WIRELESS SOIL SENSOR PODS FOR LONG-TERM DATA COLLECTION

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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, 100 cc 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 (1.84 mW), two 2500 mAh 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 mud cracks. The rover was to collect a soil sample from a depth of 10 cm or below and perform a basic evaluation of the sample using on-board instrumentation [1]. The mechanism created to accomplish this consists of a 7.5 cm diameter core drill capable of reaching a depth of 15 cm. 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 based 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 [2]. The wireless sensor pod is then deposited into the ground from where each core sample was taken. The sensor pod 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 still collecting data from past drill sites. In addition to wireless sensor pods, local atmospheric sensors wired directly on the rover 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 [3].

Figure 1: MRDT's 2018 Rover: Atlas

Figure 2: Collection Cylinder Retained in Core Drill

Figure 3: Sensor pod with Lid Removed

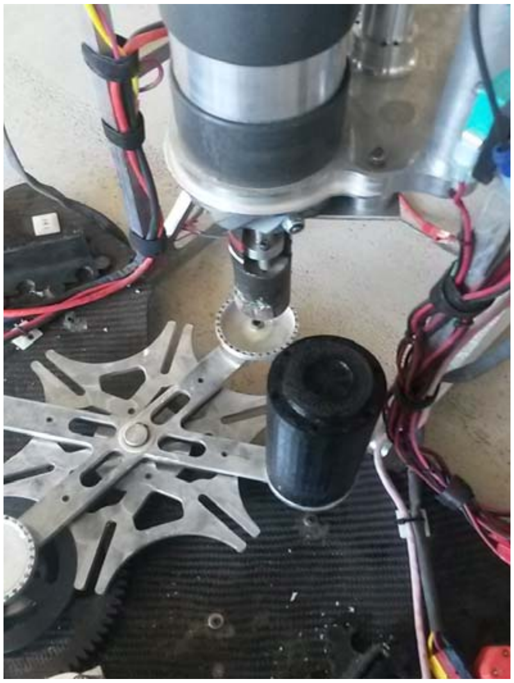

Figure 4: Sensor Pod on Geneva Sample Cache

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 because 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 wireless sensor pod consists of a 3D-printed capsule housing 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 USD. 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 [4].

Moisture Sensor

The soil moisture sensor indirectly measures the volumetric content of water by determining the capacitance between two parallel plates inserted directly into the soil. The water acts as a dielectric, changing the capacitance. An embedded microcontroller outputs an analog voltage between 1.2 V and 2.5 V 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 corrupt the measurement. The 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 47 kΩ 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, 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 2500 mAh at a nominal voltage of 3.7 V and maximum of 4.2 V. With an operating power requirement of 150 mAh at 3.3 V, this small battery pack can supply continuous power for over 30 hours. In deep sleep mode, the microcontroller consumes less than 10 μA with a power down leakage current of less than 5 μA, considerably extending the life of the battery. Because continuous telemetry is seldom necessary, the wireless 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 2500 mAh charge, the wireless 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 160 MHz 32-bit RISC microprocessor core contains an assortment of GPIOs, 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 20 dBm transmit power and –91 dBm 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 on-board 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 kb. The wireless module is driven via the serial interface of the microcontroller using the standard AT command set 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 5 V USB source or an external dedicated 3.3 V 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 4.5 V to 22 V and regulates to a fixed 3.3 V output at a maximum load current of 2 A. At the positive input supply, a 10 μF bypass capacitor is utilized to minimize voltage transients. At the output, a low-pass filter by way of a 47 μH 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 12 V and a load of 2 A is known to be 78%.

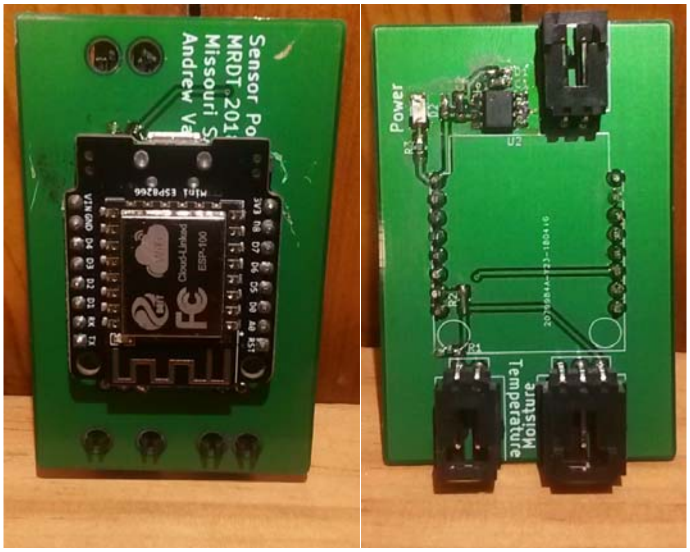

Figure 5: Front and Back Sides of the PCB Booster Board

Because the chosen microcontroller has only one 10-bit ADC, the two sensor readings are periodically muxed 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 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 12 A continuous, 40 A 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 to source the 25 continuous amps required by each motor. A 120 MHz 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 2.4 GHz 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 wireless sensor pod operates independently from the other rover systems and can maintain a wireless 2.4 GHz connection to the rover for over 150 m, relaying continuous telemetry data throughout the task. With the RoveComm UDP protocol, multiple wireless sensor pods can be connected to the rover at once. The Geneva carousel mechanism on Atlas can hold up to four wireless 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 from each drill site after sensor pod deployment, throughout the remainder of the task.

Once a wireless sensor pod is deployed from the rover, the pod will attempt to maintain a 2.4 GHz link with the 6.5 W Wi-Fi access point mounted on rover for as long as the pod is within signal range; typically, less than 1.6 km on the rocky Utah terrain. The rover Wi-Fi access point is plugged directly into the rover network switch alongside the 6.5 W 900 MHz base station link that maintains non-line-of-sight penetration well above a 1.6 km over the same terrain. In this manner, without any rover-side microcontroller involvement, 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 wireless sensor pod’s UDP packet transmit stream (Figure 6).

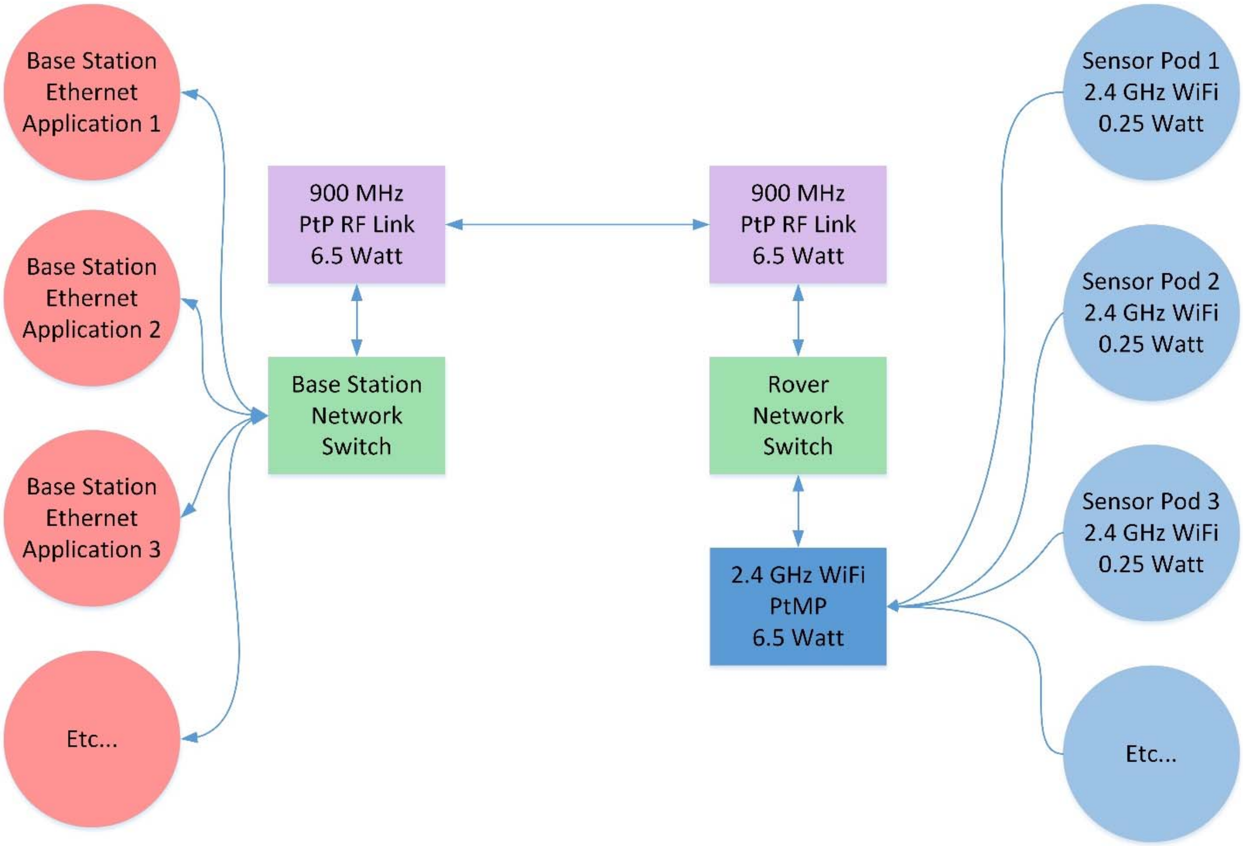

Figure 6: Radio, Ethernet, and Wi-Fi Network Diagram

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 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, many 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 collected 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 decrease, physical footprints shrink, and materials become more robust, future applications for pods of similar system level design could 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

Throughout the development cycle, mechanical issues, such as misalignments and clearance issues between the Geneva mechanism and its drive motor, the Geneva mechanism and the carousel, the carousel and the sample cache holders, and the drill and carousel, necessitated iterative redesign of the Drill-Geneva system. The initial core drill had trouble 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. The 7.5 cm diameter core drill proved to be slightly too large to firmly retain the core sample under low-humidity conditions. Finally, the wireless sensor pod would occasionally have trouble connecting to the RoveWiFi system at initial power up. Once connection was established after a few early system resets, the sensor pod would then maintain a stable connection throughout the entire duration task.

The rover successfully completed the URC Science task and received a score of 91.3 out of 100 for the task and an overall score of 339 out of 500, placing 2nd in the competition. The original wireless sensor pod design remained largely unchanged throughout the development cycle and the system successfully connected to the mobile on-rover Wi-Fi repeater and reliably transmitted sensor telemetry back to the remote base station providing a proof of concept and motivation for further development. In future designs, an external panel can be added to the pod with LEDs to indicate connection status and data transmissions. An external power switch could provide easier power cycling, and an external USB port would provide easier flashing and debugging. More research and testing should also be conducted on the nature of the boot sequence connection issues in order to determine how to improve connection robustness. A future solution to the single-ADC problem could include a dedicated 2-1 MUX, which would eliminate any interference between the sensors and allow for a cleaner sensor stack. Overall, the wireless soil sensor pod preformed remarkably well, meeting all original requirements and design specifications, and providing a platform for a variety of future features and enhancements.

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