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Enhanced multifunctional interface for reconfigurability of robotic teams in planetary applications

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***Abstract*—Exploration missions on extra terrestrial celestial bodies are to date performed by complex and heavy robotic systems. The trend is towards lighter modular systems that can be (re)configured in situ according to mission specific requirements. To facilitate flexible configurability, a multifunctional interconnect is used to mechanically couple the involved systems while providing electrical power and data transmission. The paper presents the further development of the reliable electro-mechanical interface (EMI) from the TransTerrA project, which has been proven in several field tests and reached TRL 4. Docking under loads of up to 550 N has been successfully tested with the new design. The experiments presented include undocking at various inclinations with different loads expected for the application scenario. The maximum determined static load that can be carried by the further developed EMI is 2000 N. In further experiments, new contact blocks responsible for the transfer of electrical power and data were tested for water resistance and resilience to environmental factors, as well as power and data transfer. The obtained results will be helpful in the development of a multi-functional interface suitable for lunar applications and missions having similar challenging environmental conditions.**

***Index Terms*—Planetary robotics, interface, modularity, docking, lunar environment**

I. INTRODUCTION

Driven by the increasing desire for knowledge and search for past life on planets other than Earth, the complexity of space missions dedicated to planetary exploration, such as the Mars 2020 mission, has increased dramatically compared to those launched in the early days of space exploration. As the complexity of missions has increased, so has the complexity of the robotic systems involved, such as the Mars 2020 Perseverance Rover, while the reliability, robustness, and cost-effectiveness of these same systems have had to remain the same to ensure the successful completion of these missions and their return on investment [1]. This has led to the development of unique, single-use, highly integrated systems where reliability is achieved through redundancy and the use of high-reliability components. However, due to the very nature of spaceflight and the limitations it imposes in terms of mass, lifetime, and ultimately cost, this paradigm is bound to fail as the complexity of involved systems increases.

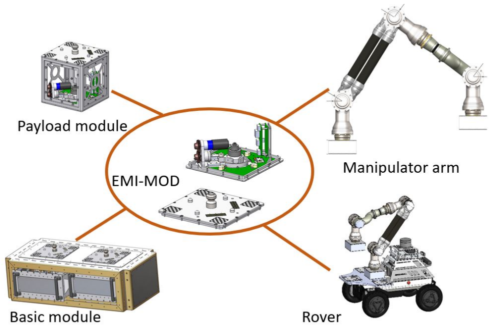

Fig. 1. Interconnection of the robotic systems in MODKOM

A paradigm shift in the system design of planetary rovers (robotic systems) is needed to ensure more cost-effective and flexible systems despite their increasing complexity. This paradigm shift needs to move away from unique, single-use, highly integrated space systems towards low-cost modular systems composed of multiple heterogeneous modules that can be connected via one or more multifunctional interfaces.

In the European context, this paradigm shift has been

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explored in the past in the projects Standard Interface for Robotic Manipulation of Payloads in Future Space Missions (SIROM) [2] and Cooperative Robots for Extreme Environments (CoRob-X) [3], where the multifunctional interfaces SIROM [4] and HOTDOCK [5], respectively, have been used to enable modular, flexible yet cost-effective robotic systems. At international level, the development of multifunctional interconnects for flexible applications in the orbital environment has not yet been pursued in a targeted manner. The literature tends to contain interconnects with few features (see Table 1 in [6]). PetLock [7] is based on the European developments mentioned above.

However, both SIROM and HOTDOCK were designed primarily for orbital applications where dust and humidity are not a concern. Therefore, in their current form, they are found not to be suitable for planetary applications.

In contrast, the electro-mechanical interface (EMI) was developed with a focus on terrestrial and extra terrestrial applications bridging the gap in the current European state of the art. The main features are dust tightness, autonomous docking using the visual servoing method, docking and undocking under load using a mechanical locking mechanism which is designed to hold a load when closed and de-energized, and transmission of electrical power and data [8].

This EMI will be further developed in the MODKOM project (Modular Components as Building Blocks for Application-specific Configurable Space Robots) as the third generation: the electro-mechanical interconnect MODKOM (EMI-MOD). As part of the MODKOM project, the goal for EMI-MOD is to combine different robot systems to extend exploration capabilities with the involved systems (i) payload model, (ii) basic module, (iii) manipulator arm and (iv) a rover (see Fig. 1) [9]. In this way, maximum modularity and flexibility is possible. The EMI-MOD is based on a gender-principle approach with one active and one passive face to be mated [8]. The structure of the remaining paper consists of the following sections. Section II is dedicated to the description of the EMI-MOD, Section III presents the experiments/tests performed so far on the available prototypes as well as the results. Finally, Section IV provides a summary of the content of the paper and gives an outlook.

II. ELECTRO-MECHANICAL INTERCONNECT

The EMI-MOD presented in this paper is a further development of the EMI from TransTerrA [8] and was modified with regard to the requirements of the new scenario and shortcomings identified when working with the previous design. During the development of the EMI-MOD, the main concerns were robustness against dust, accurate guidance when mating two interfaces, the ability to support heavy loads in the non-energy state, and the limited space within a cubic payload module. A connection of two subsystems is always done by mating two different EMI-MOD surfaces, i.e., an active part that is usually on the bottom of a robot or payload module and a passive part that is usually on top of a subsystem or payload module.

The footprint of the EMI-MOD plates is $150\text{x}150\,\text{mm}$ (see Fig. 3-left) and is based on the footprint of the EMI [8]. This has the purpose that the EMI can be exchanged for an EMI-MOD on already existing robotic systems to keep all systems up to date.

A. Active EMI-MOD

The active part of the EMI-MOD (see Fig. 2), mainly consists of an actuator (Faulhaber 2232U024S R IE2-128 201R23:1) that drives the locking mechanism. The aforementioned actuator has been used since the first version of the EMI [10]. It was chosen for its performance, which ensures the opening of the locking mechanism at higher loads, and for its small size. An integrated $8\,\text{Mpx}$ camera with a Mobile Industry Processor Interface (MIPI)-Camera Serial Interface (CSI)-2 enables autonomous docking. The camera is protected against dust and scratches on the open side with an extra transparent cover. Equipped LEDs provides required illumination to the docking process.

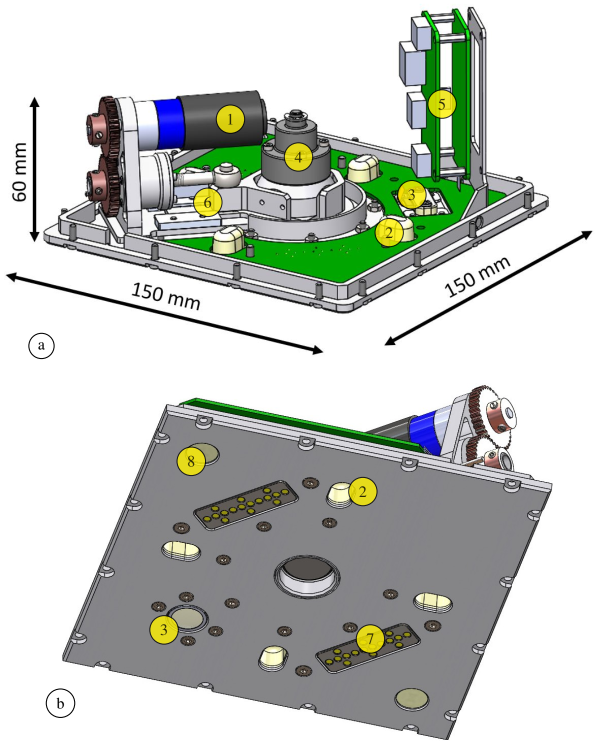

Fig. 2. EMI-MOD active side. (a) inside with 1) actuator, 2) counterpart cylinder for guiding pins, 3) camera, 4) active locking mechanism, 5) control electronic and 6) potentiometer (b) outside with 2) counterpart hole for guiding pins, 3) camera and its cover, 7) signal block and 8) LED

The active side is also equipped with two Yokowo mating pads containing flat contact pins for power and data transfer. The alignment of the mating pads allow one Yokowo pogo pin connector on the opposite side of the EMI-MOD (passive side) to make contact at every 90° step.

B. Passive EMI-MOD

The passive side of EMI-MOD has mainly a bolt for the mechanical connection with the active side (see Fig. 3),

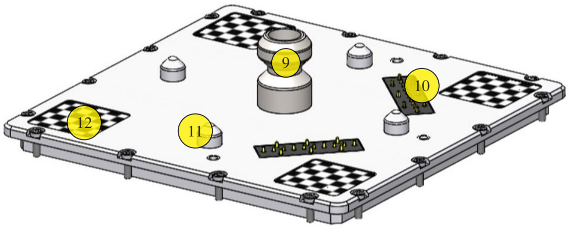

Fig. 3. EMI-MOD passive side with 9) central bolt, 10) connector with spring-loaded contact probes, 11) guiding pin and 12) marker

two Yokowo pogo pin connectors with spring-loaded contact probes and four guiding pins. The markers located on the passive side of the EMI-MOD are used for orientation determination. The docking process is performed with the visual servoing method.

C. *Locking Mechanism*

The locking mechanism is the key component of EMI-MOD and consists of a central bolt on the passive EMI-MOD side and the locking mechanism on the active EMI-MOD side (see Fig. 4). The two main design goals are (i) effective dust resistance and (ii) no energy consumption in either closed or opened state. Thus, the locking mechanism will be protected against particles by a dust cover. The two semicircular clamps driven by a spindle drive activated by the actuator ensure the connection of the central bolt after the docking process. 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.

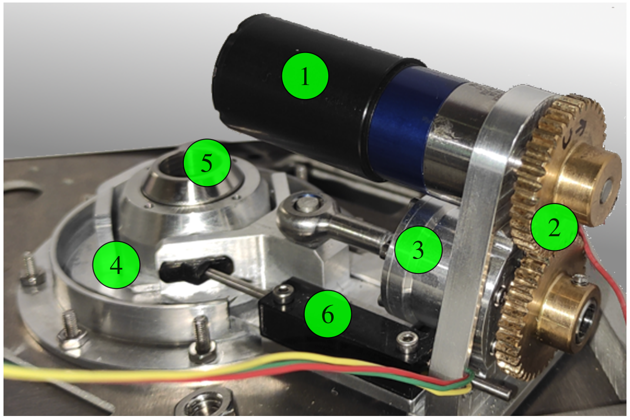

Fig. 4. EMI-MOD Locking mechanism consisting of (1) actuator (2) gears (3) spindle drive (4) semicircular clamps (5) bolt from counterpart of EMI-MOD (6) position sensor.

D. *Docking Procedure*

The docking procedure between two EMI-MODs can be divided into four steps described below. The first step is the detection of the relative pose using a visual servoing approach. The process, in order to bring both interfaces into a predefined relative pose to each other, is mainly performed by the end effector (active EMI-MOD) of the manipulator arm. In the second step, a ”blind docking” starts by a known change of poses in order to bring the two interfaces together. The tolerance can be accommodated by the mechanical design of the two interfaces. The design of both parts of the EMI-MOD allows mechanical uncertainty in horizontal positioning of $\pm 2.5\,\mathrm{mm}$ between the top of the bolt on the passive side to the counterpart hole on the active EMI-MOD and a rotational misalignment of 4° (see Fig. 5). An initial misalignment of 15° is allowed by the mechanical design. The third locking step begins when the bolt is inserted into the locking mechanism. After that, the fourth step begins with power bus activation and the start of communication. The disconnection is conducted in reverse order.

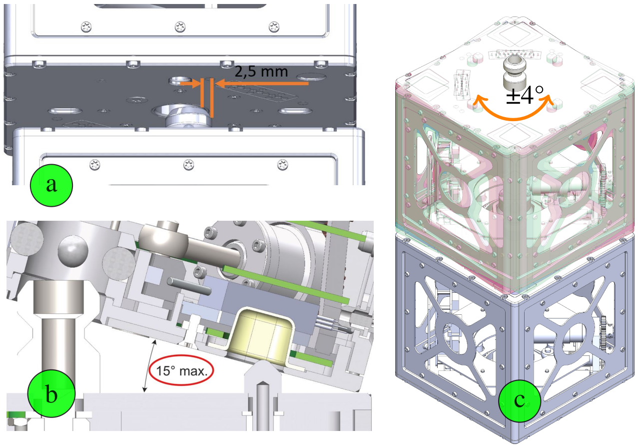

Fig. 5. CAD renderings of EMI-MOD misalignment tolerance for the locking mechanism. a) horizontal misalignment, b) initial misalignment, c) rotational misalignment

E. *Technical Improvements in the EMI-MOD Design*

The EMI-MOD interface was further developed mechanically and electrically on the second generation of the EMI [8]. An important mechanical improvement was the locking mechanism that can compensate misalignments of at least 2 mm in x- and y direction as well as a rotational misalignment of 4° and an initial misalignment of 15° during the docking process (see Fig. 5). By designing the locking mechanism as a zero point clamping system, tighter couplings are possible compared to the previous EMI, allowing less to no wiggle contact between the mating pad and the pogo pin connector. Furthermore, the previous electrical contact blocks were assembled by hand and made up of individual pins (Fig. 9 b). The production process was very difficult and had a great impact on the cost. A Commercial off-the-shelf (COTS) product, the mating pad and pogo pin connector from Yokowo as pair[1,2] with 16 pins and $3.75\,\mathrm{mm}$ pitch and with a $50\,\mathrm{m\Omega}$ contact resistance as well as IPx7 conform for USB3.1(Gen2) was found as cost-effective and efficient solution form. The Yokowo pair is 18 times cheaper than the previously used contact block pairs from Feinmetall.

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[1] https://tinyurl.com/yokowo-S-J-2600XG

[2] https://tinyurl.com/yokowo-S-J-6717XG

III. EXPERIMENTS

The tests carried out were mainly focused on analyzing the functionality of the mechanical coupling, electrical and data transfer as well as different physical tests with the Yokowo mating pads and pogo pin connectors. To evaluate the mechanical robustness of the EMI-MOD, two series of experiments were conducted: (i) opening and closing of the locking mechanism under load and (ii) continuity and the repeatability of the locking mechanism operation after consecutive series of lock/release cycles As mentioned earlier, the EMI-MOD is the third generation of the EMI. In order to obtain a direct comparison with the previous version, the locking mechanism should be able to open at least 250 N under load and be able to carry at least 1800 N static load. When conducting the electrical tests, the focus was on determining the electrical performance and data on the Yokowo contact blocks. The main objective was to find out whether the same or better performance is achieved than with the contact blocks from the predecessor EMI. Furthermore, these contact blocks have been tested under water and dirt conditions.

A. Heavy Load Tests

The test stand has been specially designed to allow both static and dynamic load testing for EMI-MOD in different slopes from 0° up to 30°.

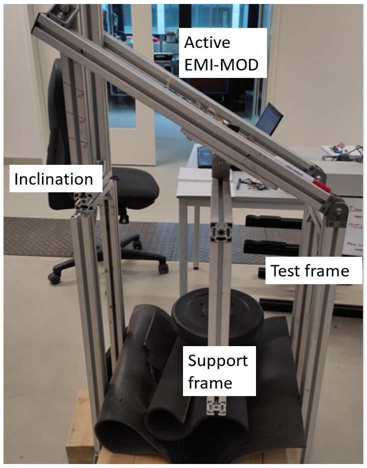

Fig. 6. Test setup for undocking the active EMI-MOD under load in different inclinations

For the heavy load test, a support frame is fixed to a central pin of the passive EMI-MOD. The support frame carries weight discs to generate different loads for opening and closing of the active EMI-MOD. The active EMI-MOD is mounted on the rigid test frame and operated by the electronics that is used in toolbox components for operating the EMI-MOD. The support frame with the central pin is placed below the EMI-MOD so that it is lifted by closing the locking mechanism (see Fig. 4) and then, the full weight is lifted and carried by the clamps. During the opening under load, the support frame can fall down freely. The test procedure for the ”undocking under load” tests were performed in 5 kg increments from 0 to 45 kg and in the different angles in 5° increments up to 25°. The power consumption and the time it took the locking mechanism to open under load were measured. The power is switched off while the load is attached to the closed locking mechanism. Specifically, the power is then 0 W. Power is only required when the locking mechanism is to be opened. When opening the locking mechanism, when no load is attached to the locking mechanism, a power of 5.678 W is required at any inclination.

TABLE I
POWER CONSUMPTION (W) BY LATCHING FOR 0 TO 25 DEGREE INCLINATION AS PERFORMANCE CRITERIA

Mass (kg)	0 Deg	10 Deg	15 Deg	20 Deg	25 Deg
0	5,678	5,678	5,678	5,678	5,678
5	5,4288	5,536	5,1168	5,4528	5,112
10	5,2896	5,52	5,0592	5,2368	5,064
15	5,6208	5,2896	5,3328	5,4912	N/A
20	5,9376	5,64	5,5728	5,6256	N/A
25	6,388	5,904	6,1968	N/A	N/A
34	6.1968	N/A	N/A	N/A	N/A
45	7.062	N/A	N/A	N/A	N/A

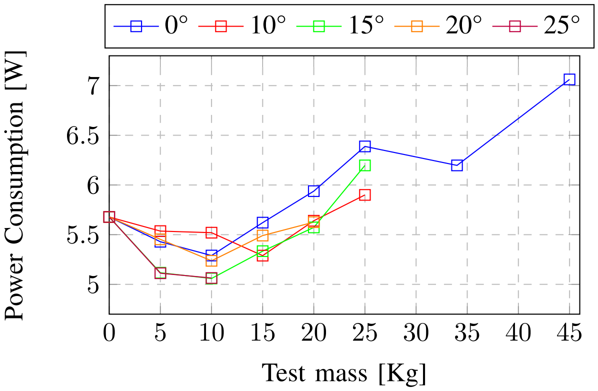

Fig. 7. Power consumption (W) during undocking under load at 0° to 25° inclination

Figure 6 shows the experiment setup with a horizontally displaced EMI-MOD with slope of 30° and a small weight on the support frame, which together results in 150 N. Figure 7 shows the power consumption in W depending on the load and inclination. Each test case was tested at least 10 times. The determined power consumption values in the Table I are average values. It can be seen that with increasing inclination the maximum load decreases. At 0° it is 45 kg, at 25° only 10 kg.The power consumption increases with increasing load, but does not change with inclination. This shows that the power consumption depends on the load and not on the inclination.

B. Continuity Test

In space environment, there might be scenarios requiring consecutive open/close cycles of the latch from EMI-MOD. Those consecutive cycles might be detrimental for EMI-MOD, due to incidents like software faults, communication errors, mechanical drifts over time, and so forth. Therefore, a necessity for a test bench to analyze the continuity and repeatability of EMI-MOD arose.

A test bench consisting of Active EMI-MOD, Passive EMI-MOD surface, data cables, and a computer, was set up for the above-mentioned purposes. Contact surfaces of both Active and Passive EMI-MOD were thoroughly cleaned. The Passive EMI-MOD was placed under Active EMI-MOD and aligned with the latch, to be locked/released from it, under the control of Active EMI-MOD. The latch lock/release cycle was made 1000 times by sending commands from the computer to Active EMI-MOD. Once Active EMI-MOD receives the command, it couples or releases the latch, and then sends the measurement of power dissipated and time elapsed throughout the execution to the computer, through Node Level Data Link Communication (NDLcom) protocol. The computer logs incoming measurement messages and evaluates them.

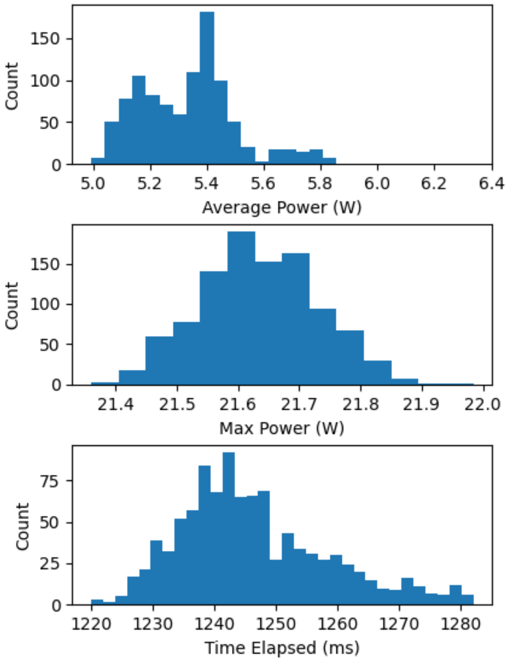

Fig. 8. Power and time consumption analysis of the continuity latching test.

The continuity and repeatability analyses of EMI-MOD were performed by inspecting power and time consumption of each lock-release cycle. Any discrepancies and erroneous incidents on each lock-release cycle were expected to be appeared on deviation from the average consumption behavior. According to results shown in Figure 8, the mean values are: 5.313 W for average power consumption, 21.632 W for maximum power consumption, and 1246.445 ms for time elapsed. Notice that the measurements taken during the release were filtered out because locking the latch consumes more power due to the increasing effort on the mechanics. Maximum power consumption is approximately four times larger than average power consumption, due to the above-mentioned increasing effort at the mechanics after latching. Having low standard deviation values for maximum power (0.479 %) and time elapsed (0.976 %) indicates physical and mechanical repeatability of EMI-MOD since these values are highly dependent on its physical properties. As for average power consumption, having a larger standard deviation value (3.412 %) is the expected result because of the variation of the starting torque value of the motor in each lock/release cycle and the intrinsic accumulation of other standard deviation values. Figure 8 shows that, there is no significant deviation from the average consumption behavior, which is an indication of continuous and repeatable behavior of EMI-MOD.

In light of this information, EMI-MOD can be claimed to be highly durable and repeatable. In comparison to its predecessor EMI, EMI-MOD is a stronger replacement of EMI due to higher power consumption and lower time elapsed values [8]. As given in Section II-C, one of the design goals of EMI-MOD is to continue its operation under high-level dirt contamination in the space environment. Therefore, in the near future, a dirt contamination analysis of EMI-MOD is planned to be carried out.

C. Electrical Tests

Electrical tests were performed to find out the suitability of the selected slots to meet the requirements of the MODKOM project.

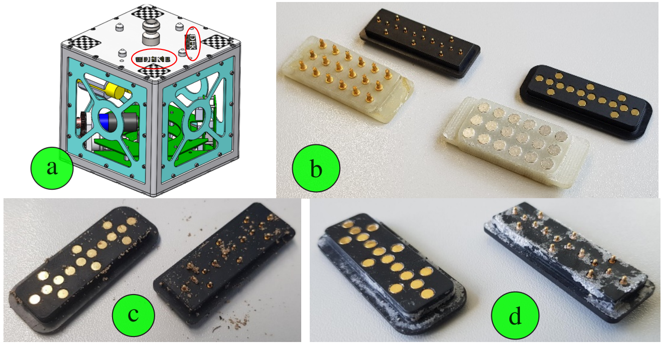

Fig. 9. Physical tests of contact blocks. a). EMI-MOD design with the contact blocks from YOKOWO on the interface contact surface, highlighted in red colour. b). Comparison of EMI (white) and EMI-MOD (black) contact blocks. c-d). 48 hours long term test of EMI-MOD contact blocks under different environmental factors. c). Water with sand, d). Salty water concentrate 0.9 %.

For this purpose, the mating pads (see Fig. 9-a) were subjected to a four-step series of tests. These tests are physical comparison, waterproofing and resilience to environmental factors, power transfer and temperature development, and data transfer tests. As a physical comparison, the previous pogo pins and the new mating pad solutions were compared in terms of dimensions and mass.

Although the surface area of both solutions is similar, the mating pad is about 54 to 79 (in total ca. 70) percent lighter and half the thickness for the female side (see Fig. 9-b). In addition, the mating pad can be integrated into the PCB thanks to its soldering extensions, making it easy to assemble. Although the 18/16 ratio in the number of pins is

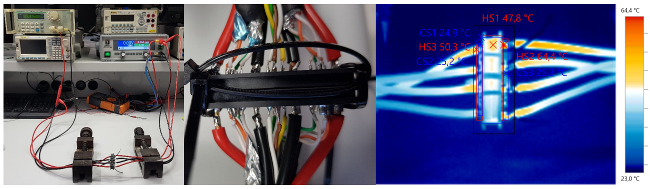

Fig. 10. Test setup for the power transmission over EMI-MOD contact blocks in laboratory-environment (left). Preparation of the contact blocks and holding the contact surfaces together in the test setup (center). Temperature measurement on the contact blocks at 2x10 A transmission after 10 minutes (right).

a disadvantage for the mating pad, it outperformed in comparison due to the suitability to the requirements and other advantages derived from other test results mentioned below. As part of the waterproofing and resilience to environmental factors, we tested the mating pads in different environmental factors such as water, sand, and salt. Although water is not an additional factor of a planetary application, water resistance is a consideration in the preliminary testing of the designed interface in construction and outdoor testing. For this purpose, in the surface water proofing test, the contact surfaces were exposed to water in the form of drops and no leakage or wetness was observed on the underlays. Thus, the matching pads were considered to be waterproof. The contact surfaces were then exposed to water and sand (see Fig. 9-c) followed by a 0.9 percent saline solution (see Fig. 9-d) for 48 hours to see if this caused any problems. In both tests, as expected, the contacts were initially contaminated, but mechanical stress on the surface tests showed that once the dirt was removed, there were no problems such as corrosion that could affect the operation of the mating pads. In order to be able to remove dust in the future, a blowing system is being developed which blows the dust away from the surface before docking. To perform the electrical tests, the mating pads were configured in the following way. 4 of the 16 pins were used for power transfer in 2 channels. The other 12 pins were tested together for two 4-wire $100\,\mathrm{Mbps}$ Ethernet and one 4-wire for RS422 communication (see Fig. 10-center). We did not encounter any problems with thermal development when we did not exceed $2\,\mathrm{A}$ within the limits given by the manufacturer for mating pads in electrical energy transmission for a test duration of 50 minutes. The same test was performed for 10 minutes for $2\mathrm{x}10\,\mathrm{A}$ above the manufacturer's limits to understand the functionality of the interface under worst-case conditions. It was observed that the temperature increased from $22.2\,^{\circ}\mathrm{C}$ to $47.8\,^{\circ}\mathrm{C}$ under laboratory conditions (see Fig. 10-left), but this difference did not cause any deformation (see Fig. 10-right).

The data transfer test of EMI-MOD mating pad plates were carried out under a current load of $2\mathrm{x}2\,\mathrm{A}$ with a looped Ethernet link of 2 channels up to $100\,\mathrm{Mbps}$ and without/with an additional RS422 link on NDLcom [11] protocol with a speed up to $1\,\mathrm{Mbps}$.

The Ethernet test was performed with the method we used in our previous works [12]. For the nominal Ethernet connection without RS422, a speed range of $90\,\mathrm{Mbps}$-$93\,\mathrm{Mbps}$ was achieved. The test with RS422 communication achieved an average speed of $89.5\,\mathrm{Mbps}$ for Ethernet. In addition, the error rate based on the RS422 miss event was measured to be $0.7\,\%$. This measured higher than with the new mating pads and $2.1\,\%$ higher than with the old pogo pins with the direct connection. According to these results, it can be concluded that the new mating pads meet the requirements and perform better than the old pogo pin solution.

IV. CONCLUSION

This paper highlights the improvements introduced in an upgraded electro-mechanical interconnect MODKOM (EMI-MOD) used in modular robot systems. The mechanical and electrical improvements made to EMI-MOD have benefited the interface in terms of misalignment tolerance and operational stability. The experiments performed are reproducible under laboratory conditions to prove these properties and demonstrate the functionality of the interface at this level. The design of the locking mechanism enable to carry a static load of 2000 N in non-energy state. More is maybe possible, the test setup, or more precisely the test frame, limited the raise of more weight. Undocking under load is possible up to 45 kg in 0° and up to 10 kg at 25° only 10 kg. For future experiments, operation in a dusty and dirty environment will be considered. Thus, a blowing system is being developed that blows the dust away from the surface before docking. The selected contact blocks from Yokowo have been tested for electrical performance and data transfer as well as for stability against influences such as dirt and water. Different water mixtures with sand and salt did not affect the properties of the mating pads and pogi pin connectors. Thus, the selected electrical contact blocks are rated as very suitable for upcoming field tests. Based on the results, the EMI interface will be further developed in this and future projects.

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