Satellite Testbed for Attitude Response

Matt Hong, Cole Glommen, Nathan Eckert, Nick Andrews, Dylan Cooper, Sasaka Bathula, Colin Peterson
University of Colorado at Boulder, Boulder, CO 80309

Cube satellites or CubeSats are small 10 to 30 cm satellites which are growing rapidly in popularity due to the increasing number of secondary launch opportunities available. While the first CubeSats had limited capability and complexity, as the technology matures the missions for these satellites have been increasing in complexity. The first CubeSats were often low-cost technology demonstrations and did not include any attitude control, however to meet the current mission needs many of today's CubeSats are 3-axis controlled similar to typical satellite missions. This increase in system performance also drives a requirement for testing infrastructure to verify the design performance metrics has been achieved. In this work, three distinct systems have been created to test the Attitude Determination and Control Systems (ADCS) of a CubeSat, its pointing actuators (magnetorquers), and its sun sensors. First, an interface board has been developed that is capable of sending simulated sensor data into the ADCS processor, allowing for the testing of the ADCS logic, while sampling the output power of the magnetorquers and the power draw of the overall system. By taking in simulated sensor data produced by Matlab over a USART line, the board transmits this data over an I²C line into the ADCS processor. It simultaneously measures the pulse width modulated signals generated from the magnetorquers and the voltage measurements of the ADCS board, and sends this data back into the Matlab simulation. Second, an apparatus has been developed to test the magnetorquers used for a satellite's attitude control. This apparatus suspends the satellite in a Helmholtz cage and allows for the verification of magnetorquer functionality. This is done by observing the spacecraft rotation in a specified magnetic field when the magnetorquers are and are not operating. While designed for magnetorquers, this apparatus could also verify the operation of reaction wheel–based attitude control systems. Third, a motorized, computer-controlled turntable has been developed to calibrate and test the sun sensors on all faces of the CubeSat. This turntable is capable of rotating and measuring its rotation angle to within 0.5 degrees of accuracy, allowing for the comparison to the angle reported by the system of sun sensors. The combination of these three systems verifies and calibrates the key operations of a CubeSat's ADCS, and provides confidence in the satellites on-orbit performance.

Nomenclature

A	=	area, m^2
ADCS	=	attitude determination and control system
α	=	angular acceleration, rad/s^2
C_D	=	coefficient of drag, unitless
C_f	=	friction coefficient on turntable
D	=	drag, N
DoF	=	degree of freedom
g	=	acceleration due to gravity, m/s^2
h	=	altitude of satellite, km
l	=	length of satellite, m
m_t	=	total mass of turntable, kg
M	=	moment of satellite
m	=	mass of satellite, kg
PWM	=	pulse width modulation

r	=	radius of sun sensor turntable, m
RPM	=	revolutions per minute
t	=	time, s
w	=	width of satellite, m
ρ	=	mass density, km/m^3
τ_R	=	torque required for turntable, Nm
θ	=	angle, radians
USART	=	universal synchronous / asynchronous receiver and transmitter

I. Introduction

Space vehicles present a variety of unique design challenges, stemming from the fact it is nearly impossible to replicate all aspects of the space environment on the ground. A space environment will have no ambient pressure, will cause outgassing of the satellite's exposed components, does not allow for mechanical repairs to be made, and presents a microgravity environment. Large, expensive programs have the opportunity for flight testing that allow the Attitude Determination and Control System (ADCS) to be tested in the space environment[5], or for long life vehicles, certain bugs can be worked out during the mission[6]. While these high cost missions do require system performance verification prior to launch, the larger budget and longer lifespan of the satellites allow for in-orbit verification as well. For low budget vehicles with short mission lifespans it is not feasible to conduct flight testing and bugs could take the entire mission lifespan to fix[7]. This leaves ground testing, which often involves testing of individual elements combined with detailed analysis to prove that the satellite will function properly in its test environment. As accurate orientation of the spacecraft is one of the most critical functions of any satellite, the ADCS must be extensively characterized to ensure that it will function as designed for its entire expected lifespan.

The QB50 is a project that will launch 50 CubeSats built by universities worldwide. The goal is to prove feasibility of scientific research through a low-cost constellation of CubeSats, providing multi-point measurements in low-Earth-orbit[8]. The University of Colorado Boulder QB50 Project CubeSat ADCS consists of fifteen sun sensors, three rate gyros, three magnetometers, and a GPS receiver for attitude determination. It also has 3 magnetorquers for attitude control. It is significant all sensors and actuators on board function correctly for accurate orientation.

The motivation of our project is to gain confidence in the operation of the CU Boulder QB50 ADCS before launch. To accomplish this, we have developed an ADCS testbed comprised of three separate systems: a hardware-in-the-loop simulation interface board; a one degree-of-freedom (DoF) suspension system inside a Helmholtz cage; and a turntable for optical sensor calibration. The hardware-in-the-loop simulation will replace the physical CubeSat with a mathematical dynamic model that sends sensor input to the ADCS and receives corresponding actuator commands from the board. Using these actuator commands, the simulation determines the motion of the Cubesat in a simulated environment, and again outputs the correct sensor data to the ADCS. By simulating different real world scenarios, and analyzing the response of the model, correct operation and performance of the ADCS system can be verified. The testbed can be seen below in Figure 1 with the hardware-in-the-loop interface board, sun sensor turntable, and HelmHoltz cage suspension from left to right.

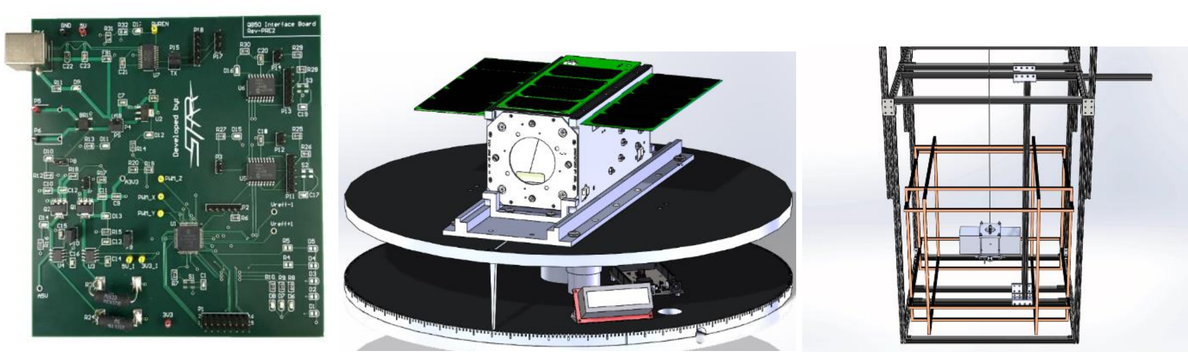

Figure 1. Testbed for QB50 ADCS

The data collected from the hardware-in-the-loop simulations will be used to verify the operation and performance of the satellite's ADCS. This will provide the confidence that, during the eight-month lifetime of the CubeSat, there will be no issues related to the attitude systems. In the long term, this testbed can be used for future CubeSat missions and make the ADCS test process faster and more reliable.

The one DoF suspension test will allow the QB50 team to test magnetorquers on board the fully-integrated CubeSat inside of a Helmholtz cage in order to validate their functionality. The Helmholtz cage will emulate the magnetic field to test the response from the magnetorquers. The test will ensure the functionality of the magnetorquers at low magnetic torque. Along with this, a turntable will be manufactured so that sun sensor calibration can be performed both manually and with automated control. The turntable will rotate with an accuracy of ±0.5° for accurate sun sensor calibration.

The paper describes the three separate test systems that are being developed, and clearly identifies the design objectives, methodology, and test results for each. Motivations for CubeSat ground testing have led to the development of similar testbeds that allow for the verification and validation of the ADCS systems. The satellites that have been tested by these other testbeds relied on the same three primary modes of attitude control once in orbit; initial de-tumble, sun-pointing mode, and mission pointing mode. The successful utilization of these other test systems proves that CubeSat testbeds are not only practical to design during project development, but also proven to be useful in achieving overall project success.

II. Interface Board

The interface board has to send simulated data from fifteen sun sensors, the X, Y, and Z components from three magnetometers, three rate gyros, and the position from a GPS receiver. This data requires transmission over two communications paths into the customer's ADCS processor: A Universal Synchronous / Asynchronous Receiver Transmitter (USART), and an Inter-Integrated circuit (I^2C). These are two forms of serial data transmission, allowing for the translation of digital data from the simulation into the ADCS processor.

In order to send this data, an interface board was created to translate and transmit the data between the Matlab simulation and the ADCS processor. This board primarily consists of an FTDI chip, a PIC18F67J94 master microcontroller, and eight PIC16F1847 slave microcontrollers. The master microcontroller's purpose is to take in PC data, transmitted over the PICThe slave PIC microcontrollers have been programmed to respond to the ADCS's queries, mimicking the sensors and sending an identical match to what their data should be.

The USART line, shown in Figure 2, is a single line which communicates data with a start bit, the eight bits of data for a single character, ending with a stop bit. The bit transmission starts from the least significant bit towards the most significant bit. In doing this, there is no need for continuous transmission between the two connections, allowing for more simplified communication.

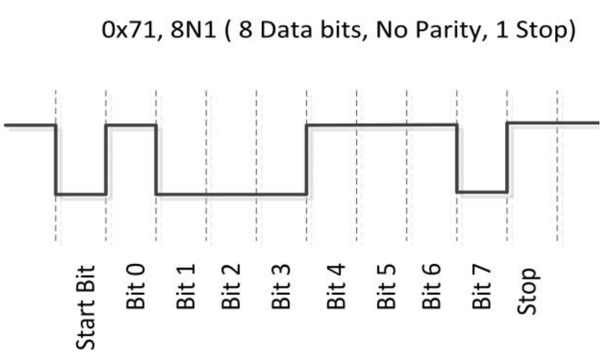

Figure 2. Example of USART [1]

The I^2C line, however, relies on two transmission lines, a Serial Clock Line and a Serial Data Line (SCL and SDA respectively). By raising and lowering the SCL voltage line, there is a clear, agreed upon transmission rate. The SDA line is driven high and low in turn to send the appropriate binary data, as is shown in Figure 3. Each transmission starts with a start condition, followed by a seven-bit address and a read/write bit. This address will determine which sensor data is being transmitted at the time, while the read/write determines if the slave is sending data to the slaves or vice versa. As the slave controllers recognize their address being sent, it will take control and respond with the data following an acknowledge bit, or ACK. Once the data is being sent, the master line will respond with a negative acknowledge bit, or NACK. With this protocol, the

ADCS processor can send the same address to all of the eight microcontrollers, but ensures that only the correct data is being received.

From the Matlab simulation, the data is sent through an FTDI chip, sending the data into the master microcontroller over a USART line. The master microcontroller, once it has determined that all of the data has been sent for this iteration, responds by transmitting the measured data. In turn, it repeats transmission of the most recent data over a second USART line which the eight slave microcontrollers are connected to. These eight microcontrollers are receiving all of the transmitted data, but are only saving the data that their designated sensors are related to. The ADCS processor uses the I²C lines to communicate with the slave microcontrollers, querying the slaves for their data by sending an address and reading in the slaves response.

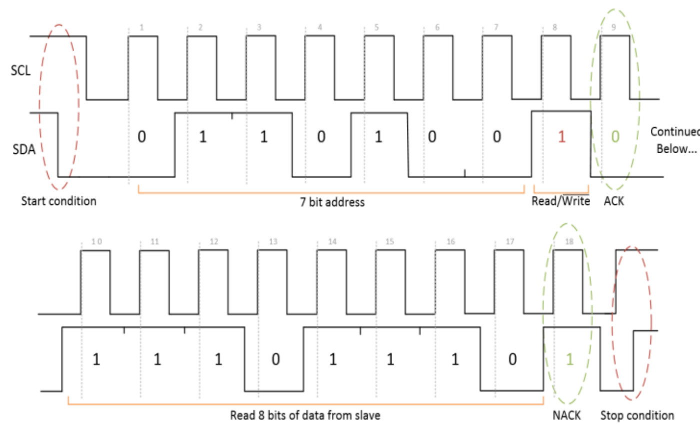

Figure 3. Example of I²C communication [1]

From here, the ADCS processor now acts as a black box in the eyes of the interface board. It makes internal calculations and sends pulse width modulated signals to the magnetorquers. This pulse width modulation (PWM) signal acts as a variable control to the magnetorquer strength, as the duty cycle of the PWM changes, so does the magnetorquers response. By using a series of interrupts on the master microcontroller, the timing of the PWM can be measured and converted into a duty cycle.

The ADCS processor operates on a pair of supply voltages, namely a 5 volt line and a 3.3 volt line. These voltages are connected into two of the master microcontroller's analog to digital converter channels. In order to measure the current output of these lines, Hall effect current sensors are connected to the 5V and 3.3 V lines. These current sensors convert the current into a voltage, and are again connect to the master microcontroller's ADCs. With the combination of the current and voltage from both of these lines, a total power draw can be calculated for the processor.

The combination of the four voltages and the magnetorquers duty cycles are converted into a series of ASCII characters. The master microcontroller will send this message in a series of bytes over the USART line back into the PC. From here, the Matlab simulation can parse the transmission and pull out the series of voltage measurements, and duty cycles created from the magnetorquers.

III. Software

The software models developed by the customer simulate the on-board software and hardware of QB50 CubeSat's ADCS. These simulation models, developed in MATLAB and Simulink, provide a reliable model for the performance of the ADCS algorithms for the estimation, control, and orbit propagation of the spacecraft attitude. The performance metrics provided by this full ADCS simulation include how phase lag, external disturbances and noise in sensor signals affect the flight software algorithms. The software package developed for this project will be responsible for integrating the ADCS flight hardware with the simulation software to conduct a hardware-in-loop simulation in order to validate the performance of the CubeSat ADCS system.

The ADCS simulation begins by inputting orbital data from an STK model, which was done by the customer to keep the dynamic and control simulations completely separate. Disturbance torques are then calculated, and a high-fidelity rotational dynamics propagator calculates the true attitude state of the spacecraft. This information (attitude state, position state, magnetic field vector, and sun vector) is then fed to the sensor models which generates simulated sensor data (in lieu of actual sensor data). These sensor models are calibrated mathematical models that estimate the sensor outputs based the attitude state. In particular, the Sun-sensor model uses sun vector and position vector to determine the voltage value that would be seen by the actual sun sensors. Similarly, the gyro-sensor model uses the angular rate and the magnetometer model uses the position vector and magnetic field vector to compute the voltage values that would be seen by the actual gyro sensor and magnetometer. These voltage values for multiple sensors with addition of noise will be concatenated into a single vector that is transmitted over USB to the FTDI chip on the interface board with the aid of FTDI-USB driver for MATLAB. The interface board will then emulate the sensor data on to the customer ADCS board as well as capture its magnetorquer PWM signal response. The PWM signal is then analyzed on the interface board to calculate the equivalent control torque vector. The control torque thus calculated along with the voltage and current consumed by the customer ADCS board is transmitted back to MATLAB software via the FTDI chip for logging. Figure 4 shows the functional flowchart of the software.

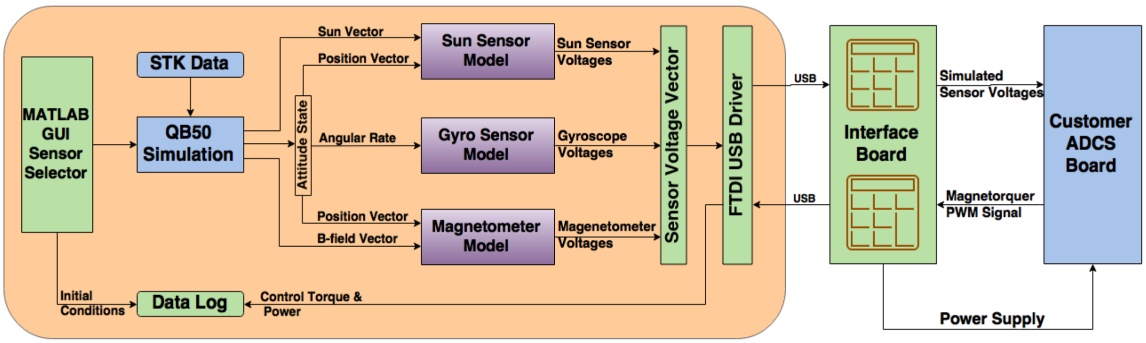

Figure 4. Software Flowchart

A graphical user interface (GUI) is also designed to be integrated with the simulation model to allow the user to control the simulation inputs as well as have a real time view of the outputs. On the main screen, the user will control the start and stop of the simulation. The main screen will display the torque output of magnetorquers, the current measured, and the voltage measured. This GUI will satisfy the project requirement to initiate the simulation with given set of initial conditions that included enabling and disabling certain sensors in the simulation in order to study the impact of malfunctioning sensors in a real mission environment.

The sensor models will convert the real attitude state of the CubeSat along the propagated orbit to attitude state as would be seen by the sensors in a real mission environment. The attitude state of the CubeSat determined in the simulation is converted from the body reference frame to individual sensor reference frames to account for the differences in orientation of the sensors when instrumented on the CubeSat. The transformed attitude state customized for each sensor is packaged into a single array of data which is then converted into ASCII representation and passed on to the interface board through the FTDI chip using a serial communication protocol. A schematic representation of the data flow through the gyro sensor models can be seen in Figure 5. The other sensor models follow a similar logic to generate the sensor inputs that will be sent to the CubeSat ADCS through the interface board.

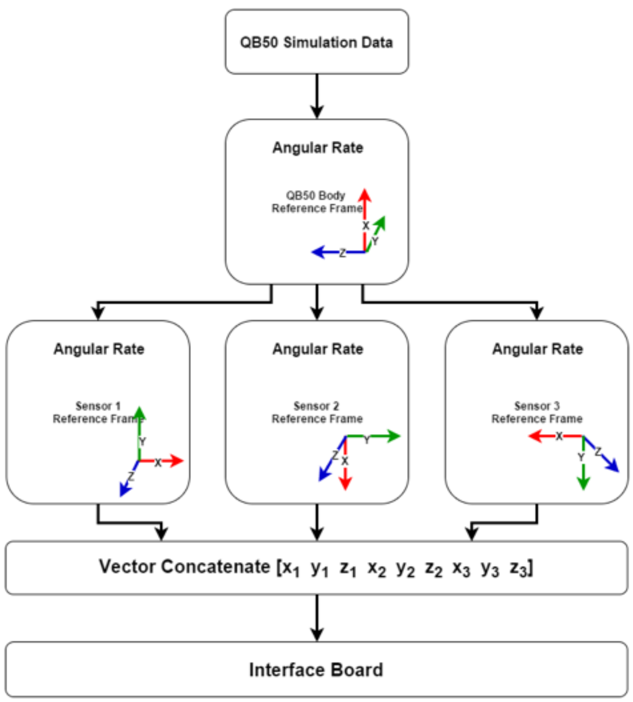

Figure 5. Gyro Sensor Model

The magetorquer response to the simulated inputs is observed by the interface board by capturing the pulse width modulation (PWM) signal generated by the ADCS. The PWM signal is converted to the torque that would be applied by the magetorquer and this time-lapse of the torque value is recorded further analysis by the customer. In addition to the torque, the voltage and current draw measurements across a 3.3V line and a 5V line of the ADCS board are also captured and recorded for analysis by the customer.

IV. Sun Sensor Turntable

The manual or motorized, computer-controlled turntable has been developed to calibrate and test the Sun sensors on all 6 faces of the CubeSat. This turntable is capable of rotating and measuring its rotation angle to within 0.5 degrees of accuracy, allowing for comparison of the physical table angle to the angle reported by the system of Sun sensors. The top surface of the board is coated in Avian Black-S coating, a spray on coating applied by Avian Technologies LLC to reduce the average reflectance of the surface to 3.5% or less over most ultraviolet, visible, and infared wavelengths. This low reflectance coating will minimize the reflected light and thus increasing the quality of the Sun sensor calibration data. In addition, the base of the turntable has ¼”-20 hole patterns compatible with most optical benches. These requirements were derived to ensure useful and accurate data could be obtained from the calibration process and were met by applying engineering principles and computer aided design models to guarantee success. No other comparable Sun sensor calibration methods were found during our initial research and thus the entire turntable is unique and has been designed and fabricated from the ground up by the CU Boulder student team.

The turntable can be simplified into 5 major components: bottom board, shaft, top board, horizontal clamp, and vertical clamp. The bottom board prevents tilting of the system and houses the motor and Arduino electronics. The bottom board has physical angle etchings along the circumference to determine the angular position of the top board. The shaft is screwed into the center of the bottom board and supports the bearing and load of the top board while housing the encoder for measuring the angular displacement of the top board. The CubeSat is attached to the top board in the desired orientation and is then rotated through a system of gears by the motor. The top board points to the appropriate angle etching with a needle pointing downwards toward the angle etchings on the bottom board. A horizontal and vertical clamp are used to secure the CubeSat to the top board either horizontally or vertically. Each clamp is compatible for CubeSats of sizes 1U, 2U, and 3U and the horizontal clamp doubles as the clamp used for thermal vaccum (TVAC) testing of the CubeSat. Each clamp has been bead blasted to reduce its reflectance to 20% or less to prevent interference with sensor calibration. All 5 of these major component were manufactured in house.

The CubeSat center of gravity is within a 0.4" diameter sphere from it's geometric center, meaning the center of gravity is roughly aligned with the rotation axis of the top board. The shaft supporting the top board has a diameter of 2.23", ensuring that the top board will not be experience any mechanical moments. A combination ball-thrust bearing is used to support the entire axial load the top board. The bearing can support up to 790lbs and the board weighs roughly 22lbs. The bearing is friction fit around the support shaft and a gear is friction fit around the bearing. This shaft bearing is screwed into the top board and meshed with a gear friction fit around the motor. Therefore, the motor turns its gear, meshes with the shaft gear, and thus turning the top board. We chose a 2:1 shaft to motor gear ratio to increase the torque produced on the top board.

The success of the turntable is primarily dependent its resolution and accuracy of sensing angular position. To maintain high resolution position, a 12-bit magnetic rotary encoder is integrated into the turtable. This provides a resolution of 0.08789° per bit. To maintain an accuracy of 0.5° the turntable utilizes a physical-electronics redundancy between the encoder, angle etchings, and clamps . The turntable is capable of displaying angular position in three ways. First is via the physical angle etchings along the base of the board. Second is through an LCD attached to the bottom board and connected through an Arduino Due being fed angular position from the magnetic encoder. Lastly, the angular position, angular rate, and relative time will be logged in Matlab and as a .txt file on the computer to later allow overaly of Sun sensor data onto angular position.

To achieve automation of the turntable, a DC motor, gears, and bearing were needed in the turntable system. The minimum torque required to rotate the board with the CubeSat and clamps attached is 0.2912 in-lbs. This was found by applying the following equation:

$$\tau_R = C_f m_t g r \tag{1}$$

Where τ_R is the required torque, C_f is the friction coefficient, m_t is the mass of the turntable, g is gravity and r is the radius of the turntable. The torque produced on the board from the motor after applying the gear ratio is 374.4 in*lbs, thus satisfying the minimum torque required to rotate the board. The DC motor is controlled through a motor driver that controls the pulse width modulation signal sent to the DC motor. This control method allows a high resolution of voltages to be sent to the motor. In addition the table must be able to rotate slow enough such that the sun sensors can sample once per degree, this is equivelant to a revoluation per minute (RPM) of 5/3. The turntable will rotate between

3/20 RPM and ½ RPM, satisfying the requirement. By adjusting the PWM signal we are able to rotate slow enough to satisfy this requirement. The table can be set for manual operation by unscrewing a set screw holding the motor gear in place, removing the otherwise locked motor from the system.

During operation, the CubeSat will be aligned with the center of the rotation axis of the board. The CubeSat will be ortiented horizontally, shown in Figure 6, or vertically, shown in Figure 7, and resting on the top board depending on the faces that wish to be calibrated. SolidWorks models of the CubeSat in the horizontal and vertical orientations are shown:

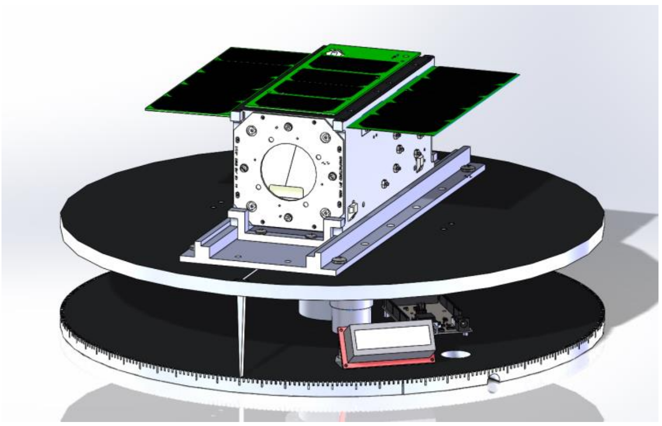

Figure 6. Turntable with Horizontal Clamp

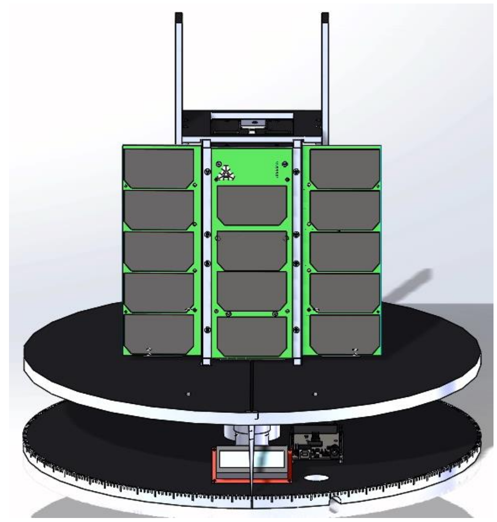

Figure 7. Turntable with Vertical Clamp

The sun sensor calibration table will have two modes of operation; "sweep" and "point". During the sweep mode, the user will input a desired rotation rate using a GUI developed in MATLAB. The turntable will then rotate at the user desired RPM. The point mode will allow automatic control to point to a user desired angle. The user will also be able to manually rotate to an angle if desired. All data will be logged and written to a text file for future analysis.

All electronics will be controlled using an Arduino Due. The motor requires power from a power supply at 12V. A motor driver is used to control the speed of the motor by sending two PWM signals. The first signal controls the direction of the motor, and the other controls the speed by varying the duty cycle. A 12-bit analog encoder is used to read the angle, and an LCD displays the current angle and RPM in real time. The LCD and motor driver are only capable of reading 5V signals, while the Arduino Due operates at 3.3V. A logic level shifter is used to convert the signals to 5V. The Arduino Due was chosen for its 12-bit ADC capabilities.

V.   Helmholtz Cage Test

The Helmholtz Cage Testing System (HelCaTS) is intended to allow for magnetorquer functionality assessment on 1U-3U CubeSats using a customer-provided Helmholtz cage. The assessment of the magnetorquers is chiefly dependent on the torque they can provide (~5 x 10^{-6} Nm in a 0.5 Gauss field) relative to the amount of resistive torque present in the system. Thus, the critical element of this design was to minimize the resistive torque in order to maximize the impact of the magnetorquers. Additional requirements are to ensure the satellite stays in a uniform magnetic field, that the satellite is safe during testing, and finally that this structure will fit with a standard lab environment.

The system design is shown in Figure 8, and will be briefly explained before the design details. This structure is made of extruded aluminum (1) and suspends the satellite using a braided nylon line (2). This braided line is strong enough to safely suspend the satellite, and provides low enough twisting resistance to allow observation of the magnetorquer impact. All attachment hardware (4) is made of aluminum. The height of this structure can be adjusted between 8'9" and 5'3" (3), allowing it to fit within any common laboratory. The attachment hardware allows for the satellite to be mounted in any orientation with or without the solar panels mounted.The structure also includes a release mechanism (5) which ensures repeatable release during magnetorquer testing.

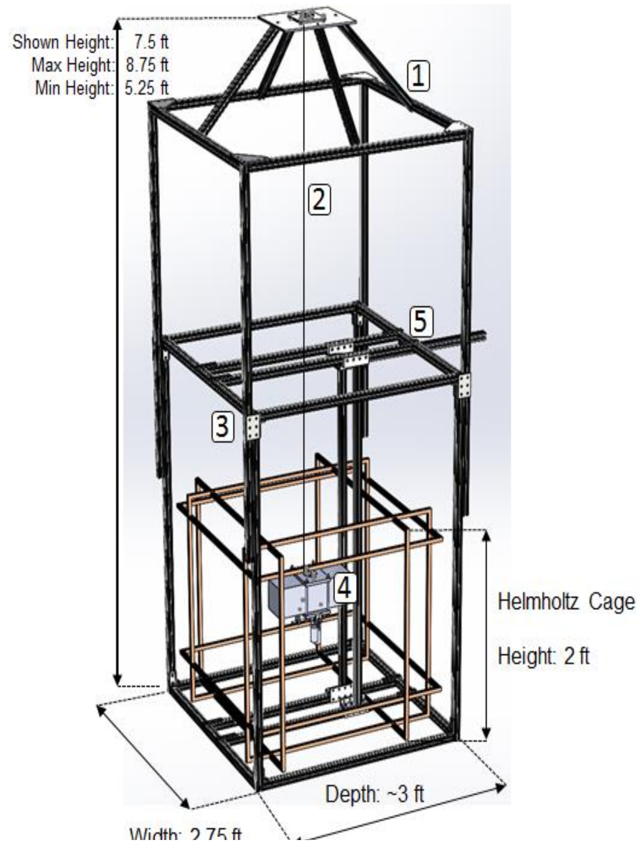

Figure 8. Hanging Apparatus

In the development of this system, multiple options were considered to provide this one degree of low resistance rotational motion. Even high quality mechanical bearings proved to have too much resistance. Similarly air bearings could not be used after considering the disturbances and the resistance present in them. A magnetic bearing is overly complex, and runs the risk of interfering with the magnetic field in the Helmholtz Cage. Thus, the optimal solution was to suspend the satellite via a braided nylon line and allow this line to twist as the satellite rotates. In addition to this design analysis, a search for industry bestpractices was performed. This provided information on a very similar project done at MIT. Their solution was also to use a string to suspend the satellite, and allow it to twist with the satellite. No analysis of their solution's effectiveness was found, but the fact that it was used to provide data they found sufficient suggested that this was a viable system. Both the modeling analysis and the presence of heritage made the team confident that the design was ready for implementation.

The first functional requirement was developed using the turning authority of the magnetorquers (0.1 Am^2 or 5 x 10^{-6} Nm in a 0.5 G field). It was unlikely the satellite would be powerful enough to rotate itself. Thus, the goal was that the magnetorquer authority be at least 20% of the resistive torque, providing for the requirement that the resistive torque be under 2.5 x 10^{-5} Nm. In other words, the satellite would not rotate on its own, but, if the line is twisted 360°, it would be able to impact the time it takes the satellite to rotate back to 0°.

Modeling was used to provide confidence in the HelCaTS' ability to provide for magnetorquer assessment. This was done by modeling the aerodynamic resistance to rotation, the impact of tilting, and iterative modeling and testing of the torque produced by the line. To develop the aerodynamic model, the drag force at the expected rotation speed was analyzed with equation 2:

$$D = 2\rho v^2 C_D A \tag{2}$$

This force was then integrated, with respect to distance, over one half the length of the satellite to provide the moment produced by drag as shown in equation 3:

$$M = 164\rho\alpha^2 t^2 h L^4 C_D \tag{3}$$

The drag coefficient was conservatively estimated as that of a flat plate (C_D = 2.05). The velocity (v) was found with rotational motion equations, assuming the torque turning the satellite is that of the magnetorquers. The density of air (ρ) was found using the standard atmosphere database at the altitude of Boulder (~1500 meters) [3].

The findings obtained through this were that, even though the torques being examined are small, the impact of drag is *very* small, and can be neglected. The moment produced by drag was modeled to be 5.4 x 10^{-14} Nm.

Due to the non-rigid support mechanism used in this design, (nylon string) the satellite is free to tilt if its center of gravity is not perfectly aligned. The test operator can shift the satellite in the clamp to account for this. However, an analysis was done to assess the maximum tilt if the satellite is clamped about its geometric center. The center of gravity of the satellite is within 1 cm of its geometric center as dictated by QB50 regulation. Thus, the tilt of a 3.6 kg mass shifted 1 cm from its support was found to be 11°. This affects the impact of the magnetorquers because the axis the magnetorquer is acting about is shifted off of the axis of rotation, and because the magnetorquer is misaligned to the magnetic field. The magnitude of these reductions were found with simple trigonometry to be 0.1 x 10^{-6} Nm each, so the resulting magnetorquer torque is 4.8 x 10^{-6} Nm, rather than 5 x 10^{-6} Nm. This reduction is small, and so the design does not attempt to correct any present tilting.

Most importantly, the resistive torque provided by the braided nylon line had to be quantified. This was done initially by modeling the line as a rigid rod, but this proved inaccurate, so preliminary testing needed to be done. In these tests, a 3.6 kg mass model on an 8 ft line was rotated 360°. It was then released, and the time for it to come back to 0° was measured. The average time to rotate (t) was 2 minutes 45 seconds ± 7.5 seconds. This was used to find the line torque using equation 4:

$$\tau_{line} = \frac{m(h^2 + w^2)\theta}{6t^2} \tag{4}$$

In this way the line torque was found to be ~1.5 x 10^{-5} Nm. Finally, this line torque was then combined with the torque of the magnetorquer to find the change in the time to rotate by solving eq. (3) for t. The time to rotate was predicted to be reduced by ~30 seconds if the magnetorquer acts in the same direction as the line torque, and increased by ~45 seconds if it acts against the line torque. The mass of the attachment hardware was not considered with this mass model, however, the attachment hardware is less than 1.8 kg, and assuming a linear increase in torque, the time to rotate will simply be about 1 minute longer, with even larger changes from the magnetorquer.

Using the design and modeling of the various parts within SolidWorks and SolidCAM, the HelCaTS parts were machined, and the structure designed in SolidWorks with extruded aluminum was assembled using pre-cut parts from 80/20.

Three tests will be done on the HelCaTS to ensure it operates as intended. First, a tensile test will be done on the braided nylon line to ensure our factor of safety is at least 2. The line will be attached to the cylinders which will hold in in the actual structure to also provide confidence in the attachment mechanism. The assembly (shown in Figure 9) will be placed in an Instron tensile testing machine, and tested to failure. Next, we will validate the time to rotate predictions which suggest the magnetorquers will have a noticeable impact. A satellite mass model will be placed in the structure, and we will measure the time it takes to rotate from 360° back through 0° acting only from the torque the line produces. Analysis of the time to rotate, and knowledge of the rotating mass will allow us to find the resistive torque of the line and the impact of the magnetorquers on the time to rotate. Lastly, a test with the magnetorquers operational will allow us to validate these predictions by measuring the increase or decrease in the time it takes to rotate from 360° to 0°.

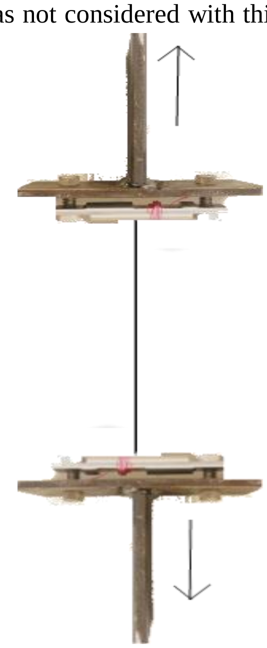

Figure 9. Tensile Test

VI. Conclusion

The CU Boulder QB50 program has been in production since early 2014, passing its critical design review in May of that year. An international network of companies and universities will launch fifty individual CubeSats together, with an anticipated launch date towards the end of 2016 into early 2017. The main goal of the project is to conduct low budget, scientific research in the lower thermosphere with a constellation of CubeSats of 1U, 2U, and 3U size. With the participation of so many programs in this project, there have been a variety of different approaches to develop confidence in each satellite's attitude determination and control systems[9]. Should our system be successful in achieving its objectives, the team that has been working on the CU CubeSat will be able to gain the confidence that their satellite will not only be on schedule to launch, but it will also function properly once launched, allowing for the accurate acquisition of scientific research data. Our testbed system is vital for CubeSat testing, and should we reach our highest levels of success, it will provide invaluable validation that the CubeSat will also be successful.

The remaining work to be done on the testbed may be considered the most important. Upon completion of manufacturing, the project will enter its final assembly and testing stages. Through this testing, our team will verify that our designs are not only functional, but that the tests we designed to validate and verify the CubeSat ADCS are also viable options moving forward. The testbed we designed has an adaptive capability in the field of CubeSats in that it can accommodate a variety of CubeSats sizes and orientations. This means that the system can be used for testing in the field for years provided it remains functional. The research we conducted and the designs that were developed are also valuable information for future cube satellite teams. The applications for small satellite testing systems are growing as the desire to conduct scientific research from small satellites is as well.

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