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## Multifunctional interconnect for future modular planetary robots

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### Abstract

Current state-of-the-art planetary robotic systems are typically designed as large, heavy, and complex systems capable of performing many tasks. The Mars rovers Perseverance or Zhurong are such examples. These one-of-a-kind, expensive systems offer little opportunity for future maintenance, upgrades, or reuse. A more environmentally friendly and cost-effective solution would be a modular system at the subsystem level, assembled for a specific task, which can be upgraded in the future using multifunctional interfaces. In this case, any future mission would only need to transport individual, self-contained subsystems on an as-needed basis, rather than a single-use system. The MODKOM project aims at realizing such systems through the development of an integrated, multifunctional interface for mechanical, data and electrical connection, the Electro-Mechanical Interface - Modular (EMI-MOD). The envisioned application scenario of the modular system is a Lunar environment. The paper describes the design of the third generation of the EMI-MOD and analyzes its suitability considering the need for scalability, reusability and compatibility. A modular 6-DoF manipulator was chosen as the design reference. This is capable of changing its host system and reconfiguring the system based on modular payloads. In addition, the paper describes the intended use of the EMI-MODs, ranging from the combination of different subsystems (once they are equipped with an EMI-MOD) to (re)configurations in so-called multi-robot teams. Finally, the results of the first tests of the breadboard components of the interface are outlined. The outcomes shall help to develop an interface for lunar applications and the respective prevailing environmental conditions as part of the envisioned mission scenario.

**Keywords:** Multifunctional interconnect, modular robot, planetary, reconfigurability (maximum 6 keywords)

### 1. Introduction

Over the last years a severe push towards modular and reusable (sub-) systems could be observed in the space domain. Currently one of the main application areas is given for orbital systems, such as for the implementation and maintenance of modular satellites [1], the construction of large structures in orbit [2] or even the realization of an in-orbit manufacturing and/or assembly capability [3]. A key part of these activities lies in the use of a standard interconnect, to allow the mechanical, electrical, and thermal connections between different modules and/or serve as standardized interface for robotic applications and tool change. Prominent representatives of such standard interconnects are e.g., the intelligent Space System Interface (iSSI) from iBOSS GmbH [4], the Mating/Demating Device HOTDOCK from Space Application Services [5] or the Standard Interface for Robotic Manipulation (SIROM) from SENER [6][7][8]. While these interconnects were designed for orbital applications, the modularization and reconfiguration of robotic systems for planetary use cases, such as on Moon or Mars, becomes more and more interesting. Especially due to the manned return to the Moon and the goal to provide infrastructure for longer manned stays on the Moon or on Mars in the future. Other than for orbital applications, the variety of standard

interconnects for planetary robotic applications is limited. Current landers and rovers, which are operating on Moon or Mars are designed as monolithic, stand-alone systems, which do not allow any reconfigurability or serviceability. However, NASA's InSight lander [9] was equipped with a robotic Instrument Deployment Arm (IDA), which was equipped with grapple mechanism, allowing to deploy instrument units to the Martian surface. This can already be considered as a standardized mechanical interface to handle system modules. Recently Astrolab introduced its multi-functional Flexible Logistics and Exploration (FLEX) rover [10] which is designed to support multiple mission scenarios, such as equipment or system transport or acting as astronaut vehicle. To allow this multi-purpose applications, the rover is equipped with several interconnects, allowing to dock additional payloads to the rover or extend its functionality by reconfiguration.

The MODKOM project (Modular Components as Building Blocks for Application-specific Configurable Space Robots) is targeting the same general idea by developing a modular building block system [11] and builds up on various results from previous research activities in this area.

MODKOM is developing not only a set of hardware and software modules that will be demonstrated in a composed system, but also software tools to assist non-experts in assembling systems from those modules.

A central aspect is the granularity. This encompasses not only the character and topology of the modules, but also the connectivity between them. The system can be configured and built using these modules that are equipped with and connected by standardized electrical and mechanical interfaces. To make the system more flexible, at least one active electro-mechanical interconnect is included in the toolkit. This interface allows the online reconfiguration of the system to fulfil a wide range of tasks and to even extend its functionality by providing new modules or components, once they are equipped with at least one interface.

For interconnecting the modules of the toolkit, a distinction is made between two primary types of interfaces: inter-modular interfaces (IMIs) and electro-mechanical interconnect MODKOM (EMI-MOD), see also Fig 1.

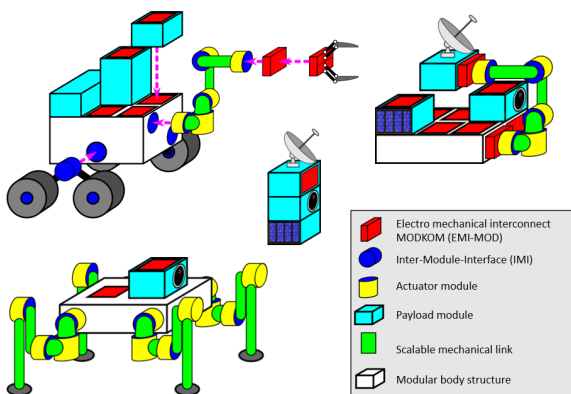


Fig. 1. Building block systematic

The IMIs (blue parts in Fig. 1) are intended to enable mechanical and electronic connections between modules. To facilitate maintenance and testing, the connections should be detachable. They are used to connect modules during configuration and integration of the overall system.

In contrast to the IMI, the EMI-MOD (red parts in Fig. 1) is a multifunctional interface consisting of a mechanical locking mechanism and interfaces for data and electrical power transmission [11]. This interface is used to (re)configure the involved systems as needed during a task or mission.

The predecessor models of the EMI-MOD are designed and conceived from the beginning as a planetary interface, with focus among other things on dust tightness and load cases. In MODKOM, the main focus of the development is also to better withstand

terrestrial conditions in order to provide a better test base for the robotic systems.

Overall, the medium-term goal is to obtain a space-qualified multifunctional interface for planetary applications.

This paper describes the EMI-MOD and how it works, as well as the combination possibilities that arise with the toolkit developed in MODKOM and beyond.

## 2. Electro-Mechanical Interconnect Overview

The development of an electro-mechanical interface (EMI) for reconfiguration in a robotic team with several involved systems started in the project RIMRES (Reconfigurable Integrated Multi-Robot Exploration System) [12]. Here, the EMI was used to couple or decouple the robotic systems with each other as needed at short notice to perform the specified tasks in the team network.

In the follow-up project TransTerra (Semi-autonomous cooperative exploration of planetary surfaces including the installation of a logistic chain as well as consideration of the terrestrial applicability of individual aspects), the EMI was further developed and is still in active use today in its second generation [13].

Field tests in Utah<sup>\*</sup>, Morocco<sup>†</sup> and Lanzarote [14] demonstrated the suitability of the EMI concept.

In order to use the multifunctional interface EMI in the long run and to bring it in the direction of flight ready hardware and software, adaptations are necessary. These enhancements are part of the MODKOM project, in which the third generation of EMI, the EMI-MOD, is being developed.

The EMI-MOD, with dimensions of 150 x 150 mm and height of 60 mm, is responsible for (dis-)connection between the different involved systems, provided they are equipped with at least one EMI-MOD.

While the goal for EMI-MOD is to be applied in lunar environment, the functional demonstrator developed here is shielded against terrestrial weather conditions, to allow extended outdoor usage during field trials. During the development of the EMI-MOD, focus is on robustness against dust and for outdoor use, accurate guiding during the mating of two interfaces, ability to carry high loads of at least 250 N in non-energy-state and limited space. A connection of two sub-systems is always done by mating two different EMI-MOD faces, namely an active part that is typically mounted on the bottom of the manipulator arm or, e.g., payload module, and a passive part that is typically mounted on top of the involved rover or a sub-system. The active part consists of an actuated latch mechanism, a Raspberry Pi camera for the autonomous docking approach, LEDs for illumination and Yokowo electrical contact blocks with pins (Fig. 2).

<sup>\*</sup> <https://www.youtube.com/watch?v=pvKIzldni68>

<sup>†</sup> <https://www.youtube.com/watch?v=-zqve9baOzM>

The passive part consists of a central docking bolt, four rotation protection and guidance pins, spring-loaded electrical connectors and four visual markers for detection through the active interface (Fig. 3)

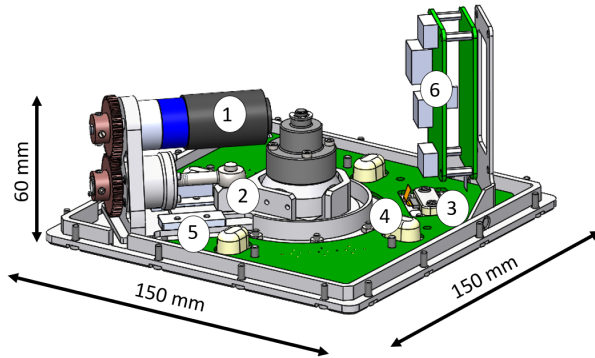


Fig. 2. Active part of the EMI-MOD, consisting of (1) actuator (2) locking mechanism (3) LED (4) counterpart cylinder (5) potentiometer (6) control electronic. Camera and signal blocks are covered below the printed circuit board

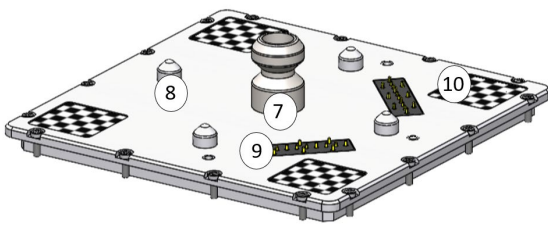


Fig. 3. Passive part of the EMI-MOD, consisting of (7) bolt for latch mechanism (8) guiding pins (9) contact block (10) marker

Both, the passive and active side of the EMI-MOD, have a universal design, which can be mounted on each used robotic system in MODKOM and also on existing robotic systems of German Research Center for Artificial Intelligence - Robotics Innovation Center, (DFKI-RIC), if they are already equipped with the EMI [13]. The dimensions of the mounting holes are such that the EMI-MOD also fits the systems that previously used the EMI. In this way, all systems can be connected to each other.

### 2.1 Locking Device

The locking device is the key component of EMI-MOD. The main components consist of the bolt, also called docking pin, and the locking mechanism. The principle is also known as zero point clamping system (Fig. 4).

As shown in Fig. 3, the bolt is mounted on the passive side. The locking mechanism is on the active side (Fig.

2). During the docking process, both sides are moved towards each other, using a visual servoing method, as outlined in [13] [15]. The bolt penetrates the passage on the active EMI-MOD side and is thus guided together with the locking mechanism. The actuator, Faulhaber 2232U024S R IE2-128 201R23:1, is then activated so that the locking mechanism can close. The locking mechanism, which is designed as zero point clamping system, creates a tight mechanical connection between the EMI-MOD sides whilst it is fully locked.



Fig. 4. Locking mechanism of EMI-MOD, opened (left) and closed (right)

### 2.2 Electronics

The main task of EMI-MOD electronics is to control the mechatronic components, to (de)couple EMI-MOD interconnects and to provide telemetry functions. For this purpose, a printed circuit board (PCB) will be designed using the EMI electronics solutions developed in the previous project and adapted to the current mechanical design and additional requirements of the EMI-MOD.

The matting pads will be soldered directly to the connection main board the active EMI-MOD and will contain an EEPROM (Erasable Programmable Read Only Memory) to store a unique ID of the system using this interconnect. A Power Management Board (PMB) will be used to manage the power bus and control the motor for the latch mechanism using a microcontroller. Furthermore, this microcontroller is equipped with various peripheral devices and therefore can be used to control payloads mounted into the payload-modules [15].

### 2.3 Node-level Data Link Communication

It is planned to use the Node-level Data Link Communication (NDLCom) for the RS422-based low-level communication between two EMI-MODs [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 [16].

### 3. Utilization

Once a robotic system or subsystem is equipped with at least one EMI-MOD, it can be connected to other systems or subsystems that are also equipped with an EMI-MOD. In this way, many configuration options are available.

In MODKOM, various modular subsystems are being developed that can be interconnected. Furthermore, Commercial off-the-shelf (COTS) such as the Rover Hunter SE<sup>‡</sup> (see in Fig. 5) are also used to demonstrate that "externally" developed systems can also be equipped with an EMI-MOD, thus providing an extended configuration option.

In this case, the Hunter SE is equipped with several passive EMI-MODs to which, for example, the manipulator arm, which is equipped with two active EMI-MODs on the end effectors, can dock. In this way, the manipulator arm is connected to the rover and can act as a new system. Other assemblies are base modules and payload modules, which can be interconnected via the EMI-MOD. The manipulator can, for example, pick up the payload modules and, with the help of the rover, set them down at other locations or, for example, connect them to other systems.

The following sections describe the systems planned in MODKOM, all of which are equipped with at least one EMI-MOD to be combined with each other to perform various mission tasks.



Fig. 5. Rover Hunter SE

#### 3.1 Manipulator arm

The aim of the development of the manipulator arm was a design that ensures a high degree of modularity coupled with maximum flexibility in design.

The basic building block is the pan-tilt unit. Here, two drives/degrees of freedom were combined in one housing, which in practice is the most common application of drives in manipulators.

Carbon tubes, which are variable in length, are used to connect the drives. For the application of use on the

mobile platform "Hunter SE" two times a link length of 530 mm was chosen, which connects three pan-tilt units. This results in a total length of 1486 mm between the base and end flanges (Fig. 6). However, this is variable and can be adapted to the task by the length of the carbon tubes.

Active EMI-MOD interfaces are flanged to both ends of the manipulator. This allows the arm to be bridged on the involved systems equipped with a passive EMI-MOD. Due to the equally long connections between the drives, this action is simplified in terms of control methodology.

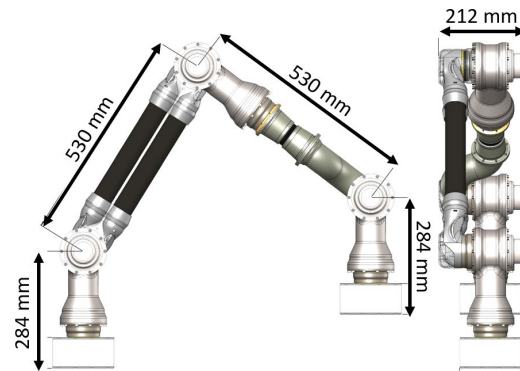


Fig. 6. Manipulator arm

The actuators used are a combination of a Robodrives ILM 70x18 motor and a HarmonicDrive CPL 25A gearbox with a ratio of 1:160. The nominal torque is 170 Nm. The short-time maximum torque is limited to 300 Nm by the gear.

In our application, we require 85 Nm for nominal operation of the manipulator in maximum workspace utilization. This results in a payload of 8.5 kg in normal operation. When manipulating with shorter reach and utilizing the drive potential, payloads of over 20 kg are theoretically possible.

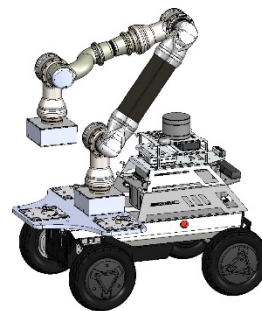


Fig. 7. Manipulator arm docked on an EMI-MOD on top of the rover Hunter SE

<sup>‡</sup> <https://global.agilex.ai/products/hunter-se>

A second, lighter version of the manipulator was also designed. Here, the pan-tilt units are equipped with Robodrive ILM 50x8 and HarmonicDrive CPL 14A. These components are compatible with each other via adapters.

For the positioning of the manipulator on the rover, a base plate is provided, which accommodates the manipulator arm with an EMI-MOD interface and additionally provide three additional EMI-MODs to accommodate payload modules (Fig. 7).

### 3.2 Base Modules

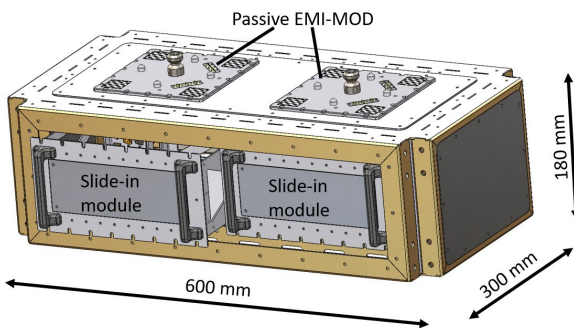


Fig. 8. Base module with two passive EMI-MODs

The base module is a basic structural unit from which larger structures and systems can be built by combining several modules (Fig. 8).

Here, individual basic modules can be combined horizontally and vertically with each other via connection profiles and theoretically extended indefinitely.

At the same time, the basic module is the carrier platform for the electronic modules and other mechanical modules, such as motors, sensors or electromechanical interfaces.

By adding electromechanical interfaces, additional payload modules can be accommodated and data transfer to them can be established. The width (300 mm) of the base modules is exactly half their length (600 mm). The height is 180 mm. This 60 mm basic grid is also used by the plug-in modules.

These EMI-MOD interfaces are in turn connected to an electronics plug-in module. Thus, communication via Ethernet and CAN, as well as the power supply, is guaranteed.

### 3.3 Payload Modules

The payload modules are used to support the project goal and to present various features in the performance demonstration [11].

The payload items developed in a previous project TransTerra [15] are used as a basis, which could be coupled with a dimension of 150mm x 150 mm x 150 mm using the EMI [13]. The dimensions will be adapted accordingly in MODKOM.

Payload modules containing, for example, a stereo camera will be developed, as well as battery payload modules to extend the lifetime of the deployed systems in the performance demonstration.

The payload modules are scalable up to 300 mm x 300 mm footprint. The EMI-MOD remains an integral part to ensure reconfigurability between the modular assemblies and components in MODKOM.

The basic payload module consists of an active EMI-MOD on the bottom and a passive EMI-MOD on the top of a structure. The structure is a frame with moveable side walls for e.g., maintenance and repair or exchange of inner components (Fig. 9).

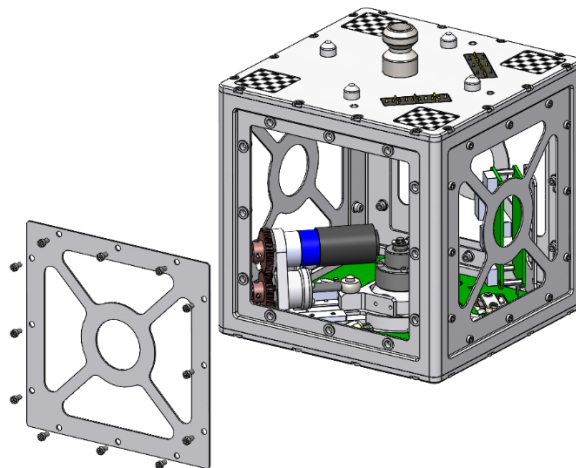


Fig. 9. Basic payload module

The following three payload modules with corresponding equipment have been designed for the performance demonstration:

#### 3.3.1 Stereo Camera Module

A stereo camera module with integrated gimbal for image stabilization is planned for system reconfiguration purposes, by combining the module with the modular manipulator via EMI-MOD to create a camera mast and mobile platform to extend the functionality of the system.

#### 3.3.2 Processing and Communication Module

The processing and communication module will be equipped with an on-board computer and mesh capable communication module. The module can therefore be used to gain additional processing power on a given system, e.g., for pre-processing of high demanding sensor data streams. The additional mesh capable communication module enables to integrate the payload module into a given communication network and even extend it, as soon as a new system entity is formed. By using the equipped EMI-MOD, the processing and communication module can be combined with other systems to increase the mission tasks.

### 3.3.3 Environmental Sensor and Power Module

This module consists of various environmental sensors for different gases, temperature and humidity and holds its own battery pack to act as a range extender or to provide power for a new system entity. The module was previously developed and tested and is described in more detail in [15]. The module will be used to demonstrate the creation and integration of new systems entities by mating via EMI-MOD with the processing and communication module.

### 3.4 Adaptation of an external multifunctional interconnect

It is expected that future planetary and also orbital missions with different robotic systems will also involve systems that use other multifunctional interfaces for interconnection. To become compatible with such systems, it is planned to build an external multifunctional interface with the EMI-MOD in form of an adapter to demonstrate the feasibility.

In MODKOM the intelligent Space System Interface (iSSI®) from iBOSS GmbH is used for this demonstration (Fig. 10) [4].

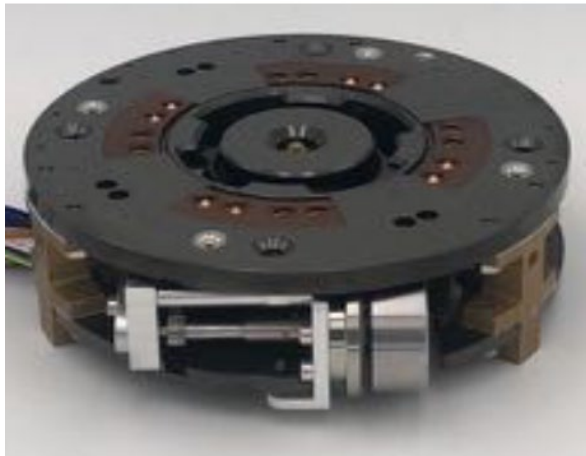


Fig. 10. Active iSSI® from iBOSS GmbH [4]

For this purpose, an adapter is being developed that combines the passive EMI-MOD and the active iSSI® within a structural frame (Fig. 11).

The passive EMI-MOD on top of this adapter can be docked to the end effector of the manipulator arm. Once docked the iSSI® serves as the end effector of the manipulator arm and can be used to grasp systems equipped with an iSSI®.

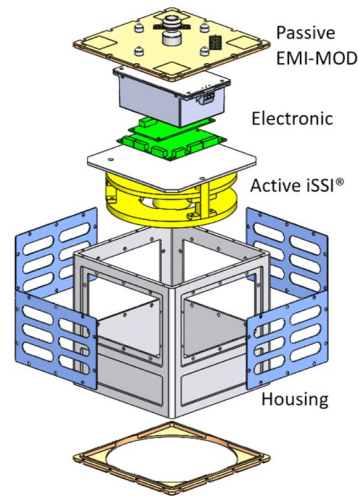


Fig. 11. Exploded view of adapter EMI-MOD with iSSI®

## 5. Interface Management

During the development of the EMI-MOD an interface management was introduced to help manage product development and achieve functional as well as physical compatibility between interconnected components in a product tree of each new component of the project, especially when efforts are distributed among different teams.

The objective of this process was to define a common and systematic approach to achieve the objectives of the project on time and within the defined budget. For this purpose, a template for an Interface Control Document (ICD) has been defined using the templates/sample documents described "tailor-made" for the purposes of the project:

- A list of all interfaces to be identified based on a product architecture definition,
- requirements for the identified interfaces derived from the overarching requirements and the functional, logical and physical architecture decomposition, as well as the verification requirements,
- a definition of the identified interfaces that is consistent with the applicable interface requirements and ensures compatibility between the modules involved.

The identified interfaces are grouped by discipline: i.e. electrical, mechanical, data and software. The document serves as a supplement to the module database for the documentation and definition of the modular units.

Table 1 shows an excerpt from the ICD with one example each from the involved disciplines electronics (EL), mechanics (MECH) and software (SW).

Table 1. Lists of the example requirements for the electrical, mechanical, data and software interfaces.

Requirement ID	Interface ID	Name	Description	Responsible	Verification method	Document type	Remark
EL-REQ-01	EL_IF-02 / 04	Nominal voltage	48V	Name	Test with power supply	Paper	[17]
MECH-REQ-02	MECH-IF-02	Max. load	Static max. load is 1.3 kN	Name	Load Test	Paper	[13]
DATA-REQ-03	Data -IF-02	serial NDL-COM Protocol	Communication between modules: NDLCOM protocol	Name	Speed test using NDLCOM Common GUI	Link	<a href="https://tinyurl.com/es-ndlcom">https://tinyurl.com/es-ndlcom</a>
SW-REQ-02	SW-IF-03	Rasp-berry-PI OS	Raspbian	Name	System function test	Link	<a href="https://www.raspberrypi.com/software/">https://www.raspberrypi.com/software/</a>

The requirement ID refers to the respective requirement on the system, the interface ID refers to the property or interface on the system. In the example EL-IF-02 / 04 it is about the electrical property "nominal voltage of 48 V. The verification method column lists how the respective property was determined. In the case of EL\_IF-02/04 the nominal voltage was tested with a power supply. The result can be found in the "Document Type" paper, the referenced paper is listed in the "remark" line.

### 5. Demonstration of Integration and Application

The demonstration starts with the base module equipped with the modular manipulator and all modular payload modules (processing and communication module, environmental and power module and stereo camera module) connected by EMI-MOD.

The mobile rover platform is leaving in its initial condition. After approaching the base module, the manipulator will grasp the processing and environmental sensor module via EMI-MOD and transfer it to the rover.

To enable this transfer, the rover has to communicate its position and orientation with respect to the base module, as it is the system carrying the mapping sensors while the manipulator has only close range visual servoing capabilities for EMI-MOD connection.

After the payload module transfer, the manipulator is supposed to switch its system from the base module to the rover by moving from EMI-MOD (base module) to EMI-MOD (rover platform). This new robotic device has now to be loaded and activated in the rover's operational layer to support the full reconfigured system. From the rover, the manipulator will dock with its EMI-MOD to the stereo camera payload module, demonstrating a successful system switch and recognition of the manipulators orientation and adaption of its kinematic

model accordingly, plus potentially integrating the additional DOF of the attached payload module.

From here the fully equipped mobile rover will head to a pre-defined location, while demonstrating the stereo-camera mast during traversal. At the goal position, the camera will be decoupled from the EMI-MOD of the manipulator and stored on the rover's deck. Now, the stack of the processor and communications module connected to the environmental sensor and power module will be deployed from the rover and activated as a new system. In this sense, a new system entity has to be created within the module management, being able to act as additional communication node and providing environmental sensor data [11].

### 6. Conclusion and Outlook

The multifunctional interface EMI-MOD developed within the project MODKOM in 3rd generation consists of an active and passive side. Robotic systems can be mechanically interconnected via these two sides if they are equipped with an EMI-MOD. After the mechanical coupling, electrical and data transmission takes place.

Different robotic systems, such as manipulator arm, base module, payload module, etc. can be configured with each other using the EMI-MOD so that new systems can be created to perform different tasks. The Rover Hunter SE presented in the paper demonstrates that COTS can also be equipped with an EMI-MOD and thus be extended with other systems, such as the manipulator arm or payload modules.

The EMI-MOD is designed to carry at least 250 N load. Heavy load tests are intended to test what maximum static load can be carried by the EMI-MOD, as well as under what load the locking mechanism still opens. Further planned tests include dust tests, misalignment tests and implementation of the software developed in

MODKOM for carrying out the performance demonstration.

Further planned tests include dust tests, misalignment tests and implementation of the software developed in MODKOM for carrying out the performance demonstration with the various robotic mobile and immobile systems that are developed or purchased in MODKOM. The EMI-MOD development will serve as the basis for further development towards the qualification model for space applications.

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