Evaluation of a Power Management System for Heterogeneous Modules in Self-Reconfigurable Multi-Module Systems

Zhuowei Wang, Florian Cordes, Alexander Dettmann and Roman Szczuka

Abstract— **This paper presents a novel homogeneous power management system for heterogeneous self-reconfigurable multi-module systems consisting of active power suppliers, diverse power consumers and hybrids. To optimize functionality of each module, a concept separating functionality from power supply is proposed and applied in immobile payload items which can be combined with mobile modules in varying configurations autonomously. By allowing consumers and power sources to connect to common power bus, the concept enhances flexibility, reusability and performance of modular robotic systems. The power management system based on the concept is implemented and evaluated. The experimental results show that power is efficiently transferred in power bus among individual modules, consumer modules without battery packs can be kept alive during switching, and the power management system can protect individual modules from hardware faults reliably.**

I. Introduction

In the field of extraterrestrial exploration where unpredictable tasks in dangerous environments have to be accomplished, autonomous robotic systems plays a significant role. It is a challenging issue to develop high-performance robotic system with low costs for space applications. Because of several remarkable features, e.g. flexibility, scalability, adaptivity, etc., modular self-reconfigurable robot systems are moving into focus in the field. Individual modules in the systems are able to connect mechanically and electrically to each other to form multi-module systems. Not only the number of modules in a system is variable but also functionality of formed multi-module systems can be reconfigured and adapted for diverse tasks. Hence, expensive missions to Mars and moon could benefit from self-reconfigurable robot systems due to their economic advantages.

Up to now, most of the modular robot systems developed can be assigned to the class of homogeneous robot system, in which each module is equipped with battery packs and has the same mechanical design and functionality. In some of the systems, individual modules are able to share energy with each other after forming multi-module systems, e.g. the SuperBot [8]. In the other systems, such power sharing is not considered, e.g. the M-TRAN [6].

Besides homogeneous modular robot systems, several heterogeneous robot systems have been developed or are in development. In the REPLICATOR [5] project, multi-robot organisms with high heterogeneity are implemented. The

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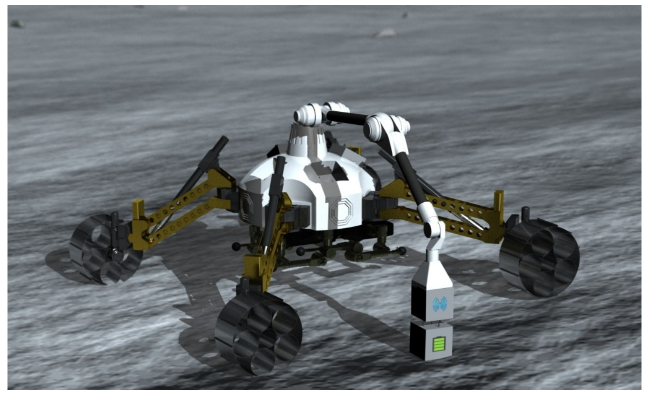

Fig. 1. RIMRES scenario in an artist drawing. The rover is about to dock a payload module to a battery module on the planetary surface. The legged robot is attached to the chassis over the EMI beneath the rover.

modules are equipped with power source individually as in the homogeneous robot systems. In comparison with the systems mentioned before, not every module in the Odin [4] robot needs own battery packs. In the XROB study [9], the European Space Agency (ESA) gives a concept based on modularity to develop a robotic system in order to reduce cost and enhance performance of the system applied in space applications.

The development presented in this paper is part of the RIMRES[1] [2] project. In the project, a versatile system consisting of heterogeneous modules is developed. This system includes the wheeled rover Sherpa[2] and the six-legged scout robot CREX[3] as the two heterogeneous "basic" modules. Furthermore, diverse immobile payload items belong also to the system. Connection among the modules of the system is achieved via homogeneous and standardized electromechanical interfaces (EMI [3]). Mechanical connection as well as intermodule transmission of power and data are supported by the EMI. The EMI enables connection among all modules in the system.

The rest of the paper is organized as follows. Section II introduces the modularity of the RIMRES system and the concept applied to develop payload items, and gives requirements on power management system (PMS) resulting from the concept. Section III proposes a homogeneous PMS for individual heterogeneous modules and presents its function-

[1]Reconfigurable Integrated Multi-Robot Exploration System
[2]Sherpa: Expandable Rover for Planetary Applications
[3]Crater Explorer

ality. Section IV presents experimental results of the PMS developed. Conclusion and outlook are given in section V.

II. Concept and Requirements

In this section, the modularity of the RIMRES system and the modules which are actually implemented in hardware are presented. The concept related to power supply in individual heterogeneous modules is proposed. Based on the concept, the requirements on a PMS are listed.

A. Modularity and Concept

In the RIMRES system, the two mobile modules Sherpa and CREX play a central role. These modules are self-sufficient and therefore can work independently. Moreover, the two modules are able to link each other via the uniform EMI and act as one single system with combined capability on demand. Sherpa has six EMIs in total: Four as docking bays for payload modules, one beneath the central body to pick up the scout, and one EMI integrated to the end effector of the manipulator arm. The scout CREX has one EMI on top of its central body to connect to Sherpa or to be equipped with additional payload items.

A payload item, which holds special functions, is encapsulated in a cubic housing with one EMI at the bottom side and one EMI at the top side. Payload items can be not only docked with each other with the aid of the manipulator arm to form independent immobile scientific payload stacks for varying tasks in exploration applications dynamically, but also assembled to the mobile modules to enhance their performance.

The following payload items are currently in development, as a first set to demonstrate the capabilities of the modular approach:

Camera Module: This item includes a camera to simulate a science module for data harvesting.

REIPOS Module: The REIPOS[4] [1] item is used for communication and relative navigation. Thus it is used to build up a science supporting infrastructure.

Mole Module: This is a subsurface sampling module which implements the Mole system, that flew with Beagle-2 in the Mars Express mission [7].

Further payload items can be added to the system. The camera module, for example, is only a replacement for "real" science instruments, such as seismometers or others.

There exist many modular self-reconfigurable robot systems. But they are not optimally suitable for space applications. On the one hand, they show certain multi-locomotion ability for varying terrain by reconfiguration; on the other hand, they have difficulty to handle exploration tasks, e.g. manipulation, navigation, etc., due to low power and performance. Therefore, relatively high supply voltage (44.4 V) and current (max. 5 A) are defined and applied in RIMRES to provide more power for individual modules.

To provide the power supply defined for the modules, 12 lithium polymer (LiPo) cells in series with a capacity of 2400 mAh are used. Taken into consideration that a compact battery pack with a nominal voltage of 14.8 V and the capacity has to consume a valuable volume of $96\,\text{mm} \cdot 35\,\text{mm} \cdot 40\,\text{mm}$, it is difficult to encapsulate each function listed and three such battery packs in a predefined restricted volume ($150\,\text{mm} \cdot 150\,\text{mm} \cdot 150\,\text{mm}$) of one cubic payload item. To avoid compromise between power supply and functionality in the dilemma, the concept that power source is separated from functionality is applied for the robot design. That is to say, battery packs and hardware for functions to be implemented are encapsulated in different modules respectively. Hence, the immobile modules listed above are not equipped with any battery packs. *Battery Module* which has power source is designed to feed the other payload items with power or enhance operational range of the mobile modules flexibly. To deploy an independent multi-module system consisting of payload items, at least one battery module has to be docked to the established system. For energy harvesting, the battery module could be replaced with a photovoltaic module. The concept optimizing the usable capacity allows scaling up the robot system by adding arbitrary tools which can be encapsulated into the cubic module.

B. Requirements on the Power Management System

Since the payload items without battery packs can not work independently, the system should dock them to mobile modules or battery modules to enable their functions. Hence, it is necessary that the modules equipped with battery packs can share power with other modules. Direct power exchange among the modules with battery packs connected to one common power bus is not considered in the PMS. Since short circuit among power sources with different charging states could occur, the PMS should ensure that only one power source is connected to an established power bus at any time. In a multi-module system formed, the PMSs of the modules have to communicate with each other in order to select a power source.

The other requirements result from a typical scenario in the application: a payload item without battery packs is stacked onto a battery module to form an active payload stack by the manipulator arm. At the beginning, the payload item is grasped via the EMI of the manipulator arm and electrically connected to the power bus of the arm. When the arm docks the payload item to the battery module, the two power sources with two different states are not allowed to connect to the power bus simultaneously. To build the stack, the PMS of the payload item should choose the power source of the battery module. If the arm cut off power supply to the payload item and retracts, voltage drop should be recognized by the PMS in the payload item and hot swapping should be executed in time in order to switch over from the arm to the battery module and prevent data loss. Moreover, the PMS should be robust and fault-tolerant, so that remaining modules in a system formed are protected from damage even if hardware fault (e.g. short circuit) occurs in several modules of the system. As defined in the RIMRES, each modules should be compatible with voltage of around 44.4 V and max.

[4] Relative Interferometric Position Sensor, developed by project partner ZARM

TABLE I

COMPARISON OF POWER BUSES USED IN RECONFIGURABLE MODULAR ROBOTS

	MTRAN [6]	SuperBot [8]	Molecube [10]	REPLICATOR [5]	Odin [4]	RIMRES [2]
Nominal voltage	12 V	7.4 V	18 V	22.2 V	11.1 V	44.4 V
Intermodule current	no current	possible	max. 8 A	max. 8 A	max. 2 A	max. 5A
Battery packs in each module	Yes	Yes	Yes	Yes	No	No
System type	homogeneity	homogeneity	homogeneity	heterogeneity	heterogeneity	heterogeneity
Docking type	autonomous or manual	manual	manual	autonomous	manual	autonomous
Power sharing	No	optional	optional	optional	necessary	necessary

current of 5 A. The relatively high voltage and current pose a challenge for the design of the PMS.

The following list gives a summary of the requirements, which the PMS has to meet in order to be suitable for the RIMRES system:

- In spite of the modules with high heterogeneity, the PMS should be designed as homogeneously as possible to reduce development time and integration complexity.
- The homogeneous PMS should be configurable to meet individual requirements of the heterogeneous modules. For example, overcurrent of a battery module is limited up to 5 A, while current limit of a payload item amounts only to 1 A.
- Payload item without battery packs can be awakened by each module with battery packs and powered continuously during docking.
- Safe and reliable hot swapping.
- Switching over among power sources with different voltages.
- Supervising power consumption.
- Over-current protection.
- Reverse current protection (in battery modules).
- Low energy consumption.
- Software independent safety features for high reliability.

Based on the requirements, several modular robot systems are compared with the RIMRES. As given in Tab. I, the RIMRES system is different from the other systems in view of power supply. To the best of our knowledge, a PMS for such a modular self-reconfigurable robot system has not been done before.

III. POWER MANAGEMENT SYSTEM DESIGN

In this section, the design is described in detail. Figure 2 gives the architecture of the PMS developed for individual payload items in the RIMRES system. Although the payload items differ from each other in functionality and power sources, the homogeneous PMS is designed for all of them. But battery packs are connected to the PMS only in battery modules. In the architecture, the components with rounded rectangle symbols belong to the primary part of the PMS. The primary part 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, payload items without battery packs can be awakened from their energetically “dead” states, if they are electrically docked to a module providing power. In a payload item, its primary part powered is able to activate other applications on demand and change topology of a power bus. The power bus located in each payload item can be connected to two neighboring modules via EMIs directly. The MOSFET-based switches (A, B and C) which can suspend or enable bidirectional power transmission are employed to control intermodule connection among battery packs and consumers.

In order to protect battery packs from damage, output current of battery packs is supervised by three approaches with different reaction time: 1) Hardware control. Unexpected overcurrent triggers switch B without microcontroller presence due to a current limiter based on *reference voltage comparator*. The absolute current limit up to 5 A is configurable by hardware. 2) Asynchronous software control. To meet individual requirements of the modules, the current limit is adjustable by pulse-width modulation. The output of the comparator can trigger an interrupt and make asynchronous control possible. 3) Synchronous software control. Traditional readout-calculation-decision is applied for routine supervision. In addition, reverse current flowing into battery packs can be detected and suppressed by using the second approach. Switch A and C are applied to choose one of external power sources connected to the power bus dynamically. In view of possible voltage gaps among different power sources, the switches based on comparators are applied to make smooth switching over possible. The secondary part (normal blue rectangles) consisting of the *hot-swap control unit* (HSCU) and the voltage regulators can be switched on or

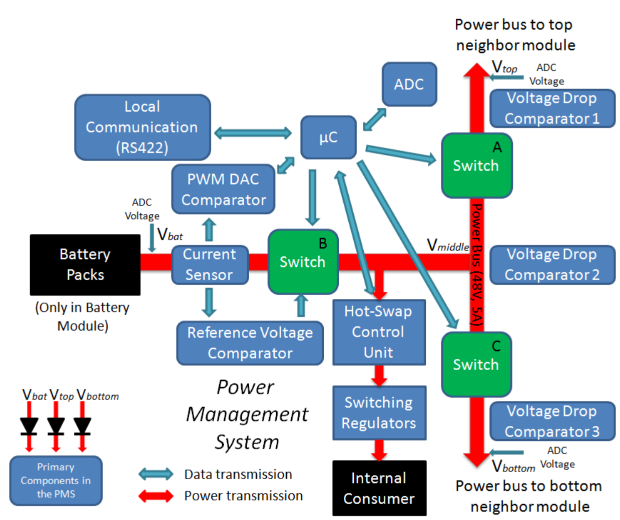

Fig. 2. Hardware architecture of the PMS in individual payload items.

off by the μC in the primary part. With the aid of the HSCU, power consumption of the internal load can be monitored and inrush current limit is adjustable.

There are different modes for switching power source connected to power bus of a module assemblage: (1) "*Hardware switching*" is used for coping with overcurrent. Output current limit of battery packs is set via a potential divider and can be arbitrarily chosen. If overcurrent occurs on a power bus, this mechanism automatically interrupts the power bus. (2) "*Software switching*" is used if a module is deliberately switched on or off or a request for connecting a power source to power bus is accepted. In case of software switching, two cases can be differentiated: (2a) "*hard switching*" immediately switches over from one power source to another, regardless of energy potentially stored in capacitors of individual modules. Hard switching can be used to switch from one power source to another with lower voltage and vice versa. In case of switching from high to low, (2b) "*soft switching*" can also be used. In this case, voltage drop comparators are used to trigger a switch connected to a second source (see also section IV-B).

To evaluate the PMS, an ATmega128 microcontroller is used to implement the control logics for the PMS and local communication between modules in multi-module systems.

IV. Experiments

This section presents experimental results of the PMS. The experiments include power loss over internal switches, switching time for changing power source and handling of short circuit on the power bus.

A. Power Loss Over Internal Switches

In this section, power loss caused by current through the internal switches (*A*, *B*, *C* and *HSCU*; seen in Fig.2) of the PMS is measured and evaluated in order to answer the question whether it is reasonable to share power among modules. In this experiment, a voltage of 48 V is provided by a power source. The power source is either connected to one of two EMIs of a payload item (consumer module) or connected to switch B to simulate a battery module supplying power to the power bus shared. The following scenarios are tested with three PMSs configured as two battery modules and one consumer module:

1) Current flows through switch A and B in battery module, or switch A and HSCU in consumer module.
2) Current flows through switch C and B in battery module, or switch C and HSCU in consumer module.
3) Current flows through switch A and C in battery module or in consumer module.

The two battery modules are connected to the consumer module over its two EMIs respectively. A constant current of 1 A (2 A) is used in the test. Hence, the total power that is lead through two switches amounts to 48 W (96 W). The power loss is calculated by the voltage drop measured across two involved switches multiplied by the applied constant current. The results of the power loss calculated are shown in Tab. II.

TABLE II

Results of the power loss experiment. Absolute loss and percentage of total power (48 W (1A) and 96 W (2A))

	Current	Battery Module 1		Battery Module 2		Consumer Module	
Switches	Amp.	Watt	%	Watt	%	Watt	%
A + B (HSCU)	1	0.03	0.05	0.03	0.06	0.05	0.11
	2	0.10	0.11	0.11	0.11	0.20	0.22
C + B (HSCU)	1	0.03	0.06	0.03	0.06	0.05	0.11
	2	0.11	0.11	0.11	0.12	0.21	0.22
A + C	1	0.02	0.04	0.02	0.04	0.02	0.04
	2	0.07	0.08	0.08	0.08	0.08	0.08
Average	1	0.02	0.05	0.03	0.05	0.04	0.09
Average	2	0.09	0.10	0.10	0.10	0.17	0.17

According to the results, the power loss resulting from conducting current through the power bus of a module remains low, in the range of one thousandth of the power transmitted. To feed an internal load in the consumer module, a combination of a MOSFET-based switch and the HSCU is applied. Compared with two MOSFET-based switches in the power bus, the combination causes more power loss due to the HSCU. It is observed that switch B with comparator-based current limiter integrated consumes more power than switch A or C. Absolute values of the power loss do not exceed 0.21 W in all the tests. The results of "A + C" are nearly the same in the three modules. With a total power of 96 W through the switches in power bus, a loss up to 0.08 W can be observed. The experiments show that the overhead of the power transmission is low by using the switches implemented in the PMS. The energy efficiency of the switches makes it possible to form large-scale multi-module systems.

B. Switching Time

In this experiment, the "*soft switching*" of the PMS is validated. Soft switching means that the switching needs computational resource as it is supervised by the microcontroller. If a voltage drop at one of the two EMIs is detected by the PMS of a payload item without battery packs, the switching over to another possible power source has to be executed in time, otherwise the supply voltage dropping below a threshold could lead to a blackout of the payload item. For the primary part of the PMS the tolerable minimum voltage is approx. $10\,V$. The experiment simulates a typical RIMRES scenario: a payload stack is disassembled and one payload module is to be powered by the manipulator arm of the rover. The setup for this experiment is as follows: Three instances of the PMS are employed. The three instances play the roles of a battery module (bottom), a payload item (middle) without battery packs, and a manipulator arm (top) respectively. At the beginning, the payload module (consumer) is docked to the battery module and also powered by it. Then, the payload module will be taken away from the stack by the manipulator arm. The start state and the end state of the test are illustrated in Fig. 3.

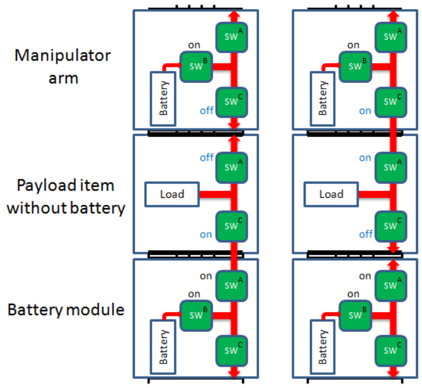

Fig. 3. (l.) Initial state of the switching time test. The battery module and the payload item without battery packs share one common power bus. (r.) End state of the switching time test. The payload item is powered by the the manipulator arm.

TABLE III
RESULTS OF THE POWER SOURCE SWITCHING EXPERIMENTS

Combination	Mean (ms)	Std. devi-ation (ms)	Max (ms)	Min (ms)
50 V to 46 V with cap.	2.14	0.05	2.23	2.07
50 V to 46 V without cap.	0.51	0.09	0.63	0.38
52 V to 46 V with cap.	3.23	0.10	3.39	3.13
52 V to 46 V without cap.	0.62	0.07	0.82	0.56

In this process, the PMS of the payload item will recognize voltage drop at the bottom EMI after switching off power supplied by the battery module and then connect to the power source of the manipulator arm. In the experiment, an electronic load is used in the payload item and draws 1 A current continuously. Taken into consideration that consumer module typically has not only resistive load but also capacitive, two different loads are applied: (1) a capacitor of 470 μF is connected with the electronic load in parallel, (2) only the electronic load is used. In addition, two different voltages (52 V and 50 V) are tested to find out whether voltage gap between power sources affects switching time. In Fig. 4 a measurement by using an oscilloscope is presented for one switching cycle (52 V to 46 V with the resistive load). From the marker (1) on, switch C of the payload module is switched off (yellow line) and therefore disconnected from the power source (52 V) of the battery module. Due to the constant and resistive load, the voltage on the load decreases linearly (blue line). After appr. 0.6 ms, the voltage drops below the voltage of the power source of the manipulator arm at the marker (2). Ideally, the PMS should now immediately switch to the power source of the manipulator arm. But the real switching over takes place after several hundred microseconds showed at the marker (3) since the voltages on the power bus are read out and compared with the 4 kHz frequency. The rising green line indicates that switch A of the payload item is turned on. After several milliseconds, the voltage reaches the voltage provided by the manipulator arm. Compared with Fig. 4, Fig. 5 shows the switching based on the capacitive load. Except the load, all the test conditions are the same. As marked by (1) and (2), the voltage of the payload item decreases much more slowly than in the test with only resistive load. The switching over is not executed until a voltage drop is detected. After the consumer pulls power from the manipulator arm, the voltage of the consumer is recovered at the mark (4).

For the two different settings, 40 measurements were taken respectively. Tab. III summarizes the results of the measurements. In comparison with the test using the battery module with 52 V, the switching from 50 V to 46 V needs shorter switching time because of the smaller voltage gap. Beyond that, the two processes are almost the same.

The experiments presented show that the *soft switching* between two power sources is possible and reliable. Payload item which has to consume power supplied by other modules does not need data backup during system self-

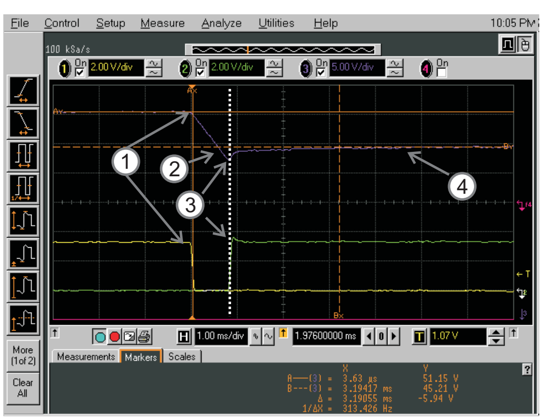

Fig. 4. Output of oscillograph in case of switching over from 52 V to 46 V with only resistive load.

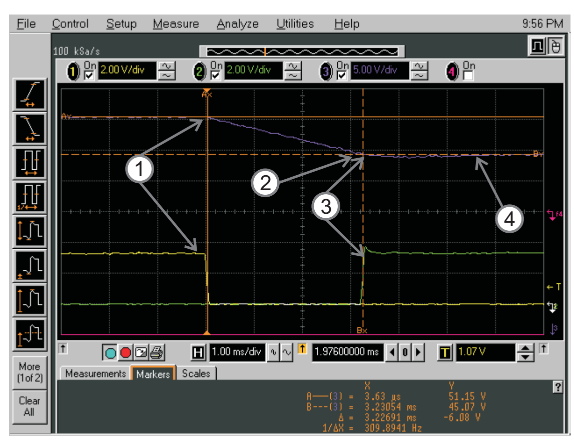

Fig. 5. Output of oscillograph in case of switching over from 52 V to 46 V with an additional capacitive load.

TABLE IV
RESULTS OF THE EXPERIMENTS RELATED TO SHORT-CIRCUIT CONDITION.

Scenario	Mean value	Std. deviation
Reaction time to hardware fault	$71.1\,\mu s$	$0.3\,\mu s$
Shut-down current in normal use case	$4.6\,A$	$0.0\,A$

reconfiguration, since the comparator-based switches developed are able to respond to external voltage drop in time and unexpected blackout is avoided. In case of switching from a voltage to a higher, the switching is achieved by the *hard switching*. In this case inrush current regulated by the HSCU flows into internal load until the voltage on the load is increased to the new supply voltage.

C. Protection

In this experimental series, short-circuit condition and reaction time are tested in two different scenarios. In the first scenario (hardware fault), a battery module shares power with a payload item and short circuit occurs suddenly in the payload item. In the second scenario (normal use case), several payload items are docked to a battery module one after another and the payload items pull more and more power from the battery module. To simulate the first scenario, a PMS is connected to battery packs providing power through switch C (Fig 2). The output of the switch is bridged to create a short-circuit condition. In the second scenario, the output current of the battery packs is gradually increased and shut-down current is measured. The current limit of the protection circuit is set to 5 A. The protection is realized by hardware in order to enhance the robustness of the system.

Tab. IV shows the results of ten measurements in the two tests. According to the measurements, the standard deviations calculated are low. The mean value of the reaction time for disconnecting short circuit amounts to $71.1\,\mu s$. In comparison: typical fuses have shut-down time in ms-range. In the second scenario, the over-current protection is triggered if output current of the battery module reaches 4.6 A, which is at 92% of the current limit configured. The reason for this behavior can be found in the tolerances of the potential divider used for setting the overcurrent limit. By calculating the differences and reconfiguring the potential divider, the difference can be minimized. The results indicate that the PMS is able to handle hardware fault and protect battery packs from overcurrent in normal use case.

V. CONCLUSION AND OUTLOOK

This paper presented the concept to optimize the design of individual payload items in restricted dimension and enhance the flexibility to utilize limited power in the system. The PMS based on the concept was introduced and evaluated for applications in modules of heterogeneous modular robot systems. The modules can either be battery modules feeding common power bus or consumer modules supplied by the power bus. In the experiments presented in this paper, the energy efficiency of power transmission over the switches in power bus and the smooth switching in a system could be proved. The PMS inhibited short circuit in power bus successfully and protected hardware in time.

As future work, the PMS will be fully integrated into the payload items. The software related to the PMS and the common functionality of the payload items (e.g. the control of the mechanical latch, the docking control, etc.) will be merged and implemented in a 32-Bit microcontroller. Furthermore, the PMS will be adapted to the two mobile modules.

VI. ACKNOWLEDGMENTS

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