Merritt Coil CubeSat Attitude Test System (MCCATS)

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I. Overview

Traditional CubeSat Attitude Determination Control Systems (ADCS) leverage the Earth's magnetic field to point and detumble satellites using magnetorquers. Very few commercially available devices, however, generate adjustable uniform magnetic fields with a sufficiently large volume to test these ADCS in 12U satellites before launch. Furthermore, the existing devices are cost-prohibitive for smaller universities and organizations interested in developing small satellites. To assuage this challenge, we developed MCCATS: a modular, low-cost, and footprint-efficient test bed capable of generating a large volume of uniform and programmable magnetic field.

The MCCATS design is based on the Merritt coil, which contains four large coils on each of the three axes. In comparison to the more ubiquitous Helmholtz coils, Merritt coils generate a larger ratio of usable volume to total cage volume. When simulated, our Merritt coil design took up less than one-third of the floor space of existing Helmholtz cages that produce a similar usable volume. Furthermore, instead of requiring 3 expensive programmable power supplies (1 per axis), we designed a system that utilizes one constant power supply and three self developed programmable coil drivers, providing a budget-friendly and flexible alternative for driving the Merritt cage. The resulting testbed was designed to be capable of generating magnetic fields up to 2.5 gauss that can be oriented in a single specified direction or configured for rotation.

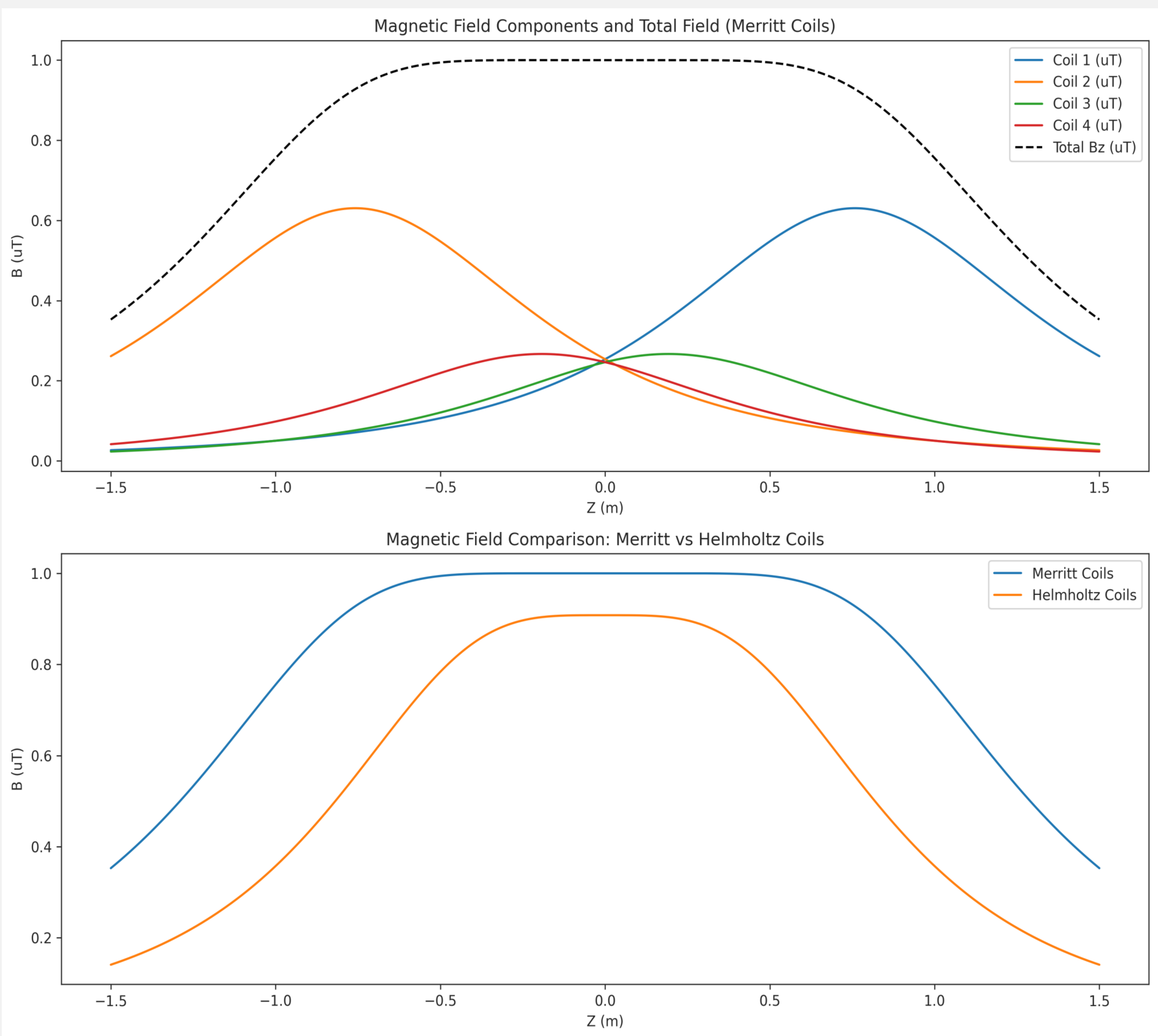
II. Background and Theory

Merritt coils have a significant advantage over traditional Helmholtz coils in generating uniform magnetic fields. While Helmholtz coils consist of two identical coils spaced apart to produce a homogeneous field, they often require a larger footprint and provide a limited uniform field volume to total volume ratio. In contrast, Merritt coils use four coils arranged optimally to extend the uniform region. By finding the magnetic field of each coil via Eq. 1 and taking the superposition of all four placed along one axis, the total field generated in one degree of freedom was calculated to be 1.25 gauss for a 2A constant current.

$$B(z,n,h) = \frac{\mu n I}{\pi} \cdot \frac{2a^2}{(a^2+(z-h)^2)\sqrt{2a^2+(z-h)^2}} \qquad \text{[Eq. 1]}$$

$\mu = magnetic\ \ constant,\ n = number\ of\ turns,\ h = coil\ offset\ ,\ and\ a = half\ side\ length$

Figure 1: The magnitude of magnetic fields as a function of position from the center point of the cage.



III. Cage Design

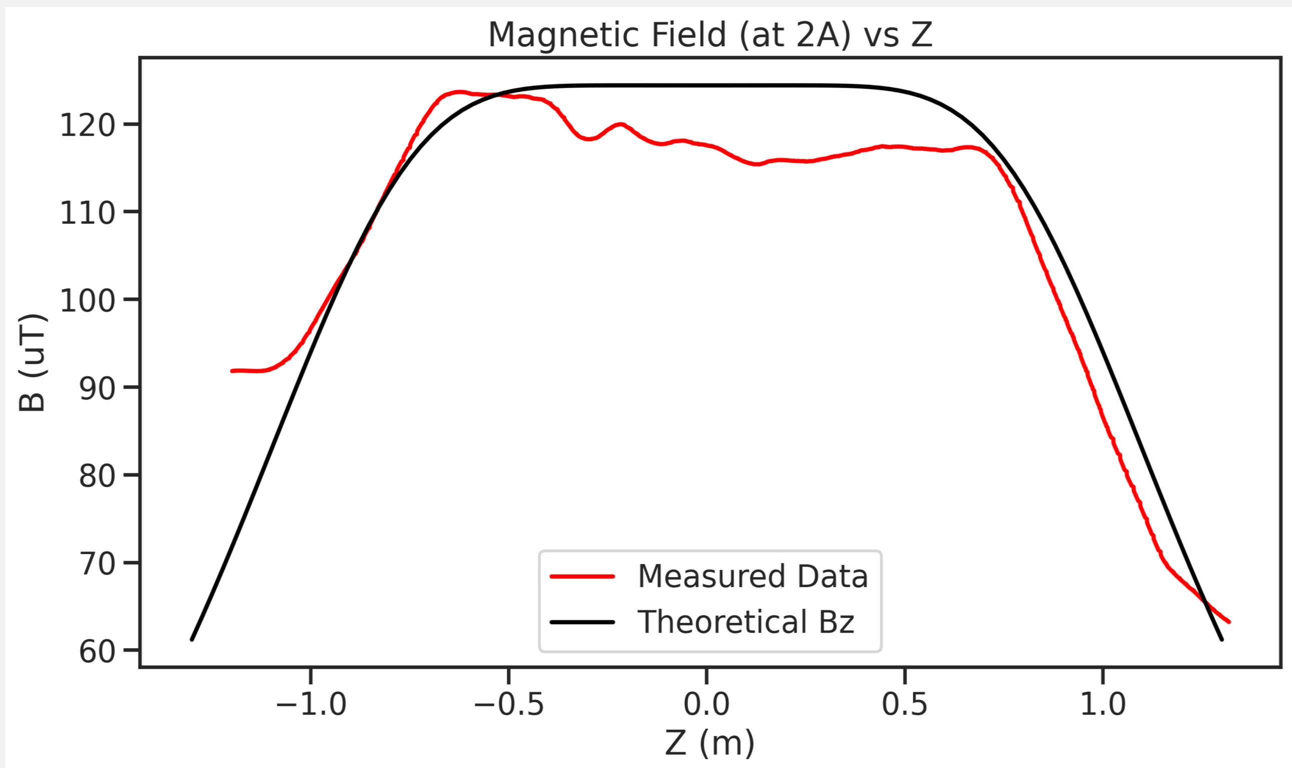
Using the work done by J.C. Olivares-Galvan et al, the ideal ratio of inner to outer turns for a Merritt coil was known to be about 0.513, which is roughly $\frac{11}{26}$. In the previous work of Meghan K. Prinkey, this generated an organically shaped uniform field that equated to a roughly 0.5 m cube in the center of the cage (large enough for a 12U CubeSat). Since field strength is directly proportional to both the current and the number of wire turns, while resistive power is proportional to the square of the current, efficiency can be improved by increasing the number of turns to 22 for the inner coils, and 52 for the outer coils, reducing the required current for the same field. MATLAB simulations based on this principle were developed and used to determine the acceptable cage size of 1.5 m which would generate a large enough uniform volume for a 12U CubeSat.

Figure 2: One axis (4 coils in series) of the Merritt Cage

IV. Results and Analysis

Once constructed, measurements were taken to characterize the coil. One axis of the cage showed an equivalent inductance and resistance of 35 µH and 13.5 Ω respectively. A simulated lumped sum elemental model of the cage indicated roughly 2 A should be flowing when switching occurs at a frequency equivalent to 0.2 τ where τ is the $\frac{L}{R}$ time constant. This matched the theoretical expectations obtained using Eq. 1.

Figure 5: The magnitude of the theoretical and experimental magnetic fields as functions of position from the center point of the cage

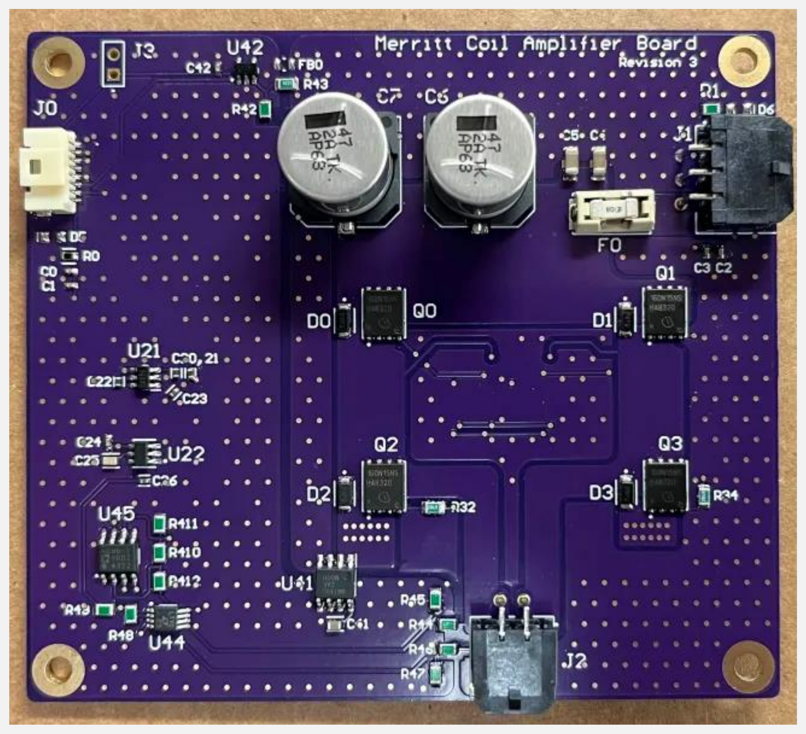


At 2A DC, the ambient magnetic field measured roughly 0.135 gauss; the maximum field measured 1.4 gauss which means the net generated field had a magnitude of 1.265 gauss, corresponding to an average error of 4.8% with respect to the expected value.

V. Coil Driver Design

The cage is driven by a high-voltage, high-current PWM waveform, which is smoothed out by the properties of the cage. A switched-mode full bridge amplifier was chosen as the topology for the coil driver as it is a simple topology for switching high DC currents, and functions well when operating below the coil's self-resonant frequency.

Figure 3: Driver and Sensing Circuit PCB



Current values were acquired using a Hall-effect IC, meanwhile, the voltage across the coils was obtained with a simple differential amplifier circuit. The design, comprised of buffer and differential op-amps, was modified via a 1.6 V biasing voltage such that – 80 V and + 80V would respectively correspond to 0 V and 3 V, a range suiting common ADC devices. Component values were refined using the derived formula in Eq 2.

$$V_{ADC} = V_B\left(1+\frac{R_8}{R_5}\right)\left(\frac{R_6}{R_6+R_7}\right) + V_2\left(\frac{R_7}{R_7+R_6}\right)\left(1+\frac{R_8}{R_5}\right) - V_1\left(\frac{R_8}{R_5}\right) \qquad \text{[Eq. 2]}$$

$$V_1 = V_{Coil1}\left(\frac{R_2}{R_2+R_1}\right) \qquad V_2 = V_{Coil2}\left(\frac{R_4}{R_4+R_3}\right) \qquad V_B = 1.6\ V$$

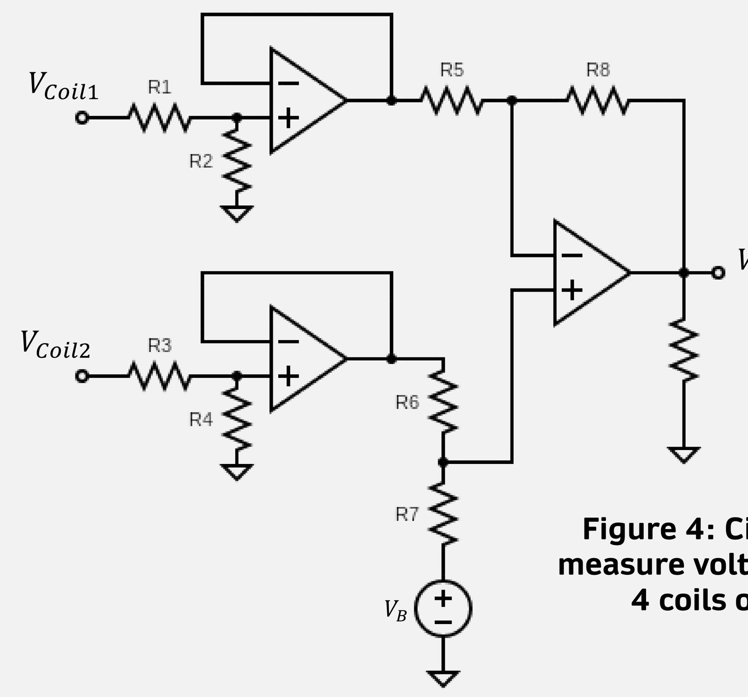


Figure 4: Circuit used to measure voltage across the 4 coils of one axis

VI. Future Work

Building off the results found in this work, we will increase the current to generate the 1.7 - 2.5 gauss that exists in LEO environment. A PID control algorithm will use the voltage and current readings of the coils to modify the duty cycle such that the desired current, and thus magnetic field, is generated. An automatic calibration routine will then be created to ensure the accuracy of the cage, and a GUI will allow the user to easily program the magnetic field using functions for each axis and view graphs of recorded statistics. Then, methods to position objects inside the cage will be developed, enabling its use for testing CubeSat magnetic systems.

VII. Acknowledgements and References

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