University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Conceptual Design Document (CDD)
QB50 ADCS Testbed

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Approvals

Position	Name	Affiliation	Approved (signature)	Date
Customer	Dr. Scott Palo	University of Colorado - Aerospace Engineering Sciences		9/28/15
Course Coordinator	Dr. James Nabity	University of Colorado - Aerospace Engineering Sciences		

Project Customers

Customer Name	Position	Email Address	Phone Number
Dr. Scott Palo	Project Customer	scott.palo@colorado.edu	(303) 492-4289
Andrew Dahir	Graduate Student	andrew.dahir@colorado.edu	
Nick Rainville	Graduate Student	nick.rainville@gmail.com	

Team Members

Member Name	Email Address	Phone Number
Colin Peterson	colin.peterson@colorado.edu	(541) 760-0378
Dylan Cooper	dylan.cooper@colorado.edu	(720) 378-3737
Nathan Eckert	nathaniel.eckert@colorado.edu	(720) 428-9862
Matt Hong	mattjoo.hong@gmail.com	(303) 868-8366
Cole Glommen	cole.glommen@colorado.edu	(719) 930-4894
Sasanka Bathula	bathula@colorado.edu	(720) 310-5053
Nicholas Andrews	nicholas.b.andrews@colorado.edu	(808) 292-3841

1 Project Description

1.1 Project Purpose

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 must hold during launch. 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. For low budget vehicles with short mission lifespans it is not possible to test launch and not acceptable to have any bugs. However, due to the low budget, a thorough testing is less likely to be done. 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 functions of the attitude determination and control system must be tested 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 elements, 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, the number of issues relating to the ADCS system will be minimized, and the system will perform as designed. In the long term, this test bed can be used for future CubeSat missions and make the ADCS test process faster and more reliable.

1.2 Project Objectives

- Develop an interface board to allow communication between a computer simulation and the customer's ADCS board. This includes sensor input for the following:

  1. 15 Coarse Sun Sensors outputting voltage
  2. Global Positioning System including X, Y, Z position and time on USART
  3. Rate Gyro on I^2C
  4. Magnetometers including X, Y, and Z magnetic field strength over I^2C

  This also includes measuring and logging the following:

  1. Voltage of the X, Y, and Z torque rods
  2. Voltage and current draw of the ADCS Board on both the 5 V line and the 3.3 V line

- Create turn table that has stepping capabilities of $\pm 0.5°$ accuracy in its rotation with a $\pm 0.5°$ repeatability

1.3 Project Concept of Operations (CONOPS)

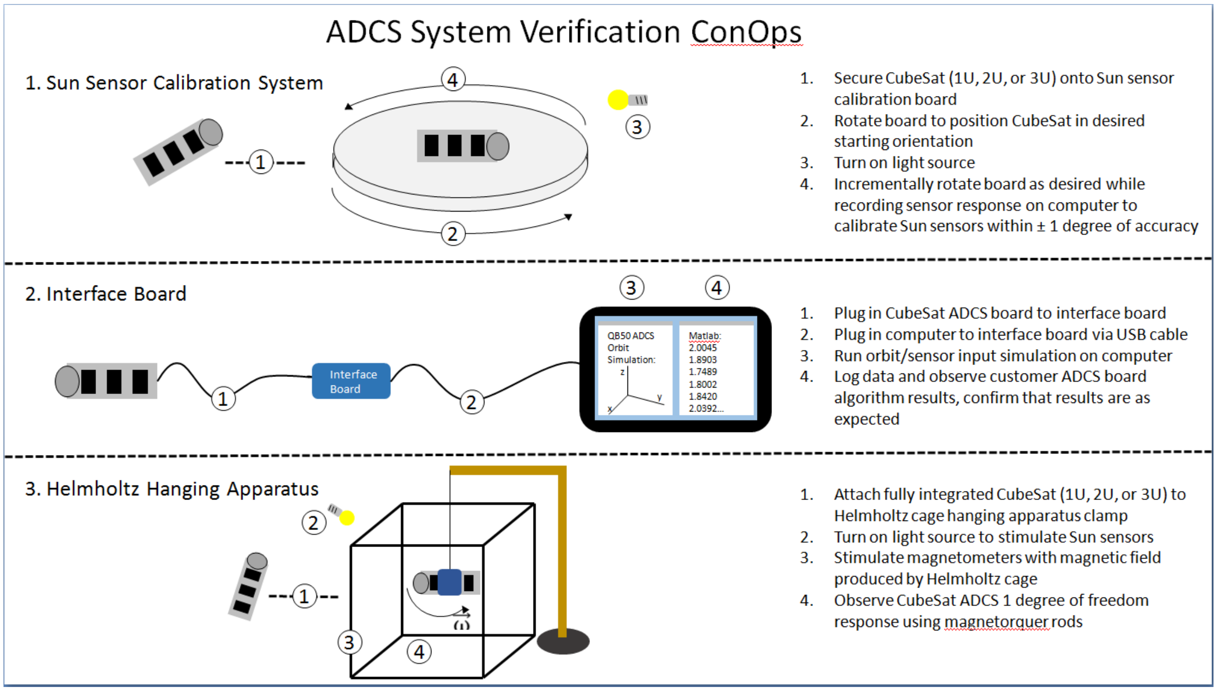

Figure 1: Concept of Operations

1.4 Functional Block Diagram

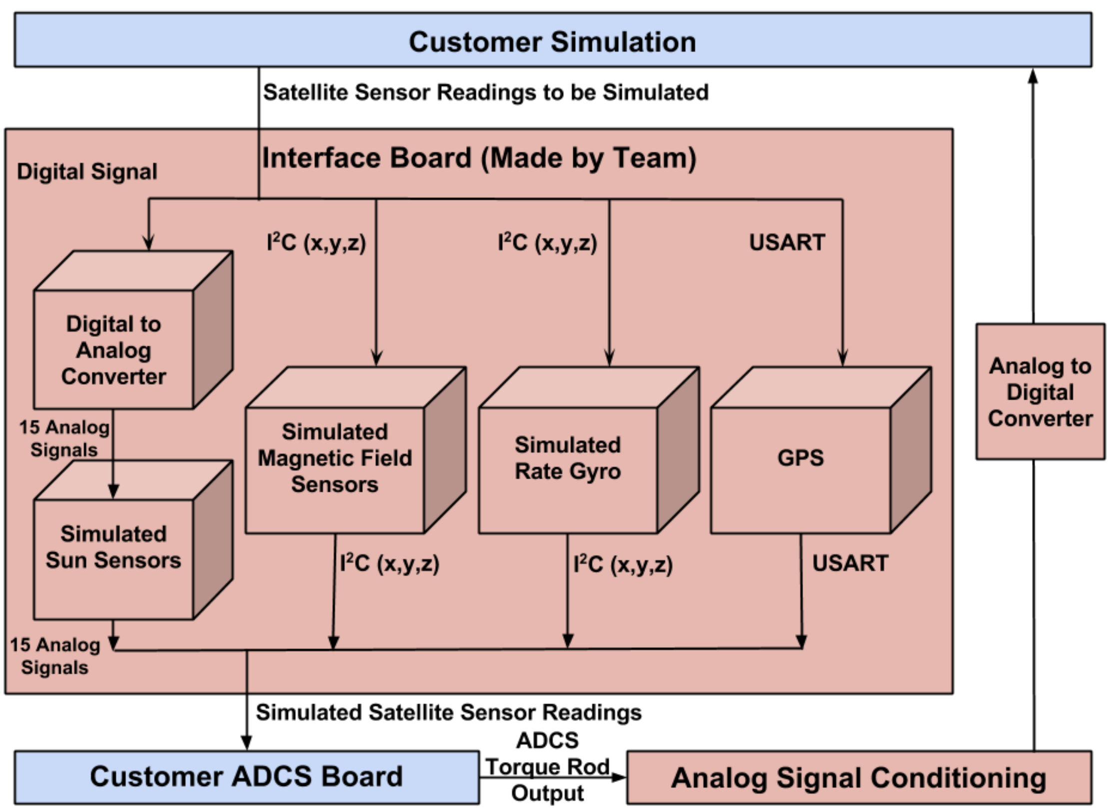

Figure 2: Functional Block Diagram for Interface Board

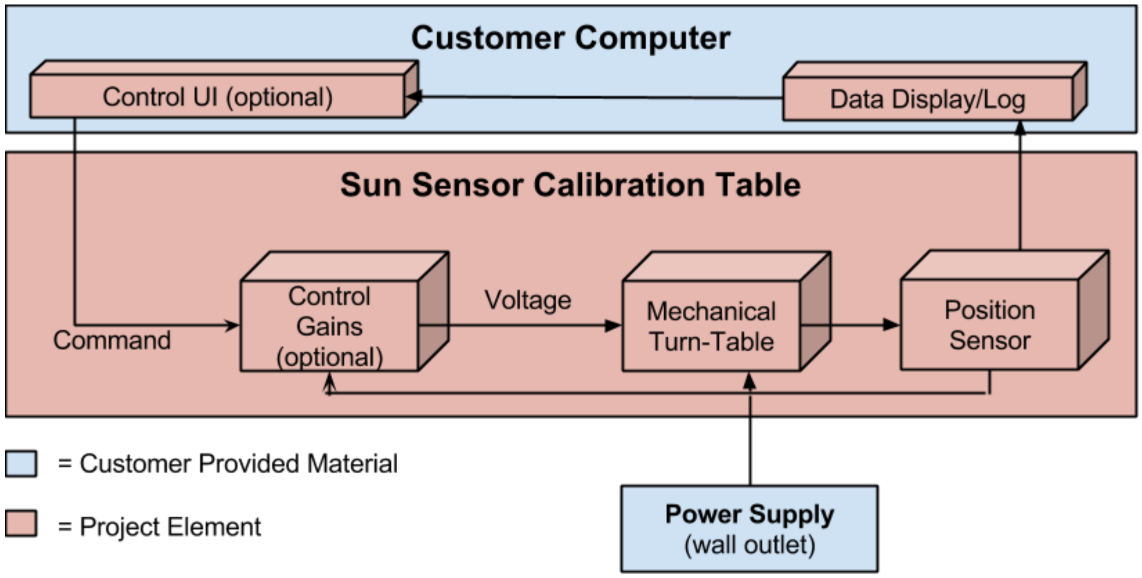

Figure 3: Functional Block Diagram for the Sun Sensor Calibration Table

2 Design Requirements

In the following design requirements table FR stands for Functional Requirement and is the highest level requirement derived directly from the customer. The next level down are the Design Requirements (DR) which are derived from the Functional Requirements.

Designation	Description	Derived From
FR.1	An interface board shall provide the means for the Matlab/Simulink simulation to communicate with the QB50 ADCS board	Customer
DR.1	The interface board shall transmit simulated sun sensor information to the ADCS board	FR.1
DR.1.1	The interface board shall convert 15 digital sun-sensor values to analog voltages	DR.1
DR.1.2	The interface board shall output analog voltages with accuracy of ±TBD volts	DR.1
DR.1.3	The interface board shall output analog voltages at a rate equal to or greater than 10Hz	DR.1
DR.2	The interface board shall transmit simulated rate gyro data, via I^2C, to the ADCS board at a rate of 10Hz or greater	FR.1
DR.3	The interface board shall transmit simulated magnetometer data, via I^2C, to the ADCS board at a rate of 10Hz or greater	FR.1
DR.4	The interface board shall transmit simulated GPS data, via USART to the ADCS board at a rate of 10Hz or greater	FR.1
DR.5	The interface board shall sample the 3 magnetorquer PWM outputs	FR.1
DR.5.1	The PWM outputs will be sampled such that the spacecraft torque generated by the magnetorquers can be calculated to an accuracy of 10% or greater	DR.5
DR.5.2	A compare, capture, and PWM (CCP) module capable of 1kHz operation shall be used to capture the PWM signals	DR.5
DR.6	The interface board shall measure the power draw of the ADCS board	FR.1
DR.6.1	The interface board shall measure the voltage and current of the individual 5V and 3.3V lines at a rate of 1kHz or greater	DR.4
DR.6.2	The interface board shall measure the voltage and current of the individual 5V and 3.3V lines with a desired accuracy of 1% and minimum accuracy of 5%	DR.4

DR.6.3	The voltage and current measurements shall be sent to the computer to be logged	DR.4
DR.7	The interface and ADCS board shall operate via USB power	FR.1
FR.2	The existing Matlab/Simulink simulation shall be modified to communicate with ADCS interface board	Customer
DR.1	The simulation shall communicate with the interface board via USB	FR.2
DR.2	The supporting simulation shall convert the magnetorquer signal to a torque value and maintain an accuracy of 10% or greater	FR.2
DR.2.1	The magnetorquer torque value shall be recorded to a file at a rate of 1kHz for the entire duration of the simulation	DR.4
DR.3	The measured voltage and current to the ADCS board shall be recorded to a file	FR.2
DR.4	A GUI shall be added to the simulation	FR.2
DR.4.1	The GUI shall allow the user to override sensor output to simulate sensor failure	DR.1
DR.5	The supporting software shall feed the magnetorquer output back into the simulation to allow for closed loop testing.	FR.2
DR.6	The supporting software shall log the simulated satellite motion computed by the customer simulation.	FR.2
FR.2	A turn table shall be delivered to the QB50 team that has resolution of 1 degree with accuracy of $\pm 0.5°$	Customer
DR.1	The turn table should have low reflectivity	FR.2
DR.1.1	The table will not have an albedo exceeding 5%	DR.1
DR.2	The table shall sense angular position and display it to the user	FR.2
DR.3	A manually operated table shall be designed such that the table motion can be automated in the future	FR.2
FR.3	A hanging apparatus shall be delivered to the QB50 team so that a CubeSat can be suspended inside their helmholtz cage with 1 DoF	Customer
DR.1	The testing apparatus shall allow for the mounting of a 1U, 2U, or 3U sized satellite	FR.3
DR.2	The testing apparatus shall allow for the support of a 1U, 2U, or 3U sized satellite	FR.3
DR.3	The testing apparatus shall not, in any way, interfere with the magnetometer sensor readings	FR.3
DR.4	The testing apparatus shall have low enough resistance/friction so that the satellite can rotate freely	FR.3
DR.4.1	The satellite shall be able to rotate up to ± 360 degrees	DR.1
DR.4.2	The resistance shall be low enough that the reaction torque does not exceed TBD N/m	DR.1

3 Key Design Options Considered

In order to thoroughly consider all possible design option, separate research was done on individual components of each deliverable. This included looking into various alternatives for interface boards and processors, analog to digital/digital to analog converters, software languages and design options for the sun sensor calibration system as well as Helmholtz cage test system.

3.1 Interface Board Processors

In order for the simulation to communicate with the customer's ADCS board, an interface board must be created. The primary challenge with this is to develop a system which can take the commanded values from the simulation and turn them into the necessary voltages that the ADCS board reads. This means that the 15 sun sensor inputs must be an analog voltage reading, the GPS must be sent through a USART line, and the rate gyro and the magnetometers must communicate through an I^2C line. For this, an electronics board processor must be used to convert said signals.

Table 1 below holds the weight table for the interface board processors. The first criteria chosen was performance, which was split into speed/frequency of processing, and power usage. This would be a major consideration, as the processor needs to have the processing speed to handle the input rate for the sensors, as well as to convert any needed values. This was considered more important than power usage, since the interface board and ADCS will initially be powered by a lab power supply and later by USB. Next, the reliability was selected to be weighted. This too was split into two components, long term usage and consistency. These were weighted equally, as we didn't want any processor that would break early on during its lifespan, or have issues with working correctly every time you tried running it. For example, setting up a program means having to set various configurations onto the processor. If for some reason power is killed to a processor and it is unable to reset correctly, some configuration might not be available for its required purpose.

The most important part of the processor would be what language it could be programmed in. This was split into two categories, the learning curve and the ease of use. The team has extensive knowledge in Matlab, so there would be a minimal learning curve for that. However, these processors tend to be programmed in C or Java, which would be a difficult language to learn comparatively. Likewise, the ease of use is important since it determines the overall difficulty of coding the actual program. Even a master of a certain language can have difficulty debugging a program or having it communicate in some way over the course of a lengthy code. Because of their importance, these two were weighted at 20% each, tying it with the available processing speed for critical elements.

Lastly, the remaining 20% was split equally between cost and support. Cost will obviously impact our project as we have limited funds. However, because the processor would be so important to this component, a large chunk of the overall funding could be used towards this purpose. This would also be based on a relative scale, as a supercomputer capable of doing everything could cost tens of thousands of dollars, but its application for this purpose is a tremendous overshoot of what is necessary. The support category is to represent the amount of on-campus or similarly nearby sources of information on any issues the processor may experience. With the large number of aerospace faculty involved in electronic projects, support for PIC and Arduino would be rather high. However, due to its difficulty, fewer resources are available for coding a field programmable gate array.

Table 1: Weight Table for Interface Board Processors

Criteria	Sub-Criteria	Percentages		Weights	
Performance	-	30%	-	0.30	-
-	Speed/Freq.	-	20%	-	0.20
-	Power	-	10%	-	0.10
Reliability	-	10%	-	0.10	-
-	Long Term	-	5%	-	0.05
-	Consistency	-	5%	-	0.15
Language	-	40%	-	0.40	-
-	Learning Curve	-	20%	-	0.20
-	Ease of Use	-	20%	-	0.20
Cost	-	10%	-	0.10	-
Support	-	10%	-	0.10	-
		100%		1.00	

3.1.1 PIC Microcontroller

PIC Microcontrollers are a family of microcontrollers developed by Microchip Technology. They originally stood for Peripheral Interface Controller, but the company has since removed the acronym. These microcontrollers are available in a massive variety, with options including the size of on-board memory, the size of bit memory, i.e. 8-bit, 16-bit, or 32-bit, and processing speed. However, since the PIC18 series of microcontrollers are being used in the Microavionics course being taught currently, this trade study will focus primarily on them. While this does not exclude other options, the overall practicality of any one given PIC microcontroller differs only slightly from one model to the other.

The PIC microcontrollers can be programmed through C, but also accept direct assembly coding. As such, they can be programmed to directly interface with the data with no extrapolation from the processor commands. This would allow for the controllers to be programmed in a way that will be both efficient and provide exact commands, meaning the data will not be manipulated in some invisible way by a program such as C. The two languages can also be used in concert with each other, allowing for general code to be used where applicable, and can be supplemented with assembly code for more direct commands.

Some of the major advantages of the PIC series is that the code is extremely efficient. This allows it to run with typically less program memory than its larger competitors. It also has a low cost for a comparatively high clock speed. Because it is also uses very low-level programming environment, it can be readily configured for each option. An additional benefit to using the PIC18s would be their ability to be coded separately. Using several different PICs would allow for an easily time configuring each input. This way, the USART line could use its own microcontroller, which would be entirely separate from the I^2C lines.

Figure 4: Example of PIC Microcontroller with kit [13]

Advantages	Disadvantages
- Efficient code requires less program memory	- Individual register size limited by 8-bit capacity
- Microavionics allows for on-campus support	- Multiple boards increases overall cost
- Team has in-depth understanding of fundamental hardware and limitations	- No single board has enough outputs for all necessary sensors

3.1.2 Arduino Boards

Arduino is both the name of the company and the overall title of what they sell; a series of open-source computer hardware and software. Arduinos are similar to the PIC microcontrollers in that they are available in a wide variety of components. The boards were originally developed for do-it-yourself kits, and being an open-source project means that there is a large community online which supports development.

The Integrated Development Environment (IDE) for the Arduino boards allows for in-depth debugging process, which can run while the Arduino itself is running the given program. It also is a cross-platform IDE, so there will be no changes between writing it in a Windows, Mac, or Linux environment. Arduino boards themselves include support for C, C++, and Java programming languages. By having several methods of programming the Arduino, the team can choose their own approach to programming based on what each board calls for.

Arduino sells dozens of individual boards. They all have a variety of processors, formats, host interface, inputs, outputs, and memory sizes, but all follow an identical IDE. Arduinos are available in several official boards, but also include options for a series of add-on expansion units called ”Shields”. These shields are pre-assembled boards which can plug into the primary board and allow for additional functionality. Shield types include board which can provide motor controls, GPS, Ethernet, LCD screens, and more. Shields can also be made by hand, and can still work with the primary board.

As mentioned earlier, there is a large community of Arduino users online. Browsing the forums reveals hundreds of thousands of posts requesting help on every aspect of the boards, ranging from programming questions to output issues to installation and troubleshooting. A particularly useful section is the ”Project Guidance” forum, which allows for anyone to post and request help or information on how to approach their project. This would be an invaluable resource, as issues with development can be asked to a community and solutions could be found in minutes, rather than needing the attention of someone on-campus. There is also a backlog of issues with already discovered solutions. If similar issues would occur, a solution could be found by a quick internet search.

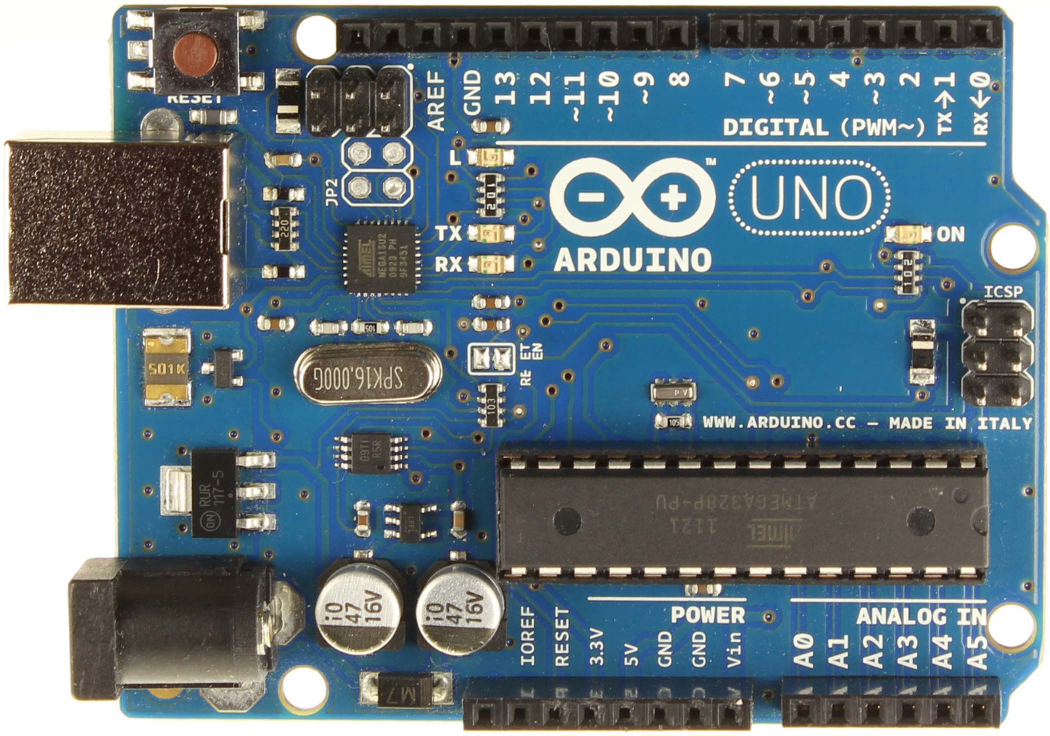

Figure 5: Arduino UNO [14]

Advantages	Disadvantages
- Company sells wide variety of individual boards - Shields allow for expandable functionality - Customer's ADCS board uses an Arduino	- Can only respond to a single I^2C address per board

3.1.3 Field Programmable Gate Array

A Field Programmable Gate Array, or FPGA, is an integrated circuit which is designed to be configured by the user after manufacturing. FPGAs contain an array of programmable logic blocks, and a hierarchy of reconfigurable interconnects which allow the blocks to be connected in different configurations.

While using FPGAs would certainly be an option, this does not come without its fair share of issues. For one, FPGAs rely on hardware description language. This is a language that is meant to program the structure, design, and operation of electronic circuits. This is the opposite of software languages, which directly interface with a processor which has a pre-generated electronic circuit.

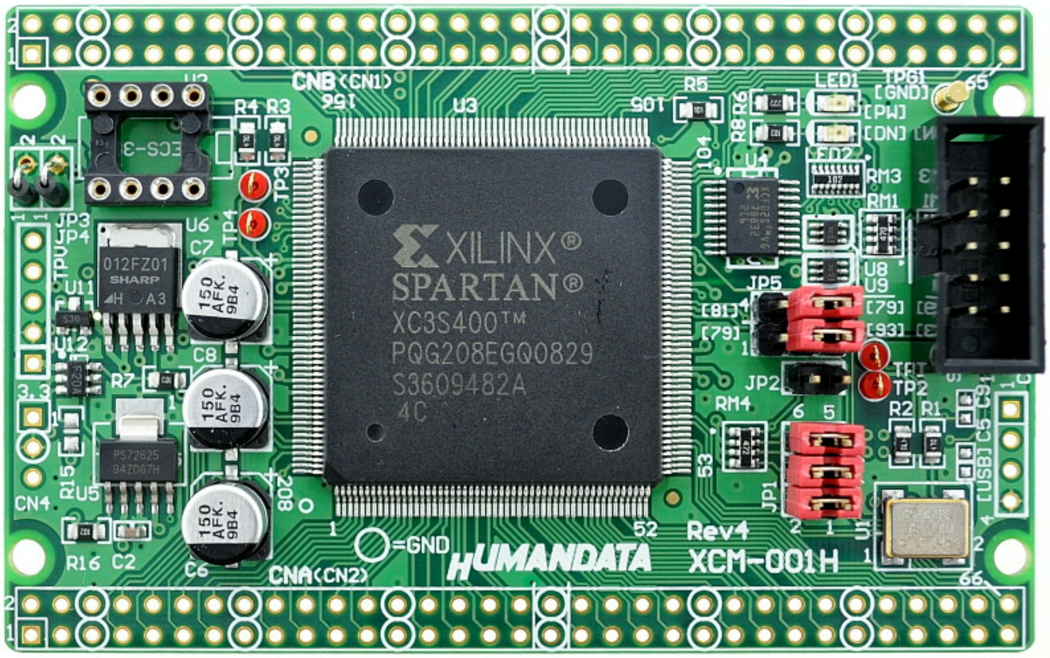

Figure 6: Example of FPGA Processor from Xilinx [15]

Advantages	**Disadvantages**
- Simulation of HDL allows for rapid prototyping	- HDL is an unknown language for the team
- Dozens of HDLs exist	- FPGAs are typically used for mass-production of a final product
- HDLs are derivatives of other languages (Python, Ruby, C, etc.)	

3.1.4 Raspberry Pi

Raspberry Pis are the general name for several small computers, which run on a Linux-based operating system. These are roughly the size of a smartphone, but have a price point of around $35. Sold as a computer in your pocket,

As opposed to the other options presented above, Raspberry Pis are not directly considered microcontrollers. Since it is a full computer, running a Linux OS, the approach to using it would be very different than the others. While programming a microcontroller would involve developing the program on another computer and then writing it to the microcontroller itself, programming the Raspberry Pi would involve both developing and writing the program directly on itself. This would allow for much more rapid testing of the software, as changes could be made on the fly.

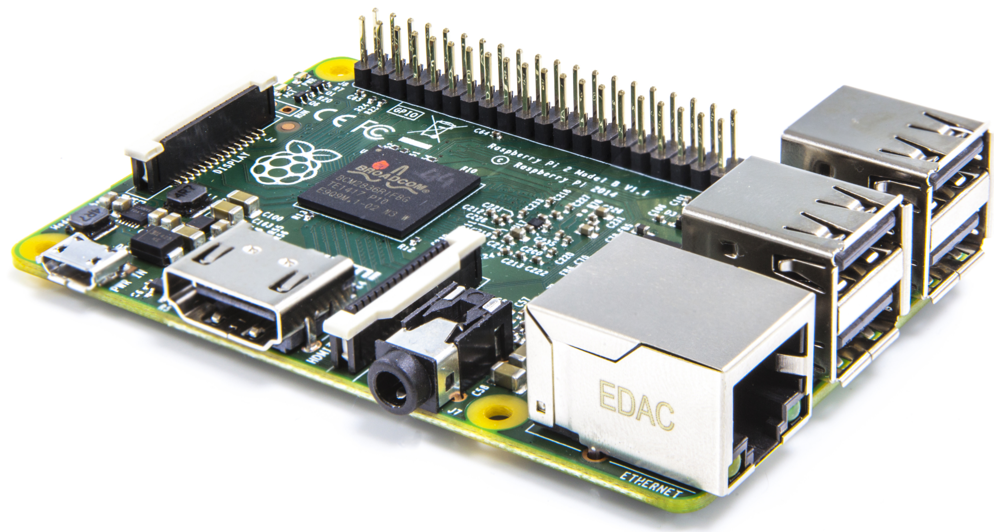

Figure 7: Raspberry Pi 2 [16]

Advantages	**Disadvantages**
- Highest processing power of all other options - USB-USB communication between Raspberry Pi and MATLAB simulation - High processing speed would allow for more accurate simulation resolution	- Meant for use as a computer, not a microcontroller - Small number of I/O ports means many Pis would be required

3.2 Analog to Digital/Digital to Analog Conversion

The QB50 uses 15 analog sun sensors. These sensors output a voltage proportional to the intensity of the light hitting them. In order for the QB50 ADCS to process this data, it must be converted to a digital signal, which is done with an analog to digital converter (ADC). Our simulation runs on a computer as digital signals, this means the simulated sun sensor data must be converted from a digital to analog signal (DAC) before it can be properly inputted to the QB50 ADCS, which is expecting an analog signal. The important criteria for digital to analog conversion are performance (resolution and sample rate), time to design, ease of use, and cost.

The first criteria chosen was performance, which was split between a resolution and a sampling rate. The resolution is much more important than the sample rate, because if the mimicked input is unable to match the resolution of the true sensor, then the test can not be considered accurate enough to mirror a true on-orbit experience. However, the sample rate is still important, as it also has to match the update rate of the sensors. The next criteria chosen was time to design, or how long it would take to implement it into the system. This was given equal weight with the overall performance, because finding a different converter, though it may be more expensive or less accurate, may take far longer to incorporate into the system and thus be an inferior option. This also ties in to the ease of use. If one converter has its own method of integration which takes several hours to set up versus another converter which can simply attach to a line and immediately start functioning, this would be non-negligible factor.

Lastly, cost was chosen as the highest weight with 40% overall. This was chosen to be the highest because of the large difference in converter cost. Equipment from one company may only cost a couple of dollars, while another company may sell another which costs several thousands of dollars. The primary difference between the two will obviously be performance, split between a resolution and a sampling rate. Given a requirement of a 10 Hz refresh rate with the electronics, there is not a need to get an incredibly powerful processor capable of several giga samples per second. While the performance is still an issue, it is factored more in to the previous criteria as opposed to the cost.

Table 2: Weight Table for Analog to Digital/Digital to Analog Conversion

Criteria	Sub-Criteria	Percentages		Weights	
Performance	-	20%	-	0.20	-
-	Resolution	-	15%	-	0.15
-	Sample Rate	-	5%	-	0.05
Time to Design	-	20%	-	0.20	-
Ease of Use	-	20%	-	0.20	-
Cost	-	40%	-	0.40	-
		100%		1.00	

3.2.1 Multifunction Data Acquisition Card

A multifunction Data Acquisition (DAQ) card is a term used to refer prebuilt data acquisition solutions, this includes PCI/PCIe, USB, and modular DAQ cards. These cards are designed to be plugged into a computer and work well with popular software (such as Matlab or LabView) and easily connect to whatever data you want to acquire. Common functionality is analog data input/output, digital input/output, and timers. These systems are easy to work with and have high performance but bring very high cost. Our project requires 15 analog outputs for the sun sensors, one popular manufacturer of DAQ cards (National Instruments) sells their cheapest USB analog output card (with 16 analog output channels) for $1,269 [8], which is 25% of our budget, and still short on analog output channel.

Figure 8: Data Acquisition cards from Elsys Instruments [19]

Advantages	**Disadvantages**
Easy to work with and interface with	Very expensive

3.2.2 Integrated Circuit Converters

Integrated Circuits (ICs) are the individual components that perform the digital to analog conversion (DAC) or analog to digital conversion (ADC). These have the major benefit of being cost effective, a typical 12-bit DAC may only be a handful of dollars [9]. The downside to using ICs is the additional board development time needed to design and implement the necessary circuits for operation.

Advantages	**Disadvantages**
Cost effective Will not be limited with bit accuracy	Requires more development time

3.3 Software & Graphical User Interface Languages

Like all projects, the right software is crucial to the success of the project. Firmware will be excluded in this section, as it will depend on our choice for the interface board. Software will be significant in 2 different aspects of the project; simulation and Graphical User Interface (GUI). The simulation is already written in MATLAB with SimuLink. A GUI will be made in order to maximize the control over the simulation of the sensors. This will include options to disable the sensor input in order to mimic what would happen with complete sensor failure. Criteria selected for the software were license, learning curve, ease of use, and compatiblity, which was split between software and hardware.

The first criteria selected was for the license. As students of the university, we would be given free access to certain programs. However, others may be limited by a fee or similar roadblock to full development. A program like Matlab with its many libraries were offered for free, while a language like C is free to develop in but doesn't have a unified environment. The next criteria selected was the learning curve of the language. Because of the potential of having to learn a whole new programming language just to communicate between the simulation and the processor, this was given a hefty weight compared to the others. Going with an easier language to learn, even if it may be more difficult to have it communicate between a computer and an input/output port, could pay off in the overall amount of time put in to it.

Tied into the learning curve and the compatibility is the ease of use. If a language is already mastered by the team but requires heavy coding just to get a simple conversion done, it may not be the easiest program to go with. Due to the incredible amounts of debugging and communication which will need to be done between the simulation and the interface board, the ease of use was given a large amount of weight. However, it does not weigh as much as the learning curve or the compatibility. Compatibility was given the highest weight, tied with learning curve, though it was split into two sections, compatibility of software and compatibility of hardware. With the simuation already being coded in a combination of Matlab and SimuLink, the GUI software would have to be able to communicate with this language in some way. Additionally, software would have to be created to communicate between the simulation and the interface board, meaning a hardware connection would have to be made. If a language has easy access to communicating over a USB or similar cable, then its benefits may outweigh its learning curve. Hardware compatibility was given precedent because of the importance of communication between the simulation and the interface board. If the GUI can interface directly with the simulation but can not transfer the data to the interface board, than it can not be considered a viable candidate.

Table 3: Weight Table for Software and GUI

Criteria	Sub-Criteria	Percentages		Weights	
License	-	5%	-	0.05	-
Learning Curve	-	35%	-	0.35	-
Ease of Use	-	25%	-	0.25	-
Compatibility	-	35%	-	0.35	-
-	Software	-	15%	-	0.15
-	Hardware	-	20%	-	0.20
		100%		1.00	

3.3.1 MATLAB Simulink

MATLAB is a programming language that has powerful computational performance great for numerical analysis. It is a language designed with simple syntax for quick computations along with a wide range of add-ons for further analysis. One of the most important add-on is SimuLink. MATLAB's SimuLink tool allows users to create simulation from a model-based design. This tool makes simulation incredibly easy for dynamic analysis.

Advantages	**Disadvantages**
High level language	Slower processing speed
Built in debugger	Not strongly compatible with hardware
Team has significant experience with language	Higher level language means less interaction with data
On-Campus faculty have huge amount of experience and support	
Can interface directly with simulation	

3.3.2 LabView

LabView is a software program created by National Instruments. Because NI does more than software, LabView was designed to have great compatibiliy with external hardware. It is considered the leader in terms of data acquisition and signal processing [21]. LabView is an unusual language that allows users to avoid conventional programming methods. Like SimuLink, coding can be done through block diagrams and models as opposed to lines of text.

Advantages	Disadvantages
Great compatibility with external hardware Great control with GUI Program has built-in compatibility with Matlab	Much harder to debug Team has less experience designing LabView programs

3.3.3 C

C may be the most powerful language yet the most difficult to use. Because it is a low level language, it will have superb performance and allow direct memory management. However, unlike MATLAB and LabView, C is not a language ”specialized” for a certain purpose. Since it has a general purpose, C is often avoided unless dealing with a wide range of back end management, like memory location and register access.

Advantages	Disadvantages
Wide range of applications Highest speed of all selected software	No common development environment Team has less experience with C programs

3.4 Sun-Sensor Calibration Turn Table

The sun sensor calibration table will be used to test the performance of the QB50 and future satellite’s sun sensors. To do this, it must allow for a 1 - 3 U CubeSat to rotate in one axis (z), while being stationary in translation and rotation in the other axes (x and y) to $\pm 0.5°$.

In developing this system both the approach and application underwent trade studies. The different approaches examine how the table will move; they decide if it will be controlled at a computer, a local control panel, or if it will be moved manually to specific angles. These different options are explained further below. Within the description of each option is a section that describes which functions could be offered. This is done to examine the capability of different options without including these functions as requirements if that option is chosen.

These options were assessed by examining how well they met the design requirements. Table reflectivity and the display of angular position are not dependent on the approach, so they were not considered with these criteria. The ability to use automated control was considered, and is mainly reflected in the ease of use criterion. To judge each approach, important criteria were decided upon, and a weighting scale was derived to quantify the relative importance of each criterion.

The first two criteria are time to design and time to make. These were examined because any solution has to be accomplished in the time available, and if these issues were not examined the project would be at more risk of not finishing. These were split up because some approaches may have more time to design than to make, or vice-versa. Also, by splitting up the two concepts a more accurate prediction of the time dependence could be found. This is because a large time dependence for time to design may be overlooked due to a small time dependence for time to make. The combined weight of these is large because it is critical that the project gets finished, and the risk of over-scoping is significant.

The next criterion was reliability. This was defined as the amount of time that the table would continue to work under normal operation. This does not consider the consistency of the table because the main differences (in means of actuation) did not vary in how consistent they would be, and the consistency of movement is significantly less concerning than consistency in sensing. This received significant weight because this table is intended to work for future projects in addition to QB50 testing, so its lifespan is of concern.

Next, ease of use was examined. This refers to how easy the table would be to operate and test with as a user. This criterion received significant weight because there was a lot of variation between the options, and the time of the users (professors and grad students) is important. Ease of use directly corresponds to how long the table takes to use, thus ease of use was found to be important.

The last criterion was cost. This option received the smallest weight because the overall cost of this project is fairly small and the largest costs would be a motor and reducing the table reflectivity. A motor (if used) would not be prohibitively expensive because it would not be under significant load, nor would it need to turn quickly. The table reflectivity is independent of the chosen approach, and thus was not a concern in examining possible approaches.

Table 4: Weight Table for Sun-Sensor Calibration Turn Table

Criteria	Sub-Criteria	Percentages		Weights	
Time to Design	-	25%	-	0.25	-
Time to Make	-	25%	-	0.25	-
Reliability	-	20%	-	0.20	-
Ease of Use	-	20%	-	0.20	-
Cost	-	10%	-	0.10	-
		100%		1.00	

3.4.1 PC Control

The table itself would have some automated control device (motor, actuator, etc.). This device would be controlled via a computer, which would run a user interface. This simple interface would allow for the user to define an angle that the table (and satellite) would point in, and the table would then execute this command. A time-history of the table attitude would be recorded and stored on the computer. It is possible to allow the table to do one full rotation, and a time history would be returned of the table's position, this feature is called a "full angle sweep". Should the automated controls fail, it would also be possible to add provisions such that the table could be manually operated to point in a specific direction.

Advantages	**Disadvantages**
- Very Easy to Use	- Design and Development time intensive (GUI, Control Loop, more overall programming)
- Motor provides redundant pointing measurement	- Accuracy dependent on time spent in developing control loops
- Allows for full angle sweep	

3.4.2 Local Control

This method would also use some form of automated control, but would not interface with a computer. Alternatively, it would have a display which would read out the current table angle. A local control panel would allow the user to rotate clockwise or counterclockwise, until the desired angle is reached. It is also possible to make the full rotation and specific angle functionality with this local control panel. Like the PC Control, should the automated controls fail, it would still be possible to add provisions such that the table could be manually operated to point in a specific direction.

Advantages	**Disadvantages**
Fairly Easy to use	Moderately time intensive
Requires less development than a PC Control System	Still requires motor
Motor provides redundant pointing measurement	Does not allow for a full angle sweep
	Less easy to use than a PC Control System

3.4.3 Manual Control

This is the most simple method. It would use a form of ratchet system to ensure the user is able to move the table to a specific angle, and a lock that would keep the table pointed in that direction. This option would not allow for a full angle sweep at a constant angular velocity.

Advantages	**Disadvantages**
Fairly Easy to Use	Requires user to provide movement
Requires much less development time	No redundant pointing measurement
	Movement is less accurate (takes more time to find a specific angle)
	Does not allow for full angle sweep

3.4.4 Types of Motor Control

- Rotary Motor: A rotational motor will be used to impart the rotary force on the tabletop.
  - Direct Control: The tabletop shaft is mounted directly above the motor shaft, and these are coupled. This means the motor would have to be controlled with enough accuracy to land on the desired angle directly.

Advantages	Disadvantages
Mechanically simple	Requires precise motor
Can do full angle sweeps	Requires precise control laws to point in the correct orientation

– Indirect Control: The tabletop shaft is rotated using a gear or belt assembly, which is powered by the motor. This allows for the use of gears, which can reduce the need for very accurate control and motor response.

Advantages	Disadvantages
Can be very accurate without thorough control law development or precise motor	Mechanically complex
Can do full angle sweeps slowly (with higher resolution)	

- Linear Actuator: A linear actuator would be used to push a specific location of the tabletop a specified amount. This could be done somewhat far from the axis of rotation to allow for smaller step sizes, but would require the actuator cycling in and out multiple times to fully turn the tabletop.

Advantages	Disadvantages
Can be very accurate without thorough control law development or precise motor	Mechanically Complex
Can do full angle sweeps slowly, and at distinct intervals	Operates slowly

3.5 Types of Angular Position Sensor

The angular position sensor is the most important part of the sun-sensor calibration turn table because it must be able to measure within the customer's specified $\pm 0.5°$ accuracy. The two primary options for sensors are a potentiometer or an optical encoder. Both solutions have the capability to measure well beyond the customer's requirements but vary significantly in cost, life cycle, and integration capabilities. The advantages and disadvantages of the two solutions were weighed and compared in a trade study. We put the most weight into accuracy because the customer specified that the sensor must have a $\pm 0.5°$ accuracy, if this is not fulfilled then the Sun-sensor calibration test will be faulty. We gave software/electronics integration the next highest weight because the customer wants to be able to log the data. We gave cost a 20% weight because some of the sensors cost at least a couple hundred dollars. Life cycles and ease of use were additional factors that were considered.

Table 5: Weight Table for Types of Angular Position Sensor

Criteria	Sub-Criteria	Percentages		Weights	
Accuracy	-	40%	-	0.40	-
Integration	-	25%	-	0.25	-
Life Cycle	-	5%	-	0.05	-
Ease of Use	-	10%	-	0.10	-
Cost	-	20%	-	0.20	-
		100%		1.00	

3.5.1 Potentiometer

A potentiometer measures an internal resistance and outputs a voltage linearly proportional to the angular displacement. A potentiometer has an infinite resolution but loses it's accuracy when converting from voltage to angular position. They cost less than $100 and come in a variety of sizes. On the down side potentiometers require a fair amount of electronics work to operate, can't distinguish turn direction, can't rotate more than 360°, and have a medium length life cycle of roughly 5 million cycles.

Advantages	Disadvantages
Cheap	High amount of electronics work
Infinite resolution	Cannot differentiate turn direction
Wide variety of options	Medium to low life cycle

3.5.2 Optical Encoder

An optical encoder measures angular position based on a pattern inscribed on the disk inside of the encoder. This means that the encoder outputs the absolute angular displacement measurement without needing to convert from voltage. In addition, an optical encoder can differentiate rotation direction and can easily be integrated with software. A typical life cycle of an optical encoder is around 10 million cycles. High quality optical encoders typically cost around $500. The price is highly dependent on the number of bits/resolution of the encoder.

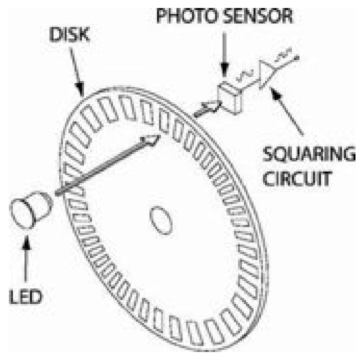

Figure 9: Diagram of Optical Encoder functionality [20]

Advantages	Disadvantages
Outputs absolute measurement Easy to work with Can distinguish rotation direction	Expensive Need enough bits to fulfill customer precision requirement of $\pm 0.5°$

3.6 Helmholtz Cage Suspension Method

The Helmholtz cage testing structure will allow the QB50 team to perform a one degree of freedom rotation test on the flight ready CubeSat. The testing structure will suspend the CubeSat in the Helmholtz cage and allow it to rotate with minimal resistance. Translation motion will be inhibited by securing the CubeSat to a clamp. The clamp will also balance the mass distribution of the CubeSat during testing and secure the CubeSat from getting dropped or damaged during testing. Four solutions were considered and compared via trade study: magnetic levitation, mechanical bearing, air bearing, and hanging by string. Table 6 is the weight table used in the trade study for the four potential solutions. We put the most weight into the resistance criteria because a low resistance is essential for the customer and if the resistance is not low the entire Helmholtz cage test is meaningless. Time to make had the second highest weight because some of the solutions might be machine shop intensive and require more time than available during the length of the senior projects course. We gave additional components and ease of use equal weights because the customer desires a solution that is easy to use and can stand alone without extensive preparation and additional components. Time to design and cost are additional factors that we considered for the trade study weighting.

Table 6: Weight Table for Helmholtz Cage Suspension Method

Criteria	Sub-Criteria	Percentages		Ratios	
Resistance	-	30%	-	0.30	-
Time to Design	-	10%	-	0.10	-
Time to Make	-	20%	-	0.20	-
Additional Components	-	15%	-	0.15	-
Ease of Use	-	15%	-	0.15	-
Cost	-	10%	-	0.10	-
		100%		1.00	

3.6.1 Magnetic Levitation

Magnetic levitation was considered because it would ideally have zero rotational resistance during testing. However, magnetic levitation would require an extensive amount of work to prohibit translational movement and prevent interaction with the magnetic field of the Helmholtz cage. In addition, magnetic levitation may require a power supply for electromagnets if traditional magnets are not strong enough to suspend the CubeSat.

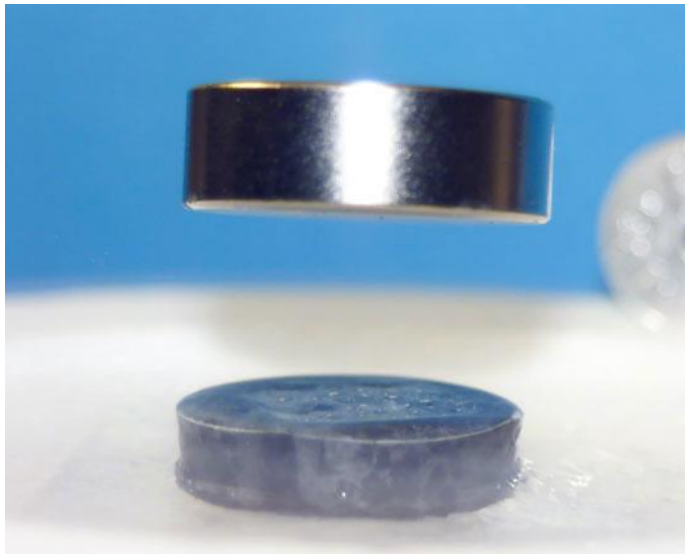

Figure 10: Example of magnetic levitation [17]

Advantages	Disadvantages
Ideally zero resistance	Potential interference with Helmholtz cage magnetic field Complicated to design Could require additional power supply

3.6.2 Mechanical Bearing

A mechanical bearing would have the highest resistance of the four solutions but has the potential to decrease it's resistance significantly depending on how much money we invest. A typical high quality ceramic bearing starts at about $300. This solution would be the easiest to work with and offers a variety of sub-solutions depending on if the CubeSat is supported from the top or bottom. However, the mechanical bearing would frequently require maintenance and lubrication to maintain its optimal performance.

Figure 11: Example of a mechanical bearing [18]

Advantages	Disadvantages
Easy to work with Variety of ways to integrate bearing	Requires constant maintenance Can get expensive

3.6.3 Air Bearing

An air bearing system would have a very low rotational resistance and has the potential to be compact, making it easy to integrate with the Helmholtz cage. Similar to the magnetic bearing solution, an air bearing system would be difficult to design to prevent translational movement. In addition, air bearings introduce additional disturbances and require a supply of compressed air.

Advantages	Disadvantages
Very low resistance Compact and easy to fit into Helmholtz cage	Requires compressed air source Difficult to design Introduces additional disturbances

3.6.4 Hanging

The hanging by string solution is the simplest and cheapest of the four solutions. This solution would suspend the CubeSat from a high suspension fixture, minimizing rotational resistance. In addition to the string a suspension support structure and CubeSat clamp will need to be built to balance the mass and safely secure the CubeSat. The main disadvantage of the hanging solution is that testing cannot take place in the lab because there is no where high enough to hang the CubeSat, this in turn means that the Helmholtz cage will have to become mobile.

Advantages	Disadvantages
Cheap Simple to design and build	Need high suspension fixture Helmholtz cage must be mobile Requires clamp and support structure

4 Trade Study Process and Results

4.1 Interface Board Processors

Summary Matrix			PIC		Arduino		FPGA		Ras Pi	
Criteria	Sub-Criteria	Weight	Raw Score	Weighted Score	Raw Score	Weighted Score	Raw Score	Weighted Score	Raw Score	Weighted Score
Performance	-	30%	-	-	-	-	-	-	-	-
	Speed/Frequency	20%	3	0.60	3	0.60	5	1.00	4	0.80
	Power Use	10%	3	0.30	4	0.40	5	0.50	2	0.20
Reliability	-	10%	-	-	-	-	-	-	-	-
	Long Term Use	5%	5	0.25	5	0.25	5	0.25	5	0.25
	Consistency	5%	4	0.20	4	0.20	5	0.25	4	0.20
Language	-	40%	-	-	-	-	-	-	-	-
	Learning Curve	20%	4	0.80	4	0.80	1	0.20	3	0.60
	Ease of Use	20%	4	0.80	5	1.00	1	0.20	3	0.60
Cost	-	10%	5	0.50	4	0.40	5	0.50	4	0.40
Support	-	10%	5	0.50	4	0.40	2	0.20	3	0.30
TOTAL			-	3.95	-	4.05	-	3.10	-	3.35

4.2 Analog/Digital Conversion

Summary Matrix			DAQ		IC Component	
Criteria	Sub-Criteria	Weight	Raw Score	Weighted Score	Raw Score	Weighted Score
Performance	-	20%	-	-	-	-
	Resolution	15%	5	0.75	3	0.45
	Sample Rate	5%	5	0.25	3	0.15
Time to Design	-	20%	4	0.80	2	0.40
Ease of Use	-	20%	3	0.60	4	0.80
Cost	-	40%	1	0.40	5	2.00
TOTAL			-	2.80	-	3.80

4.3 GUI

Summary Matrix			Matlab		LabView		C	
Criteria	Sub-Criteria	Weight	Weighted Score	Raw Score	Weighted Score	Raw Score	Weighted Score	Weighted Score
License	-	5%	5	0.25	2	0.10	4	0.20
Learning Curve	-	35%	5	1.75	4	1.40	3	1.05
Compatibility	-	35%	-	-	-	-	-	-
-	Software	15%	5	0.75	4	0.60	3	0.45
-	Hardware	20%	4	0.80	5	1.00	3	0.60
Ease of Use	-	25%	4	1.00	4	1.00	2	0.50
TOTAL			-	4.55	-	4.10	-	2.80

4.4 Sun-Sensor Calibration - Rotational Input

Summary Matrix		Manual		Semi-Manual		PC	
Criteria	Weight	Raw Score	Weighted Score	Raw Score	Weighted Score	Raw Score	Weighted Score
Time to Design	25%	5	1.25	3	0.75	2	0.50
Time to Make	25%	4	1.00	3	0.75	1	0.25
Reliability	20%	5	1.00	4	0.80	2	0.40
Ease of Use	20%	2	0.40	4	0.80	5	1.00
Cost	10%	5	0.50	3	0.30	2	0.20
TOTAL		-	4.15	-	3.40	-	2.35

4.5 Sun-Sensor Calibration - Angular Position Sensor

Summary Matrix		Potentiometer		Optical Encoder	
Criteria	Weight	Raw Score	Weighted Score	Raw Score	Weighted Score
Accuracy	40%	4	1.60	4	1.60
Integration	25%	3	0.75	5	1.25
Life Cycle	5%	3	0.15	5	0.25
Ease of Use	10%	3	0.30	5	0.50
Cost	20%	5	1.00	3	0.60
TOTAL		-	3.80	-	4.20

4.6 Helmholtz Cage Suspension

Summary Matrix		Magnetic Levitation		Mechanical Bearing		Hanging		Air Bearing	
Criteria	Weight	Raw Score	Weighted Score	Raw Score	Weighted Score	Raw Score	Weighted Score	Raw Score	Weighted Score
Resistance	30%	5	1.50	3	0.90	4	1.20	3	0.90
Time to Design	10%	2	0.20	4	0.40	3	0.30	2	0.20
Time to Make	20%	3	0.60	4	0.80	4	0.80	2	0.40
Additional Components	15%	3	0.45	5	0.75	4	0.60	2	0.30
Ease of Use	15%	4	0.60	5	0.75	2	0.30	3	0.45
Cost	10%	3	0.30	3	0.30	5	0.50	2	0.20
TOTAL		-	3.65	-	3.90	-	3.70	-	2.45

5 Selection of Baseline Design

We were able to reduce our options to a baseline design by performing trade studies on each of the possible solutions to the key design components. For the interface board processors we will be carrying forward both PIC and Arduino options. The trade study was too close to declare a definite better option, and since neither option will be a significant financial setback, we will consider both as solutions. For the analog/digital conversion we have decided to use an IC component primarily because of it's ease of use and low cost. For a graphical user interface, we will be using Matlab because the team has significant experience with it and it is more common than LabView. This also has the additional benefit of being able to communicate directly with the simulation, instead of going through an additional channel. We will design the Sun-sensor calibration rotational input to be manually driven but with the potential to have a motor integrated later. We chose manual operation because of it's time to design, time to make and overall cost. The customer specified that if we chose manual rotation then it must have the capability for a motor to be installed. We have chosen to use an optical encoder to measure angular position because of it's simplicity and ease of use. Lastly, we will be carrying forward both mechanical bearing and hanging as solutions to the Helmholtz cage suspension. Both will require further rotational resistance analysis and comparison. Although magnetic levitation had a close total score we eliminated it because of the analysis that would be involved to convince the customer that it was not interfering with the magnetic field of the Helmholtz cage.

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.

[7] "Arduino - Products." Arduino - Products. N.p., n.d. Web. 28 Sept. 2015.

[8] "NI 9264 Measurement System 16 Ch Voltage Output Module for USB, Ethernet, or Wi-Fi." NI 9264 Measurement System. N.p., n.d. Web. 28 Sept. 2015.

[9] "Rohm Semiconductor BH2221FV-E2." Digikey. N.p., n.d. Web. 28 Sept. 2015.

[10] "Www.vxb.com." Www.vxb.com. N.p., n.d. Web. 28 Sept. 2015.

[11] "Rotary Encoders – Understanding for Practical Implementation - Electro-Labs.com." Electro-Labs.com. N.p., 24 Jan. 2014. Web. 28 Sept. 2015.

[12] "Potentiometers: A Proven Position Sensing Solution That Every Engineer Needs to Consider in Modern Designs." Potentiometers: A Proven Position Sensing Solution That Every Engineer Needs to Consider in Modern Designs. N.p., n.d. Web. 28 Sept. 2015.

[13] http://3.imimg.com/data3/VQ/JH/MY-3187696/pic-development-kit-500x500.jpg

[14] http://files.tested.com/photos/2013/06/12/48912-arduinouno_r3_front.jpg

[15] http://www.hdl.co.jp/XCM-001/top.800.jpg

[16] https://www.raspberrypi.org/wp-content/uploads/2015/01/Pi2ModB1GB_-comp.jpeg

[17] http://ffden-2.phys.uaf.edu/212_fall2009.web/Wendy_Presler/magnetic_levitation.jpg

[18] http://static.filmannex.com/users/galleries/294836/Deep-Groove-Ball-Bearing_fa_rszd.jpg

[19] http://www.elsys-instruments.com/images/tpcx_banner.jpg

[20] http://www.sayedsaad.com/montada/imgcache/4836.imgcache

[21] http://annals.fih.upt.ro/pdf-full/2012/ANNALS-2012-3-68.pdf