NASA Solar Panel Design

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Design Document

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Executive Summary

Software based

Our project has a Field Programmable Logic Array (FPGA) that will be mounted on the inside of a CubeSat and will control the operations needed in order to deploy and retract the boom. This consists of a motor that will deploy and retract a tape measure boom and a roll of solar cells. The FPGA will also control multiple sensors to show when deployed and when retracted. The FPGA will also be able to interpret the signal it is sent that says weather we want the boom deployed, retracted or held in place with a stop function. This FPGA will work in tandem with a motor controller that gives us feedback on the motor so we ensure we don't over torque anything.

Hardware based

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

Then 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 and these will make contact either when the boom is fully deployed or when the boom is fully retracted. The motor controller can measure the amount of current needed to operate the motor and if the current spikes then we know the system is being held up. This option would also save us space and be more versatile.

Lastly we have the cube set which is the box in which all of these components are stored in during launch. This box is 10cm x 10cm x 10cm or 1U, 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. This compact size will allow for easier installation on to multiple satellites for future use.

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 would have allowed 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 is 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 meetings 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 diameter cylinder that will be almost the full length of the inside of the box. 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 14 feet (4.3 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, their 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 solenoids are zero-power-to-hold, 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 they recharge 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 weighing the pros and cons of each, we decided on using a digital FPGA 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 FPGA. 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. Working in Low Earth Orbit comes with several considerations that need to be taken into account including: temperature, radiation, vacuum conditions, and 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 similar conditions. The given temperature range described above is the range for the outer surface of the ISS. This wide range of temperatures is excludes many ordinary electronic components from being considered. Temperature tolerance is a factor that cannot be ignored in a reliable design. We expect that our circuit will be protected or shielded inside the CubeSat relieving the extreme temperature range.

Our second consideration 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 be our FPGA, 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) receive a typical dosage of radiation from 100-1000 rad(Si)/year. In a high inclination ($20 < I < 85$) the typical dosage 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 we therefor expect our circuit to experience a similar range of radiation. 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 and considering the circuit will be protected by the outer shell of the CubeSat for some time.

Another consideration of ours is the vacuum conditions of space. What vacuum means is that it is a condition well below normal atmospheric pressure where pressure is being measured in pressure units (pascal). Described as feeling in free fall. At sea level pressure is 101 kilopascals (kPa) while the atmospheric pressure in LEO is about 1 nanoPascal (nPa). Though pressure is significantly lower in LEO as compared to Earth there may be slight atmospheric drag. 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. In this design we have decided to create a system that would be attached in all aspects, example being a surface mounted FPGA, preventing 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 other satellites. It is assumed that the outer casing of the CubeSat will protect the entire system when not in use. Unfortunately our system cannot be protected at all times such as when it is deployed. We have integrated some sensor fail-safes into our design to avoid any malfunctions of the system due to objects.

When designing a circuit for Low Earth Orbit (LEO) 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 both 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 integrity of the system. 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.

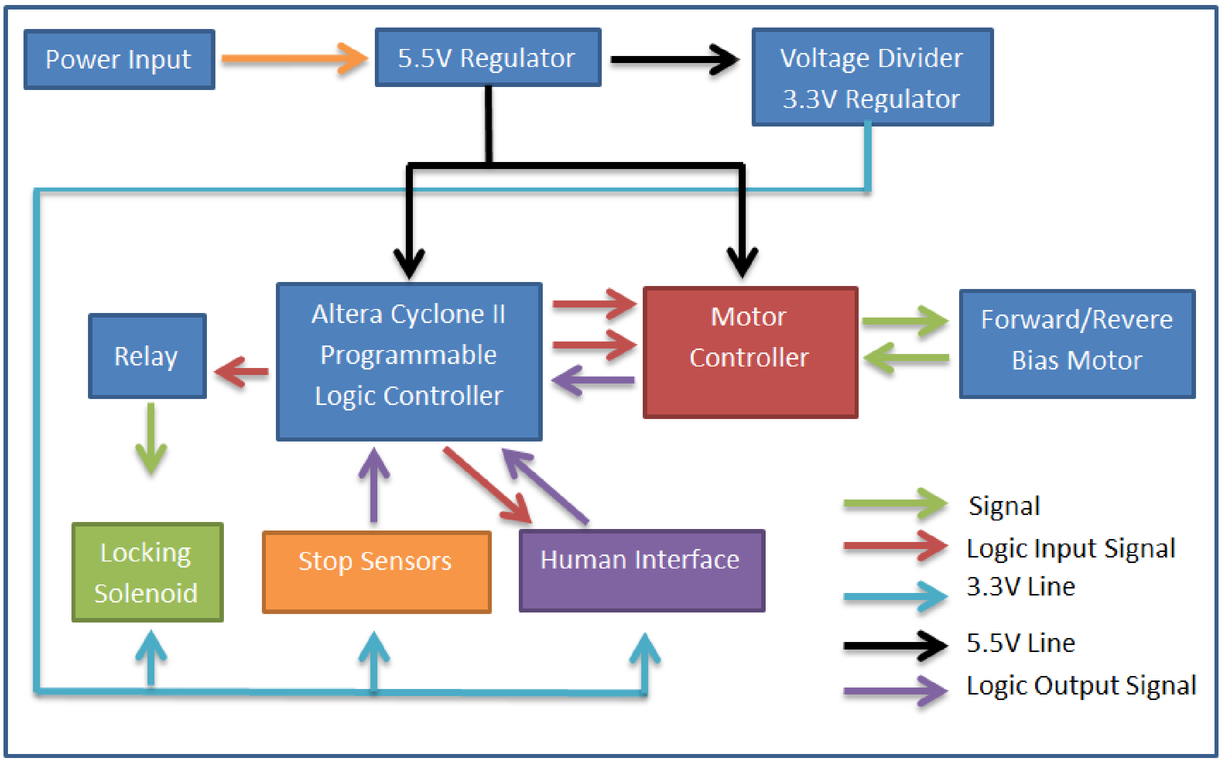


Figure 1 Systematic Design

Field Programmable Gate Array

For the test example we are using an Altera Cyclone II Field Programmable Gate Array. This FPGA 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 FPGA 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 FPGA 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 FPGA 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 Field Programmable Gate Arrays (FPGA) 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.

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.

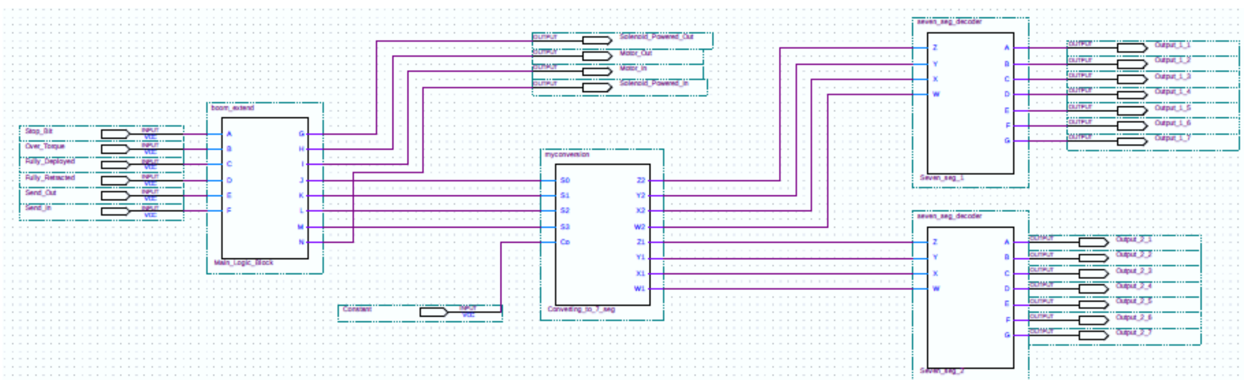


Figure 2 Quartus II Logic Layout

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

In our system design we use a motor controller to extend the capabilities of our motor. This controller will feed the motor the appropriate voltage needed to power the boom, while still being able to accept 3.3V control signals from the FPGA. With the use of this controller, our secondary system will be able to take in a voltage ratio reading and this signal will be interpreted as a torque sensor. This torque sensing ability of the motor controller adds an additional layer of protection in case the boom hangs up on anything. Through this sensor our FPGA will automatically send a stop signal to the motor controller once the torque is outside the normal bounds. This signal will also be able to be seen by our seven segment display to notify the user of the problem.

Forward/Reverse Bias Motor

For our system we are using a forward and reverse bias electric motor capable of at least 270 oz-inch torque. Since the motor will be in space for what could be long periods of time, we decided on a brushless design since a brushed motor might lock in place. The motor will give us the sufficient power to extend and reverse the boom in the near-zero gravity environment. While a 270 oz-inch torque isn't needed to extend the boom we have included a buffer zone of 50% torque to ensure the motor will have sufficient torque through all operations and snags. This design choice will ensure that the motor can run into issues and not become damaged. The motor chosen must also be able to 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.

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 FPGA 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.

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 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 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 FPGA to operate all controls in the design. The FPGA 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 FPGA is prefabbed. Therefore, the only remaining task once the FPGA 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 FPGA, which will execute the command while monitoring for problems.

Basic Operations:

FPGA

- 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 exerted on the shaft by the motor 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 FPGA.
- 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.

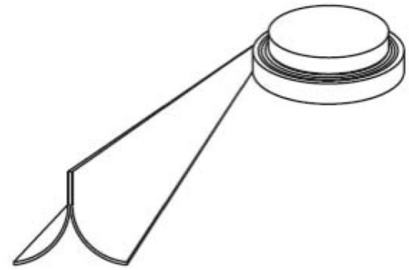


Figure 3 Tape Boom

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.

Figures 3 and 4 are courtesy of United States. Department of the Air Force. Air University. PROTOTYPE DEVELOPMENT AND DYNAMIC CHARACTERIZATION OF DEPLOYABLE CUBESAT BOOMS. By Grant M. Thomas. Wright-Patterson Air Force Base: Air Force Institue of Technology, 2010. Print.

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

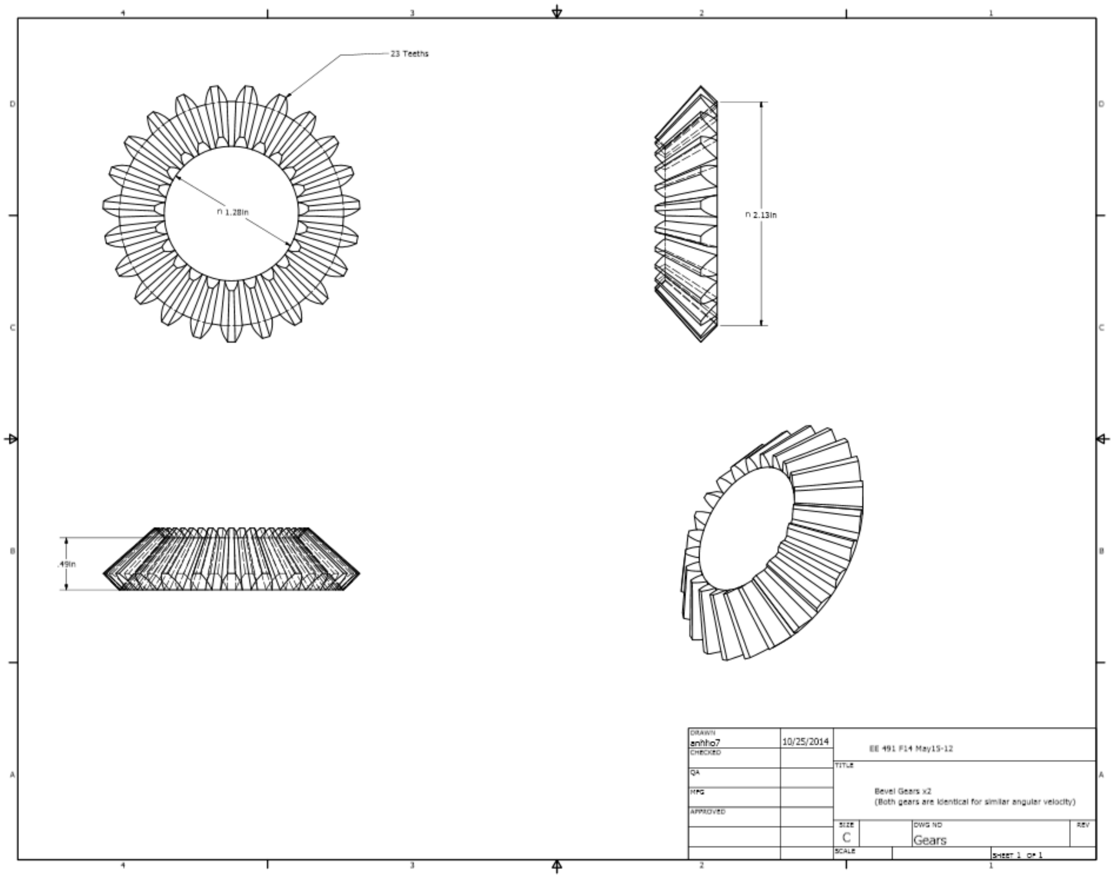


Figure 5 Gear Model

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

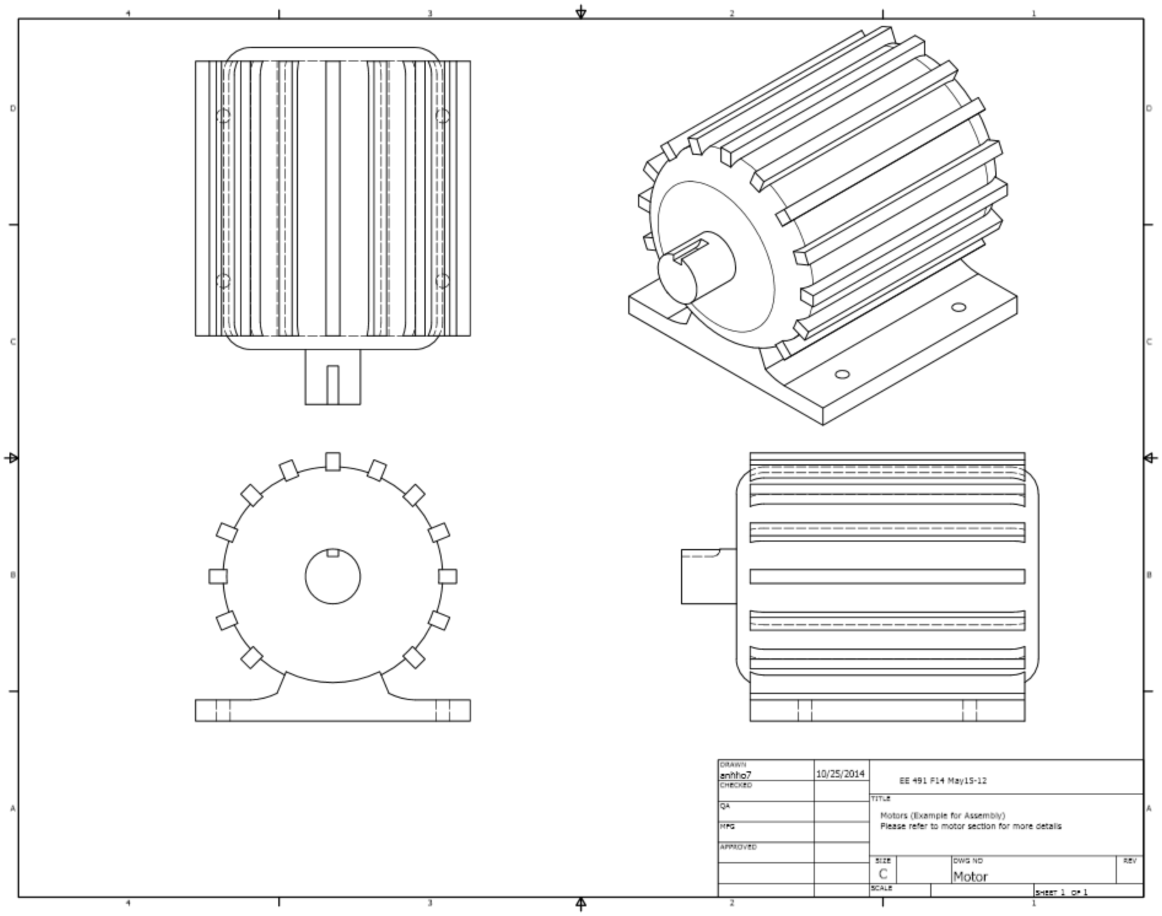


Figure 6 Motor Model

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.

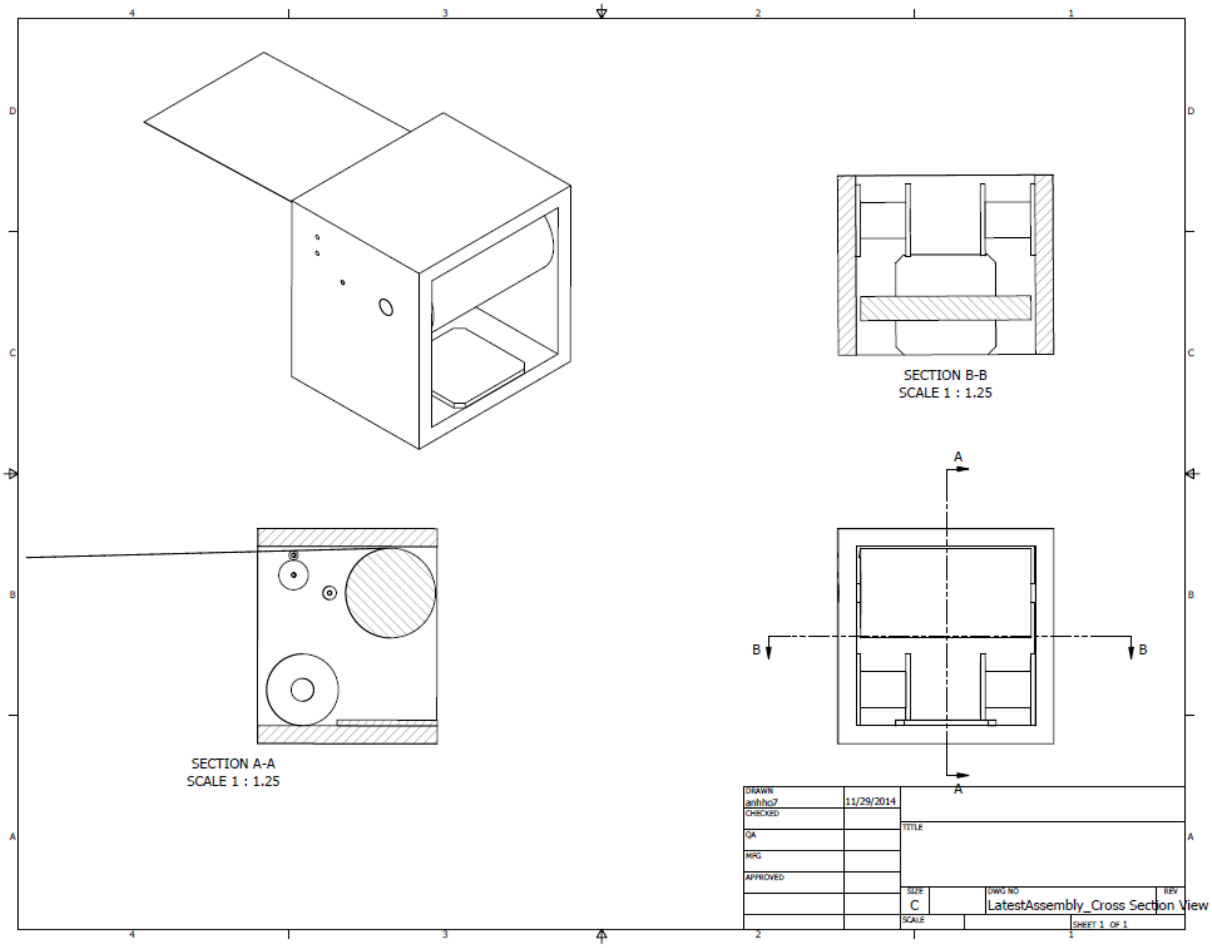


Figure 7 Cube Schematic

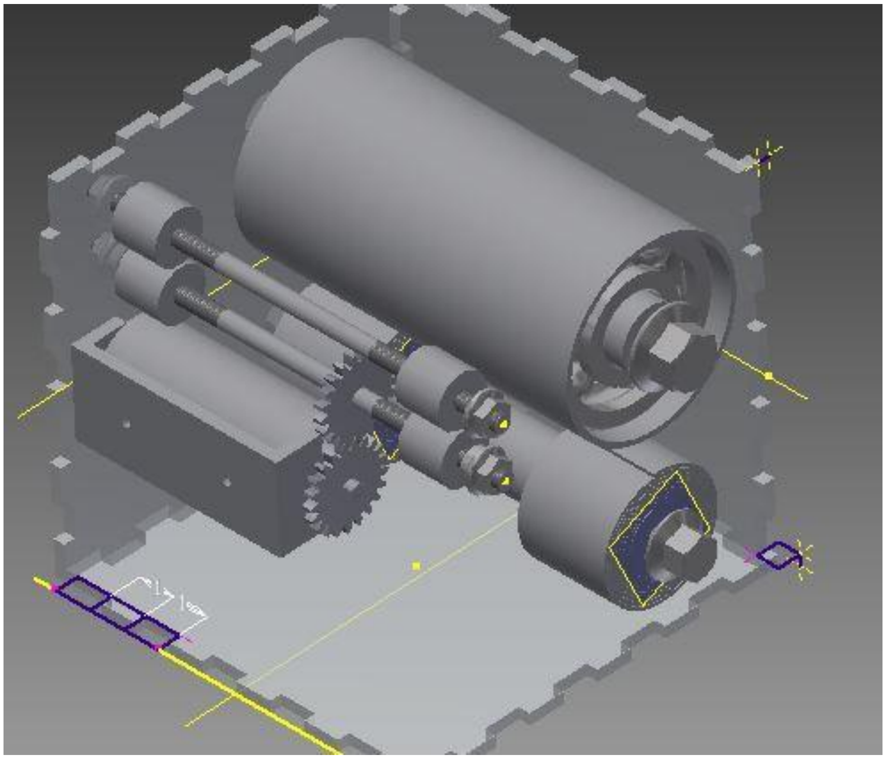


Figure 8 Interior View of Cub

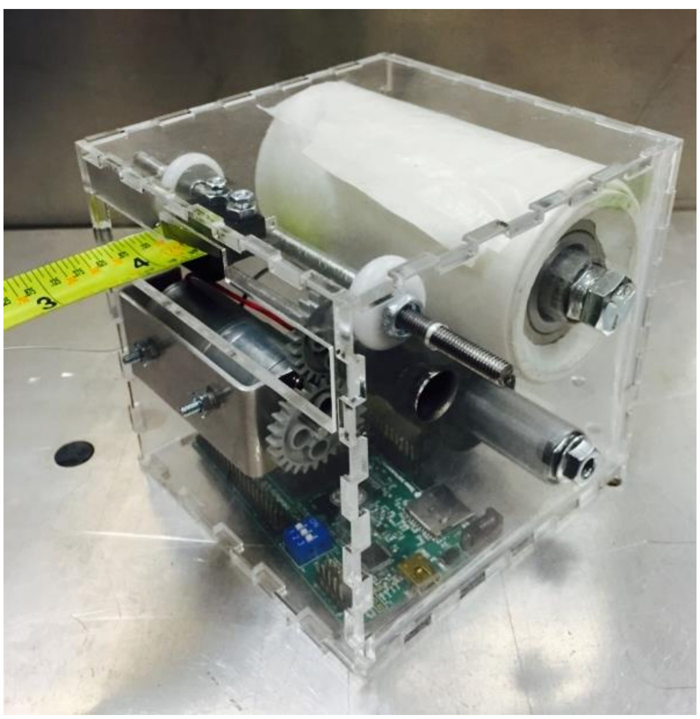


Figure 9 Completed Design

Interface

For the interface between our Arduino FPGA and our motor that will be turning the screw that extends our boom we will be using a motor driver to help improve our programs 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 30 A and outputs an analog voltage. This feature was of grave importance to us since we will be using this as our work around 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 figure 10.

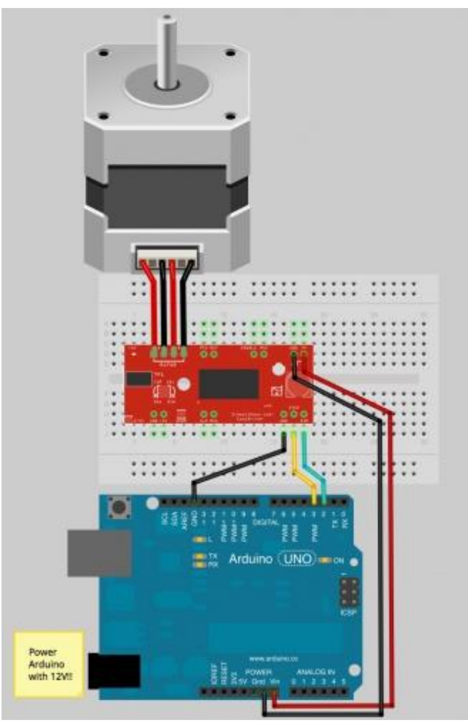


Figure 10 *FPGA to Motor Interface, Pololu - VNH5019 Motor Driver Carrier. (n.d.). Retrieved April 28, 2015*

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.

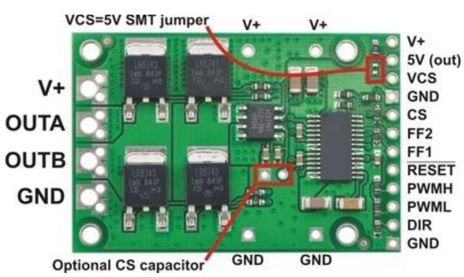


Figure 11 Motor Controller, Pololu - VNH5019 Motor Driver Carrier. (n.d.). Retrieved April 28, 2015

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 12 Motor Controller Connection Bits, Pololu - VNH5019 Motor Driver Carrier. (n.d.). Retrieved April 28, 2015

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 purposes.
- What are the objectives?
  - Designers has certain goals to make the products feasible, durable, lightweight 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 or customers' leniency.

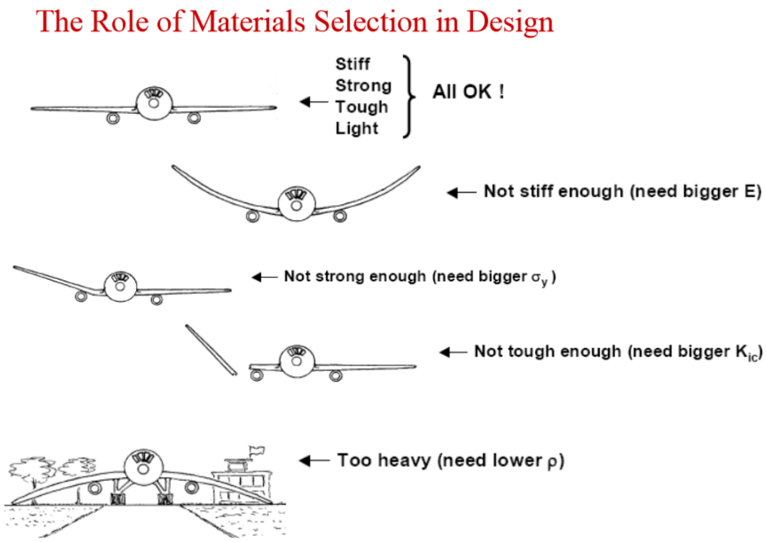


Figure 13 *Ashby - Materials Selection in Mechanical Design (2004).*

Figure 13 shows the behavior of the product when certain objectives are not met. E – Young's Modulus, σ_Y – Yield Strength, K_{ic} – Toughness, and ρ – density.

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

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.

1. 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.

2. 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.

3. General

- Cost.

Materials Research

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

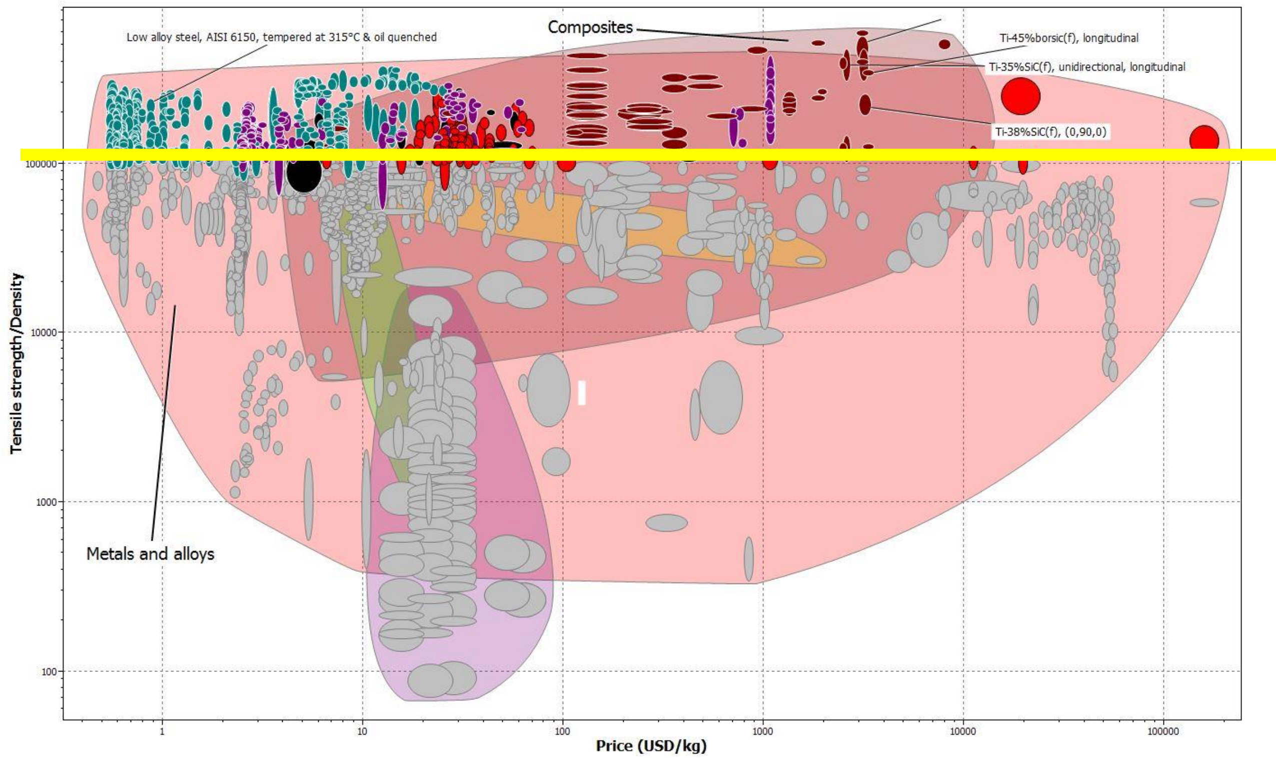


Figure 14 Cost comparison of the four material

The above figure shows that specific strength of each metals are way above 200 kN-m/kg, but in comparison with cost Titanium and tungsten are in the hundreds of dollars/kg range, thus surpassing the cost constraint for the project.

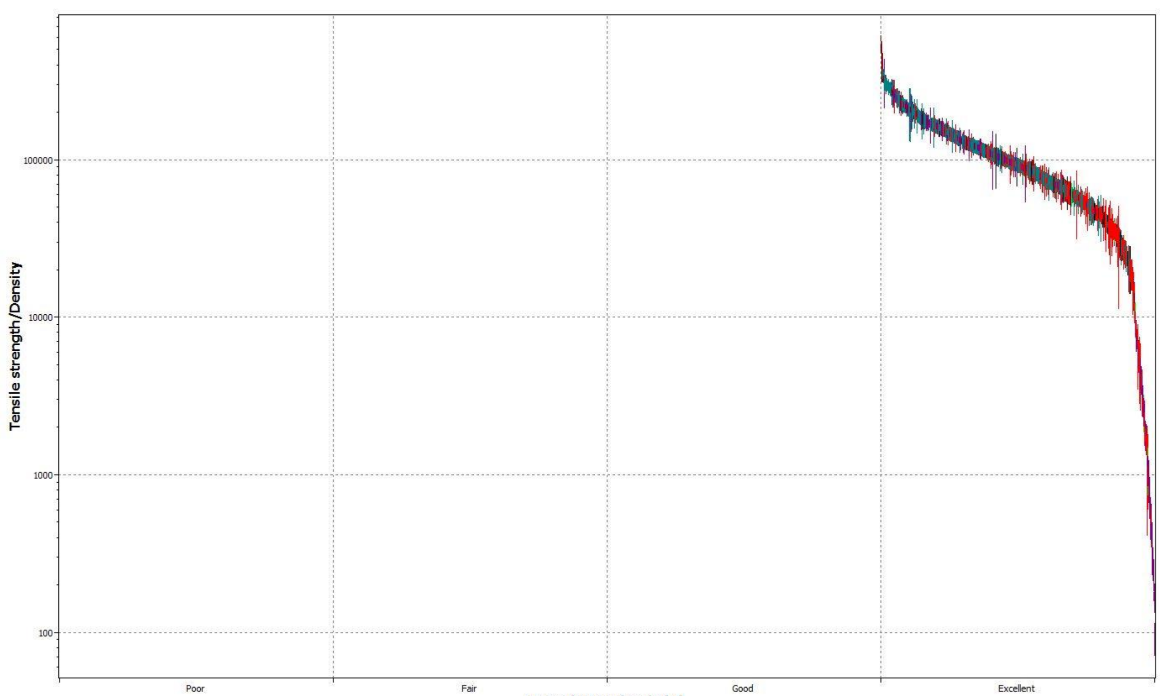


Figure 15 UV radiation comparison.

Figure 15 shows that most metals are in the excellent range when the project requires to have high strength and high protection from UV radiation.

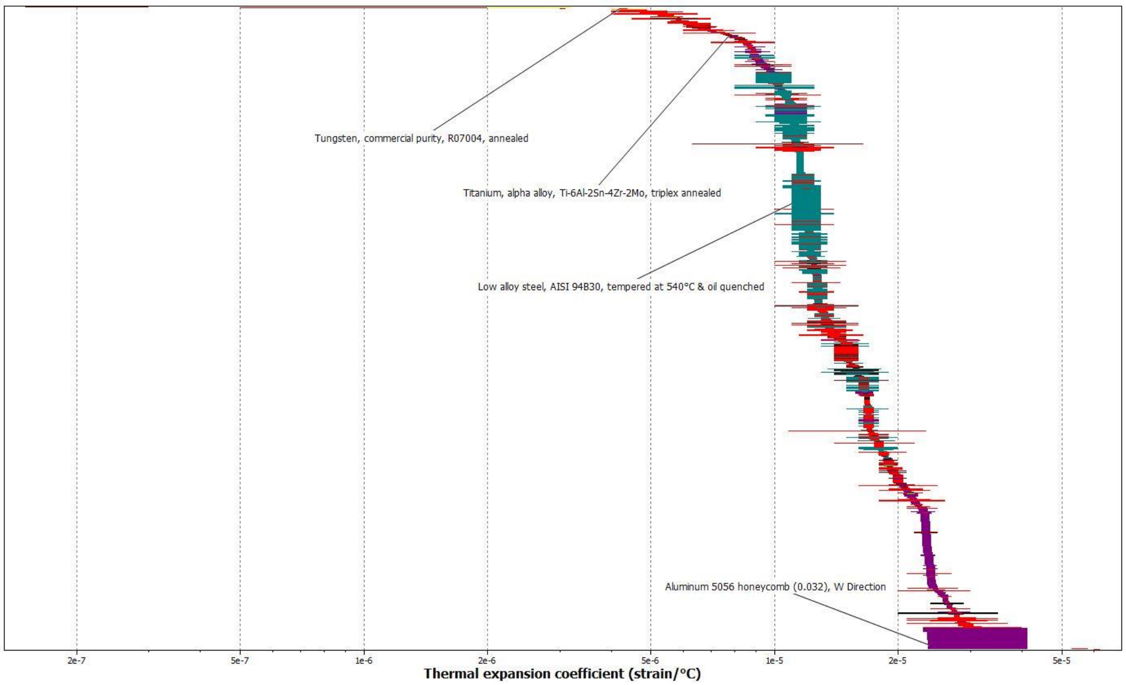


Figure 16 Thermal coefficient comparison.

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

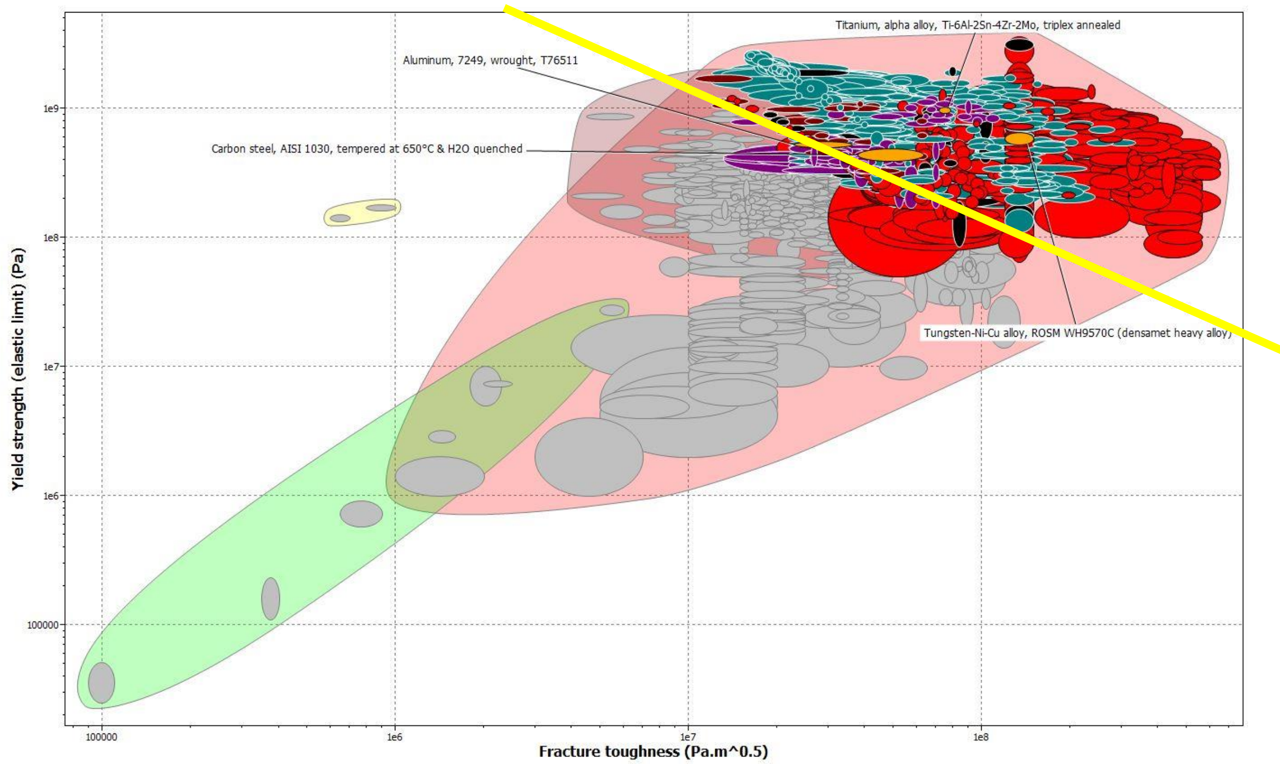


Figure 17 Stiffness and Fracture toughness.

Figure 17 shows that all four materials are in the high range of stiffness and fracture toughness, with a 1:1 importance rating; using the linearity of y=-x.

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 require high quality machining process. As a result, 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 potential risks associated in Low Earth Orbit (LEO) these risks must be considered with the utmost care as to have a reliable system. Due to the environment in which our system will be operating in we cannot simply repair or maintain our device in the occurrence of an unfortunate event. In creating our design as well as choosing parts we always considered the fact that our device may never be retrieved upon deployment in LEO. Upon deploying our device into space a number of events could occur that threaten the integrity of our system that have been 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 as best as we could.

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, leading to failure in logic gates. Being that we are using a FPGA the effects of radiation is a very important consideration. In choosing parts we were able to find a Rad-Hard FPGA 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, longevity of parts becomes a necessity in the design. The parts must be able to withstand the temperature range, radiation, consume low power, and space efficient. By creating a design addressing these different requirements we can best create a system that is reliable needed to withstand LEO conditions. We must also take the specifications given for each part for face value. This means that we must trust that our supplier have given us parts that truly meet the specifications given. However, individual tests for each part were created 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, FPGA, and microcontroller that requires 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 is another consideration needed in a design for LEO. 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. We are also suggesting silicone wheels that will be made to withstand the extreme temperature range. If the wheels do not meet the temperature requirements they may deform lose functionality.

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 last consideration. 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.

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.

Actual testing of the spring here was mostly limited to making sure it isn't too powerful or too weak to be useful to us. The best way to test that was to just build the assembly and try it out, which we did. Our motor was able to expand and retract the spring with no problems, owing to its large torque. 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 began by taking them to the lab to make sure they operate as expected. We looked to make sure that the linear pull is long enough, however the solenoid will not function if given a three volt input, and therefore must be driven by a relay. We have now integrated 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 in the conditions in low earth orbit. As stated above, if the solenoids do not work, custom ones can always be built.

If the solenoid from Bicron Electronics does 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).

FPGA

Testing of the FPGA for the system shall take into consideration the performance of the FPGA to be used once deployed and the FPGA 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

We tested the motor by attaching it's axel to the spring we used in our project, and seeing if it would be able to pull the spring out and let it back in smoothly. At around 5 volts and 600mA, or 3W, the motor was able to do this flawlessly. This is mostly due to the fact it has a large gear ratio reduction of 171.79:1, which makes it's motion slow but powerful.

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 our design we chose to use silicone rubber wheels to drive out the tape measure supporting the solar cell and substrate. Due to the extreme temperatures of low earth orbit (LEO) material integrity is of utmost importance. Silicone rubber is known for its elasticity as well as resilience in adverse conditions.

Often silicone is made to withstand extreme temperatures up to 300 C while the lower temperature extreme for silicone rubber can be found as low as -100 C. Silicone at high temperatures will become soft and irreversibly deform. “At very low temperatures silicone will stiffen and become "glass-like".”("Low Temp Silicone." *Primasil Silicones*. Primasil, 1 Jan. 2014. Web. 1 Jan. 2015. <http://www.primasil.com/en/content/cms/home/silicones/products-services/material-formulation/low-temp-silicone/>.)

Primasil advertises having developed phenyl-based compounds that allow for function at these extreme low temperatures. Though they advertise the low temp silicone, they do not explicitly state the maximum temperature it can reach. It would be advised to use Primasil’s silicone being that it is one few companies offering low temp silicone. Primasil has listed out the low temperature capabilities as shown in the Figure 18 below.

Low Temperature Capability

- Durometer Hardness (Shore A) 30 – 70
- Specific Gravity (g/cm3) 1.15 – 1.22
- Tensile Strength (Mpa) 6 – 8
- Elongation (%) 200 – 550
- Tear Strength (N/mm) 10 – 22
- Min Temperature -100C
- Catalyst type M / E
- Compression Set % (22h @ 175°C) 20 – 45
- Approvals FDA
- Colours available: All

High Temperature Capability

- Durometer Hardness (Shore A) 40 – 70
- Specific Gravity (g/cm3) 1.1 – 1.2
- Tensile Strength (Mpa) 6.6 – 8
- Elongation (%) 200 – 450
- Tear Strength (N/mm) 12 – 20
- Max Temperature 300C
- Catalyst type M / E
- Compression Set % (22h @ 175°C) 20 – 40
- Colours available: All

Figure 18 Capabilities of Primasil."("Low Temp Silicone." Primasil Silicones. Primasil, 1 Jan. 2014. Web. 1 Jan. 2015.

Figure 18 (L) shows the low temperature silicone capabilities and Figure 18(R) shows the high temperature silicone capabilities.

Along with their low temperature silicone Primasil also has their high temperature silicone. It is advertised that the high temperature silicone can last up to 3 weeks at 300C, however, it is not advised to do. It is suggested that the silicone only be subjected extreme temperatures briefly and periodically, if possible, to preserve its structural integrity. Again, in Figure 2 are the capabilities of this high temperature silicone made by Primasil.

Alternative to Primasil the company Likon boasts an ultra-low temperature silicone reaching down to -116C. More often silicone rubber is made to withstand extreme high temperatures due to human use while companies advertising low temperature silicones are less common.

To test the silicone a variety of tests can be performed: brittleness, temperature retraction, and static/kinetic friction. Brittleness measures the ability to withstand breaking without significant deformation at a given temperature. Temperature retraction is the ability of the rubber to be stretched and measure the retraction length or ability to return to initial state. Last, the static and kinetic friction may be tested using a weighted sled. The sled may be placed upon the rubber surface and weight may be applied or decreased to pull the sled across the surface helping determine the coefficient of friction.

One chemical modification process that is commonly used is Photosil. According to the article "Surface Modification Technologies for Durable Space Polymers", "The photosil process is based on a silylation reaction and allows Si to be incorporated into the sub-surface region of the originally treated material. The surface becomes a new material and attains new properties."(pg. 56). What this process does is creates a stable protective oxide layer helping prevent erosion and etching in LEO.

One physical modification process that may be used is implantox. The article states, "In the Implantox process, a high-dose single or binary ion implantation of metals or semi-metals into polymers is performed that, when combined with special oxidation post-treatment following ion implantation, produces a graded oxide(s)-based surface layer with a variable degree of carbonization, chemically bonded to the original polymer and highly resistant to erosion and oxidation."(pg. 58, Surface

Modification Technologies for Durable Space Polymers). This process protects the polymer, increases oxidative resistance, improves durability, and allows various tailoring abilities.

Boom

Testing of our boom happened in two stages. For our design we will be using two carpenters tapes' (tape measure) welded together on one side while the other side is able to curve out. This will result in a 'v' shaped boom, similar to the TRAC boom produced by the AFRL. The first attempt to produce this boom was to tig weld the two pieces together, but after many attempts, the weld would not hold. Next, the boom pieces were taken to a shop that has spot welding capabilities where the two halves were successfully bonded together. We found that the carpenters tape's themselves were rigid enough to support the weight placed upon them, but upon attempting to roll them, the spot welds broke.

The boom that will be used in a deployed CubeSat 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 as these parameters fall generously within the specifications necessary; this portion of our design has already been tested and approved by NASA for LEO.

Schedules

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

Table 1 Beginning Schedule

Due Date	Tasks	Team Assignment
Oct-5-14	**Wired filters or FPGA**	
	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 2 Updated Schedule

Due Date	Tasks	Team Assignments
10/5/2014	**Wired Filters or PLC Paper**	
	Design Simplicity	Luke
	Size	Dustin
	Cost	Tom/Isaac
	Realiability	Tom/Isaac
	Fabrication	Antjuan/Ryan/Anh
	Implimentation	Antjuan/Ryan/Anh
	Testing	Antjuan/Ryan/Anh
10/31/2014	**Circuit Ourline and Implrovements**	Team
11/1/2014	**Design Constraints were changed**	Team
11/12/2014	**Rediign inside of 1U CubeSat**	
	3D Model, size, and position	Ryan
	Motor	Luke/Antjuan
	Motor Controller	Antjuan
	Locking Mechanism	Tom
	Choose PLC	Team
	Constant force spring	Ryan
	Rollers	Isaac
	Tactile bump sensor	Issac
	1U acrilic box	Team
	PLC logic	Luke

	Bearings and Lubricants	Dustin
12/19/2014	**Final Circuit Compleation** **Materials Selected** **Bill of Materials**	Team Anh Team
12/12/2014	**Send draft design to NASA**	Team
1/20/2015	**Order Materials**	Team
2/2/2015	**Began Building CubeSat**	Team
3/28/2015	**Final Presentation**	Team
4/21/2015	**Project Poster**	Team
4/25/2015	**CubeSat Complete**	Team

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.

List of Tables

List of Figures

Appendix I:

Setup for the CubeSat is quite simple: the box will need a 6 Volt power source. To operate the system, the operator will need to use the HMI. To start, flip Switch One to extend the boom. If, at any point during extension, the torque exerted to extend the boom exceeds our predetermined threshold, the process will terminate. To restart the process once the box and boom have been inspected, the reset button needs to be pressed on the HMI. To retract the boom, flip Switch Two. As before, if the torque exerted to retract the boom exceeds our threshold, the process will terminate, requiring the reset button to be pressed to restart. At any time, if the operator would like to stop the current process, Switch Three can be flipped to terminate any process. If the process is operator terminated, the reset button does not need to be pressed before resuming the process.

Table 3 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

Table 4 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

Appendix II:

According to our preliminary design constraints of a one cubic foot box, our initial prototype was similar to a scissor jack. The prototype could easily deploy nine square feet of solar array. A bidirectional motor capable of three foot pounds of torque would need to drive a threaded rod to draw the floating base point toward the fixed base point, causing the system to extend. This system seemed to work well, however it was abandoned when our design constraints changed to 1U.

Figure 19 Scissor Design

After the sponsor had a meeting with his team, the new problem statement became

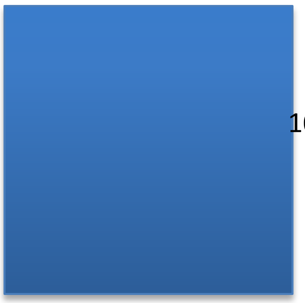
> "Team is tasked with designing and implementing a deployable and retractable boom to extends a minimum area of $4ft^2$ using bendable solar arrays and fits within a CubeSat or 1 U (10 x 10 x10 cm^3)".

The alternative design to the tape measuring roller design was to use a traditional 360° silk fan design. In the preliminary fan design one dual phase motor would be needed as well as multiple servomotors. One motor would first need to deploy the circuit up and then unfold the fan design. It would need to be gear driven with one at the pivot point able to allow 360° rotation. Another gear to unfold achieving more than 1 foot radius of the solar cell and substrate. Given the space constraint and what was needed in this design it was found very challenging to achieve the $4ft^2$.

Number of servos calculations:

Assuming

- Using the longest dimension of the box
- Using the whole area of the fan for solar cells
    - In reality, the smallest solar cell is 1cm x 1cm



Solar array area = $4ft^2 \sim 3716.12\ cm^2$

$$Diagonal\ Distance = \sqrt{10^2 + 10^2} \approx 14.14\ cm$$

$$Area\ of\ Circle = \pi R^2 \approx 3716.12\ cm^2$$

$$R \approx 34.4\ cm$$

The design is great to implement but the main problem may have too many mechanical components failures.

Appendix III:

Design constraints were soft set at 1U, but could be expanded to 2U if absolutely necessary. We elected to go with a 1U design to challenge ourselves and to provide the best possible solution for NASA when it comes to size concerns. With a 1U design, NASA is left with much more space to put diagnostic and data gathering equipment in the CubeSat. Using a 1U sized design also allows these solar panel modules to be used in a modular fashion- if a particular satellite needs more power than one can provide they can be linked together to increase the total amount of power generated.

We overcame many challenges in the course of two semesters when designing and building our CubeSat. This allowed us to learn many skills that will be required of us in the workforce. We started off as a large group of different engineers and came together through struggles and problems that arose. Our group faced several time constraint issues when it came to other classes and assignments we had. This lead to better time management as a whole that allowed us to meet our requirements on time and even do some other things that NASA didn't have in the original document.

As a group we also faced challenges when it came to bringing the group together to build a final project. This allowed us to make a final project that fit NASA's requirements and was a reasonable solution to the given problem. We did face some changes to our space constraints when we built our final concept and this lead to some redesigning and some material changes that gave us a better design in the end.

Appendix IV:

Table 5 Seven Segment Decoder Code

```
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
```

Table 6 Boom Code

```
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
```