Modular Power System: Enabling Scalable Missions for the 1W to 1kW Range

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ABSTRACT

As small satellites are increasingly tasked with more aggressive and responsive missions, the utility of scalable, modular and standardized avionics has become evident. A power system offering standard interfaces, with high efficiency across wide power throughput ranges, and late-stage expandability is clearly advantageous for a wide range of missions, particularly responsive ones. In order to address this need, the University of Toronto Space Flight Laboratory (SFL) has developed a modular power system (MPS) to facilitate missions with power requirements spanning two orders of magnitude. The presented case study on the modular power system consists of various modules responsible for power conversion and load switching. A central backplane enables the various MPS modules, as well as mission specific modules to either draw from or energize distributed power buses and interface to the systems digital communication busses. The MPS is designed to provide "only as much power system as needed", and the ultra-high efficiency of each card makes the system suitable for missions ranging from the 1-10W nanosatellite class (such as SFL's CanX-7) to the 100-500W class microsatellite (such as SFL's NEMO-HD). The first MPS deployment, on the Canadian Space Agency's Mars Exploration Science Rover (MESR), developed by MacDonald Dettwiler and Associates Ltd., was configured to run sustained loads of 1.3 kW. This paper provides a high-level overview of the MPS, how the system can be configured for missions ranging from cubesats to kW-class small spacecraft, and the impact modular avionics have on the rest of the satellite system.

INTRODUCTION

Of critical importance to any spacecraft bus is its electrical power subsystem. The power subsystem interfaces with every subsystem, providing the power required to operate all of the critical bus and payload electronics. In general, without the ability to provide reliable power to the various loads of the spacecraft, its mission could not be accomplished, at least not without significant degradation in performance.

Due to its central role, the power system avionics are often required early in the mission development to test the interfaces with the spacecraft loads and to front load any risk reduction testing and qualification on this critical subsystem. However, the power subsystem is often the last system to be frozen, often having to adapt its interfaces and occasionally grow in scope to accommodate changes to payloads and other systems that can occur during mission development.

In addition, the challenges of scale for small spacecraft have not limited the imagination of payload providers, who have, and continue to, produce ever-more power hungry instruments. Thus there is a need for maximum power system performance and end to end efficiency.

In order to address these requirements, and in response to taking on missions of increasing scope with widening payload requirements, the Space Flight Laboratory (SFL) has developed the Modular Power System (MPS), described herein: the design of which is predicated on an "only as much power system as you need" philosophy. The architecture described in this paper was first deployed on the Canadian Space Agency's Mars Exploration Science Rover (MESR), which had sustained loads greater than 1kW. Present implementation of the MPS include the NEMO-HD Earth observing microsatellite mission (200W-class), the CanX-7 deorbiting sail technology demonstration mission—a triple cube nanosatellite (< 10W-class), as well as two recent additions, NORSAT-1 and another commercial satellite, both in the 50-100W-class. In each case, the same building blocks have been used to deliver scaled, high efficiency power systems.

OVERVIEW

Architecture

The Modular Power System is built upon a central backplane, known as the Power System InterFace (POSIF) Module, which distributes power and data to the various power cards. The power cards can either draw from or energize one of the multiple distributed power busses located on the POSIF. Each slot on the POSIF, the number of which can be sized for a specific mission, is identical. This flexibility allows the power modules to be located wherever they best facilitate the spacecraft's wiring and mechanical design. This further decouples the electrical and mechanical design, reducing serial dependencies in mission development.

Topology

The Modular Power System is compatible with many different power system topologies. To date, the MPS has been deployed using a series peak power tracking with battery regulation for high power implementations, as well as a direct energy transfer with parallel peak power regulation for lower voltage applications.

In the series peak power tracking implementation, power is stepped down from the solar arrays to the battery voltage using high efficiency DC/DC converters that provide both battery charge regulation and solar array peak power tracking. No battery discharge regulation is required which suits payloads with high power transients, and the low battery impedance contributes to power system stability. A block diagram overview of a generic MPS implementation is shown in Figure 1. This is the topology deployed on the MESR and NEMO-HD missions, which are described in more detail below.

For missions that have short solar cell strings, where the nominal solar cell voltage overlaps the nominal operating voltage of the spacecraft, such as on a cubesat mission like CanX-7, the direct energy transfer topology is more appropriate in terms of system efficiency.[1] When using this topology, the MPS provides parallel regulation using a high efficiency Battery Charge and Discharge regulator (BCDR).

MODULES

The functionality of the MPS is derived from specialized modules in the form of interchangeable cards. The functional elements of a typical power subsystem are localized on these modules, allowing the selection of either a few or many cards, allowing a system designer to exactly tailor the power subsystem of any given mission. For maximum flexibility, each of the power modules has been designed to act as a standalone functional element, and includes all telemetry gathering and command decoding. By compartmentalizing the functionality of the modules, each individual module can be developed and tested in isolation before integration into the subsystem at a later date. Cards that are not required for all phases of the mission can be selectively disabled to save power, allowing the modularity to be leveraged on orbit as well as during development.

The power modules themselves have been designed to cover typical functional requirements as generically as practical. The most common modules include a scalable solar array/battery regulator, generic DC power supplies, customizable switch power nodes, and a smart battery node. Each module is 50mm x 55mm and weighs approximately 30-40g. These modules are shown in Figure 2, and described in detail below.

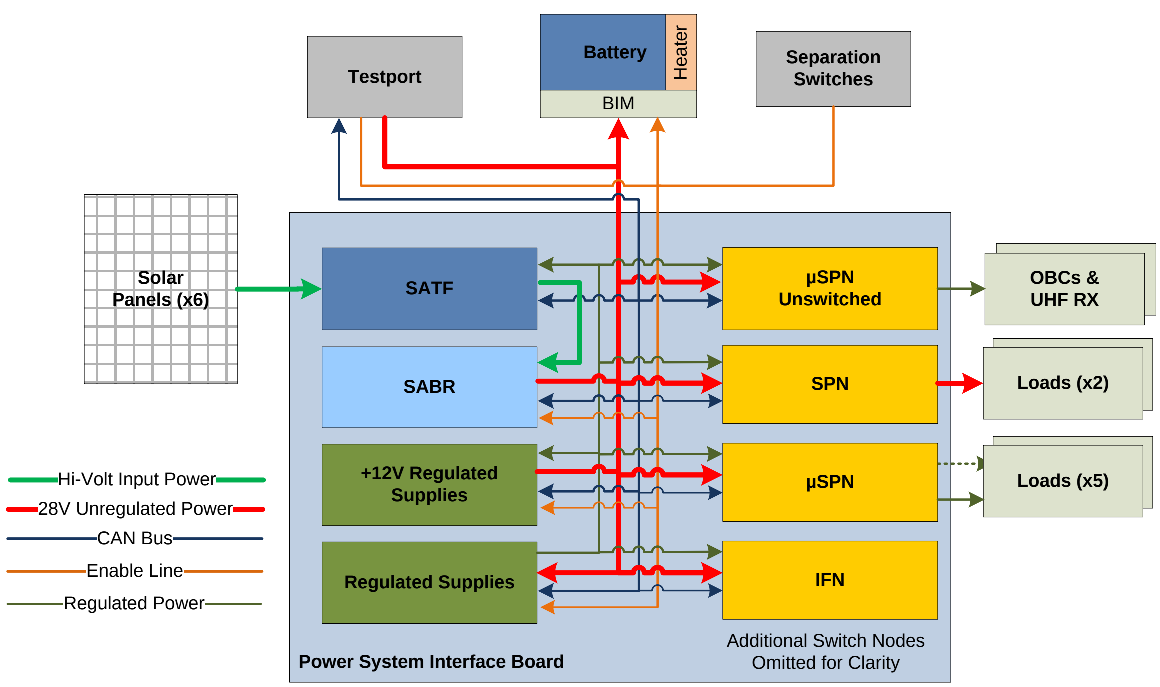

Figure 1: MPS Block Diagram

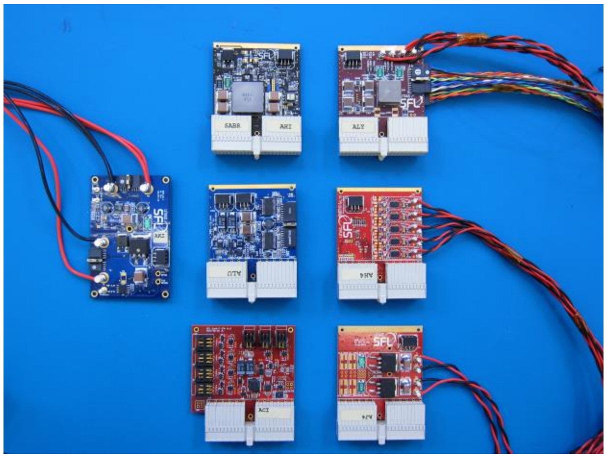

Figure 2: Several modular cards including a SABR (top center), SATF (top right), BIM (middle left), IFN - NEMO-HD (middle center), µSPN (middle right), IFN – Canx-7 (bottom center), and SPN (bottom left)

Solar Array / Battery Regulator

The Solar Array / Battery Regulator (SABR), shown in Figure 2, is a DC/DC convertor that regulates the solar arrays and the charging of the batteries. The SABR is a synchronous buck converter, configured to charge Li-Ion batteries between 5V to 34V while accepting solar array voltages up to 65V. Each SABR has a throughput of up to 180W and operates at efficiencies above 95%.

Control feedback of the converter is accomplished through a hybrid scheme with a high-speed analog controller and a supervisory digital controller. The analog controller is responsible for battery regulation and system stability, the supervisory adjusts the maximum allowable duty cycle digitally, allowing the solar array voltage to be controlled, enabling peak power tracking. The microcontroller on the SABR can be loaded with a variety of peak power tracking algorithms, depending on the specific characteristics of the solar array. This dual control approach allows for fixed-point solar array operation, peak power tracking, and battery trickle-charging.

A single SABR is typically all that is needed, but if additional power throughput or added redundancy is desired, multiple SABRs can operate in parallel. When there are multiple SABRs connected, the controllers will be clocked by a single "Master" SABR to synchronize all slave units in polyphase to reduce the output ripple. If the SABRs are connected to independent solar arrays, they can independently track the peak power point of their connected array. If multiple SABRs are instead connected to the same array, the master SABR will control the peak power tracking, and the slave SABRs will act as hot spares, augmenting the power throughput when the master reaches its design current capacity.

Since the SABR is a high efficiency, high bandwidth buck converter, additional SABRs can be added to the system to provide any regulated voltage rails required by other subsystems that are below the battery voltage. By leveraging the existing SABR design and software, additional voltage regulators can be added for low additional cost.

Switched Power Node

The power distribution of the MPS is done by the Switched Power Nodes, SPNs, and Micro Switched Power Nodes, µSPNs. These modules tie into the main voltage rails of the power subsystem (either regulated or unregulated), and distribute it to the spacecraft subsystems. Each switch card contains multiple solid-state switches with fault protection and telemetry, as well as a dedicated microcontroller for command and data handling. The SPN, shown in Figure 2, has two switches per card, capable of providing between 9V and 34V at 10A per switch. The µSPN, also shown in Figure 2, has five switches per card, capable of providing between 3.3V and 12V at up to 5A per switch. Every switch is equipped with soft-start behaviour and software over-current functionality to protect the loads from transients as well as hardware over-current to protect the power system from critical faults such as short circuits.

Power switches on the SPN and µSPN can be configured as either a switched or unswitched load. Switched outputs will implement a latching overcurrent protection mechanism, which will trip off under overcurrent conditions and remain off until manually reset via a command from an operator. Conversely, unswitched outputs will implement a non-latching overcurrent protection mechanism, which will trip off under overcurrent conditions, but then attempt to reset autonomously. The latter variety of power switch is useful for loads that must be protected, but which should never be permitted to permanently turn off such as command receivers and housekeeping computers.

Solar Array Telemetry and Filtering

To decouple solar array sizing and configuration from the SABRs, the input filtering, muxing, and telemetering of the array is done on a separate module called the Solar Array Telemetry and Filtering (SATF) module. Each SATF, shown in Figure 2, comes with six telemetry channels for array current, voltage, and temperature, with a peak throughput of 20A. The solar array can be scaled up by adding additional SATF modules to meet specific mission requirements. A filter is implemented to attenuate switching noise produced by the SABR from propagating back onto the solar arrays, which could produce unwanted RF emissions.

Mission Specific Module

The MPS has been deployed in a variety of systems including nanosatellites, microsatellites and rovers. Each of these systems has special interface and mission-specific functional requirements. The Interface Node (IFN) provides this mission/bus specific functionality and will typically be the only card that needs to be designed/modified from mission to mission. Functionality that typically appears on the IFN includes hardware decoded command handling, system reset functionality, temperature monitoring, protection features and translation of the physical layer for communications interfaces.

In addition, these mission specific IFNs can carry additional functionality tailored to its mission. As an example, the NEMO-HD IFN was equipped with the electronics to drive various mechanisms involved in the payload. The flexibility of the MPS has allowed for these systems to be placed in the power system to the benefit of the mechanical layout without introducing the risk of late stage modifications to the entire power system as the payload development matures. Instead the IFN alone is coupled to the payload.

For CanX-7, the IFN includes low power versions of the solar array inputs and a DC/DC convertor to provide a regulated voltage rail used by some subsystems. This replaces the need for a SATF and a SABR configured as a DC/DC convertor, shrinking the size of the power system to fit into the constrained triple cube form factor.

Battery Interface Module

The Battery Interface Module (BIM) sits between the battery and the main power bus to provide battery protection and monitoring. The BIM is integrated directly with the battery pack converting it into a smart node capable of collecting its own telemetry and operating independently, similar to the other cards in the system. To accommodate the range of power levels handled by the MPS, the BIM has been designed for a range of Li-Ion battery packs from 34V down to 9V, while allowing up to 40A of discharge current. The BIM provides over discharge and over current protection while continually monitoring the capacity and health of the battery. Since the BIM is an integral part of the battery, the telemetry and protection features are always available during handling and isolated testing.

Battery Charge and Discharge Regulator

The Battery Charge and Discharge Regulator (BCDR) provides the parallel regulation and peak power tracking for the direct energy transfer topology variant. The BCDR replaces the BIM when used, and like the BIM, the BCDR is integrated directly with the battery, and provides thermal monitoring and control. In addition to the battery protection features of the BIM, the BCDR also has a bi directional Boost-Buck convertor which can regulate the main bus voltage to 3.2V-5.5V in order to regulate the charging or discharging of the battery. The BCDR is designed for a single Li-Ion cell at 3.4-4.2V, and is capable of providing 7A of discharge current.

MODULE INTEGRATION

As discussed above the backbone of the MPS is a passive backplane that interconnects the modular cards that compose the power system without the complexity of a spliced wiring harness. The backplane consists of a multi-layered PCB with board-mounted connectors that mechanically support each card and provide electrical interconnection, as shown in Figure 3. Each connector interface is generic and identical supporting any combination of cards (SABRs, SPNs, DC/DC converters, etc…) as required for a particular mission.

The backplane routes all common electrical interfaces to each card including unregulated and regulated power rails, solar power, analog/digital I/O, and the communications interface. Special jumpers located in the backplane can be used to connect a card to any of the common I/O lines for control or telemetry.

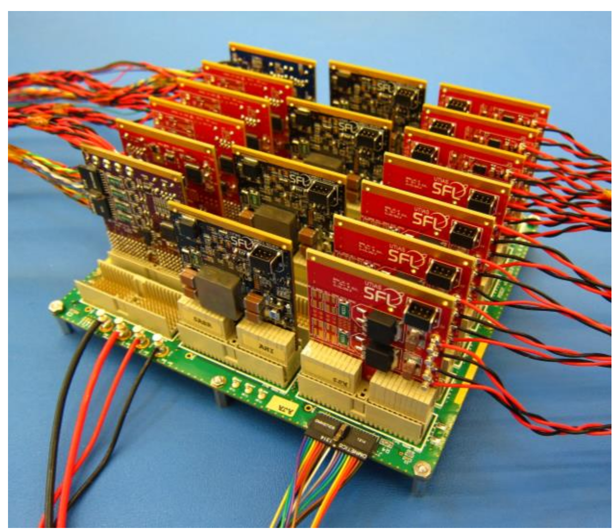

Figure 3: Passive backplane with integrated modular cards – NEMO-HD flight configuration

Each connector interface has dedicated pins that assign the attached card a unique address used for identification purposes. The software loaded onto each class of card is identical and includes a configuration file that is loaded when the card in inserted into the backplane. This has the advantage of making software upgrades generic and replacement of failed units can be performed without pre-configuration.

The size of the backplane and number of modular interfaces is typically customized for a particular class of mission. The power plane copper thickness of the backplane PCB can be increased for high power applications or reduced in order to save mass. Typically several spare generic interfaces are included to permit last minute upgrades to the power system if needed.

COMMAND AND TELEMETRY

Each modular card in the MPS includes a dedicated microcontroller and can be considered a smart node. All commands and telemetry handling is distributed, with each card responsible for managing its own functionality, telemetry and command interface. The software running on each unit consists of a common executive which performs command handling and memory management and an application which provides unit specific functionality.

The physical communications interface typically consists of a CAN Bus although I^2C and UART interfaces are also available on spacecraft that do not support CAN. CAN is ideally suited for this type of distributed architecture as it has support for multiple masters with a hardware arbitration scheme based on carrier sense multiple access with bitwise arbitration (CSMA/BA). Each card is one node on the multi-drop Bus and can be addressed with a global broadcast, device type broadcast, or unit specific address.

All communications with the MPS use the NanoSatellite Protocol (NSP) developed by SFL and used on all SFL missions. This is the same protocol used for the ground to spacecraft link and all intra-satellite communications. Use of this standard protocol permits the power system to be seamlessly integrated with any SFL bus and to take advantage of existing NSP command and telemetry terminals.

APPLICATIONS

As of the time of writing the MPS has been deployed in five very different applications. The scalability of this modular approach is emphasized by the fact that these missions ranged in output power from 5W to 1.3kW and bus sizes from as small as a carton of milk to as large as a golf cart. While the size and capabilities of these systems varied extensively, they all had the same basic requirements: to provide switched power, fault protection, battery charge management and solar array peak power tracking.

CanX-7

CanX-7 is a 3.5kg nanosatellite with the mission of demonstrating an SFL-designed drag sail for de-orbiting nanosatellites and microsatellites from LEO at the end of their mission.[2] CanX-7 is a very simple spacecraft, and requires few subsystems to achieve its mission. Its power demands range between 0.5W to 5W with an average of 3W of power generated by the solar array. The power system topology for CanX-7 is the direct energy transfer variant of the MPS and consists of two µSPNs, a BCDR (connected to a 16Wh Li-Ion battery) and an Interface Node. The main power bus operates at 4.2V which can be used directly by the loads without additional serial regulation. The CanX-7 structure consists of a triple cube form factor with dimensions of 10 x 10 x 34cm and is shown in Figure 4

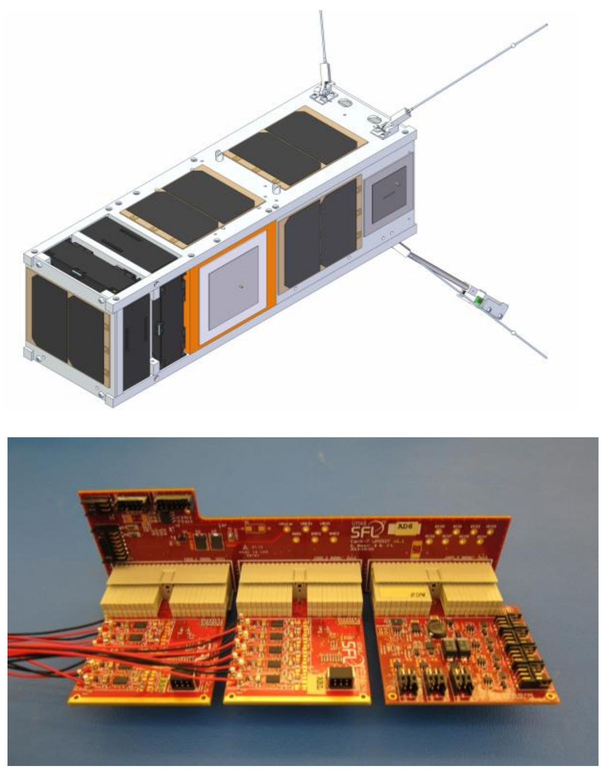

Figure 4. By reducing the dimension of the passive backplane the MPS was made to easily fit inside this small spacecraft. CanX-7 is under development with support from COM DEV Ltd. and Defence Research and Development Canada (Ottawa) and the Natural Science and Engineering Research Council (NSERC).

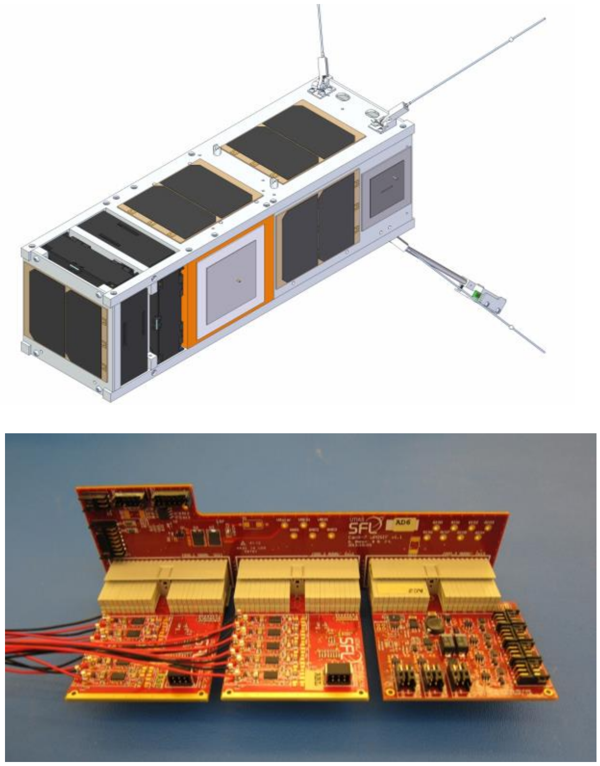

Figure 4: CanX-7 spacecraft (top) and MPS implementation (bottom)

NEMO-HD

NEMO-HD (Nanosatellite for Earth Monitoring and Observation – High Definition) is an Earth observation satellite that will provide multi-spectral imaging with a GSD of 2.8m and real time high definition video.[3] NEMO-HD has been designed and developed by SFL for the Slovenian Centre of Excellence for Space Sciences and Technologies Space-SI. The spacecraft has dimensions of 63 x 63 x 38cm and a mass of 50 kg and is shown in Figure 5. With seven cameras and an X-Band transmitter the power demands of NEMO-HD are an order of magnitude higher than CanX-7 and range from 10W to 220W during nominal operations. The NEMO-HD solar array typically produces 50W of power on average, which is used to power the loads and charge a 300Wh Li-Ion battery. The NEMO-HD power system provides 28V unregulated power plus regulated 5V and 12V power buses. Power is distributed to the loads using five SPNs and six μSPNs. A single SABR provides peak power tracking and battery charge regulation while three additional are SABRs configured to produce regulated voltage rails used by various subsystems. The NEMO-HD mission is expected to launch in 2014.

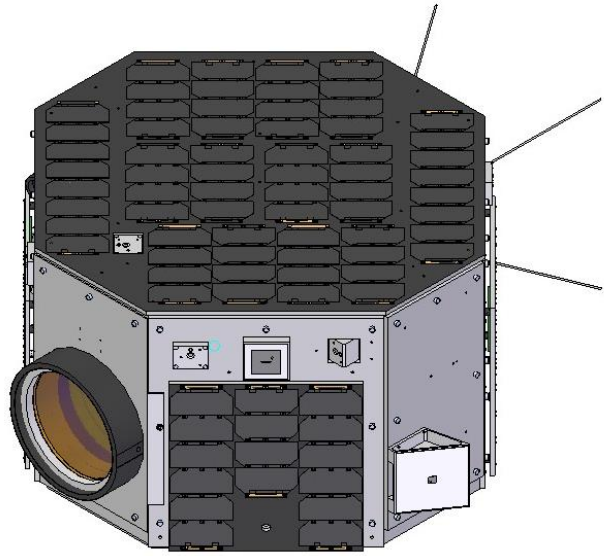

Figure 5: Solid model of the NEMO-HD spacecraft

MESR

The third deployment of the MPS was not in a spacecraft but rather in a terrestrial Mars rover prototype, called the Mars Exploration Science Rover or MESR, shown in Figure 6. MESR is a six-wheeled rover designed to support autonomous science prospecting and in situ geological analysis operations.[4] The rover has a wheelbase of 180cm and a payload capacity of 70 kg. The rover includes a full suite of instruments for autonomous navigation and science experiments. MESR presented a unique challenge as the power requirements were far in excess of any spacecraft that SFL had built before. Nevertheless, the rover peak power requirements of 1.3kW were met with 12 SPN cards providing 28V unregulated power to the loads, a 1.2kWh Li-Ion battery and two SABRs operating in parallel to pull power from a 300W solar array. MESR was built in partnership with MacDonald Dettwiler and Associates Ltd and has already been delivered to the end user, the Canadian Space Agency. MESR is currently undergoing field trials at the CSA Mars yard.

CONCLUSION

As the number and scope of small satellite missions has increased, the utility of scalable, modular and standardized avionics has become evident. SFL has developed a high-efficiency, highly-modularized and highly-scalable power system which has been deployed on systems with power demands spanning 1W to 1kW. It is anticipated that the MPS presented in this paper will continue to enable a wide range of mission types, sizes, and power demands, and will serve as the backbone of increasingly ambitious small missions in LEO to come.

Figure 6: The Mars Exploration Science Rover (MESR) terrestrial prototype with the MPS power system visible in the gold box in the central cavity of the rover

ACKNOWLEDGEMENTS

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