

POWER TELEMETRY ONBOARD A SEMI-AUTONOMOUS MARS ROVER

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ABSTRACT

This paper explores the telemetry of the power distribution system utilized onboard a semi-autonomous Mars rover. The Missouri S&T Mars Rover Design Team designs and fabricates such a rover to compete in the University Rover Challenge, a competition whose tasks simulate a future manned mission to Mars. To maximize efficiency during competition, the rover's modular power distribution system consists of three separate units: a 72 Watt-hour, Lithium-polymer battery pack; a custom Battery Management System (BMS); and a central power board. The BMS and power board measure and process electrical and environmental data autonomously, creating a self-regulating system onboard the rover. The two also form a communication chain between team teleoperators and the battery pack. This continuous stream of real-time data enables the team to quickly monitor the rover's safe operation, to make informed decisions during competition, and to apply this data to the design of future power systems.

INTRODUCTION

The Mars Rover Design Team (MRDT) at Missouri University of Science and Technology was created five years ago as an opportunity for students to develop and innovate space technology. The team's primary purpose is to design and fabricate a next-generation Mars rover over the course of a year to compete in the University Rover Challenge (URC) (Figure 1) [1]. Hosted by the Mars Society in Hanksville, Utah, the competition tasks simulate a future manned mission to Mars. Each rover must be able to assist astronauts, collect and analyze a series of samples, service various pieces of equipment, and traverse rugged terrain [1].

To complete these tasks quickly and efficiently, MRDT's 2017 competition rover, Gryphon, utilizes a custom power system whose specifications meet not only URC requirements, but also those that arise from the power needs of the rover's other sub-systems. Team members create a power budget to reference throughout the design and development cycle. However, as designs for other systems onboard the rover have the potential to change dramatically throughout the year, the power budget anticipates extra current draw to provide security in the case of unexpected power needs.



Figure 1: MRDT's 2017 Competition Rover, Gryphon

By creating an adaptable, versatile power distribution system, the team has flexibility in its design cycle without sacrificing or taxing the rover's power needs. This adaptability also presents additional challenges. A vehicle built to encounter harsh terrain, the components of a rover must be both durable and well secured. Special consideration must be given to the power distribution system - it must be able to protect itself amid a mechanical failure. Should electrical components loosen, there is a possibility that they could short or spark and harm connected devices or other sub-systems. On the other hand, the power distribution system must also remain both easily serviceable and accessible for the dynamic design and development cycles of the other sub-systems. In response, the team has created a modular power distribution system characterized by its independent component designs. This design method also provides an additional benefit through the formation of a communication chain between the rover and team operators. To function safely and properly, individual units of the power distribution system continuously relay data about their present operating conditions. The team can then monitor these conditions in real time, and adjust them as necessary while the rover is in operation. The result is an innovative, effective solution to the challenges of competition.

THE POWER DISTRIBUTION SYSTEM

The purpose of the rover's power distribution system is to create, allocate, and manage power across each of its other five major sub-systems. These include the following: Drivetrain, Ground Support Systems, Manipulators, Rovecore, and Science [2]. Gryphon's power distribution system is composed of three distinct units: a Lithium-Polymer battery pack, a custom Battery Management System (BMS), and a central power board. To streamline this design, the battery pack and BMS are contained within a single structure known as the battery box. The system's configuration is illustrated below in Figure 2.

Each aspect of Gryphon's power system was developed according to additional team-mandated requirements. First and foremost, the team wanted each element of the system to be easily accessible for testing and maintenance throughout its development. Second, as each sub-system

has its own current and voltage requirements, the power distribution system must be compatible with a wide range of devices without decreasing its power output. Lastly, MRDT wanted to incorporate both manual and automatic safety features and controls into the battery pack, BMS, and power board. These additions protect the electrical components and devices onboard the rover in case of a major failure.

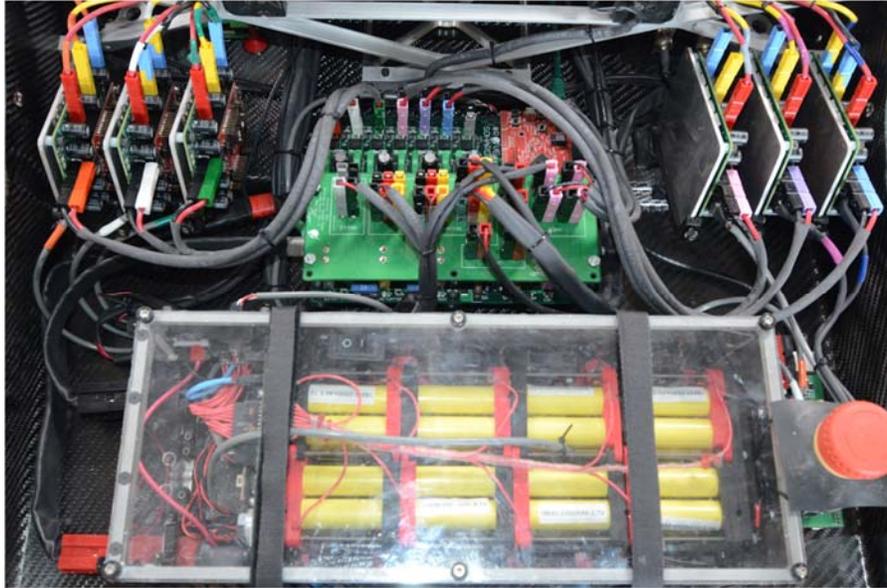


Figure 2: The Power Distribution System Positioned Between Gryphon's Motor Controllers

To meet these requirements, the team chose a modular design for Gryphon's power distribution system. This means that each unit of the system operates almost completely independently of one another, which allows the team greater control of the entire system. They can also be tested and developed simultaneously, affirming the system's versatile nature. Modularity represents the biggest design consideration of Gryphon's power distribution system – it ensures that each device onboard the rover is interchangeable yet able to operate according to its own unique power needs and specifications.

THE BATTERY PACK

To power Gryphon, the team chose Lithium-Polymer (LiPo) 18650 cells for their excellent energy density, as their energy to size ratio is significantly higher than other battery options [3, 4]. These batteries have also been utilized in previous MRDT rovers, and have shown to be a reliable power source during competition. The battery pack must have the potential to supply a maximum sustained peak current of 180A to the rover - a situation that only arises when all of the drive motors, telecommunications systems, camera gimbals, and the robotic arm are operating simultaneously. Additionally, after establishing the power budget and studying the performance of the team's previous rover, it was determined that a battery pack of the same type and size - but not mechanical structure - should be utilized in Gryphon's power distribution system. The structure of the previous pack arranged the cells in a flat sheet, but it proved to be flimsy and difficult to

service. Gryphon's battery pack, therefore, was designed to be sturdier, and is shown below in Figure 3. Individual LiPo cells are contained in 3-D printed cell holders in groups of ten, and are then connected in parallel to create a single battery block. Gryphon's battery pack is composed of eight of these blocks connected in series.



Figure 3: The Battery Pack

The LiPo cells are arranged in a 2x5 array within each block, and each block features conductive tabbing spot-welded across its top and bottom. By attaching bus bars across one end of the battery pack and two separate contacts at the other, this design enables connection when the blocks are simply bolted together. The bus bars are composed of electrical grade aluminum, while the contact points are electrical grade aluminum washers placed into recessed ports in the battery pack's plastic endcaps. These cell holders also feature small holes through which team members can measure the voltage of individual blocks. Digital temperature sensors are also embedded within the pack to ensure the batteries' safe operation. The innovative structure of Gryphon's battery pack enables MRDT operators to remove and replace individual cell blocks easily in the case of malfunction or damage. Its design streamlines the pack's wiring and voltage measurements, both electrically and manually, while the pack's assembly maintains the proper condition of the cells and their connections. Additionally, the recessed design of the pack's contacts ensure that they can only be accessed deliberately, lowering the chance of both injury and accidental pack shortage.

THE BATTERY MANAGEMENT SYSTEM

The primary purpose of the BMS is to monitor and manage the condition of the battery pack. As LiPo batteries that operate below or beyond their rated voltage can ignite or explode, it is imperative that the team is able to continually assess their condition while operating the rover. Most of the concepts behind Gryphon's BMS were adapted from the design of the BMS onboard the team's previous rover. Its execution has been very different, however, as the former BMS was never fully operational. As a result, MRDT carefully considered the design and fabrication of

Gryphon's BMS. The device encompasses a custom printed circuit board coupled with an MSP432 microcontroller, various MOSFETs, and an array of individual sensors (Figure 4) [3].

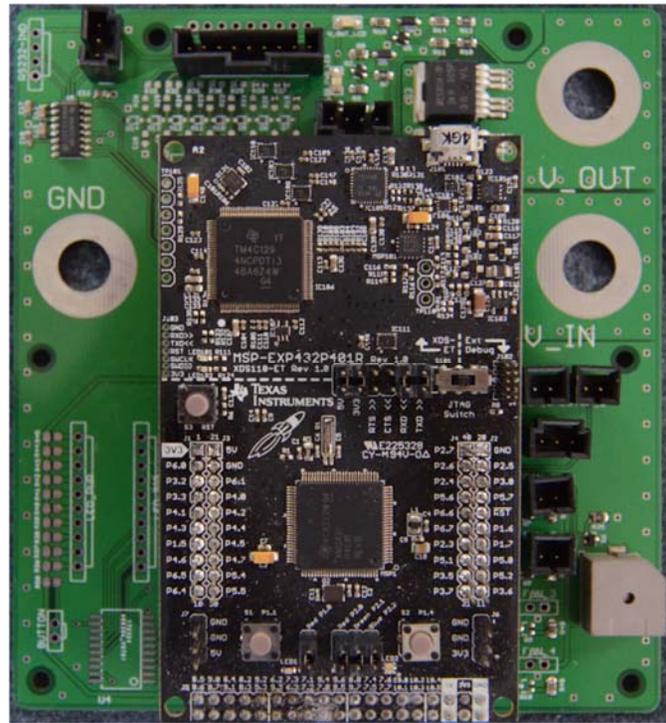


Figure 4: The BMS

These additions enable the BMS to continuously measure and record the temperature, voltage, and current draw of the battery pack. As data is collected, the microcontroller communicates this information to team operators and, if necessary, protects the pack from danger. All readings are transmitted to the team's base station, an external communication center. It allows team operators to collect telemetry from each onboard system, display it for analysis and discussion, and send commands back to the rover. By analyzing these readings, the team can monitor Gryphon's status during competition and make informed decisions as it runs. Additional abilities of the BMS are completely autonomous. The device can assess and adjust dangerous or unfavorable temperature conditions within the battery pack by operating up to four fans positioned throughout the battery box. Furthermore, the BMS protects the entire power distribution system against overcurrent by automatically shutting down the rover should it detect current levels greater than the allotted 180A output of the batteries. Coupled with a manual emergency stop button that disconnects the rover's batteries from the power board completely, these two emergency stop functions ensure the safety of team operators should any type of problem arise concerning the rover's sub-systems. In the case of the batteries reaching dangerously low voltage, the BMS will turn off power to the rover, and then itself, by means of an electrically resettable rocker switch. It will also automatically turn itself off to save power if it is left on while the rover is off for more than an hour. The streamlined design of Gryphon's BMS offers a functional, practical approach to navigating competition tasks safely, while its communication chain of power system data enables team members to operate the rover efficiently and effectively.

THE POWER BOARD

The power board is responsible for regulating and distributing the power received from the battery box to the rest of the systems onboard the rover. It does so by relying upon a combination of hardware and software power controls. While influenced by previous designs, the layout of Gryphon's power board was reorganized to give team operators more control over the total distribution of power by separating critical and noncritical system devices. This separation helps to protect the rover and its systems in the case of an electrical short. Should there be a shortage in the rover's robotic arm, for example, this design prevents other systems from shorting as well.

As illustrated in Figure 5, power is allocated from the batteries to the other sub-systems through a collection of eleven different buses. Seven of these buses are responsible for distributing power directly from the battery pack to Gryphon's motor controllers, a group of devices that control the rover's propulsion system. The remaining four buses - communications, logic, actuation, and extra - power devices across the rest of the rover's sub-systems. As these four buses must receive power at a constant rate of 12V, pack voltage and current first pass through one of three different 12V buck converters to accommodate this restraint. This is necessary because the typical range of pack voltage is 25 - 32V.



Figure 5: The Power Board with Its Seven Motor Buses and Four Specialized Buses

The communications bus powers all of the communication devices onboard Gryphon, while the logic bus powers all of its other integrated circuits and microcontrollers. The actuation bus powers the higher current devices, such as the cameras onboard the rover or the motors that open and close the rover's drop bay. These devices may draw anywhere from 1 - 6A continuously, as opposed to most of the rover's other devices that operate within a 100 - 500mA range. The extra bus provides additional power to any systems if necessary. It was added as a security measure for cases where systems need more current than they were originally allotted in the power budget.

Each of the eleven buses have their own independent current sensors, switching MOSFETS, and fusing. The current sensors report data about each bus to the microcontroller which has software defined current limits. Should the current draw for any bus rise above the set limit, the microcontroller will automatically disable that bus. The fuse for each bus is installed in series to provide a hardware backup should the microcontroller fail. The motor buses connect directly to their specified motor controller by means of Anderson Powerpole connectors on the power board, while the remaining buses pass through an additional printed circuit board known as the patch panel before connecting to their portion of the rover. The patch panel is a separate board mounted onto the power board that provides each bus with multiple vertical Anderson connector pairs. Both the power board and the patch panel are shown below in Figure 6.

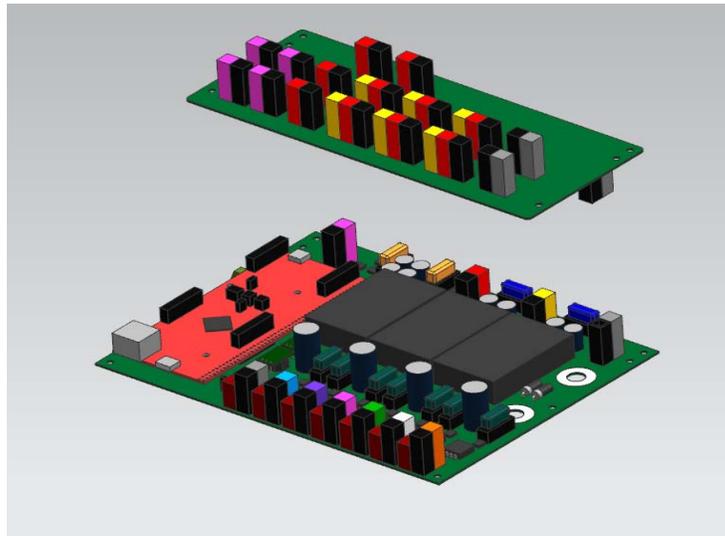


Figure 6: 3-D Model of Gryphon's Power Board (lower) and Patch Panel Attachment (upper) Generated in Siemens NX Modeling Software

Every competition task requires its own specialized devices, so it is extremely valuable for the team to be able to connect different devices to the power distribution system. The same connection is used for both the rover's science arm and its robotic arm, for example, and the team must remove and replace these devices between the science and equipment servicing tasks. Gryphon's power board is designed to offer additional protection and utility through the separation of each bus to manage situations such as these. The practice of separating the buses streamlines and manages the power output from the batteries safely and rapidly. This method also protects Gryphon from major electrical damage due to a short, as it would affect an individual system as opposed to all boards and components. The separated buses ultimately allow MRDT operators greater control of specific devices on the rover, as well as more reliability as vital devices are independently powered.

SYSTEM INTEGRATION AND TELEMETRY

Gryphon's power distribution system has two separate communication methods that are bridged within the power board. There is an internal communication system for the power board and BMS to exchange data, and an external system which is used to communicate between the rest of the rover and the base station. The internal communication is achieved with a three wire RS-232

connection, whereas the external communication utilizes MRDT's custom protocol, RoveComm. This divide between internal and external communication is necessary due to the lack of support for RoveComm on the hardware of the BMS. The low-power MSP432 microcontroller on the BMS does not support the Ethernet connectivity necessary for RoveComm, so RS-232 was chosen as a suitable alternative. By using these two communication methods in tandem, the team receives a continuous stream of reliable data that allows operators to make informed decisions during competition.

INTERNAL COMMUNICATION

Power board to BMS communication is implemented by combining the RS-232 protocol with a three-wire serial line. RS-232 uses +15V as a logical low and -15V as a logical high. This design decision was made because the standard Universal Asynchronous Receive/Transmit (UART) protocol generated by the microcontrollers on the BMS and power board only have a range of 0V - 3.3V. As the layout of the rover was not finalized when the team selected the communication protocols, the team needed to employ one that would be reliable regardless of the noise level surrounding the signal wire. For this reason, the team chose to utilize RS-232. Its higher voltage range reduces noise on the signal line caused by the large buck converters on the power board itself in addition to the noise generated by the motor controllers situated on either side of it. By implementing this communication protocol on Gryphon, the team increases the reliability of messages sent between the power board and BMS while retaining the unit's flexible design. Messages sent from the power board include commands to turn on and off the fans in the battery box, to reset the battery pack power output, and to shut down the pack output. Upon receiving these commands, the BMS acts accordingly and then responds to the power board. It primarily sends data about the current being drawn from the battery pack, the battery pack voltage, and the temperature of the battery pack to the power board. This data sent between the power board and BMS is crucial to the safe operation of the rover. Most importantly, it allows the team to monitor and adjust the condition of the battery pack. To ensure that these messages are properly delivered and received, MRDT chose this method of communication because it reduces the distortion and damage of the messages sent between the BMS and power board. This, in turn, improves the rover's performance during both development and competition.

EXTERNAL COMMUNICATION

Base station operators utilize a team generated software known as Rover Engagement Display (RED) to relay commands to the devices onboard the rover during operation. This is made possible through a custom communication protocol known as RoveComm, which connects the base station to the rover's power board. It is inherited from MRDT's 2016 competition rover and is based on the lightweight User Datagram Protocol (UDP), a protocol that provides no guarantee of message delivery or packet duplication protection. RoveComm takes advantage of UDP's lightweight messages but adds its own message verification system. This implementation makes RoveComm a reliable communication system without being as resource intensive as Transmission Control Protocol (TCP). The header of a RoveComm message includes data about the version of the protocol used to send the message, the type of data being sent, the size of the data, and a flag to specify whether an acknowledgement response is required. Its packet structure allows for a variety of message types to be sent to the different devices on the rover.

As RoveComm is a protocol used by every device on the rover, its numerous types of data are divided according to each device's purpose. Thus, a section of RoveComm is reserved specifically for messages to and from the power board. These commands are typically used to disable and enable the motor, actuation, extra, and logic buses, but the power board also continuously sends data about the current readings of each bus to the base station. This communication channel is what allows the team to direct Gryphon during operation, as the base station operators use the information conveyed by the power board to determine their next command to Gryphon. They view the status and current draw of each of the various buses on the power board via a readout generated by RED, shown in Figure 7. This information is then used to make decisions about the rover's performance during its operation. For example, the URC science task requires a team's rover to take soil samples from a chosen location. MRDT operators would typically direct Gryphon to lower its science arm and begin drilling into the soil, but the cameras onboard the rover cannot always view the drill. This means that the team does not always know if the drill is spinning. To compensate, the team studies the current draw levels indicated by RED. As the science arm is connected to the actuation bus, the current level of the bus will fluctuate as the drill is used. The changes in the actuation bus's current level are shown in RED, so the team can evaluate the situation and respond accordingly. As each component of the power board listed in RED acts in a similar manner, team operators can monitor each sub-system onboard the rover during its operation. Developed by MRDT to enhance a rover's performance, RoveComm contributes to the safe, efficient operation of Gryphon and the communication chains the rover relies upon to succeed in competition.

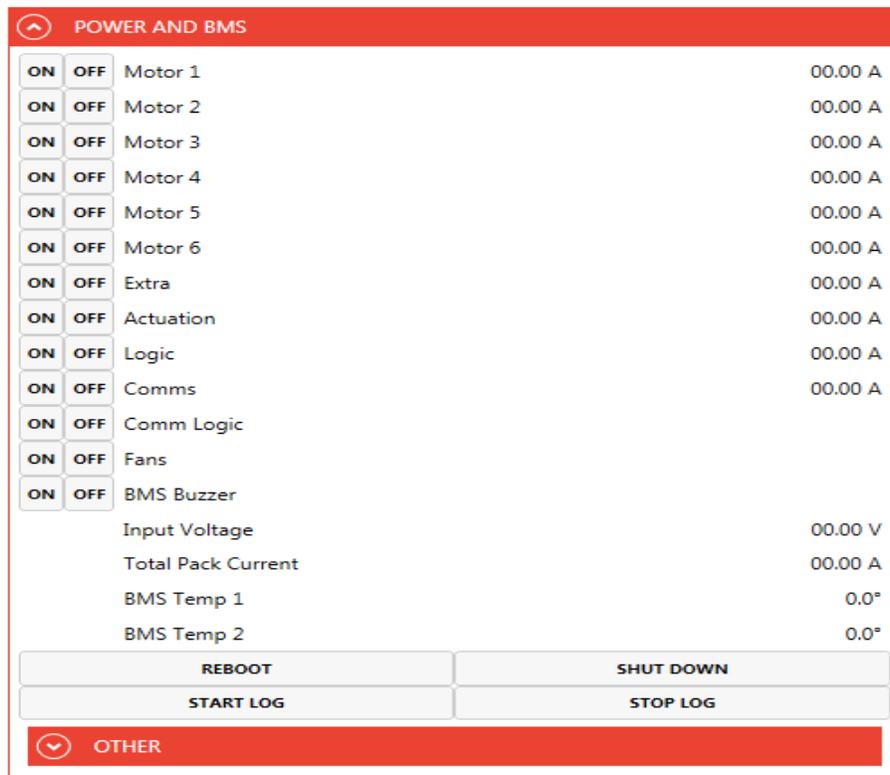


Figure 7: Example Readout of the Power System Toggles in RED

CONCLUSION

The power distribution system is an integral part of a rover's design and functionality. While Gryphon's reliable, modular structure ensures the rover's safe and effective operation, MRDT strives to further develop its designs for future competition rovers. By analyzing the performance of Gryphon's power distribution system, the team has chosen to begin by introducing active monitoring and, eventually, active balancing of individual blocks within the battery pack. Doing so would allow the team more precise control of the health and safe operating conditions of the battery pack. If the BMS could measure the voltage of individual battery blocks, it could register that a block's voltage level was approaching its lower limit and shut off the battery in response. While team members tried to incorporate active battery monitoring into Gryphon's power distribution system, they were never able to do so successfully. Active monitoring is a more accurate means of prevention than the method that the team currently uses, which is to assume that all of the battery blocks have equal voltage levels. Unfortunately, this practice requires that team members overcompensate the minimum useable voltage as a result. Should MRDT employ active monitoring, it could also implement active balancing more easily. This practice would enable the BMS to alter the current draw from each of the individual battery blocks to ensure that their voltage levels were evenly balanced - a condition that would extend the life and available use of the battery pack during the rover's operation. Yet even without these features, Gryphon's power distribution system remains an innovative solution to the challenge of powering a semi-autonomous rover. Its adaptability accommodates the needs of the rover's other sub-systems without sacrificing its own design considerations, while its constant communication of device conditions on both internal and external levels allows team operators to formulate tactical responses during competition. The implementation of a modular design is a simple way to allocate energy to all of Gryphon's sub-systems and devices rapidly and effectively, and has proven to be a strong foundation for the team's future design visions.

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