that, as Scout, aims at combining the advantages of wheeled and legged locomotion. SherpaTT however has four actively actuated legs with wheels at the end, in other words an active suspension system. [32] details the experiment site, setup and results that show impressive versatility and capacities to cover many kinds of difficult terrain. Very recently, SherpaTT took part in a large field test on Lanzarote in the framework of the EU *CoRob-X* project [33]. It was joined by the medium-sized wheeled rover *Luvmi-X* and *Coyote III*, a rover with rimless wheels and segmented body, to build a heterogeneous team. Tasks performed by the rover team during CoRob-X resemble those of ARCHES.

In [34], a rover with rimless wheels called *FASTER* (**F**orward **A**cquisition of **S**oil and **T**errain Data for **E**xploration **R**over) is used to study soft soil properties, especially sinkage estimation. After development of an algorithm and single wheel tests, the rover is operated in a large Martian analog field. There, different types of rimless wheels are tested and the approach to estimate sinkage, also for conventionally wheeled rovers, is verified. In contrast to the present text, the field in [34] is artificial and the focus is not on long and steady driving of rovers. Moreover, many tests are solely performed with a conventional rover at which a module with two rimless wheels is attached.

In conclusion, while the literature knows numerous rimless wheel rover concepts, none of them to the knowledge of the authors has gone through a similar test campaign in terms of natural terrain, duration and remote operations than what is related here for the DLR Scout rover.

### 2.2. Haptic Control Devices

Teleoperation has played an important role throughout the history of space exploration and will likely continue to do so [35]. Early works like [36] which operated a robotic arm mounted on the **E**ngineering **T**est **S**atellite No.**7** *ETS-VII* from Earth used the $2\,\mathrm{DOF}$ haptic device *Impulse Engine 2000* by Immersion Co. [37] reports on using two $3\,\mathrm{DOF}$ input devices to control the translational and rotational movements of a $7\,\mathrm{DOF}$ robotic arm mounted on US space shuttles. More recent experiments such as the Interact mission [35] used a *sigma.7* $6\,\mathrm{DOF}$ haptic device alongside a $3\,\mathrm{DOF}$ custom built joystick, indicating a trend towards higher DOF input devices. Additionally, all of the aforementioned publications point out the benefits of using haptic devices capable of providing force feedback to the operator.

As the input devices are usually used to control a pose with up to $6\,\mathrm{DOF}$, devices featuring $6\,\mathrm{DOF}$ are of special interest. [38] compares various $6\,\mathrm{DOF}$ haptic devices that have been proposed in literature regarding their workspaces and their ability to provide force feedback. Based on this analysis, using a collaborative robotic arm as a haptic device is proposed. In this work we utilize and evaluate this system as it features a comparably large workspace and the ability to provide meaningful force feedback [38], thus enabling e. g. experiments with cooperative operator assistant systems or personalized haptics.

## 3. PREPARATION OF THE SCOUT ROVER FOR THE ARCHES DEMOMISSION SPACE

Every expedition-style mission is unique. Even though there was heritage with Mount Etna from ROBEX [25], the mission profile, the rovers and the team changed. Hence, planning was alike, but not identical. Postponing the mission twice due to the COVID-19 pandemic posed further obstacles during the preparation phase, but also brought time and forced training in flexibility and remote working.

### 3.1. Hardware Preparations and Logistics

Logistics to Mount Etna prevent from taking everything that might be possibly needed. Thus, preparations included tests of each single sub-team training in mission-like scenarios to build the required heritage. Nevertheless, some conditions, such as the environment on the mountain, tourist streams and fast weather changes could not be simulated but had to be prepared for.

As the pandemic prevented rehearsal tests, these mission-like scenarios were conducted mostly remotely with minimal personnel on site. Moreover, each sub-team operated strictly at the home base using their own hardware in their own test fields. Thus, remote access to the rover with connection of the systems via the internet (for Scout personnel not on site and for external partners) was a major factor to enable. Likewise, mission visualization and transmission of on-board footage of the rover was a major key to bringing the systems virtually together and building up immersive training missions for the operators. With this, long-range communication like on Etna was trained by default. This also complied with the baseline of the Scout team to use as little personnel on the mountain as possible. However, this verdict required adaptability and posed some risk due to possibly quarantined key personnel.

The training offered the possibility to test components more isolated and one at a time. First, the Scout rover software and control but also sensors and camera systems were improved or consolidated. Then, connection to KIT only was established. The Scout camera feed was always sent to KIT only from where it was injected to the software network common to the whole ARCHES system. On the same line in reverse direction, commands from the haptic control device were transmitted. Third, more entities were added to the network to receive telemetry from Scout and KIT.

What finally to take to the campaign is mainly the result of the remote training missions. However, stuff had to be organized in a way to be easily and quickly available once on the mountain. The "lab environment" on Etna had to be set up anew every day and, due to the pandemic, space in the containers was used very carefully. Thus, minimal debugging setups, even working right in the field, had to be planned.

Packing up itself is a compromise on its own (the $0$-$1$ knapsack problem has no greedy choice property [39]), negotiating between little space and mass requirements as well as easy access. Compared to the other rovers and rover teams, and even considering that the rover itself is smaller, the hardware need for Scout is less. Efficient packaging managed to reduce the volume taken to Etna to three boxes with size $120\,\mathrm{cm} \times 80\,\mathrm{cm} \times 50\,\mathrm{cm}$. In these were two Scout rover prototypes, a handful of spare spokes, feet and vertebrae, spare electronics (CPU, PCDU and motor controllers), three sets of Li-ion-batteries with recharging station, the Scout notebook workstation and the necessary tools (screwdrivers, wrenches, soldering station etc.). A significant reduction for packing space is due to the common ARCHES infrastructure for wireless communication between operators and rovers.

### 3.2. Simulation Sessions for the GEO II Mission

The mission control team members met $9$ times online for simulation sessions in 2021 and 2022, all but one of those with virtual rovers only. Due to the unavailability of all rovers in suitable analog test settings, ESOC set up and organized the simulations, with control systems connected to simulators and 3 D engines for graphical representation of environments. The main goals of these sessions were to train the people for their roles and how to use the software tools, interactions between the teams and to set the software tools to proper tests. Some procedures, e. g. during intensive science proximity operations such as soil sample acquisition, changed and the number of voice loops was increased as implementations of lessons learned of the simulations.

## 4. THE SCOUT ROVER IN ARCHES GEO II

The most important setting for Scout on Etna was the Geological Mission II *GEO II*. There, it served mainly as terrain trafficability investigator and communication relay for the ESA Interact rover. This was the climax session after training and simulation activities of cooperation between DLR, KIT and ESA. DLR and KIT provided each one core team member and their expertise in space robotics and human-machine interface for the Scout rover. ESA provided the Interact rover, common software tools, planetary geologists and the rest of the team including support staff.

For ESA, GEO II was designated *Analog-1* and integrated into the **M**ultipurpose **E**nd-To-**E**nd **R**obotics **O**perations **N**etwork *METERON* framework. In most lunar exploration scenarios currently being considered, humans and robots will be involved, thus human/robotic collaboration will be required. The aim of METERON is to prepare for such missions. METERON has developed an international framework to test and validate end-to-end communications and robotic control strategies and to evaluate operational considerations. Analog-1 was set up by ESA as an experiment including a simulated lunar surface mission and technical rover demonstration and validation tests [40].

The major part of this section will focus on the role and experience of the Scout rover during GEO II/Analog-1.

### 4.1. Mission Profile

The story line of GEO II set the Interact and Scout rovers on the surface of the Moon after landing and egress from the lander. The lander served as operational and scientific mission basis and provided communication from the rovers to the ground station and vice versa. Choice of rovers fell on Scout and Interact because these two are very different from each other and one goal was to demonstrate how heterogeneous rovers collaborate. Flying robots were not included to stay in a surface operations scenario on a celestial body with, at most, a very thin atmosphere.

The Interact rover served as a highly equipped research rover and mobile laboratory with diverse and sensitive scientific instrumentation. It also carried a robotic arm to take surface samples. The operational range of the Interact rover is however limited by the allowed slope and obstacle limits and the rover cannot reach all points in the field without loss of communication to the lander. Distances $> 60\,\mathrm{m}$ or hidden places like local sinks or depressions are places where the direct communication link between the Interact rover and the lander was disrupted.

In contrast to Interact, the Scout rover can reach highly demanding terrain such as rugged places, steep slopes or scree and boulder fields. The first task of the Scout rover was to do what it can best: investigate terrain of unknown characteristics and surface composition. This is already valuable science in its own right and further was used to estimate trafficability for the Interact rover. Thus, sites of scientific interest which Scout deemed accessible were studied in detail by Interact, the other ROIs identified by the science team were only visited by the Scout rover. As its only payload was the camera facing in front, full $360^\circ$ point turns were performed as reduced scientific investigation.

Further, the Scout rover was equipped with powerful repeaters which ensured communication with the lander over large distances $> 400\,\mathrm{m}$. Thus, the second task of the Scout rover was to maintain communication between the Interact rover and the lander when direct communication was not possible. Swapping the roles, i. e. using Interact as relay between Scout and the lander, while technically possible, was of no importance during GEO II because the operational range of the Scout rover on its own was enough given the short mission duration of four days.

Three representative scenarios depending on the communication situation were possible during the GEO II mission:

1) *Interact and Scout Standalone:* Interact and Scout operate within the network coverage of the lander. Interact and Scout perform explorations with direct communication to the lander. Both rovers operate simultaneously

and independently from each other but might exchange operational and scientific information.

2) *Interact Spearhead:* Interact operates outside the network coverage of the lander. The Interact rover performs explorations while the Scout rover maintains communication between Interact and lander. Both rovers operate simultaneously and collaborate with each other.
3) *Scout Spearhead:* Scout operates outside the network coverage of the lander. The Scout rover performs explorations while the Interact rover maintains communication between Scout and lander. Both rovers operate simultaneously and collaborate with each other.

Meanwhile, the control team was sitting in the control rooms of Catania and Darmstadt. GEO II was performed resembling elements of a real, future lunar surface mission. Hence, the teams employed different roles to execute coordination and management similar to such missions. ESOC in Darmstadt acted as overall Mission Operations Centre with project leader, surface operations manager, software coordinator and the Interact driving duo (navigator and driver). All these positions had a delay of $2.5\,\mathrm{s}$ to the rovers on Etna and were allowed to talk directly to each other without going through the voice loop communication system, the so-called “air loop”. Two control rooms were set up in Catania. The first for the science team, the second for the Scout driving duo (navigator and driver), also with delay to the rovers. They were joined by the astronaut for the last day of operations to serve as an alternate rover driver without delay to the rovers for critical situations where low latency is important. The communication system included a delay of $2.5\,\mathrm{s}$ from astronaut to all other positions, for obvious reasons “air loop” was forbidden.

### 4.2. Remote Control of the Scout Rover

The task to remotely control the Scout rover was assumed by a navigator and a driver. The role of the navigator was to communicate with the surface operations manager and discuss ways to achieve set goals with the Scout rover. Using the mission control software by ESA, the navigator laid out the paths that the rover should follow and took camera pictures for the science team. The driver focused solely on physically driving the rover. The paths laid out by the navigator were transmitted to the driver’s control software, further instructions and precisions were communicated verbally through the dedicated Scout rover voice loop.

FIG 3. View from lander over mission area to base camp

The remote control of the Scout rover by the Scout rover driver was performed using the haptic interface by KIT [38], which allows two-dimensional motion control. The linear velocity of the Scout rover was adjusted by moving the interface back and forth. The angular velocity to rotate the rover was done by moving it sideways. A simultaneous rotational and translatorial movement of the Scout rover was restricted due to the limited view of the driver by the low-positioned onboard camera. The interface allowed for a very intuitive learning of this behavior, as its two degrees of freedom were mapped matching the rover’s behavior.

In addition to the manual operation of the Scout rover, an automated mode could be switched on at the haptic interface. This navigated autonomously to the next waypoint of the path set by the Scout rover navigator. In the automated mode, the control signals provided by the haptic interface could be oversteered by the driver at any time.

### 4.3. Mission Experience

This subsection first reports about the experience on site. Topics covered are a description of the test area and an assessment how well the rovers performed. Then, mission scenario experience is related. The last part focuses on the experience of the operators in the control rooms.

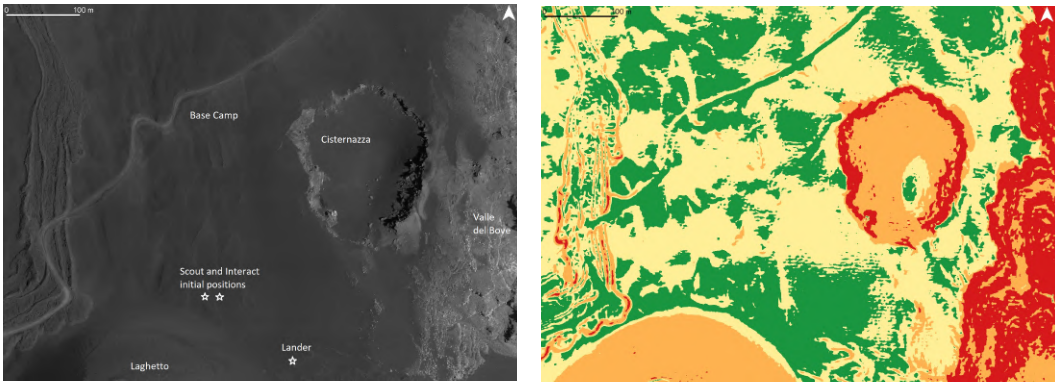
#### 4.3.1. On Site

The GEO II mission took place at *Piano del Lago* on the upper slopes of Mount Etna. The mission site is located at approximately $2600\,\mathrm{m}$ above sea level and covers an area of approximately $500\,\mathrm{m} \times 500\,\mathrm{m}$. Figure 3 shows the view from the lander in direction of the base camp. Figure 4 shows an aerial view and slope maps of the whole site.

The area is geologically characterized by relatively even and gently rolling, predominantly loosely granular to moderately rock-strewn volcanic terrain with rocky to highly consolidated bedrock and overlying medium- to fine-grained, sharp-edged to weathered and partially fractured igneous rock with loose ash and lapilli. The overall terrain is crisscrossed by little individual sharp-edged to weathered prominent rock outcrops and fractures exposed by erosion and drifting with numerous smaller sinks and terrain depressions partially filled by drifts and deposits of lapilli and ash. In the peripheral area of the mission site are the foothills of the so-called *‘Laghetto’* cinder cone and the *Cisternazza* crater. These were outside the area surveyed during the GEO II mission, because exceeding the allowed safe operating conditions of Interact, but were visited by Scout later as part of its extended scouting mission in the ARCHES experiments, see section 5. The base camp was located in the higher northern part of the mission area on a slight elevation with good overview. The difference in altitude between the highest point in the northern part and the lowest point in the southern part of the mission area was about $40\,\mathrm{m}$. The base camp had a visual link to the control center in Catania with $23\,\mathrm{km}$ of distance. In summary, the mission site had good traversability properties for the Scout rover and challenging but in general not insurmountable for the Interact rover. Places with highly demanding environmental conditions were only located at the periphery or outside of the mission site.

During the GEO II mission, Interact and Scout rover worked together in order to fulfill common mission targets. The cooperation between Interact and Scout focused on collaborative interaction to establish, maintain and operate an autonomous robotic network. The rovers had to interact with each other to maintain a communication link with the lander, to reach predefined regions of scientific interests within the mission area, to perform operations on the mission site and to comply with mission goals.

The focus of rover cooperation was to keep inside the areas with network coverage and communication link to the lander rather than collaborative locomotion on hazardous and unknown terrain. The network coverage by the lander, Interact and Scout was simulated with network circles around the



**(a) Aerial view**

**(b) Slope map: green $< 10^\circ$, yellow from $10^\circ$ to $20^\circ$, orange from $20^\circ$ to $35^\circ$, red $> 35^\circ$**

**FIG 4. The GEO II mission area at $50\,\mathrm{cm}$ resolution, the 'Laghetto' cinder cone is at the bottom left, the Cisternazza crater at the middle right, the base camp is at the middle left, the lander is at the bottom, the Valle del Bove is at the right**

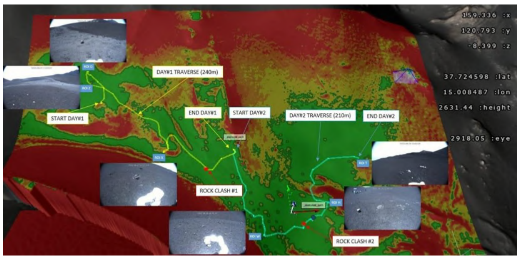


**FIG 5. Same than Figure 4 as viewed in `3DROCS` ( [40, 41]) with Interact's paths, labels and some camera captures, this software was also used by the Scout rover navigator**

respective nodes. The operations needed to consider necessary intersections of the network circles during mission operations in order to maintain communication.

### 4.3.2. Mission Scenarios

Mission scenario $1$, as defined in the mission profile, applied to situations where scientifically interesting points were located inside the network coverage of the lander, locomotion to these places was possible for Interact and Scout and both rovers possessed the scientific instruments required for their respective mission tasks. Interact and Scout acted as individual entities within this mission scenario. The rovers operated in the vicinity of the lander and held communication with the lander on their own. Simultaneous and independent operation increased the exploration possibilities and shortened the overall mission duration.

It was also in this setting that most of the trafficability analysis for Interact was done by Scout. Scout's communication system being stronger than Interact's, it could cover the whole area identified as scientifically important for the four days of operations. Assessing trafficability from the Scout rover motion only, proved to be more challenging than expected. The high agility but also high jerkiness made it difficult to ensure that the whole path driven by the Scout rover at no place would be too risky for the Interact rover. In addition, the low camera position of the Scout rover returned images not easy to interpret for the control team accustomed to having a view from human body height.

Mission scenario $2$ applied to situations where interesting points were located outside the network coverage of the lander, exploration of these places or objects required investigations by the instruments of the Interact rover and locomotion to these places was possible for the Interact rover. Interact acted as a fully equipped exploration rover with diverse scientific instrumentation. The Scout rover in contrast adopted the task of Interact's highly mobile attendant.

A trafficable path for the Interact rover had already been lain out by Scout in mission scenario $1$ setting. Now, Scout accompanied Interact to scientifically interesting points and maintained communication to the lander. Interestingly, although this scenario is labeled as "Interact spearhead", it was in general Scout in front when driving in convoy, to make sure that the terrain in fact would be traversable. The choice of giving Scout the larger communication area to the lander turned out to be wise for this reason.

Mission scenario $3$ applied to situations where locomotion was too hazardous or too energy expensive for the Interact rover in potentially risky and unknown terrain. The Scout rover explored the terrain and searched for reachable and scientifically interesting points. The Scout rover analyzed trafficability for the Interact rover or performed scientific investigations on its own. Interact accompanied the Scout rover and maintained communication with the lander.

While the first two mission scenarios were extensively performed during the four days of operations, mission scenario $3$ was never done in the framework of GEO II. There are a few reasons for this:

- Paths to most of the ROIs identified by the scientists could be traced along terrain within the capabilities of Interact by the navigator. Thus, Interact visited these ROIs to conduct a full scientific investigation.
- Scout's range of communication to the lander was much higher, thus it could reach the other ROIs without Interact as relay in mission scenario $1$ situation.
- As mission scenario $3$ is the same as mission scenario $2$ with inverted roles for the rovers (spearhead and relay), at least from a communications point of view, proof of concept was already done.
- The challenging terrain for Scout, Cisternazza and so-called 'Laghetto', were visited outside the GEO II framework, see section 5, where indeed a communication relay between Scout and the lander had to be set up.

### 4.3.3. In the Control Rooms

For the team in the control rooms, the experience was positive overall, and the usefulness of the simulations (subsection 3.2) was proven. With the experience of one session with rovers, the team had confidence in the systems and knew the reactions of the rovers to commands. But also, the other simulations were key to the success of GEO II as the people were familiar with the software, the procedures and also with each other. This latter fact should not be underestimated, team building takes time and needs constant repetition as has been again proven here.

Driving Scout on site was challenging because the camera showed a very close-to-the-ground image due to the flat design of the rover. Combined with the characteristic kinematics of the rover, this resulted in a rather shaky image while driving. In unknown terrain, it was therefore necessary to move slowly, as foresight was very low due to the low camera and the wobbly image. Overview images of the environment for the science or Interact operations team could only be taken from small hills. The training completed prior to the final demo combined with the information available from software and verbal communication with the other staffed positions resulted in growing experience, which increased confidence in controlling the Scout rover.

Automated mode was very helpful for the driving task because the mental load for the Scout driver could be reduced. Instead of the driving task to be performed, the Scout driver had only a supervising task. Additionally, the composition of three different communication channels led to a holistic communication experience: high and medium level information from the mission team and Scout navigator was received via voice loops. More concrete path information, announced verbally, was visualized on the rover control system and could be adopted by the driver through a button-press which activated the path following automation. This could then be observed twofold: haptically through the interface as well as visually by observing Scout's movement in the rover control system and through camera images. However, the automatic mode worked better in the mission simulations compared to the real mission because the real position signal was too error-prone.

In the end, the team feels to have trained well because we adapted well to the differences of the real field mission compared to simulations and also coped well with changes in the operations plan, those happened more than once during the GEO II mission.

## 5. ADDITIONAL MISSIONS

The Scout rover was presented as a particularly maneuverable and robust robot and indeed the whole design and development primarily aims at fulfilling this goal. However, the terrain and topography of the GEO II area turned out to be modest for the capabilities of the Scout rover with long but not very inclined slopes of up to $10°$ and relatively homogeneous soil without many obstacles. In those places conventional wheeled rovers like LRU and Interact performed nearly equally well as Scout in terms of mobility.

Somewhat aside the main area however, are two sites perfectly suited to test the capabilities of the Scout towards its main goal. Scout's role is chiefly to go to the places no other rover can reach, ultimately to explore extraterrestrial caves [5]. Thus, it was natural to send it on survey missions on the two most extreme terrain features in the ARCHES area. By this, mission scenario $3$ not tested in GEO II (see further above) could also be put into practice.

### 5.1. 'Laghetto' Cinder Cone

The foothills of the cinder cone formed by the $2001$ eruption, colloquially referred to as 'Laghetto' [42, 43], marked the southwest-to-west periphery of the GEO II mission site. They consist of ash and lapilli forming a conical-shaped ash hill at the angle of repose $38°$. Robots and people alike tend to bury themselves and have difficulty progressing uphill because the soil is a lot less densified than the rest of the Demomission area, although being visually similar.

The Scout test area at DLR has one similar facility. But the slope there is "only" $30°$, much shorter and uniform.

Due to the steeper slope at 'Laghetto', compared to the Scout test area and other similar facilities where the Scout rover has been operated so far, it had to drive slower and heading had to be corrected more often, due to higher slippage. Scout climbed a height of about $37\,\mathrm{m}$, that is $60\,\%$ of the cone's height. The top was not reached because increased obstacle density and decreased soil density in the scoria made progress steadily slower. In addition, Scout was sent there without more communications support than the lander (mission scenario $1$ in section 4) which did not fully support this area aside from the main mission site. Figure 1 shows the Scout rover climbing 'Laghetto' cinder cone.

### 5.2. Cisternazza Crater - Skylight Analog Test

The ARCHES site was also located in the vicinity of the Cisternazza crater, an almost circular crater of $100\,\mathrm{m}$ diameter and maximum depth of $20\,\mathrm{m}$, a remainder of the $1792$-$1793$ eruption [44]. The crater walls bounded the GEO II mission site to the east. The Cisternazza crater with its sharp terrain break-lines and rocky outcrops, its cliffs partly exposed by drifts and partly covered by deposits of lapilli and ash, and its steep crater walls and depressions excessively filled by fine-grained volcanic material thereby forms the geologic counterpart to the rest of test site of the mission.

This site offers a similar challenge to what the Scout rover is designed for: Martian and Lunar skylights, featuring sharp rims with vertical drops, steep slopes with deep and soft soil at the angle of repose, rocks of a wide range of size and risks of avalanches. The final operation of the Scout rover during ARCHES Demomission Space was to enter the Cisternazza crater on a cliff and attempt to get out without the intervention of humans or other robots. This is the most challenging test the Scout rover has ever been subject to.

One of the challenges, besides the extreme terrain, was to set up an antenna and a small control station for the operator with a good field of view into the crater. From a communication point of view, this is equal to mission scenario $3$ of section 4 that was not performed in GEO II as mentioned in subsection 4.3. Scout explores an unknown area of high difficulty and far away from the lander supported by another ARCHES team member that ensures communication.

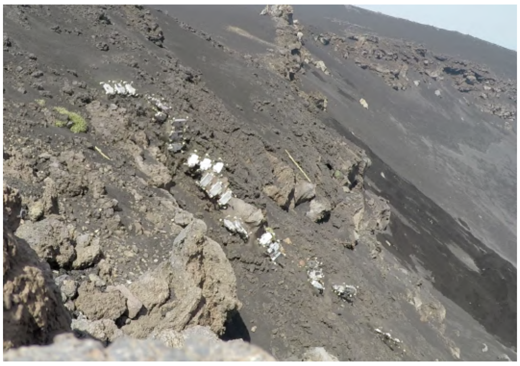


FIG 6. Scout rover jumping into the Cisternazza crater

Figure 6 shows the beginning of the test as overlaid frames, Figure 7 snapshots of the whole test in row-major order. After an attempt of slowly entering the crater through the north cliff (frames $1$ and $2$ of Figure 7), the Scout rover jumped

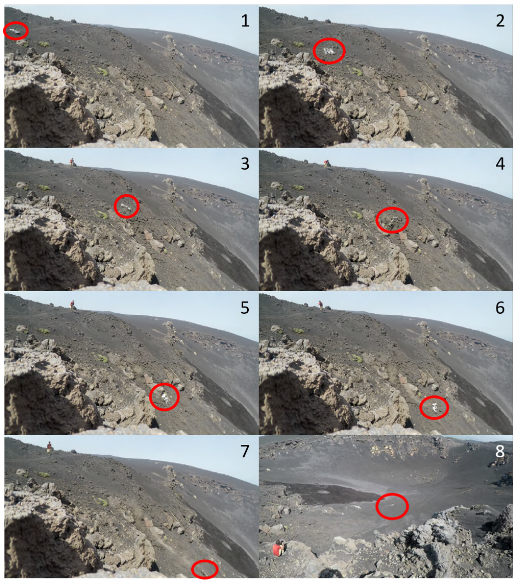


FIG 7. Scout rover Cisternazza crater robustness test

over the crater rim (frames $3$ and $4$ of Figure 7). At this side of the crater, rocks and cliffs are up to $2\,\mathrm{m}$ high and the overall slope reaches $39^\circ$ for almost the entire depth of $20\,\mathrm{m}$. As visible in Figure 6 the rover began an uncontrolled fall for a total length of more than $15\,\mathrm{m}$ (frames $5$ to $7$ of Figure 7). On the way down three spokes on different wheels were lost and one vertebra was partially broken. This was expected to some extent. The rest of the rover remained intact, also the electronics, power supply and drive units secured with foam material inside the casings.

Unfortunately, the rover came to rest upside down. As the dual antenna setup was not installed yet, shadowing of the single antenna led to loss of signal. This required to manually flip the rover over, which infringed with the “no human help” rule to some extent. Thereafter, the rover progressed on downwards the crater as visible in frame $8$ of Figure 7.

The intended path to exit the crater was not as steep as the entering cliff, but with $28^\circ$ still as steep as the landing slope (frame $7$ of Figure 7). Upon reaching the southern side of Cisternazza, when the terrain began to be uphill again, the rover was repeatedly starting small avalanches. This effect was increased, compared to the similar conditions on the ‘Laghetto’ cinder cone, by the missing three spokes which result in more uneven rover motion and harder work on the soil. The test was aborted a fourth way up to not risk burying the rover or endangering personnel upon retrieval. In addition, the rover was getting low on power.

The test is deemed a success, although partially violating the self-set rules. The rover survived the drop and carried on with its operations. Thus, the team is positive that future tests in similar terrain, using dual antennas and the new battery power supply, will be a full success, including exit.

## 6. THE SCOUT ROVER AS RESEARCH ENABLER

In the grand framework of ARCHES, not only the pure robotic side was in focus. Neither was the pure space side in focus of the Demomission on Etna. A successful mission needs a lot of systems and their interplay, thus teams from diverse fields and different backgrounds were together, worked together and profited much from each other.

Two examples, where the Scout rover played an essential role, are detailed in the following. First, a much robotic focused test campaign for the control device designed and developed by KIT, where the Scout rover served as the robot subject to be controlled. Second, an experiment conducted by DLR KN to collect ground truth data for their sensors and data systems, where the Scout rover served as one among a few mobile robots to generate realistic data.

### 6.1. KIT Haptic Control Device

The Scout rover, depicted in Figure 8, was remotely operated using a haptic HMI based on a KUKA LBR iiwa 14 [38], shown in Figure 9, both during preliminary testing and during the missions. It is capable of exerting meaningful interaction wrenches of up to $140\,\mathrm{N}$ thus allowing for a wide range of cooperative operation concepts where the operator is supported by automations. The ability to use up to $6\,\mathrm{DOF}$ allows for a generic application to all kinds of pose control tasks. Here, the two degrees of freedom of the Scout rover were linearly mapped to the $xy$-plane of the HMI.

FIG 8. Scout during the ARCHES Demomission Space on Etna

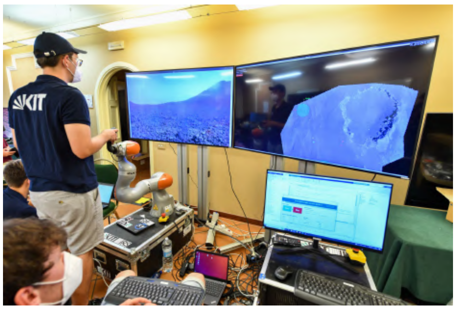


FIG 9. The KIT haptic device in the control room in Catania

To ensure safe operations, the operator was trained to either drive straight or perform point turns. The HMI ensured this by guiding the operator to areas of the workspace that either feature high velocities or high angular velocities but not both at the same time. The potential field used to generate the wrenches for this functionality is depicted in Figure 10. The wrenches were set as described in [38] by computing and evaluating the gradient field of the depicted potential field. In addition to this static behavior of the HMI, the operator had an adaptable automation available that allowed to switch between two levels of automation, namely a fully manual mode and a cooperative automated mode. The automated mode overlays another potential field over the one shown in Figure 10 to shift its minimum to an input value computed by a path following automation thus automatically guiding the Scout rover on the path planned by the navigator. Nevertheless, the operator was still in charge of the Scout rover at all times as they were able to overrule or adjust the input generated by the automation by exerting a sufficiently large force on the haptic device.

The HMI was implemented with the aim of contributing to a holistic communication experience which allows for a seamless transfer and acceptance of navigation information that enables the operator to fully concentrate on the task of safely traversing the terrain without putting too much mental strain. This goal was pursued by interlinking three channels of communication: The operator received high-level information regarding routing verbally via voice loops from the navigator. Concrete route suggestions based on mid-resolution topography of the environment could be created by the navigator and were provided to the operator visually through a rover control system which displayed them as well as the rover's position and ROIs on a map of the terrain based on satellite imagery. The operator was then able to activate the previously mentioned path following automation that followed the suggested and visualized paths. The HMI allowed the operator to haptically experience the automation intentions, keeping the operator closely in the loop and allowing to quickly and easily intervene in case of unforeseen obstacles.

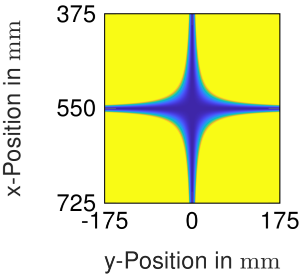


**FIG 10. Potential to compute gradient field for set-wrenches**

The task of operating the Scout rover within the ARCHES Demomission Space was an interesting application of the HMI for two reasons: First, the robustness of Scout rover allowed for the training of untrained operators and the evaluation of experimental features during this process. Second, the high performance and availability requirements of the mission alongside the iterative nature of the training sessions allowed to exploit and apply one of the core strengths of the HMI: its generic adaptability. Operational issues and personal preferences of the operators that were identified during the test sessions, such as the difficulty of precisely following a straight path, the preferred level of interaction forces or the preferred haptics to issue a command that brings the Scout rover to a halt, were addressed between the training sessions in an agile way to give the operators the HMI that best fits their needs and thus to achieve the best performance possible.

## 6.2. KN UWB Experiment

On the last day of experiments, the Scout rover took part in a swarm navigation experiment with a four-wheeled rover and a hexacopter from DLR's Institute KN. A detailed description of the developed network localization system and the experiment can be found in [45].

At KN, a complete solution on a self-organized swarm localization network is under development. It employs low-cost and light-weight **u**ltra-**w**ide **b**and *UWB* devices. These devices utilize the UWB signals propagating among them to obtain distance estimations with a centimeter level precision. This precision can support estimating not only the relative positions of the robots, but also, when multiple devices mounted on each robot, the relative orientation of them.

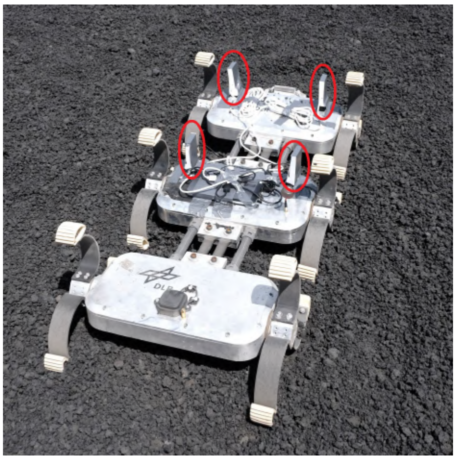


**FIG 11. Scout carrying transceivers for the KN experiment**

**FIG 12. The rover swarm performing the KN experiment**

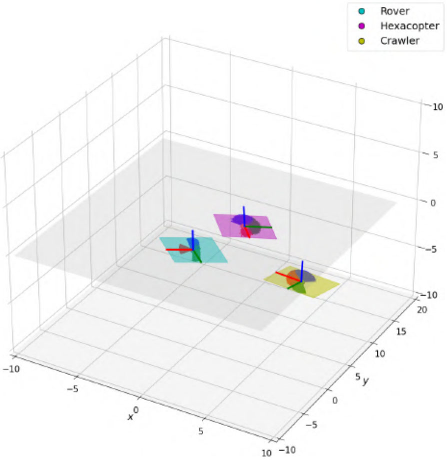


**FIG 13. KN experiment 3 D position and orientation estimation**

In this experiment, the Scout rover, a commercial hexacopter and a commercial rover, each equipped with four UWB devices, made manually controlled maneuvers, and their relative positions and orientations were estimated with decentralized particle filters. The placement of the UWB devices on the Scout rover is shown in Figure 11.

Figure 12 and Figure 13 show the scenario and the corresponding output of the decentralized particle filters.

The Scout rover was suitable for this experiment because:

1) Its three-body structure leads to maneuvers that are different from the hexacopter and the wheeled rover.
2) The Scout rover is very close to the ground, which leads to a unique radio propagation property.

Both of the uniqueness made the tracking of position and orientation interestingly challenging.

## 7. LESSONS LEARNED

The ARCHES Demomission Space set the Scout rover to unprecedented stress because of the natural terrain, the duration of operations, remote control from afar and weather.

### 7.1. Lessons Learned for the Scout rover

The moderate slopes and absence of large obstacles over large areas of the site mean that the wheeled rovers Interact and the LRUs performed very well in terms of mobility. Scout is able to drive significantly faster, at the price of more energy consumption and shaky behavior impacting payload and camera image to the operator. The long days of operation require to change the battery packs of the Scout rover more often than for the other rovers, even considering that the capacity of Scout's battery packs is much smaller.

When the operator has visual contact to the rover, driving is as easy as with any other mobile robot. However, as related by the Scout driver during GEO II and other untrained people using KIT's haptic device, remote control relying solely on sensors (IMU and GNSS) and the front facing camera is significantly more challenging. First, the rimless wheel and segmented body causes the image to shake. Second, the camera is placed much lower than on pan-tilt units typically mounted on masts, see the LRUs for example. This is less intuitive because human beings are used to see their surroundings from eye height. Coupled with their higher and more versatile payload capacity, the conclusion is that conventional rovers can be more efficient than Scout in moderate terrain. This is not unexpected and confirms the correct strategy followed by the Scout team. The Scout rover is developed for the highly challenging terrain and for missions with heterogeneous teams, proof of concept has been done.

The terrain on Mount Etna is an environment with scoria, lapilli, and ash which are extremely sharp and lead to increased wear on certain components. Especially difficult are buttons on the rover itself that rapidly can become blocked. Even though these buttons only serve prototype functions and will not be included in a flight model, their essential functions for e. g. safety are important. This was the major challenge coming from the natural, and not artificial terrain as “at home”, as most of the topography was benign for Scout's capabilities. The exception of course being the additional missions related in section 5.

As expected, the Scout rover experienced minor malfunctions on numerous occasions. Most could be fixed by simple remote debugging. Some were caused as the wiring was set to wear because of the push and pull in the conducts between the modules when operating on the uneven terrain. Some others were caused by the long stand-still periods, e. g. waiting for Interact science operations to finish, which lead to unnecessary power drain and buildup of heat in the actuation units. In its design scenario, exploring extraterrestrial caves, the rover moves almost all the time, as the battery lifetime is limited. In collaborative surface scenarios as shown in ARCHES, additional power savings should be considered, e. g. switching actuation fully off if there is no movement for longer than one minute. The complete restart procedure (not only CPU restart) currently requires screwing up the main segment casing and disconnecting the power supply. A more automated procedure, or at least a well-sealed switch accessible from the outside would greatly simplify and speed up this procedure. This would also suit a later flight model, as reboots could be required on Mars or Moon as well.

Lastly, the rover experienced total failure a handful of times during the four weeks on Etna, a partly welcome consequence of the intense operation. Compared with such situations “at home”, where spare parts and tools are readily available and the rover never is far away from the workshop, this laid annoyance on the personnel on site. Even not particularly heavy, the lack of a proper transportation concept for the Scout rover is another lesson learned from the Demomission. The rimless wheels prevent the rover from being pushed as can be, and was, done by the team members of the LRU and Interact rovers. This lesson is more important than it seems: Scout is also intended for Earth applications in caves or collapsed building and will have to be transported easily to such places. Two concepts are already in the making to solve this issue: a backpack carrying device for the rover as a whole, and bag to put the unscrewed wheels, module boxes and screwdriver for quick assembling and disassembling.

### 7.2. Lessons Learned from ARCHES GEO II

The most important lessons learned for the GEO II mission can be summarized by the fact that there can't be enough tests and simulations before real operations. This is not a new insight, as has been experienced by all rover operations team, e. g. the Mars 2020 team stating that

> « Value of rich simulation framework cannot be overstated. » [46]

In the first development phase “simulation” for the Scout rover has focused on the development of the mobility subsystem (multibody dynamics, control and sensors). The experiences of the ARCHES Demomission Space have revealed that “simulation” can, and must, go much further, e. g. for navigation and driving, mission goals and most importantly all aspects of communication. This means communication in the technical sense of signals being relayed to and from the rover, but also communication in the sense of the operations team. Here the simulation sessions proved to be extremely important to build an efficient team. It should also be stressed that continuity in these sessions towards the final operations is important, both in terms of schedule to remain in a trained state, in terms of team members and in terms of software tools.

## 8. CONCLUSION

We have reported about the DLR Scout rover during the ARCHES Demomission Space from $13$ June to $8$ July $2022$ on the slopes of Mount Etna in Sicily. The rover successfully mastered all assigned tasks, specifically acting as partner of the ESA Interact rover in the GEO II mission and test platform for KIT and DLR KN. Also, the stretch goal ended with an almost complete success. The Scout rover came to rest upside down after jumping into the Cisternazza crater which required manual turn around because the dual antenna solution had not been implemented yet. It also lost three spokes and partially broke one vertebra. Yet, the rover continued the traverse at the bottom of the crater. The driving efficiency because of the fractures finally was reduced too much for the steepest slopes of the exit way. This combined with the low power level, made an abort of the test inevitable. Still, the rover performed over the expectations also during this test.

Many lessons were learned, some of which had already been identified before ARCHES and the Demomission showed that steps undertaken are in the correct direction.

These include the need to increase robustness for example of the camera casing and spokes, new designs were already in the making in Summer $2022$. Similarly, communication and power supply didn't fully support all demands for the rover and the duration of different tasks. A dual antenna and a new battery generation are in the making in $2023$. The tests have also shown that Scout's potential is not fully exploited. Depending on the slopes, soil and obstacles, the gait patterns already show that terrain adaptation increases Scout's mobility efficiency. The curved shape of the spokes hypothesizes that driving backwards can further increase the gait possibilities and thus the mobility. However, there is currently no rear-facing camera to permit backwards operation in a remote-control situation. A new rover design iteration in the planning adds this feature. Finally, guidance and control through different devices is another point that needs improvements.

The Scout rover during ARCHES also enabled other teams to get insights and lessons learned for their research in guidance and control through a haptic HMI operated by experts and laypersons and radio navigation.

**FIG 14. Scout after the ARCHES Demomission Space**

So, the overall conclusion of the Scout rover experience during the Demomission is positive, the rover got some scratches as visible in Figure 14 but performed above expectations. This is the outcome of a well-thought-out rover concept to fulfill the intended vision, and the dedication of the team members. This is also good motivation to pursue the development towards the goal of having a space mission on Moon or Mars with the Scout rover as a team member around $2030$. Further work includes implementing the lessons learned mentioned throughout this text, but also deciding what payload to carry, improvements in control and software updates. These will again first be tested “at home” and then in steadily more difficult environments and more extensive and scenarios, future missions as the $2022$ ARCHES Demomission Space will follow.

May ARCHES, the Demomission Space $2022$, the Geological Mission II, the METERON Analog-1 mission, the Etna, the Scout rover and this text be inspiring and motivating to continue acquiring “Knowledge for Tomorrow”.

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