WIRELESS SOIL SENSOR PODS FOR LONG-TERM DATA COLLECTION

Jacob Lipina, Andrew Van Horn, Judah Schad
Advised by: Dr. Kurt Kosbar
Missouri University of Science and Technology, Rolla MO, USA

ABSTRACT

This paper discusses the applications of a wireless telemetry module used to collect remote sensor data used in a teleoperated electric vehicle that competed in the 2018 Mars University Rover Challenge (URC). Remote wireless soil sensor pods, 100cc in volume, equipped with a 32-bit microcontroller and embedded IEEE 802.11 b/g/n Wi-Fi were distributed at key locations to relay soil moisture and temperature values over a local repeater to a remote base station. Combined with a low power deep sleep mode (1.84mW), two 2500mAh lithium-ion polymer batteries, and voltage regulation electronics, such a device could periodically relay telemetry data for many years without recharge. The small size presents the opportunity for large scale production and distribution across exoplanetary surfaces for monitoring soil characteristics over time.

INTRODUCTION

The Missouri S&T Mars Rover Design Team (MRDT) designed and built a teleoperated electric rover that competed in The Mars Society's 2018 University Rover Challenge (URC) (Figure 1). The competition simulated tasks that a rover could face while assisting astronauts in the exploration of Mars. The tasks were presented in the Martian-like terrain of southern Utah and include extreme retrieval and delivery, equipment servicing, autonomous traversal, and a science cache task [1].

The science cache task required the operators to select a site with a likelihood of harboring microbial life through visual observation of cues such as cryptobiotic soil crust, washes, and mudcracks. The rover was to collect a soil sample from a depth of 10cm or below and perform a basic evaluation of the sample using onboard instrumentation [1]. The mechanism created to accomplish this consists of a 7.5cm diameter core drill capable of reaching a depth of 15cm. To preserve the soil horizons and to prevent contamination, the collection cylinder is retained inside the drill and can be released into the sample cache and sealed using neodymium magnets (Figure 2). The 6-position Geneva drive sample cache carousel rotates allowing the drill to pick up one of many wireless sensor pods containing sensors for moisture and temperature measurements (Figure 3,4). The Geneva drive is a specially designed mechanical system that converts continuous rotary motion into intermittent motion, allowing for precise positioning of the carousel [4]. The sensor pod is then deposited into the ground from where each core sample was taken. The sensor pod then continues to transmit sensor data from the drill site well after the heat and moisture generated by the collection process has dissipated. The rover may immediately move to another drill site, while also still collecting data from all past drill sites. In addition to remote sensor pods, local atmospheric sensors wired directly on the rover also measure air temperature, humidity, UV intensity, barometric pressure, and methane and ammonia concentration. In conjunction with these measurements, a custom on-rover FT-Raman spectrometer analyzes the collected soil sample for potential biomarkers such as chlorophyll and protein [2].

Figure 1: MRDT's 2018 Rover, Atlas

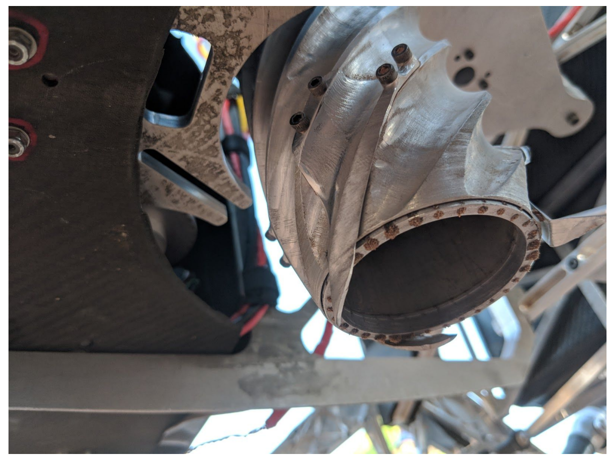

Figure 2: Collection Cylinder Retained in Core Drill

Figure 3: Sensor pod with Lid Removed

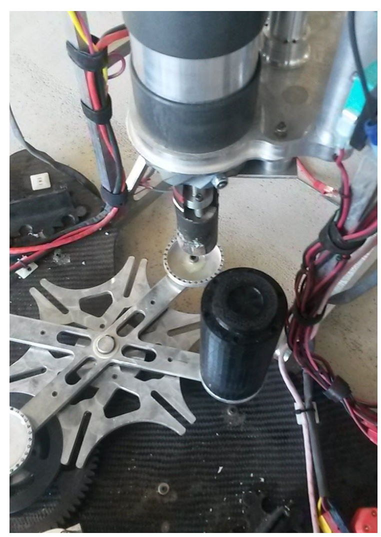

Figure 4: Sensor Pod on Geneva Sample Cache

This paper focuses on the wireless sensor pod design, implementation, and potential application in the aerospace industry and on MRDT vehicles. Devices like the wireless sensor pod are becoming more attainable to budget constrained engineers such as students, hobbyists, and researchers who now have easy access to sensor and signal hardware for rapid prototyping and development as a result of the electronics advancement over the past ten years in embedded Wi-Fi microcontrollers. Large companies that already maintain such technological capability may now develop devices like the wireless sensor pod in larger quantities on a tighter budget and with a smaller package size. This opens the opportunity for mass production and distribution of data reporting probes for long term monitoring of various environments and systems.

DESIGN

The MRDT soil sensor pod consists of a 3D-printed capsule hosing a soil moisture sensor, a soil temperature sensor, a rechargeable two-cell lithium-ion battery pack, and a custom-designed PCB booster board mounting a Wi-Fi microchip with TCP/UDP/IP stack, integrated RF circuitry, an on-board antenna, and a step-down DC/DC converter. The total cost of all components and fabrication is under $50. All relevant schematics, PCB designs, and gerber files for MRDT designed electronics are open source and made freely available along with any applicable software and firmware files at the MRDT github organization [3].

Moisture Sensor

The soil moisture sensor indirectly measures the volumetric content of water by measuring the capacitance between two parallel plates inserted directly into the soil. The water acts as a dielectric, thereby changing the capacitance. An embedded microcontroller outputs an analog voltage between 1.2V and 2.5V based on the measurement, and an on-board analog to digital converter (ADC) on the microcontroller measures this voltage. A microcontroller digital output pin on the main PCB generates a toggleable DC voltage to turn on and off the sensor. Because this sensor operates by capacitance, any minerals present in the sample may throw off the measurement. This sensor was calibrated using the soil approximating its intended sample and using filtered water.

Temperature Sensor

The temperature sensor thermistor is made of a semiconducting material which changes resistivity based on temperature along a known curve. A constant voltage is supplied by the microcontroller to act as a toggleable DC-voltage source for the sensor. The thermistor is wired in series with a 47kΩ resistor going to ground creating a voltage divider circuit. This resistor value was chosen because its resistance was near that of the thermistor at the expected operating temperature around 25°C, the allowing for the best voltage resolution below and above that value. An ADC measures the voltage between the thermistor and resistor which changes based on the resistivity of the thermistor.

Power

Two series-connected 18650 lithium ion polymer batteries each supply up to 2500mAh at a nominal voltage of 3.7V and maximum of 4.2V. With an operating power requirement of 150mAh at 3.3V, this small battery pack can supply continuous power for over 30 hours. In deep sleep mode, the microcontroller consumes less than 10uA with a power down leakage current of less than 5uA, considerably extending the life of the battery. Because continuous telemetry is seldom necessary, the sensor pod can remain in deep sleep mode for days or weeks before waking for a few seconds to connect to the Wi-Fi network and relay the telemetry data before returning to deep sleep. Using this power saving routine and a full 2500mAh charge, the sensor pod can remain active for up to a year on battery storage alone. Combined with a renewable energy source, this low-power module could remain powered for years.

Microcontroller

Both the microcontroller, and Wi-Fi microchip, are integrated as a single system on chip. The 160MHz 32-bit RISC microprocessor core contains an assortment of GPIO's, dedicated SPI, I2C, UART peripheral interfaces, a single 10-bit successive approximation ADC, and a real-time clock capable of driving the deep sleep modes of the system. The Wi-Fi microchip maintains 20dBm transmit power and –91dBm receiver sensitivity across an integrated transmit/receive switch that alternates the transmitter and receiver to a shared PCB balun, low noise amplifier, power amplifier, π-type matching network, and PCB antenna. The device operates in the 2.4 GHz band with WPA/WPA2 support, is configurable as both a client or an access point, and is compliant with IEEE 802.11 b/g/n. The system on chip provides an onboard crystal reference, voltage controlled oscillator, phase-locked-loop, bias circuitry, and power management unit. The RISC microprocessor core has no programmable ROM, therefore the system maintains an SPI accessible flash to store the user program. The vendor Internet Protocol Software Development Kit shares user memory and therefore allows additional user programmable space accessible in heap and data section of roughly 50 kilobytes. The wireless module is driven via the serial interface of the microcontroller using the standard AT command set in order to provide the application level code with a simple interface to generate and consume Wi-Fi transmit/receive data.

Printed Circuit Board

The microcontroller used was mounted on a development board and features an on-board USB to TTL Serial converter that allows for simple flashing ability and provides simple USB connection for communication with the microcontroller. The development board also has an internal DC buck converter to power the device either by the 5V USB source, or an external dedicated 3.3V source when operating without the USB tether. A booster board was designed and fabricated for mounting and powering the module and breaks out the development board's header pins to connectors allowing the analog sensors and battery pack to be easily replaced (Figure 5).

A monolithic IC for a step-down DC/DC converter accepts an input voltage range from 4.5V to 22V and regulates to a fixed 3.3V output at a maximum load current of 2A. At the positive input supply, a 10µF bypass capacitor is utilized to minimize voltage transients. At the output, a low-pass filter by way of a 47µH inductor is in series with the load. The built-in switching transistor on chip senses the regulated output voltage to complete the feedback loop. The converter efficiency with an input of 12V and a load of 2A is known to be 78%.

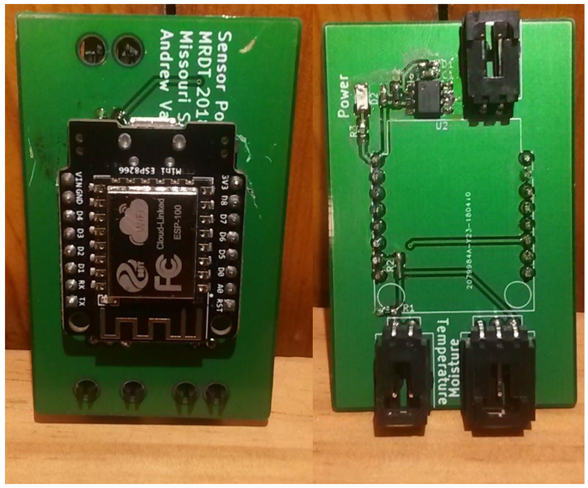

Figure 5: Front and Back Sides of the Booster Board

Because the chosen microcontroller has only one 10-bit ADC, the two sensor readings are periodically muxed in order to read both values independently. To avoid added hardware, the input for each sensor is routed to a digital output on the development board, and by pulling the power for one sensor high while pulling the other low, the microcontroller can capture the analog reading of each independent sensor one at a time. The high internal resistance of the microcontroller pin then keeps current from flowing back through the return path when the power pin is low.

Firmware

The analog reading is returned as an integer between 0 and 1023. The sensor is then calibrated by mapping the analog reading between two points at the extreme of the operating window. The temperature sensor returns an ADC value of 213 at 0°C, and 933 at 50°C. These temperatures were chosen because they encompassed a reasonable range for expected soil temperatures. The ADC values are then constrained between the two measured limits to avoid errors when the value drops out of the range. Finally, the reading is mapped to a linear regression based on the real temperature and the ADC value at that point. At a temperature of 25°C, the ADC values returned were around 573, which maps to approximately 25°C. The same procedure was used to calibrate the moisture sensor, using values obtained from dry and water-saturated soil as the baseline. For the purpose of this task, only the raw data was transmitted, however a moving average filter can be used to provide more stable results.

Deployment

The Geneva and lead screw motors are controlled by a custom brushed motor controller PCB designed around a 12A continuous, 40A peak full bridge motor driver IC integrating two monolithic high-side drivers and two low-side switches. The PCB features four motor driver ICs configured in two independent drive stages, one per motor, each stage consisting of a parallel set of drivers, in order to source the 25 continuous amps required by each motor. A 120MHz ARM Cortex-M4 CPU with a floating point unit and integrated 10/100 ethernet MAC + PHY executes the control code and responds to base station commands.

Signals

The data is relayed back to the rover through a local 2.4GHz gateway, using a custom publish-subscribe UDP library developed by the MRDT called RoveComm which enables multiple endpoints on the network to access the data feeds anytime. With an on-board power supply, the sensor pod operates completely independently from the other rover systems and can maintain a wireless 2.4GHz connection to the rover for over 500ft, relaying continuous telemetry data throughout the task. With the RoveComm UDP protocol, multiple sensor pods can be connected to the rover at once. The Geneva-Carousel mechanism on Atlas can hold up to four sensor pods or core samples, but the telemetry module and UDP protocol is scalable on the network.

APPLICATION

The final drill-Geneva system featured open-loop control of the drill, leadscrew, and Geneva carousel motors, as well as position control using limit switches and state-logic to track the carousel and leadscrew positions. With these functions paired with the on-rover GPS receiver and point to point navigation, the rover can deploy multiple pods at selected site waypoints while maintaining constant telemetry streams of each drill site simultaneously after each sensor pod deployment, during each successive deployment, and throughout the the remainder of the task.

Once a wireless sensor pod is deployed from the rover, the sensor pod will attempt to maintain a 2.4 GHz link with the 6.5 Watt Wi-Fi access point mounted on rover for as long as the sensor pod is within signal range, typically less than a mile on the rocky Utah terrain. The rover Wi-Fi access point is plugged directly into the rover network switch alongside the 6.5 Watt 900 MHz base station link that maintains non-line-of-sight penetration well above a mile over the same terrain. In this manner, without any rover side microcontroller involvement at all, the wireless sensor pod will continue transmitting soil temperature and humidity directly to any base station application that has requested a RoveComm UDP data stream subscription, with the rover signal network acting as a mobile IP repeater for each sensor pod's UDP packet transmit stream (Figure 6).

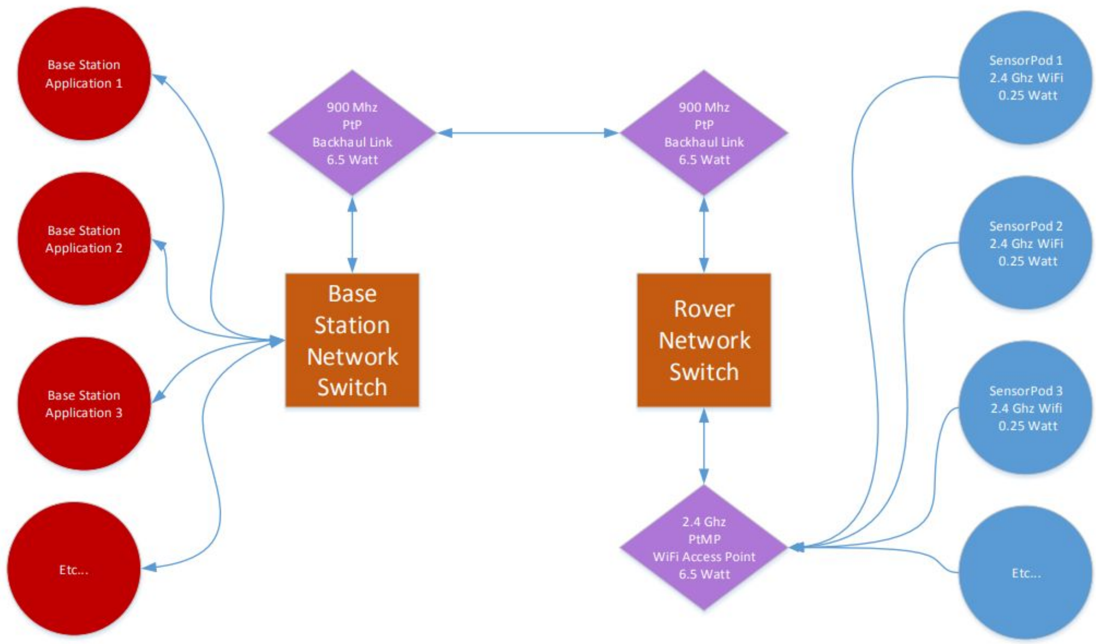

Figure 6: Radio, Ethernet, and Wi-Fi Network Diagram

FUTURE APPLICATIONS

This wireless sensor pod implementation proved to be so useful and effective that MRDT is further developing the system for many more applications on next year's rover. Beyond just acting as soil sensor telemetry, the self contained rechargeable wireless microchip can be used anywhere that data needs to be sent, such as on rover, when the mechanical design does not easily allow for the physical wires. MRDT presently maintains both a three axis infinite-rotation gimbal, and six degree of freedom infinite-rotation robotic arm, utilizing slip rings on every axis of rotation. The control schemes would benefit from inertial measurements, however the team has not found a wiring solution that fits with in the mechanical specification for the data routing of such readings. Designing around the complexity of such a mechanical system can be simplified with the Wi-Fi embedded microcontroller by replacing the soil sensors with an inertial measurement unit and mounting the wireless sensor pod at strategic locations. All that is required is a space for the circuit board and battery if detached power is needed.

The Wi-Fi-embedded microchip also provides the ability for cheap and simple IoT applications. For example, the team plans on using this technology to develop a wireless emergency stop button for the rover to be used during testing. Currently such a button exists tethered to the rover, but two of these microchips could set up a wireless bridge to communicate between each other to trigger the stop remotely. This will add another layer of safety during testing in case of electrical or mechanical failure.

The wireless soil sensor pod itself provides scalability in future applications with the tantalizing real-world application in analysis of exoplanetary surfaces. Surfaces such as on Mars, Titan, and Enceladus have been of scientific interest for decades but simultaneous measurement of soil and air characteristics in multiple locations has never been conducted. Whether by rover or some other method, a large quantity of pods could be spread over a surface to create a network of connected devices. Through use of signal repeaters, data could be transmitted to a rover, habitat, or more powerful antenna to be relayed to an orbiting satellite. Finally, the collective data could be sent to Earth where scientists would have a better understanding of the weather patterns and soil characteristics of the surface over time. As prices come down, physical footprints get smaller, and materials become more robust, future applications for pods of similar system level design may even one day be distributed throughout our solar system. One can imagine seeding Saturn’s rings with a multitude of such modules to observe the chemical composition of multiple regions with the potential to analyze the interaction of particles and larger objects within the rings as matter orbits Saturn.

CONCLUSION

The rover competed in the URC Science task and received a score of 91.3 out of 100 for the task and 339 out of 500 overall, placing 2nd in the competition. Certain mechanical issues prompted extensive redesign of the drill-Geneva system up until the competition time. Misalignments between the Geneva mechanism and its drive motor, the Geneva mechanism and the carousel, the carousel and the sample cache holders, and the clearance between the drill and carousel set back production of the soil cache system. At first, the core drill proved to be ineffective at penetrating the soil due to the blunt edge on the original design, prompting the fabrication of a serrated edge which proved to be more effective. Furthermore, the 7.5cm diameter core drill proved to be too large to effectively retain the core sample under low-humidity conditions. These mechanical issues will be worked on for next year's competition.

The sensor pod remained largely unchanged throughout the development cycle. The microcontroller would occasionally have trouble connecting to the RoveWiFi system, but once connection was established after the microcontroller is reset a few times it would maintain a stable connection throughout the task. In future development, an external panel will be added to the pod with LEDs to indicate connection to the rover and data transmission, an eternal power switch for easier power cycling, and an external USB port for easier flashing and debugging. More research will also be conducted on the nature of the connection issues and how to improve connection reliability. A future solution to the single-ADC problem could include a 2-1 MUX, thereby eliminating any interference between the sensors and allowing for a cleaner sensor stack. The sensor pod successfully connected to the mobile on-rover Wi-Fi repeater and transmitted sensor telemetry back to the remote base station, providing a proof of concept for the wireless sensor telemetry system to be further developed in future years.

REFERENCES

[1] The Mars Society, “Requirements & Guidelines,” [Online]. Available: http://urc.marssociety.org/home/requirementsguidelines.
[2] Mars Rover Design Team, “MRDT Science Plan 2018”, Rolla, MO, 2018.
[3] Missouri S&T Mars Rover Design Team Official GitHub [Online]. Available: https://github.com/MSTMRDT/.
[4] Bickford, John H. "Geneva Mechanisms". Mechanisms for Intermittent Motion, New York Industrial Press inc., New York, NY, 1972, pp 127-138