# MODULAR EPS FOR SMALL MOBILE ROBOTIC SPACE SYSTEMS


1st Benjamin Hülsen
*YardStick Robotics GmbH*
*Robotics Innovation Center*
*DFKI GmbH*
Bremen, Germany
benjamin.huelsen@yardstick-robotics.com

2nd Patrick Schöberl
*Robotics Innovation Center*
*DFKI GmbH*
Bremen, Germany
patrick.schoeberl@dfki.de

3rd Niklas A. Mulsow
*YardStick Robotics GmbH*
*Robotics Innovation Center*
*DFKI GmbH*
Bremen, Germany
niklas.mulsow@yardstick-robotics.com



***Abstract*—Within this paper we present the design and implementation of the electrical power system (EPS) for a small lunar rover. We are giving insight in the design of the EPS, the tailoring to the rover system requirements, and component selection. The EPS is designed to act as technology demonstrator for testing different electrical energy storage technologies to be used for future space applications. Experimental results of the evaluation of supercapacitors are described. The presented results are based on the DFKI's outcome of the project SEARCH[1]**



***Index Terms*—EPS, Supercapacitor, maximum power point tracking (MPPT), gallium nitride - field effect transistor (GaN-FET)**


## I. Introduction and Related Work

Research on the exploration of the lunar surface and other celestial bodies with compact robotic systems and landing platforms is ongoing worldwide. More and more commercial companies are taking part in the contest. To be mentioned here are, for example HAKUTO from iSpace [1] and the CubeRover from Astrobotic [2], but also to be mentioned developments from agency like the Martians Moons eXploration (MMX) rover [3]. One of the central building blocks for any mobile systems for space missions, is the EPS. Although the form factor and mass requirements are similar in the CubeSat segment, these components are not a suitable choice. In comparison to orbiting space-crafts, we found the needs for mobile systems, like exploration rovers differs in terms of less predictable power profile due to the actuation under surface conditions associated with higher peak currents depending on the locomotion system. Also the availability of the electricity supply capacity under various thermal conditions within a smaller system, due to the high temperature contrasts on the lunar surface, is also a challenge for the storage system of the EPS.

The envisioned operation time is scheduled for a 12 day lunar surface mission where the operation radius from lander or the mother system is around 500 meters and a complete system loss can be tolerated.

To respond to this various requirements, the EPS we are presenting based on a modular approach. It was developed during the research project SEARCH, where the overall goal was to investigates technologies for a small and simplistic rover for future lunar exploration [4]. Thereby, the MoVe[2]

Fig. 1. Visualization of the MoVe rover with EPS inside. The rover serves as testbed for the EPS technologies developed within the project SEARCH

rover (Fig. 1) served as a testbed to assess requirements for the EPS on the one hand, and to evaluate the performances of the selected technologies in a real system on the other. The total mass of the rover is about $5.8\,kg$ whereas the EPS can take, depending of configuration, a maximum of 25% of the system mass. The selection of energy storage technologies and modularity of the system differs from previous developments with similar requirements [5] and allows a combination of supercapacitors, primary and secondary battery cells. Especially,

[1]https://robotik.dfki-bremen.de/en/research/projects/search


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[2]**Mo**on **Ve**hicle


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the selection of super capacitors enables high peak currents under unpredictable power profiles, provides a large working temperature window, and there is no danger of deep discharge. There also allowing to design simplistic EPS solutions for short time use systems to act completely independent of chemical storage. To accelerate the development, a commercial off the shelf (COTS) approach with a space related selection of parts was chosen for the EPS hardware development.

## II. DESING APPROACH

### *A. Modular Design and Backplane*

Enabling high flexibility while keeping the complexity for integration low, the EPS design based on a backplane, used as inter-connector of the single boards and providing power, communication, and discrete signals for 10 slots. The backplane layout consisting of an eight-layer HTg FR4 laminate with 2 mm thickness. Each of the connected boards implements a separate function of the EPS, allowing to interchange features and technologies separately by replacing the boards. This approach is also in line with accelerating the verification process of the COTS based circuits, to have the possibility to test and modify single functional blocks. [6] Individual modules developed for the EPS were: power generation, storage of energy, power regulation and distribution, system management, system monitoring and communication. An Overview is given in Figure 2. Although the module size is $110x110\,mm$ caused

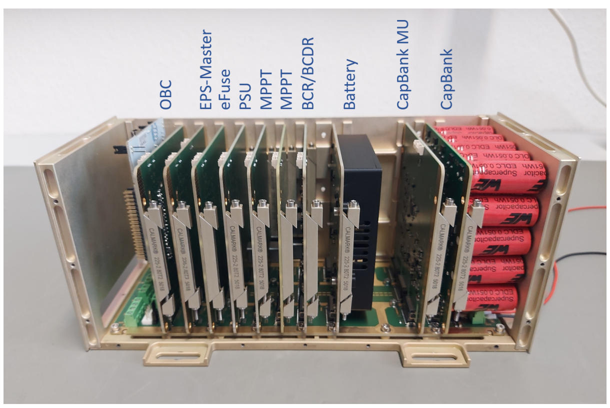


Fig. 2. Integration of the EPS. Cover and side panel removed for illustration. EPS including also supplementary modules as an OBC Board for controlling the rover, separate monitoring units for the CAP-Bank and the Battery module and an additional MPPT-Controller.

by wedgelock mounting, only the CubeSat common size is used on the boards for assembly and routing to enable a further use for orbital systems. As mentioned before the housing of the electronic compartment, is designed for the wedge lock mounting of the Boards and has an overall thickness of 2 mm aluminium as shielding. Notwithstanding of the overall size (lwh) of $330x120x120\,mm$ and a mass of $1.2\,kg$, we assume that the EPS would fit into a $0.5\,U$ format by omitting no necessary boards and functions and the use of a more compact placement. Here we could name for example specific monitoring units which were just required for evaluation of performance and are not necessary in operation. Furthermore, redundant storage could be reduced or selected to specific operational needs. A block diagram of the EPS is depicted in Figure 3. For the sake of simplicity, the OBC is integrated into the EPS to keep the harness as simple as possible. However, this is not part of the EPS technically speaking.

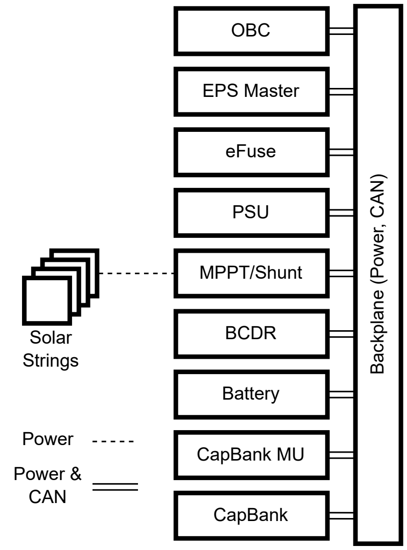


Fig. 3. The EPS and its components. It is comprised of multiple modules to implement the different functionalities for harvesting, storage, distribution, and control of power. The backplane provides power lanes and communication via CAN bus.

### *B. Selection criteria*

We primarily used generic components for our evaluation platform to enable portability for the purpose of technology readiness level (TRL) enhancement with space-heritage components. Thus, for the Electrical, electronic and Electromechanical components (EEE) used such as OpAmps, simple logic ICs (buffers or shift registers), transistors or diodes, replacement types with electrically comparable properties can also be found on the European Preferred Part List (EPPL). By using non highly specialized peripherals like analog-to-digital converter (ADC) or pulse-width modulation (PWM) timers of the microcontroller unit (MCU), the use of specialized components for the charge and discharge controllers as well as for the MPPT controller could be avoided. These used peripherals can be found on space qualified MCUs as well. The electronics are designed from the outset for a minimum operational temperature range of $-40\,°C$ till $+85\,°C$. This specification is consistent with the temperature range of the supercapacitors if they are derated properly. Since the identical MCU was used on all modules that required programmable logic, large areas of development (schematic and layout) could be reused between modules. This reduced the development effort for the individual modules. For example, the external clock, interfaces, and power connections could be kept electrically identical between module designs. This also positively influenced software development, since large parts of the software were also kept identical between the different modules.

### C. Design approach and requirements

Lowering the entrance barrier for in-orbit testing with the goal of TRL increase, the routing and placement of EEE-components of the printed circuit board (PCB) were restricted to an area of $85x95\,mm$ (CubeSat formfactor). This offers opportunities to piggyback missions. However, to address the vibrations of a rover and the climatic conditions of a lunar mission, the PCBs were expanded to a dimension of $110x110\,mm$. This made it possible to use wedge-locks for the simple thermal as well as mechanical connection to the housing, which are unusual for low earth orbit (LEO) CubeSat missions. To reduce the integration effort and thus the risk of errors in the production of a cable harness, we decided to use a backplane solution. All electrical signals, as well as the power lines between the individual modules, are carried out via the backplane. This also has a positive effect on the electromagnetic compatibility (EMC) behaviour, since this can be better considered in the layout of the backplane than having to protect countless discrete signals, bus signals and power lines from each other in a cable harness. Also, the integration of a backplane into a housing is much easier compared to the mechanically challenging arrangement of a cable harness regarding vibrations. By using the backplane, defined interfaces to the modules, and the low integration effort, it is also possible to replace functionally equivalent modules without great effort. We have taken advantage of this, for example, with the solar controllers and developed an S3R in addition to the MPPT module. These are interchangeable.

TABLE I
SELECTED COTS COMPONENTS AND POTENTIAL ALTERNATIVES

| Type | Selected COTS | Space proven |
|---|---|---|
| GaN-FET | EPC2055 [7] | EPC7019G [8] |
| MCU | STM32L433 [9] | SAM3X8ERT [10] or VA41620 [11] |
| CAN | TCAN330 [12] | SN55HVD233-SP [13] |
| LVDS | SN65LVDS179 [14] | SN55LVDS32-SP $(4xRx)$ [15] and SN55LVDS31-SP $(4xTx)$ [16] |

*1) GaN-FET:* GaN-FET were selected for the synchronous step-down switching regulators of the MPPT converters as well as for the SEPIC switches of the battery charge regulator (BCR) and battery discharge regulator (BDR). They are characterized by their small gate capacitance, low ohmic losses, small size, and low gate voltage. In addition, GaN-FETs are a radiation tolerating material thanks to their isolation layer and protected, non charge accumulating protection dielectric around the gate, compared to classical silicon-based metal oxide semiconductor field-effect transistors (MOS-FET).

*2) MCU:* We chose a generic MCU because it provides, for instance, a CAN-bus controller, ADC, PWM-capable timers, UART, and memory in the required range. We decided in advance on a universal or "general purpose" MCU, since it's not very specified hardware peripherals make porting or realization to a radiation tolerant or radiation resistant type easier.

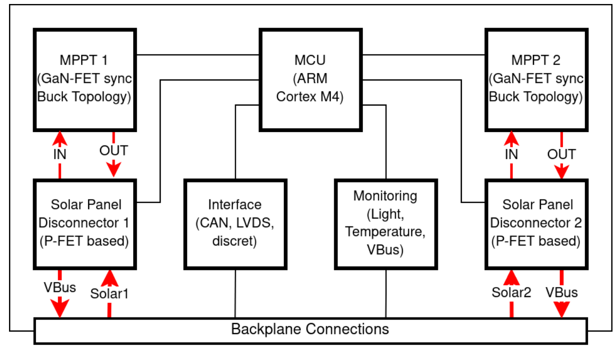


Fig. 4. The MPPT module consists of two identical channels controlled by a microcontroller. Since the solar panels have a higher voltage than the bus voltage of the rover, a synchronous buck topology based on GaN-FET was implemented.

*3) Transceiver:* Both controller area network (CAN) bus and low-voltage differential signaling (LVDS) transceivers are available now with wider selection in space rating. However, to keep the cost of the evaluation platform low, we chose 3.3 V only COTS component here. Only for LVDS there seems to be no compact solution. - Here, transmitter and receiver are offered individually instead of in combination in space grade.

## III. POWER GENERATION

### A. Solar Control

The main energy source for the envisaged application scenario of the EPS is solar power. The backplane of the EPS is capable of handling two electronics boards for solar control, indicated in Figure 4 with MPPT. Two separate solar control electronics with different control approaches were implemented and are interchangeable. These are:

*a) MPPT:* The MPPT electronic boards have two separate MCU controlled channels per module each with solid-state input separator to enable N cold redundant modules in parallel. It is implemented as a synchronous step down topology, based on GaN-FETs. The control algorithm is a MPPT approach with variable step size within initial search of maximum power point and during continous tracking with reduced step size to reduce oscillations. Furthermore, there is a safety monitor integrated in firmware to protect the EPS from overvoltage damage, as the MPPT directly charge the supercapacitors.

*b) Solar Shunt:* To test an alternative to the MPPT controller, an basic sequential switching shunt regulator (S3R) shown in Figure 5 as additional or replacement module was also developed for testing purposes. It is characterised by its simplicity, and it only consists of generic components that could be replaced by a space-rated functional equivalent components with little effort. Furthermore, it does not contain any programmable logic such as an MCU or field programmable gate array (FPGA) and is fundamentally based only on simple two-point controllers, main error amplifier (MEA) and the shunt switching elements. Extending this, the S3R also works

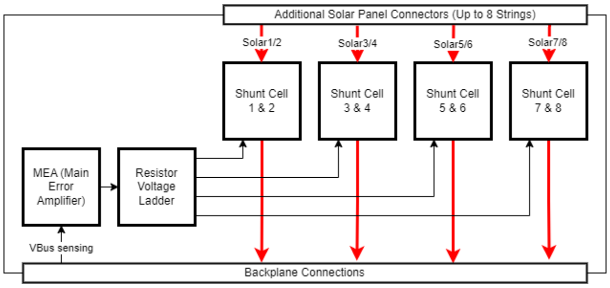


Fig. 5. The S3R does not contain a microcontroller. The control is done by a simple two-point controller that is controlled by an MEA which monitors the bus voltage and activates the individual shunt cells via voltage ladder if needed.

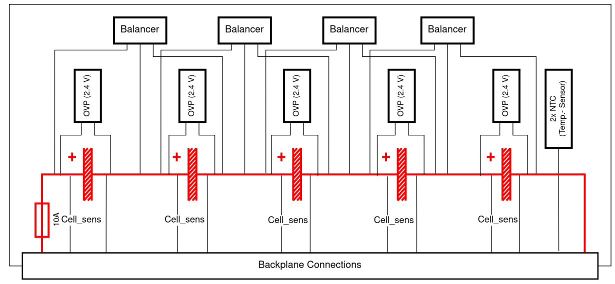


Fig. 6. The schematic diagram represents a CapBank module. In each instance, 5 supercapacitors, each of the 50F are connected to form a parallel network with its own overvoltage protection. Alternating across two of these arrangements are balancers. A $10\,A$ fuse is provided to protect the system.

if the bus voltage of the rover is completely discharged to zero, which is an allowed condition for supercapacitors. In this case, the serial diodes of the shunt cells conduct the energy of the solar cells via direct energy transfer (DET) into the bus and acts as an current source until the MEA begins to compensate and activate the shunt switches till the bus voltage reaches a full-state level. MPPT converters, on the other hand, already need energy to start to supply the switching power semiconductors and the programable logic. Since the solar panel and the bus voltage were already defined at the time the S3R controller was developed, and an ideal performance design for the EPS based on the S3R was therefore no longer possible, the efficiency in this design must not be considered as optimal. However, with adapted solar panels or adaptation of the bus voltage, the efficiency could be significantly increased.

*c) Solarpanels:* In its current configuration, the rover is equipped with six solar panels, each consisting of seven serial connected triple-junction GaAs solar cells [17]. One panel is placed at the front and one at the back and two at the sides. For the MPPT, the side solar panels are connected in parallel and for the S3R, each module is connected individually to the controller. All panels are identically constructed, consist of a FR4-PCB laminate and, in addition to the solar cells, also feature temperature sensors and optional light sensors implemented in the form of PIN diodes. In order not to design individual panels for a special mounting location, only one panel with optional cut-off corners was designed.

*d) Recuperation:* Aside from solar power as primary power source, recuperation is a conceivable power generation scenario for mobile systems with electronic motors for locomotion. The recuperation of the EPS is limited only by the current absorbed and charge level of the super capacitors. The present EPS is designed to absorb currents up to 10 A per bank at $11\,V$. These 10 A are given by the current load capacity of the connectors and the traces on the PCB and are protected by an additional fuse in the CapBank modul.

## IV. Energy Storage

### A. Supercapacitors

The CapBank module, shown in Figure 6, is a bank of super capacitors as energy storage and replacement of typical capacitors directly connected to the bus voltage. The CapBank consist of 25 supercapacitors [18] in 5 serial and 5 parallel, with a overall capacity of $50\,F$ at $11\,V$ at proper derating. The CapBank integrates voltage balancer and overvoltage protection based on discrete components and gets along without programmable logic. A derating from $2.7\,Vmax$ / $2.85\,V_{surge}$, down to $2.2\,V_{max}$ / $2.3\,V_{surge}$ was done to increase the operation temperature window according to the manufacturer's specifications from normal $-40\,°C$ till $+65\,°C$ to $-40\,°C$ till $+85\,°C$ and beyond. Because supercapacitors store their energy electrostatically instead of electrochemically, like battery cells, their performance is primarily not temperature-dependent and does not require a minimum voltage to protect a chemistry.

### B. Primary Battery Cells

In addition to the CapBank, primary (non-rechargeable) or secondary batteries (accumulators) can be optionally added to the EPS. In comparison to the CapBank the battery modules are not connected directly to the bus voltage but instead coupled to the bus voltage via charge and discharge regulators. For primary cells SAFT LSH-20 $(Li - SOCl2)$ [19] were selected. The cells are arranged in a series of three (3SP1). For the secondary cells LiFePo4 APR18650 [20] $(LiFePo4)$ were selected. Here the cells are arranged in a series of four (4S1P).

### C. Battery Charge Regulator (BCR) / Battery Discharge Regulator (BDR)

TABLE II
Energy Source and Regulators

| Type | Energy Source | Energy Destination | Output |
|---|---|---|---|
| BDR | 3S Prim. Cells | Supercapacitors | up to $4\,A$ |
| BDR | 4S Sec. Cells | Supercapacitors | up to $4\,A$ |
| BCR | Supercapacitors | 4S Sec. Cells | up to $1.5\,A$ |
| MPPT | Solarpanel | Supercapacitors | up to $8\,W$ per Panel |
| S3R | Solarpanel | Supercapacitors | up to $0.5\,A$ per Panel |

We implemented two separate regulators with MCU-based control on one compact PCB as shown in Figure 7. Technical summary can be seen in Table II. The charge and discharge controller is implemented as a PI-controller in firmware with

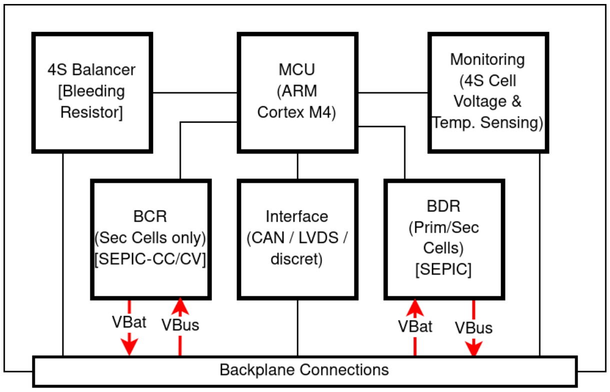


Fig. 7. A microcontroller provides central control and regulation of the charge and discharge controllers. If necessary, it can activate a passive "bleeding resistor" balancer. This module is universally designed, so that it is suitable for both primary and secondary cells.

an additional balancer control loop following a top balancer methodology.
We choose single ended primary inductance converter (SEPIC) topology to build the BCR and BDR and added a 4-channel bleeding resistor voltage balancing for 4 serial rechargeable lithium cells and voltage monitoring in addition. As SEPIC switching transistor GaN-FETs are used. The BDR discharges the battery (primary or secondary) into the CapBank, dirctly connected to VBus to maintain a system voltage of up to $11\,V$ if solar power generation is temporarily not sufficient.

We chose the SEPIC topology because the input voltage can be higher or lower than the output voltage. Consequently, a buck-boost topology would have been necessary, for example. However, this is based on considerably more switched semiconductors than SEPIC. Also, galvanically isolated topologies such as push-pull or flyback would require more control effort, a custom-made transformers and would probably also be larger and heavier. Since SEPIC includes both a capacitor and a diode in series, no current can flow uncontrolled back to the source in the event of a fault (DC-Blocking). Also, the switching transistor, in our case the same type of GaN-FET used for the MPPT converters (improvement in bill of matrials) and is connected to zero potential on the source side, which simplifies the drive circuit and control.

### D. Additional System Modules

*a) PSU:* A power supply unit (PSU) module features 4 independent step-down regulators, capable of supplying up to 3A each. These can be activated independently by a MCU. In order to monitor the connected loads, the output voltage and current of each regulator is monitored by the MCU and the information is available on the bus. Two channels are exclusive as system supply with $3.3\,V$ and $5\,V$, the other two are for payloads of $5\,V$ each.

*b) PDU:* A 7-channel power distribution unit (PDU) also called "eFuse" module consisting of current-limiting P-FET circuits has also been implemented. For each of the seven channels, the output voltage and current are monitored by a MCU. This MCU can activate the channels individually, and displays the measurement information on the bus. The PDU module is supplied directly from the bus voltage of the supercapacitors and distributes it e.g. individually to the four motors.

## V. System Management & Monitoring

### A. EPS-Master

The EPS-Master is the central management unit of the EPS. It implements communication with a higher-level system to provide monitoring of the subsystems of the EPS. This is especially useful during commissioning of the EPS and when it comes to experiments with the system. The EPS-master orchestrates the EPS in terms of power management and provides health monitoring measures like watch-dog functionalities and temperature monitoring of each of the EPS modules.

### B. CapBank Monitoring Unit

The CapBank monitoring unit (MU) is specifically designed for monitoring of the CapBank. Due to the fact, that the CapBank itself has no programmable logic like an MCU, an external board is required to monitor the behavior of the super capacitors in operation. The CapBank MU allows to monitor the state of charge by sensing the different cell voltages of the CapBank.

### C. High Current Test

To test the performance of the supercapacitors and the related circuitry under significantly increased power levels, a CapBank module was modified. For this purpose, among other things, the $10\,A$ fuse was removed, and high-current bus bars were added to the module, as the design of the backplane is not designed for these currents to be tested. Since the supercapacitor modules are not designed for such modifications, these modifications were made manually.

For the test, a powerful digitally adjustable $100\,Amax$ switching power supply with external sense lines was connected to the CapBank module. The high currents and the resulting losses in the cable connections made it necessary to use the external sense lines (4-wire measurement / Kelvin connection) on the power supply unit to compensate for the cable-related losses. Unfortunately, since no electronic load of this rating was available for the experiment, a purely resistance-based load was used. This consisted of six parallel-connected high-load resistors with a sum resistance of $0.2\,\Omega$. For the test, the modified CapBank module together with the CapBank-MU were installed as the only modules on a backplane. The CapBank-MU module serves as a measuring module and transmits the individual cell voltages of the supercapacitors to a PC in real time. For the test, the power supply was configured with currents of $5\,A$, $10\,A$, $25\,A$, $50\,A$, $75\,A$ and $100\,A$ at a maximum of $10\,V$ CC-CV (Constant Current - Constant Voltage). Before starting the test and between each current step, the CapBank module was discharged to below 100mV total voltage via a $0.2\,\Omega$ resistive load. After reaching

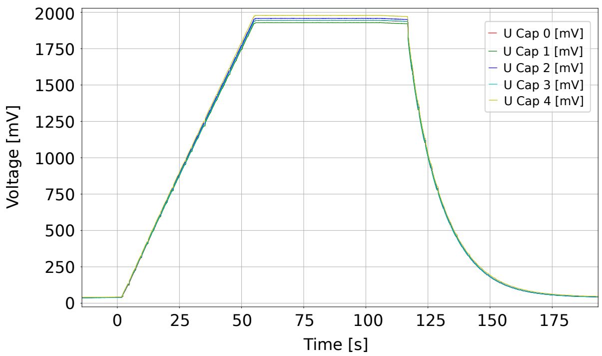


Fig. 8. $5\,A$ charge test with modified CapBank. Full charge of the CapBank took at $5\,A$ constant charge current around 55s.

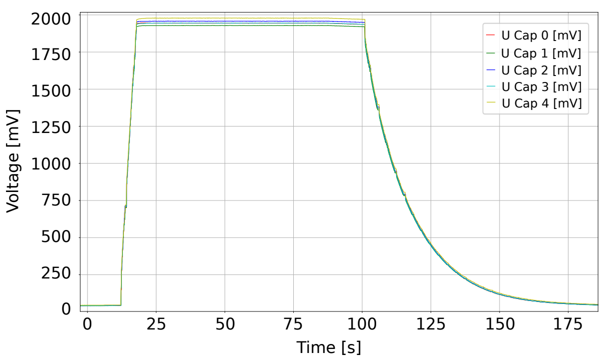


Fig. 9. $100\,A$ charge test with modified CapBank. Full charge of the CapBank took at $100\,A$ constant charge current around 8s. Also under these conditions the balancer keeps the voltage difference between the highest and lowest cell below $80\,mV$.

the set maximum voltage of $10\,V$ in charge process, we left it on for about $50\,seconds$ before disconnecting from the supply and connecting the load to discharge it. For illustration we picked the $5\,A$ and $100\,A$ performance test depicted in Figure 8 and Figure 9.

The CapBank module passed the test without failure even under the highest load. The measurements of the cells did not show any deviations of more than $50\,mV$ between the cells in the charging process as well as in the discharging process. However, it is not exactly certain whether this is only because the individual supercapacitors used came from one batch and thus only had a small scatter among each other, or whether the balancer caused this.

## VI. Conclusion

The requirements regarding compactness and mass of the EPS are comparable to components from the CubeSat market. Nevertheless, the requirements regarding energy storage capacity and peak charge and discharge currents are much higher for mobile systems in comparison to CubeSats. As a result, we presented here a modular EPS for small mobile robotic space systems which is specifically designed for these requirements. The shown EPS is a technology demonstration. The modularity and choice of energy storage technologies is especially notable. Redundant energy storage modules were implemented to investigate different technologies. An operational EPS tailored to specific requirements could be massively reduced in size and mass.

We presented detailed development, design and component selection based on COTS of the EPS. In the area of power generation the main power source are solar cells. Here we implemented an MCU based MPPT and an alternative solar shunt regulator which comes without an MCU. In the area of energy storage primary, and secondary battery cells were implemented for technology demonstration. In addition, an supercapacitor module was implemented. We tested extensively the charge and discharge performance of the super capacitors way above the initial design goal of $10\,A$ with success.

As this is an early technology demonstration, the next step for TRL increase is the identification of critical functions and according parts in terms of radiation and introduction of mitigation techniques.

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## References

[1] J. Walker, L. Burtz, F. Dubois, A. Calzada-Diaz, and T. Tanaka, "ispace Modular Rover Design," in *70th International Astronautical Congress (IAC)*, Washington, DC, USA, 21-25 October 2019.

[2] *CubeRover Payload User's Guide v.1.7*, Astrobotic Technology, 2021.

[3] N. Murdoch, P. Michel, S. Ulamec, M. Grott, U. Böttger, P. Vernazza, D. Arrat, M. Chalon, S. Tardivel, J. Biele, J. T. Grundmann, H. Miyamoto, and the MMX rover team, "The Martians Moons eXploration (MMX) Rover to Phobos," *Europlanet Science Congress 2020*, vol. 14, no. EPSC2020-247, 2020.

[4] N. A. Mulsow, B. Huelsen, and P. Schoeberl, "Towards Influences of the EPS on Lunar Rover System Design," in *16th Symposium on Advanced Space Technologies in Robotic and Automation, ASTRA*, ESA-ESTEC, Noordwijk, Jun. 2022.

[5] L. Schirone and M. Macellari, "Design Issues for the Power System of a Lunar Rover," in *10th European Space Power Conference (ESPC)*, vol. ESA SP-719, ESA-ESTEC, Noordwijk, Apr. 2014.

[6] B. Hülsen, P. Schöberl, and P. Hernandez, "COTS-BASED MODULAR BLDC POWER STAGE USING GaN-FETS FOR ROBOTIC SPACE APPLICATIONS [Manuscript submitted for publication]," Robotics Innovation Center, DFKI GmbH, Bremen, Germany, 2023.

[7] "EPC2055 – Enhancement Mode Power Transistor," 2022. [Online]. Available: https://epc-co.com/epc/Portals/0/epc/documents/datasheets/EPC2055_datasheet.pdf

[8] "EPC7019G Datasheet," 2022. [Online]. Available: https://epc.space/documents/datasheets/EPC7019G-datasheet.pdf

[9] "STM32L433xx," 2021. [Online]. Available: https://www.st.com/resource/en/datasheet/stm32l433cc.pdf

[10] "Radiation-Tolerant 32-bit Arm® Cortex®-M3 Microcontroller," 2020. [Online]. Available: https://ww1.microchip.com/downloads/aemDocuments/documents/AERO/ProductDocuments/DataSheets/SAM3X8ERT_Datasheet_DS60001614B.pdf

[11] "Radiation-Hardened Arm® Cortex®-M4," 2023. [Online]. Available: https://www.voragotech.com/products/va41620

[12] "TCAN33x 3.3-V CAN Transceivers with CAN FD (Flexible Data Rate)," 2019. [Online]. Available: https://www.ti.com/lit/ds/symlink/tcan334.pdf

[13] "SN55HVD233-SP 3.3-V Radiation Hardened CAN Transceiver," 2017. [Online]. Available: https://www.ti.com/lit/ds/symlink/sn55hvd233-sp.pdf

[14] "SN65LVDSxxx High-Speed Differential Line Drivers and Receivers," 2019. [Online]. Available: https://www.ti.com/lit/ds/symlink/sn65lvds179.pdf
[15] "HIGH-SPEED DIFFERENTIAL LINE RECEIVER," 2012. [Online]. Available: https://www.ti.com/lit/ds/symlink/sn55lvds32-sp.pdf
[16] "HIGH-SPEED DIFFERENTIAL LINE DRIVER," 2012. [Online]. Available: https://www.ti.com/lit/ds/symlink/sn55lvds31-sp.pdf
[17] "30% Triple Junction GaAs Solar Cell Assembly," 2016. [Online]. Available: https://www.azurspace.com/images/products/0003805-01-01_DB_3G30A.pdf
[18] "WCAP-STSC Supercapacitors (EDLC's)," 2022. [Online]. Available: https://www.we-online.com/components/products/datasheet/850617022002.pdf
[19] "LS, LSH, LSP Cells," 2023. [Online]. Available: https://saft.com/products-solutions/products/ls-lsh-lsp
[20] "LITHIUM-ION 18650 POWER CELLS," 2023. [Online]. Available: https://lithiumwerks.com/products/lithium-ion-18650-cells/