DEVELOPING WIRELESS IMUS TO SIMPLIFY INTEGRATION INTO DYNAMIC SYSTEMS

Jacob Lipina, Austin Christman, Rebecca Marcolina
Advised by: Dr. Kurt Kosbar
Missouri University of Science and Technology, Rolla, MO, USA

ABSTRACT

This paper discusses the development of wireless inertial measurement units (IMUs) designed to transmit data from a prototype Mars rover to a remote base station. These nine degree of freedom, multi-chip modules provide measurements for linear acceleration, angular rotation velocity, and magnetic field vectors for the rover's chassis and robotic arm end-effector. To facilitate integration into these dynamic systems, each unit is independently powered and has a form factor of 108 cc. IMU data is sent from 32-bit microcontrollers with embedded IEEE 802.11 b/g/n Wi-Fi to the rover via UDP transport through a custom publish/subscribe distributed IP protocol. Data is relayed over two circular polarized omnidirectional antennas to the base station's dual linear MIMO Yagi-Uda antenna. The information gathered provides operators a heading and orientation to improve situational awareness, as camera visuals are often inadequate.

INTRODUCTION

The Missouri S&T Mars Rover Design Team (MRDT) is an undergraduate student organization that designs and fabricates a teleoperated, prototype Mars rover that competes in the University Rover Challenge (URC) held at the Mars Desert Research Station in Hanksville, Utah. The 2019 URC consisted of four tasks that simulated a manned mission to the planet: extreme retrieval and delivery, science, equipment servicing, and autonomous traversal [1]. One of the more challenging aspects of this competition, the autonomous traversal task requires a rover to navigate to given GPS waypoints without operator assistance (Figure 1) [1]. A rover must be continuously aware of its position relative to coordinate headings to complete this task successfully and this year the team chose to develop an onboard inertial measurement unit (IMU) to record the rover's orientation and then communicate this data to the team's remote base station.

The IMU system onboard the team's 2019 competition rover, Valkyrie, was wired. The system was mounted to the core of the rover for the duration of the competition, received regulated power from the rover's battery pack through a printed circuit board (PCB) designated for power distribution, and transmitted data to a PCB designated for navigation directly connected to the rover's network switch. Though the initial purpose of the IMU was to enhance the rover's performance during the autonomous traversal task, the system remained onboard Valkyrie for the remaining tasks after team operators recognized the value of continuously monitoring the rover's position and direction relative to other objects in the field (Figure 2). By implementing an IMU system, the team can overcome the limitations of relying on calculating positions from camera feeds alone, a process that is both time consuming and often limited by blocked line of sight, low image quality, and poor depth perception. More importantly, this device can improve the team's spatial and situational awareness, allowing task managers to make more informed decisions in situ and technical operators to control the rover with greater precision.

Figure 1: Valkyrie Approaching a Waypoint

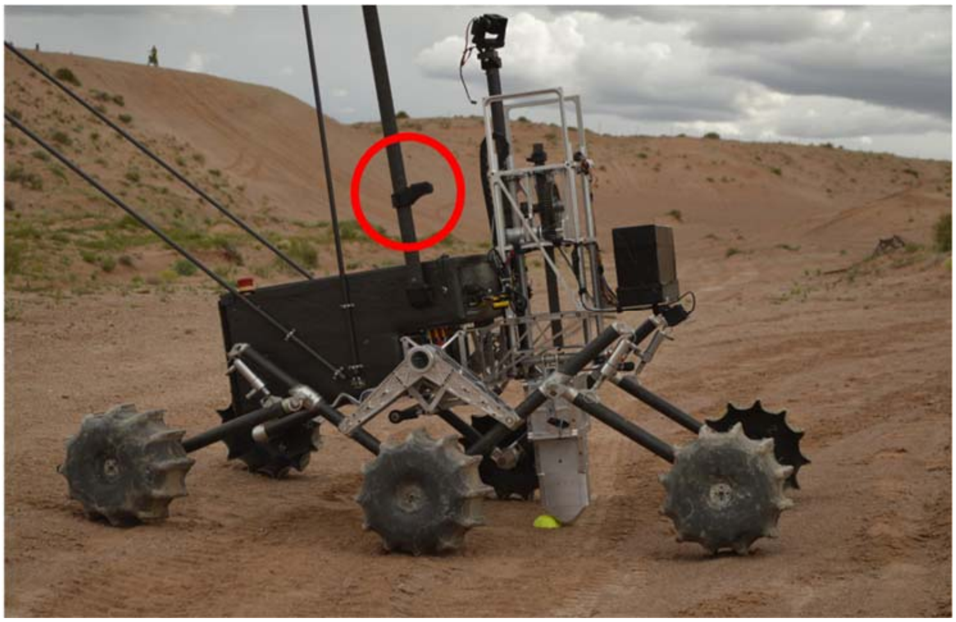


Figure 2: Wired IMU Placement (Circled in Red)

It is challenging to place IMUs in systems with multiple degrees of motion because the creation of multiple interfaces between moving parts complicates wire routing. Every slip ring, panel mount, and hinged channel that wires pass through increase the chance of failure within a circuit. Likewise, testing could indicate subsystems that would benefit from this technology, but the addition of IMUs into an established system takes time and may require modifications that could alter the integrity or operation of the initial hardware. Consequently, MRDT sought to further develop an IMU as a wireless system to allow for quick and convenient placement on dynamic systems.

DESIGN

MRDT's proposed wireless IMU package facilitates the transmission of data gathered by a nine degrees of freedom (9DOF) IC consisting of the rover's accelerometer, gyroscope, and magnetometer, to operators at base station without any wired connection to systems onboard the rover [2]. This design advances a wired intermediary prototype consisting of two small PCBs, with an IMU chip situated on one board, and a microcontroller on the other. Three wires – power, ground, and data out – connect this IMU to the team's network through the rover's navigation board. The team's wireless IMU package design on the other hand, would mount an IMU chip to one PCB booster alongside a step-down DC/DC converter and Wi-Fi chip running a TCP/UDP/IP stack by featuring integrated RF circuitry and an onboard antenna. This system would be powered by a rechargeable lithium-ion battery pack and housed in a 3D-printed shell of PETG. The critical aspects of each system component are discussed in further detail in the following sections.

IMU Chip

Both the wired and wireless IMU designs feature a monolithic IC that contains three separate three-axis sensors. The first sensor is a linear accelerometer adjustable along a full scale of ± 2, 4, 8, or 16 g [2]. Acceleration is calculated through the changing capacitance between two plates whose distances relative to one another change as acceleration forces act upon the sensor. The second sensor is a gyroscope where, in the space of 100 μm, a shifting mass within the device generates a small current that is then amplified to record the angular rate of change along a scale of ± 245, 500, or 2000 dps [2]. The third sensor is a magnetometer that uses changes in Hall voltage to measure magnetic field in scales of ± 4, 8, 12, or 16 gauss [2]. The cohesive package for all three sensors provides a digital interface for interpretation in either I2C or SPI protocols [2].

Microcontroller

Though the team's wired IMU prototype uses a microcontroller without wireless capabilities, MRDT's wireless IMU design features a 160 MHz, 32-bit RISC microprocessor core with embedded Wi-Fi module [3]. The microprocessor core provides an assortment of GPIOs, dedicated SPI, I2C, UART peripheral interfaces, a single 10-bit successive approximation ADC, and a real-time clock [3]. It has no programmable ROM yet the system maintains an SPI accessible flash to store the user's programs. 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 [3]. The module presents 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 [3]. 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 [3]. The system on chip provides an onboard crystal reference, voltage-controlled oscillator, phase-locked-loop, bias circuitry, and power management unit [3]. These features allow the team to quickly and accurately process data from the IMU.

Power

The IMU chip and microcontroller each operate on 3.3 V and together consume 155 mAh of power, leading to the implementation of two 18650 lithium-ion polymer batteries arranged in series to provide 2500 mAh at a nominal voltage of 7.2 V and maximum of 8.4 V [4]. This configuration independently powers the wireless IMU system enabling continuous transmission of data. To prevent damage to the battery pack, the microcontroller can monitor battery charge state and shut itself off to avoid reaching a voltage lower than 5 V, or 2.5 V per cell.

Printed Circuit Board

Valkyrie's onboard wired IMU system consists of two small PCB breakouts to allow for the IMU and the microcontroller to be mounted (Figure 3). For the IMU breakout, the PCB routes the I2C and power traces into a four-pin connector. That connection leads to the microcontroller's PCB, which passes SDA and SCL through bidirectional level shifters comprised of two N-channel MOSFETs and four pull-up resistors to safely convert the 5 V data from the IMU to 3.3 V for inputs on the microcontroller. An additional four-pin connector passes power and processed data to the navigation board to obtain access to the rover's network.

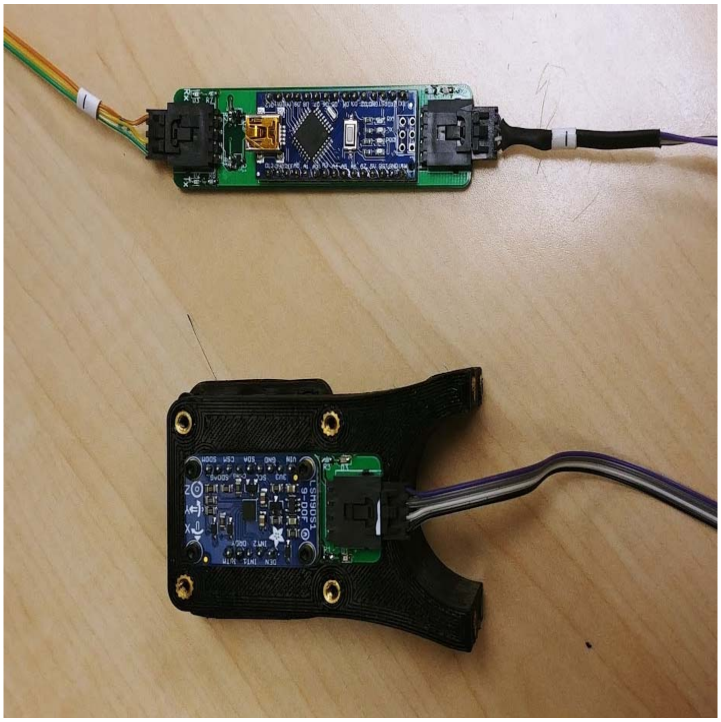


Figure 3: Wired IMU Consisting of Two PCBs

With a wireless IMU, the module and the microcontroller would be placed on a singular PCB and give access to a USB to TTL serial converter so that operators could flash their code. This PCB would build-in a DC/DC converter that would step-down and regulate the power provided from the battery pack. The converter's accepted input voltage ranges from 4.5 V to 22 V and outputs a fixed 3.3 V at a maximum load current of 2 A [5]. To minimize any voltage transients, a 10 µF capacitor is placed at the positive input supply. On the output, a low pass filter is created with a 47 µH inductor in series with the load. The built-in switching transistor on chip senses the regulated output voltage to complete the feedback loop [5]. The converter efficiency with an input of 12 V and a load of 2 A is known to be 78% [5].

Firmware

The aim of the firmware is to interpret output from the IMU by implementing a 9DOF extended Kalman filter in order to gain absolute position and orientation. This filter, developed by Sebastian O.H. Madgwick, fuses the measurements from the gyroscope, accelerometer, and magnetometer together to make a single estimate for the unit's orientation [6]. While an orientation can be obtained through calculations with any one of these sensors, the measurement will likely have a high margin of error. For instance, a gyroscope's measurements for angular velocity may be integrated over time to obtain an orientation [7]. However, measurement errors on each individual axis become compounded when combined in that calculation. Similarly, an accelerometer and magnetometer can provide an absolute reference of orientation by measuring the earth's gravitational and magnetic fields [7]. However, high levels of noise can be observed when acceleration due to motion of the unit corrupts measured direction of gravity [6]. The filter can take each estimate for orientation, along with its level of uncertainty, and observe them all over time to produce its own estimate that tends to be more accurate. Madgwick's implementation does so while requiring a lighter computational load; thus, it is more optimized for embedded systems such as this self-contained IMU [6].

Before the filter is ever applied, measurements from each sensor must be calibrated. To do so for the magnetometer, one must rotate the unit in circles on all rotational axes while plotting XY, YZ, and XZ. The output should be three circles which are then normalized by aligning all their centers with the origin. The magnitude of the maximum and minimum values measured should then be scaled to the maximum and minimum values of earth's magnetic field in gauss [2]. For the gyroscope calibration, it should be placed on a level surface and any resting deviation from zero on an axis should be corrected with an offset [2]. This process is the same for the accelerometer, except that the z-axis is assumed to be 9.8 m/s^2 [2].

Signals

Each software and electronic device on the rover operates as an independent modular endpoint. Any device may communicate with any other device via UDP transport through MRDT's custom publish/subscribe distributed IP protocol, RoveComm. Traffic is controlled using a managed network switch both on rover and at base station with Rapid Spanning Tree Protocol to avoid background radiation and simplify transitions between RF links. The links are established over two MIMO connections to base station from four circular polarized omnidirectional antennas on rover (Figure 4). A high-bandwidth RF link operates in the 5.8 GHz band through a vertical beam dual linear MIMO sector antenna, spanning a 90-degree horizontal and vertical sightline. This setup provides low-latency control for several camera feeds, but only during line-of-sight situations. The secondary low-bandwidth RF link operates in the 900 MHz band through a dual linear MIMO Yagi-Uda antenna with a 30-degree conic beam. The longer wavelength penetrates terrain during non-line-of-sight; thus, it carries drive commands and other telemetry. A third RF link exists locally in the 2.4 GHz band through a fifth omnidirectional antenna on the rover. This link allows for telemetry from modules such as the wireless IMU system to be relayed back to the rover and then passed to base station over 900 MHz.

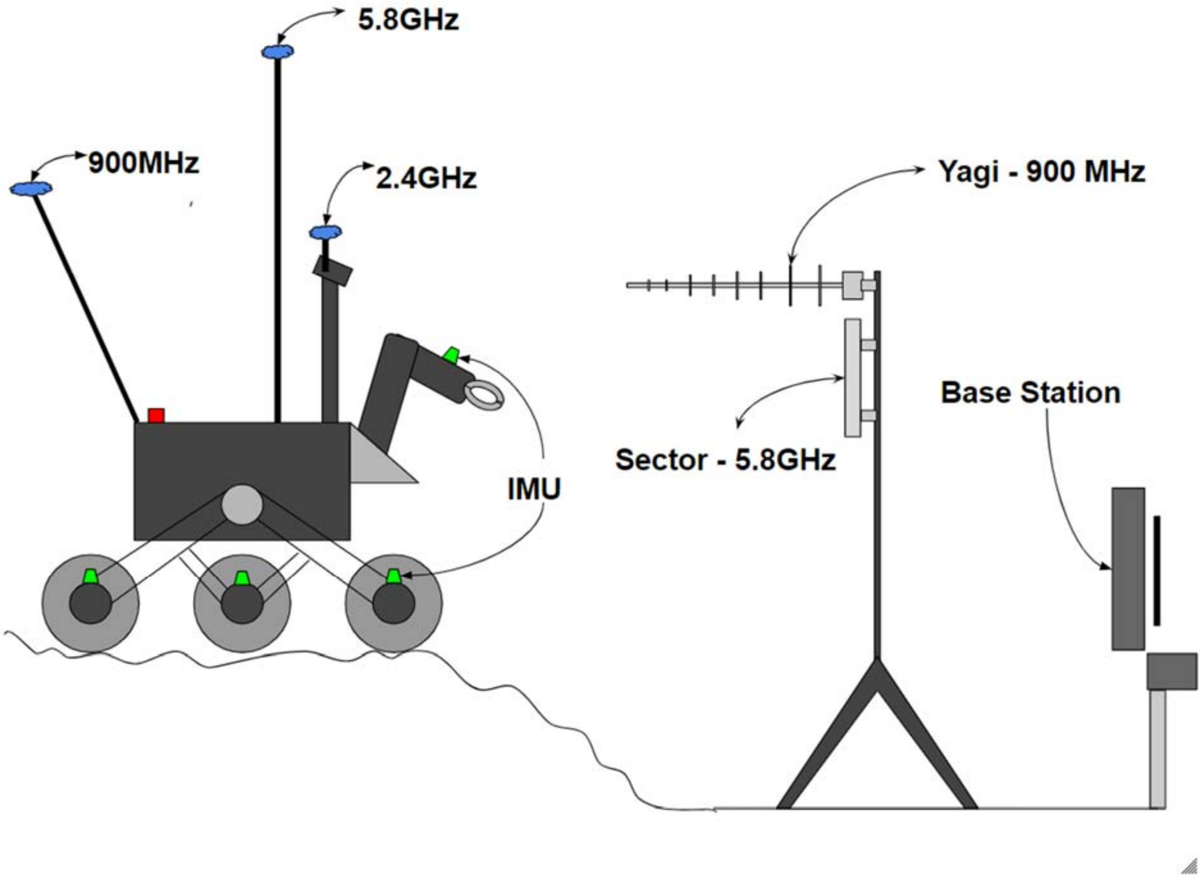


Figure 4: Representation of the Antennas on Rover and at Base Station

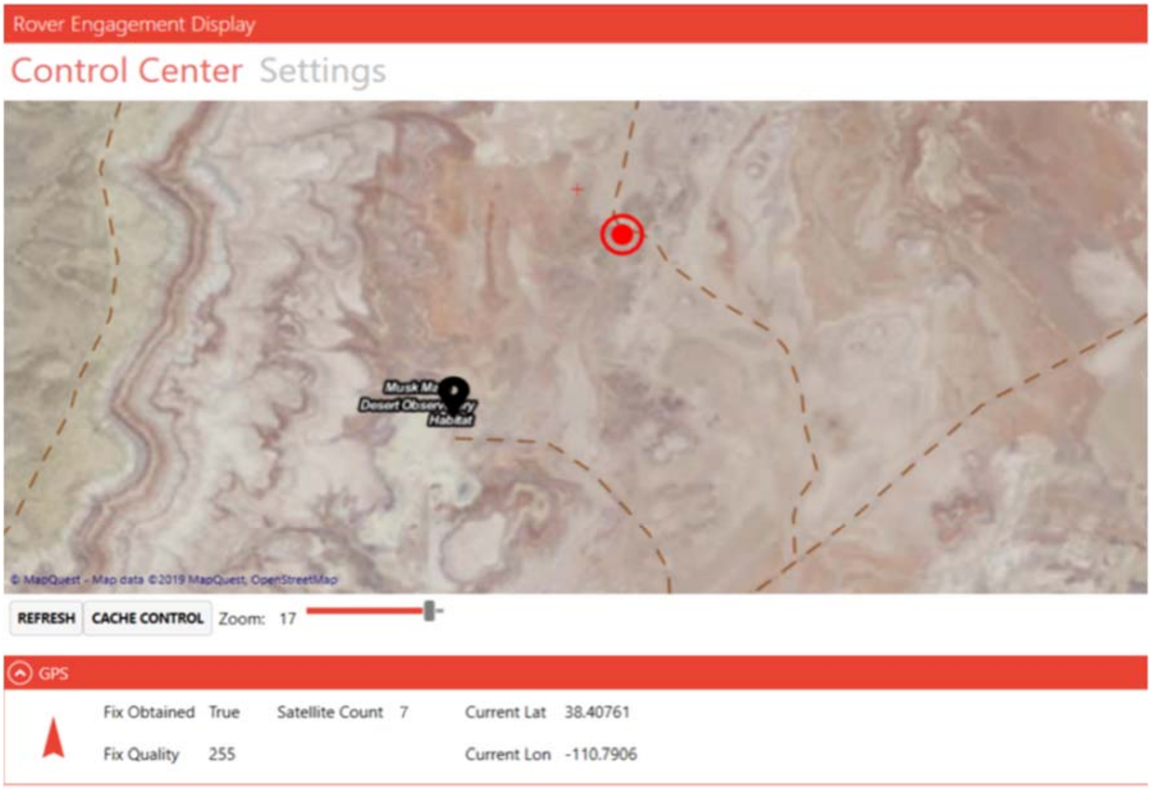
DEVELOPMENT

To implement a wireless IMU into the dynamic systems onboard the team's rover, MRDT must first focus on successfully calibrating a wired IMU to consistently produce reliable data during operation. After completing this development phase, the team can then begin to refine, integrate, and test its wireless IMU design. The team constructed and tested a wired IMU design over the course of four months in spring 2019 in preparation for the 2019 URC held May 30th to June 1st.

During the testing process, operators were able to transmit data to the team's external base station and display it on screen, yet the data itself was largely inaccurate. While the magnetometer produced acceptable circular graphs with minimal errors within the XY and YZ planes, the graphs generated for the XZ plane were neither accurate nor viable. Additionally, the gyroscope offsets changed between power cycles. These changes produced drift in the filter that caused the unit to assume it was spinning even when the instrument itself was motionless. Due to this lack of consistent, feasible data, the team chose not to pursue full implementation of the extended Kalman filter using all three sensor measurements, but instead chose to prioritize basic system functionality.

As a simple heading on the XY plane was the only reading Valkyrie required to successfully complete the autonomous traversal task, the team chose to prioritize the development of the magnetometer's XY plane. This task requires a rover to navigate without operator assistance to given GPS waypoints indicated by tennis balls in sequential order (Figure 1). As teams advance through each gate, the path not only increases in difficulty by incorporating obstacles such as steep inclines and cliffs, but later waypoints are not situated at the provided GPS location [1]. Each rover must enter a searching pattern and use computer vision to identify the tennis ball and stop within two meters of it [1].

Valkyrie's wired IMU enabled its onboard computer systems to be aware of its position along a compass heading relative to the given GPS locations. MRDT successfully reached three waypoints before an unrelated mechanical failure immobilized the rover, forcing the team to end the task prematurely. Nevertheless, the wired IMU remained onboard the rover throughout the remaining three tasks during which operators used its projected heading and GPS locations to better understand Valkyrie's relation to objects in the field and thus approach tasks more efficiently. This data is captured by a directional arrow in Figure 5.



Zoom: 17

Fix Obtained True
Satellite Count 7
Current Lat 38.40761
Fix Quality 255
Current Lon -110.7906

Figure 5: Display Allowing Driver to See Rover's Location and Heading in Field

APPLICATIONS

Valkyrie's reliance on data produced by the IMU during the additional three tasks of the 2019 URC illustrate that the benefits of a wireless system could not solely be limited to the rover’s autonomous activity. For example, the wired IMU identified the rover’s X and Y coordinates after being placed atop a mast situated on Valkyrie’s right side. Permanently incorporating a wireless IMU into the main body of the rover’s drivetrain subsystem could allow operators to record the rover’s X, Y, and Z orientation and continuously transmit this data to the team’s base station. These coordinates could then be processed by the team’s custom user interface, Rover Engagement Display (RED), and projected as a display similar to that of an artificial horizon used within aircraft. This horizon could be superimposed on a live camera feed, allowing operators to directly see where the rover is positioned. Additional IMUs could be fixed to the motor casings on each of the rover’s six wheels to monitor their acceleration in the Z direction. This data could be processed and projected by RED in a similar manner and alert operators to any critical values that could damage the rover’s suspension.

A wireless IMU can also improve the rover’s robotic arm. Operators manipulating Valkyrie’s robotic arm during the equipment servicing task, for example, were only able to control the apparatus with visual cues captured by cameras mounted on each joint and projected at base station via RED. A wireless IMU can help operators determine the exact orientation of the arm by producing a 3D view of its position. When this data is considered in tandem with the arm’s camera feed, the operator can employ finite control during the task and perform more complicated maneuvers. This allows MRDT to gain more control over the rover and protect its subsystems against incidental damages that may occur during its operation.

At the 2019 URC, Valkyrie’s suspension system experienced an accidental mechanical failure that ultimately prevented the team from completing a task. MRDT members were not immediately aware of the situation due to the team’s limited views of the rover. If the team could implement a wireless IMU module, problems such as this one could be recognized almost instantaneously at base station, allowing members to more fully assess the situation and respond more effectively.

CONCLUSION

Although the team is still in the process of fully developing a consistent wired IMU, the data collected throughout the 2019 URC demonstrates the merit of this technology despite the challenge of its integration and implementation in dynamic systems like a next generation Mars rover. Though the team initially experienced setbacks during testing, the use of even only the magnetometer provided operators with a proper heading of the rover along the XY plane. This technical feature undoubtedly helped MRDT receive the second highest score in the autonomous traversal task and fifth place out of 34 teams in total.

Members have already started developing subsystem designs for MRDT’s 2020 competition rover and will use the data generated throughout the spring to refine the currently wired IMU’s accelerometer and gyroscope – the first step to achieving a functional extended Kalman filter. This filter could assist the team in producing more accurate data, a necessity for pursuing a wireless

IMU design. The competition field steadily becomes more challenging each year, thus making a fully operational IMU with the rover's orientation on terrain displayed reliably in RED more prudent. A continuous stream of accurate data from an IMU can improve the technical performance of the team's rover as well as the adaptability of the team's operators in situ.

ACKNOWLEDGEMENTS

The authors would like to thank fellow MRDT team members Ethan Arneson, Eli Verbrugge, and Andrew Van Horn of Missouri University of Science and Technology for their contributions to both this project and this paper.

REFERENCES

[1] The Mars Society, "Requirements & Guidelines," [Online]. Available: http://urc.marssociety.org/home/requirementsguidelines.

[2] STMicroelectronics, "iNEMO inertial module: 3D accelerometer, 3D gyroscope, 3D magnetometer," LSM9DS1 datasheet, Dec. 2013 [Revised Nov. 2014].

[3] Espressif Systems, "ESP8266EX Datasheet ", ESP8266 datasheet, June 2015.

[4] LG Chem, "Rechargeable Lithium Ion Battery", 18650HE4 datasheet, May 2013.

[5] Diodes Incorporated, "150kHz, 2A PWM Buck DC-DC Converter", AP1509 datasheet, October 2018.

[6] S.O.H. Madgwick, "An efficient orientation filter for inertial and inertial/magnetic sensor arrays," 30 Apr. 2010.

[7] João Luís Marins, Xiaoping Yun, Eric R. Bachmann, Robert B. McGhee, and Michael J. Zyda "An Extended Kalman Filter for Quaternion-Based Orientation Estimation Using MARG Sensors," Proceedings of the 2001 IEEE/RSJ International Conference on Intelligent Robots and Systems, Maui, Hawaii, USA, Oct. 29 - Nov. 03, 2001, pp.2003-2011. http://hdl.handle.net/10945/41567