REMOTE FAULT HANDLING OF A TELEOPERATED ROBOTIC POWER SYSTEM

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ABSTRACT

This paper examines the use of telemetry on the power system of a prototype Mars rover designed to compete in the 2021 University Rover Challenge. The power system, comprising of the battery management system and power distribution boards, is controlled by two microcontrollers. These microcontrollers receive commands, transmit data, and monitor the status of the battery as well as the other subsystems on the rover. The microcontrollers provide remote current and voltage monitoring, as well as fault handling by the battery management system and the power distribution board. The microcontrollers communicate this telemetry to a remote base station over a 900 MHz ISM band radio link. This ensures the base station operators have accurate and timely information about the status of the rover and allows the operators to intervene or react quickly to any electrical issues.

INTRODUCTION

The Mars Rover Design Team (MRDT) is a student design team out of the Missouri University of Science and Technology, or Missouri S&T. They design and manufacture a prototype Mars rover for the annual University Rover Challenge, or URC [1]. The competition includes four main tasks in which the rover must:

- Conduct experiments to determine the possibility of life in a sample (Science Task),
- Traverse extreme terrain while relocating various objects (Extreme Retrieval)
- Exhibit fine control of a robotic arm to interact with a panel (Equipment Servicing), and
- Use GPS and a computer vision system to navigate autonomously to waypoints (Autonomy Task).

Due to the cancellation of URC for the 2020-2021 academic year because of the COVID-19 pandemic, the 2021 MRDT rover was field tested internally in accordance with the URC Rules and Regulations [2] during a mock competition. Telemetry from the rover is critical to successful operation of the rover. It gives the operators real-time data as to how rover systems are performing and allows them to make educated decisions about how they will approach each of the four URC tasks.

ON-ROVER NETWORK AND WIRELESS COMMUNICATIONS

The MRDT uses two radio frequency bandwidths while operating the rover. A 5.8 GHz connection is used for line-of-sight (LOS), higher bandwidth applications such as when multiple camera feeds and sensor data are pushed through the network during the Science Task. While this is extremely useful for LOS scenarios, the team commonly switches to a 900 MHz frequency for the added range it provides for non-line-of-sight (NLOS) applications on the order of 150 Mbps [3]. Both communication standards were used in the 2021 MRDT rover. The rover was also equipped with a 2.4 GHz antenna to allow a computer to perform system checks easily over Wi-Fi but was not used for communication otherwise due to the effectiveness of the 900 MHz and 5.8 GHz pairing. Telemetry from the rover includes on-board measurements, camera data, science sensor data in the case of the Science Task, and arm velocity and position data. The network connection also allows for commands to be sent to the rover in the form of toggling power ports on the power distribution board, drive and arm control commands, and rebooting the rover, among others. The reader should note that the internal tests performed by MRDT were NLOS and thus 900 MHz communication was used for the mock URC competition.

Base Station Network Configuration

The base station application runs on a computer in a custom enclosure to house it, four monitors used for displaying rover telemetry and data, and a separate mounting system for the 900 MHz and 5.8 GHz antennas, or the "signal stack." These all are assigned specific IP addresses and are connected to a network switch. The antennas each use a different polarization pattern based on their use case, as shown in Figure 1. The 900 MHz communications use a Yagi-Uda antenna with a roughly 30° beamwidth. This, combined with the longer wavelength and cone-like shape of the signal give the 900 MHz frequency and antenna an advantage for NLOS tasks. The 5.8 GHz communications use a Sector antenna with a wider, prism-like beam that makes it more suitable for LOS applications.

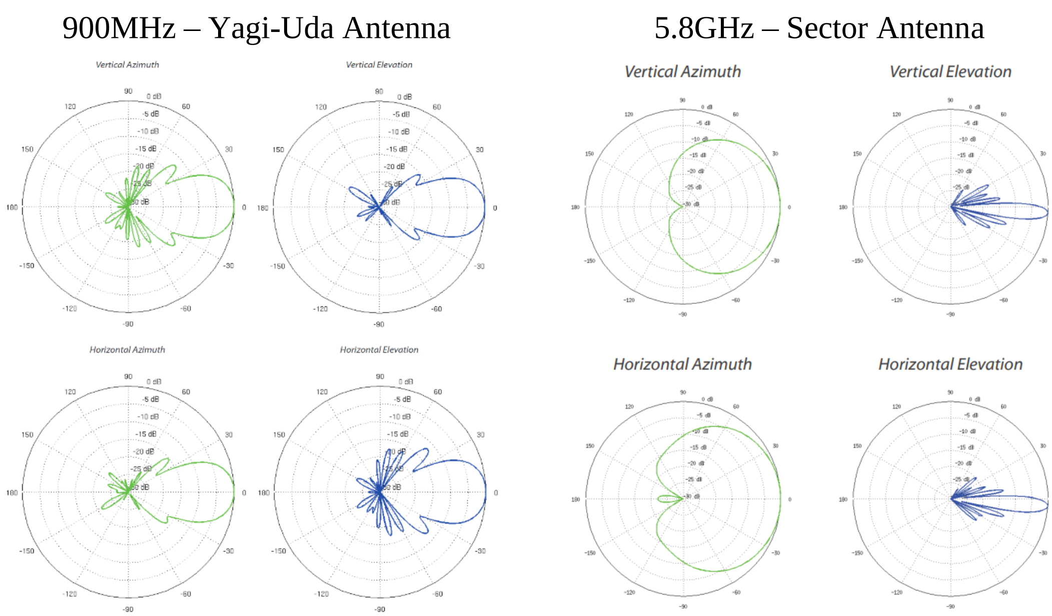

Figure 1 - Antenna Polarizations [3]

Rover Network Configuration

The rover-side network includes the radio transceivers and the subsystem boards required for rover operation, including the battery management system and power distribution boards. These are all connected to a central network switch and assigned a static IP to identify individual boards. Each of the sub-systems on the rover include either a microcontroller [4] or a microcomputer as both devices possess onboard ethernet protocols and thus can be connected to the network with relative ease. The power system on the rover utilizes the microcontroller.

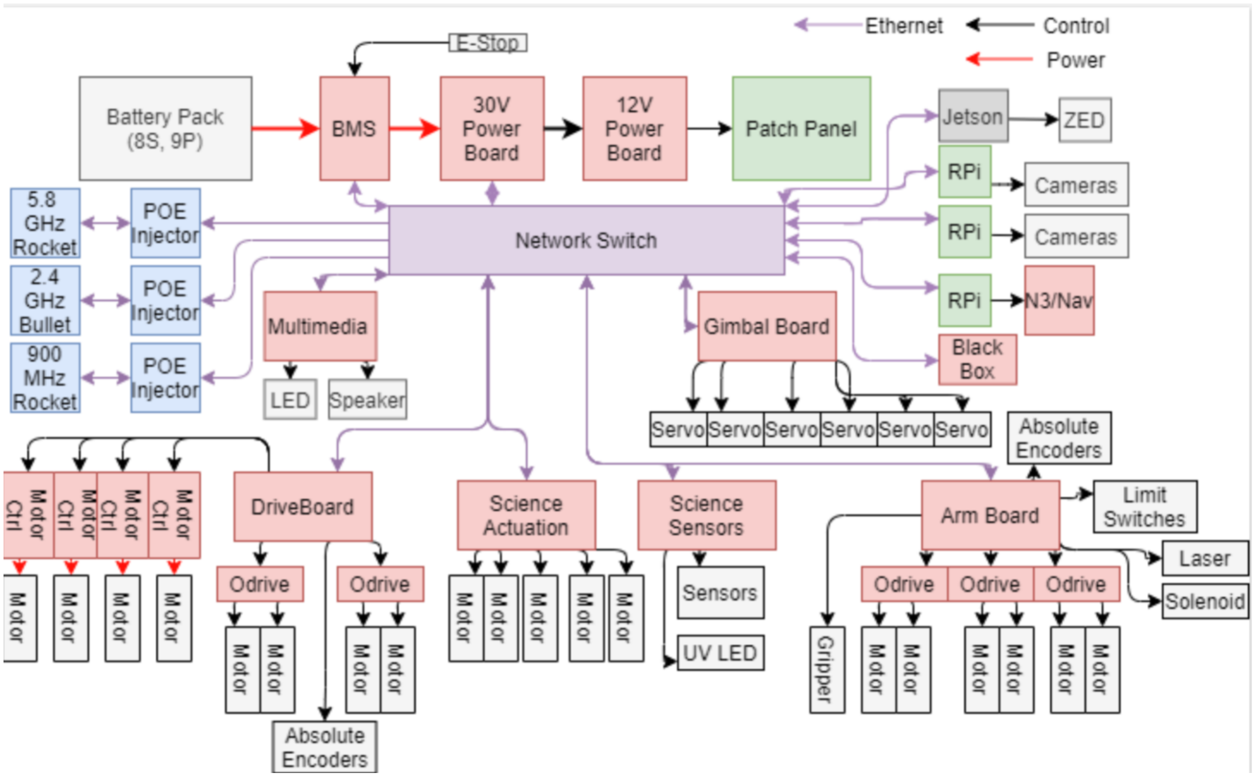

Figure 2 - Rover Control and Data Block Diagram [5]

Wireless Communications

Each PCB that MRDT designs has a microcontroller that is programmed in C++. The basestation is programmed in ReactJS, a JavaScript library used to make graphical user interfaces [6]. To communicate with the rover remotely and control it, MRDT designed their own open-source networking protocol called RoveComm [7]. RoveComm has a custom packet size and type for different kinds of telemetry and expects specific telemetry from each microcontroller through ethernet. Through ethernet, RoveComm uses two protocols. RoveComm expects telemetry, such as current values, voltages of battery cells, and the states of ports in UDP. Commands, such as toggling power ports, are sent through TCP.

BATTERY MANAGEMENT SYSTEM

The Battery Management System (BMS) for the 2021 MRDT rover monitored the custom 8s9p lithium-ion battery pack that was designed to power the rover. The battery was built using LG Chem 18650 HE4 cells connected via nickel strips. A spot welder was used to connect each cell, which were then placed in a 3D-printed mounting system inside of a battery box for easy removal from the rover as depicted in Figure 3.

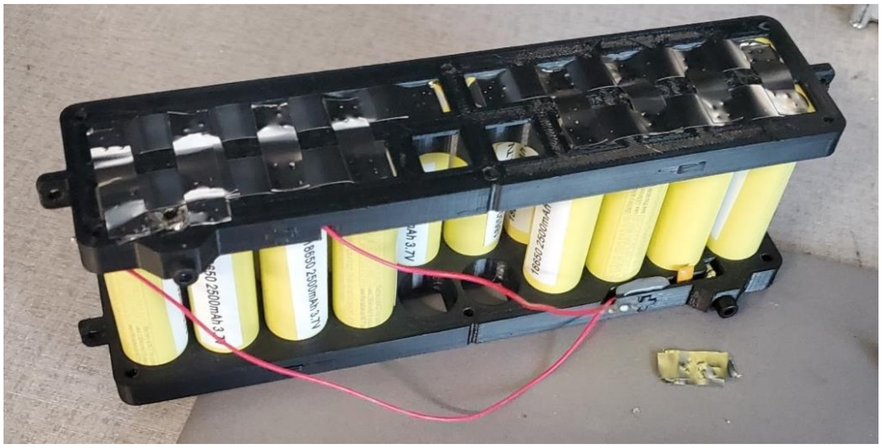

Figure 3 - 18650 Cell Mounting System

The purpose of the BMS was not only to send battery telemetry from the rover, but also to protect the battery itself. As such, the BMS was built to detect various faults in hopes to prevent any subsequent damage to other rover systems. The BMS monitored pack and cell voltages, pack current, and temperature of the battery. Using both a 3.3-volt and 5-volt buck converters, it also operated a series of LEDs, a buzzer, and an LCD screen to indicate battery data when in a situation where it is not connected to the network, such as during boot. The BMS also contained an emergency stop (E-STOP) circuit that would power down the rover when triggered via an E-STOP button, from the base station, or if the condition of the battery became dangerous such as in the event of an undervoltage, overcurrent, or high temperature scenario.

Fault Detection

As mentioned previously, the BMS can detect various types of faults that can occur in the battery pack. The pack and cell voltage measurements are arguably one of the most important as they determine how long the battery can power the rover. Lithium-ion cells must retain a certain voltage difference to safely be recharged. The output "pack" voltage is put through a voltage divider so it can be monitored by the microcontroller, which has a max input voltage of 3.3 volts. The BMS monitors the individual cell modules, so they never drop below this safety net. The cell filter circuit utilized operational amplifiers to minimize the power draw of the circuit, which would reduce idle drain of the battery pack. Connected in a differential amplifier configuration through voltage dividers as seen in Figure 4, a cell voltage would be connected to V1 with the following cell being connected to V2. The resulting signal, Vs, is then sent to an analog read pin on the microcontroller. This signal is proportional to the voltage drop across the cell.

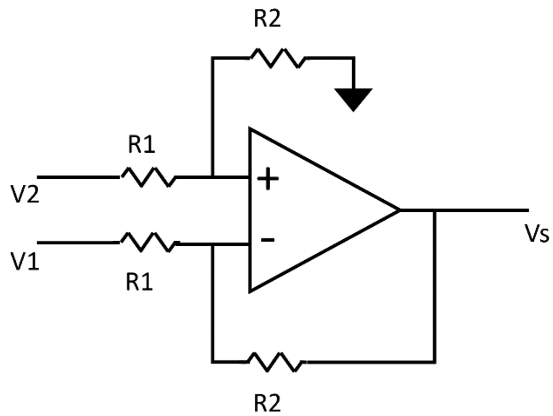

Figure 4 - Differential Amplifier Schematic

The cumulative current draw of the rover is valuable data about the operations of rover systems. Although the power distribution boards included current sensing for individual subsystems on the rover, an overall current measurement was required to ensure protection of the battery in the event of an overcurrent. A Hall-Effect current sensor was used to detect the current draw from the battery. Lithium-ion batteries must be safely operated within a specific temperature range. The BMS uses a temperature sensor for monitoring the pack temperature. These sensors all output an ADC value that is proportional to the respective measurement. Lab equipment was used to simulate the edge cases for the respective sensors i.e., a maximum cell voltage of 4.2 volts and a minimum cell voltage of 3.0 volts. As all the sensor circuits were connected to the microcontroller, the ADC values for these edge cases could be mapped to their measurement values. This allows for the microcontroller to measure pack and cell voltages, pack current, and battery temperature at any point in time.

Telemetry and Rover-side Interventions

The outputs for these circuits are all directed into the microcontroller which, as discussed above, is connected to a network switch. There, the data is interpreted and converted so it can be transmitted to the base station using RoveComm. The data can be sent to the base station operators to monitor for them to intervene if necessary. However, if they do not recognize the telemetry (for example, due to focus on controlling the rover for a task), the BMS offers on-board control of its various systems. The microcontroller uses the telemetry and checks for certain fault conditions that would require action such as a system reboot due to high temperatures or an overcurrent.

In the mock URC competition, this fault detection and action system was critical to protecting the rover [8]. The eighth cell of the battery measured lower than the other cells (3.0 volts versus the nominal 3.7 volts). If the final cell would have been allowed to drain below a safe limit it would have posed a risk to the battery and subsequent systems. The BMS used this data in combination with these predetermined limits to power down the rover. This sequence of events could have been performed by the base station operators, but they were focused on a section of the Extreme Retrieval task. The measurements and telemetry protected thousands of dollars of on-rover equipment.

POWER DISTRIBUTION BOARDS

To safely distribute power from the battery to the rest of the rover, the team designed and manufactured two custom PCBs, the power distribution boards. These boards ensured that all other subsystems on the rover received adequate power for their respective purposes.

Pack Voltage Distribution Board

The first of these boards, Pack Voltage Distribution, receives 180 amps at 33.6 volts from the battery pack. From there, the power is distributed among ten output ports. Each port is equipped with a high-precision current sensor and a shunt resistor which use a high-side current sensing circuit [9] to sense instantaneous current, as illustrated in Figure 5. As these circuits are monitored, telemetry is used to manage overcurrent. If an overcurrent does occur, the microcontroller then sends a signal to a MOSFET at the output of the circuit that has the overcurrent, closing the port on that circuit until the underlying issue can be resolved. Each port's current state is sent to the base station through the microcontroller over our network, as well as the current at that port. That way, remotely, the operators can see the overcurrent happening without having a view of the rover. From the base station, the operators can also close and reopen any port. This is to allow the restart of any electrical system being powered by the Pack Voltage Distribution board. Each output circuit is also equipped with a 20-amp fuse as a fail-safe. During startup, to prevent an overcurrent, each motor is turned on sequentially.

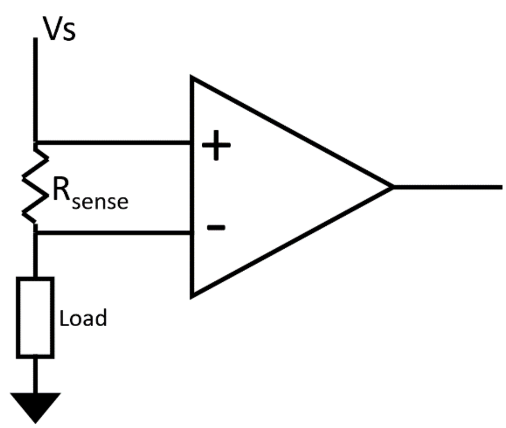

Figure 5 - High Side Current Sensing Schematic

12 Volt Distribution Board

To keep the power system modular and easy to maintain, a separate PCB was designed to distribute 12 volts to electrical systems. This board contains three 60 watt, 5-amp ports, and six lower power ports. With the three high current ports, the same current sensing circuit, but with a lower power rated MOSFET, is used to monitor the ports in the same fashion as the Pack Voltage Distribution Board. Using an onboard buck converter, a separate power line is used to differentiate the low current application such as microcontrollers and high current motors. The two busses each have a 5-amp fuse in place to prevent an overcurrent and to act as a redundancy measure for the current sensing of each port.

Telemetry

One of the many issues encountered during rover operation is the occurrence of an overcurrent. Constant monitoring of the power system is required so in the case of an overcurrent, the amount that is damaged is minimal. The first safety measure we take is sending the current value of each port consistently. The microcontroller makes a record of these measurements and acts first, powering down the port in case of an overcurrent. The current draw at each port is also sent to the base station. In case the microcontroller does not react, or there is a visible issue with the electrical system, the port can manually be closed and opened remotely from the base station. If there is a fault such as a motor receiving low power or inconsistent GPS telemetry, the power distribution boards can restart them. In addition to being a safety feature, a log of each port's current is kept to document power draw. This knowledge of how much power is required is essential in minimizing power usage to optimize the custom battery pack. These features allow for remote control and moderation of the power system to reduce the likelihood of a physical intervention to debug on-rover systems (a penalty for the URC competition).

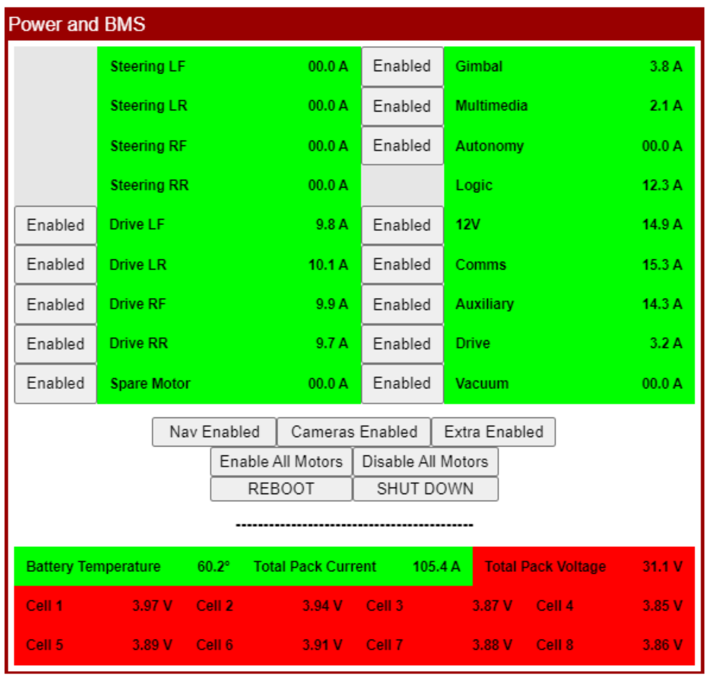

Figure 6 - Base Station Power Readout

CONCLUSION

Creating prototype rovers designed to function and assist scientists on Mars requires an electrical system tailored to the specific needs of the operators. Thus, it requires specifications that may not be standard practice in industry. Therefore, the MRDT designs and manufactures every aspect of the electrical system from the ground up.

The battery pack, manufactured with eight lithium-ion cells in an 8s9p configuration, provides the rover with 33.6 volts at a maximum of 180 amps and lasts close to 3 hours. To safely maintain the battery pack, a BMS was designed with pack and cell voltage sensing, pack current sensing, and temperature sensing circuits. This allows the operators to restart the battery pack, visualize each cell's voltage as well as the current draw of the rover, and ensure safe operation of the battery. The Power Distribution Boards (comprised of Pack Voltage Distribution and 12 Volt Distribution) offers a modular power system to protect and safely power each subsystem. Each high current port can be remotely shut off by the operator, as well as automatically by the microcontroller. This is a necessary measure in the case of an overcurrent, a condition monitored by current sensors. As a last resort, each port on the power distribution system, as well as the battery management system, is equipped with a fuse.

Per competition standards, the operators may only interact with the rover remotely through the base station. No physical contact is allowed during a task. The telemetry sent to the operators ensures that they have a full understanding about the condition of the rover. It helps guarantee safe and efficient functionality of rover subsystems. By utilizing telemetry, the operator can focus on accomplishing a task rather than the condition of the electrical system.

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