Modular Payload-Items for Payload-assembly and System Enhancement for Future Planetary Missions

Wiebke Brinkmann, Florian Cordes, Thomas M. Roehr,
Leif Christensen, Tobias Stark, Roland U. Sonsalla,
Roman Szczuka, Niklas A. Mulsow, Daniel Kuehn
Robotics Innovation Center
DFKI GmbH
Robert-Hooke Strasse 1
28359 Bremen, Germany
firstname.lastname@dfki.de

Abstract—**This paper describes the development and verification of immobile modular compatible and combinable payload-items, which can serve as multi-purpose containers in future robotic missions. The core payload-item is a cube-shaped container (154 mm x 154 mm x 154 mm) with a rigid internal frame with easily detachable side panels; its main features are two electromechanical interfaces (EMIs), one on the top and one on the bottom. Several payload-items were developed to realize an adaption of the robots according to mission requirements; a battery module in order to extend the power capacity of robots and/or to allow the creation of standalone sensor modules, a camera assembly for observation purposes, a DGPS module to provide a high precision positional reference sensor (in earth bound test scenarios), and a device for collecting soil samples. Along with the design and development of the payload-items and the associated modules, this paper presents the conducted tests and experiments in laboratory and field environments, deploying the integrated modules with the rover systems. The lessons learned as based on these experiments are given within the paper as well as an outlook to further developments and utilization of the modular payload-items.**

TABLE OF CONTENTS

1. INTRODUCTION

On Mars the Valles Marineris is a landscape created from past volcanic activity, furthermore references to water resources are extremely promising for a variety of scientific issues[1]. With an up to 7 km deep jagged rift valley, the Valles Marineris places high demands on robotic exploration missions. In particular, areas which are difficult t o access have to be included in the exploration as these promise to assemble a comprehensive picture of Valles Marineris and potential niches for extraterrestrial life. Due to the versatility and spaciousness of the terrain, special requirements apply to the robotic systems. To explore such areas, a heterogeneous team of reconfigurable robots, as schematically shown in Fig. 1, seems to be one of the most promising approaches.

Introducing modularity and reconfigurability to robotic systems offers the possibility to carry out many-faceted missions and, if necessary, react to previously unknown states [2]. In addition, modularization leads to an increased robot resilience by allowing to exchange unnecessary modules for special missions or even replacing defective components, consequently realizing self-repair mechanisms up to a certain degree.

Developments in the field of satellite technology show that it is quite possible to use modularity in space applications.

The intelligent building blocks for on-orbit satellite servicing (iBOSS) [3] are composed of components that are homogeneous and near-homogenous in shape and function, and whose physical arrangement can be reconfigured. The Reconfigurable Space System (RSS) realizes sustainable space system through orbital reconfiguration and recycle of space infrastructure. CellSat, designed for the RSS, consists of many cells, which can be assembled and reconfigured by a space robot [4]. The Modular Rapidly Manufactured Small Satellite (MRMSS) project applies modular building block systems to space applications. The need to reduce mass for spaceflight applications and to reuse resources are critical requirements needed for long duration space missions. The MRMSS project consist of two major components: a basic research component demonstrating electronic materials, and a technology demonstration applying the modular building block based systems concept to the CubeSat form factor [5].

CubeSat is a developed standard for design of picosatellites to reduce cost and development time, increase accessibility to space, and sustain frequent launches. Its basic dimension is 100 mm x 100 mm x 100 mm with a mass of up to 1,33 kg [6]. Although CubeSat is not modular, it shows the possibility to insert complex systems in small volumes in almost same dimensions like the developed payload-items.

Modularity as a principle has already been applied in satellite technology, yet not in real planetary exploration missions. So far deployed robots on Mars, namely the Mars Exploration Rovers (MER) Spirit and Opportunity as well as the rover Curiosity are single mission systems with a specific set of instruments. Their objective is to work as "robotic geologists" with in-situ analysis of samples [7]. These missions offer a baseline for future sample return missions (SRMs), where the application of multi-robot systems has to be considered as well. Merlo et al. [8] provide an example for such an SRM: a caching rover collects and deposits sample caches onto the Martian surface which are then collected by a sample

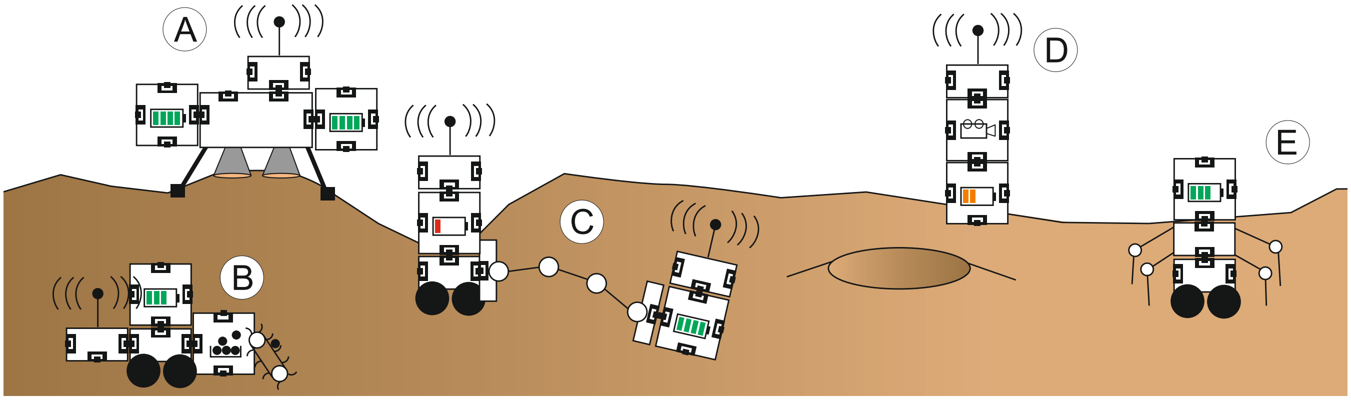


Figure 1. Schematic overview: A heterogenous robotic team with modular components in a Mars exploration scenario. Depending on the functionality, the payload-items serve as range extenders or allow the different systems to be equipped with different scientific modules, based on the context of the current mission.

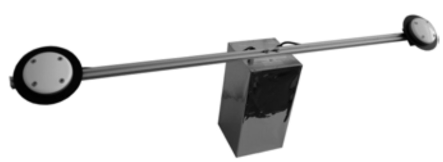
fetching rover (SFR). The sampling fetching activity is of central importance to the design of an SRM. Haarmann et al. [9] introduce the sample fetching rover Mobile Payload Element (MPE): its main objective is to use an embedded Mole sampler to gather regolith samples. After collecting the samples MPE is intended to transport them back to the landing unit for further analysis. Schuster et al. [10] describe the Light Weight Rover Unit (LRU) which can collect samples by its grappling system on the manipulator arm. The main focus on the mentioned systems is their high level functionality which is achieved mainly without or at least a very limited degree of modularity. Such approaches constrain the system's interaction and reconfigurability and thus limit the potential extent of deviating from the original mission scenario or building upon existing systems for subsequent missions.

A multi-robot system can consist of several mobile and stationary systems, however a uniform electro-mechanical and software-technical interface, which is used on all systems, is a necessity for flexible reconfiguration. Such an interface allows not only robot-to-robot interaction but also the application of different payload-items (PLIs). PLIs have the advantage that robots can also be equipped with a new equipment at a later stage of the mission. This paper describes the development and usability of PLIs, their stand alone possibilities as well as the improvements that they can contribute to a robotic team. Functional units have been analyzed which are needed in various kinds of systems. Based on these relevant and recurring functions, for example, five different PLIs were implemented; namely (1) a battery module as power source (shown in Fig. 2(a)) in order to extend the power capacity of robots and/or to allow the creation of standalone sensor modules, (2) a camera assembly (shown in Fig. 2(b)) for observation purposes and as an example for any data acquiring payload-item, (3) a Differential Global Positioning System (DGPS) module (shown in Fig. 2(d)) to provide a high precision positional reference sensor as navigation infrastructure, (4) a device for collecting soil samples (see Fig. 2(c)) as a scientific instrument payload, and (5) a gas sensor module for search and rescue scenarios, Fig. 2(e). In addition, the modular symmetrical interface manipulator (SIMA) used onboard of a robot or a BaseCamp, as a stationary module to handle all PLIs, was developed as well, Figure 3(b). This paper presents the development and improvements of the core PLI as well as the development of equipment providing specific functionality. The core elements of the payload items are described according to electro-mechanical interface


(a)Battery module


(b)Camera module


(c)Sampling module


(d)DGPS module


(e)Gas Sensor module

Figure 2. The five developed functional PLIs

(EMI), general structural payload design, interface and module management electronics and the applied Node-level Data Link Communication (NDLCom) [11].

The following sections of this paper present (i) the utilization of the PLIs within the context of modular and reconfigurable robotic systems, (ii) a description of the implemented devices, presenting the realization of various PLIs with different specific functionalities along with the robot design to support the approach of system reconfiguration, (iii) an overview of the core systems, describing the basic elements as the EMI, the core structure of a general PLI, the interface and module electronics along with the communication protocol used as well as a visual servoing approach allowing to handle and combine different PLIs, (iv) a proof of concept during experiments and function tests, carried out in laboratory and field environments, (v) and a conclusion and outlook.

2. Utilization

One core element of the PLI is an EMI [12]. Due to the EMIs uniform design and function, they can be used in a wide variety of systems. Once a robotic system is equipped with at least one EMI, already developed as well as future PLIs can be connected and utilized. Currently, several mobile

(a)BaseCamp with a docked sampling module and SherpaTT (b)Coyote III equipped with the manipulator module SIMA (c)Via the electro-mechanical interface on CREX back the robot can be connected to the Sherpa rover for travelling longer distances (d)The hominid robot Charlie within an artificial moon crater. The shoulder housing allows the uptake of additional equipment, e.g. the PLI.

Figure 3. Mobile robotic systems for system enhancement

robots and stationary systems are either already equipped with an EMI: The hybrid four wheeled-leg rovers Sherpa[13] and SherpaTT [14], as well as their manipulator arm, the BaseCamp (the later three are shown in Fig. 3(a)), the rover Coyote III [15] including the modular manipulator arm SIMA (both shown in Fig. 3(b)), the six-legged walking robot CREX (CRater EXplorer) [16] (see Fig. 3(c)) furthermore the technological conditions are given to equip the hominid robot Charlie [17] with the interface to extend the infrastructural possiblity , Fig. 3(d). Due to the homogeneous interface, PLIs are able to extend all these different systems after connecting with the systems via the EMI. Naturally, the versatile PLIs (see Fig. 2) are as well equipped with at least one EMI.

The PLIs can be stored on a BaseCamp, which can be seen as an extended PLI. Thus, also the development and functionality of the BaseCamp is described.

3. IMPLEMENTED DEVICES

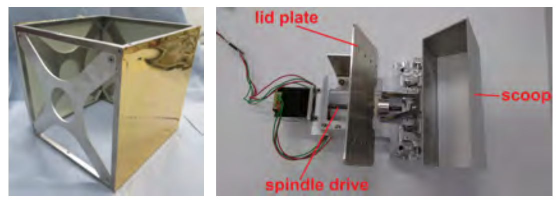
The immobile payload modules have been integrated so far and are described in more detail in the following paragraphs:

- battery module for extra power source used by the rover SherpaTT or shuttle Coyote III
- camera module as a scientific-mockup module
- sampling module as a scientific instrument payload for SherpaTT for collecting soil samples by using the manipulator arm
- DGPS module, as navigation infrastructure, for ground truth data in navigation experiments
- a gas sensor array for search and rescue scenarios
- modular manipulator module SIMA for handling of PLIs

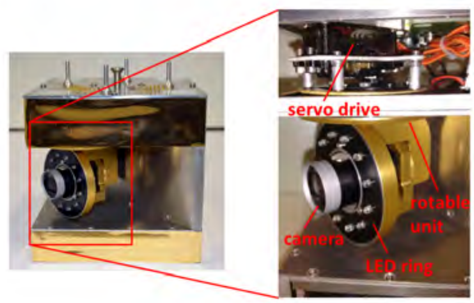
Furthermore the design of the BaseCamp, which can be seen as an (temporary) deployment station for the PLIs, e.g., (i) for charging of the battery modules, (ii) for storing of the sampling modules, (iii) as a standalone module with the DGPS module, or (iv) as a standalone module with a camera module, is described.

Excluding the BaseCamp, the core structure of the PLIs, as shown in Fig. 4(a), serves as the baseline module housing. This structure has been adopted for special modules like the battery module, sampling module, camera module, and DGPS module.

All the modules can be carried by Sherpa, SherpaTT, CoyoteIII, CREX and, if equipped with an EMI, Charlie and other systems. Furthermore the PLIs can be stored on the BaseCamp.



(a)PLI core structure (b)Scoop assembly



(c)Camera assembly

Figure 4. PLI core structure and assemblies of the sampling and camera module

Battery Module

The battery module is a PLI which can act as a power supply and consists of batteries integrated into the basic PLI structure. The battery modules are used to provide a power source for stacked PLIs, e.g., to provide power to stand alone instrument modules. Docked to any mobile system these modules can provide power for an extended operation time. The BaseCamp can be used to recharge the battery modules and serves as distribution point within an exploration mission.

Two options of battery modules are currently available: a flat battery module, with a height of 80 mm and a capacity of up to 2400 mAh, and the general PLI with a height of 154 mm (Fig. 4(a) and Fig. 2(a)) and a capacity of 4800 mAh (at 44.4 V nominal voltage). Depending on the cell size and cell type higher capacities are possible.

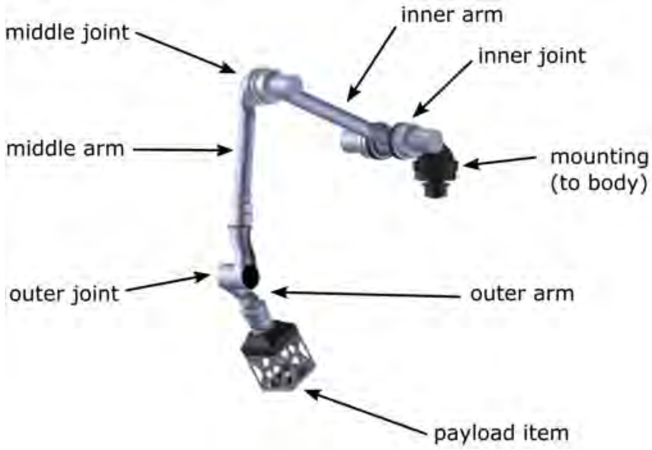


Figure 5. Schematics of SherpaTT's manipulator with mounted PLI.

Figure 6. SherpaTT with docked BaseCamp to its body and DGPS module mounted to the rear payload bay. Rover is in its max body-ground clearance position.

Sampling Module

One requirement for an exploration mission scenario is the ability for soil sampling by using a configured PLI. During the sampling execution the sample must be sealed inside the sampling module. The sampling module can be used by the manipulator of SherpaTT (see Figure 5) to collect soil. After collecting of samples the sampling module can be transferred by, e.g., SIMA to the BaseCamp for storing.

The main focus is on collecting surface samples without drilling through several soil layers. The rationale is to demonstrate the general possibility of collecting soil samples with a modular approach. The design of the sampling module allows to collect and store samples with particle diameters of 0.05 mm as well as to transport contaminated material in terrestrial transfer scenarios, while the inner actuators and control elements are protected against dust.

The principle of the sampling module is a rod-leaded scoop that is driven by a linear actuator. The chosen actuator, Haydon Kerk E28H47-2.1-906, with a spindle drive allows to retract the scoop with samples gaining a weight of at least 1000 g. Three rods of different length are attached to the scoop in two fulcrums (Fig. 4(b)). This allows the actuator to hold the scoop against a lid in closed state and to bring it in a position outside the PLI when it is used for scooping.

Camera Module

The camera module, Figure 2(b), provides a optical sensor unit which can be used in a wide range of applications. Docked to a manipulator self-inspection of the system as well as dedicated camera placement can be performed. In case the camera module is placed on one of the rovers, it can be used for monitoring manual control tasks or even to enable autonomous methods. Furthermore a stationary deployment of the camera module is possible on the BaseCamp or as stand alone system while stacked to a battery module. In this case the camera allows to monitor its environment, e.g., during infrastructure set-up or search and rescue missions.

The structure of the camera module is an alteration of the core PLI structure in which a camera assembly is integrated. The camera assembly, see Figure 4(c), was successfully used and tested in the previous project RIMRES and contains a camera paired with an LED-based illumination rig and can be remotely rotated by 180°. The adaptation of the PLI structure was necessary to provide an unobstructed field of view for the camera within its 180° operational range.

DGPS Module

The main purpose of the DGPS-module is to provide a high precision positional reference sensor to establish a ground truth for experiment evaluation in the demanding Mars-like desert environment with no further laboratory infrastructure. In the current scenario, the module is not used to enhance the pose estimation, although it integrates a high quality low drift inertial measurement system (Advanced Navigation Spatial Dual). The data is only used for ground truth. This may be different when deployed in terrestrial applications, e.g., Search and Rescue scenarios. The module incorporates a dual L1/L2 frequency receiver and has real time kinematic (RTK) capabilities for highest precision position measurements of $1\,\mathrm{cm}$ to $2\,\mathrm{cm}$, but RTK would require extra infrastructure in form of an extra base station. Therefore, the commercial *OmniSTAR HP* satellite correction service was used. This has a 2σ $(95\,\%)$ accuracy of $10\,\mathrm{cm}$.

The module consists of two antennas (Antcom G5 53AT1), which are mounted on a stack made of two PLIs, in order to ensure the required assembly space for all components as module electronics, communication transducers and DC/DC converter. On the bottom PLI is an active EMI, which is modified in order to establish a manually adjustable version. The actuated spindle drive is replaced by a cardan joint, which allows to fixate the module manually on both mobile robot systems. An angle adapter allows adjustment of the antennas on SherpaTT and Coyote III. The passive EMIs on the body of SherpaTT are mounted with an angle of $35°$. In order to horizontally align the antennas to the horizontal plane an angle adapter is required. Fig. 2(d) shows the DGPS module with the angle adapter.

Docked on a battery module, camera module or BaseCamp, the DGPS module can be used as a reference or navigation point.

Gas Sensor Module

The gas sensor module consists of a sensor stack as a small device with different sensors for gas

- 1x MQ-2 Sensor: Methane, Butane, LPG, smoke

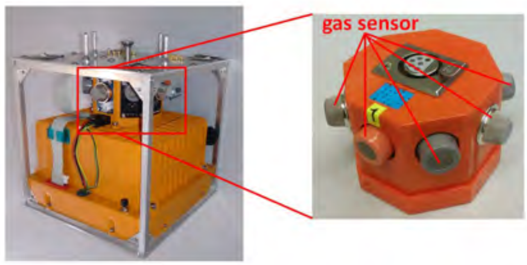


Figure 7. Gas sensor module

- 1x MQ-3 Sensor: Alcohol, Ethanol, smoke
- 1x MQ-4 Sensor: Methane, CNG Gas
- 1x MQ-5 Sensor: Natural gas, LPG
- 1x MQ-6 Sensor: LPG, butane gas
- 2x MQ-7 Sensor: Carbon Monoxide
- 1x MQ-8 Sensor: Hydrogen Gas

and one sensor for temperature and humidity.

The module features a microcontroller, which is used to preprocess data and generate filtered values for the gas types. Communication with the main system carrying the sensor is done via UART and the EMI. The start up sequence begins with a preheating phase in order to ensure that the gas sensors heated up. The next step is the calibration phase. In this phase the sensor stack samples all the gas sensors and compares the temperature and humidity compensated results with clean air values. This step makes sure that the sensor stack is powered up and calibrated in a clean air environment. The measured values during this phase will serve as baseline values for the following measurements.

Figure 7 shows the gas sensor module and its sensor stack with different gas sensors and the blue sensor for temperature and humidity (DHT11).

BaseCamp

BaseCamps are helping to bridge long communication distances or built up a logistics chain within an exploration scenario. As functional modules they can be used as relay stations to provide an extended wireless communication range for the mobile robotic systems. Furthermore, they can be used as intermediate storage for samples and required modules, as well as energy deposit to enlarge the range of Coyote III and SherpaTT.

As shown in Fig. 8(a) the developed BaseCamp consists of five passive EMIs for docking with the different mobile and immobile robotic systems. The design, with an overall dimension of 520 mm × 520 mm × 145 mm, was chosen with respect to an optimal interaction with Coyote III's manipulator. The inclination of the four outer EMIs allows PLI disposal by Coyote III with SIMA. The cross shape helps to position Coyote III close to the BaseCamp and within the work-space of SIMA. Therefore, a payload deposition as well as bridging over to the BaseCamp is possible.

Furthermore, the design allows (i) to store at least five PLIs, Fig. 8(b), (ii) a pick-up by, e.g., SherpaTT using either the manipulator or body mounted EMI, (iii) the EMI control and power bus management, (iv) the deployment as communication relay without PLIs, (v) the stackability with other BaseCamps, and (vi) adjustment to the terrain during drop-off by spring-loaded feet.

SherpaTT, as well as Sherpa, can transport the BaseCamp, currently with a weight of 6.1 kg, to selected locations. In this case, the BaseCamp is docked with its 30 mm higher middle EMI below the body of the rover (cf. Fig. 6). During the placement of the BaseCamp, SherpaTT keeps it in horizontal orientation above the ground and the spring loaded feet are released and pushed into the soil. This enables a secured foothold in horizontal position. Afterwards SherpaTT undocks the BaseCamp.

Manipulation Module SIMA

SIMA is a robotic manipulator with 5 DoF, which is designed for PLI handling. Its symmetrical design with an active EMI on each end-effector side allows a full integration into the presented modularity concept. The main purpose of SIMA is to serve as modular payload handling device on the shuttle rover Coyote III, where it can be docked to one of the shuttles EMIs. Due to its symmetrical design it is however possible to apply the manipulator to another system, e.g., to bridge over from the shuttle to a BaseCamp for PLI reorganisation. In combination of specialized PLIs, providing the needed system functions, it would be possible to even use SIMA as stand-alone manipulation unit.

To support the symmetrical design of SIMA, five identical actuator modules (Fig. 9) are used in the manipulator. Each joint includes a Robodrive ILM 50×14 bldc-motor, paired with a Harmonic Drive gear with a reduction ratio of 160:1, gaining a nominal torque of 80 Nm and 224 Nm stall torque. While each actuator module is equipped with its own FPGA based motor driver, the communication and power management for

(a)BaseCamp with five passive EMIs (b)BaseCamp with several docked PLIs

Figure 8. BaseCamp without and with docked PLIs

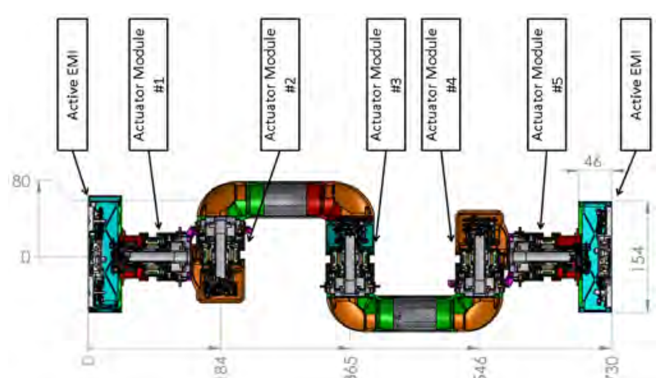


Figure 9. Schematic drawing of the manipulation module SIMA

(a)Manipulation module SIMA with active EMI

(b)Active EMI at the manipulator arm of the rover ShepraTT

Figure 10. Active EMIs on the manipulator hands

the manipulator and potentially docked PLIs is done by the EMI electronics. The overall length of SIMA is 730 mm, with a mass of 6.6 kg. The layout and design of the manipulator tailored to handle PLIs of up to 5 kg on Coyote III and/or a BaseCamp.

Manipulator arms for payload handling

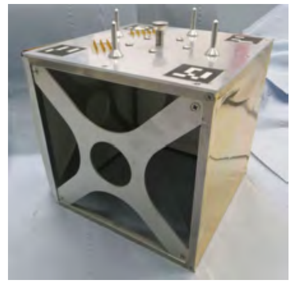
SherpaTT and Coyote III are using manipulators for handling and deployment of PLIs. The manipulators are therefore equipped with active EMIs at the end-effector, allowing to dock to the passive counterpart on the PLIs, BaseCamp or even the rovers themselves. SherpaTT has a fixed manipulator arm with 6 DoF as shown in Fig. 5. Its end-effector mainly consists of the active part of EMI and a six axis force torque sensor (FTS). The FTS is used, e.g., to stop the manipulator in case of overloads and to allow a force-feedback controlled operation. The FTS can also be used to allow a force guided stacking of the payloads. Both manipulators are shown in Fig. 10.

4. Core System

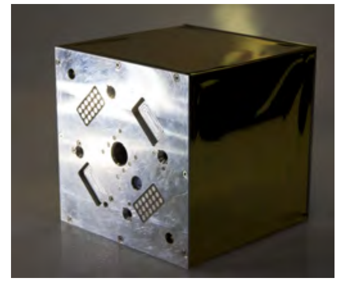
The PLIs come with a processing unit (Gumstix) to run a high-level software framework and a microcontroller to support low-level intelligence, e.g., to communicate with an EMI. As part of a low-level intelligence, an internal communication protocol has been designed allowing to infer the current topology of a stack of at least two PLIs from the EMI connections, and control basic operations such as opening and closing the mechanic latch to attach an active EMI to a passive one. These capabilities are exposed to higher levels of control to allow for more complex reconfiguration activities leading to various system combinations. This section describes the main components of the modular system as the EMI in general and its sub-components, as well as the PLI core structure.

Electro-Mechanical Interface (EMI)

The EMI ensures a reliable mechanical and electrical connection between linked robotic systems to allow for force, data and power transfer. The design of the interface focuses on reusability, redundancy and robustness, e.g., the latch mechanism can handle a static load of up to 1300 N and undocking is feasible under a load of up to 300 N within different inclined positions [12].



(a)Basic PLI with passive EMI on top, golden covering and cross-shaped stiffening



(b)Basic PLI with active EMI on bottom

Figure 11. A generic PLI

To address the special needs of planetary space exploration the EMI remains operative in dusty environments. The EMI consists of an active and passive part, which interlock using a latch mechanism after docking. Optical markers on the passive part of EMI and a camera on the active part allow for a visually guided docking approach. During the docking procedure the guiding pins on the passive part of EMI and the counterpart conical shaped cylinders on the active part of EMI enable docking in 4 different orientations (90° steps) and tolerates misalignment in the horizontal plane of up to +/- 5 mm and up to 40° and a rotational play of up 7°.

Important considerations during development process were the design of the assembly groups with lightweight material and structures in order to keep the weight low. Furthermore, a high stiffness and robustness against dust were important design criteria.

General Payload-Item

A PLI is a modular unit, which can be equipped with different assemblies (payloads) providing specific functionality, e.g., collecting soil samples. Therefore, PLIs allow to complement the mobile robots SherpaTT and Coyote III during a mission, while providing additional mission-specific functionalities to the rovers.

The basic structure of a standard PLI has an outer dimension of 154 mm x 154 mm x 154 mm, based on the given dimensions of the EMI. Each side panel is easily detachable while keeping the structure intact. Depending on limitations of the manipulator arm and its end-effector to handle a stack of two docked PLIs, a maximum overall mass of up to 5 kg (with all components)per PLI is accounted for. However, the EMI-structures in general allow higher loads.

Each PLI has a passive EMI on the top face and an active EMI with actuated latch mechanism and camera for positioning on the bottom face of the cube. Fig. 11 shows an empty standard PLI. The height of the EMI itself has been minimized as much as possible, in order to maximise the space usable for payloads within a PLI. Payloads with dimensions 140 mm x 140 mm and a maximum height of up to 90 mm can be comfortably housed. For bigger (i.e. higher) payloads, the cube can be extended to have alternative heights. However, due to the design approach, the payload must fit into the area provided by an EMI.

Electronics

Interface/Module Electronics— The electronic boards are specifically designed to fit neatly into the mechanical structure. The electronics are separated in three Printed Circuit Boards (PCBs) as shown in Figure 12. The connection mainboard is directly soldered to the electronic connection pins in the active EMI and features an EEPROM to store a unique ID of the system using this EMI. A Power Management Board (PMB) is stacked onto the connection main board managing the power bus and controlling of the motor for the latch mechanism using a microcontroller. Furthermore, this microcontroller is equipped with several peripheral devices and hence can be used to control payloads mounted into the payload-container. A calculation board hosting a Gumstix micro PC connected to a camera can also be stacked to the mainboard, this is used mainly for acquiring camera images used for visual servoing in the process of connecting an active EMI to a passive EMI. All cable connections originate on the mainboard. The top EMI is connected over a flat ribbon cable to the bottom EMI. The overall height of the stacked PCBs is 15 mm.

Each basic PLI houses a 44.4V/10A (operating range: 40 V-52 V) power bus with three IN/OUT power ports constituting a power bus between top and down EMI and additionally allowing the connection of a battery within a PLI (hence forming a battery module), Fig. 13. An additional internal power outlet is present for powering the Gumstix micro PC and the actual payload of the cubic module marked as internal consumers. The PMB features a 12-cell battery monitor for monitoring an internal battery when present. Two RS422-ports connect the microcontroller of the PLI to top and bottom EMI, allowing for local communication between neighbouring connected systems. A motor driver for opening and closing the latch mechanism is present on each PMB. With an emergency opening mechanism, each PLI can open the latch of its top-neighbouring PLI in case of a failure of that system. A second motor driver is provided for potential payload use. The illumination LEDs in each active EMI are controlled by the PMB's microcontroller. Furthermore, the PMB features a low-cost 6-axis IMU sensor for orientation detection of the EMI/PLI. Additional communication interfaces are provided for control of internal payload systems.

Fig. 13 shows the architecture of the Power Management System (PMS) developed for individual PLIs. Although the PLIs differ from each other in functionalities and power sources, the homogeneous PMS is designed for all of them.

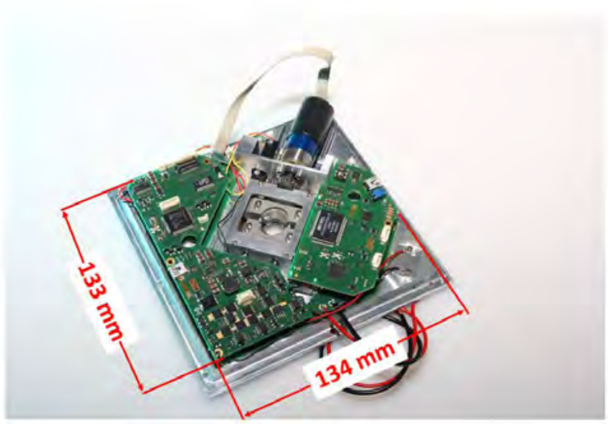


Figure 12. The three PCBs attached on the active part of EMI

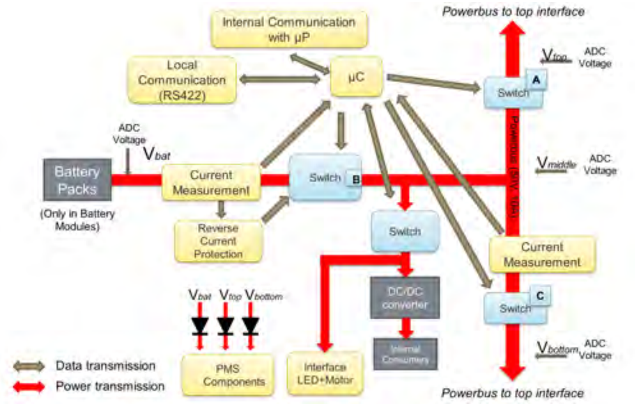


Figure 13. Hardware architecture of the PMS in individual PLIs

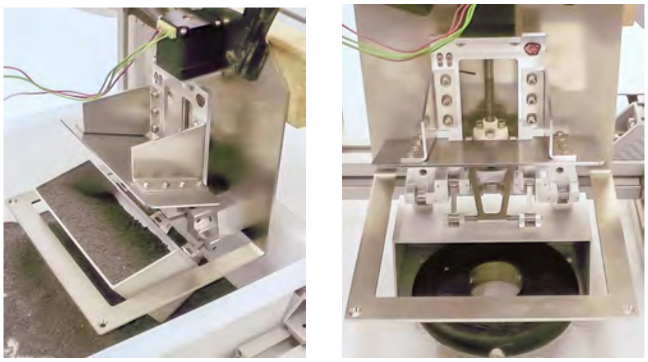
The components with yellow rectangle symbols belong to the primary part, which is supplied by one of three possible power sources directly, i.e. internal battery packs, power sources connected to the top and bottom EMIs. Hence, PLIs without battery packs can be awakened from powerless state, if they are electrically docked to a module providing power. The primary part powered in a PLI is able to activate other applications on demand and change the topology of a power bus. The power bus can be connected to two neighboring modules via EMIs directly. The MOSFET-based switches (blue rectangles A, B and C) enable bidirectional power switching, and are employed to control intermodule connection among battery packs and consumers. Switch B for the battery interface has also a hardware-based reverse current protection in case of error while connecting two battery modules to the power bus.

Node-level Data Link Communication

For the RS422-based low-level communication between two EMIs the Node-level Data Link Communication NDLCom is used [11]. This protocol is designed for heterogeneous embedded communication networks and is used within all the robotic systems mentioned in this paper to connect different electronics, like FPGA-based motor electronics and uC-based sensor processing units. Due to the design of NDLCom it can be used with every physical layer which provides a byte-oriented transport mechanism, like RS422. For easy configuration and data exchange a register-based approach is used with which the EMI-electronics as well as all other components within the systems can communicate with each other.

Handling of PLIs within the multi-robot system

The EMI is the key requirement for the presented reconfigurable (multi-)robot system. However, for autonomous reconfiguration and thus high-level operations such as a PLI pickup and handover with a manipulator arm, the interface design relies on a visual servoing process. Primarily for this purpose the active EMI houses a Gumstix micro PC and a camera, while the passive EMI features two sets of visual markers: four markers in each of the corners and at least two markers close to the central pin; this allows servoing within close proximity of both EMIs. This feature augmentation of the EMI allows for a two staged servoing approach to achieve the millimeter precision needed for automated docking. The markers in the corners of the top EMI are visible in Fig. 11(a).



(a)Scoop with 200 g granularity (b)Sccop with a 550 g weight on the lowest position

Figure 14. Weight tests with the scoop assembly

5. Experiments / Mission Scenarios

This section describes laboratory experiments and field tests. In the laboratory environment, the scoop assembly of the sampling modul is tested, as well as the feet of the BaseCamp. Tests with different weights will show the ability of the scoop to retract with soil samples and are used to determine the maximum assumed payload of 500 g, with which the scoop must be able to retract failure-free into the sampling module. In addition, the dust-proofness of the scoop assembly is tested in closed position with different sizes of collected soils.
In a further experiment the feet of the BaseCamp are tested on their sturdiness against sinking in the soil. The subsection field experiments describes the functionality and interaction between the different PLIs and other robotic systems in a rock desert.

Sampling Module

Main task of the PLI is to extend the ability of single robotic systems within planetary mission scenarios. One scenario envisages that the sampling module is attached on the end-effector of SherpaTTs manipulator arm and thus add the ability to collect samples to the robotics functionality. As described in section 3 the sampling module consists of a scoop assembly.

One test series was performed to demonstrate the ability of the scoop and the chosen motor to retract collected sample soils with different weights. Within the test-set up the scoop assembly was mounted on a frame, whereas the opened scoop, in starting position of the test, was in a box with granulate. The tests were carried out with two different weights, 20 times in each cases: (i) 200 g granulate and (ii) 550 g weight disc (see Figure 14(a) and 14(b)). The tests begin with the opened scoop filled with granulate or weight discs. After start of retracting, the scoop had to reach the lid plate as end-position (Figure 4(b)).

The test rows showed that the scoop retracts failure-free with weights of up to 550 g, more than the expected 500 g.

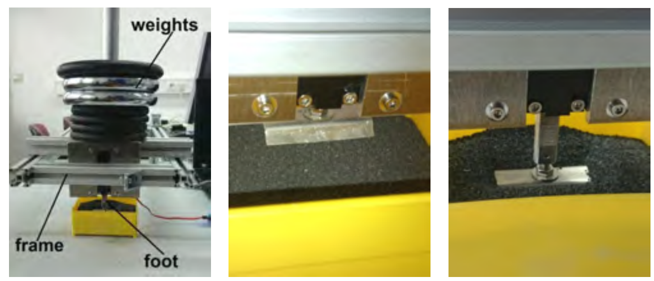
The next experiment series was performed to verify the dust proofness of the retracted scoop with different granulate types. Within these tests the scoop assembly was mounted in the sampling module. Following regolith granulate types were tested:

- Type A, grain size 0.02 mm up to 0.2 mm
- Type B, grain size 0.7 mm up to 1.3 mm
- Type C, grain size up to 5 mm

The tests began with filling the opened scoop with one type of granulate and retracting of the scoop to the end-position, which means that the scoop is in closed position to the lid plate. The next step was to shake and rotate 10 times the PLI $360°$ each axis in order to check a possible fall out of the granularity. The tests showed that no granulate of type C and B with an amount of 200 g each dropped out of the closed scoop. With type A, an amount of 0.3 g that is tolerable for the electronics and mechanics escaped the closed scoop.

BaseCamp

The feet of the BaseCamp were tested on her sturdiness against sinking in the soil dependend on the load attached. It was presumed that one foot in granulate of sizes of up to 3 mm will sink 5 mm as maximum depth with loads of up to 200 N.



(a) Test arrangement (b) Incoming foot (c) Released foot

Figure 15. Testing the weight load capacity of the BaseCamps feet

The load capacity of the BaseCamp's levelling feet was tested under laboratory conditions. Therefore, one foot was mounted above the ground at a test rig, which could be burdened with weight to simulate the BaseCamp's and PLIs weight. Regarding the space exploration scenario regolith with sizes of 1 mm of up to 3 mm was chosen as ground. The test procedures was as follows: Firstly release the foot and shot it onto the ground, then remove the rig that the foot got loaded with weight and finally increase the weight up to the maximum value. Figure 15 shows the test procedure described above.

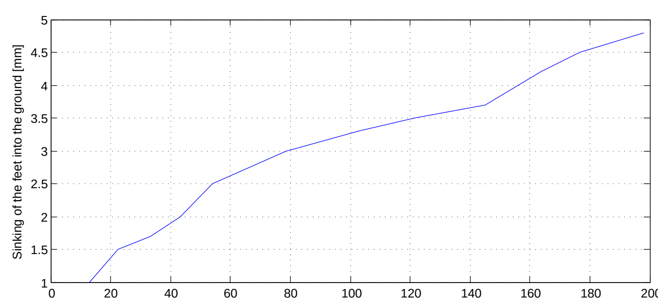


Figure 16. Weight tests with one foot of the BaseCamp

The measured data in figure 16 show the correlation between the weight force and the sinking depth of a foot into the ground. It can be seen that one foot sinks 4.8 mm under a maximum load of 200 N. This results that the BaseCamp with 4 feet provides a safe placement on sandy grounds which is

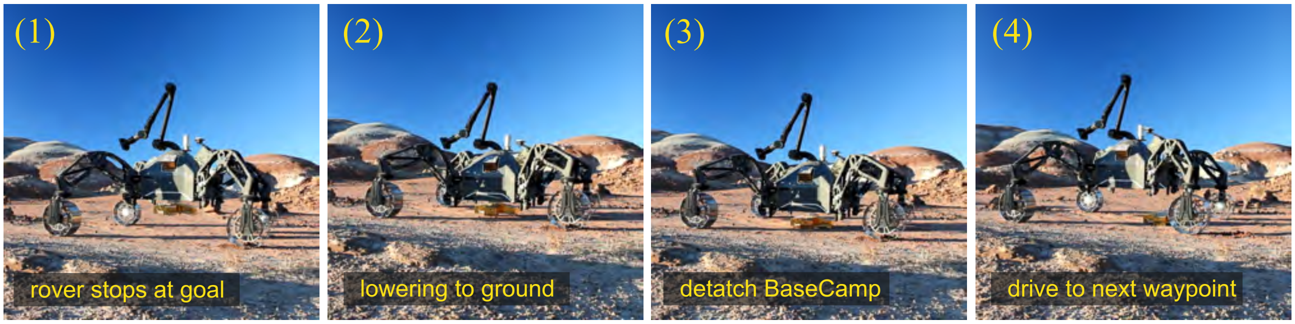


Figure 17. Sequence of BaseCamp deployment. From left to right: (1) SherpaTT stops driving and starts lowering of the body. (2) BaseCamp is close to the ground, feet are released. (3) Rover released BaseCamp and starts to move body upwards. (4) Driving away from deployed BaseCamp.

important for a good the payload handling with up to four PLIs. Additional tests regarding dynamic weight loads and field tests could be expedient for further improvement of the foot design.

Field Tests

The general feasibility of using modular payload-cubes was demonstrated in an field testing campaign in the desert of Utah in October/November 2016[2] [18]. During the tests, the systems had to withstand weather conditions with heavy winds carrying dust/sand particles and temperatures between -5° C and +28° C as well as the generally rocky and dusty area of the desert.

In the campaign the DGPS-module was used on the two deployed mobile systems (SherpaTT and Coyote III and additionally on the stationary BaseCamp) for gathering ground truth data during experiment runs. Hence, it was shown that additional sensors can be used with the systems. The DGPS-functionality was not foreseen during design of SherpaTT and Coyote III, yet the data is easily available for the systems using the modular interfaces.

As part of the test campaign, SherpaTT successfully deployed a BaseCamp. Figure 17 shows the sequence of the deployment. In the sequence, the rover stops its traverse at the point of deployment and lowers its body until the BaseCamp is in the vicinity of the ground. In the conducted experiment, the ground distance was manually provided, however, the front laser range finder of SherpaTT is mounted such that it can be tilted to measure the ground distance below the center of the body to autonomously assess the ground shape below the robot. After lowering the BaseCamp close to the ground, the command to release the BaseCamp‘s feet is given to fixate the pose on ground. By opening the latch of the rover’s body EMI, the BaseCamp is released and the rover can move its body up and proceed with its traverse.

A second experiment analyses the functionality of the sampling module. The sampling module was used as part of a semi-automated soil-sampling procedure, verifying (i) the functionality of power management by powering the sampling module through the manipulator’s EMI, (ii) the automated start-up of the PLI, (iii) the control of the scooping mechanism, (iv) and the high-level control design and actual performance of an overall sampling process.

[2] Video with overview on conducted experiments available at: `https://youtu.be/pvKIzldni68`

Figure 18. Part of the scenario of a logistics chain: SherpaTT is about to put the sampling module onto Coyote III.

While all functionalities were successfully verified by full completion of a semi-automated soil sampling, the design of the sampling module itself showed a lack of performance with a limited opening angle of the scoop. Using the sampling module in combination with SherpaTT’s manipulator allows for scooping the top of small sand-hills, but sampling planar surfaces might result in scratching the surface with one of the manipulator’s wrist joints. Following the field test, the shovel design was altered in order to give the manipulator more room for a simplified and improved sampling process. However, note that the design of the sampling mechanism is not the main interest in this project. The main interest is to show the general feasibility of integrating a (any) sampling mechanism in the modular framework of the heterogeneous multi-robot system.

Furthermore, a successful autonomous payload transfer between the two mobile robots was shown. Fig. 18 provides a photograph of the systems exchanging a PLI. In this case a sampling module is put onto Coyote III for transport to the simulated landing site.

Furthermore, the grasping and drop-off of a PLI by Coyote III using the SIMA manipulator was demonstrated during the campaign. In this setting, a manipulator arm that is made of 5 actuators and two EMIs was successfully used on a mobile robot, making use of the electro-mechanical interface as manipulator mount on the one end and as end-effector on the other end of the manipulator.

6. CONCLUSIONS AND OUTLOOK

The generic container design of a PLI embeds the EMI as standard interface and in effect allows extending any EMI-compatible robotic system with any of the special modules: battery module, sampling module or camera module or future payload-items. The presented approach offers a high degree of flexibility for the compensation for the loss of individual PLIs, as well as for tackling future, yet undefined tasks for the robotic system.

While use of the cube-like design has been predominant, this paper already shows alternative designs, e.g., the BaseCamp and the DGPS module (cf. Section 3) taking advantage of PLIs and a modified active EMI (for manual usage), verifying the scalability of this approach.

Laboratory tests showed that the scoop assembly of the sampling module needs a better sealing to become completely dustproof against granulate of size below 0.2 mm. However, the sampling module is a proof-of-concept system, a dedicated sampling mechanism with sealing needs to be incorporated for real space missions. Since field experiments showed the limitation of the scoop while collecting samples with the manipulator, the scoop is currently being modified.

The performed (field) experiments showed that mission scenarios can be extended by using different robotic systems. To increase the possibility of different mission scenarios, Charlie will be equipped with an EMI.

Operating conditions in planetary environments require thermo-mechanical and thermal geometric stability. Therefore the EMI should ensure to conduct the thermal energy between the connected robotic systems. The current design of the EMI allows to introduce a thermal transfer between the guiding pins of passive part and the counter-acting cylinders of active part. This is however not included in the current state of developments. Both, guiding pins and counter-acting cylinders are moveable parts, permitting the evaluation of different materials for the pins to improve thermal transfer.

ACKNOWLEDGMENTS

The work presented is part of several projects funded by the German Space Agency (DLR Agentur) with federal funds of the Federal Ministry of Economics and Technology in accordance with the parliamentary resolution of the German Parliament. This includes the projects TransTerrA (grant no. 50RA1301), FT Utah (50RA1621 and 50RA1622), and VIPE (50NA1516).

REFERENCES

[1] K. R. Blasius, J. A. Cutts, J. E. Guest, and H. Masursky, “Geology of the valles marineris: First analysis of imaging from the viking 1 orbiter primary mission,” *Journal of Geophysical Research*, vol. 82, no. 28, pp. 4067–4091, 1977.

[2] M. Yim, W. m. Shen, B. Salemi, D. Rus, M. Moll, H. Lipson, E. Klavins, and G. S. Chirikjian, “Modular self-reconfigurable robot systems [grand challenges of robotics],” *IEEE Robotics Automation Magazine*, vol. 14, no. 1, pp. 43–52, March 2007.

[3] M. Kortmann, S. Rhl, J. Weise, J. Kreisel, T. A. Schervan, H. Schmidt, and A. Dafnis, “Building block - based ”iboss” approach: Fully modular systems with standard interface to enhance future satellites,” in *2015 66 International Astronautical Congress (IAC)*, 2015.

[4] H. Tanaka, N. Yamamoto, T. Yairi, and K. Machida, “Autonomous assembly of cellular satellite by robot for sustainable space system,” in *Proceedings of the 56th International Astronautical Congress (IAC2005)*, 2005.

[5] G. T. Trinh, D. Cellucci, W. Langford, S. Im, A. G. Luna, and K. C. Cheung, “Modular rapidly manufactured small satellite (mrmss),” in *53rd AIAA Aerospace Sciences Meeting, Kissimmee, Florida*, 2015, pp. 5–9.

[6] A. Mehrparvar, D. Pignatelli, J. Carnahan, R. Munakat, W. Lan, A. Toorian, A. Hutputanasin, and S. Lee, “Cubesat design specification rev 13,” *The CubeSat Program, Cal Poly San Luis Obispo, US*, 2014.

[7] R. A. Lindemann and C. J. Voorhees, “Mars exploration rover mobility assembly design, test and performance,” in *Systems, Man and Cybernetics, 2005 IEEE International Conference on*, vol. 1. IEEE, 2005, pp. 450–455.

[8] A. Merlo, J. Larranaga, and P. Falkner, “Sample fetching rover (sfr) for msr,” in *Proceedings of the 12th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA 2013)*, 2013.

[9] R. Haarmann, R. Jaumann, F. Claasen, M. Apfelbeck, S. Klinkner, L. Richter, J. Schwendner, M. Wolf, and P. Hofmann, “Mobile payload element (mpe): Concept study for a sample fetching rover for the esa lunar lander mission,” *Planetary and Space Science*, vol. 74, no. 1, pp. 283 – 295, 2012, scientific Preparations For Lunar Exploration.

[10] M. J. Schuster, C. Brand, S. G. Brunner, P. Lehner, J. Reill, S. Riedel, T. Bodenmller, K. Bussmann, S. Bttner, A. Dmel, W. Friedl, I. Grixa, M. Hellerer, H. Hirschmller, M. Kassecker, Z. C. Marton, C. Nissler, F. Ruess, M. Suppa, and A. Wedler, “The lru rover for autonomous planetary exploration and its success in the spacebotcamp challenge,” in *2016 International Conference on Autonomous Robot Systems and Competitions (ICARSC)*, May 2016, pp. 7–14.

[11] M. Zenzes, P. Kampmann, M. Schilling, and T. Stark, “Ndlcom: Simple protocol for heterogeneous embedded communication networks,” in *Proceedings of the Embedded World Exhibition and Conference*, Feb 2016.

[12] W. Wenzel, F. Cordes, and F. Kirchner, “A robust electro-mechanical interface for cooperating heterogeneous multi-robot teams,” in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Sept 2015, pp. 1732–1737.

[13] T. M. Roehr, F. Cordes, and F. Kirchner, “Reconfigurable Integrated Multirobot Exploration System (RIMRES): Heterogeneous Modular Reconfigurable Robots for Space Exploration,” *Journal of Field Robotics*, vol. 31, no. 1, pp. 3–34, 2014.

[14] F. Cordes and A. Babu, “Sherpatt: A versatile hybrid wheeled-leg rover,” in *Proceedings of the International*

Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS 2016), 2016.

[15] R. U. Sonsalla, J. B. Akpo, and F. Kirchner, "Coyote iii: Development of a modular and highly mobile micro rover," in *Proc. of the 13th Symp. on Advanced Space Technologies in Robotics and Automation (ASTRA-2015)*, 2015.

[16] J. Machowinski, A. Boeckmann, S. Arnold, C. Hertzberg, and S. Planthaber, "Climbing steep inclines with a six-legged robot using locomotion planning," in *International Conference on Robotics and Automation. International Conference on Robotics and Automation, May 29, Singapore, Singapore*. IEEE, 5 2017.

[17] D. Kuehn, M. Schilling, T. Stark, M. Zenzes, and F. Kirchner, "System design and testing of the hominid robot charlie," *Journal of Field Robotics*, vol. 34, no. 4, pp. 666–703, 2017.

[18] R. U. Sonsalla, F. Cordes, L. Christensen, T. M. Roehr, S. Planthaber, T. Stark, and E. Kirchner, "Field trials to demonstrate a cooperative multi-robot mission in mars analogue environment," in *Proceedings fo the 14th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA'17)*, 2017.

BIOGRAPHY

Wiebke Brinkmann *studied Aeronautical and Astronautical Technologies at the University of Applied Sciences Aachen (Germany) and received her diploma in 2003. Before her change to the German Research Center for Artificial Intelligence Robotics Innovation Center (DFKI-RIC) in 2010, she worked as a project engineer at the Center of Applied Space Technology and Microgravity (ZARM) in Bremen, Germany. She is member of the team System Design and works in the Space Robotics department.*

Florian Cordes *received his Diploma in Mechatronics (Dipl.-Ing.) from the Technical University of Hamburg-Harburg (TUHH) in 2007. He has since been a researcher and project leader at the German Research Center for Artificial Intelligence - Robotics Innovation Center (DFKI RIC). Amongst others he was project leader in RIMRES and TransTerrA in which the PLIs and EMI presented in this paper were developed. His expertise is in reactive locomotion control for robots in rough terrain, with a focus on hybrid wheeled-leg rovers.*

Thomas M. Roehr *holds a Master of Computer Science from Victoria University of Wellington, New Zealand, which he received in 2009. He started as researcher at the German Research Center for Artificial Intelligence – Robotics Innovation Center (DFKI RIC) in 2008 in the area of space robotics. With main contributions to the projects RIMRES and TransTerrA his research focuses on autonomous operation of reconfigurable multirobot systems.*

Leif Christensen *received a master degree in computer science (Dipl.-Inf.) from the University of Bremen in 2008. He has since been a researcher at the German Research Center for Artificial Intelligence - Robotics Innovation Center (DFKI RIC) and was in charge of several projects related to underwater and space robotics in the last years. He also managed the navigation and planning group at RIC. His previous experience includes probabilistic robotic navigation with a special focus on magnetic field based localization.*

Tobias Stark *received a master degree in technical computer science (Dipl.-Ing.) from the Technical University of Berlin in 2007. From 2007 until 2009 he was employed as a researcher at the University of Duisburg-Essen, Germany (chair of mechanics and robotics). Currently he is working at the German Research Center for Artificial Intelligence Robotics Innovation Center (DFKI-RIC), focussing on the programming of FPGAs and other low-level devices.*

Roland U. Sonsalla *is Researcher at the German Research Center for Artificial Intelligence Robotics Innovation Center (DFKI RIC), which he joined in 2012. He is responsible for the management and technical execution of projects in the context of space exploration, search and rescue and security robotics. He has a background in aerospace and space engineering, which he studied at the Delft University of Technology and Berlin Institute of Technology, where he graduated as Diplom-Ingenieur (equiv. M.Sc.).*

Roman Szczuka *received a master degree in electronics engineering in 2010 from the University of Applied Sciences in Bremen. He has since been a researcher at the German Research Center for Artificial Intelligence - Robotics Innovation Center (DFKI RIC) working in different space and automotive projects, developing Electronics and low level software for power and battery management systems.*

Niklas Alexander Mulsow *received a bachelor degree in mechanical engineering (B.Sc.) from the Technical University of Ilmenau in 2015. He has since been a research assistant at the German Research Center for Artificial Intelligence Robotics Innovation Center (DFKI RIC) and works in the Space Robotics department.*

Daniel Kuehn *received his Diploma in computer science (Dipl.-Inf.) from the University of Bremen in 2007. He has since been a researcher at the German Research Center for Artificial Intelligence Robotics Innovation Center (DFKI RIC) and was in charge of several projects related to space robotics in the past. In 2015, he received his PhD degree (Doctor of Engineering). His research interests includes locomotion approaches for mobiles robots in different domains.*