NASA Solar Panel Design

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Design Document

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Executive Summary

Software based

Our project has a PLC that will be mounted internally and will control all the operations needed in order to deploy the boom. This consists of a motor that will deploy and retract the boom and a roll of solar cells. The PLC will also control multiple sensors and possibly a torque sensor. The PLC will also be able to interpret the signals sent to it that say whether the boom is to be deployed, retracted or held in place in what we call a stop function. This PLC will be the only control center we need because it has the capability to control much more than even what we need it for.

Hardware based

The hardware used on this design consists of a roll-out, tape measure inspired boom that will give steady support to the solar cells that we deploy. This design is very compact and will allow for the smallest amount of space used when stowed while also giving us the greatest amount of extended reach when fully deployed.

Next we have the roll of solar cells that will be geared with the boom to ensure they deploy and retract at the same speed so we can lower the chance of damaging the solar cells once in space.

To tell the motor when to stop deploying or retracting we have two sensors that will be contact switches, which will make contact either when the boom is fully deployed or when the boom is fully retracted and send a signal to the PLC to stop all motion.

Next there is the torque sensor which will tell us if the motor is binding up anywhere and will allow us to stop the motor from continuing its operation and save the cells from damage. This sensor may be replaced with a controller at a future date due to the small size of a controller. The controller can measure the amount of current needed to operate the motor and if the current spikes then we know the system is binding somewhere. This option would also save space and be more versatile.

Lastly we have the cube-sat which is the box in which all of these components are stored during launch. This box is either going to be 10cm x 10cm x 10cm (1U) or 10cm x 20cm x 10cm (2U), limiting the amount of room we have and the amount of ways we will be able to configure how components fit and will work together.

System Design

System Description

Our goal with this project was to be able to deploy a certain area of flexible solar panels with a system that would also be as compact and lightweight as possible when retracted. How we were to accomplish this was left entirely up to us.

We considered a few different types of designs, and initially ended up going with a scissor-jack type boom. Compared to other designs we looked at, it will allow the biggest change in size between its retracted and extended states. This is important since on a spacecraft, small size and low weight is always a plus, and with solar panels, having a large surface area is important since the more area exposed to the sun, the more power generated. However, this design was intended for when we were initially told we would need to create a boom that could support between 4 and 9 square feet of solar panels and fold down into a volume of around 1 cubic foot. A little more than halfway through the semester we were told that in fact that was a mistake. The actual design requirements stated that we needed to design a system that could repeatedly deploy and retract at least a square meter of solar panel from a 1U (10x10x10 cm) cube. We had a few meeting where we tried to figure out ways to adapt the scissor-jack design to these new restraints, but quickly realized that it just wasn't going to work. We looked at using umbrella type designs that would unfold the solar panels like an umbrella or the petals of a flower, but we couldn't find a design that would give us enough surface area. Instead, we went with a tape-measure like design.

The new current design fits inside the 1U space we have and actually leaves some empty space inside. The panels will be rolled up onto a 5cm cylinder that will be almost the full length of the inside of the box when retracted. When deployed, two curved metal rolls will unfurl via an electric motor. They will be attached to a rigid bar at the end of the solar panel, and will pull the panel out to its full length of around 12 feet (3.7 meters). Having two of them (one on each side) will provide enough strength to deploy the panel in microgravity to its maximum extended length, and nearly all of that here on Earth. The roll the panels are wrapped around when stored is spring loaded with a constant force spring so that when the metal tapes are retracted the solar panel is pulled tautly back around the cylinder so it doesn't get caught and foul up the mechanism. Because reliability and low power use are paramount in this project, we needed to find a way to make sure the boom and solar panels would stay deployed when extended. Since the panels are going to be spring-loaded, they're natural state is to be retracted. This means they'll stay retracted on their own, but that also means when they're extended either the motor will have to stay powered up continuously or some system will need to be activated to keep them from retracting. To solve this we are going to install a solenoid that will extend a strut into holes that will be pre-cut into the near ends of the metal tapes to keep them from rolling back up, which will keep the whole system open. The natural state of the solenoid is to be in its extended position, so if all power fails the panels will be stuck open rather than closed, which we feel is the better direction to go in since this way there is a chance the extended panels can be used to restart the satellite once it recharges its batteries enough.

The boom is only one aspect of the project however. We also had to design the controls for it. This involved even deciding whether or not we wanted to use analog or digital controls. After weighting the pros and cons of each, we decided on using a digital PLC due to its greater durability and flexibility. This means that we had to figure out how many inputs and outputs we would have on the system so that we could design the software needed to run the PLC. By making a truth table with all the possible outcomes and what should be done when they arise we've done just that, and now the boom can report its position and any errors to the computer while it's in use.

Being in space, this project has to deal with certain problems other terrestrial projects won't, namely extreme temperature and pressure swings, radiation, and a period of high G forces during launch. This makes the material selection very important. We've had to look at what will offer a good combination of light weight, durability, radiation hardness and ability to withstand temperature. This means using many materials only common in the aerospace industry including a type of slippery plastic called vespel and aluminum, as well as shielding the electronics.

All of these aspects have been carefully considered and weight against all the alternatives we could find. Our design won't be flown by NASA into space, but it will serve as a preliminary design for NASA engineers to work off of, so hopefully one day a satellite with parts of our design will be in orbit.

Operating Environment

In our project the team is faced with the task of designing and creating a circuit that will work in space. With that there are several considerations that need to be taken into account including temperature, radiation, vacuum conditions, and the potential for impact by space debris.

For our project we are specifically working in Low Earth Orbit (LEO), which helps us to determine what kind of temperature range we are to expect. LEO is approximately 99 miles to 1,200 miles above the Earth's surface. To determine the temperature in LEO we must know the height at which we will be operating. Being that NASA would like to launch the CubeSat we are mounting our circuit into from the International Space Station (ISS) we expect the conditions our circuit will face would be similar conditions to that of the ISS. It is known that the ISS maintains an orbit at an altitude between 205 miles and 270 miles above Earth's surface. According to NASA the ISS sun-facing side experiences a temperature of approximately 250 degrees Fahrenheit while the dark side experiences approximately -250 degrees Fahrenheit. Given NASA's information of the different temperatures the ISS experiences we can assume that we will face the same conditions. This wide range of temperature is not feasible for today's electronic components so they must be protected from varying temperatures with insulation. We were told by NASA to expect that our circuit will be protected or shielded inside the CubeSat from this great range of temperature thus reducing the range significantly.

Our second concern is radiation. Being that LEO is not protected by the Earth's atmosphere, the radiation from space can directly affect our electronic components. Radiation is an important factor, because over time it will degrade electronic components ultimately causing failure. An example of a failure may just be our programmable logic controller (PLC) sending a 1 instead of a 0 which can be very detrimental to our system, because it will no longer function as needed. Radiation in LEO is dependent on the orbital inclination around the earth. At low inclinations (I < 28 degrees) a typical dose rate would be from 100-1000 rad(Si)/year. In a high inclination (20 < I < 85) the typical dose rate can be from 1000-10,000 rad(Si)/year. It can be seen that inclination is an important factor in determining the amount of radiation to expect. It is known that the ISS has an orbital inclination of about 51.65 degrees thus for our circuit we can expect radiation in the high inclination range. Fixing components in space is cumbersome and comes at extreme costs, so we must select components that will not require constant maintenance due to radiation degradation. To overcome the challenge of radiation we have selected Rad-Hard components with the desired radiation tolerance as well as the circuit being protected by the outer shell of the CubeSat.

Another consideration of ours is the vacuum conditions of space. What vacuum means is that it is a condition well below normal atmospheric pressure. Pressure is measured in Pascals. For reference, at sea level pressure is 101 kilopascals (kPa) while the atmospheric pressure in LEO is about 10^-8 Pa. Though pressure is significantly lower in LEO as compared to Earth there are still enough molecules present to cause a slight atmospheric drag effect. In our project it is not our task to counteract this orbital decay, however, it is our task to keep our circuit intact while in orbit. Due to this low pressure it is possible our components can detach over time, so we have decided to use a PLC with surface mount components to prevent loss of components.

Our last consideration is debris. This, again, is not a challenge that we are tasked to address, but we must at least consider it. Debris in space can either be natural or man-made. Natural debris can be in the form of meteoroids whereas man-made may be shrapnel from previous collisions of parts. It is expected that NASA will provide protection for our circuit from any sort of space debris when retracted. Unfortunately our system cannot be protected at all times such as when it is deployed. We are integrating sensors as fail-safes into our circuitry to avoid any malfunctions of the system due to debris.

When designing a circuit for space conditions there are many considerations that we do not face on a daily basis. Temperature and radiation are the two major considerations in designing a circuit for space, because either of these will degrade the circuitry. The two lesser considerations of vacuum conditions and debris are still important, because parts can either float off into space or collide with debris damaging the point of impact. In space there is far less room for error demanding a robust and reliable system that can overcome these atypical constraints.

Detailed Design

Hardware Specification

The original design worked with the concept based around using a scissor jack as our deployment and retraction mechanism. As outlined below we were able to accomplish this using a singular power supply down rated to 3.3V.This design is outlined in Figure ##. After the redesign we had to include a locking solenoid to hold the new boom. This impacted the design and the logic necessary to control the system. This new design is outlined in Figure ##. Each of the elements are described below.

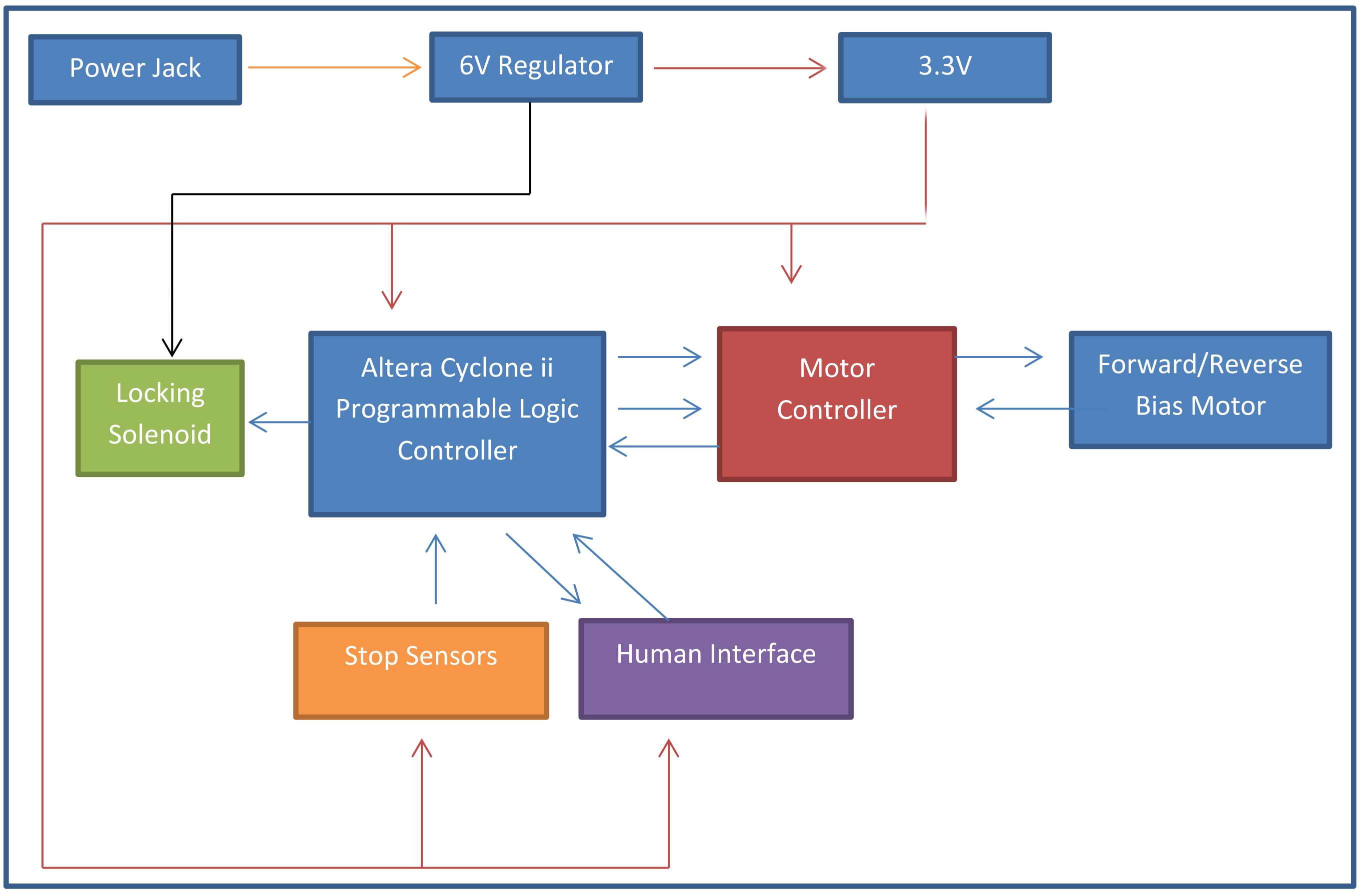

Figure 1 Systematic Design

Programmable Logic Controller

For the test example we are using an Altera Cyclone II Programmable Logic Controller. This PLC can simulate a wide array of logic systems but uses solid state components instead of relying on several discrete logic gates. Overall all this will increase the reliability of the system and allows minor changes to several systems to occur without changing the building process. In our system the PLC will:

- Conduct all of the logic processing.
- Accept inputs from sensors to determine the state of the system.
- Send/Receive information to the end user to make further decisions.
- Send start/stop signal to the motor controller.

This acts as the main controller for the entire system. All inputs and outputs are run through our PLC for processing before being sent to another part of the system. This ensures that the entire system is acting in unison and nothing is being overlooked. The PLC has been programed to the specifications as outlined below.

The logic controller for this design is based off an Altera Field Programmable Gate Array (FPGA). This microprocessor was chosen for its inherent ability to execute logic arrays in a fast and reliable manor. The AT40KEL040 used in our design is made for use in LEO due to its functionality and durability. The chip is not degraded by radiation and can withstand extreme temperatures. This was a major deciding factor when compared to other options. Various Programmable Logic Controllers (PLC) were evaluated but were not certified to environment specifications necessary for our design. The chip/board combination can support all necessary logic functions while maintaining functionality.

Table 1 below illustrates the specifications of our device family:

Table 1 AT40KEL040

Device	AT40K05	AT40K10	AT40K20	AT40K40
Usable Gates	5K – 10K	10K – 20K	20K – 30K	40K – 50K
Rows x Columns	16 x 16	24 x 24	32 x 32	48 x 48
Cells	256	576	1,024	2,304
Registers	256(1)	576(1)	1,024(1)	2,304(1)
RAM Bits	2,048	4,608	8,192	18,432
I/O (Maximum)	128	192	256	384

For our Simulation we may use the comparable Cyclone II (as found in the EE281 lab). These chips perform similarly without the cost of purchasing the actual component as described.

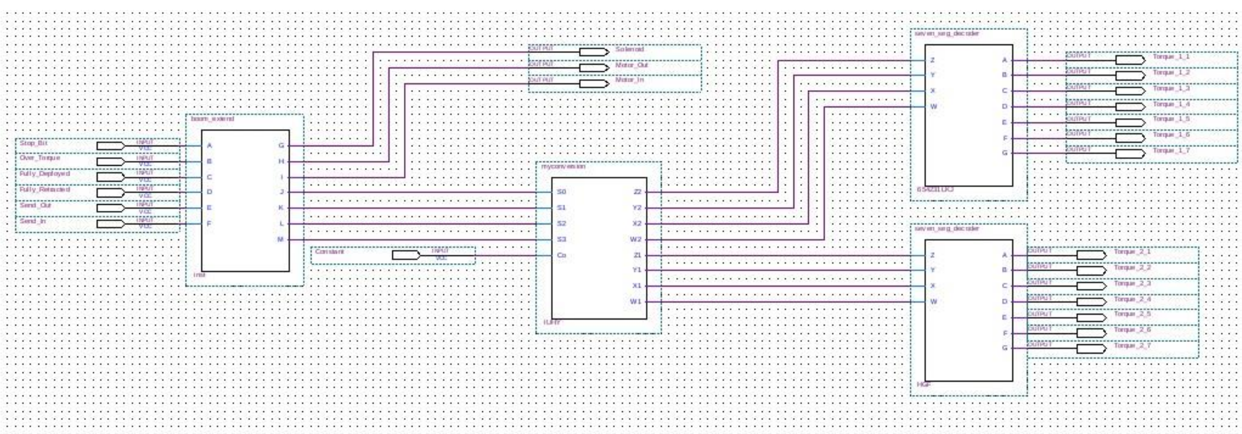

Figure 2 Quartus II Logic Layout

Table 2 Verilog Code for Boom_Extend Moduel

```
module boom_extend (A,B,C,D,E,F,G,H,I,J,K,L,M);
input A,B,C,D,E,F;
output G,H,I,J,K,L,M;
        assign G = (~A & ~B & ~C & E & ~F) + (~B & ~C & ~D & E & ~F) + (~A & ~B & C & ~D & E);
        assign H = (~A & ~B & ~C & E & ~F);
        assign I = (~A & ~B & ~D & ~E & F);
        assign J = (C & E) + (C & D) + B + A ;
        assign K = ((~B & ~C & D & ~E) + (~B & ~C & D & F) + (~B & C & ~D & ~E & ~F) + (B & ~C
                  & ~D & ~E & F) + (B & ~C & ~D & E & ~F) + A);
        assign L = (~B & ~C & E) + (C & ~E & ~F) + (C & D) + (B & ~E & ~F) + (B & D) + (B & C) + A
                  + (~C & E & F);
        assign M = (~A & ~C & ~E & F) + (~A & ~D & F) + (~A & C & ~D & ~E) + (~A & B & ~E)
                  +(~A & B & D) + (~A & B & C) + (A & ~B & ~C & ~D & E & ~F);
endmodule
```

Table 3 Verilog Code for Seven Segment Decoder

```
module seven_seg_decoder (A,B,C,D,E,F,G,Z,Y,X,W);
input Z,Y,X,W;
output A,B,C,D,E,F,G;
        assign A=((~Z&~Y&~X&W)|(~Z&Y&~X&~W)|(Z&~Y&X&W)|(Z&Y&~X&W));
        assign B=((~Z&Y&~X&W)|(~Z&Y&X&~W)|(Z&~Y&X&W)|(Z&Y&~X&~W)|(Z&Y&X&~W)|(Z&Y&X&W));
        assign C=((~Z&~Y&X&~W)|(Z&Y&~X&~W)|(Z&Y&X&~W)|(Z&Y&X&W));
        assign D=((~Z&~Y&~X&W)|(~Z&Y&~X&~W)|(~Z&Y&X&W)|(Z&~Y&X&~W)|(Z&Y&X&W)|(Z&~Y&X&~W));
        assign E=((~Z&~Y&~X&W)|(~Z&~Y&X&W)|(~Z&Y&~X&~W)|(~Z&Y&~X&W)|(~Z&Y&X&W)|(Z&~Y&~X&W));
        assign F=((~Z&~Y&~X&W)|(~Z&~Y&X&~W)|(~Z&~Y&X&W)|(~Z&Y&X&W)|(Z&Y&~X&W));
        assign G=((~Z&~Y&~X&~W)|(~Z&~Y&~X&W)|(~Z&Y&X&W)|(Z&Y&~X&~W));
endmodule
```

For the actual Cubesat an Atmel® AT40KEL chip will be used due to its design. This chip has been produced for space use and can withstand the environmental conditions it will be exposed to. When paired with the MQFPF 256 Development Board the AT40KEL has 233 user definable input/output pins which support the necessary configuration.

Motor Controller

The motor controller has been added to the system to allow the motor the appropriate voltage needed to power the boom while still being able to accept 3.3V signals from the PLC. This also allows a secondary system to interpret the torque sensor from the motor before that information is sent to the PLC. The motor controller is programed to send a signal once the torque goes outside set bounds. The torque sensor is built into the motor controller which adds an additional layer of protection. The activation of this sensor will automatically send a stop signal to the motor and sends a warning signal that an over-torque event is occurring to the end user through the human interface.

Forward/Reverse Bias Motor

For our system we are using a forward and reverse bias electric motor capable of at least 30 inch-pounds of torque. This will give sufficient power to extend and reverse the boom in the microgravity environment. We have also included a buffer zone of 50% torque to ensure the motor will have sufficient torque. The motor chosen must also lock in place when power is not applied. This will decrease the power consumption of the system and ensure the boom stays in the extended or retracted position.

Human Interface

The human interface portion of our system consists of two 7-segment LCD displays and three 2-position switches. The two seven-segment displays relay position information that can be understood by the end user using the table below. The position information values will correspond to a set table of values where each value corresponds to different situations as shown below. All of these components are powered off of the 3.3V power supply.

Table 4 Feedback Values

Value Displayed	Meaning
0	No signal
1	Send in signal received, motor Reverse Powered, Solenoid Pullen In
2	Send out signal received, motor Forward activated and solenoid powered out
3	Send out and in signals received
4	Fully Retracted Success
5	Fully Retracted and Send in signal received
6	Fully Retracted, receiving signal to send out and in
7	Fully Deployed Success, solenoid no longer powered
8	Fully deployed but still receiving signal to send out, solenoid still energized to push out
9	Fully Deployed but receiving signal to send out and in, solenoid still energized to push out
10	Receiving fully deployed and fully retracted signal and possibly others
11	Over torque signal received
12	Over torque signal received while deploying, motor stopped
13	Over torque signal received while retracting, motor stopped
14	Stop Bit Received
15	Stop Bit Received while sending out, solendoid powered

Stop Sensors

At each end of the screw that moves the boom there are contact sensors. When the boom reaches these sensors a signal is sent to the PLC that stops the motors and sends this information back to the end user through the human interface. These normally open contacts close then activated sending a 3.3V signal.

Table 5 I/O Pins

Node Name	Direction	Location	I/O Bank	Fitter Location	I/O Status	Current Strength

Boom Extend	Input	PIN_AD13	8	PIN_AD13	3.3 V	24mA
Boom Retract	Input	PIN_AF14	7	PIN_AF14	3.3 V	24Ma
Motor Forward	Output	PIN_AE23	7	PIN_AE23	3.3 V	24mA
Motor Reverse	Output	PIN_AF23	7	PIN_AF23	3.3 V	24mA
Pressure Sensor	Input	PIN_N26	5	PIN_N26	3.3 V	24mA
Stop Signal	Input	PIN_N25	5	PIN_N25	3.3 V	24mA
Retract Stop	Input	PIN_P25	6	PIN_P25	3.3 V	24mA
Extend Stop	Input	PIN_AE14	7	PIN_AE14	3.3 V	24mA
LCD_1	Output	PIN_L3	2	PIN_L3	3.3 V	24mA
LCD_2	Output	PIN_L2	2	PIN_L2	3.3 V	24mA
LCD_3	Output	PIN_L9	2	PIN_L9	3.3 V	24mA
LCD_4	Output	PIN_L6	2	PIN_L6	3.3 V	24mA
LCD_5	Output	PIN_L7	2	PIN_L7	3.3 V	24mA
LCD_6	Output	PIN_P9	2	PIN_P9	3.3 V	24mA
LCD_7	Output	PIN_N9	2	PIN_N9	3.3 V	24mA

Solenoid

A solenoid is composed of a coil wound around a hollow tube within which a ferrous material is placed. By energizing the coil, the ferrous core is either pulled into or pushed out of the coil. The latching mechanism will be used to hold the boom at full extension and relieve tension from the drive rollers. The latching mechanism will have a shaft that is inserted through the tape measure style boom, perpendicularly, and will need to consume no power while in either the extended or retracted state. We found a few solenoids that may work, but have settled on a C-Frame Magnetic Latching Solenoid from Bicron Electronics Company. The Magnetic Latching function of the solenoid means that the coil needs to be energized to move the core, but the core will remain in its final position until the coil is re-energized with opposite polarity.

The solenoid listed above has been chosen because of the price point and the way it functions. Two solenoids in each of two configurations have been procured for testing and possible implementation, free of charge (Part Numbers: SC0424L2410 and SC0424L0625). The sales representative from Bicron Electronics did ask that we return some basic testing data if the solenoids are used. The specifications of the Bicron Solenoid, as far as length and force of pull, are 0.08 inches of pull at approximately 10 ounces of force. The solenoid is rated at 6 volts and has dimensions of 1.1 X 1.1 X 2.4cm. Bicron electronics has the in-house capability to produce custom aerospace rated solenoids with relatively short lead time (around five to ten days to begin prototyping). During actual implementation, it may be better to have an aerospace rated solenoid.

Bearings

The roll for the solar cells we are using needs to be at least 5 cm in diameter and will be placed over a rod that is connected to each side of the box. The bearings that we are using for our prototype will be 0.75” bore x 1-5/8” OD x ½” W. These are single row bearings made of steel, and are filled with 35% grease. These will be purchased from Fastenal because we are asked to use off the shelf parts and we feel that this will satisfy our needs here but we will be advising NASA to use different materials for space applications.

We need bearings for our design and have found multiple products, companies and types that would work. Here are a few the options that we turned down. The 3030 single seal from RBC Bearings. These bearings are made from hardened steel, have a nylon retainer, and are pre greased. The speed range on these bearings are for 2500 to 3000 RPMs. These have been tested for aerospace applications and would be well suited for what we are looking for. These would be great to use but we feel the ones from Fastenal are more suited for our needs and our budget.

Lubrication

Next we need to look at what lubricants can be used for our demonstration and for space applications. For our demonstration the lubrication already found in the Fastenal bearings will work great for our on earth applications. Now NASA has posted documents on what lubricants they use. NASA is against using oil and grease due to the difficulty of applying it and the temperatures it can withstand. For this reason NASA prefers to use solid lubricants and uses liquid and gas lubricants only if they have to. MoS_2 has a low coefficient of friction in a vacuum and in the atmosphere. This looks to be the lubricant of choice followed by graphite, PTFE or Vespel, and other soft metals.

Software Specification

We will be using a PLC to operate all controls in the design. The PLC will be programmed with Altera Quartus II software using code written in Verilog, an IEEE standardized hardware description language commonly used for digital logic programming. Using the Verilog language for programming ensures quick and easy reproducibility by our client, as the PLC is prefabbed. Therefore, the only remaining task once the PLC has been received is to load the program and attach the board the CubeSat. Once fully assembled and deployed, a signal will be received from the operator and interpreted by the PLC, which will execute the command while monitoring for problems.

Basic Operations:

PLC

- The system must be able to receive a deployment signal from the operator.
- The system must be able to interpret the received extension signal.
- The system must be able to execute the deployment command.
- The system must be able to receive an error for excessive boom tension, indicating a problem with deployment.
- The system must be able to automatically stop deployment at full extension.
- The system must be able to return a signal that the boom successfully extended.
- The system must be able to latch the extended boom in place.
- The system must be able to receive a retraction signal from the operator.
- The system must be able to interpret the received retraction signal.

- The system must be able to unlatch the boom.
- The system must be able to execute the retraction command.
- The system must be able to receive an error for excessive boom tension, indicating a problem with retraction.
- The system must be able to automatically stop retraction at full retraction.
- The system must be able to return a signal that the boom successfully retracted.
- The system must be able to receive a stop signal to interrupt deployment or retraction during any step of command execution.

Note: The communication between the base station (operator) and the satellite will be taken care of by NASA.

We will be using a motor controller to determine the torque which the motor is exerting on the shaft during operation. By using our knowledge from classes, we know that the harder a motor is working, the electric potential across the input terminals will decrease and the current draw will increase. By monitoring these values in comparison to predetermined threshold values, we can monitor for torque and locked rotor conditions.

Motor Control Circuit

- The system should be able to measure current draw.
- The system should be able to measure electric potential.
- The system should be able to decide which threshold range the values fall into.
- The system should be able to determine what needs to be done within that threshold range.
- The system should be able to return a decision to the PLC.
- The system should be able to constantly iterate these checks and evaluations during boom operation.

Based on the requirements for this motor control circuit, we have found a motor controller that will meet the minimum specifications required to drive a motor for our application. The motor controller that has been located should take only minimum programming to set the threshold values for our system.

Boom Design

The solar panels will be supported by a scissor type boom. When retracted the boom will fit completely inside of the cube satellite. The individual parts of the boom will be built as shown below.

Our boom will consist of two measuring tapes stitched back to back to form a triangular shape, similar to the TRAC (Triangular Rollable and Collapsible) Boom constructed by the AFRL (Air Force Research Laboratory) for NASA's Nanosail-D Project. For the prototype deployment mechanism we will be using standard aluminum measuring tapes to keep costs to a minimum.

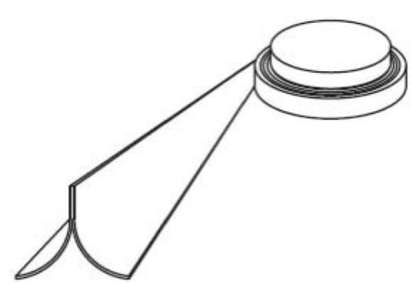

Figure 3 Tape Boom

The guide plate for the boom will need to keep the boom in its triangular shape, as seen in Figure ASDFG below (taken from the AFRL thesis paper for the TRAC boom project). Once retracted the triangular shape can be pressed flat and wound tightly around a shaft for storage, as seen in Figure 18 (taken from the AFRL thesis paper for the TRAC boom project). This arrangement has already been proven to meet structural rigidity requirements at extensions up to thirteen feet in testing conducted by the AFRL.

Figure 4 Boom Exiting

The TRAC boom is comprised of a stainless steel alloy called Elgiloy for a number of reasons:

1. Possession of the structural composition for repeatable boom extensions and retractions.
2. Reduction of fissures in the seam welds when wrapped repeatedly.
3. Resistance to seam weld oxidation.
4. Increased material integrity.

Elgiloy has a coefficient of elasticity of E=190 GPa, a maximum strain of 1%, and a density of 8.3 g/cm^3. Being an extremely light material with decent rigidity and little deflection at the lengths we will be using, it has been recommended that Elgiloy is used for final implementation.

Gears

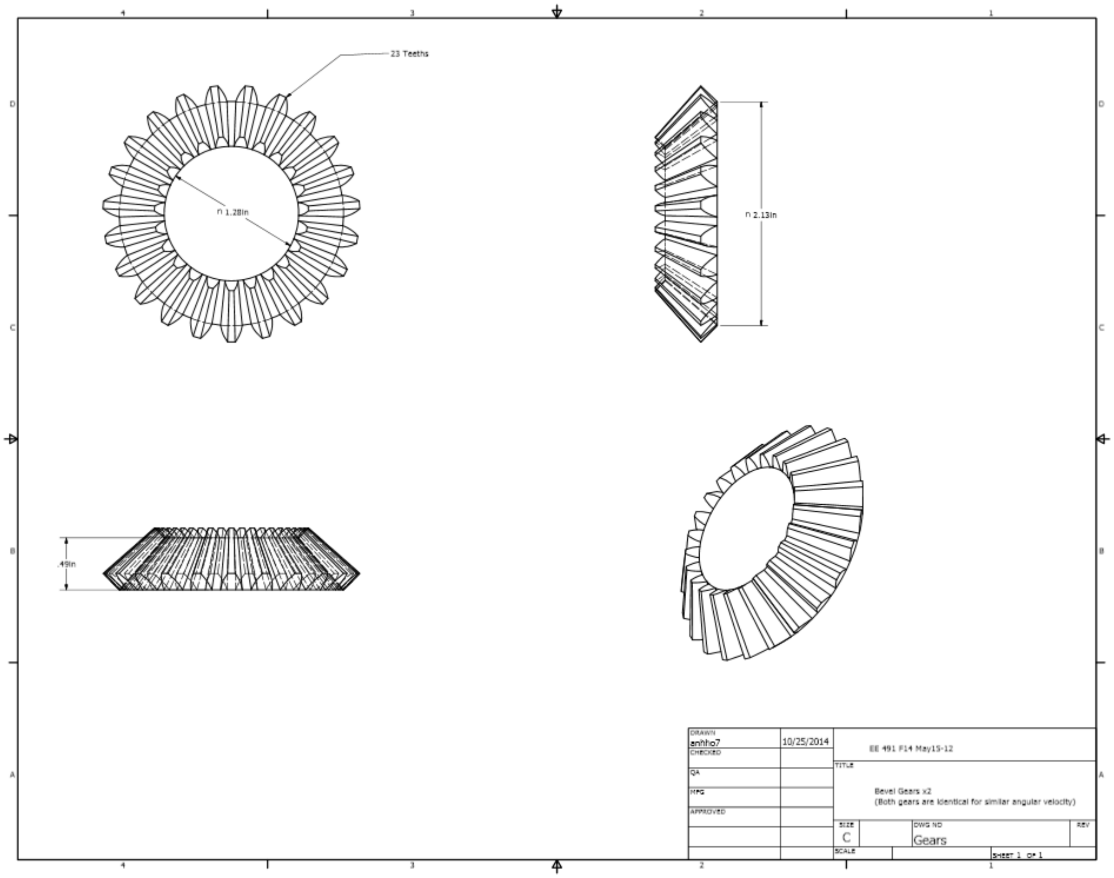

Figure 5 Gear Model

Gears: The gears are responsible for coupling the drive motor to the extension / retraction shaft. By selecting the proper number of teeth for the gears, we can change the rate of deployment and retraction, as well as the mechanical advantage achieved, thus reducing the torque required by the motor.

Motor

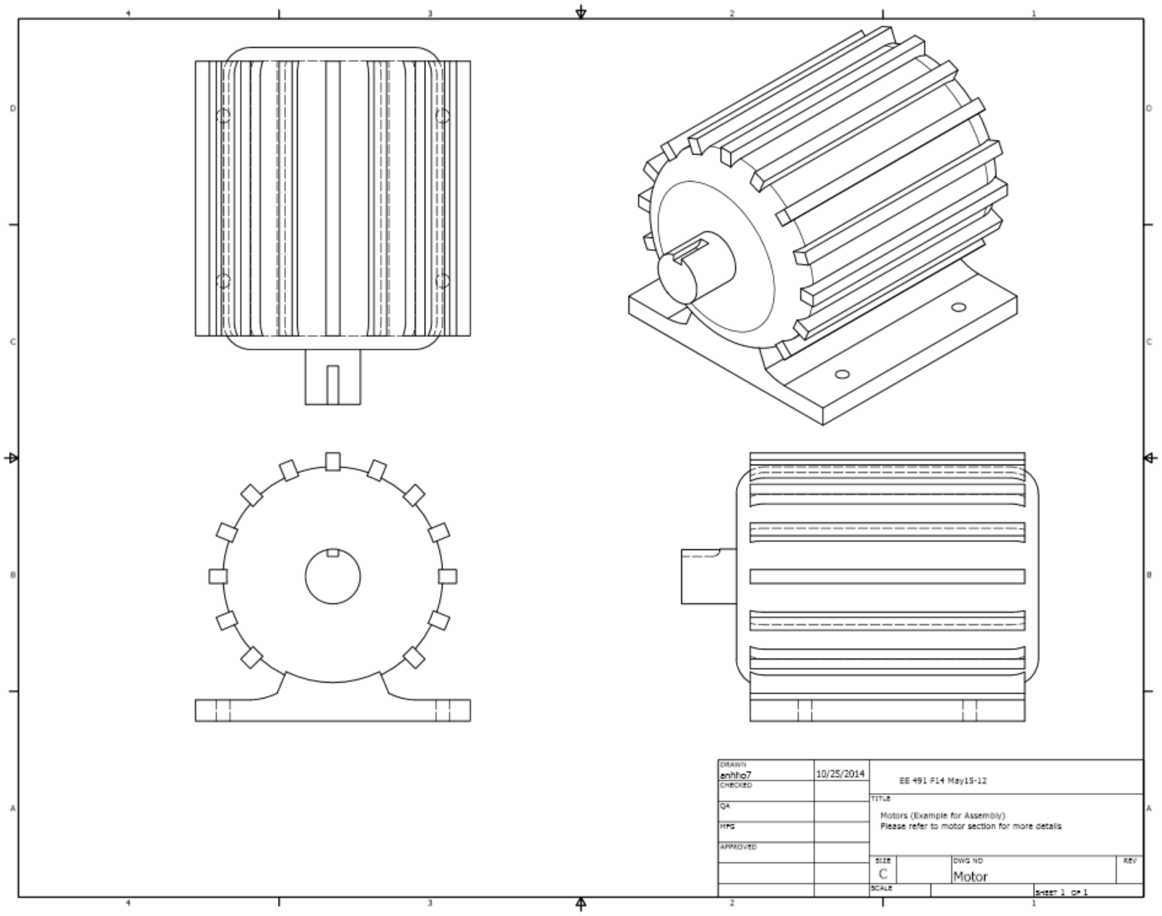

Figure 6 Motor Model

Motor: The motor is responsible for driving the extension / retraction shaft. The proper motor needs to be selected to give us enough torque to deploy the boom.

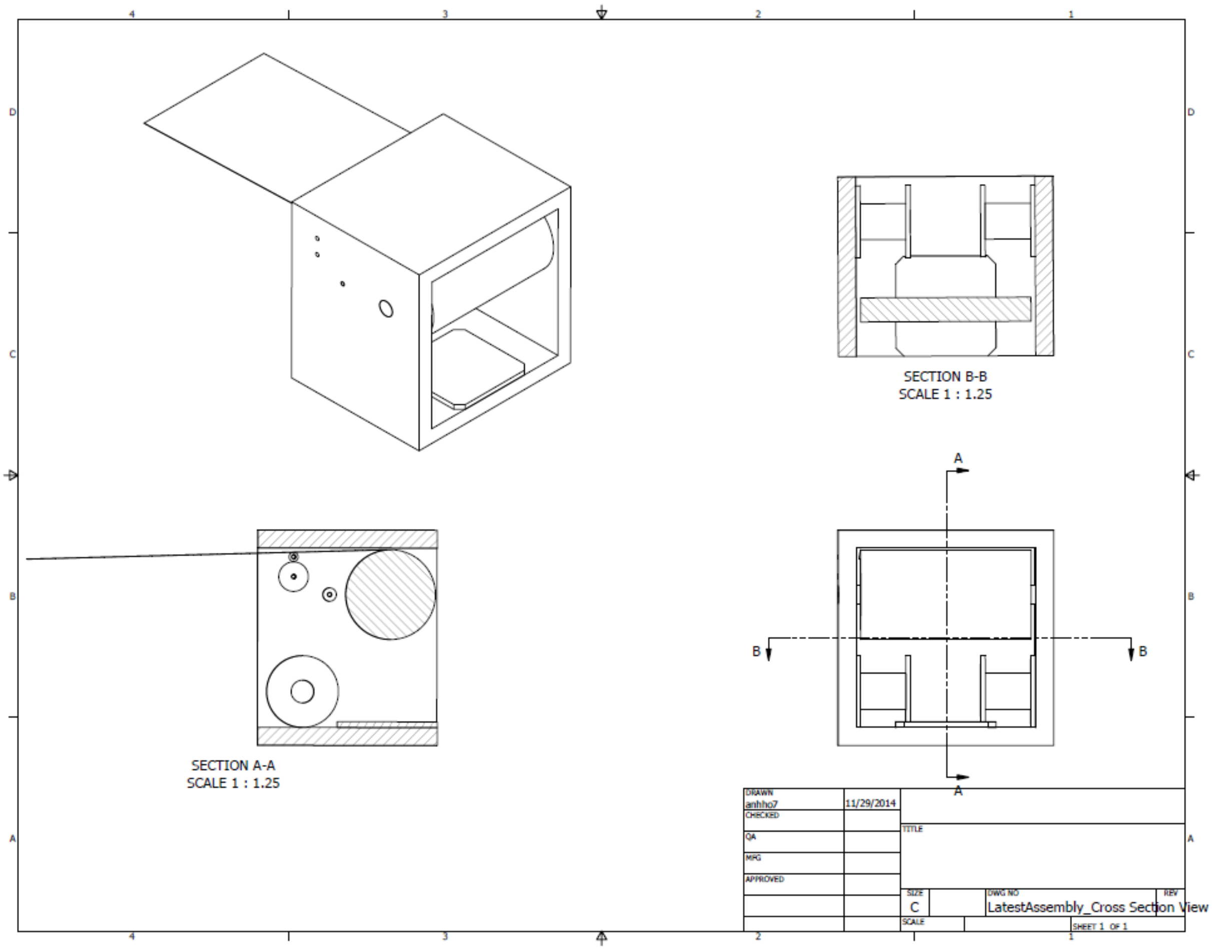

Figure 7 Cube Schematic

Interface

For the interface between our Arduino PLC and our motor that will be turning the screw that extends our boom we will be using a motor driver to help improve our program's abilities. For our motor driver we chose a high-power motor driver which uses a discrete mosfet H-bridge designed to drive large DC brushed motors. The H-bridge uses one N-channel mosfet per leg and these mosfets determine the board's performance. For the model we picked the mosfet's have an absolute maximum voltage rating of 40V and can deliver up to 23A of continuous current with a board size of only 1.8" by 1.2" and no required heat sink. Since optimization of size is very important for our design this driver works perfect.

The module offers a simple interface that requires two I/O lines while allowing for both sign-magnitude, locked-antiphase operation, and coasting. Some of its available applications are motor control, load detection and management, switch-mode power supplies, and overcurrent fault protection. This board also features a current-sensing circuit that measures bidirectional motor current with a magnitude up to 30A and outputs an analog voltage. This feature was of grave importance to us since we will be using this as our workaround for torque sensors as they were very expensive or impossible to find in motors of our caliber. Also integrated into the circuit is detection of various short-circuit conditions and failure protection which are shown in the table.

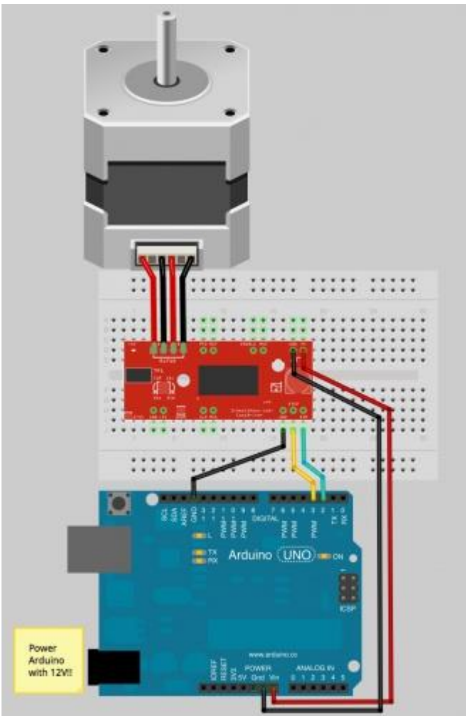

Figure 8 PLC to Motor Interface

Connections

The motor and motor power connections are on the left side of the board, and the control connections are on the ride side. The motor supply will need to be capable of the high current the motor will require. To limit noise we will need to install a capacitor between V+ and ground close to the motor driver. With the two axial capacitors that are included with the driver will be installed by soldering them into the V+ and GND pins along the top and bottom of board. There are two options for connecting to the high-power signals (V+, OUTA, OUTB, GND) but we will use the pairs of 0.1"-spaced holes that can be used with breadboards, and 0.1" connectors.

The logic connections are designed to interface with 5V systems, with a minimum high input signal threshold of 3.5 V. In our configuration, only PWML isn’t of worry because we do not need to use coasting but this may change. The two fault flag pins FF1 and FF2 can be monitored to detect problems and will be used for unsafe shutdowns through our program. The RESET pin is pulled up to V+ through a 20 kΩ resistor so when it’s held low, it puts the driver into a low-power mode and clears any stuck fault flags. The V+ pin on the logic side of the board gives you access to monitor the motor’s power supply or pass it on to low-current devices. The board also provides a regulated 5V pin which can provide a few milliamps which we will short to VCS to power the current sensor. When the current sensor is powered by applying 5 V to VCS, the CS pin outputs 66 mV/A for currents between -30 and 30 A centered at 2.5 V.

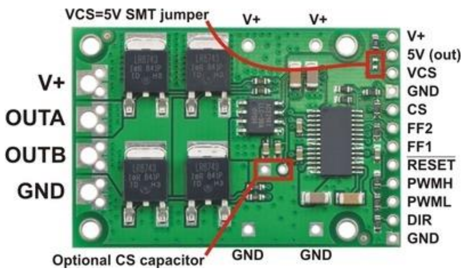

Figure 9 Motor Controller

PIN	Default State	Description
V+		This is the main 5.5 – 40 V (absolute max) motor power supply connection, which should typically be made to the larger V+ pad. The smaller V+ pads along the long side of the board are intended for power supply capacitors, and the smaller V+ pad on the logic side of the board gives you access to monitor the motor's power supply (it should not be used for high current).
5V (out)		This regulated 5V **output** provides a few milliamps. It can be shorted to VCS to power the current sensor. This output should not be connected to other external power supply lines. **Be careful not to accidentally short this pin to the neighboring V+ pin while power is being supplied** as doing so will instantly destroy the board!
VCS		Connect 5 V to this pin to power the current sensor.
GND		Ground connection for logic and motor power supplies.
CS		ACS714 current sensor output (66 mV/A centered at 2.5 V).
OUTA		A motor output pin.
OUTB		B motor output pin.
PWMH	LOW	Pulse width modulation input: a PWM signal on this pin corresponds to a PWM output on the motor outputs.
PWML	HIGH	Control input that enables coasting when both PWML and PWMH are low. See the "motor control options" section below for more information.
DIR	LOW	Direction input: when DIR is high current will flow from OUTA to OUTB, when it is low current will flow from OUTB to OUTA.
RESET	HIGH	The $\overline{\text{RESET}}$ pin is pulled up to V+ through a 20 kΩ resistor. When held low, it puts the driver into a low-power sleep mode and clears any latched fault flags.
FF1	LOW	Fault flag 1 indicator: FF1 goes high when certain faults have occurred. See table below for details.
FF2	LOW	Fault flag 2 indicator: FF2 goes high when certain faults have occurred. See table below for details.

Figure 10 Motor Controller Connection Bits

Materials

Material Selection

A designing process of materials' physical properties.

The main objective of design is to produce an effective, safe product at an acceptable cost. Materials are selected by satisfactorily achieving a ranges of individual properties. More often, however, materials are selection involves seeking the best materials that are able to achieve multiple constraints.

Methodology

Translate design requirements into materials specifications. There should be a vast consideration in the design objective, constraints, and free variables.

Screening out materials that doesn't meet the criteria.

Rank materials by their abilities to meet the objectives (Material Indices).

Determine a supporting information for the material candidates.

Use Ashby chart to for selection.

Defining Design Requirements

- What does the component do?
    - Any engineering component has one or more objectives
- What are the objectives?
    - Designers has certain goals to make the products feasible, light or high safety standards.
- What are the requirements?
    - Objective must be achieved subjected to fixed variables.
- What is the designer free to change?
    - Free variables?

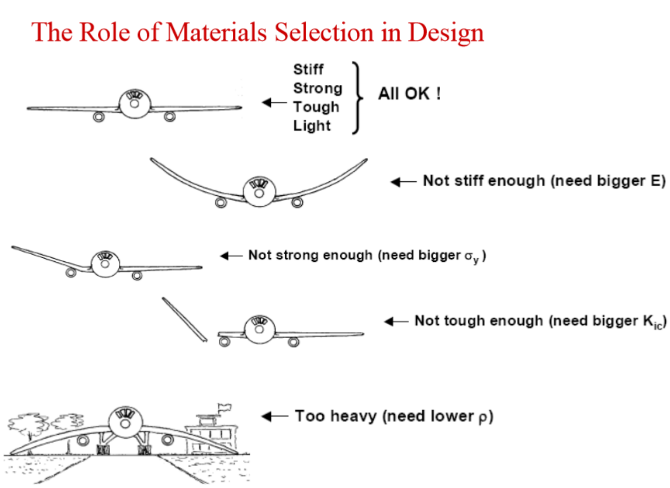

Figure 11 *Ashby - Materials Selection in Mechanical Design (2004)*

Figure 12 shows the behavior of the product when certain objectives are not met.

In the case of this project, the main objective is to have a boom to hold solar panels outside of Earth's atmosphere.

The following is research found from the Course PH 508 Department of Astronomy, University of Kent

Spacecraft structures:

Minimize mass without compromising reliability.

Must support itself and its loads through all phases of the mission.

Environmental protection

Some Suggested Materials – Beryllium, Titanium, Magnesium, Aluminum,

Beryllium – Stiffest, low density, high specific strength, high temperature tolerance, expensive and difficult to work.

Titanium – Lightweight with high specific strength, stiff, high temperature capability, less ductile, lower availability.

Magnesium – High stiffness, good specific strength, workable, but chemically active.

Aluminum – Low density, good specific strength, easily workable, cheap and widely available, but has low melting point (933K)

Tungsten - Highest melting point besides diamond.

Thus, components must be lightweight, have a low thermal coefficient high specific strength, fracture resistance and stiffness. They also need to be able to withstand UV radiation and outgassing.

Some material properties that are used in this project. Since there is a maximum cost for the project, materials have to be low cost.

Mechanical

- Tensile Strength – Maximum stress that a material can withstand before failing or breaking.
- Specific Strength – Materials tensile strength divided by its density.
- Yield Strength – Stress at which material begins to deform.
- Fracture Toughness – Ability of a material containing a crack to resist fracture.
- Young's Modulus – Stiffness of an elastic material and is a quantity used to characterize materials.

Physical/Thermal/Chemical

- Density – Property to determine the weight of the material. Mass per unit volume.
- Thermal Expansion – Tendency of materials to change through heat transfer (temperature).

- UV Radiation – Due to materials being in vacuum.
- Outgassing – Due to materials being in vacuum.

General

- Cost

The following Ashby charts are generated by CES Edupack 2013 to finalize product design and only compares between aluminum, steel, tungsten, and titanium.

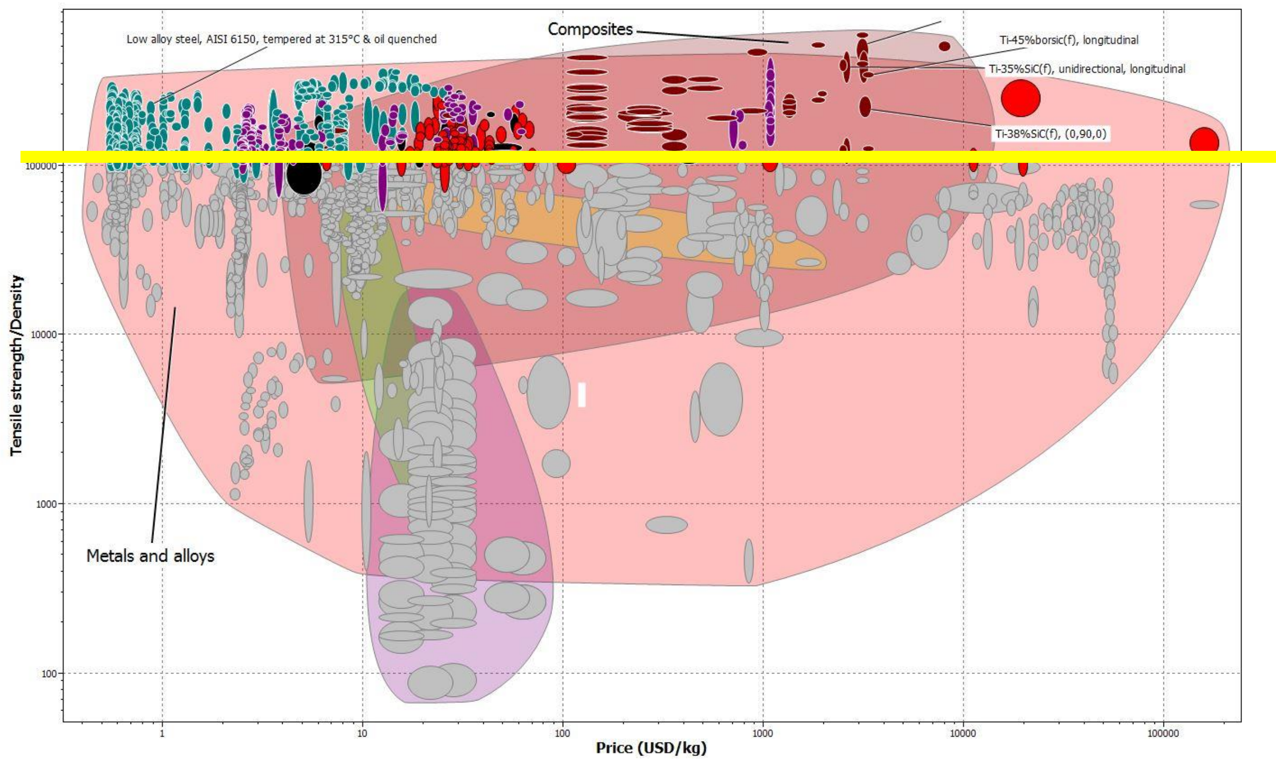

Figure 12 Cost comparison of the four materials.

The above figure shows that specific strength of each metals are way above 2 MPa of strength, but in comparison with cost Titanium and tungsten are in the hundreds of dollars/kg range, thus way out of the cost constraint for the project.

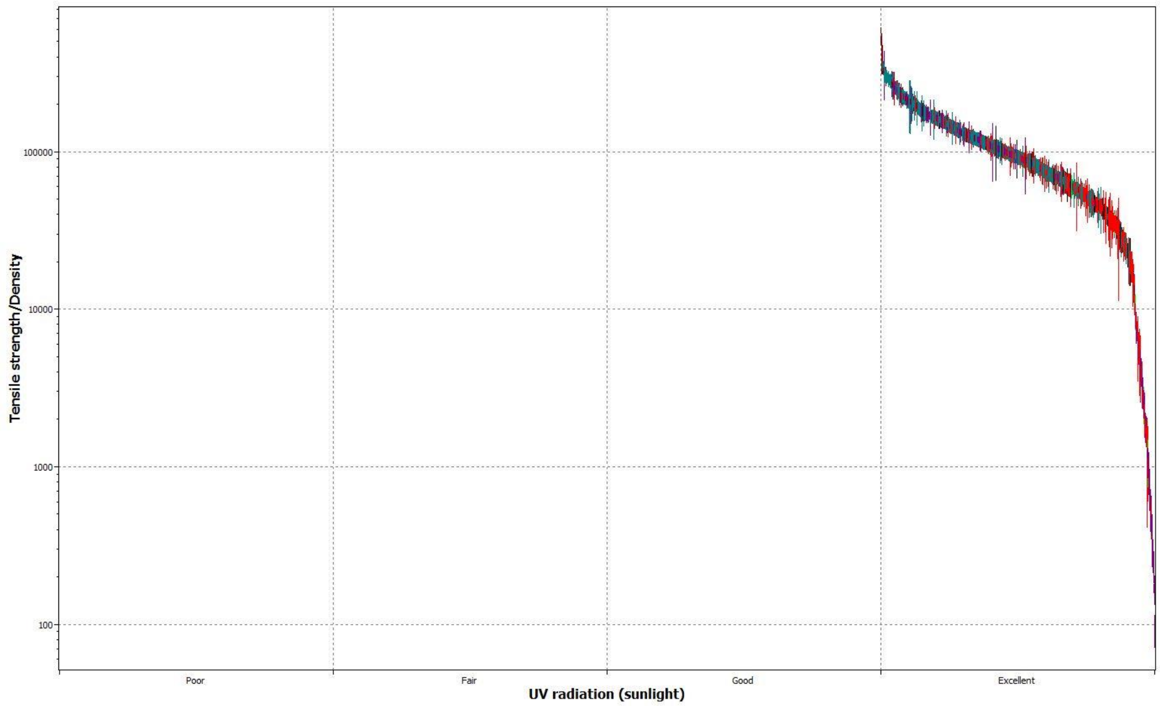

Figure 13 UV radiation comparison.

Figure 14 shows that most metals are in the excellent range when compare between specific strength and the reliability in atmosphere when dealing with radiation.

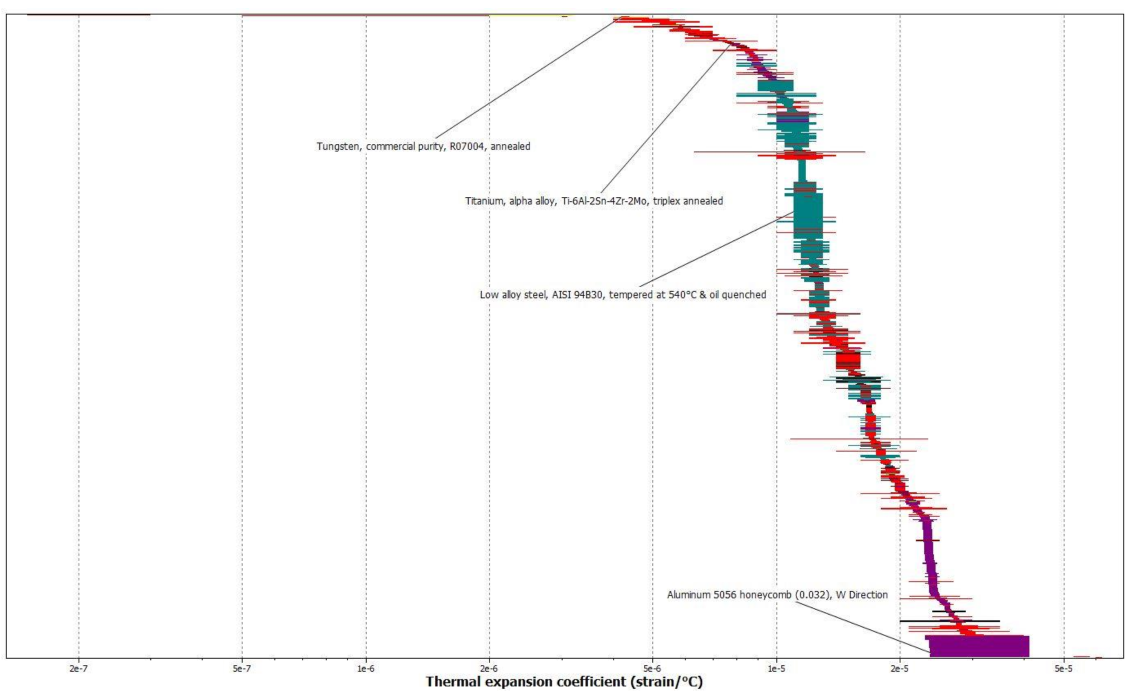

Figure 14 Thermal coefficient comparison

As can be seen it is correct that titanium and tungsten have a much higher thermal resistance than both steel and aluminum.

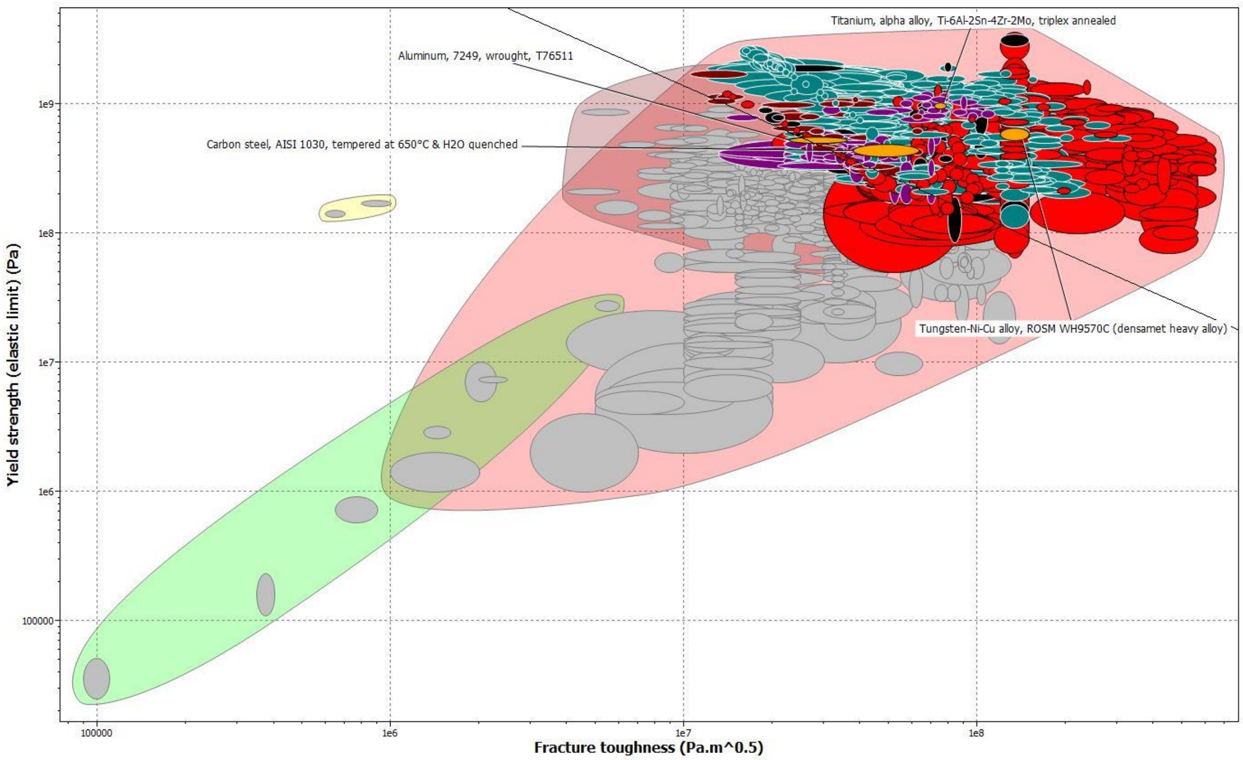

Figure 15 Stiffness and Fracture toughness

This graph also shows that all four materials are in the high range of stiffness and fracture toughness.

It would be a great idea to use the best materials for the space-worthy model, but with small amount of money compared to what NASA uses for their project, it would be very difficult to get such materials. Also, the materials that are suggested from the University of Kent, are mostly low availability, and would need a certain expensive machines to work with. Thus, this selection process is to find (almost) the best material that can at least withstand the environmental condition in the area of Ames, IA.

Project Risks

When considering risks/issues that are associated with an object in Low Earth Orbit (LEO) these risks/issues need to be considered very carefully. Due to the environment in which our system will be operating in we cannot simply repair or maintain our device in the event of a problem happening. When creating our design as well as choosing parts we always considered the fact that our device may never be retrieved upon deployment in LEO. We have tried to design a long-lasting device; however, no device is perfect and is insusceptible to failure. Upon deploying our device into space a number of events could occur that may threaten the integrity of our system, so they must all be considered.

Temperature happens to the biggest issue we must consider in our design. In LEO temperatures can range from -250 degrees Fahrenheit up to 250 degrees Fahrenheit. This extreme range of temperature is something that our system can't escape. Constantly changing temperatures can make the pieces of our system brittle ultimately leading to failure. An example would be the wheels that drive the tape becoming so brittle they cannot achieve enough friction to drive the tape out. In this situation the entire system would fail due to inability to push the tape out. In choosing parts temperature specifications were of utmost importance for creating a durable and reliable system. Speaking to our client it was said that we do not need to expect such extreme temperatures, because the walls of the CubeSat should provide some insulation. Though we were given this assumption to go by we still tried to achieve this temperature range, within reason.

Radiation is our second most important risk that we must consider. What radiation does is increase the entropy of the circuit which causes malfunction. Permanent bits may become flipped or threshold shifts in CMOS transistors, which leads to the failure of logic gates. Being that we are using a programmable logic controller (PLC) the effects of radiation is a very important consideration. In choosing parts we were able to find a Rad-Hard PLC capable of functioning in space. It is likely that our electronics will be shielded from the radiation of space with the wall of the CubeSat, choosing Rad-Hard components further ensures the reliability and longevity of the system.

Lifetime of the parts is a potential issue in this design. Creating a cost-efficient system is ideal, but we need a highly reliable and quality system and cannot sacrifice quality for price. To ensure that we have a reliable and durable system we must consider all other potential risks mentioned. The parts must be able to withstand the temperature range, radiation, consume low power, and space efficient. By considering these different issues we can best create a system that is reliable and has the durability needed to withstand LEO. We must also take the specifications given for each part for what it's worth. This means that we must trust that our supplier have given us parts that actually meet the specifications given. We plan to create our own tests to ensure our parts meet their specifications.

Power also becomes an issue for our design. We do not know the solar cells will always be sun-facing enough to supply power to our system. It may be that the solar cells are pointed in the wrong direction or CubeSat is in the shadow of the Earth. On our end of the design we found a motor, PLC, and microcontroller that require minimal power consumption. It is assumed that the power consumption will always be monitored in using this device ensuring that it always has enough in reserve to function.

Elasticity of the substrate and solar array can also be an issue. Because we are using a spring to keep the substrate and array taut when deploying and retracting it may compromise the integrity of the substrate and array. A constant pull on the array may cause cracks or tears. Cracks can lead to solar cell failure whereas a tear may cause separation from the tape that supports the solar array, thus no longer able to be deployed or retracted. Finding a spring that keeps the array taut, but does not create excessive pull is what we would like to ideally achieve.

Communication with the motor to determine deployment length may not always be accurate. We may find that the boom has already extended the required length and the motor continues to drive the tape out due to electrical failure. In our design we plan to use sensors to help determine amount of deployment and retraction achieved so that we not only need to rely on information given to us by the motor.

Debris is flying around all over in space and is something we must consider. There may be a situation where our boom is deploying/retracting and a piece of space debris gets caught in its axis of movement. In our design we must be able to monitor the torque on our motor to identify a situation of this time. In the case that something does come into the axis of movement the motor should stop and retract or deploy, whichever direction is opposite of what has been bumped. Having sensors for our fail safes will be an important part of ensuring the system will function within its environment.

Testing

Springs

Testing the springs we will use in this project is difficult, since many of the problems they will face can only be replicated in specialized testing facilities. Extreme temperature, for example, can affect steel springs and radiation can weaken metals through ablation. Testing these two extremes ourselves will be impossible, so all we can do is try and find parts using materials that will survive them. The spring we've chosen to use in our model can be found here: http://www.amazon.com/Constant-Stainless-Extended-Diameter-Capacity/dp/B0085ZXEXW/ref=sr_1_7?ie=UTF8&qid=1416414087&sr=8-7&keywords=constant+force+spring.

This spring is a low to medium carbon steel, which is better in extreme temperatures than high carbon steel. The spring will be inside the 1U box, which itself will be inside the satellite which we were told in addition to being insulated will also have some degree of radiation protection as well, so even this cheap spring should be fine in space. However, to guarantee we can use parts proven to work in space, we would recommend NASA buy an identical spring from Vulcan Springs (http://www.vulcanspring.com/) which we can't order from since they only sell in bulk. Their springs are designed and rated for use in space, and actually have worked for NASA before.

The actual testing of the spring here will be mostly limited to making sure it isn't too powerful or too weak to be useful to us. The best way to test that is to just build the assembly and try it out, but we've calculated that it should work with our current design. NASA will be able to test it in extreme cold, vacuum and in a high radiation environment in their special test chambers when we ship the prototype down to their facilities in Huntsville, Alabama.

Solenoids

For testing the solenoids, we will begin by taking them to the lab to make sure they operate as expected. We will be looking to make sure that the linear pull is long enough, and that it will still function if given a three volt input. Once that has been confirmed, we will integrate them into our functional model for further analysis. The functional model will be shipped to NASA for final testing and we will find out for sure if the solenoids will work. As stated above, if the solenoids do not work, custom ones can always be built.

If the solenoid from Bicron Electronics will not work for our proof of concept, the backup that was selected is the STA-Mini Pull Tubular by LEDEX / Johnson Electric. However, after speaking with a sales representative from LEDEX, the STA-Mini Pull Tubular solenoid is not one that they have ever made, and will not be an option unless a large number are ordered (and would, in turn, have a very large lead time).

PLC

Testing of the PLC for the system shall take into consideration the performance of the FPGA to be used once deployed and the PLC used in lab tests. The Altera Cyclone II shall be tested to the specifications listed in the hardware description to ensure all logic gates have been laid out accordingly. LED's shall simulate the motor controller receiving a start, stop and reverse signal. Push Buttons shall denote all stop sensors and the necessary human interactions. Environmental considerations shall be made using the boards given specifications and quality grades given by the manufacture. These specifications are outlined below.

- Tested up to a Total Dose of 300 krads (Si) according to MIL STD 883 Method 1019
- Quality Grades
  - QML -Q and -V with SMD 5962-03250
  - ESCC with 9304/008
- FPGAs utilize a reliable 0.35µm single-poly, 4-metal CMOS process and are 100% factory-tested.
- Supply Voltage 3.3V and 5V Tolerant

Motor

In the first test we will check the voltage constants to make sure the motor is operating properly and doesn't have any shorts. For brush dc motors, measure the dc voltage generated by the motor with a Multimeter.

Terminal Resistance Test

For this test we will attach the motor terminals to a dc power supply and set the current limit of 25 percent of the rated motor current. Acquire the voltage necessary to drive the current through the motor for calculation of resistance *(R = V/* I).

Torque Testing

We will then be testing the motors torque by seeing how well it works under loaded conditions while monitoring its current. To do this we will connect the motor to varied loads where we can see where it peaks, stalls and runs continuously at to verify that it will fit our design.

Bearings

NASA says that they use ball bearings anywhere that rolling bearing can be used. They say that a deep groove in the bearing and a two piece cage is preferred with the exception of a one piece cage with open sided pockets. We need self-aligning bearings to help prevent our solar cells from binding and adding too much resistance.

Next we found RTF bearings made by Timken and these bearings are made for Aerospace applications. The manufacturing of these bearings consists of vacuum-melt 52100 or VIM-VAR M-50 steel and have a tolerance class 5. The extreme use for these bearings means that they must meet stricter standards. Some of the bearings include self-aligned seats, flange mounts, oil groves and low drag seals. This is meant to keep as much lubrication in while allowing for the lowest amount of friction possible.

Lubrications

Liquid lubricants can be used on NASA applications as long as they are not being used in dirt laden environments, contaminating its surroundings, require servicing to inaccessible areas, or for prolonged storage or stationary service. This means that depending on the duration of the solar cells use we may be able to use high temperature grease and keep it in the bearings from Timken.

Silicone Wheels

In testing the silicone wheels we must meet the temperature requirements of Low Earth Orbit (LEO). What would need to be analyzed is the coefficient of thermal expansion of the silicone. Because of silicone's elastomer properties it is more susceptible to becoming brittle and failing to maintain its grip strength. The silicone wheels should be tested at the LEO temperature range of -250 to 250 degrees Fahrenheit. Silicone rubber happens to be more durable in positive heat range than in the negative. Lower temperatures would have more effect on the wheels. Though the silicone rubber wheels that we are using may work for us here on Earth LEO comes with different challenges in terms of environment.

If we were to send this into LEO we would need to consider surface modifications of the silicone rubber wheels. There are several processes to modify their surface for protection from UV rays. A few of the processes to modify the surface are: photosil, UV-induced oxidation, oxidizing plasmas, flame treatment, ion bombardment, or wet chemical treatment. These kinds of treatments are called chemical modification processes and on the other hand there are also physical modification processes. One physical modification process is from the use of high-energy ion beam sources to modify material prior to being sent into space. Another physical modification process called implantox uses a high-dose ion implantation when combined with a special oxidation post-treatment following ion implantation. The thickness one would expect from implantation would be about 50-100 nm protective oxide-based layer.

Another important test required of the wheel is that it will maintain enough friction with the tape to be able to drive the tape out. If there is not enough friction between the tape and the wheel then the solar cells cannot be deployed. To ensure wheel's ability to maintain friction several trials at different temperatures will be needed. "Polymers are usually tested dry against a sled with a calibrated load. Static friction is the force that holds back a stationary object up to the point that it just starts to move. Thus, the static COF concerns the force restricting the movement of an object that is stationary on a relatively smooth, hard surface. It is calculated by finding the initial peak force required to move the sled and dividing the value by the weight of the sled. Once static friction is overcome, kinetic friction follows and is the force holding back regular motion. This kinetic COF concerns the force restricting the movement of an object that is sliding on a relatively smooth, hard surface. It is calculated by finding the average load during the test and dividing this by the weight of the sled, which holds the other material." ("Friction Testing", Lloyd Material Testing).

"Friction Testing." *Friction Testing*. AMETEK, 1 Jan. 2012. Web. 4 Dec. 2014. <http://www.lloyd-instruments.com/Resource-Center/Test-types/Friction-testing.aspx>.

Boom

Testing of our boom shall happen in two stages. For our design we will be using two carpenters tapes' (tape measure) welded together on one side will the other side is able to curve out. This will result in a ‘v’ shaped boom. We suspect that the carpenters tape’s themselves will not be rigid enough to support the weight placed upon them therefore they will be tested on a flat surface (the floor of an open room).

The boom that will be used in a deployed spacecraft will be much more rigid. This boom type has been tested and in fact used by NASA in their NanoSail-D. These booms are made from a Stainless Steel Elgiloy metal with the following parameters: E = 190 GPa, ϵ_{max} = 1.0%, ρ = 8.3 g/cm^3. Elgiloy was chosen These parameters fall generously within the specifications necessary. Since this portion of our design has already been tested and approved by NASA for LEO.

Conclusion

This project involves creating the first generation of a product for a very demanding client. As a project meant for use in space, everything absolutely must work, every time. If our part of the satellite fails, so will all the others. That means picked the right materials, checking our design for any potential flaws, and testing everything we buy or make is of paramount importance. Our abilities to replicate the conditions found in LEO here at ISU are very limited, but eventually we will be able to send the prototype we build next semester to NASA’s Marshall Space Flight Center in Huntsville, Alabama, where they will be able to test it in vacuum, high radiation, extreme heat, extreme cold, and all the other challenges space represents.

We believe our design is robust enough to survive any tests they throw at it and are very excited to hear what they have to say.

Schedules

These are the following due dates that we have chosen for major steps in our senior design project.

Table 6 Beginning Schedule

Due Date	Tasks	Team Assignment
Oct-5-14	**Wired filters or PLC**	
	Design Simplicity	Luke/Dustin
	Size(mass)	Luke/Dustin
	Cost	Tom/Isaac
	Reliability	Tom/Isaac
	Fabrication	Antjuan/Ryan/Anh
	Implementation	Antjuan/Ryan/Anh
	Testing	Antjuan/Ryan/Anh
Oct-31-14	**Circuit Outline/Improvements**	Team
Nov-14-14	**Final Circuit Completion**	Team
	Material Selections	Anh
	Bill of Materials (BOM)	Team
Nov-20-14	**Material Ordering**	Team
Dec-12-14	**Draft Design and BOM send to NASA**	Team
Jan-30-15	**Circuit Assembled**	Team
Feb-6-15	**On surface Testing**	Team
Feb-20-15	**Testing Completion**	Team
	Ship Circuit to NASA	Team
	Boom Design	Team

Here is our updated schedule after our meeting with John Carr. During a meeting we had we found out that our constraints had changed and that we had to change the overall size of cube we were designing. This meant that we would also need to change our boom design and keep things as small as possible. Below is a copy of our new schedule that we started based on the new design and time constraints.

Table 7 Updated Schedule

Due Date	Tasks	Team Assignments
10/5/2014	**Wired Filters or PLC Paper**	
	Design Simplicity	Luke
	Size	Dustin

	Cost	Tom/Isaac
	Reliability	Tom/Isaac
	Fabrication	Antjuan/Ryan/Anh
	Implementation	Antjuan/Ryan/Anh
	Testing	Antjuan/Ryan/Anh

10/31/2014	**Circuit Outline and Improvements**	Team

11/1/2014	**Our design constraints were changed**	Team

11/12/2014	**Redesign inside of 1U box**	
	3D Model, size and position	Ryan
	Motor	Luke/Antjuan
	Motor Controller	Antjuan
	Locking Mechanism	Tom
	Choose PLC	Team
	Constant force spring	Ryan
	Rollers	Ryan
	Tactile bump sensor	Isaac
	1U Holding Compartment	Tom/Isaac
	Re work logic	Luke
	Bearings and Lubricants	Dustin

11/26/2014	**Final circuit completion**	Team
	Material Selections	Anh
	Bill Of Materials	Team

12/1/2014	**Material Ordering**	Team

12/12/2014	**Draft Design and BOM sent to NASA**	Team

1/30/2015	**Circuit Assembled**	Team

2/6/2015	**On surface Testing**	Team

2/20/2015	**Testing Compleation**	Team
	Ship Circuit to NASA	Team
	Boom Design	Team

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