The DLR Moon-Mars Test Site for Robotic Planetary Exploration

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***Abstract*— Building robots for planetary exploration missions requires intensive testing throughout all phases of the design process. Especially, during hard- and software development as well as mission training the process benefits of easy-to-access test sites that offer realistic conditions. For this purpose we have built the 1500 m² DLR Moon-Mars test site in Oberpfaffenhofen, Germany. The facility provides a large variety of geological formations and ground substrates on a compact terrain as well as a rich set of power and network connections. As a unique feature of the outdoor test site, we prepared a dedicated link to the German Space Operations Center that enables telerobotic experiments from ISS. Furthermore, we provide an optical tracking system for ground truth measurement and control. We describe the design and construction process of the test site and present an overview of its features. Three experiments with our robots LRU1, LRU2 and the Scout rover regarding autonomous navigation and mapping, autonomous manipulation and sampling as well as advanced mobility tests demonstrate the usage of the test site.**

I. INTRODUCTION

Over the last decades, robotics has been an enabling technology for the exploration of our solar system. Well known examples are NASA's rovers Spirit and Opportunity [1] as well as their advanced successors Curiosity [2] and Perseverance [3] which delivered profound insight into the nature of Mars. The helicopter Ingenuity [4] completed its first flight in extremely thin Martian atmosphere in 2021, and thus demonstrated the potential of aerial robots for planetary exploration missions. Regarding challenging conditions, the German-French robotic asteroid scout MASCOT [5] collected invaluable scientific data of asteroid Ryugu as part of the Japanese mission Hayabusa 2. Due to its successful deployment within a micro-gravity environment, DLR and CNES obtained the opportunity to send rover Idefix [6], [7] in 2026 to the martian moon Phobos as part of the current Japanese Martian Moons Explorer mission.

Refocusing on Moon, space agencies and private companies currently plan to deploy mobile robots in scientific radio astronomy missions [8], as utility systems in support of astronauts [9], [10] and for prospecting and in-situ resource utilization at the lunar south pole region [11]. In all these scenarios robots are mission critical systems that provide mobility as well as manipulation and perception capabilities at an increasing degree of autonomy. Throughout the whole development process of robotic hard- and software as well as mission training, testing in relevant terrain is vital. Especially on mission level, tests in planetary analog sites [12], [13], [14] are a standard procedure. Some examples for geological Mars analog terrains are the Moroccan desert, the Utah desert as well as Spitzbergen while Mt. Etna in Sicily serves as Moon analog [13]. Testing at such remote locations requires high financial, personnel and logistics efforts. Therefore, at early and intermediate development stages, easy-to-access test sites are required that provide the necessary infrastructure for maintenance and repair of the robotic systems. The new DLR Moon-Mars test site for robotic planetary

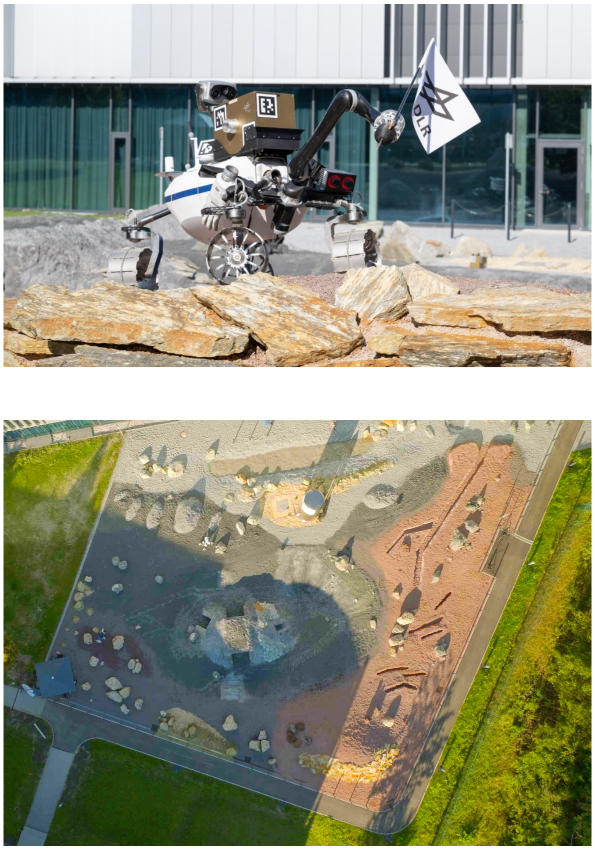

Fig. 1: DLR Moon-Mars test site at DLR-RMC in Oberpfaffenhofen, Germany: LRU2 autonomously places a DLR flag during the inauguration ceremony (top), birds eye view of the test site (bottom)

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exploration shown in Fig. 1 is such facility that provides a large number of geological features and ground substrates on a compact terrain as well as power and network connectivity, an optical ground truth measurement system and access to the workshops and infrastructure of DLR's Institute of Robotics and Mechatronics. With its design it complements our indoor labs as well as the mobility test bed of the Scout rover. One outstanding feature of this new test site is the dedicated fiber connection to the German Space Operations Center (GSOC) that allows to establish a bi-directional link to the International Space Station (ISS). In future, this link will enable telerobotic experiments in the test site similar to the successful Surface Avatar series of experiments [15], [16].

In the following, we give a brief overview of test sites for robotic planetary exploration and present the requirements for the new DLR Moon-Mars test site. We provide insight into the design and construction process, present the test site features and showcase first exemplary experiments with our robotic systems. We conclude with an outlook on future usage and developments.

II. OTHER TEST SITES

Throughout the world several space agencies, research labs and companies provide indoor and outdoor test sites to support the development, testing and verification process of planetary exploration robots. These test sites usually mimic a variety of relevant geological features of the target area of a future mission. Most indoor test sites have sand boxes that allow to perform basic mobility tests in loose soil. Examples are DLR's $55\,\mathrm{m}^2$ Planetary Exploration Lab (PEL) [17] with a $3\,\mathrm{m}$ x $5.5\,\mathrm{m}$ variable slope partition in Oberpfaffenhofen or the PTS Spacelab in Rostock, Germany. Larger indoor facilities are the $390\,\mathrm{m}^2$ Airbus Mars Yard in Stevenage, UK and the similar sized Mars Yard built by a consortium of Italian Space Agency ASI, ESA and industry at the Altec premises in Turin, Italy. The latter not only provides a large sandbox but also an $8\,\mathrm{m}$ x $8\,\mathrm{m}$ tilting platform to simulate slopes of up to $30°$. Figure 2 shows another interesting indoor test site, the LUNA analog facility [18], which is currently built in Cologne, Germany. This ESA and DLR joint venture comprises $700\,\mathrm{m}^2$ filled with EAC-1A lunar regolith simulant, a sloped area, a sun simulator and a gravity offloading system for astronaut training under reduced loading conditions. Meant for mission simulation it comprises several elements of a Moon station as well as a control center.

While indoor environments allow for year-round testing under controlled environmental conditions, outdoor test sites usually are more spacious and challenge the robustness of robotic systems due to natural changes of weather and lighting. A prominent example is JPL's $2000\,\mathrm{m}^2$ outdoor proving ground Mars Yard III [19] in Pasadena, USA, that hosts two siblings of Curiosity and Perseverance for testing and verification purposes. The ground substrate of Mars Yard III is a composition of beach sand and decomposed granite and volcanic cinders enriched with red and black basaltic rocks in Mars-like size and distribution. Seven variable angle and cohesion slopes further allow for climbing and mobility tests. Another outdoor test facility is the Mars Yard of the Canadian Space Agency [20] in St. Hubert, Canada. This $7200\,\mathrm{m}^2$ large test site is covered with sand and hosts 3 craters, 4 rock beds and 4 summits as well as a tunnel network. A European outdoor testing facility is the $4000\,\mathrm{m}^2$ SEROM Mars Yard [21] in Toulouse, France, that is operated by CNES. It is characterized by a rather flat surface covered with red lava gravel and rocks. Over the last years the European Rover Challenge hosted in Poland provides a yearly changing $35\,\mathrm{m}$ x $45\,\mathrm{m}$ outdoor Mars Yard [22]. The participating robots compete in navigation, sampling and maintenance tasks on this site that shows many geological features like craters, hills, tunnels, trenches and rock fields on a very compact terrain.

Fig. 2: Rendering of the regolith area of the ESA/DLR LUNA analog facility in Cologne, Germany

III. REQUIREMENTS AND FEATURES

Using two illustrative examples, we give a brief overview on the deduction of test site requirements based on use cases. We categorized all requirements in three major groups that are related to - *robotic system capabilities, mission scenarios* and *test site operations*.

In a first use case, we look at the exploration of craters in the search of volatiles. NASA, for example, has selected the illuminated rim of Shackleton crater at the lunar south pole as potential landing side for Artemis III [10]. China follows a similar plan when it chose the same region for its Chang'E-7 mission [23]. While the dimensions of the 21 km wide and 4 km deep Shackleton crater are by far out of bounds for any test site, we derived requirements for our crater with the following scenario - *On its search for volatiles a midsize robot (mass up to 150 kg) has to access a crater either along a moderate slope covered with loose material or along a steep rocky slope. The robot has to move to the bottom of the crater where it takes material samples. The robot has to return to its starting point.* Based on this use case and the available space in the test site we deducted the first eight requirements for the crater. We obtained the last three from considerations on test site operations:

1) The crater shall be $10\,\mathrm{m}$ wide and at least $2\,\mathrm{m}$ deep.
2) The crater bottom shall be at least $2\,\mathrm{m}$ wide.

Feature	Details
Size	$1500\,\mathrm{m}^2$
Elevations	$4\,\mathrm{m}$
Formations	crater, hill, tunnel, canyon, bumps, cracks, rough walls
Substrates	sand, breccia, gravel: basalt, lava, granite
Boulders	basalt, lava, granite, suevit, conglomerate
Tracking	optical tracking system - ground truth + control
Power	$230\,\mathrm{V}$, $400\,\mathrm{V}$ three phases
Connectivity	network access, Wifi, GSOC link
Control	from 2 outdoor spots and from indoor lab

TABLE I: Main features of the DLR Moon-Mars test site

3) The crater shall be accessible and traversable for wheeled and legged robots of up to $150\,\mathrm{kg}$.
4) The crater bottom shall be made of loose material.
5) The crater shall be placed next to a hill resulting in a total of $4\,\mathrm{m}$ height difference from top to bottom.
6) The crater shall have a $15°$ slope with loose material.
7) The crater shall have a $35°$ slope made of solid material with distributed rocks.
8) The crater shall be mostly covered with material of volcanic origin as geologically relevant parts of Moon and Mars are formed by lava flows.
9) Rain shall easily drain in the crater.
10) The crater shall be built to ease/reduce weeding.
11) The crater bottom shall be visible from a visitors area.

A second use case example is the robotic exploration of lunar lava tubes and skylights. *In this use case the robots access, explore and map lava tubes. They take material samples from the ground and the walls and rappel instruments and other equipment into skylights.* This scenario and the given spatial conditions result into the following requirements for the tunnel.:

1) The tunnel shall be $4\,\mathrm{m}$ long with an cross sectional area of $1.5\,\mathrm{m}$ x $1.5\,\mathrm{m}$.
2) The tunnel shall have two branches with smaller cross sectional areas of $1\,\mathrm{m}$ x $1\,\mathrm{m}$ and $0.5\,\mathrm{m}$ x $0.5\,\mathrm{m}$.
3) The tunnel branches shall be straight to simplify construction.
4) The tunnel walls shall have a rough surface.
5) The tunnel walls shall provide pockets at different heights to place material samples.
6) The tunnel branch with the smallest cross section shall exit into the crater.
7) The tunnel roof shall be accessible for humans and robots.
8) The largest tunnel shall be accessible from the tunnel roof.

Similar to the examples above, all desired terrain features and the related requirements have been derived from specific use cases as well as spatial and operational conditions. Table I briefly lists core terrain as well as technical equipment features of the test site.

IV. DESIGN AND REALIZATION

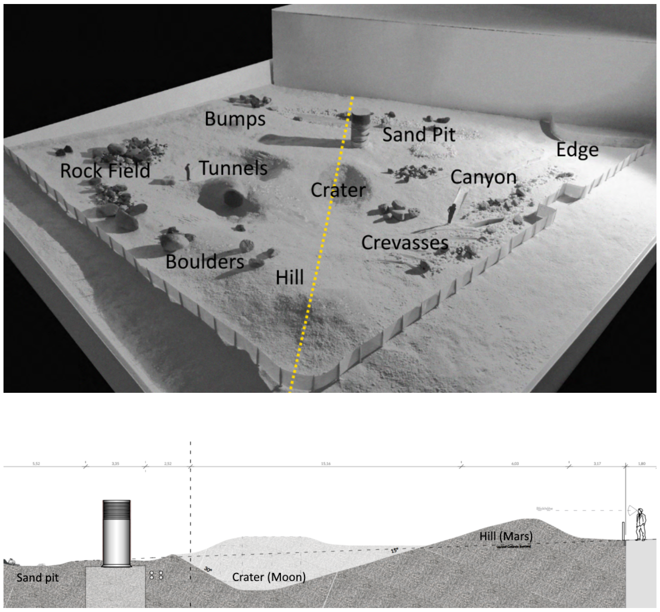

Fig. 3: Sand model of the DLR Moon-Mars test site with terrain features (top), cross section of the crater-hill area along the yellow line (bottom)

Based on our needs and requirements we went through an iterative design process. This process started with mood boards based on detailed landscape pictures from the Apollo missions [24] as well as photos from Mars taken by Curiosity and Perseverance [25]. Furthermore, we took a detailed look at several analog sites and special geological formations of interest. Our goal was to fit a large number of challenging formations and a broad variety of materials into the available $1500\,\mathrm{m}^2$. To accommodate both, Mars and Moon scenarios, we decided to split the test site into two sections, approximately two thirds Moon and one third Mars. At the center of the test site we placed a $2\,\mathrm{m}$ deep Moon crater with slopes varying from $15°$ to $35°$. Next to the crater we placed a $2\,\mathrm{m}$ high hill as shown in the bottom image of Fig. 3. The resulting $4\,\mathrm{m}$ height difference allowed us to integrate a $15°$ slope with loose material to allow for longer climbs. We decided to built the $35°$ slope with drainage concrete to simulate a rocky descent and to avoid a slide off of the slope. Right next to the crater we placed our $4\,\mathrm{m}$ long and $1.5\,\mathrm{m}$ wide tunnel as shown in Fig. 4. This tunnel has two branches, one $1\,\mathrm{m}$ wide and another $0.5\,\mathrm{m}$ wide that leads directly into the crater. The tunnel as well as the $0.5\,\mathrm{m}$ wide canyon and the crevasses have also been built of concrete for stability and persistence reasons. The concrete is colored in red and grey and contains large amounts of rocks and gravel aggregates. This custom making of the concrete allowed to give the walls a more natural surface finish and to integrate small pockets with dedicated materials for future sampling tests. Both the hill and the crater have a rugged side built of unevenly arranged gneiss flagstones. Throughout the whole test site we placed large lava, basalt, granite and conglomerate boulders as obstacles and targets for material sampling tests. We decided to cover the area mostly with gravel of different size and materials and avoided

Fig. 4: DLR Moon-Mars test site during the construction process (top), finished Moon-Mars Test Site (bottom)

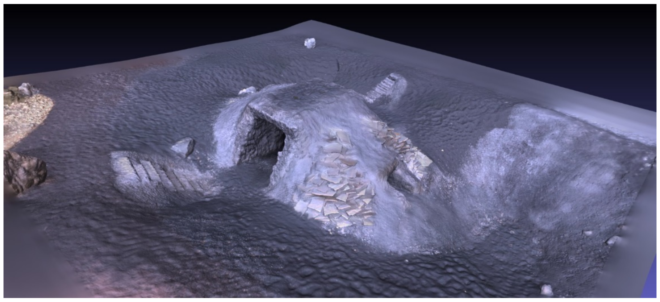

Fig. 5: Surface mesh of the tunnel and crater of the DLR Moon-Mars test site generated from a dense colored point cloud obtained with a Z+F FlexScan 22

fine sand and dust as found on Moon and Mars. This was a pragmatic choice to avoid dust being blown to the nearby car park and mud during rainy periods. For the Moon area we selected brown lava and basalt gravel as materials of volcanic origin and further added a larger area of light grey granite. While granite not appears on Moon it adds another kind of material with different properties to test perception and classification algorithms. Furthermore, we added patches of suevit and breccia from the impact crater Nördlinger Ries in Germany as an impactite with interesting material properties for scientific exploration scenarios. In the Mars area we used red granite since it was easily available from nearby sources and its color gives a Mars-like appearance. We added red and brown lava as gravel and boulders to include material of volcanic origin. All over the terrain we can further place samples of materials that are of interest for prospecting or science missions. Considering loose soils, we included a 16 m x 2 m sand patch for drilling and mobility tests that we placed in a slight depression to avoid that the sand is blown across the area. As we have integrated many distinct mobility challenges into the terrain we also designed several 200 m long and 2 m wide closed paths throughout the whole terrain that are easy to traverse for navigation and exploration tests. Several artificial composite material boulders of up to 2 m height, 3 m width and 60 kg mass allow to manually adapt the terrain and paths.

For operations, we included two specific areas as shown in Fig. 4, one close to the building at the entrance to our mobile robotics lab and the other at the opposite corner of the test site. These areas are level and each provides a cabinet with multiple power and network outlets. We prepared easy to use mobile operator desks that are quickly operational with a single network and power plug. Additionally, our test site wiring allows to operate the robots in the test site from our mobile robotics indoor lab as well as the space operations room of the institute. As a unique feature we implemented a direct link to the GSOC that technically enables experiments involving the ISS. To mount the ground truth measurement system as well as lights and other additional equipment we placed concrete foundations in each corner of the test site where we can attach vertical truss towers. On two sides of the Moon-Mars test site, a paved sidewalk allows easy access to the terrain and grants visitor a good view during tests. Along this way we placed a cable duct for cabling of additional equipment. The optical ground truth measurement system will allow tracking and real-time control of multiple robots with an accuracy of up to two millimeters in four dedicated tracking volumes and centimeter accuracy over the whole terrain. A 360° panorama view of our Moon-Mars test site is available on our website: https://rmc.dlr.de/360/. In order to prepare physical tests using simulations we create surface meshes of the Moon-Mars test site as shown in Fig. 5. These meshes are generated from dense colored point clouds that were obtained with support of Zoller+Fröhlich GmbH using their Z+F FlexScan 22 platform.

V. EXPERIMENTS

The following section presents three exemplary robotic experiments on autonomous navigation, autonomous sampling and rough terrain mobility that utilize the test site. A video of these experiments is available at: https://www.youtube.com/watch?v=8Fa8yqZA5TIt=1s.

A. *Navigation Experiment*

At first, we conducted autonomous navigation experiments in the Moon-Mars test site and used it to demonstrate the waypoint navigation and obstacle avoidance capabilities of our Lightweight Rover Units [26] during the inauguration ceremony. In Fig. 6, we show both rovers in operation during navigation and manipulation tasks. During navigation, the rovers build a 3D map of the environment online and onboard based on dense depth gathered via stereo cameras in their pan/tilt sensor heads. They classify the traversability of

Fig. 6: LRU1 and LRU2 during navigation and sampling experiments in the DLR Moon-Mars test site

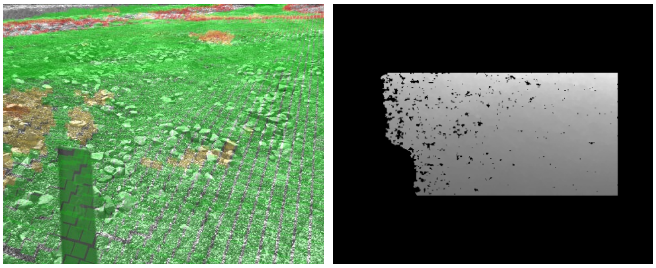

Fig. 7: Camera image with terrain traversability classification (left) and raw stereo depth image (right) as seen by the LRU1 during a navigation experiment.

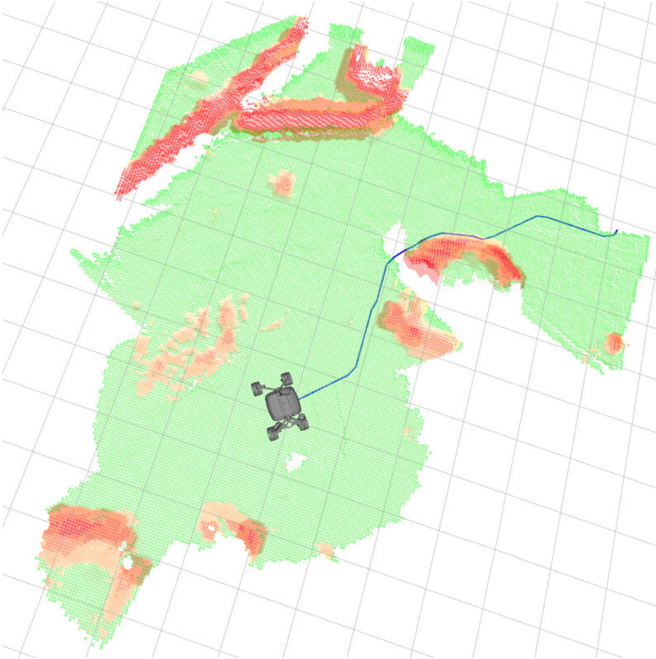

Fig. 8: Elevation map annotated with traversability classification and planned path (blue) for the LRU1 rover during a navigation experiment at the Moon-Mars outdoor test site. Green areas are easy to traverse, whereas yellow indicates slopes and small stones and red untraversable larger rocks as well as the steep slopes into canyons and craters.

the surrounding terrain based on steps and slopes detected in the stereo, see Fig. 7, and then plan a path around obstacles in the resulting map, see Fig. 8. Each rover localizes itself without the help of external global positioning systems, such as GPS, solely based on its on-board sensors via a fusion of visual odometry, wheel odometry, and inertial measurements. Sharing this data with other agents in a robotic team allows it to collaboratively create 3D maps of the environment and localize all agents therein, see [27], [28] for more details on our navigation and mapping methods.

During the test site opening demonstration, we successfully commanded the LRU1 rover to navigate back and forth between several waypoints, avoiding obstacles on its way such as the canyon and the large ventilation outlet shown in Fig. 6. So far, we used settings that caused the rover to avoid very challenging terrain. However, the large variety of features of the test site allows to gradually increase the difficulty for the locomotion skills of the robotic systems, and to set new challenges, for example to climb steep slopes, rappel into the crater, or traverse small ditches in the future. The test site also provides ideal conditions for setting up challenging scenarios to test autonomous exploration methods, such as [29], which we previously demonstrated with our rovers on the Volcano Mt. Etna [28]. Its dense collection of different terrains and environment features will also support ongoing research on semantic classification, mapping, and exploration, moving towards a more human-like understanding of the terrain features and their implications on navigation, mission-planning, and task-distribution in heterogeneous robotic teams.

B. Sampling Experiment

Next, we used the test site to perform an autonomous sampling experiment with LRU2 as the collection and analysis of samples is an important part of any scientific exploration mission on Moon and Mars. Since there are many different sampling scenarios, the manipulator of LRU2 allows to dock a variety of tools and end effectors to its integrated docking interface [30]. In our experiment, LRU2 employed a robotic hand to collect small stone samples as shown in Fig. 9.

All processes which steer the sampling operation run on the computation hardware of the rover system. Instructions from mission control are transmitted to the state-machine execution software RAFCON [31]. During the sampling process, the state-machine initiates a request to mission control to establish a connection via the sample selection interface. This interface interacts with a stone segmentation perception software. Once mission control identifies a stone and issues the corresponding request, the state-machine stores the selected stone from the sample selection interface. Prior to executing any movements, the environment modeller generates a model of the previously unknown portion of the scene as a voxel grid, using depth data from the stereo cameras. The depth data is further analyzed by a grasp planner to identify the correct grasp on the current stone. The state-machine then selects the optimal grasp candidate

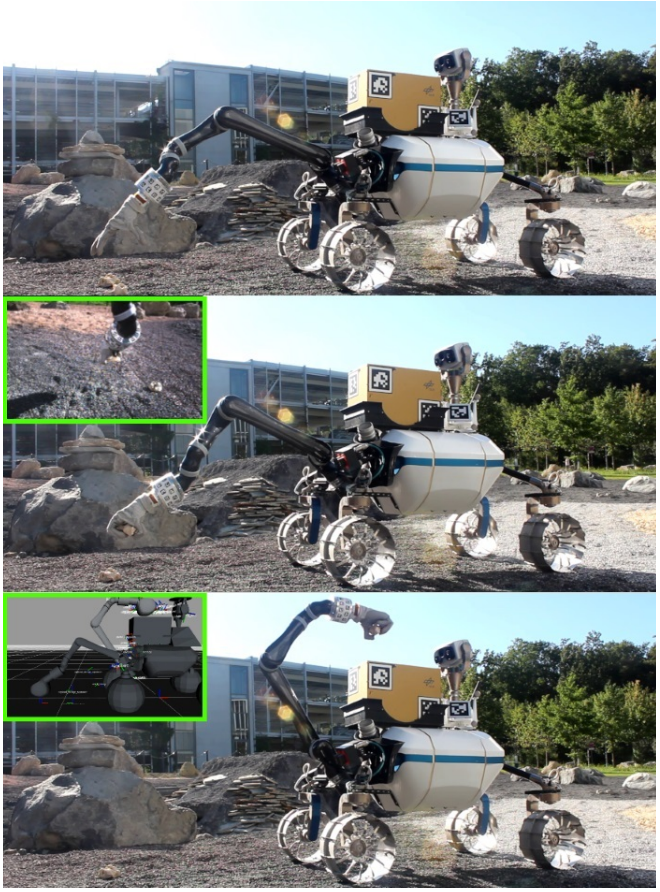

Fig. 9: LRU2 in the autonomous process of picking up a stone in the DLR Moon-Mars test site

and requests the motion planner to calculate safe manipulator motions. The state-machine forwards the computed motions to the manipulator controller, which guides the manipulator along the intended joint path. As the manipulator approaches a contact point, the state-machine switches the mode of the manipulator controller to impedance control, a mode that actively manages forces during contact. Once a defined contact is established, the state-machine triggers the hand to close and to grasp the stone. After grasping the stone, the manipulator transfers the stone to a payload box on the carrier of the rover.

As such a robotic system involves many software and hardware components, the test site will allow extensive testing of each single component as well as the whole autonomous sampling process to ensure reliability, functionality, and adaptability. Different ground substrates and varying lighting conditions will challenge the perception system, while the canyon, the crevasses and the rough side of the hill provide confined, hard-to-reach spaces for sample acquisition. Furthermore, taking samples in sloped or rough and broken terrain will require the use of whole body control algorithms that simultaneously control interaction forces at the end effector and the wheels.

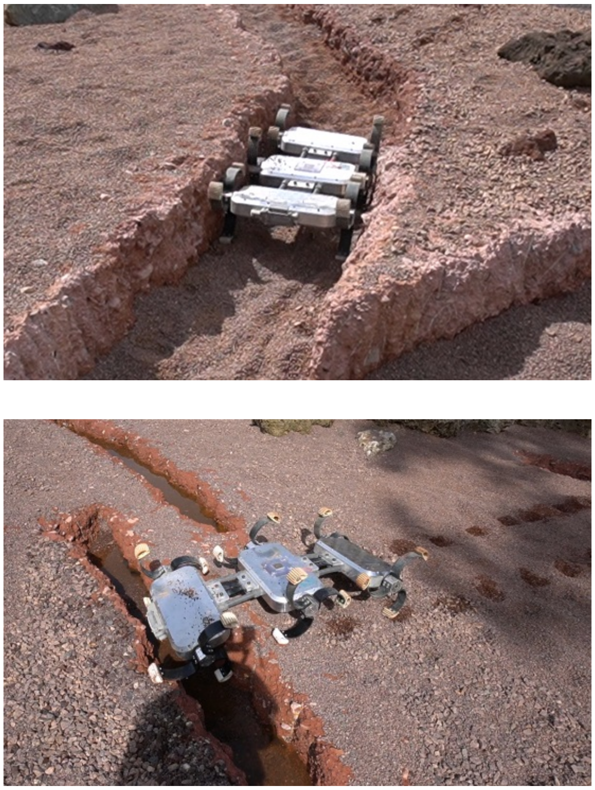

Fig. 10: DLR Scout rover following a narrow trench (top) and crossing a smaller one (bottom)

C. Mobility Tests

At last, we conducted first locomotion experiments with the Scout rover [32], [33] in the DLR Moon-Mars test site. Thereby, we used the terrain features as obstacles to test the terrain traversability of our robot. Searching for the most challenging parts of the test site, we identified several obstacle types:

1) small obstacles, where spokes could get stuck
2) large obstacles, where the rover could get trapped
3) slopes and steps, both up and down
4) tunnels and ”squeezes”

During the opening demonstration as well as the training beforehand we have been able to successfully traverse most of the obstacles. Namely, we have been able to traverse the trenches along their direction and orthogonal to it without further problems as shown in Fig. 10. In the larger trenches the Scout rover naturally lifts itself up and shifts its weight such that it even navigates corners in parts that are not wider than the rover itself. Crossing trenches in orthogonal direction we found that small trenches where capable of entrapping and damaging the spokes of the rover. However, breaking off single spokes is an intended behavior once a spoke got trapped. In future work, these trenches may be used to develop algorithms in order to detect entrapped spokes and omit breaking them by special movements. Crossing the larger trenches posed fairly easy, even though it might take a second attempt dependent on the rovers initial position and

Fig. 11: DLR Scout rover going down a steep descent (top) and is about to drop $2\,\mathrm{m}$ from the tunnel ceiling (bottom) into the DLR Moon-Mars test site

the depth of the trench. After few attempts an experienced operator was able to cross the trenches without problems.

A second set of obstacles have been rough ascents and descents as shown in the top of Fig. 11. While being quite safe to navigate upwards, i.e. the rover could stop at any given point, the navigation downwards poses special risks of falling and dropping. With the normal sloped and stepped obstacles we have not been able to provoke falls of the rover. It was possible to traverse the terrain safely and mostly controlled, despite smaller slipping downhill. Uphill, it was also possible to traverse most stepped obstacles and slopes, whereas the slopes with loose granular material were easier to traverse, while hard ground needed extra care from the operator. The only uphill obstacle not traversable over the full length has been the harsh assembly of gneiss flagstones next to the small tunnel. As a test for the robustness of the system we also drove up the tunnel obstacle and drove the rover over the edge of the higher side, which results in a $2\,\mathrm{m}$ drop. In any tested condition the rover flipped and was able to go on without any damage.

In terms of the traverse of the tunnel we have been challenged with the smallest tunnel that is exactly as wide as the rover and smaller in some areas as shown in Fig. 12. Nonetheless, the rover was able to shift itself up and down due to its modular and compliant design and traversed even the smallest tunnel with ease. During these tests we found, that stiffer back-bone plates perform better in narrow spaces.

Fig. 12: DLR Scout rover successfully traverses the smallest tunnel in the DLR Moon-Mars test site

As an outlook, we will further improve the control of the Scout rover in order to tackle the last missing uphill stepped obstacles and will work on autonomous locomotion of the system over all the obstacles within the upcoming years.

VI. CONCLUSION

With our Moon-Mars test site we have built a compact, easy-to-access test ground to support the development of planetary exploration robots that provides a rich set of terrain features and ground substrates, an optical tracking system as well as a link to the German Space Operations Center. We gave a brief overview of its design and demonstrated its first use by three experiments with our robotic systems. In the future, we want to establish our test site in the community and plan to provide access for testing to universities, research labs, and industry. We currently create a terrain model of the test site that can be used with simulators to test and train algorithms in preparation of on-site experiments. Furthermore, we work on the definition of benchmark scenarios to compare capabilities of different robotic systems with regard to relevant future missions scenarios.

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