University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Project Definition Document (PDD)
QB50 ADCS Testbed

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Approvals

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1 Problem or Need

Space vehicles present a unique design challenge as 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 structures experience a microgravity environment. Large budget vehicles may have the opportunity for test launches that allow the Attitude Determination and Control System (ADCS) to be tested in the space environment, or for long life vehicles it may be acceptable to have minor bugs that can be worked out during the mission. For low budget vehicles with short mission lifespans it is not possible to test launch and not acceptable to have any bugs. This leaves ground testing, which is often a test of individual elements and performing detailed analysis to prove that the satellite will function properly in its test environment. With one of the most critical subsystems of any satellite being its ability to point correctly, the attitude determination and control systems must have extensive analysis on it to show that it will work for its entire expected lifespan.

The motivation of this project is to gain confidence in the QB50 ADCS. To accomplish this we will develop an ADCS test bed compromised of three systems, a hardware in the loop simulation, a 1 degree-of-freedom (DoF) suspension system inside a Helmholtz cage, and a turn table for 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 motion of the model, correct operation and performance of the ADCS system can be verified.

The data collected from the simulations will be used by the QB50 team to verify the operation and performance of the satellite's ADCS. This will provide them with the confidence that, during the 8 month lifetime of the CubeSat, there will be no issues related to their attitude systems. In the long term, this test bed can be used for future CubeSat missions and make the ADCS test process faster and more reliable.

The 1 DoF suspension test allows the QB50 team to test the fully integrated CubeSat inside a Helmholtz cage. Along with this, a turn table will be made so that Sun sensor calibration can be performed.

2 Previous Work

The 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. 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.

Companies such as Clyde Space have additionally created small testbeds[1] for other CubeSats. While their system is not intended to be used specifically by the QB50, many of the general principles apply. Their testbed relies solely on using the magnetorquers on-board the CubeSat, and can monitor the telemetry of the magnetorquers firing rates, other telemetry from the solar panels embedded magnetorquer coils, and the ADCS board's magnetometers and rate sensors. This has proven that a small testbed is not only practical, but has been actively achieved by other companies. Their satellites also have the same three primary modes of attitude control; an initial de-tumble to stop extraneous roll, a sun-pointing mode, and a mission point mode. The results from their testbed shows that all three modes are viable given the expected sensor inputs for the modes.

Understanding the satellites ability to generate a sun vector and its algorithms to change its current pointing vector is key to the overall success of the simulation. With the flight software being pre-generated, the internal algorithms the ADCS board uses to both determine its attitude and change it appropriately are already created. This allows for a testbed to connect directly into the pre-established software without relying on additional modeling in the simulation.

Because of the work of the customer and earlier groups[6], a rudimentary simulation, created in Matlab and SimuLink, has already been created. So far, the model outputs the position, solar vector, spacecraft attitude vector, and magnetic field, but they need to have increased accuracy to represent the true performance. The project will use this simulation as a starting point in creating a more advanced and accurate model, and allow it to communicate with the ADCS board. With the customer's proximity to this project, their help will be invaluable to the success of the testbed, and understanding of the challenges ahead.

3 Specific Objectives

The primary project deliverable is an interface board. Thus, the project must provide a tested and verified interface board that will: a) Send the simulated sensor input into the customer's ADCS board, b) Record the voltage output of the three magnetorquers, and c) Communicate with the customer's board in its native frequency and format. Additional objectives include designing and building a motor-driven turn table that has stepping capabilities of ± 1 degree, and creating an apparatus to allow a 1-3U CubeSat to hang suspended in a Helmholtz cage. For the motor-driven turn table, the main deliverable is to have an accurate enough step in its rotation such that accuracy is constantly held to ±1 degree, regardless of how many individual steps take place. The main deliverable of the Helmholtz cage is to design an apparatus such that the CubeSat's own ADCS will allow it to turn, as opposed to relying on an external actuator.

	Software	**Interface Board**	**Testing Apparatus**
Level 1:	• Create software for embedded components on interface board that controls the flow of data from simulation to ADCS • Create software that translates simulation data into sensor data to be sent to interface board via USB • Create software that logs magnetorquer output signal to a file	• Create an interface board that converts digital sun sensor values to analog voltages to be sent to the ADCS • Create an interface board that controls flow of digital sensor data to ADCS using an embedded microcontroller • Interface and ADCS board will be powered by a lab power supply • Computer and interface board will communicate over USB and include provisions to power everything over USB (at the flip of a switch) in future board revisions • Interface board will convert the magnetorquer pulse width modulation (PWM) signals into analog voltages then into digital signals that can be sent back to the computer via USB	• Create a motor driven turn table that has stepping capabilities of ±1 degree accuracy in its rotation • Motor should be able to turn up to TBD kilograms
Level 2:	• Add a graphical user interface (GUI) that allows the user to interact with and control the simulation • Feed magnetorquer output back into simulation for open loop testing • Log CubeSat simulated dynamics so the QB50 team can analyze performance	• Increase interface board efficiency to meet USB power delivery specifications so that the interface and ADCS board can be powered over USB	• Create an apparatus that allows a 1U, 2U, or 3U CubeSat to move with 1 degree of freedom (DoF) in a TBD Helmholtz cage
Level 3:	• Add GUI ability to over-ride simulated sensor output to user defined values	N/A	N/A

4 Functional Requirements

There will be multiple systems created in order to serve the overall goal of building confidence in the attitude determination and control system. These will include an interface board, a sun sensor calibration table, and a suspension system that will allow a satellite to rotate with one degree of freedom.

The most significant aspect is the electronic board that will interface between the customer's simulation and the satellite's ADCS board. This interface board will allow the customer to assess the functionality of the satellite's ADCS system by convincing the satellite sensors that they are in space. The customer will then determine how well the ADCS board responds to simulated inputs using data we record. This is done by analyzing the signal sent from the ADCS board to the torque rods, which is sent via a Pulse Width Modulation (PWM) signal. The goal of this analysis is to convert the signal sent from the ADCS board from the PWM signal to a torque which can be interpreted by the customer simulation.

The next most important aspect will be the sun sensor calibration system. This system will be composed of a platform which can turn very accurately at the customer's command, a light source to serve as the Sun, software that will allow the customer to control and view the position, and electronics to communicate between the software and a motor.

Also, as a higher level requirement, we will provide the customer with the ability to test the QB50 Satellite's hardware by suspending it in a Helmholtz cage. This cage will cancel out Earth's magnetic field[5], and create its own, to simulate the conditions at 300 - 400 km Earth altitude. This suspension system will allow the CubeSat to rotate with one degree of freedom to assess the functionality of the satellite's hardware, mainly the torque rods and magnetic field sensors.

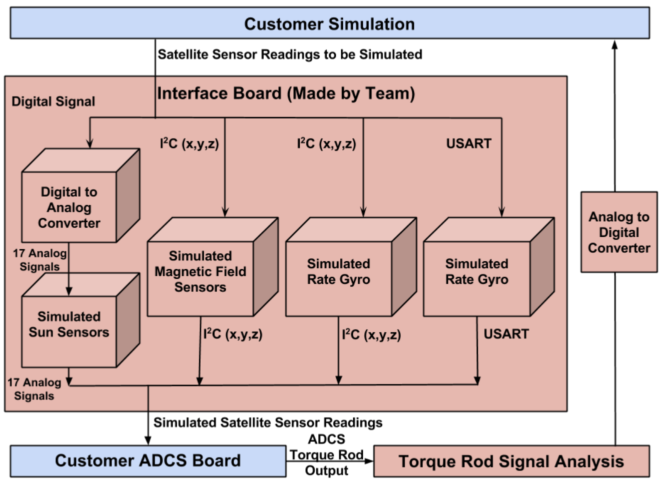

Figure 1: Functional Block Diagram for Interface Board

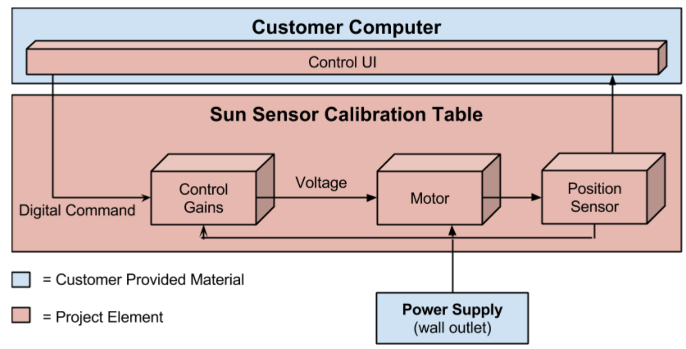

Figure 2: Functional Block Diagram for the Sun Sensor Calibration Table

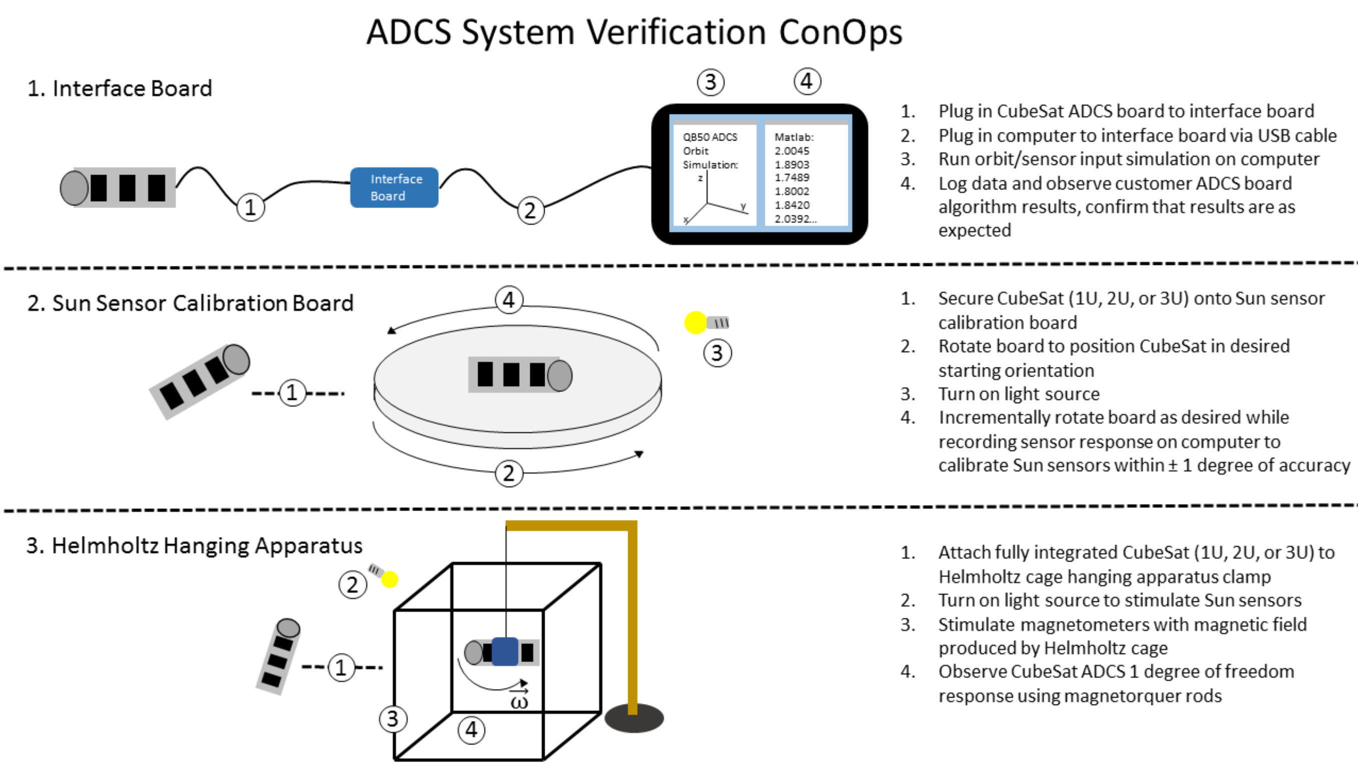

Figure 3: Concept of Operations

5 Critical Project Elements

5.1 An interface board must be created to handle all data communication between the Matlab/Simulink simulation running on a computer and the QB50 ADCS. The board must communicate with the computer by USB and incorporate an embedded microcontroller that handles digital data delivery to the ADCS. Digital sun sensor data will also have to be converted to analog voltages using a digital-to-analog converter. The PWM output signals for the magnetorquers will also be converted to an analog voltage then to a digital signal to be sent back to the computer via USB. This will be particularly difficult because it is a complex electronics project (an area where none of our members have extensive expertise) and because it is an element dealing exclusively with interfaces (an area where many projects fail).

5.1.1 Interface board must be tested to verify data transfer between simulation and the customer's ADCS board is correct. If incorrect data is being sent, than the response of the torque rods are meaningless.

5.1.2 The interface board must communicate between the simulation and the ADCS board at the necessary frequencies. If the two are not talking at the correct rates, then the board may experience buffer errors or dropped data points.

5.2 Code must be written that will allow data from the simulation to be sent to the interface board via USB. In order to meet the above frequency requirements, if Matlab proves too slow, the code will have to be re-written into a lower-level programming language. This is critical because any errors or failure in the firmware will make the interface board significantly less useful, if not useless.

5.3 A suspension apparatus must be built for the satellite which will allow it to rotate about 1 axis using its magnetorquers. Because the CubeSat will be in a non-micro gravity environment, its weight will cause a significant amount of friction. Also, the magnetorquers can only produce about 0.1 A-m^2, meaning the resistance in the bearing must be low enough to allow for this torque to rotate the CubeSat.

5.4 A motorized turn table must be built that can be controlled via computer, support 1U, 2U, and 3U CubeSats, and has stepping accuracy of 1 degree. This is particularly difficult because it involves very precise hardware (including accurate motors which may be expensive), additional electronics, and additional firmware.

6 Team Skills and Interests

The following team skills and interested are listed below in concordance with the Critical Project Elements. Team member skills are denoted with an (s), and interest is denoted with an (i).

Project Elements	**Team Members and Associated Skills and Interest**
Electronics and Embedded Systems	• Colin (s,i): Some experience building and testing Arduino boards. Currently enrolled in the Microavionics course. • Dylan (s,i): Experience designing, populating (through hole and surface mount), and testing printed circuit boards. Currently enrolled in Microavionics. • Matt (s,i): Enrolled in Microavionics. Worked with Arduinos in Gateway and Space Grant. • Nick (i): Understands circuits. • Nathan (s): Understands basic circuit operation, experience in testing and constructing circuits and circuit boards. • Cole (i): Experience with basic circuit design and operation.
Software	• Colin (s): Experience coding in Perl, creating scripts for satellite actions in CCL, developing user interfaces in Matlab. • Dylan (s): Experience with Matlab performing data acquisition and designing graphical user interfaces. Also has knowledge of C++. • Sasanka (s,i): Experience in MatLab and Simulink programming, software user interfacing and C programming. • Matt (s,i): Experience in C++, Java, MATLAB, python, VBA • Nick (s,i): MATLAB, Simulink, and Java experience. Could do LABVIEW. • Nathan (s): Experience in MATLAB, simulink, C, C++, and Java • Cole (s): Experience in MATLAB and Simulink programming and modeling.

Manufacturing and Prototyping	• Colin (s): Experience in SolidWorks, going through the manufacturing processes and working in machine shops. • Nick (s): Can use laser cutter, SolidWorks, AutoCAD, Revit, and basic machine shop equipment. • Nathan (s,i): Experience with SolidWorks, SolidCAM, CNC machines, Bandsaws, Welding Equipment, Grinders, Lathes, and in professional machine shops in general • Cole (s): Experience with machine shop equipment and manufacturing processes.
Testing	• Colin (s): Experience in testing software for failure, analyzing failure modes, and iterating on initial designs • Sasanka (s,i): Software testing and troubleshooting. • Matt (s): Debugged and updated old simulations and did performance analysis • Nathan (s): Significant professional experience with vibration testing Experience in debugging software, electronics testing, and material strength testing

7 Resources

Project Elements	Resources
Electronics and Embedded Systems	• Project team has access Altium for printing circuit boards • Knowledgeable People: Trudy Schwarts, Bobby Hodgkinson, Dr. Weibel, Dr. Chu
Software	• Matlab/SimuLink software development has already started on a sensor input simulation by the graduate students involved with the project. • Knowledgeable People: Trudy Schwartz, Bobby Hodgkinson, Dr. Frew, Dr. Scheeres
Manufacturing and Prototyping	• Access to ASEN machine shop • Knowledgeable People: Trudy Schwartz, Bobby Hodgkinson, Matt Rhodes
Attitude Determination and Control Systems	• ADCS algorithms have already been written for the QB50 CubeSat • Knowledgeable People: Andrew Hadir, Nick Rainville, Scott Palo, and Dr. Schaub
Testing	• Knowledgeable People: Trudy Schwartz, Bobby Hodgkinson

8 References

[1] Clyde Space. ”CubeSat ADCS Testbed.” YouTube. YouTube, 23 May 2014. Web. 14 Sept. 2015.

[2] Farhat, Assaad, Jighjigh Ivase, and Ye Lu. Attitude Determination and Control System for CubeSat. Tech. Worcester: Worester Polytechnic Institute, 2013. Print.

[3] Meissner, David M., Marcello Romano, and Riccardo Bevilacqua. A Three Degrees of Freedom Test Bed for Nanosatellite and CubeSat Attitude Dynamics, Determination, and Control. Tech. Monterey, California: Naval Postgraduate School, 2009. Print.

[4] Crowell, Corey W., and David W. Miller. Development and Analysis of a Small Satellite Attitude Determination and Control System Testbed. Tech. no. 02-11. Cambridge, Massachusetts: Massachusetts Institute of Technology, 2011. Print.

[5] Prinkey, Meghan K., and David W. Miller. CubeSat Attitude Control Testbed Design: Merritt 4-Coil per Axis Helmholtz Cage and Spherical Air Bearing. Tech. Cambridge, Massachusetts: Massachusetts Institute of Technology, 2013. Print.

[6] Palo, Scott. Challenger QB50 CubeSat (US01): Senior Project Idea. Boulder, Colorado: University of Colorado, 2015.