FIELD TESTING OF A COOPERATIVE MULTI-ROBOT SAMPLE RETURN MISSION IN MARS ANALOGUE ENVIRONMENT

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ABSTRACT

This paper presents the evaluation of a heterogeneous robotic team for planetary exploration purposes. An extensive test campaign with a duration of four weeks was conducted in October/November 2016 in the desert of Utah, USA. The employed robotic systems were tested on natural and unstructured Mars analogue terrain and remotely operated from a control station in Bremen, Germany. The paper details the performed system tests as well as the conducted cooperative mission sequences in the scope of a sample return mission. Furthermore, the planning and preparation of the field trial campaign as well as the infrastructure set-up in Utah and Bremen and the test execution are presented with regard to lessons learned in the field and at the control center in Bremen.

Key words: Mars Rover, Field Trial, Robot Team, Modularity.

Figure 1. The employed systems in the field trials: Hybrid wheeled-leg rover SherpaTT (left, with modular sampling tool attached to the manipulator arm), Coyote III (center background and inset, with modular manipulator arm SIMA) and BaseCamp (right, with attached sample container)

1. INTRODUCTION

Mars is the most attractive planet within our solar system for human exploration, providing an atmosphere, moderate temperatures and is in general similar to Earth. Currently, geological and biological robotic exploration is of main interest for gathering knowledge on the history of Mars and possible former or present life on Mars.

In the future, more sophisticated and complex mission scenarios are envisaged for Mars exploration as it is one of the main targets announced by NASA and ESA [1, 2]. Ranging from robotic exploration over sample return to human exploration missions, including the potential set-up of support infrastructure, a need arises for highly capable robotic systems to meet the requirements. One approach to tackle these challenges is to introduce a multi-robotic team in contrast to the common single system set-up, e.g. for sample acquisition and return [3] and/or to increase the overall safety, speed and exploration range of robotic systems [4]. In order to test such systems against their suitability for Mars exploration, field tests provide a good way to deploy the systems in natural analogue environments along with the whole mission command and control architecture [5].

Geological sampling and sample-return might be conducted by a multi-robot team where single units are specialized on taking samples from various locations or fetching stored sample containers to transfer them to a return stage for sending the samples back to Earth. Such a scenario was tested in a four week field trial, as described in this paper. For the experiments, the TransTerrA system [6] was deployed in the desert of Utah during October and November 2016. Fig. 1 displays the systems in the test environment. The multi-robot system is composed of (i) the main exploration and sampling rover SherpaTT, (ii) the shuttle/scout system Coyote III, equipped with (iii) the modular manipulator arm SIMA, (iv) various modular payload-items (PLIs) for sample collection, storage and transfer, (v) a BaseCamp with five docking bays for the PLIs, additionally, a (vi) “Ground Control Station” in Bremen, Germany was used to control the execution of the mission sequence via a satellite link.

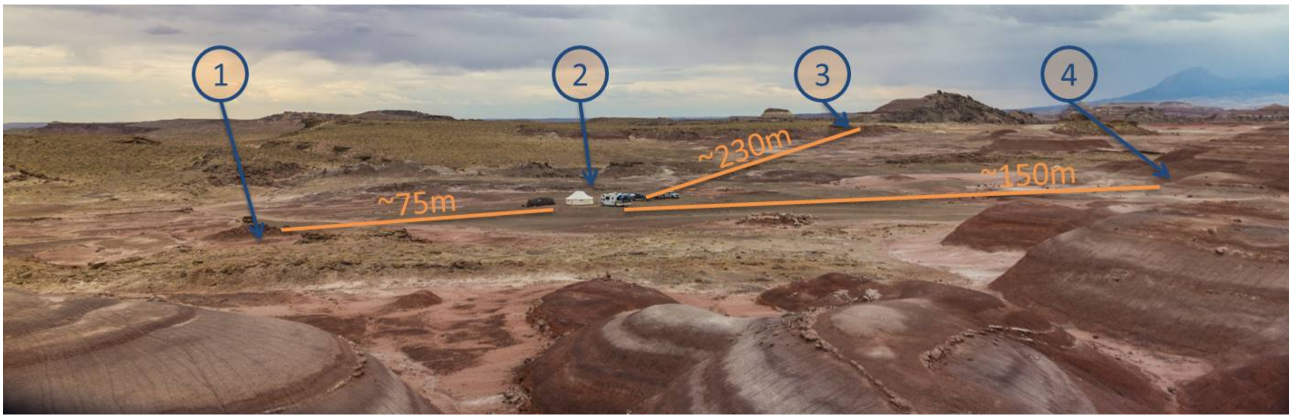


Figure 2. Overview on the testing area with indications of main test spots and distances. (1) The testing area for the mission sequence, see also Figure 9, (2) The camp with materials tent, working tent for repair and local mission control (3) Spot for cliff exploration (4) Slope climbing with SherpaTT and Coyote III

2. TEST SITE AND INFRASTRUCTURE

The test site for the field trials is located near Hanksville in Utah, USA, at 38° 24' 46.141" N and 110° 47' 1.118" W. The landscape represents a Mars analogue environment as described in [7, 8] and is marked by vast plains, rocky hill formations and mesas as shown in Fig. 3. The landscape was formed due to erosion, leaving inverted river beds with steep slopes and fluvial channels formed by clay-rich soils and sandstone. Similar formations were found on Mars and are of high interest for further exploration. The test site presents a wide variety of soils and slopes, ranging from flat terrain to steep slopes with inclinations of over 50° and even cliffs with overhangs. Firm clay-based soils as well as gravel and very loose sandy soils are present in the plain. Different slopes with unstructured rocky terrain, layered sandstone as bed-rock and duricrust are within the vicinity of the test site (cf. Fig. 5). Due to its analogue features other test campaigns have been conducted at the test site by the Canadian Space Agency (CSA) in 2015 and 2016 [8, 9] and the UK Space Agency (UKSA) in 2016 [10, 11].

As no infrastructure was available at the test site, a base station was set-up in the desert. The core elements of the base station were a materials tent, a working tent and a caravan, as shown in Fig. 2. The materials tent with approximately 20 m^2 was mainly used as storage space for equipment boxes and robot transport cases. The working tent with approximately 30 m^2 was used for local mission control and system maintenance. The tent was equipped with a local control station, as well as a small electromechanical workshop for in-field repair of the systems. Moreover, all robotic systems were placed in the tent and the tent was heated by two fan heaters during night. This precaution was taken, to avoid water condensation due to a temperature drop and to keep sensitive electronic parts as well as the robot batteries above 0° C during the night. The base station was completed by a caravan, which was mainly used as sleeping place for the night crew. Furthermore, it served as food and water storage and was used as gathering and working place with reduced wind and dust pollution.

Figure 3. Overview of the main testing area with SherpaTT in the foreground and inverted river beds in the background

The power supply was realized with three independent systems. These were two fuel driven power generators as well as a solar array. A coupling of these systems to a stand-alone power station was not realized. The working tent was connected to a solar array bench, consisting of five 100 W solar arrays which were connected to a 12 V secondary battery for energy storage and a voltage converter providing 230 V. The power generated by the solar arrays was e.g. used to recharge the batteries of laptops, walkie-talkies, cameras and portable floodlights. Furthermore, the working tent was equipped with LED based illumination tubes, which ran on solar power. In addition a 100 W solar array in combination with a secondary battery was used to provide the power for a transportable communication relay link in the field. The two power generators were mainly used stationary at the base station. They provided the power for the local control station as well as additionally needed laboratory power supply.

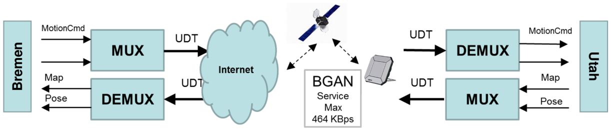


Figure 4. Schematic representation of the established satellite communication link between the test site in Utah, USA and Mission Control in Bremen, Germany

For robot communication in the field a local WiFi-based communication mesh was established enabling the robotic team to operate independently of a central access point. All robotic systems, the local control station and the remote control station were linked through this mesh. Each of the participating nodes served also as communication relay, resulting in an extended communication coverage in the field. To communicate with the mission control in Bremen an Inmarsat/BGAN satellite modem was used, providing up to 464 kbps of bandwidth. The satellite modem was connected via Ethernet to the local control station which managed the exchange of telemetry data and commands between the control station in Bremen and the robots in the field. A schematic diagram of the communication link architecture is shown in Fig. 4.

3. ROBOTIC SYSTEMS

This section provides an overview on the mobile and immobile robotic systems involved in the field trials. Both mobile systems are shown in Fig. 5. The mission control is described in Section 5.

3.1. Exploration Rover SherpaTT

SherpaTT is a rover of about 150 kg mass with a hybrid wheeled-leg actively articulated suspension system [12]. With its suspension, the system is able to actively adapt to irregular, natural terrain and slopes. Each of the four legs that constitute the suspension has a total of five active Degree of Freedom (DoF). Apart from its four legs forming the suspension, the rover features a 6 DoF manipulation arm. As part of the modular multi-robot system, the rover is equipped with six electro-mechanical interfaces (EMIs) [13], four passive interfaces are mounted around the central manipulation tower, an active interface is used as end-effector of the manipulator for grasping the passive counterpart on any other modular payload or mobile system. A second active interface is mounted beneath the rover's main body structure, mainly for transporting and deploying a BaseCamp (see Section 3.4).

A rotating lidar sensor is used for generating point clouds of the environment which are transformed into Multi-Level Surface (MLS) and traversability maps. The lidar is mounted on the manipulator tower such that it rotates with the first joint of the arm. This configuration allows the sensor to be mounted on top of the rover where it can provide the best environment data while at the same time a rotation of the sensor/manipulator allows full view around the rover without occlusion by the arm structure.

Figure 5. SherpaTT during a single system test concerning slope driving capabilities (top) and Coyote III in preparational tests for cliff exploration scenarios (bottom)

3.2. Shuttle and Scout System Coyote III with SIMA manipulation arm

Designed as a micro rover with a mass of approximately 15 kg Coyote III is considerably smaller than its teammate SherpaTT. By use of four directly driven hybrid legged-wheels on a passive chassis the rover gains a high mobility performance in unstructured terrain and steep slopes as can be seen in Fig. 5. Equipped with its own power source, computer and on-board sensor suite, including a laser range finder and a camera, Coyote III is able to perform autonomous exploration tasks. The communication subsystem allows to cooperate with other systems, such as SherpaTT.

Coyote III is equipped with two passive EMIs and its own payload management system, allowing to dock additional payload elements such as PLI to the rover. Due to the lightweight and robust structural design of Coyote III, it is possible to apply several kilograms of additional payload to the rover. In this way, Coyote III can not only act as a scouting system for SherpaTT but as a support system by transporting PLIs and providing shuttle services. In order to handle the PLI, e.g. for deployment, Coyote III can be equipped with the SIMA module. SIMA is a full 5 DoF manipulator arm which is equipped with two active EMIs. The arm can be docked as additional payload to one of Coyote III's payload bays. Fig. 10 shows Coyote III with attached manipulator arm during rendezvous with SherpaTT. Both systems, Coyote III and the manipulation arm SIMA are described in more detail in [14].

3.3. Modular Payload-Items

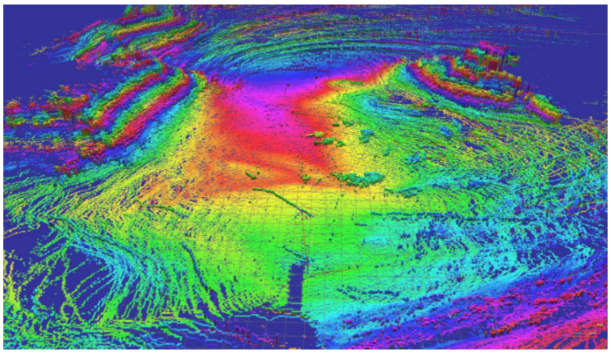
Modular payload-items in the sense of the system presented here are cubic modules with an edge length of 15 cm. Each PLI has a passive EMI on the top and an active EMI on the bottom face of the cube [13]. A PLI can generally contain any payload needed for a specific mission purpose, PLIs with a height of more or less than 15 cm are possible, for ground truth, a D-GPS (differential GPS) system was integrated in a PLI and used in the field trials in Utah.

For the mission sequence during the field trials, battery and sampling modules were implemented. A battery module can be used to power any system (mobile and immobile) via the connecting EMIs of each subsystem, a battery module is typically integrated in a standard (15×15×15cm) cube. The sampling module features a retractable shovel, simulating a sealing of a sample within the sample container and is also integrated into a standard cube. For taking a soil sample, the module is attached to SherpaTT's manipulation arm (as depicted in Fig. 1), pulled over loose soil and than closed by retracting the shovel.

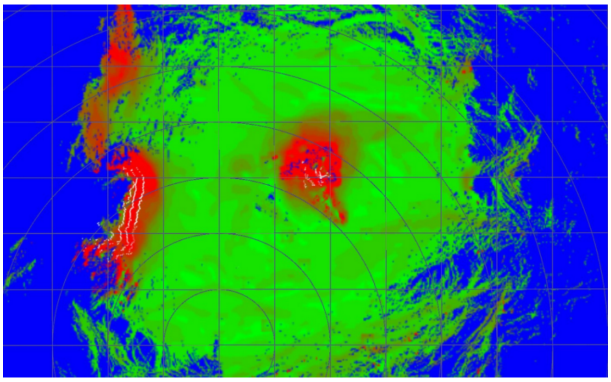
3.4. BaseCamp

A BaseCamp is a special type of immobile payload. It has roughly the size of five standard PLIs arranged in a cross-like manner with one PLI in the center and the remaining four PLIs attached to each side of the central cube, a deployed BaseCamp can be seen Fig. 1.

A BaseCamp is transported by SherpaTT via the EMI located in the central body's ground plate. By lowering the rover's body and releasing the mechanical connection by opening the EMI's latch, the BaseCamp can be deployed on the ground. It can however, be handled by SherpaTT's manipulator as well, as it uses the same EMI. Main tasks for the BaseCamp are (i) to act as a communication relay for the mobile units, and (ii) to provide a sample/battery cache. In later development stages, the BaseCamp might be equipped with solar panels in order to be able to recharge battery modules.



(a) Multi Level Surface (MSL) Map. Color indicates height, color cycle repeats each 1 m in height



(b) Traversability Map. Red is not traversable, green areas are possible to be navigated through.

Figure 6. SLAM-based maps as created by the rovers at the Utah test site

4. SOFTWARE DESIGN

Establishing a common platform for autonomy for a distributed, heterogeneous and reconfigurable team of robots has been the major driver of the software design. The key requirements were autonomous navigation in unknown environment including a distributed mapping approach, manipulation capabilities, and establishing a general decentralized infrastructure to allow for reconfigurability.

As a baseline for all robotic systems the Robot Construction Kit (Rock) [15] has been used in order to support a modular development approach. The high modularity of the software components allows high reusability for the heterogeneous team of robots, so that for example the mapping infrastructure can be designed generically. In this context, the field test served also as evaluation of a Debian-based binary package distribution which was used for a common set of packages on all robotic systems.

The starting point of autonomous operations has been the consistent creation of a shared environment representation. The robots used throughout the field testing comprise different set of sensors which might result in distinct environment representations when operated standalone. However, to enable rendezvous maneuvers for reconfiguration a consistent shared environment representation on each of the robots has to be created. This has been achieved by operating the team of robots as a sensor network, and sharing pointcloud data among all navigating robots; the communication mesh was used in combination with a distributed communication architecture to multicast sensor data (cf. [16] for further details).

To plan a path to an exploration or rendezvous target, the environment map is converted by each robot into a robot specific traversability map, Fig. 6. This traversability map is synchronized with new environment information in regular intervals and updates trigger a replanning of the path. Hence, obstacles can be avoided without a highly reactive layer, but based on the assumption of a low dynamic environment. Both navigating robots use the same mapping software infrastructure, though require an individual parameter tuning to deal with sensor characteristics.

5. MISSION CONTROL

For the control of the mission and for interfacing with the robotic systems in Utah via satellite link a ground control station (GCS) was developed. It makes use of a 3D virtual control environment, i.e., a Cave Automatic Virtual Environment (CAVE) running the custom simulation software "Machina Arte Robotum Simulans" (MARS) [17]. Hence, the robots were displayed by means of close to realistic physical simulations of the real robots in a map generated from their sensors' input. In comparison to video live feed, a generated map displayed in virtual environment is especially advantageous for steering robots under visually challenging conditions like sandstorms.

In addition to showing the robots' pose in the virtual environment, a graphical user interface was needed to display additional data and especially to send commands to the robots. The operator was able to set waypoints, request a camera image, a pose update or a map update, stop the robot or set the update rate for automatically sending telemetry data. A direct control mode was implemented to control SherpaTT's manipulator arm. The map as well as widget-based icons for control are optimized in appearance to minimize load on the operator. For this design optimization, online as well as offline EEG analysis was performed, [18]. Fig. 7 gives an overview of the mission control facility.

The telemetry for Bremen was collected in Utah by a single control station. After the robot telemetry was collected using the native, CORBA-based communication of the Rock framework [15], the samples were multiplexed into a single data package. The resulting telemetry container package was compressed and sent to Bremen via satellite using the UDT protocol [19]. UDT was able to handle conditions with ping times of up to 22 seconds without suffering package loss. The control station in Utah ran an HTTP-based API server to control

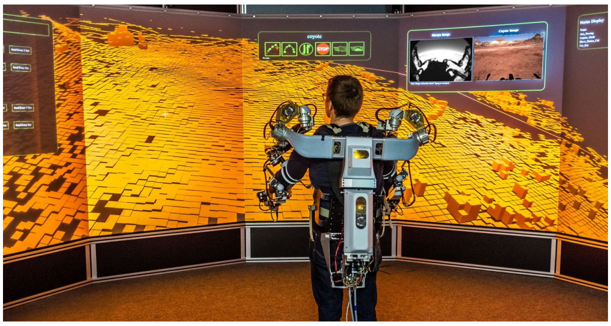


Figure 7. Mission control in Bremen using an exoskeleton. The operator is in the center of a multi-projection area ("CAVE"), in the image a 3D environment representation generated from SherpaTT in Utah (yellow tiles) and nav-cam images of SherpaTT and Coyote III are shown (top right)

the telemetry contents and data intervals to be included in packages sent to Bremen.

To control the robots, the CAPIO exoskeleton [20] or a wand was used as an input device. The wand was tracked by an inertial-ultrasonic hybrid tracking device. It was mainly used to set waypoints for the robots and to change the virtual camera by rotating, zooming and translating. The exoskeleton could be used for this as well but was further used to intuitively control SherpaTT's arm in manipulation tasks while providing force feedback. Therefor the exoskeleton is equipped with seven active DoF at each arm and a multi-input hand-interface. It provides two tele-operation modes. In case of exploration the exoskeleton uses the virtual environment in order to control the virtual cursor and therefore choose a robot, send way points, update and navigate the map and request photos from a rover, as shown in Fig. 7. In case of manipulation mode the operator controls SherpaTT's manipulator with the right exoskeleton arm and can request a force feedback. The usage of the exoskeleton enables the operator to interact with the robot in a natural, intuitive and haptic way. This could be shown over a distance of 8.300 km with performance restricted by the lack of bandwidth due to the chosen communication. The field test showed the applicability of an exoskeleton over a large distance and supports its usage during extraterrestrial exploration and manipulation.

6. SYSTEM TESTS AND MISSION SEQUENCE

The field trial campaign was based on a three layered system evaluation: (i) single system tests concerning locomotion capabilities and performance parameters, (ii) single system tests concerning autonomy and cooperative tasks and (iii) full system test in a simulated mission scenario with the primary focus on the execution of a semi-autonomous sample return mission sequence, including all robotic systems as previously described.

Table 1. Slope inclination profile for slope tests

Distance [m]	0-1	1-2	2-3	3-4	4-5	5-6
Inclination	9.5°	10°	10°	11°	15°	16°
Distance [m]	6-7	7-8	8-9	9-10	10-11	11-12
Inclination	28°	22°	25°	28°	28°	20°
Distance [m]	12-13	13-14	14-15	15-16	16-17	17-18
Inclination	20°	15°	10°	10°	0°	0°

The following paragraphs present an overview of the conducted tests. A detailed description of the experiments and outcomes is, however, beyond the scope of this paper. Further publications are currently prepared, elaborating in detail on the experiments and their results.

6.1. SherpaTT and Coyote III Single System Tests

Prior to the mission scenario several single system tests regarding locomotion and autonomous behavior were conducted with SherpaTT and Coyote III. Both systems performed odometry tests after their deployment. The tests were performed on flat and relatively firm terrain. The tests were used to assess (i) the wheel based odometry of the systems as well as (ii) the influence of the implemented trajectory followers and the active ground adaption of SherpaTT on the quality of the odometry performance.

During slope tests both systems showed their climbing capability. Both systems performed a test series on a slope with a varying inclination profile as given in Tab. 1 and shown in Fig. 5 (top). The slope was covered by loose soil and thin duricrust. SherpaTT mastered the slope with up to 28° inclination in upward and downward direction. Further successful test drives have been performed with Coyote III on slopes with duricrust at inclinations of up to 42° and up to 32° inclined slopes with bed-rock.

Furthermore, different general mobility tests were performed with SherpaTT, especially to evaluate the active suspension system. These tests included the active force leveling (load sharing of wheels) with different foot prints (suspension system configurations) in flat terrain and moderate slopes as well as the evaluation of active roll/pitch adaption. With Coyote III a general mobility assessment was performed with regard to static and dynamic stability, driving over steps and tranches as well as on very unstructured terrain. Additionally, different cliff driving tests have been performed to assess the behavior of Coyote III in precipitous slopes as shown in Fig. 5 (bottom).

In preparation for the cooperative mission sequence, both systems were first put to single autonomous operations tests and later on tested in a cooperative manner. These tests were used to test and tune the self localization and mapping (SLAM) capabilities of the systems (see Fig. 6), as well as to perform and evaluate autonomous operations, such as path planning, obstacle avoidance and autonomous waypoint based navigation.

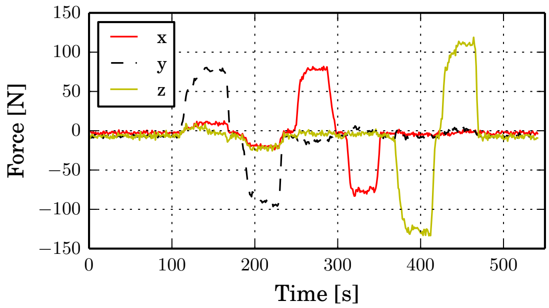


Figure 8. Measured forces at SherpaTT's end effector

6.2. Manipulator Control with an Exoskeleton

The CAPIO exoskeleton was used as input device for SherpaTT's manipulator. In this mode the Cartesian position of the exoskeleton's end effector was up scaled and transferred from Bremen to Utah on SherpaTT's manipulator.

Vice versa the exoskeleton was used as output device to the human operator. In order to gain initial experiences under the given circumstances, the first force feedback test was done with prerecorded data from the test side. Following this pretest the experiment was repeated successfully with the entire communication chain and live data. A human pushed and twisted SherpaTT's manipulator in orthogonal directions generating forces and torques. An example of the measured and transferred data is depicted in Fig. 8.

The measured data where then downscaled by a factor of 10 and applied as force-torque-vector to the end effector. The distribution of the joint torques at the exoskeleton is calculated by the RBDL-library [21]. Thereby the exoskeleton triggered a forced movement of the operator. Further work will focus on the employment of the force feedback on the soil sample process.

6.3. Mission Sequence

In the demonstrated mission sequence, SherpaTT acted as exploration and sample acquisition rover. Coyote III took the role of a scout and shuttle rover, supposed to collect sample containers and to transport them back to a fictional sample return stage. An overview of the area of operations is given in Fig. 9, highlighting the key waypoints of both systems and their approximate traversal.

The mission's command and control was based in the GCS located in Bremen. All steps of the mission were controlled from the GCS in Bremen by operators with no direct knowledge of the area of operations [22]. The operator used the exoskeleton to request a three dimensional map of the environment and to order photos from the camera of both rovers. The mission control in Bremen commanded the systems to target waypoints, where

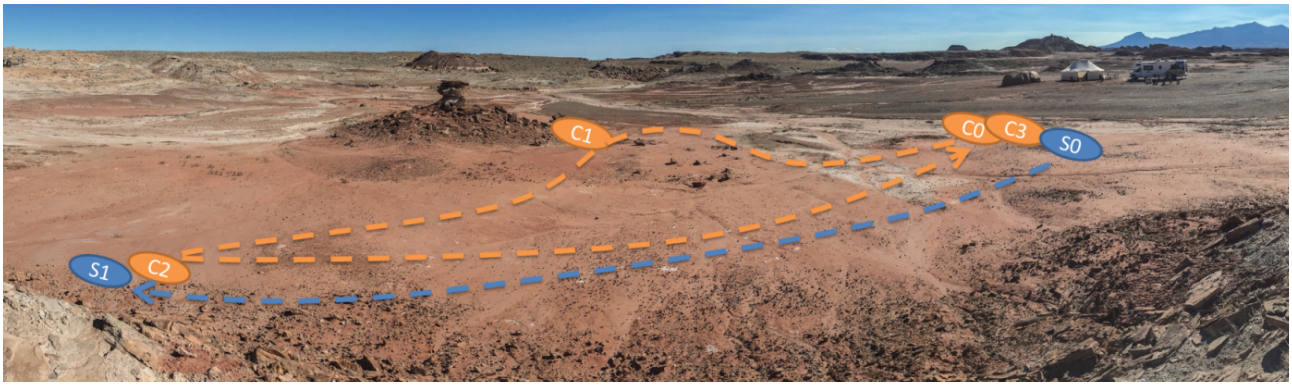


Figure 9. Mission sequence with waypoints for SherpaTT (blue) and Coyote III (orange). Both systems had a rendezvous at S1/C2. Panoramic image stitched from single pictures.

Figure 10. Rendezvous of SherpaTT and Coyote III during the mission sequence. Coyote III's manipulation arm SIMA is in a pose to give room for transfer of the sample container.

each of the waypoints was associated with an assumed (but not performed during the test sequence) activity such as soil sampling or robot rendezvous. Rovers were navigating autonomously to all waypoints by relying on the distributed mapping approach described in Section 4 and planning a path through known, traversable terrain. Successive updates of the environment map and image data improved the operator's situational awareness for the remote area.

While SherpaTT started directly off to its sampling point S1, Coyote III was heading towards C1 for scouting. Due to this maneuver SherpaTT could not be seen by the operator on Coyote III's camera any longer and was operating outside the mapping area of SherpaTT. Simultaneously to the scouting operation of Coyote III SherpaTT's manipulator was remotely controlled by an operator in Bremen, using the exoskeleton to simulate soil sampling actions. Thereafter, Coyote III and SherpaTT met up for a rendezvous at S1/C2 for payload hand-over simulation. After the rendezvous of both rovers Coyote III drove autonomously back to its starting point by a manually given goal way point.

The actual soil sampling process as well as the payload exchange were not included in the mission sequence controlled from Bremen but have been performed by SherpaTT and Coyote III in previous cooperative tests. Soil sampling, using a modified PLI, could successfully be demonstrated by SherpaTT, as well as a payload hand over from SherpaTT to Coyote III during a rendezvous as shown in Fig. 10. The PLI was than transported to its goal destination by Coyote III and deployed using the SIMA module.

7. LESSONS LEARNED, CONCLUSION AND OUTLOOK

During the field test campaign described in this paper, single system and cooperative multi-robot system tests were conducted. The single system tests were focused on the locomotion capabilities of both deployed mobile systems, while the multi-robot scenario explored the capabilities concerning cooperative mapping, rendezvous and handover of sample containers between the two systems.

In the locomotion experiments, the exploration rover SherpaTT was able to climb slopes of up to 28° covered in soft soil/duricrust, while the shuttle and scouting rover Coyote III was tested in slopes of up to 52°, successfully managing slopes of 42°. Additionally, vertical cliff walls and overhangs were negotiated with Coyote III where a human simulated a tether management system. Experiences from these tests are going to be exploited for future developments with a robotic tether management system, mounted on SherpaTT or with an new type of PLI with an anchoring and cable winch mechanism. Both systems showed a very high mobility performance in natural and unstructured terrain, mastering various obstacles.

In preparation for a sample return mission sequence, both rover were taken through thorough tests, regarding their sensor calibration and autonomous behavior. Both systems were independently able to perform autonomous go to goal way point navigation while mapping their environment, using a graph-based SLAM approach. In order to allow cooperative tasks and perform rendezvous maneuvers, a distributed mapping approach was successfully tested with both systems, enabling to merge the independently generated maps into a consistent global map.

All key aspects of a sample return mission sequence have been demonstrated by the heterogeneous robot-team during the field trials. The soil sampling task has been conducted by SherpaTT, using a specifically equipped PLI. The soil sampling device could successfully be docked and deployed by SherpaTT's manipulator. Autonomous docking by using visual odometry and handling of the PLI could be demonstrated in natural terrain with representative lightning conditions. Both rovers were applied in a closed mission sequence which was controlled from a ground station in Bremen, Germany. The control station was equipped with a multi-projection area and a dual-arm upper body exoskeleton to perform the mission execution. It proved to provide a good mission overview and situational awareness, allowing to perform complex multi-robot mission sequences. For a smooth mission operation, a clear role allocation among the operational staff proved to be very helpful. A stable communication link between mission control and the robots in the field is, however, an important prerequisite.

Overall important insights and results could be gathered during the field trails regarding the robustness and mobility of the systems as well as their autonomous and cooperative behavior for exploration in naturally unstructured terrain. The results of the field trial campaign will be further investigated and serve as additional input for the TransTerrA project. The gathered results, know-how and impressions will further drive the improvement of all involved systems and may lead to follow up analogue test campaigns in the future.

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