Heterogeneous Modules with a Homogeneous Electromechanical Interface in Multi-Module Systems for Space Exploration

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Abstract— **The work presented in this paper is part of the RIMRES[1] project. We describe the design and development of an electromechanical interface for combining heterogeneous modules. The interface has a male and a female face and allows docking in 90-degree steps. The developed concept guarantees a secure connecting and disconnecting in rough environments with fine dust as existing on celestial bodies such as Mars and Moon. A short introduction into the project RIMRES is given with focus on the modularity of the system. After providing the design considerations for the interface, experimental results with the hardware are presented. The experiments show that the interface is capable of operating mechanically with heavy loads of up to 40 kg. The proposed latch mechanism tolerates layers of dust of up to 2 mm. Thus, an electrical as well as mechanical connection in dusty environments is realized.**

I. Introduction

Multi-module systems can change their shape and functionality by adding or removing modules. In this way, modular systems can be dynamically adapted to unforeseen tasks. The majority of current developments is in the field of homogeneous reconfigurable multi-robot systems. These systems make use of a high number of modules of one distinct type. These modules, typically with one or two degrees of freedom, can be found in systems like M-TRAN [1], ATRON [2], SuperBot [3], and CKBot [4].

There are other concepts where a main system's functionality can be enhanced or extended by adding various payload modules. The main system is fully functional by itself and already covers key functionalities such as locomotion. Each limb of the ATHLETE [5] with six degrees of freedom, for example, is equipped with a quick-disconnect tool adapter, so that it can be used as general purpose manipulator which can perform different tasks with various tools.

The XROB [6] study by the European Space Agency (ESA) analyzes the needs for exploration missions and defines robotic concepts that can fulfill these needs in a cost-efficient way. The authors conclude that modular robotic systems are essential for exploration tasks to limit load, cost, and development time. In their preliminary modular system concept, they declare standardized interfaces as crucial for manipulating as well as for mechanically and functionally connecting modules to the main system.

The goal of the project RIMRES is to develop key technologies for modular reconfigurable robot systems for extraterrestrial exploration missions and to demonstrate them under earth conditions. The robotic system consists of mobile units to explore extraterrestrial surfaces as well as immobile payload items which either can be stacked to form a scientific package or connected to the mobile units to enhance their functionality or to extend their life cycles [7], [8].

Planetary exploration involves additional difficulties which the RIMRES system has to resolve. The communication delay especially to Mars complicates tele-control, so an intelligent autonomous behavior is needed to automatically explore the surface and deploy scientific payloads [9]. In particular fine dust is a serious threat [10], especially when using a modular system which needs to dock and undock its modular elements to use its full potential. This has also been identified for the PolyBot-system [11], however, this requirement has not been taken into special account in the design of the interface for the modules. In the future, the SINGO connector [12] for the SuperBot system shall be improved to endure dirt. In literature, heavy-duty capability is more common, like the DRAGON connector [13] which can hold over 70 kg load or the active connection mechanism based on physical latching by Sproewitz et al. [14]. The design of the electromechanical interface (EMI) for the RIMRES system pays special attention to the robustness and dust-resistance of the mechanical latching mechanism and the electric connections.

The paper is structured as follows: The basic concept of the overall system is given in section II. The requirements for the interface in the context of the RIMRES system as well as its design are given in section III. The experiments for verifying the interface and their results are provided in section IV. The last section concludes the paper and gives an outlook on future work.

II. Modular Concept of RIMRES

The multi-module system RIMRES consists of mobile units and immobile payload items (see Fig. 1). The rover Sherpa[2] provides four wheeled legs for energy-efficient locomotion in lunar landscapes. It is the main system which is able to carry all other modules and to deploy payload items with a manipulator arm on its back. The walking robot CREX[3] serves as scout and can climb steep inclines to reach areas which the rover cannot access.

[1]Reconfigurable Integrated Multi-Robot Exploration System

[2]Sherpa: Expandable Rover for Planetary Applications

[3]Crater Explorer

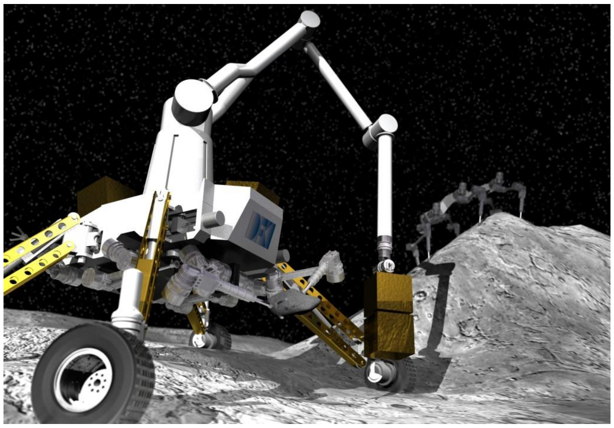


Fig. 1. Artist drawing of the RIMRES system. One legged scout is climbing a steep slope while a second is mounted beneath the rover. The wheeled rover is deploying a stack of two payload items on the surface.

The payload items can be arranged to autonomous module stacks as well as to enhance the performance of the mobile units by providing extra energy, communication, or sensors [7]. For an independent configuration of the modular system, an EMI is developed to exchange data and energy among all kinds of modules and to securely connect them. Each payload item is equipped with one EMI on the top side and one on the bottom side. Sherpa makes use of four docking bays with integrated EMIs on the back for transporting payload items, one EMI on the bottom to connect to the scout and one EMI as end effector of the manipulator arm. CREX has one EMI on its back to connect to the rover and to carry payload items.

A. Communication

Communication plays a significant role in modular robotic systems. Varying communication approaches are applied in many developed multi-robot systems, e.g., SuperBot [3] with local communication (infrared), M-TRAN II [1] with global communication (Controller Area Network), and CKBot [4] with local and global communication. By reason of the heterogeneity of the RIMRES modules, diverse channels are employed to cover different communication levels as outlined in Fig. 2. The proposed components were chosen for an earth demonstrator, but can easily be exchanged for a flight system.

1) *Local Communication* is used to exchange simple, yet important information between neighboring modules, e.g., identification and fitness status of modules. The acquired information makes cooperation and topology recovery of a formed subsystem possible. The widely used infrared approach is not suitable for application in dusty environments, since the communication channel can easily be obstructed by loosely bound dust. In order to implement a reliable data connection, EIA RS-422 using balanced signaling is employed as physical transmission layer for local inter-module communication. The information acquired over this channel facilitates many other applications in the system, e.g., docking and power sharing among the modules.

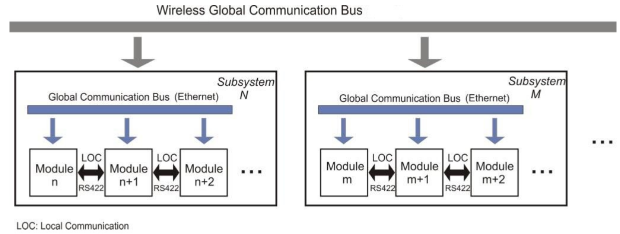


Fig. 2. Three communication levels in the RIMRES system: Modules can communicate with their direct neighbors via local communication (RS-422) (used for docking procedure and topology recovery), Ethernet is used for wired communication in a physically connected system. Wireless communication is employed between remote subsystems.

2) Cooperation and sharing of computational resources between individual modules inside of a subsystem is based on *Global Communication* via Ethernet. The hardware used within the modules is 100BaseT compatible which provides high speed transmission and robust performance.
3) The RIMRES system can be divided into several spatially separated subsystems. Thus, a *Wireless Global Communication* is needed as well. It is realized via the REIPOS[4]-system [15], a subsystem developed within RIMRES for communication and navigation purposes.

B. Power Management

Since all modules in one physical connected subsystem share a common power bus, a homogeneous power management system was developed. On the one hand, it supplies passive payload items with energy from the power bus to activate their functionality. On the other hand, the power management guarantees safe power supply of active modules to the power bus. The 48 V of the power bus will be converted down by the power management to the needed voltages of the module consumers. Since several power sources can be autonomously assembled in one subsystem, the power management is able to securely connect and disconnect the modules via a hot swapping functionality allowing just one power supply on the power bus.

C. Module Components

Fig. 3 gives an overview of the components that are common in each RIMRES module. A microprocessor provides high-level functionalities and uses global communication to cooperate with other modules. In addition, its computational power is used to process sensor data. The microprocessor can be shut down when its capability is not needed. It directly communicates with a microcontroller unit which handles the latch mechanism of the EMI, controls the power management, and communicates via local communication with potential module neighbors. The module-dependent special hardware is controlled by the microprocessor and supplied by the power management.

[4] Relative Interferometric Position Sensor

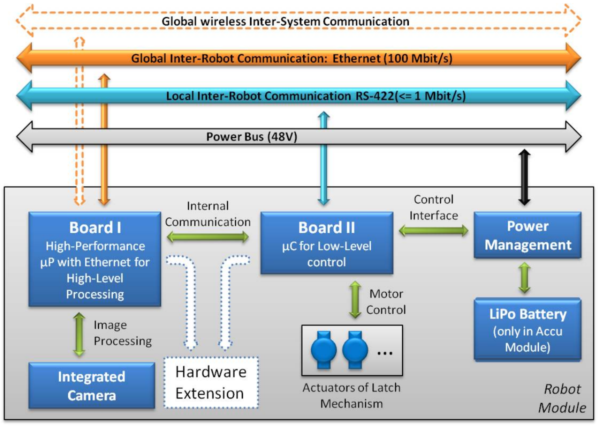


Fig. 3. Basic components in each module. The three bus systems energy, local communication via RS-422, and global communication via ethernet are provided by the electrical part of the EMI.

III. Electromechanical Interface

This section describes in detail the design of the EMI which securely connects and disconnects all RIMRES modules in dusty environments. The EMI is a key element for modularity in the RIMRES system. Since RIMRES is an earth demonstrator for extraterrestrial exploration missions, the challenges of Martian and lunar surfaces have to be taken into account. Even though space qualification is not necessary in this project phase, the components should be exchangeable to facilitate a potential qualification in follow-up phases.

A. Requirements on the Electromechanical Interface

The following requirements were considered to assure a secure mechanical and electrical connection.

Robust Connection The latch mechanism has to be able to hold complete module stacks as well as CREX with a mass of approx. 25 kg.

Energy Efficiency Because energy is a valuable resource in space applications, the latch should not consume energy in closed or opened state.

Mechanical Guidance The docking procedure is supposed to run autonomously, the interface itself should eliminate small positioning errors caused by sensor and actuator inaccuracies.

Play The play should be kept to a minimum when modules are attached to each other, in order to ensure a reliable electrical connection.

90°-Steps Docking To reduce the handling complexity and maximize the multi-module robot flexibility, the modules should support docking in 90°-steps of orientation.

Size The interface is limited to the quadratic size of a payload item's ground plate (150 mm x 150 mm). The height of the EMI itself has to be kept to a minimum to allow maximum space for module components.

Dust-Resistance The latch mechanism should be able to work in dusty environments and also prevent dust from entering into the module.

Energy Bus The EMI has to withstand currents which can be considered around 5 A, if in the worst case the actuators of the rover are supplied by energy payload items.

Data Transmission Local and global communication signals are transmitted over the EMI.

Sensors To achieve a successful autonomous docking, the module surfaces have to be aligned. Therefore, the sensor data have to be accurate and work from long distances of about 2 m to short distances where the remaining offset can be eliminated by a given trajectory to complete the docking procedure.

Actuators The latch mechanism needs a reliable drive which is able to open and close the latch.

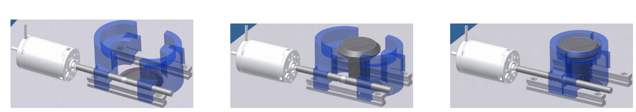
Contact Probes The contact probes actually have to realize the electrical connection for energy and data transfer. Since dust is one of the major concerns, the heads of the contact probes should cope with that.

B. Mechanical Structure and Latch Mechanism

We decided to develop an EMI which consists of an active female part located on the bottom side of each module and a passive male part located on the top side of each module. This male/female combination has several advantages: (1) The top side of each module, where it is more likely that dust particles can accumulate, is completely closed. (2) The end effector of the manipulator arm that is always powered from the rover's main batteries has an active part of the EMI included, thus it is always possible to connect to unpowered modules. (3) A simple, yet robust design is possible.

Due to the main concern of robustness even in tough environments, an active opening and closing of the latch was chosen. After experiments with different concepts, a design employing a small motor with a spindle drive to open and close two braces was chosen (Fig. 4). The counterpart is a pole on top of the passive part of the EMI which is held by the closed braces. Due to the conical shape, the two modules are firmly pressed against each other when the latch is closed. A housing surrounds the latch mechanism protecting the module interior from potentially entered dust.

As depicted in Fig. 5, the latch mechanism is located in the center of the module face. A linear potentiometer is attached to the latch mechanism to signalize the opened or closed state. The closing of the latch is initiated when the pole of the passive part of the EMI reaches its end position which is detected by an inductive distance sensor. Four cylinders with conical mouths are located around the electronic parts. Their purpose is to receive four dome-shaped centering pins from the passive part of the EMI to avoid rotations between modules while they are connected and locked. Their conical



(a) Opened Latch Mechanism
(b) Bolt of passive part of EMI inserted
(c) Closed Latch Mechanism

Fig. 4. Latch mechanism

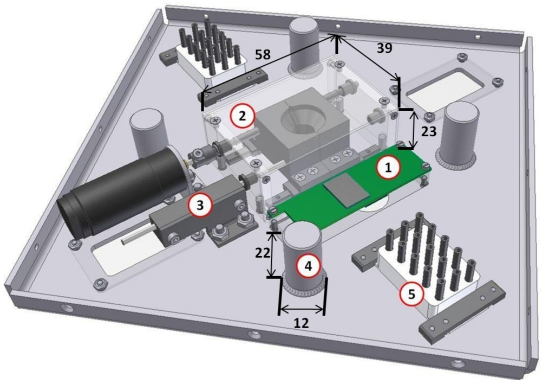


Fig. 5. Active part of electromechanical interface integrated in module bottom with dimensions in mm 1) Camera 2) Mechanical latch mechanism with spindle drive and dust protection housing 3) Linear potentiometer 4) Cylinder with conical mouth 5) Block of contact plates

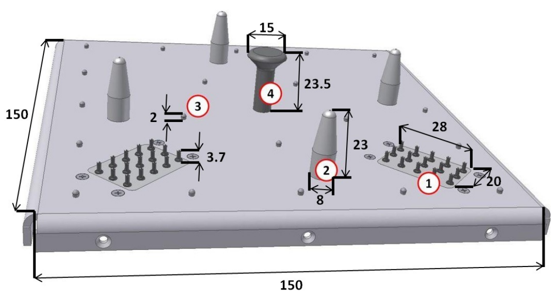


Fig. 6. Passive part of electromechanical interface on module top with dimensions in mm 1) Block of contact probes 2) Dome-shaped centering pins 3) Distance pins 4) Bolt for latch mechanism

shape increases the tolerance during docking procedure by providing mechanical guidance. The active part of the EMI also includes a camera with additional light-emitting diodes which are used for visual servoing during docking procedure. Two blocks of contact plates for energy and data transfer between modules which withstand physical force are aligned kitty-cornered, while two blocks of contact probes on the passive EMI are located on one half of the module (see Fig. 6). In that way, connecting in 90°-steps is possible with a minimum number of connectors. Smaller mechanical distance pins all over the module surface lead to a gap when two modules are docked. So, minor dust accumulations do not influence the docking procedure.

C. Spring-Loaded Contact Probes

The electrical connection is established by blocks of spring-loaded contact probes integrated in the passive part of the EMI and blocks of contact plates integrated in the active part (Fig. 7(a)). The chosen components are resistant to the required currents during power transmission and support high-frequency data streaming. The spring in the contact probes allows a variable length which creates a vertical docking tolerance of 2.2 mm. In addition, the spring force secures a constant electrical contact while the system is exposed to vibrations. Each probe is equipped with a 4-point crown head. The pointy endings are able to penetrate a layer of dust. The round contact plates have a larger diameter than the probes. So, a horizontal docking tolerance of 3 mm is obtained.

Pin	Description
1	RS-422 CH1 H
2	Ethernet TX+
3	RS-422 CH2 H
4	RS-422 CH1 L
5	Ethernet TX-
6	RS-422 CH2 L
7	Current (RC)
8	Ethernet RX+
9	Enable (RC)
10	Position (RC)
11	Ethernet RX-
12	Phase (RC)
13	VCC (+ 48 V)
14	NC
15	GND

(a) 4-point crown head and contact plate

(b) Pinout of the contact blocks (view from connection side)

Fig. 7. Contacts and Pinout

Each contact block consists of 15 contact probes or plates. Two pins are used by the power bus. The global communication over Ethernet and the local communication via RS-422 need four pins each. Additional four pins will be used to implement a fault-tolerant interface control which enables the lower module to open the latch mechanism of the upper module. In this way, defect modules can be removed from the system. Fig.7(b) illustrates the pinout.

D. Sensor System

In the LUNARES project [16], we demonstrated successfully that visual servoing is a feasible approach for equipping systems with payloads in environments similar to the lunar surface. Thus, a docking mechanism based on visual servoing will be implemented for the RIMRES system as well. Since the cubic modules might obstruct a wrist cam on the manipulator arm, a small camera board is implemented in the active part of the EMI (Fig. 5).

A linear potentiometer is used to verify the absolute position of the braces of the latching mechanism. An inductive distance sensor attached on the latch housing signals the success of a docking approach.

IV. Experimental Results

This section presents experiments proving basic functionalities of the EMI. Since dust resistance is an important aim, we use two different kinds of regolith substitute for our dust experiments. On the one hand, we test the interface with basalt chips of 0.7 mm to 1.3 mm graining representing rough dust. On the other hand, crystalline Durubas micro basalt of of 0.02 mm to 0.2 mm graining is used to simulate very fine dust. Both regolith substitutes have a weak magnetic character.

A. Load Test for the Latch Mechanism

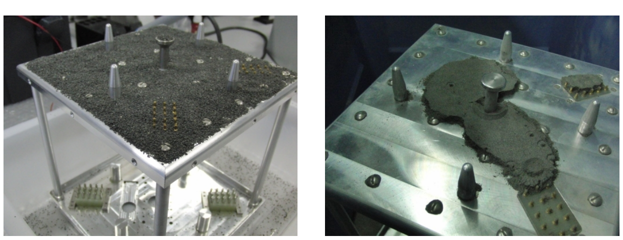
To test the heavy-duty capability of the proposed design, we fixed the active part of the EMI with reduced complexity on a rigid support frame. Weights were attached to the central bolt of the passive part, which was then fixed in the latch mechanism of the active part. With the load hanging free under the latch mechanism, the actuator was driven in order to open up the latch. The aim was to test whether the latch mechanism gets jammed under loads or not. Currently we were able to test with loads of up to 40 kg in steps of 5 kg. Each weight was tested 10 times.

The latch mechanism is able to open properly to masses of up to 40 kg in all cases. In average, it takes around 2 s to open or close the latch. 3.1 W are needed and both power and time are independent from the applied load. Because no power is used in opened and closed state, the proposed design is suitable for multi-module systems. Since the scout robot with its mass of approx. 25 kg will be the highest load for the interface, the tested 40 kg are more than sufficient for the RIMRES scenario. However, in a new test setup we want to test even higher loads.

B. Docking with Dust

This experiment shows how the proposed design copes with varying layers of the above-mentioned dust types. In our setup, we established a plain layer of dust on the top of a module (Fig. 8(a)), afterwards connected both EMI parts and and finally closed the latch mechanism. Each layer of dust was tested ten times before increasing the thickness of the layer in 1 mm steps.

In general, dust layers of up to 2 mm cause no problems while docking. Most of the dust slides down from the conical distance pins of the lower module. Potential rest accumulations are pressed aside by the lower surface of the top module. In this way, the distance pins always build a constant contact surface for the upper module. At a layer of 3 mm and above, dust particles are trapped between the mechanical distance pins and the lower surface of the active part, thus causing a gap which prevents the latch mechanism from closing. We discovered that the rough basalt chips are loosely bound together and slight vibrations cause the dust to fall from the sides which continuously decreases the layer of dust. So, shaking makes a connection between two modules possible again. In contrast to the rough dust, the fine dust compressed by the pressure of the top module starts to stick to the surface. Shaking the module does not help to reduce the layer of dust (Fig. 8(b)). Thus, a docking above a layer of 3 mm is impossible with fine dust.



(a) Plain layer of rough dust

(b) Rest of compressed fine dust after experimental trial

Fig. 8. Dust experiments: Contamination of the interface

In addition, we tested the docking with four small spots of fine dust accumulations across the surface. In this case, debris cones up to 12 mm height are not causing any problems. Higher accumulations cannot be pressed aside to reach the needed docking distance due to the adhesive characteristic of the compressed fine dust.

During these experiments, dust could enter the module interior because the proposed bristles, which prevent dust from entering the module, were missing. Anyway, the entered dust did not harm the latch mechanism. The distance pins fulfilled their task of guaranteeing a safe docking to dust layers of up to 2 mm.

The experiments were conducted under worse conditions than could be expected for a real scenario. A homogeneous layer of dust was applied to the module face, Fig. 8(a). In reality smaller deposits of dust are likely. However, in the experiments we showed, that the interface can cope with extreme contaminations.

C. Reliability of the Electrical Connection

In this experiment we distributed a layer of approx. 1 mm of the above-mentioned rough and fine dust over the passive part of the EMI and manually connected it with the active part to test how the spring-loaded contact pins with their 4-point crown heads cope with dust. After the connection was established, the microcontroller of each module was supposed to start the local communication with its neighbor. Since the established contacts do not always stand statically in practice, we provoked external dynamic disturbances which could cause negative influence to the contacts, e.g., manipulator moves immobile payload items or Sherpa crosses rough terrain. Table I summarizes the results of the 50 trials per dust type.

Without dust, the microcontrollers start to communicate with each other as soon as the connection is established. It works reliably and shaking the module stack does not influence the connection. Rough dust can cause connection problems when bigger dust particles accumulate in the middle of a a 4-point crown head. This happened in 12% of our test cases, thus preventing one or both microcontrollers to start the communication. If the communication starts, shaking does not disturb the established data transfer. In just 78% of our test cases during the fine dust experiment, all necessary pins connected from the beginning with their counterparts, thus enabling the communication to start. A failure occurs when either the 4-point crown heads are filled with dust or a layer of dust sticks to the flat surfaces of the contact plates due to magnetic force. But in most

TABLE I
SUCCESS OF DATA TRANSFER

without dust	communication started	100%
	after disturbances	100%
rough dust	communication started	88%
	after disturbances	88%
fine dust	communication started	78%
	after disturbances	92%

of the failure cases, shaking the module causes the dust particles separating the contacts to fall off, thus resolving the connection problem.

Summing up, the heads basically work but not reliably enough. Consequently, more head types have to be evaluated, e.g, a spike or a sharp angle, which could potentially prevent dust accumulations. The usage of spring-loaded contacts turns out to be a good choice. Besides the redundancy in horizontal and vertical direction, the established connection is reliable regarding possible external disturbances.

D. Power Transmission

We connected two modules and distributed power over two pins of the EMI to test the power transmission. An electrical load represented potential consumers in an active multi-module system. In this experiment, we tested with and without dust a nominal current of 5 A and over-current of 8 A at a constant voltage of 25 V. Temperature and resistance of the contact were measured periodically during the test.

As shown in the temperature-time diagram in Fig. 9, the temperature of the contact rises drastically at the beginning of the connection. After the first minute, the temperature tends to be stable. The comparison between the two currents shows that higher current increases the contact temperature. Due to reduced heat conduction, the temperature is even higher when the probes are covered with dust. Nevertheless, the temperature is not critical in our application since the contact temperature is always lower than 80°. The resistance of the connections remains almost constant.

V. Conclusion and Outlook

This paper shows the development of an EMI for a heterogeneous multi-module system. Mechanical as well as electric connections of a first laboratory sample of the EMI have been tested. The data gained from the presented experiments suggest that the chosen approach has the potential to be used in a complex multi-robot scenario during operations in rough surface environments. The latch mechanism can hold a load of up to 40 kg and tolerates dust accumulations between module faces of up to 2 mm. The work presented here is preliminary and will be substantiated in additional experiments in the upcoming phase of the project. Additionally, the EMI will be integrated into payload items and mobile systems.

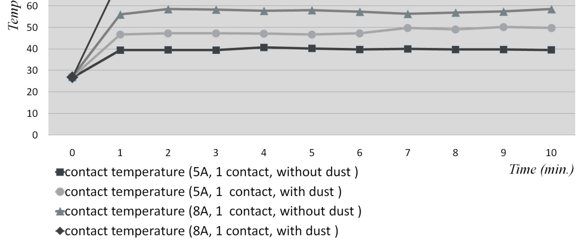


Fig. 9. Temperature of the contact probes

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