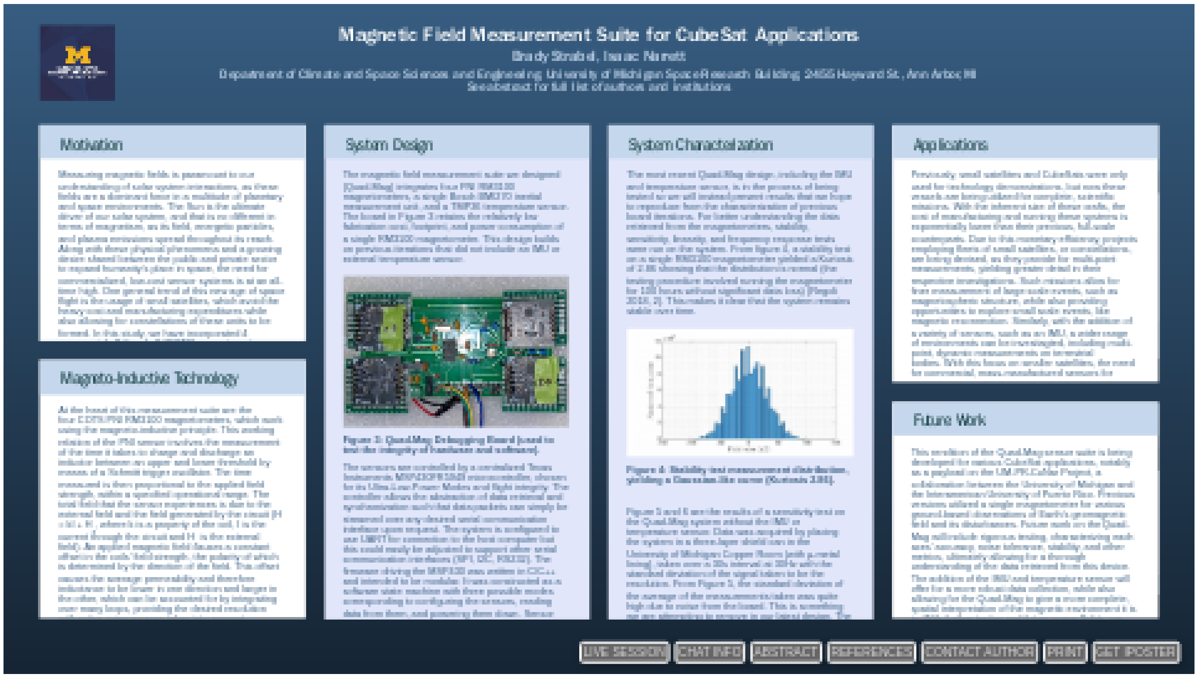
Magnetic Field Measurement Suite for CubeSat Applications



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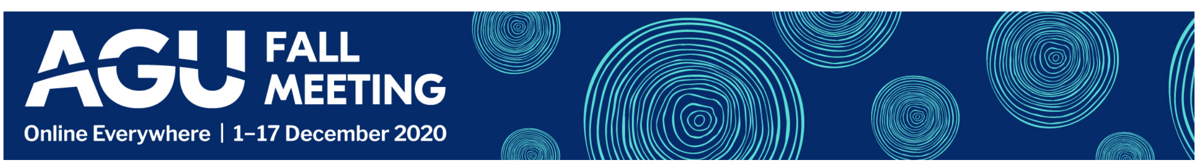

MOTIVATION

Measuring magnetic fields is paramount to our understanding of solar system interactions, as these fields are a dominant force in a multitude of planetary and space environments. The Sun is the ultimate driver of our solar system, and that is no different in terms of magnetism, as its field, energetic particles, and plasma emissions spread throughout its reach. Along with these physical phenomena and a growing desire shared between the public and private sector to expand humanity's place in space, the need for commercialized, low-cost sensor systems is at an all-time high. One general trend of this new age of space flight is the usage of small satellites, which avoid the heavy cost and manufacturing expenditures while also allowing for constellations of these units to be formed. In this study, we have incorporated 4 commercial off-the-shelf (COTS) magnetometers along with an inertial measurement unit (IMU), temperature sensor, and a microcontroller on a 16 square centimeter printed circuit board primed for CubeSat and other small satellite applications. The combination of four magnetometers allows for cutting the noise floor of the system by a factor of two, allowing for more precise measurements. Additionally, the incorporation of the IMU allows for measurements of the magnetic field to be taken in dynamic applications, while also giving insight into the geometry of the environment.

MAGNETO-INDUCTIVE TECHNOLOGY

At the heart of this measurement suite are the four COTS PNI RM3100 magnetometers, which work using the magneto-inductive principle. This working relation of the PNI sensor involves the measurement of the time it takes to charge and discharge an inductor between an upper and lower threshold by means of a Schmitt trigger oscillator. The time measured is then proportional to the applied field strength, within a specified operational range. The total field that the sensor experiences is due to the external field and the field generated by the circuit ($H = kI + H_E$, where k is a property of the coil, I is the current through the circuit and H_E is the external field). An applied magnetic field causes a constant offset in the coils' field strength, the polarity of which is determined by the direction of the field. This offset causes the average permeability and therefore inductance to be lower in one direction and larger in the other, which can be accounted for by integrating over many loops, providing the desired resolution with active noise sources taken into account.

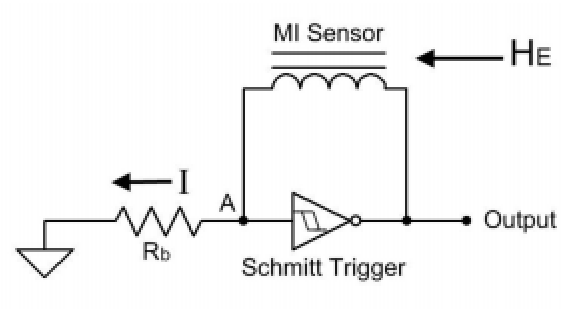

Figure 1: Schematic of circuitry involved in magneto-inductive devices (from Leuzinger and Taylor, 2010).

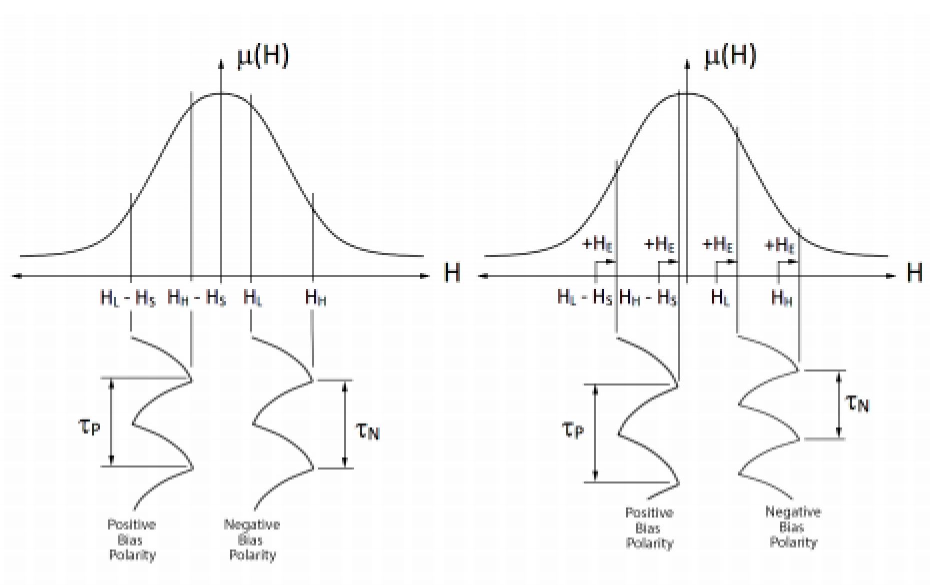

Figure 2: The induction in the coils as a function of applied magnetic field (top) and the traces of the oscillating current in the solenoid and the period for positive and negative bias polarity (bottom) (from Leuzinger and Taylor, 2010).

SYSTEM DESIGN

The magnetic field measurement suite we designed (Quad-Mag) integrates four PNI RM3100 magnetometers, a single Bosch BMI270 inertial measurement unit, and a TMP36 temperature sensor. The board in Figure 3 retains the relatively low fabrication cost, footprint, and power consumption of a single RM3100 magnetometer. This design builds on previous iterations that did not include an IMU or external temperature sensor.

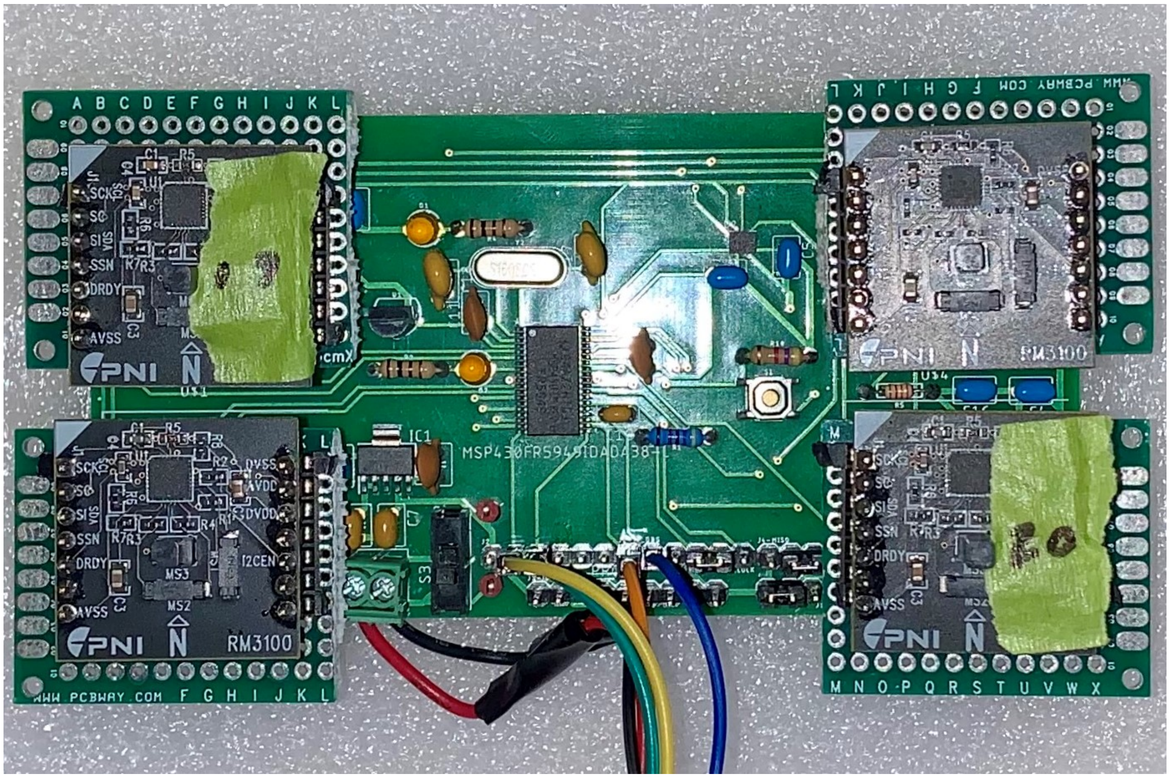

Figure 3: Quad-Mag Debugging Board (used to test the integrity of hardware and software).

The sensors are controlled by a centralized Texas Instruments MSP430FR5949 microcontroller, chosen for its Ultra-Low-Power Modes and flight integrity. The controller allows the abstraction of data retrieval and synchronization such that data packets can simply be streamed over any desired serial communication interface upon request. The system is configured to use UART for connection to the host computer but this could easily be adjusted to support other serial communication interfaces (SPI, I2C, RS232). The firmware driving the MSP430 was written in C/C++ and intended to be modular. It was constructed as a software state machine with three possible modes corresponding to configuring the sensors, reading data from them, and powering them down. Sensor configuration is done by the host computer through a custom command packet interface. Sample rate and resolution (among various other parameters) can easily be adjusted by the user, in alignment with our aim of a modular design. The option also exists to disable individual sensors if there is limited bandwidth or a need to save power.

SYSTEM CHARACTERIZATION

The most recent Quad-Mag design, including the IMU and temperature sensor, is in the process of being tested so we will instead present results that we hope to reproduce from the characterization of previous board iterations. For better understanding the data retrieved from the magnetometers, stability, sensitivity, linearity, and frequency response tests were run on the system. From figure 4, a stability test on a single RM3100 magnetometer yielded a Kurtosis of 2.86 showing that the distribution is normal (the testing procedure involved running the magnetometer for 100 hours without significant data loss) (Regoli 2018, 2). This makes it clear that the system remains stable over time.

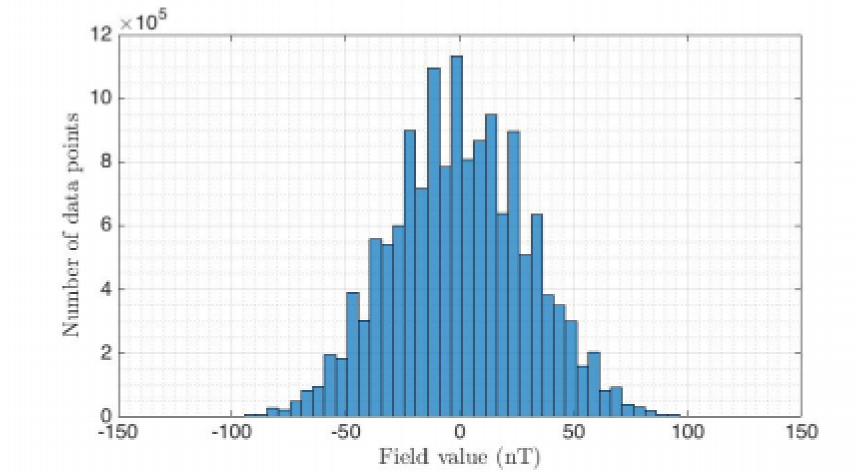

Figure 4: Stability test measurement distribution, yielding a Gaussian-like curve (Kurtosis 2.86).

Figure 5 and 6 are the results of a sensitivity test on the Quad-Mag system without the IMU or temperature sensor. Data was acquired by placing the system in a three-layer shield can in the University of Michigan Copper Room (with μ-metal lining), taken over a 30s interval at 30Hz with the standard deviation of the signal taken to be the resolution. From Figure 5, the standard deviation of the average of the measurements taken was quite high due to noise from the board. This is something we are attempting to remove in our latest design. The Y-axis, because of the way the sensor is oriented, contains the least magnetic noise from the board and is, therefore, the only axis used in Figure 6, which illustrates the noise floor for different averaging windows. Even with the issues of the board design, a 25% improvement in resolution was achieved for the Y-axis. This is exciting as we expect this to represent the ceiling of our latest board design.

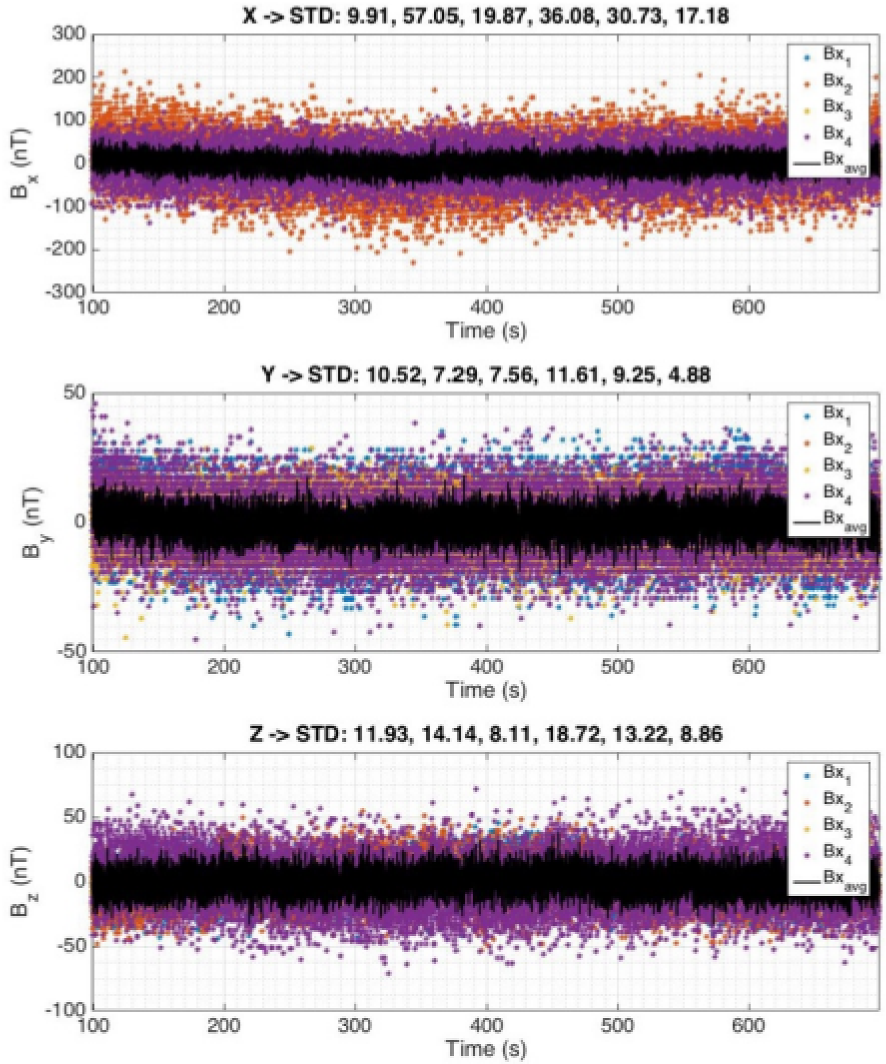

Figure 5: Data from the resolution test for the three axes. Numbers on the top of each panel correspond to the standard deviation of the measurements.

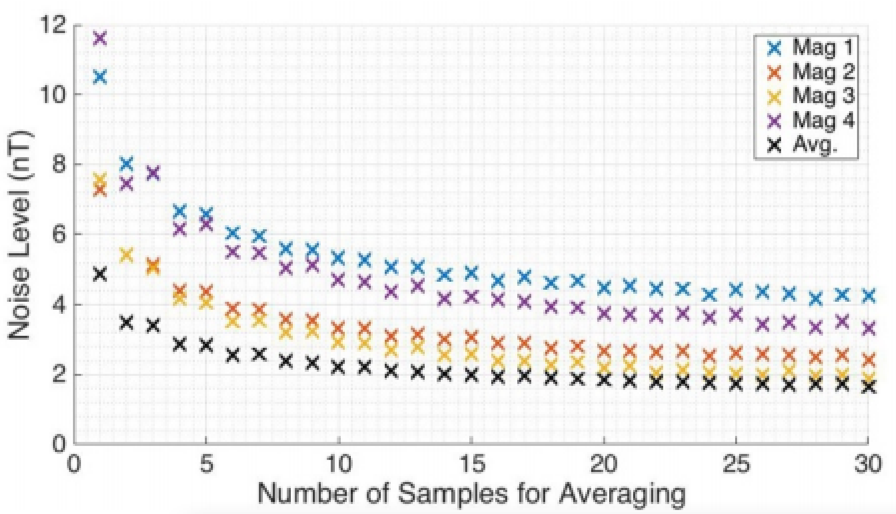

Figure 6: Resolution of the four individual magnetometers and of the average of the four values as a function of the width of the averaging window.

Figure 7 displays some preliminary results from testing of the latest board involving the additional IMU and temperature sensor. Here, we can see the linearity of the X-axis for each of the four magnetometers. This test was run by subjecting the sensor suite to varying magnetic fields in the range of -100,000nT to 100,000nT (data points were taken every 10,000nT). The four slopes are close to 1, varying by no more than 4.4%, meaning the system's X-axis remains linear over the range tested. Future tests will be run to confirm the same linear relation for the other axes.

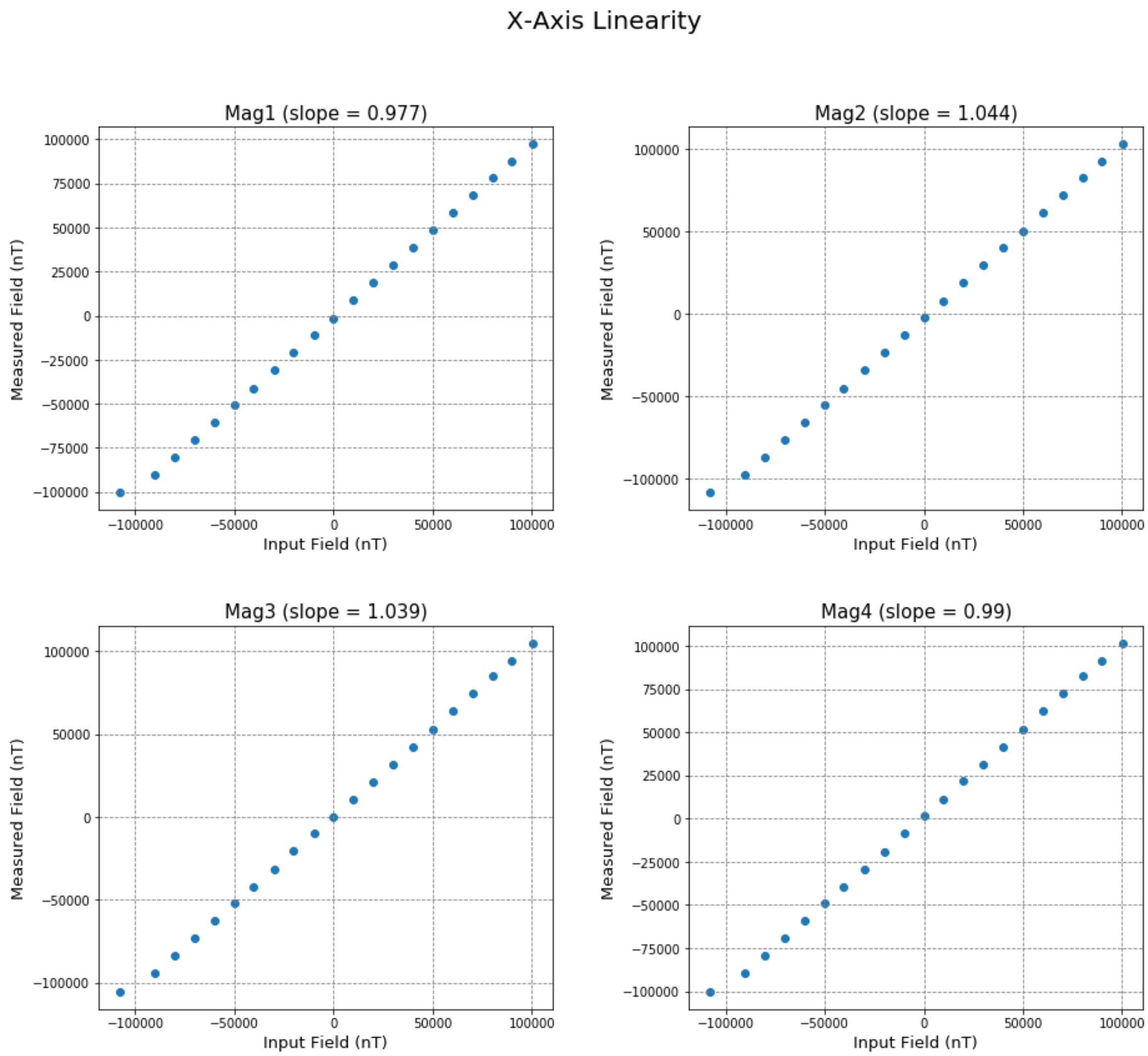

Figure 7: Results of the linearity test shown as the output (measured) field vs. input (applied) field for the x-axis of the four magnetometers.

For the RM3100 magnetometer to be considered for space physics applications, it must be capable of distinctly detecting magnetospheric waves, generally categorized as low amplitude and in the ULF range, up to 5 Hz. Regoli et al. were able to determine a single PNI RM3100 magnetometer's ability to accomplish this, which we will extend to the Quad-Mag system following the same testing procedure.

Beyond these four tests, we will also need to run thermal, vibration, and radiation tests in addition to other characterizations of the magnetometers and IMU. Performing these will ensure this sensor suite's ability to effectively measure magnetic activity in various space environments.

APPLICATIONS

Previously, small satellites and CubeSats were only used for technology demonstrations, but now these vessels are being utilized for complete, scientific missions. With the inherent size of these crafts, the cost of manufacturing and running these systems is exponentially lower than their previous, full-scale counterparts. Due to this monetary efficiency, projects employing fleets of small satellites, or constellations, are being devised, as they provide for multi-point measurements, yielding greater detail in their respective investigations. Such missions allow for finer measurement of large scale events, such as magnetospheric structure, while also providing opportunities to explore small scale events, like magnetic reconnection. Similarly, with the addition of a variety of sensors, such as an IMU, a wider range of environments can be invesitagted, including multi-point, dynamic measurements on terrestrial bodies. With this focus on smaller satellites, the need for commercial, mass-manufactured sensors for space has risen. Studies on the development of sensor suites, such as this one, will pave the way for this new era of space investigation. Additionally, this sensor suite can be used for ground-based observations, showing the range of possibilities of this system.

FUTURE WORK

This rendition of the Quad-Mag sensor suite is being developed for various CubeSat applications, notably as a payload on the UM-PR-CuNar Project, a collaboration between the University of Michigan and the Interamerican University of Puerto Rico. Previous versions utilized a single magnetometer for various ground-based observations of Earth's geomagnetic field and its disturbances. Future work on the Quad-Mag will include rigorous testing, characterizing each axes' accuracy, noise tolerance, stability, and other metrics, ultimately allowing for a thorough understanding of the data retrieved from this device. The addition of the IMU and temperature sensor will offer for a more robust data collection, while also allowing for the Quad-Mag to give a more complete, spatial interpretation of the magnetic environment it is in. With further testing and future space flights, we hope to raise this system's TRL and ultimately make it a central player in future space missions.

ABSTRACT

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A magnetic field measurement suite intended for CubeSat and ground-based geomagnetic applications is presented. The system is composed of commercial-off-the-shelf sensors (COTS), which include four PNI RM3100 magnetometers, a Bosch BMI270 inertial measurement unit (IMU), and a TMP36 thermal sensor. The instruments are collectively operated by a Texas Instrument's MSP430FR5949 microcontroller. The novel measurement principle employed by the magnetometers permits a low fabrication cost, power consumption, and footprint; in turn, this enables the incorporation of four magnetometers (theoretically many more), reducing the magnetic noise floor and increasing the resolution by a factor of two in this case. Additionally, the inclusion of a COTS IMU allows us to reliably establish the orientation of the sensor package, thus permitting a better understanding of the geometry of the surrounding magnetic field under static or dynamic conditions. The system has been tested and characterized in a controlled laboratory environment with the intent of flying aboard the PR-CuNaR2 CubeSat, set to launch early next year. This mission will raise the technology readiness level (TRL) of the system (current TRL is approximately 4/5) and provide us with valuable measurements of the magnetic environment at Low-Earth-Orbit.

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