EML 4905 Senior Design Project

A B.S. THESIS
PREPARED IN PARTIAL FULFILLMENT OF THE
REQUIREMENT FOR THE DEGREE OF
BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING

Lunar Excavator: NASA Lunabotics Competition 100% Report

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December 2012
This B.S. thesis is written in partial fulfillment of the requirements in EML 4905.
The contents represent the opinion of the authors and not the Department of
Mechanical and Materials Engineering.

Ethics Statement and Signatures

The work submitted in this B.S. thesis is solely prepared by a team consisting of Maria Wilhelm, Stephane Briette, and Diego Bolivar and it is original. Excerpts from others' work have been clearly identified, their work acknowledged within the text and listed in the list of references. All of the engineering drawings, computer programs, formulations, design work, prototype development and testing reported in this document are also original and prepared by the same team of students.

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Abstract

The Lunabotics Mining Competition is a college competition held by the National Aeronautics and Space Administration (NASA). In order to participate, students must design and build a mining robot to function in a lunar environment. The competition consists of five categories: On-Site Mining, Systems Engineering Paper, Outreach Project, Slide Presentation, and Team Spirit. In order to qualify for the remainder of the categories, the robot, also called a Lunabot, must complete two rounds of the On-Site Mining category. It must mine a minimum of ten kilograms in ten minutes on each round. Senior Design Team Seven will participate in the Lunabotics Competition of 2013. Previous to designing the Lunabot, the team conducted preliminary research, focusing mostly on previous competitors, mining equipment, and the properties of the regolith simulant to be mined in the competition, Black Point-1. Next, multiple conceptual designs were drawn using SolidWorks. From these designs, a proposed design was generated. Additionally, mechanical analysis will be performed on the design using SolidWorks motion study and others. Data and observations acquired through this process were used to revise the proposed design and make needed changes. The final model was constructed and tested. The mobility and mechanical operation of the robot was tested on different sand surfaces, as well as its mining abilities. The results were compared to those obtained from the simulations and reasoning for the deviation between both results were explored.

NASA created this contest to attract and retain science, technology, engineering, and mathematics majors by “engaging them in an exciting environment” [1]. Also, the agency has long term plans for lunar colonization. A first step for the construction of bases is the mining of

the moon soil in order to prepare the land for construction. From this competition, NASA seeks to acquire inspiration to carry out this project in an innovative and creative way.

1. Introduction

1.1 Problem Statement

The purpose of this project is to design and manufacture a robot for NASA Lunabotics Mining Competition. The robot must be equipped with Black Point-1 excavating, storage, and dumping mechanisms. Additionally, it must be able to maneuver through rough terrain, either autonomously or remotely by a competitor and function in a lunar environment.

1.2 Motivation

The competition allows student to apply the knowledge they have accumulated through their academic career into a challenging project that requires competitors to come up with an innovative design. Thus, students competing will be motivated to continue pursuing a career in science, technology, engineering, and mathematics. Additionally, the most ingenious designs provide NASA with new ideas that they will apply to future space projects.

1.3 Literature Survey

The Literature Survey was divided into two categories based on whether the information was of a regulatory or scientific nature.

1.3.1 Rules

NASA posts the competition rules on their official Lunabotics website [2]. Teams registered to compete must enter three different categories: On-Site Mining, Systems Engineering Paper, and the Outreach Project. Additionally, teams may choose to compete in the Slide Presentation and Team Spirit categories. The On-Site Mining Category is scored using the table shown below. Each team is given two rounds to score the maximum number of points. The team with most points is deemed winner of this category.

Table 1: LunaPoints per Round

Elements	LunaPoints	Elements	LunaPoints
Safety Inspection	0 or 1000	Regolith over 10 kg	+2/kg
Bandwidth	-1/50kb/s	Lunabot Mass	-10/kg
Report Energy Consumed	+100	Dust Tolerant/ Free	0 to +200
Obstacle Autonomy	+250	Full Autonomy	+500

Every team must pass the safety inspection in order to continue. Points are reduced per 50 kilobits per second of bandwidth of the controller and per kilogram for of mass of the robot. Reporting energy consumed, giving the robot partial or full autonomy, having dust tolerant design, and excavating over ten kilograms awards the team LunaPoints.

The Lunabot will excavate in the LunArena shown below. The Black Point-1 must be deposited in the LunaBin, which is placed 0.5 meters (1.64 feet) above the BP-1 layer.

Each run, the robot must begin at the marked starting point. From there it drives through an obstacle course and finally arrives to its designated mining area. It may only mine in the mining area. It travels back to the LunaBin, where it must dispense the BP-1 in order to be counted for LunaPoints. Each run is 10 minutes long.

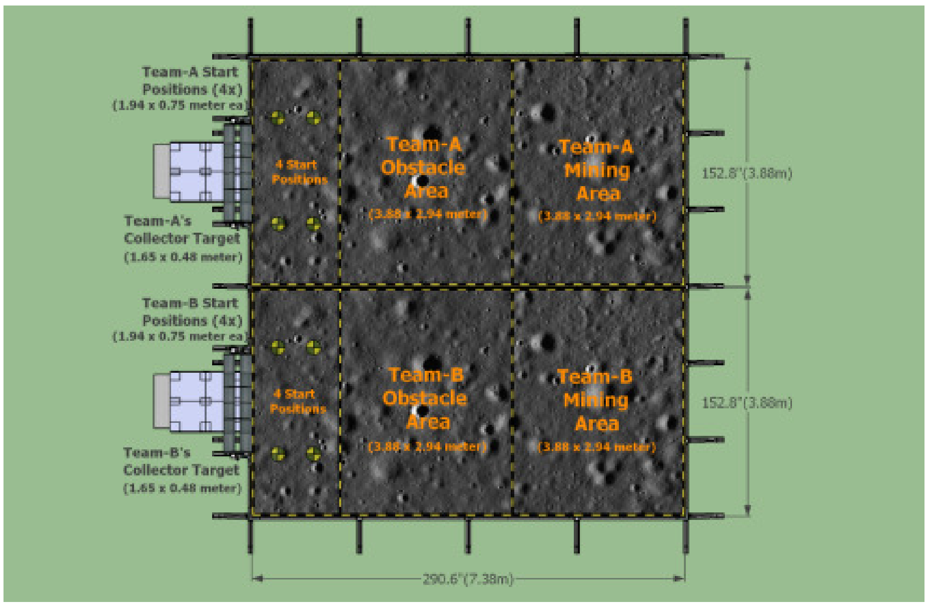

Figure 1: LunArena

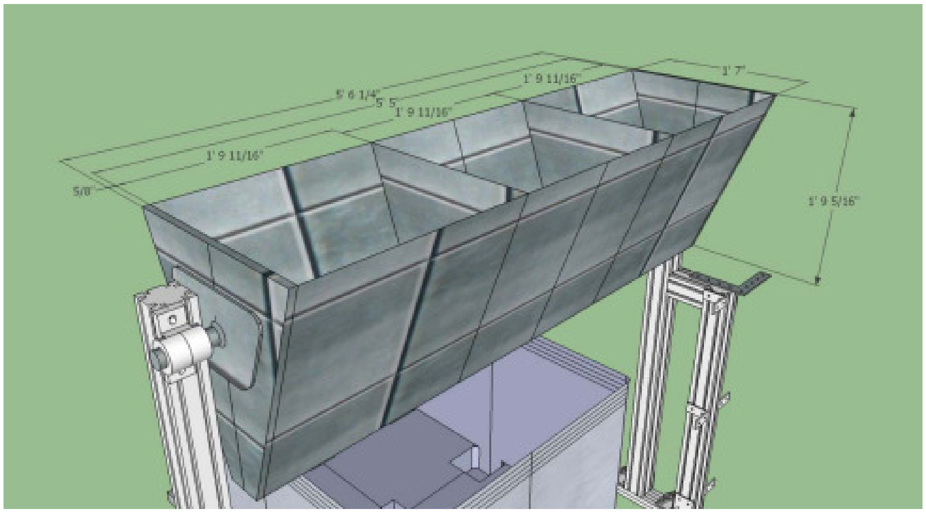

Figure 2: LunaBin

The Systems Engineering Paper is scored based on its intrinsic and technical merit, the scores ranging from zero to four, four being the best. The same is applied to the Outreach Project. For Outreach, each team must take part in a school career fair, science fair, or other similar educational projects. Again, a report must be submitted explaining the project chosen. In addition to the two optional categories (Team Spirit and Slide Presentation), there is a category for bonus points. For this category, teams who collaborate from majority and minority institutions are awarded extra points. Multidisciplinary teams are also awarded extra points.

Awards are given for each category. The winner of the overall competition is awarded the Joe Kosmo Award for Excellence.

1.3.2 Scientific Review

In preparation for the competition, the team reviewed several materials from which to fabricate the Lunabot. Also, the nature of the material mined was studied, due to its unusual nature. Lastly, different electrical and computational systems were reviewed as well.

1.3.2.1 Black Point-1

Black Point-1 (BP-1) named after the Black Point basalt flow from the San Francisco Volcanic field (Arizona), from where it is extracted. The Black Point basalt is fairly alkaline and is high in iron magnesium [3]. The table below contains the chemical makeup found in two samples of Black Point flow. W172158 corresponds to the sample used on the western portion of the flow and W172154 corresponds to the eastern flow.

Table 2: Chemical Make-Up of BP-1 [3]

Sample	W172158	W172154	Sample	W172158	W172154
Latitude	35.67	35.67	CaO	9.2	9.6
Longitude	-111.47	-111.35	Na_2O	3.5	3.4
SiO_2	47.2	46.9	K_2O	1.1	1.1
Al_2O_3	16.7	16.4	P_2O_5	0.52	0.51
TiO_2	2.3	2.2	$H_2O -$	0.11	0.51
Fe_2O_3	5.9	8.2	$H_2O +$	0.41	0.69
FeO	6.2	3.7	CO_2	0.05	0.26
MgO	6.5	5.6	Total	99.90	99.28
MnO	0.21	0.21	FeO_{Total}	11.7	11.4
			% An	47.1	46.7

An important characteristic of BP-1 is its particle size. BP-1 is found in multiple grain size, however it is most abundantly found in the form of fine coarse particles. Thus, BP-1 represents a challenge for its abrasive nature and harmful effects on technological equipment. The figure bellow compares the particle size of BP-1 and other materials against its abundance.

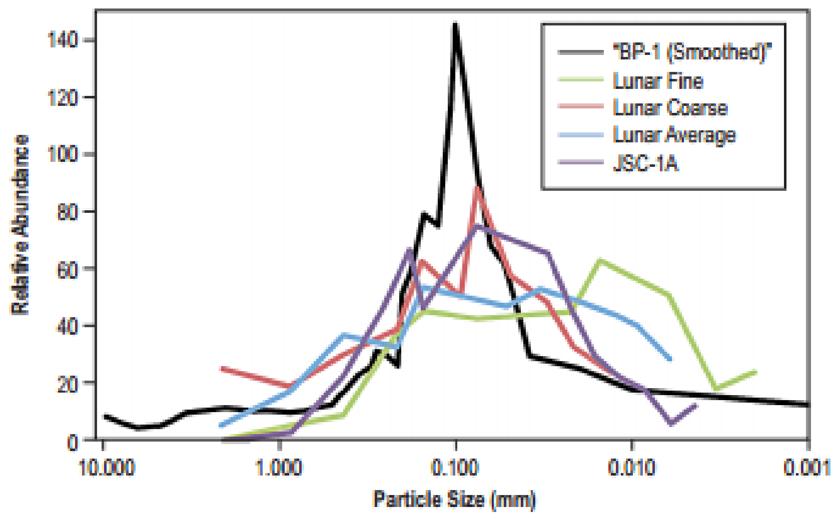

Figure 3: Particle Size [3]

According to the Lunabotics' official rules, the density of BP-1 is between 1500 and 1800 kilograms per meters cubed for the lower more compact layer. The top layer has an average density of 750 kilograms per meters cubed.

1.3.2.2 Mechanisms

Excavating mechanisms corresponds to the method by which the robot will collect BP-1. In the past two years of competition, there have been approximately 15 different types of excavating mechanisms employed. The most popular mechanisms are the bucket ladder, bucket belt, and bulldozer.

Below are the mentioned mechanisms. The Lauretian University won first place for both the mining category and the competition with the design displayed above. It was able to collect 237.4 kilograms of BP-1 on both runs. The previous year, Montana State University collected

21.6 kilograms on both runs, also wining first place using a bucket ladder. The popularity and success of the bucket ladder is due to its low power consumption and high excavation capacity [4].

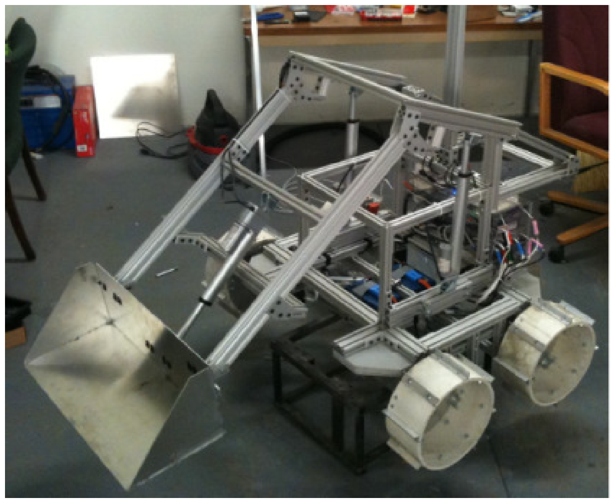

Figure 4: University of Alabama

Figure 5: Lauretian University

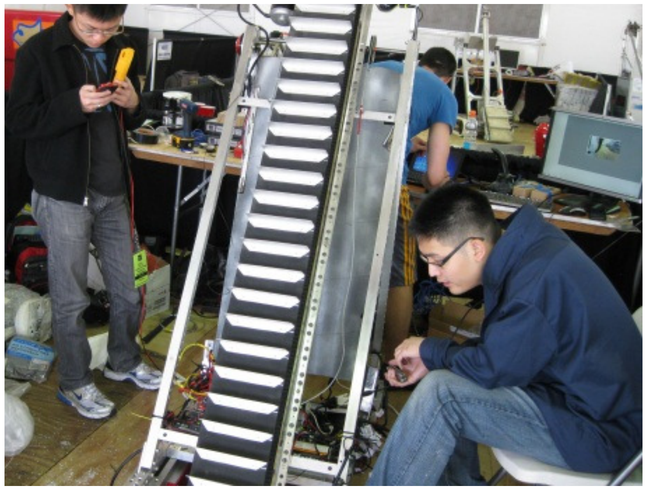

Figure 6: NYU Poly Tech

The transfer mechanism refers to the component used to transfer the BP-1 from the excavating structure to the bin. Note that not all designs require this to be an extra component, since there are techniques used encorporate this along with the digging mechanism. The bucket ladder, for example, uses a number of chains (usually ranging from one to four) with multiple small buckets attached. The chain rotates, causing the small buckets to scoop sand as they pass by the lowest point. The ladder continues to rotate, dumping the BP-1 into the larger bucket once it reaches the highest point in the ladder. For transfer mechanisms, the bucket ladder was once more the most popular choice, followed by the conveyor belt and impeller as far second and third design choices.

For storing the BP-1, there were different forms of 'buckets' used. The most used was the hopper, followed by the scoop, and the scraper. The hopper is a bucket with a chute at the bottom. A scooper is another word for a simple bucket, and a scraper is a detachable hopper. To dump the collected BP-1, most teams choose the to tilt the hopper or scoop over the

LunaBin. For the teams who created a stationary hoppers, converyor belts were mostly used to carry the sand into the LunaBin.

Deciding on the mobility mechanisms for the Lunabot is key, particularly since the Lunabot must pass through an obstacle field when going between the dumping to the mining area. Overall, Lunabots using tracks showed better mobility throughout the mining course than those that used wheels. Wheels would typically get stuck when going through the obstacle area. Never the less, last year's winner (Lauretian University) used four wheels in its design. [4]

1.3.2.3 Materials

The first material considered was aluminum 6061. Historically, aluminum allows are known for their aerospace applications. This is due to the metal's low density and resistance to chemical reactions such as oxidation. Furthermore, aluminum alloy 6061 is most available type of aluminum alloy as well as the most used one by manufacturers in need designs that are resistant to corrosion. It is useful for temperature resistant applications, and easy to work with in terms of welding, heat treating, and forming.

The table below summarizes the physical and chemical make-up of aluminum 6061.

Table 3: Physical Properties for Aluminum 6061 [5]

Physical Property	Quantity
Density	2700 kg/m^3 (0.0975 lb/in^3)
Specific Gravity	2.7
Melting Point	587.78 C (1090 F)

Table 4: Chemical Make-Up for Aluminum [5]

Physical Property	Quantity	Physical Property	Quantity
Aluminum	Balance	Chromium	0.04-0.35
Copper	0.15-0.4	Iron	0-0.7
Magnesium	0.8-1.2	Manganese	0.15
Silicon	0.4-0.8	Titanium	0.15
Zinc	0.25	Other	0.15

Table 5: Mechanical Properties of Aluminum [6]

Property	Quantity	Property	Quantity
Hardness	95 (Brinell) 120 (Knoop)	Hardness	40 (Rockwell A) 60 (Rockwell B)
Tensile Yield Strength	276 MPa (40000 psi)	Ultimate Tensile Strength	310 MPa (45000 psi)
Elongation Prior to Failure	12%-17%	Modulus of Elasticity	68.9 Gpa (10000 ksi)
Notched Tensile Strength	324 MPa (47000 psi)	Ultimate Bearing Strength	607 MPa (88000 psi)
Bearing Yield Strength	386 MPa (56000 psi)	Poisson's Ration	0.33
Fatigue Strength	96.5 MPa (14000 psi)	Fracture Toughness	29 Mpa-m (26.4ksi-in)
Shear Modulus	26 GPa	Shear Strength	207 MPa (30000 psi)

	(3770 ksi)	

Other materials explored come from the family of plastics. Melamine resin is a plastic used mostly for kitchen and construction applications. It is heat and fire resistant, and will not melt. However, the issue with this plastic is that it must be manufactured from its powered form and casted into the required form. Thus, there is no room for mistakes.

Polyether ether ketone (PEEK) is a plastic largely used in engineering applications for its advantageous mechanical and chemical properties. Amongst other things, the material is resistant to fatigue, has a low friction coefficient, and is resistant to aggressive chemical environments. This last quality makes it of special importance, since due to the BP-1 the Lunabot will be submerged in. A summary of the material properties can be found below:

Table 6: Mechanical Properties of PEEK

Element	Quantity
Density	1320 kg/m^3 (0.0477 lb/in^3)
Young’s Modulus	3.6 GPa (522000 psi)
Tensile Strength	95 MPa (13779 psi)
Elongation	50%
Melting Point	343 C (649.4 F)

Furthermore, this material is widely used aerospace, medical, and automotive applications. On the other hand, PEEK’s coveted properties create a high demand, which results in high prices for it (around a thousand dollars per square meter). Polyetherimide (called PEI commercially) is a less expensive alternative to PEEK; however, it is less resistant to impact and temperature changes. Below is a summary of its properties:

Table 7: Mechanical Properties of PEI

Element	Quantity
Density	1270 kg/m^3(0.0459 lb/in^3)
Young's Modulus	2.965 GPa (430000 psi)
Tensile Strength	104.8 MPa (15200 psi)
Elongation	60%
Melting Point	218.9 C (426 F)

The prices for this material are considerable lower, costing about one-hundred and sixty dollars per meter squared.

Polycarbonate is another material which is widely used in the industry because of its ability to mold and thermoform with ease and impact resistance. As the molecular mass decreases, the material becomes easier to mold and process but also weaker and less tough. Their applications range from construction to aerospace industry, to electrical components. Below is a summary of its properties:

Table 8: Mechanical Properties of Polycarbonate

Element	Quantity
Density	1210 kg/m^3(0.0437lb/in^3)
Young's Modulus	2.0 GPa (290000 psi)
Tensile Strength	55 MPa (7977 psi)
Elongation	80%
Melting Point	276 C (528.8 F)

Poly(methyl methacrylate) (PMMA but known in industry as acrylic glass or Plexiglass) is a synthetic polymer often used as a glass replacement for applications that require a lighter, stronger alternative that is easy to process. PMMA is closely related to polycarbonate. It is less expensive, however, does not have the ability to be processed or formed at room temperature (unlike polycarbonate) since it is considered brittle. Below is a summary of the properties of PMMA:

Table 9: Mechanical Properties of PMMA

Element	Quantity
Density	1180 kg/m^3(0.0426 lb/in^3)
Young's Modulus	3.3 GPa (479000 psi)
Tensile Strength	80 MPa (11603 psi)
Elongation	5.5%
Melting Point	160 C (320 F)

Polyvinyl chloride (PVC) is a widely used material in engineering applications. It is easy to manufacture and process as well as inexpensive. PVC is also resistant to harsh chemical environments. Thus, it is often used in sewage systems. Furthermore, this material is adaptable many other applications, by the use of additives which make it more flexible, stronger, or insulating. Below is a summary of the properties of PVC:

Table 10: Mechanical Properties of PVC

Element	Quantity
Density	1500 kg/m^3(0.0515 lb/in^3)
Young's Modulus	2.413 GPa (350000 psi)
Tensile Strength	50 MPa (7300 psi)
Elongation	24%
Melting Point	182 C (359.6 F)

1.3.2.4 Electrical Systems, Software and Communications

In order to move the Lunabot, electric motors will be employed. In specific, linear actuators and windshield wiper motors have been considered. Windshield wiper motors have a relatively high torque (usually between 15 lb-ft and 18 lb-ft) [8], which is desired when moving through rough terrain. Recall that torque (with units in N-m or lb-ft) deals with the amount of force applied by the motor. Thus a higher torque means a greater force translated to the wheels. Additionally, there is usually a trade of between torque and angular velocity; meaning the more revolutions per minute (rpm), the lower the torque applied. Furthermore, torque and angular acceleration can be related to power.

$$P = T\omega$$

P is the symbol used for power, T for torque, and ω for angular velocity. Consider the specifications for the windshield wiper motor produced by Shanghai Xinyonh Auto Parts. They are DC motors available in the form of 12V or 24V, with a power of 50W. They move between 40 rpm and 70 rpm, with a mass of 1.6 kg or 3.53 lbm.

The motor will be connected to a circuit in order in order to be powered and controlled. Typically, a microcontroller is used to communicate control the motor. Microcontrollers are computers in the sense that they posses all its vital elements: memory, processor, and i/o peripheral. Microcontrollers require a power source, additional to that one required by the motor connected to it. Typically a regular 9V battery is used.

Furthermore, with the increasing use of computational devices, microcontrollers are manufactured with varied specifications in order to meet the market’s demand. Arduino is a widely used open-source microcontroller. Its wide variety of applications mae it useful for hobbyist as well as engineers. Furthermore, additional hardware (also know as a shield) may be attached to the microcontroller in order to make it WiFi compaticle.

Most teams opted to use programs such as LabView since sophisticated programs such as these are more efficient when obtaining advance control systems. Another option (as previously mentioned) is to program microcontrollers, which are less sophisticated but more affordable than the previously mentioned option. Arduino uses its own language, resembling C++. A technique known as ‘pulse-width modulation’ can be used to control the motor speed and power. Most microcontrollers already include the required hardware necessary for this technique. Pulse width modulation (PWM) is used on a great variety of applications, including controlling microprocessor's output in an analog circuit. PWM uses digital controlers to encode an analog signal. An analog circuit, in simple terms, is a circuit whose voltage varies over time. As mentioned by the Embedded Systems Programming magazine, the nine volt battery is an example of this type of circuitry. This is because the output voltage measured from the device in real time changes, typically ranging from 9.6V to 5V. The previously mentioned range goes from fully charge to dead. For analog circuits, the output is directly proportional to the input by means of a linear function. On the other hand, analog circuits also suffer from overheating and tuning. While the last mentioned issue can be solved with the use of more precise and expensive components, heating increases with voltage (since it is due to power dissipation).

PMW works by modifying the duty cycle of a square wave, via voltage over time. Below is an image depicting the square wave output after being manipulated. The term 'duty' refers to the amount of on time in one period. Lastly, note that at all times during the cycle, the voltage supply is either fully on or off.

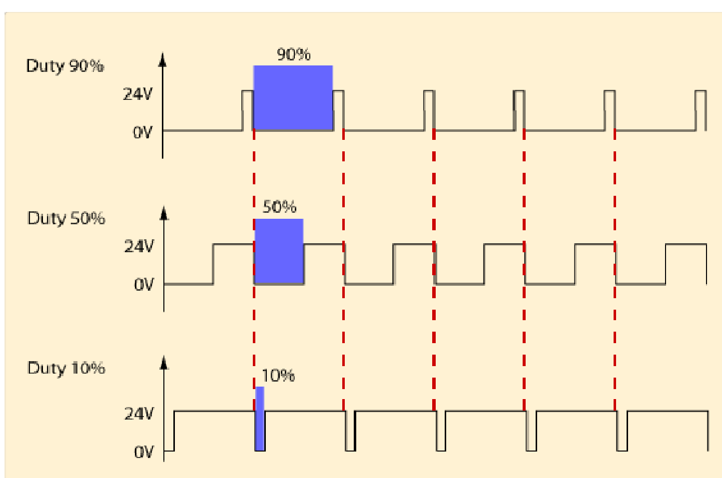

Figure 7: PWM Output [11]

The figure below shows a simple circuit which uses PMW in order to control the lamp's on and off settings. The duty cycles indicates for how long the switch must be closed. When the switch is open, the lamp does not receive any voltage. When it is closed the lamp recieves 9V. Also, the number of times the cycle is repeated per second is called the 'modulating frequency,' and it is measured in units of hertz (Hz).

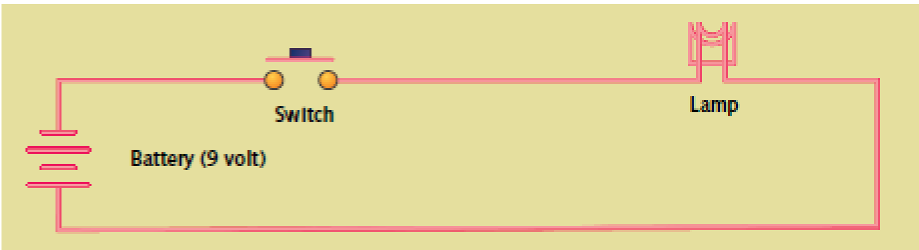

Figure 8: Lamp Circuit [10]

Assuming that one cycle takes one second to be completed, if users wish to switch the lamp on for half a second, then the corresponding duty cycle would be of 50%. If this cycle is repeated over a long period of time, the lamp would seem be on at half the intensity and using half the voltage. In order to increase the intensitiy of the light, the duty cycle needs to be increased.

Unlike analog signals, digital signals are minimally affected by noize. This is an advantage for PWM methodology since it inputs and outputs are given in the form of 0's and 1's (fully on or fully off). For control and communication systems, the PWM signal remains digital when going between the processor and the circuit.

When writing a program using PWM methodology, the following steps underline the procedure for writing said program. First, use the period set by the counter to provide the square wave and designate the on-time on the control. Select the direction of the wave output and start the timer. Lastly, enable the PMW controller.

In order to power the Lunabot, different forms of batteries were considered. Particularly, lithium-ion polymer batteries (Li-poly) were studied. These batteries are different from traditional lithium-ion because the electrolyte is held in a gel based polymer (usually vinylidene flouride) rather than a solution. Li-Poly batteries perform better than the regular lithium-ion kind, however they are also cost more and are of volotile nature. Charging beyond capacity, short circuiting, and cell damage are amongst the causes for accidental ignition of the battery. Furthermore, if they are discharged beyond their recommended capacity, Li-Poly cells lose their ability to charge to full capacity. These batteries have a life of about 500 charge/discharge cycles before there is a drop in the battery efficiency. Lastly, recall that in order to increase the voltage output, batteries are connected in series, while connecting them in parallel increasses current.

1.4 Discussion

After problem at hand, a literature survey was conducted based on the nature of the project. The literature survey was divided into several sections. First, the rules of the competition were outlined, allowing the team to identify the parameters by which the Lunabot must be designed. Special aspects to of the competition where identified and further studied, including the use of BP-1 and its possible impact on the Lunabot. Additionally, successful competitors were studied in order to increase the chance of a successful design.

2. Project Formulation

2.1 Overview

A mining robot adapted to lunar environment will designed and built using the rules and regulations set by NASA. In order to complete this project, mechanical, electrical, and computer engineering principles will be applied. In building the Lunabot, it is crucial to consider the environment it will be subjected to. The presence of BP-1 means that the Lunabot must be built to withstand corrosive conditions.

Furthermore, the team also seeks to complete this project in a timely and economic manner.

2.2 Project Objectives

There are a set number of objectives which are crucial for the success of the prototype.

- The Lunabot must be able to pick up twenty kilograms of regolith per scoop.
- The Lunabot must be able to collect an overall amount of sixty kilograms in the bin.
- The Lunabot wheels must provide enough friction to pass through a short obstacle course. The Lunabot frame must be stable enough to pass through said obstacle course.

2.3 Design Specifications

- The Lunabot must have an easily accessible button in case it of an emergency.

- The Lunabot must be below eighty kilograms in total.
- The bandwidth must be below fifty kilobytes per second.
- The Lunabot's performance must be weighed against cost, weight, and bandwidth.
- The Lunabot must maintain a low center of gravity in order to maintain stable movement.

2.4 Constraints and Other Considerations

As previously stated, the constraints are set by the NASA Lunabotics rule guide. The appendix is attached at the back for reference. Furthermore, an additional goal for this project is to manufacture the Lunabot with a budget of $4000. Typically, these robots cost between $8000 and $12000 dollars, making the competition expensive and seemingly inaccessible for prospective competitors. Successfully building the robot under the previously stated budget will demonstrate the competition to be more accessible and encourage more school to participate.

2.5 Discussion

Constraints and specifications were defined in this section in order to give the team a better understanding of the requirements for this competition. The rules and regulations outlined by the Lunabotics board are lengthy and complex. Thus, this section gives the team a clearer understanding of the design goals.

3. Design Alternatives

3.1 Overview of Conceptual Designs Developed

Below are different alternatives developed by the team through the design process. As noted in the literature survey, special attention was paid to past competitors who experienced great success during their competition when assembling these designs. The strongest features were picked from each alternative to be considered for the proposed design. Likewise, the features most likely to fail from each design were also noted, however to be excluded from the proposed design. More effective substitutes were implemented instead, and a final design was chosen.

3.2 Design Alternative 1

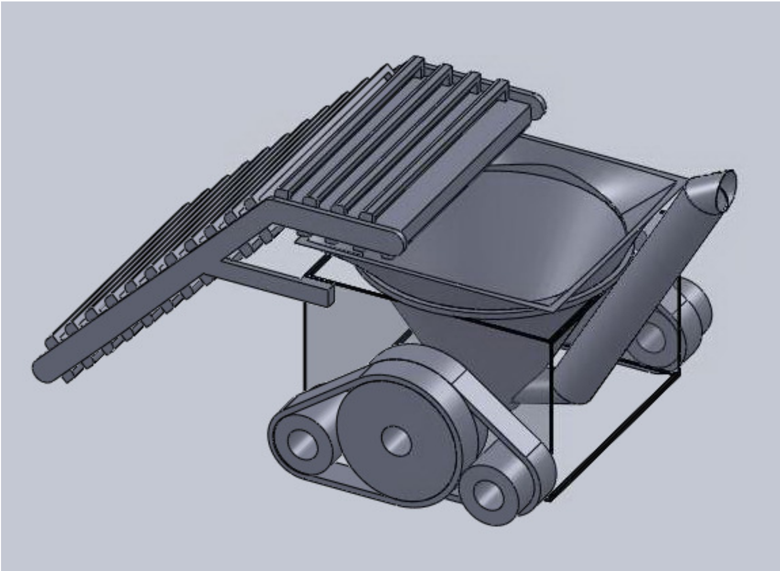

Figure 9: Alternate Design 1

This design consists of a bucket belt, an auger, a bucket, and two pairs of tracks. The two pairs of track provide stability while the robot is moving through the rocky terrain. The bigger middle wheel on both sides creates a greater tangential velocity than a smaller one would while using the same torque. The bucket belt works by moving the belt in a clockwise motion so that the multiple scoops will pick up the sand and deliver it to the conical bucket. The bucket was chosen in a conical shape to ease the movement of the sand towards the bottom of the tank, where the auger will pick it up and dispose of it at the top of the pipe. The auger was placed at an angle of 45 degrees to ease the BP-1's movement towards the exit of the cylinder.

3.3 Design Alternative 2

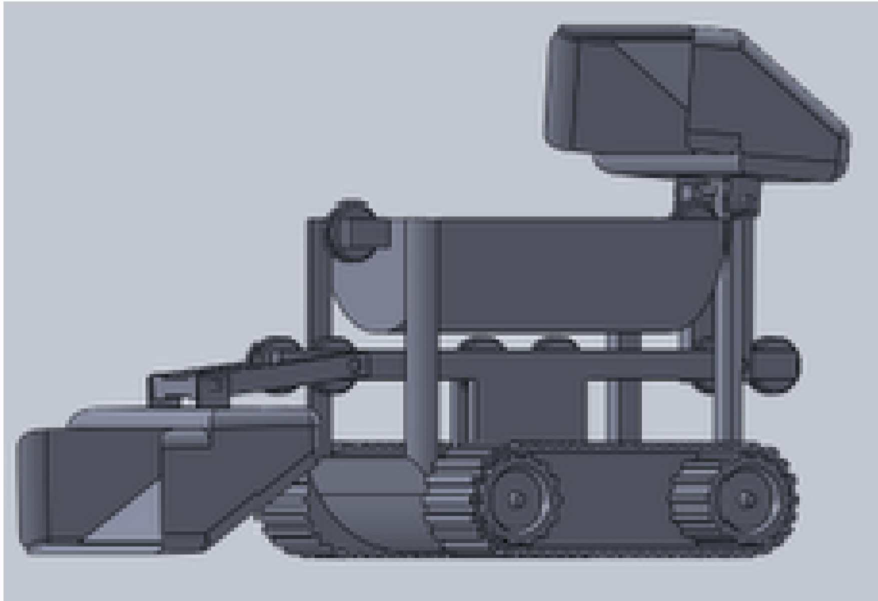

Figure 10: Alternate Design 2

In this design, a system of pulleys is employed and connected to a motor. The design gains a mechanical advantage by using a scoop on each side of the robot with only one motor. The scoops will rise and deposit the sand on the bucket. The bucket will have a 45 degree inclination allowing to be dropped on the lunar bin. For the movement of the robot in figure 6 we decide to use tracks.

3.4 Design Alternative 3

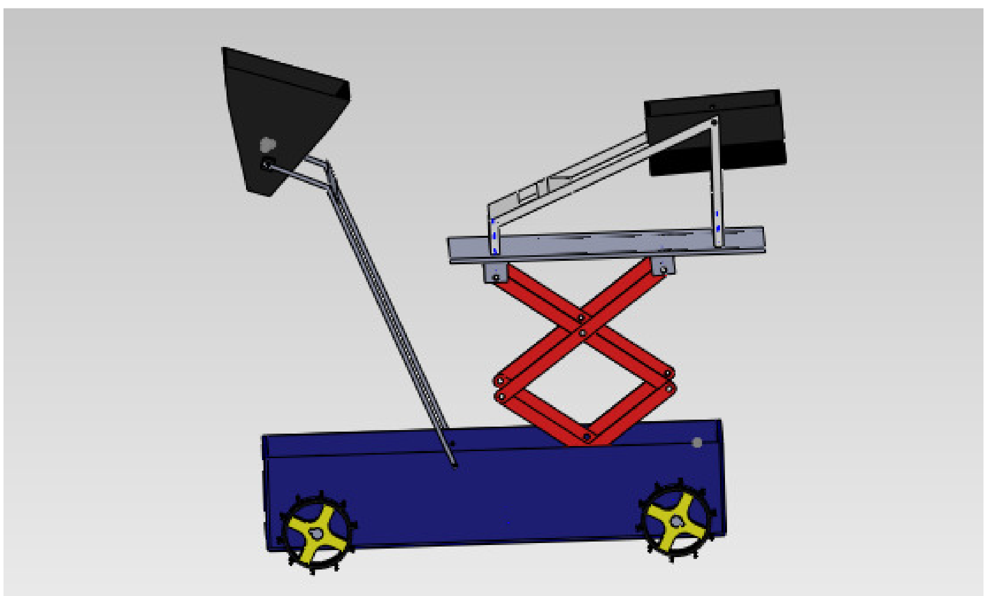

Figure 11: Alternate Design 3

This design mimics the collection technique used by a highly popular piece of heavy machinery to collect regolith, the bulldozer. Just like its full size counterpart, this design alternative uses a shovel or scoop to pick up the material. Next, it is deposited into a bucket located at the rear of the Lunabot. Finally, the bucket rises using a scissor lift and dumps the material into the collector.

3.5 Feasibility Assessment

Feasibility assessments are performed in order to determine the practicality of a design. Factors that affect the feasibility of a product or project include manufacturing costs, difficulty of construction, and availability of materials required. When designing the Lunabot, economic availability was a major factor in deciding the feasibility of the design. Due to financial constraints, the team chose to design the Lunabot so that the total costs would not surpass five thousand dollars. When choosing parts, their availability and compatibility with the rest of the design was also taken into account. Furthermore, since this is the team's first attempt at creating a prototype, simple designs were preferred over complex ones for their easiness to build. Additionally, a simple design is much easier to optimize and make adjustments to when needed.

3.6 Proposed Design

The final design, shown below, was strongly inspired by the third design alternative. The scooping mechanism used is, as previously mentioned, similar to the one used by bulldozers, however the collection and deposit mechanisms have both been modified to better fit the cost parameters and competition time constraints.

Figure 12: Proposed Design (Isometric View)

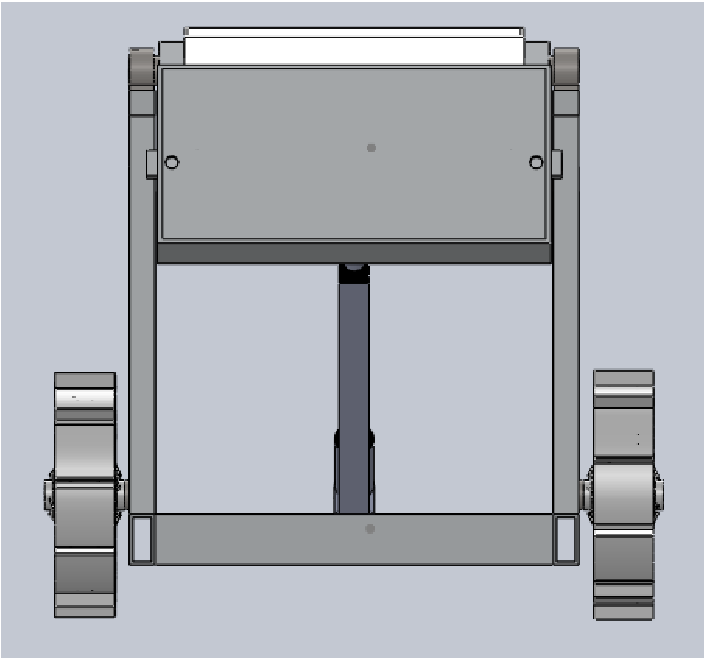

Figure 13: Proposed Design (Front View)

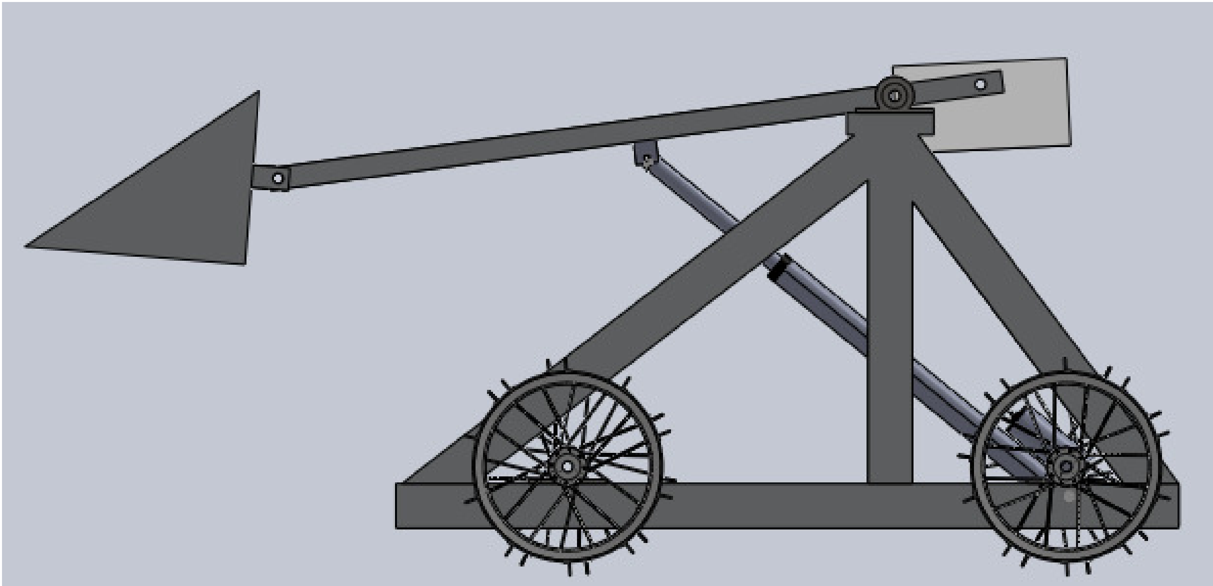

Figure 14: Proposed Design (Side View)

The design for the Lunabot must comply with the competition rules, by adhering to the dimensions range, and only using parts that can be used on the moon. The design consists of three main components; the power-train, the chassis and the arm with the scoop to excavate sand.

In the environment where the robot operates, the loss of traction is a prominent issue for the Lunabot. While tracks provide better traction, they are also expensive and harder to manufacture. Also, they are more prone to failure during the competition due to derailment. Thus, wheels were chosen for their affordability and ease to use. Furthermore, the wheels designed contain fins, which also aid with traction. In order to overcome the lack of traction, large diameter wheels are used to gain more surface area (between 0.1 and 0.3 meters). To power the wheels, two motors are connected to two wheels to give a two by two wheel drive. Moving each motor separately allows for it to be steered in any direction. Pulleys will be placed on each of the shafts manufactured. Belts are attached to the pulleys and finally to the each motor (also employing pulleys) so that each belt connects the two wheels on each side and also to one motor. Thus only two pulleys are employed for this system. The chassis was designed as a triangular box of aluminum. The triangular shape was chosen because of its higher resistance to internal stresses as opposed to other shapes, such as a squared box. Thus, this shape requires less material to support the structure. It supports the excavating mechanism while keeping a low weight of the overall structure. The frame contains two rotational mechanisms, one that will move the arm up and down and another that will rotate the scoop.

Furthermore, the motors used will be wiper motors, the same kind as those used in the Toyota Camry. These motors where picked because they have high torque, which is preferred when moving through tough terrain.

Unlike in the alternate design, the proposed robot does not have a bin for collection after the regolith has been excavated. Thus, it is critical to note two things regarding the robotic arms that will be used for collection: first the bin with which the arms will excavate will need to be sufficiently large so that the time spend moving between the collection site and the site of regolith deposit is minimized, and second the arms must be strong enough to sustain the load of the bin once it is filled with regolith.

After the sand is gathered, the Lunabot will then transport it to the desired location.

For the electrical aspect of this design, the team decided to use two 12” linear actuators to move the bucket, and two windshield wiper motors. They will be controlled using two motor drivers which will be connected to microcontroller. The microcontroller will receive data from the computer using a shield as a receiver.

3.7 Discussion

Three different design alternatives were explored in order to come up with one final and efficient design. Taking into account the previously mentioned parameters, a final design was reached. Even though bucket ladder systems are faster when collecting BP-1, they are also more difficult and expensive to manufacture. Bulldozer-like systems, on the other hand, are easier and more cost effective to manufacture.

Furthermore, it is important to note the final design was put together with the contribution of every team member. Also the entire team must agree to the final design.

4. Project Management

4.1 Overview

Below is a summary of the year-long project organization. Time constraints and the strengths of each student were taken into account when dividing responsibility amongst team members. Responsibilities were broken down into an efficient and fair manner.

Additionally, each student is in charge of logging their own hours and providing feedback to others on their progress. This is done to aid the advancement of the project in an optimal manner.

4.2 Breakdown of Responsibilities

- *Project formulation*

  Teammates responsible for task: Maria Wilhelm, Stephane Briette, Diego Bolivar

- *Design Alternatives*

  Teammates responsible for task: Maria Wilhelm, Stephane Briette, Diego Bolivar

- *Proposed Design*

  Teammates responsible for task: Stephane Briette, Diego Bolivar

- *Design Analysis*

  Teammates responsible for task: Maria Wilhelm, Stephane Briette

- *SolidWorks Modeling*

  Teammates responsible for task: Maria Wilhelm, Stephane Briette, Diego Bolivar

- *Part List/Cost Analysis*

  Teammates responsible for task: Stephane Briette

- *Prototype Construction*

  Teammates responsible for task: Maria Wilhelm, Stephane Briette, Diego Bolivar

- *Prototype Testing*

  Teammates responsible for task: Maria Wilhelm, Stephane Briette, Diego Bolivar

- *Prototype Optimization*

  Teammates responsible for task: Maria Wilhelm, Stephane Briette, Diego Bolivar

- *PowerPoint Preparation*

  Teammates responsible for task: Maria Wilhelm, Stephane Briette, Diego Bolivar

- *Report Preparation*

  Teammates responsible for task: Maria Wilhelm

- *Final Presentation*

  Teammates responsible for task: Maria Wilhelm, Stephane Briette, Diego Bolivar

- *Competition*

Teammates responsible for task: Maria Wilhelm, Stephane Briette, Diego Bolivar

4.3 Organization of Work and Timeline

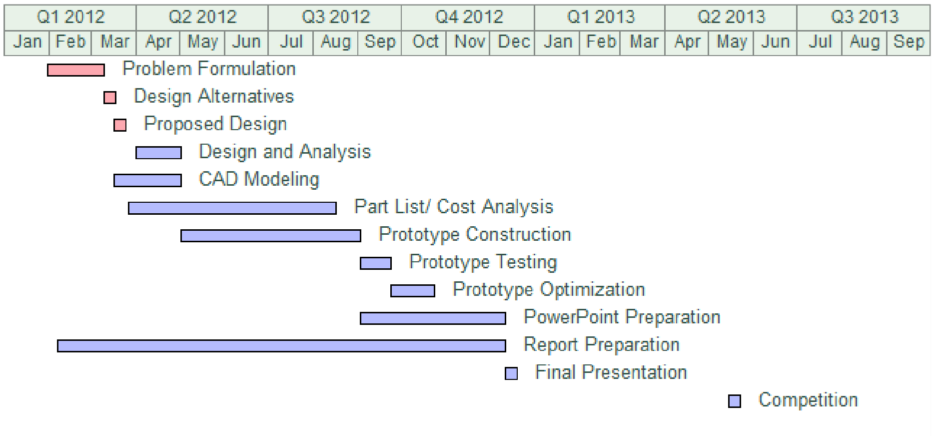

Figure 15: Timeline

4.4 Commercialization of the Final Product

Due to the nature of the project, the final prototype has no plans for commercialization. The Lunabot was design with the task of mining in lunar conditions. This is a specific task that, unfortunately, does not have enough of a prospective market in order to consider commercialization. Regardless, future teams wishing to enter the NASA's Lunabotics competition will benefit from studying the team's design process and outcome.

4.5 Discussion

Project management is crucial when working on projects of this scale. Responsibilities were broken down according to the experience and skills of each member. A project timeline was created in order to outline the time frame in which the different aspects of the project need to be completed. Furthermore, the nature of this project makes it lengthy. Thus, in order to make sure time is distributed adequately, the timeline was created as a quick overview. Lastly, it was concluded that there is no possibility for commercialization in the near future for the final prototype. Future competitors, however, will benefit from studying the team's process and design.

5. Engineering Design and Analysis

5.1 Mass Analysis

The importance of mass related analysis relates directly to the robot's ability to bend or tip over. The robot left and right sides where designed to mirror each other, thus distributing mass more evenly and contributing to the design's over all stability. Furthermore, by calculating the center of mass the team is able to determine whether or not the Lunabot will tip. The higher the center of mass, the easier the robot will lose balance. From the table below, the team concluded the design is stable and resistant to bending.

```
Mass properties of assembly 8-25-2012 ( Assembly Configuration - Default )

Output  coordinate System: -- default --

Mass = 64.65 pounds

Volume = 456.50 cubic inches

Surface area = 7175.79 square inches

Center of mass: ( inches )
      X = -4.01
      Y = 10.49
      Z = -9.84

Principal axes of inertia and principal moments of inertia: ( pounds * square inches )
Taken at the center of mass.
       Ix = (0.95, -0.32, -0.00)    Px = 6985.59
       Iy = (-0.00, -0.00, -1.00)                          Py = 14068.45
       Iz = (0.32, 0.95, -0.00)     Pz = 14661.58

Moments of inertia: ( pounds * square inches )
Taken at the center of mass and aligned with the output coordinate system.
      Lxx = 7758.53            Lxy = -2309.83          Lxz = -16.30
      Lyx = -2309.83           Lyy = 13888.68          Lyz = 7.21
      Lzx = -16.30             Lzy = 7.21              Lzz = 14068.41

Moments of inertia: ( pounds * square inches )
Taken at the output coordinate system.
      Ixx = 21126.69           Ixy = -5025.71          Ixz = 2532.82
      Iyx = -5025.71           Iyy = 21187.61          Iyz = -6663.47
      Izx = 2532.82            Izy = -6663.47          Izz = 22213.32
```

Figure 16: Mass Properties for Lunabot

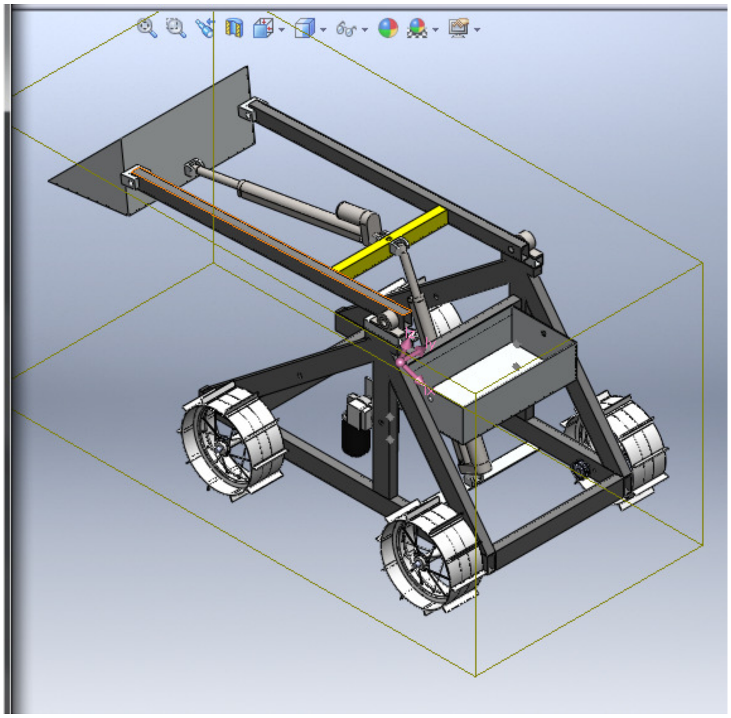

Figure 17: Lunabot Reference Axis

Mass properties of assembly 8-25-2012 (Assembly Configuration - Default)

Output coordinate System: -- default --

The center of mass and the moments of inertia are output in the coordinate system of assembly 8-25-2012
Mass = 15.74 pounds

Volume = 161.37 cubic inches

Surface area = 2626.60 square inches

Center of mass: (inches)
X = -0.51
Y = 8.31
Z = -9.82

Principal axes of inertia and principal moments of inertia: (pounds * square inches)
Taken at the center of mass.

Ix = (0.99, 0.12, 0.00)	Px = 1489.08
Iy = (0.00, 0.00, -1.00)	Py = 2124.40
Iz = (-0.12, 0.99, 0.00)	Pz = 2571.07

Moments of inertia: (pounds * square inches)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 1504.62	Lxy = 128.75	Lxz = 0.00
Lyx = 128.75	Lyy = 2555.53	Lyz = 0.00
Lzx = 0.00	Lzy = 0.00	Lzz = 2124.40

Moments of inertia: (pounds * square inches)
Taken at the output coordinate system.

Ixx = 4111.15	Ixy = 61.68	Ixz = 79.27
Iyx = 61.68	Iyy = 4078.79	Iyz = -1285.26
Izx = 79.27	Izy = -1285.26	Izz = 3215.94

Figure 18: Mass Properties for Frame

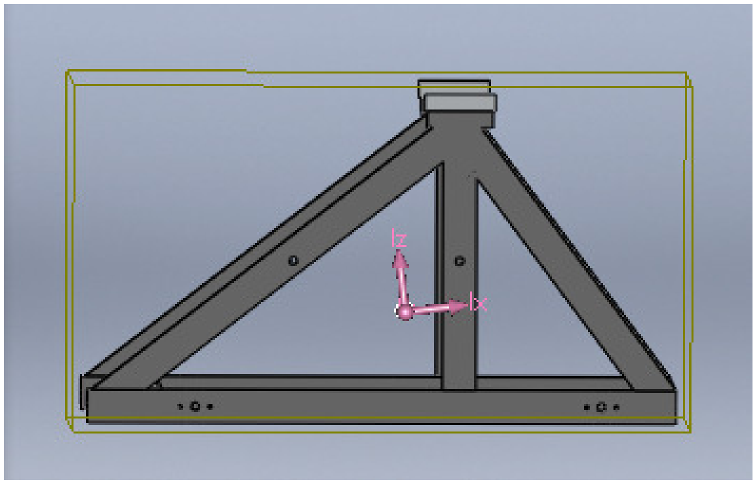

Figure 19: Reference Frame for Chassis

5.2 Force and Stress Analysis

A major concern throughout any engineering project is the effect applied forces have on the prototype. During the modeling stage, a series of failure analysis were performed in order to ensure that once the entire Lunabot is assembled the parts will sustain the given loads. Forty pounds of force (177.93 N) where used on the bucket, and 35 pounds force (155.68 N) were used on the bin responsible for holding the battery and electronics. Below is a graphical representation of the simulation.

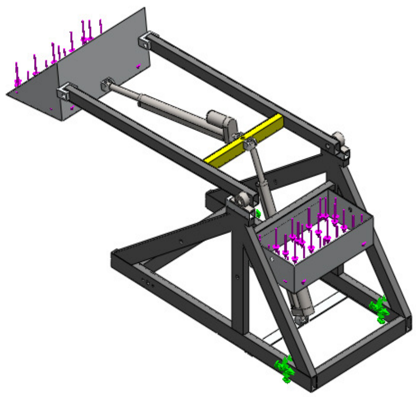

Figure 20: Model with Forces

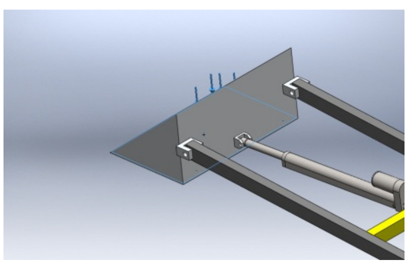

Figure 21: Bucket Force

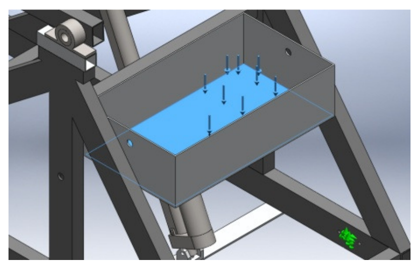

Figure 22: Bin Force

Table 11: Force Value for Bucket

Entities:	1 face(s)
Type:	Apply normal force
Value:	177.92 N or 40 lbf

Table 12: Force Values for Bin

Entities:	1 face(s)
Type:	Apply normal force
Value:	155.68 N 35 lbf

When creating three dimensional modes on the computer, mesh sizes are employed to simulate the structure modeled. It is useful to compare these meshes to placing a net over the body modeled. The smaller the size of the holes on the net, the more surface of the model that is actually covered by the net. In a similar form, mesh sizes determine the accuracy of the simulation. The graphical representation for the mesh is shown below.

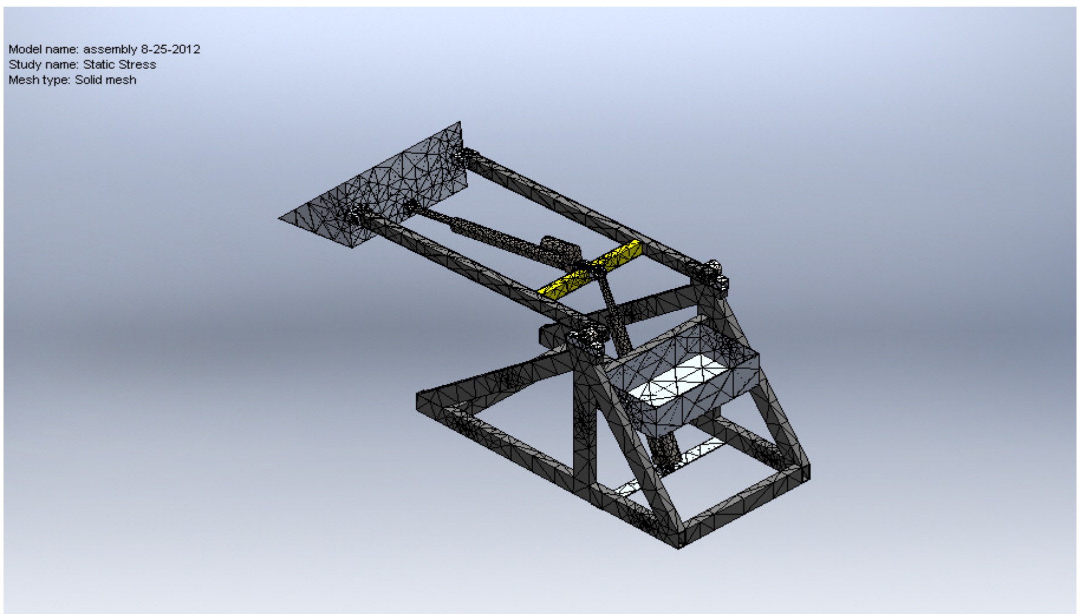

Figure 23: Model Mesh

Using the Von Mises yield criterion, SolidWorks calculated the stresses on the frame and arms. Note that the highest stress found to be 5.19463e+007 Pa, or 7534.17 psi. Furthermore, these loads placed on the robot will also cause deformations. Once more, using the static load study, the deformation due to the load on the Lunabot was found to be equal to 6.8129 mm or 268.22 mil. Furthermore, another aspect of deformation, known as strain, is defined as the deformation of a body relative to its displacement. The maximum strain found for this assembly was equal to 0.000419.

It is important to consider the previously mentioned factors for the design in order to determine whether or not the design will fail. The strain, displacement, and strain were all found to be with in an acceptable range. Furthermore, one last factor to take into consideration is the factor of safety. Generally speaking, factor of safety uses the stress experienced by a design over the allowed stress of said design to calculate its possibility for failure. A factor of safety below one indicates failure. Also, high factors of safety are usually indicative of overuse of material.

Below are all the previously discussed results summarized.

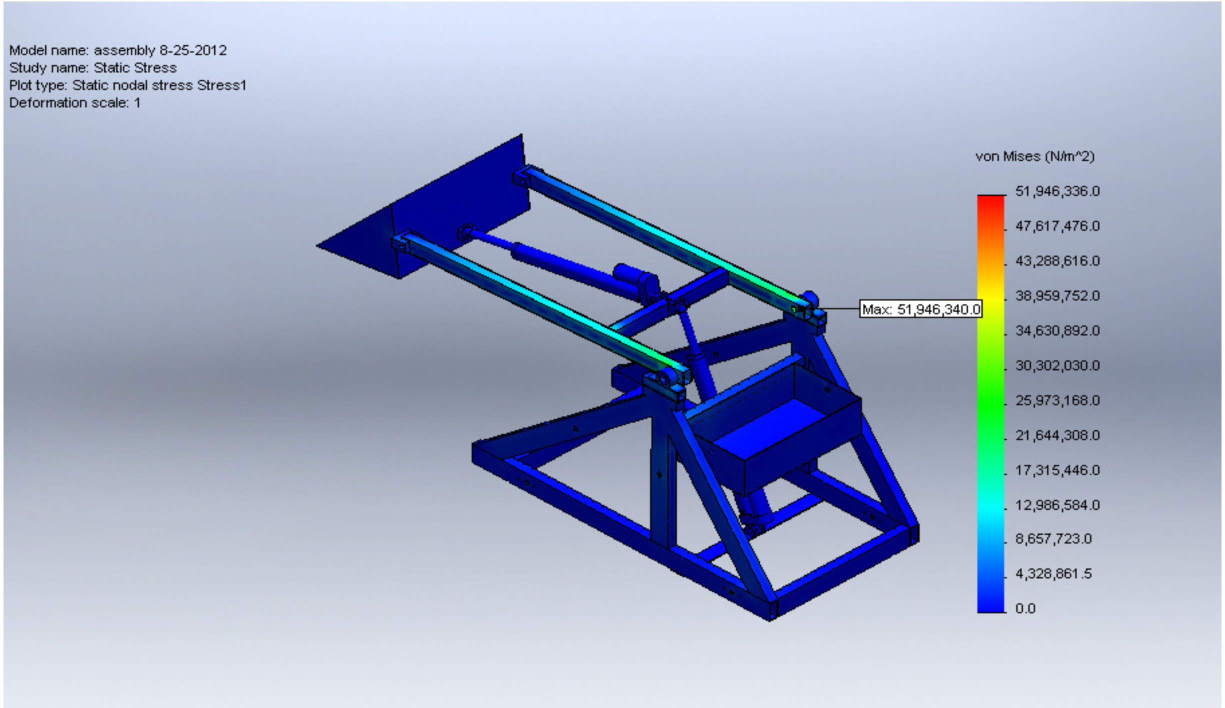

Figure 24: Von Mises Stress

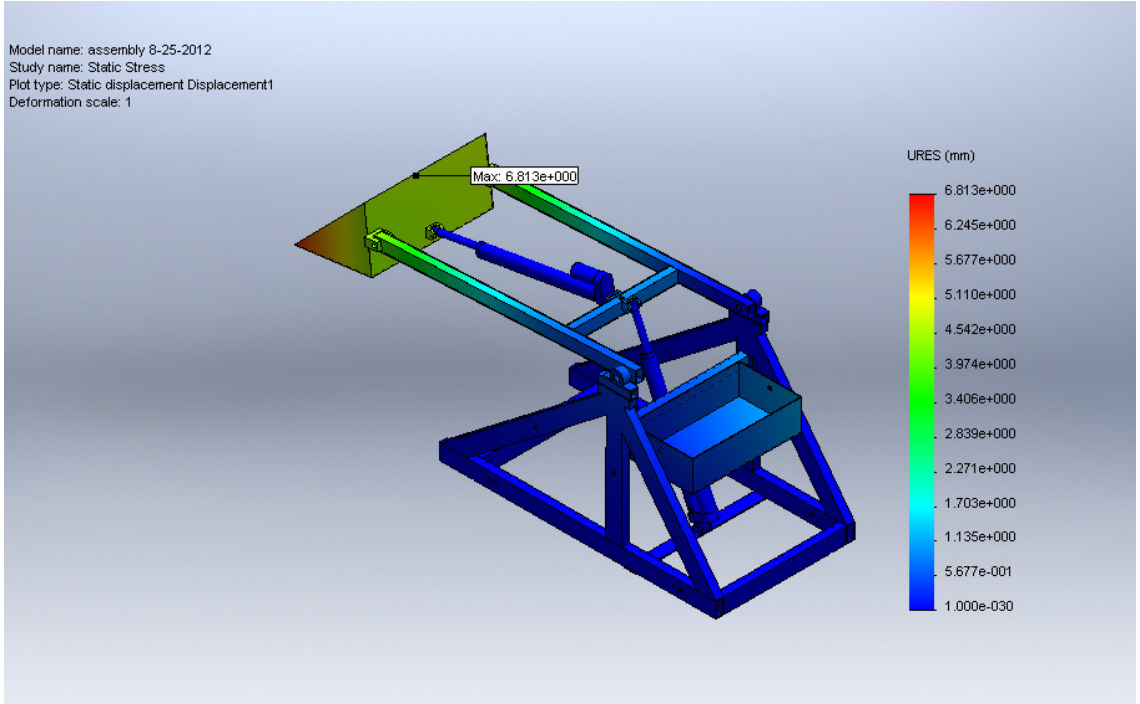

Figure 25: Displacement

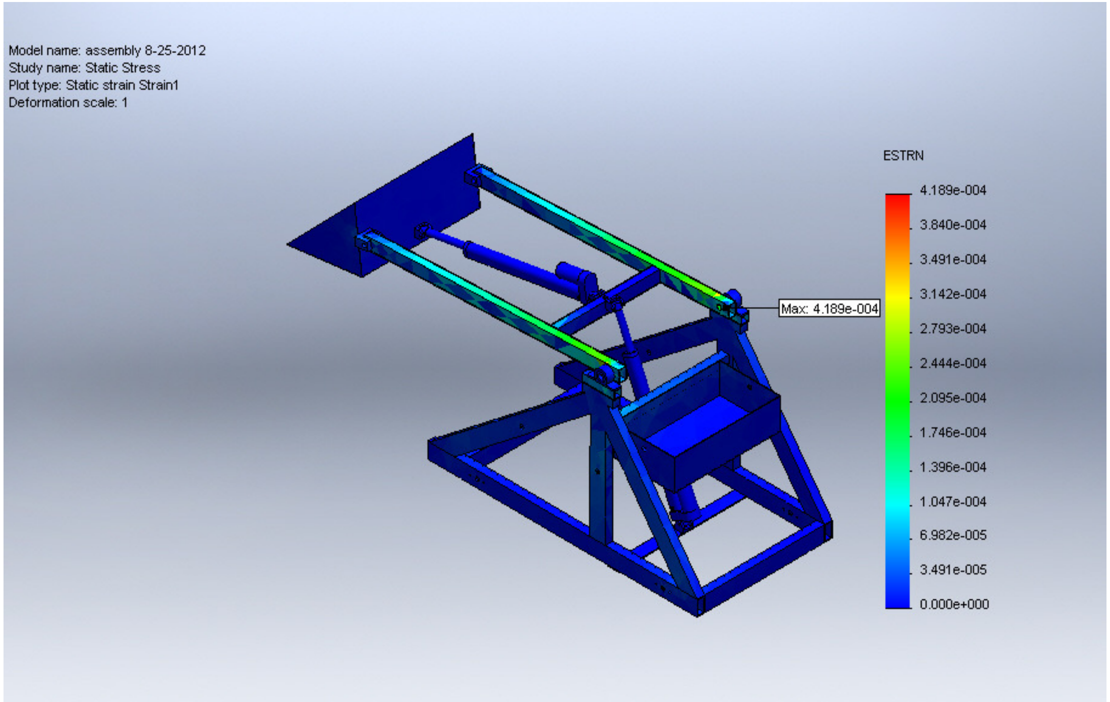

Figure 26: Strain

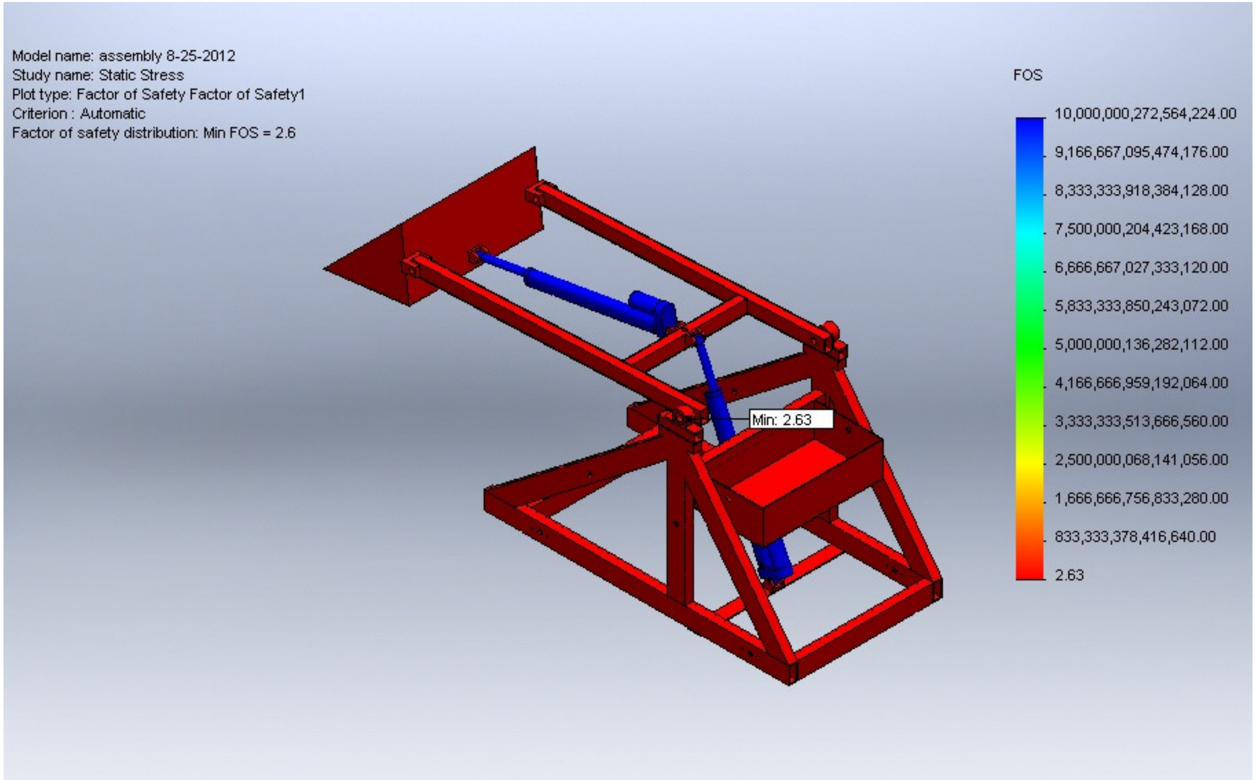

Figure 27: Factor of Safety

5.3 Material Selection

When selecting the materials, there were three main factors taken into account. First, the material must be strong and resistant to fatigue in order to go through all the motions successfully. Also, the materials chosen must be light, in order to maximize the number points totaled. Lastly, the materials must be chemically resistant to their environment, thus resisting corrosion and damage due to the BP-1. The main material chose, thus, was aluminum 6061 because of it successfully covers the properties previously mentioned. Also, it is an abundant material and thus is found at economically affordable prices when compared to other forms of aluminum. Furthermore, this material is easy to work with and is of a high quality.

Furthermore, note that materials such as Plexiglas and PVC where also considered. Due their high cost and manufacturability they were not chosen over aluminum.

Using SolidWorks, below is a summary of the different types of materials used. The areas shadowed in blue are those of the material indicated by their perspective table.

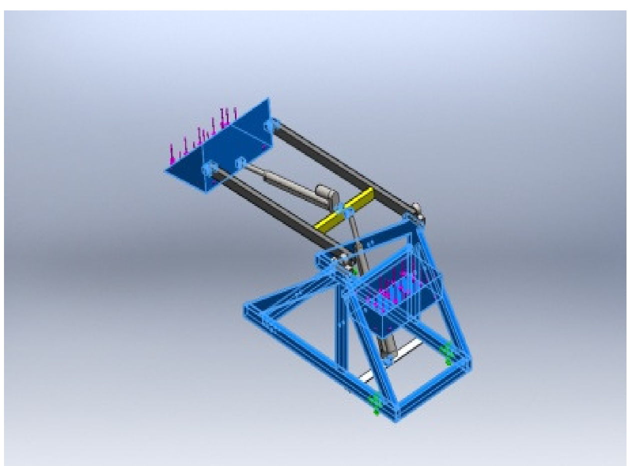

Figure 28: Aluminum Parts (a)

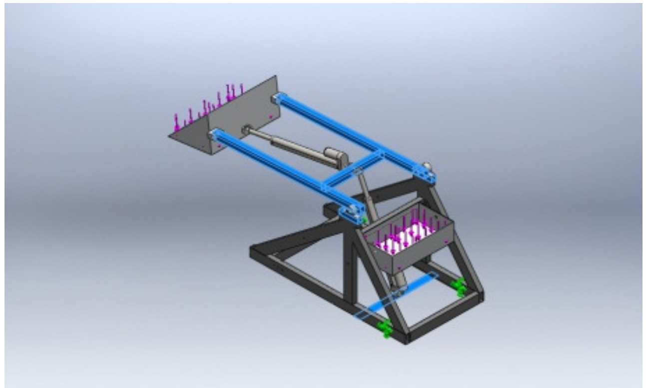

Figure 29: Aluminum Parts (b)

Table 13: Properties of Aluminum (SolidWorks)

Name:	6061-T6 (SS)
Model type:	Linear Elastic Isotropic
Yield strength:	2.75e+008 N/m^2
Tensile strength:	3.1e+008 N/m^2
Elastic modulus:	6.9e+010 N/m^2
Poisson's ratio:	0.33
Mass density:	2700 kg/m^3
Shear modulus:	2.6e+010 N/m^2
Thermal expansion coefficient:	2.4e-005 /Kelvin

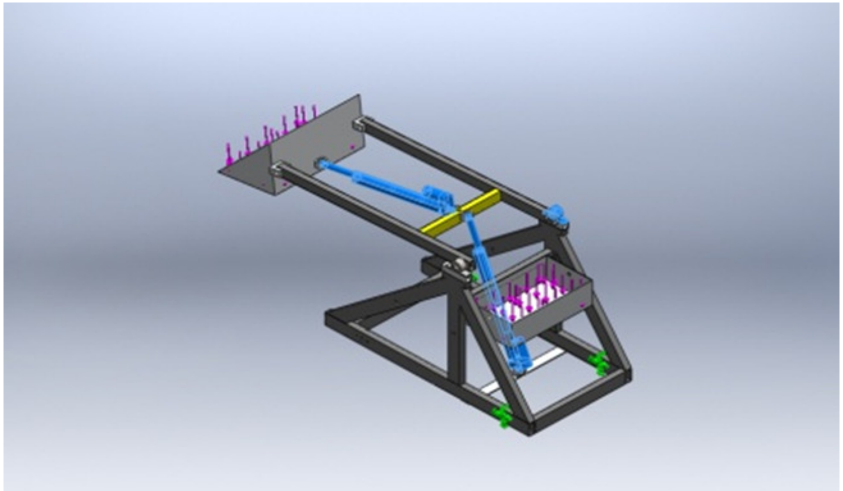

Figure 30: AISI 1020

Table 14: AISI 1020 Properties (SolidWorks)

Name:	AISI 1020
Model type:	Linear Elastic Isotropic
Yield strength:	3.51571e+008 N/m^2
Tensile strength:	4.20507e+008 N/m^2
Elastic modulus:	2e+011 N/m^2
Poisson's ratio:	0.29
Mass density:	7900 kg/m^3
Shear modulus:	7.7e+010 N/m^2
Thermal expansion coefficient:	1.5e-005 /Kelvin

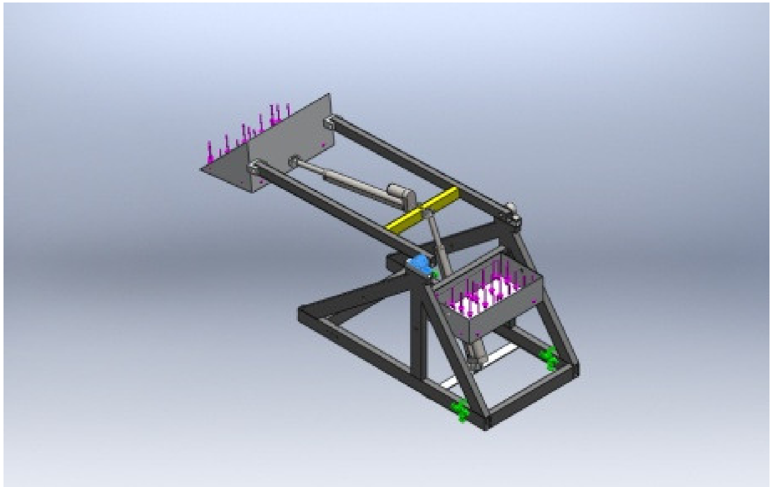

Figure 31: Stainless Steel Parts

Table 15: Stainless Steel Properties (SolidWorks)

Name:	Stainless Steel (ferritic)
Model type:	Linear Elastic Isotropic
Yield strength:	1.72339e+008 N/m^2
Tensile strength:	5.13613e+008 N/m^2
Elastic modulus:	2e+011 N/m^2
Poisson's ratio:	0.28
Mass density:	7800 kg/m^3
Shear modulus:	7.7e+010 N/m^2
Thermal expansion coefficient:	1.1e-005 /Kelvin

5.4 Dumping/Collection System Mobility

In order to collect the regolith and travel through the track with as much ease as possible, the Lunabot was designed with the ability to lower and raise the arms attached to the bucket. The idea behind the design is to give the Lunabot the clearance needed by raising the bucket as the Lunabot is going through the obstacle course, and lower them once it reaches the mining area. In order to achieve this, two 12” linear actuators were used. One to move the arms up and down, and another to rotate the bucket about the pivot point on the arms. The specifications for the selected actuators are shown in the table below.

Table 16: Actuator Specifications

Compressed Length	40.64 cm or 16 in
Extended Length	71.12 cm or 28 in
Extension Shaft Length	30.48 cm or 12 in
Maximum Lift	90.72 kg or 200 lbm
Speed	12 mm/s or 0.47 in/s

The actuators are placed as shown below, with their dimensions outlined.

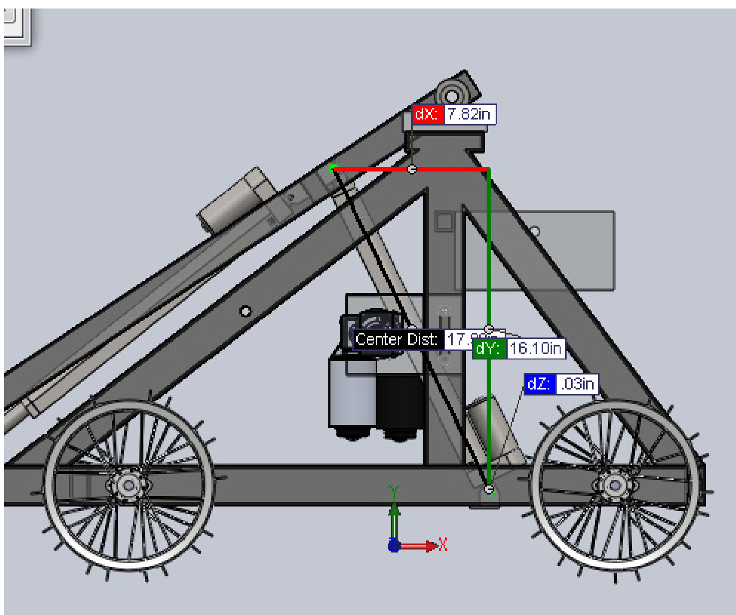

Figure 32: Arm Actuator Compressed

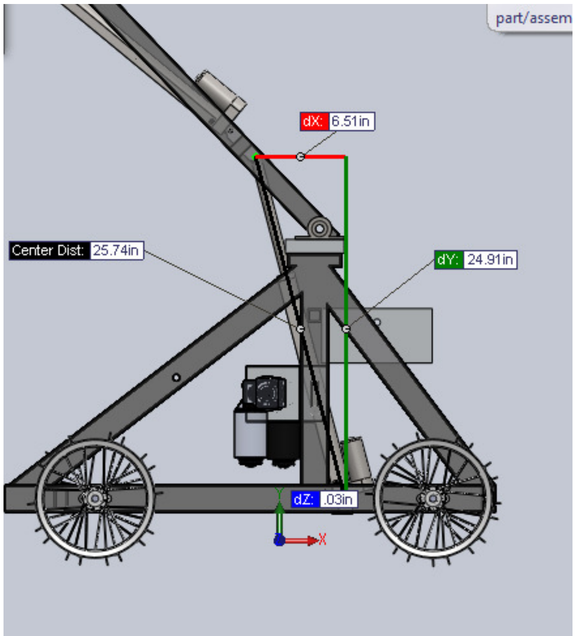

Figure 33: Arm Actuator Extended

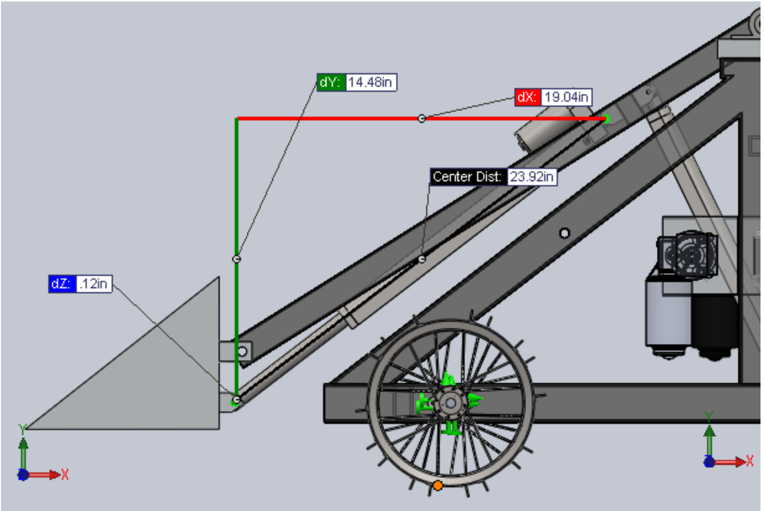

Figure 34: Bucket Actuator Extended

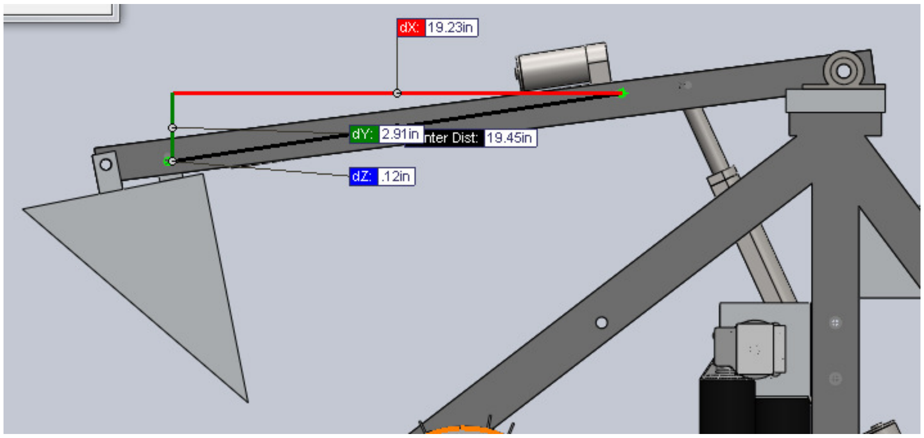

Figure 35: Bucket Actuator Compressed

Furthermore, due to the regulations set up by the Lunabotics Committee, the robot cannot surpass a required height, length, and width. The maximum height is found at the point in which the actuator responsible for lifting the arm is fully extended. The maximum length is found when the actuator responsible for the bucket is extended. Lastly, while the width remains constant and is not a critical part of the dumping mechanism, the measurements are added in this section for the purpose of simplicity.

A summary of the maximum distances are found below.

Table 17: Maximum Distances

	Maximum Distance Measured	Maximum Distance Required
Height Extended	49.65 in (1.26 m)	59.06 in (1.5 m)
Length Extended	51.17 in (51.17 m)	59.06 in (1.5 m)

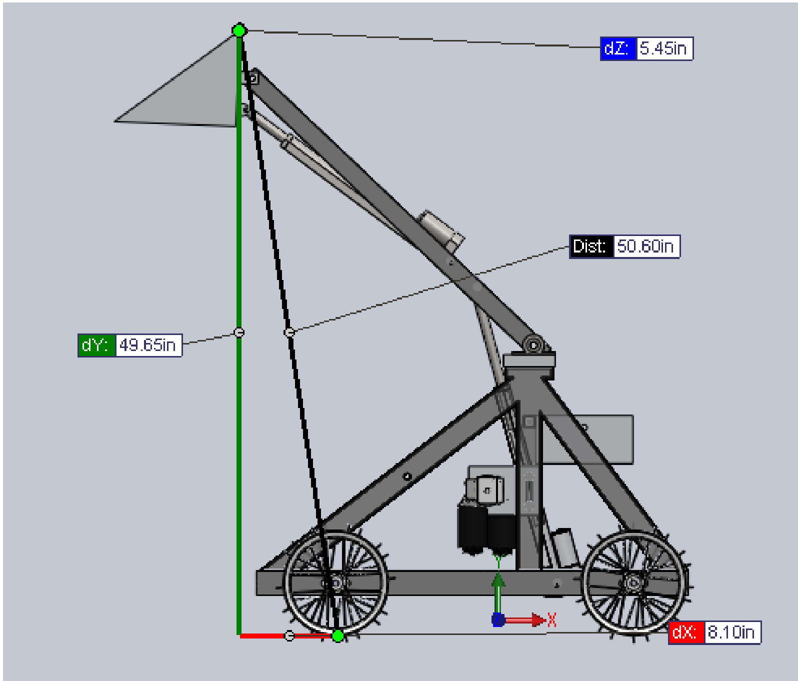

Figure 36: Extended Height

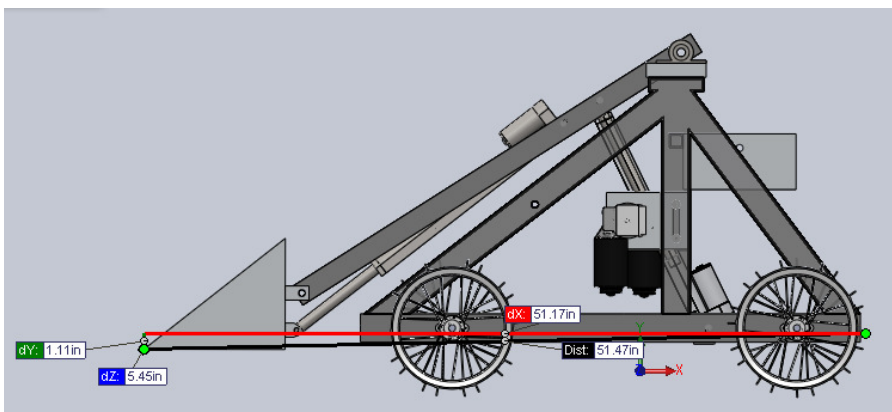

Figure 37: Extended Length

It is also important for the bucket to be able to rotate the degrees necessary to ensure all of the regolith collected is deposited in the bucket. The image below shows that the bucket is able to rotate a total of 111.49 degrees from its resting position. This is more than enough to allow the bucket to face down and deposit the regolith.

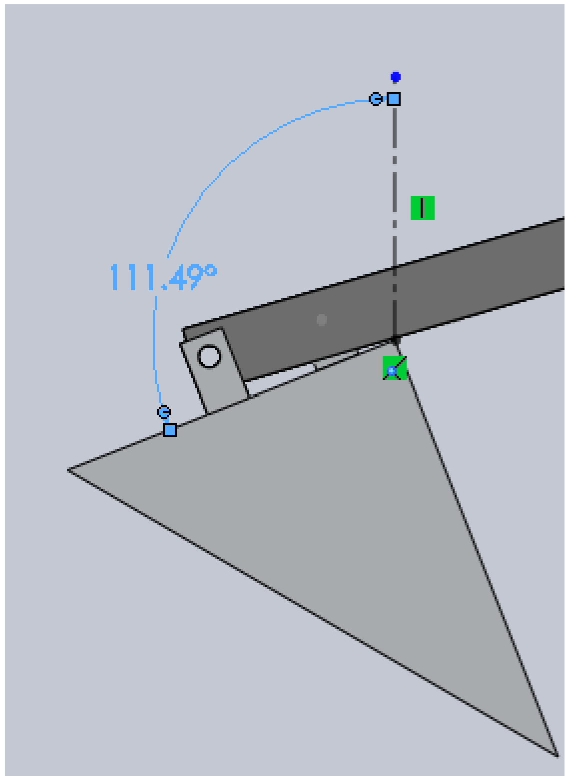

Figure 38: Bucket Rotation

In order to avoid interference amongst the moving parts, and to reassert the required motions are being completed, a motion study was performed on the Lunabot.

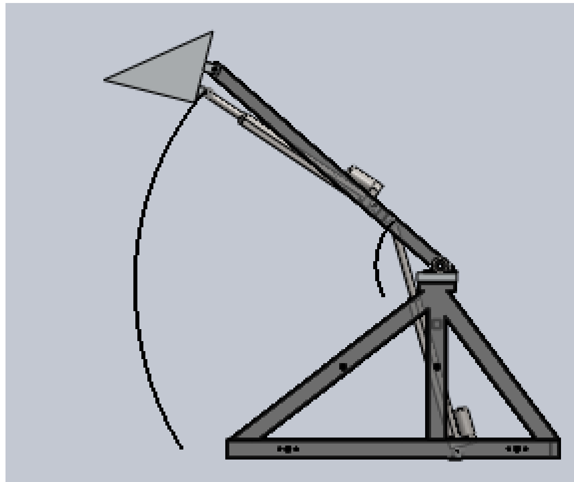

Figure 39: Actuator Paths

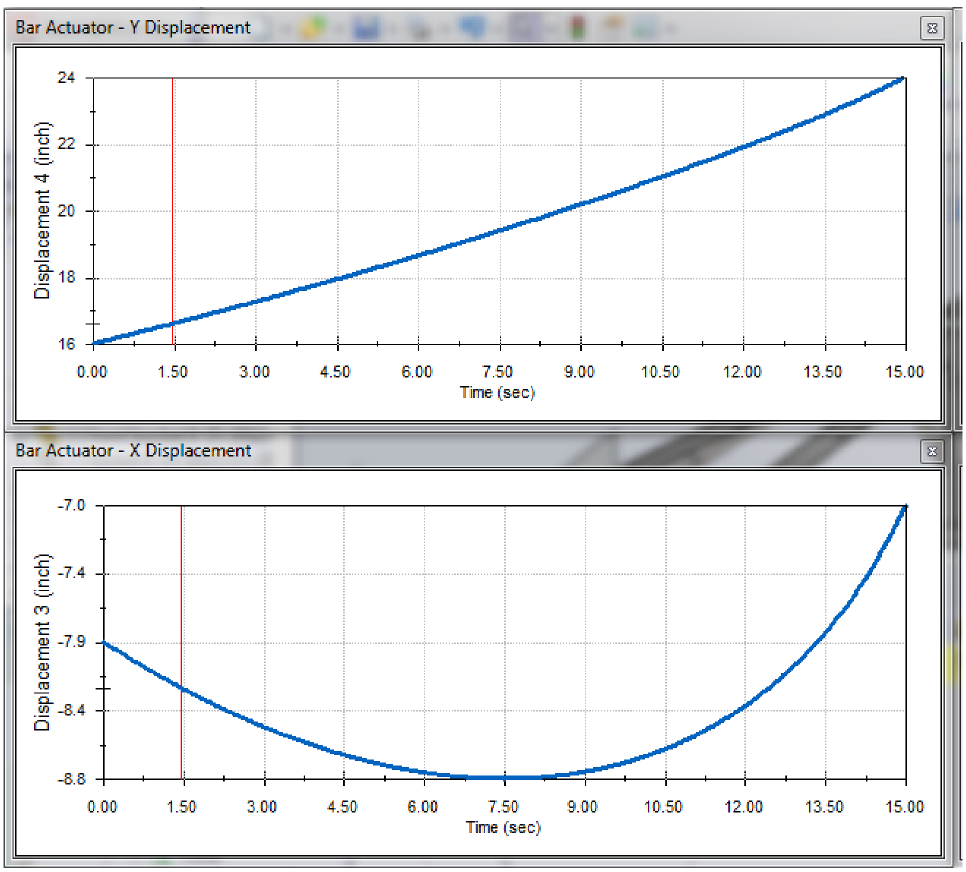

Figure 40: Bar Actuator Displacement

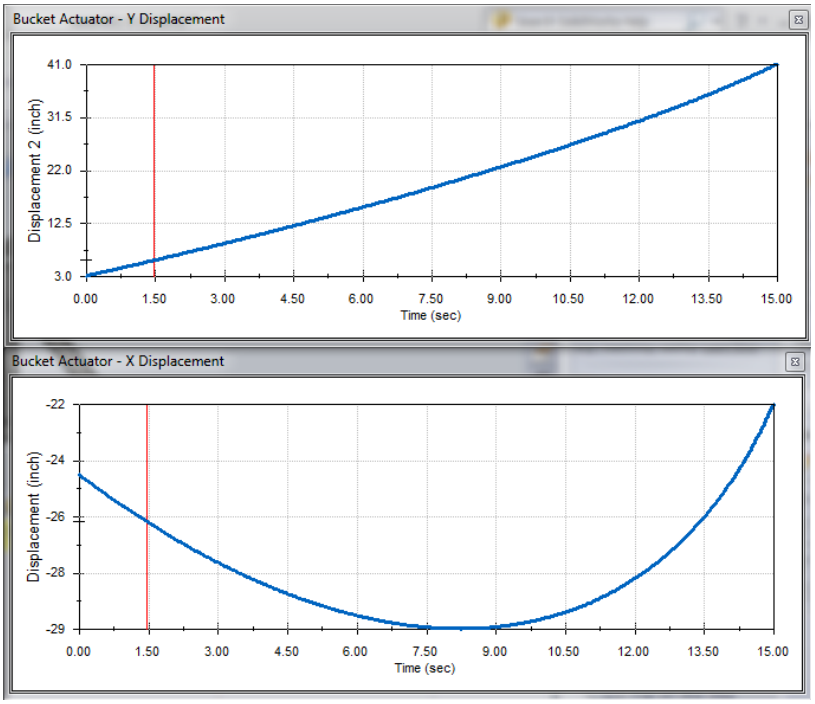

Figure 41: Bucket Actuator Displacement

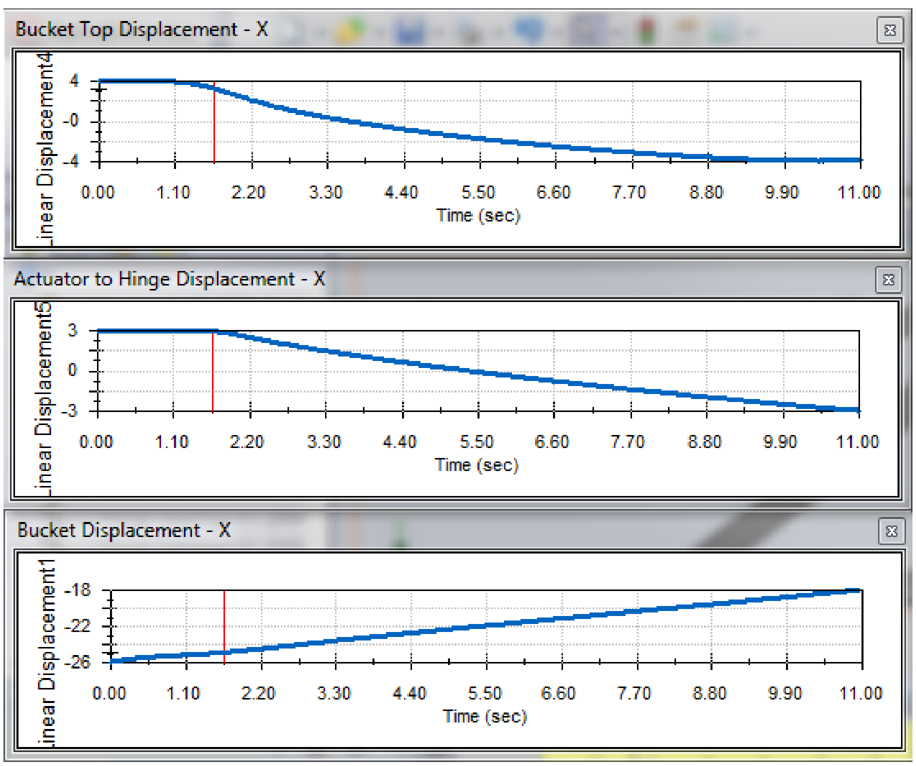

Figure 42: Bucket X-Axis Displacements with Reference to Bolt

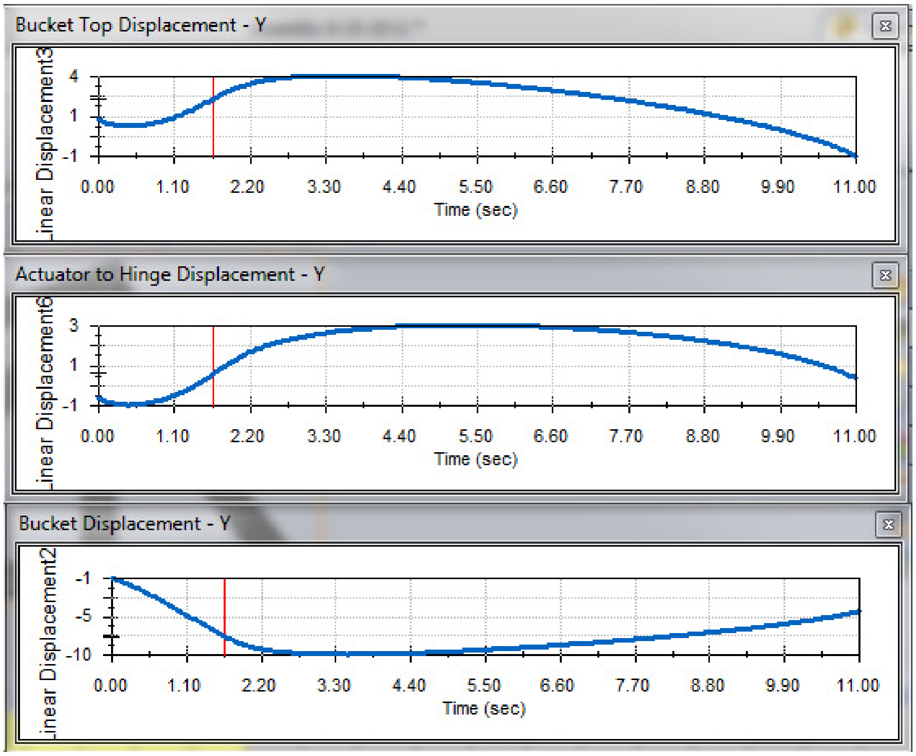

Figure 43: Bucket to Bold Displacements with Reference to Bolt (Y-Axis)

The velocities are also included on this motion study. The reference points are outlined below. The velocity calculations are crucial to the design, since they allow the team to plan and estimate the time that will be required in order to excavate the 10 kg that are needed in order to qualify.

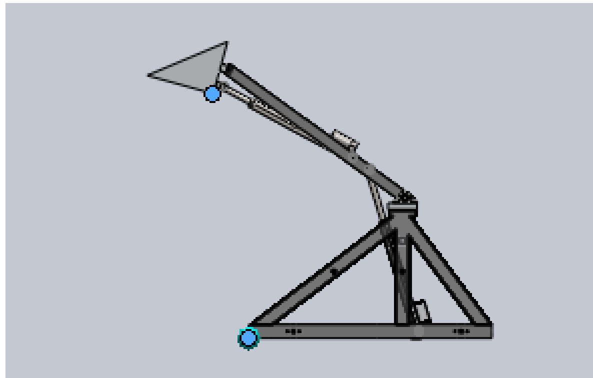

Figure 44: Reference Points

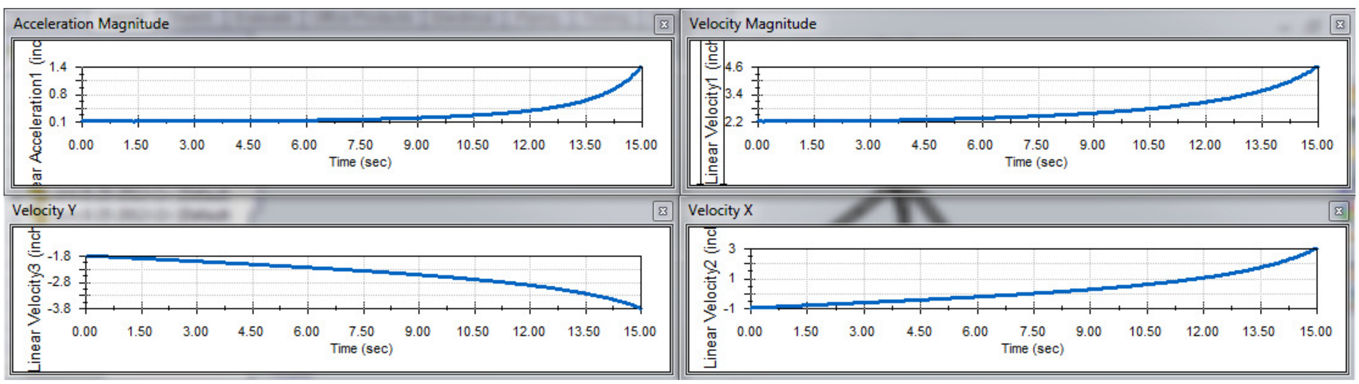

Figure 45: Calculated Velocities and Accelerations

Another vital crucial aspect involved in the planning and design stage is determining the amount of regolith that will be carried in the bucket. Unlike other designs, this Lunabot does no employ a collection bin. For this reason it is of most importance that the bin is of an appropriate size so to minimize the amount of trips made from the mining site to the deposit post.

Using the volume of the bucket and known density of regolith, the maximum amount of regolith that can be deposited on a single run is 37.75 lbm (17.127 kg) for the dense areas and 31.46 lbm (14.273 kg) for the less dense areas.

5.5 Mobility

One of the most common problems observed during the Lunabotics competition is the failure of the robot's drive system. Usually, the robot's wheels or tracks will malfunction, or the object will get stuck while going through the obstacle course. This caused a lot of teams to be disqualified. For this reason, the Lunabot's drive system is easily one most crucial aspects of the design. Furthermore, in order to begin this analysis, the maximum mass that the Lunabot will employ at any time during the competition must be calculated. This mass accounts for the mass of the robot's structure, electronics, and the maximum amount of regolith collected. Taking all these factors into consideration, the total mass for the Lunabot is equal to 97.75 lb (44.33 kg) (assuming the team is using LiPo batteries). Due to the nature of this project; the weight was calculated using the gravitational acceleration on the moon and on earth. Gravity on the moon is equal to 5.31 feet per second squared (1.63 m/s^2 on the moon). The weights for each case are summarized below.

Table 18: Weights of the Lunabot

	Maximum Weight of Lunabot (lbf)
On Earth	97.78 (434.96 N)
On the Moon	16.24 (72.27 N)

The drive system is split into two different sections: wheels, and motors.

For the wheels, in order to ensure the correct model is chosen, first calculations regarding the contact area and load must be made. To calculate the area of contact, approximations must be made since there are no preexisting formulations that will adhere to the mode designed by the team. First, a minimum assuming contact area is found. This is done by assuming the wheels to be smooth, without fins, and for contact to be done between the wheels and a solid concrete surface. Note that the equations used below are created by the industry and based on contact mechanics. A diagram depicting the basic scenario of contact between a cylinder and a solid surface is shown below.

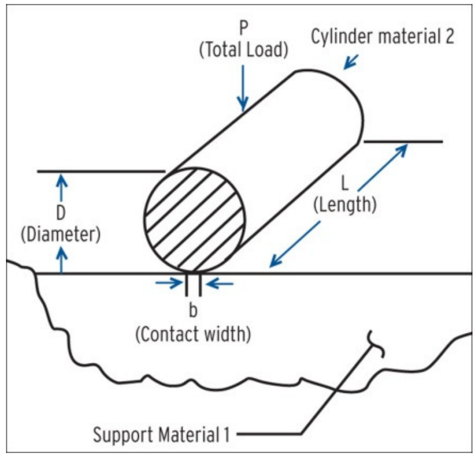

Figure 46: Contact Mechanics Diagram

$$b=1.6 \sqrt{p \times K_D \times C_E} \quad \text{(see Figure 2)}$$

Where:

p = load per unit length = P/L

$K_D = D_2$, (since the support material is flat, not curved)

$C_E = (1 - v_1^2)/E_1 + (1 - v_2^2)/E_2$

E= See Figure 1 and Table 1.

Figure 47: Basic Formulas Used

Concrete f'c (psi)	E concrete (psi)[2]	Maximum Nominal Bearing Strength (psi)[3]
3,000	3,122,000	5,100
4,000	3,605,000	6,800
5,000	4,030,000	8,500

[1] f'c = concrete compressive strength, psi = pounds per square inch.

[2] E concrete = 57,000√(f'c) (from ACI 318)

[3] ACI 318-08, Section 10.14, Maximum Nominal Bearing Strength, B_N = 0.85 x f'c x 2.0., where 2.0 is the maximum amplification factor permitted; accounting for the effects of confinement provided by the surrounding concrete.

Figure 48: Table of Values

For details on these calculations, see the appendix portion of this report. The minimum contact area assuming it to be between concrete and the metal wheel was found to be of b = 0.9 in (0.023 m), with the area being equal to 3.6 inches squared. Furthermore, these calculations were repeated using soft clay as the surface in contact. Using clay, the surface area in contact is found to be 21.52 inches squared. Thus, the total contact area is equal to about 86.08 inches squared. Below are the results summarized.

Table 19: Wheel calculations

Young's Modulus – Clay	7251.89 psi (50 Mpa)
Poisson's Ratio – Clay	0.3
Young's Modulus – Aluminum	10000000 psi (69 Gpa)
Poisson's Ratio – Aluminum	0.33
Contact Area (Single Wheel)	15.12 in^2 (97.55 cm^2)
Total Contact Area	60.48 in^2 (390.19 cm^2)

These results do not include the addition of the fins. With the fins added to the wheel, and assuming one fin to be in contact with the ground at all times (which is a safe assumption since the fins are only placed 3 inches (7.62 m) apart), the new surface area at contact becomes 60.48 inches squared.

Furthermore, in order to calculate the required torque to move the Lunabot, the rolling resistance, incline resistance, and acceleration force of the motors used. First, the acceleration force is that force required accelerating the robot at a specified speed in a defined amount of time. In order to determine the acceleration force, first the velocity of the robot must be defined. The motors used to drive the Lunabot were measured to have the following RPMs:

Table 20: Motor Velocities

Angular Velocity - High (RPM)	**58.4**
Angular Velocity - Low (RPM)	41.3
Angular Velocity – 0.9 (RPM)	22.55

Pulleys connected to the motors through a shaft have the same angular velocity. Since all pulleys on this system have the same radius, their angular and tangential velocities are the same. The radius of the wheels that are moved by the pulleys is 4.5 in. The tangential velocity is then found below.

Table 21: Tangential Velocity

Tangential Velocity - High	**2.29 ft/s (0.70 m/s)**
Tangential Velocity - Low	1.62 ft/s (0.49 m/s)

However, these velocities are found to be two high. Higher velocities result in more dust particles becoming airborne during the translation portion of the competition. For this reason, a velocity of 0.9 ft (0.27m/s) is preferred for the robot. Using this new velocity and assuming it to be reached within 3 seconds, the accelerations for each velocity is found.

Table 22: Acceleration

Acceleration - High ft/s^2	**0.57 ft/s^2 (0.17 m/s^2)**
Acceleration - Low ft/s^2	0.41 ft/s^2 (0.12 m/s^2)
0.9 Acceleration	0.3 ft/s^2 (0.091 m/s^2)

Thus, the acceleration force is found by multiplying the above acceleration by the mass of the Lunabot.

Table 23: Force Due to Acceleration

Acceleration Force - High (lbf)	**1.70 (7.54 N)**
Acceleration Force - Low (lbf)	1.19 (5.31 N)
0.9 Acceleration (lbf)	0.905 (4.03 N)

Next, the rolling drag is calculated. Rolling drag is defined as the force resisting the rolling motion of a body. Much like friction due to normal force, this force is essential to the movement of the Lunabot. Rolling resistance is calculated by multiplying the total weight of the body rolling by the coefficient of rolling resistance. Here another assumption must be made. For Loose, dry sand, the rolling coefficient was found to be between 0.2 and 0.4. The rolling resistance is equal to 39.11 lbf (173.95 N). Furthermore, it is also necessary to assume that the Lunabot will drive through inclines, as the rule book states small craters and obstacles are placed around the field. Due to this, and incline angle of 30 degrees was assumed. The incline resistance is then the maximum weight times the sine of the assumed angle. In this case, the incline resistance is equal to 48.88 lbf (217.44 N). Using all these values the tractive force is calculated by adding the forces due to acceleration, rolling resistance, and incline resistance. The tractive force is equal to 89.68 lbf (398.93 N). Note that the largest value for the required acceleration force is used in order to ensure the torque requirements are met. Next, the torque required from the each motor is calculated. This is done by multiplying the radius of the wheel used times the traction force times the resistance factor. The resistance factor accounts for frictional losses between the wheel, its axel, and bearings. This value usually ranges between 1.1 (10%) and 1.15 (15% of loses). In this case, 1.15 is used. The required wheel torque is then equal to 38.68 ft*lbf (52.44 Nm). For each wheel then, the required torque is 9.67 ft*lbf (13.11 Nm).

For the rotary motors, the following data was measured.

Table 24: Windshield Wiper Motor Specifications

Current (A)	10
Voltage (V)	12
Angular Velocity - High (RPM)	58.4
Angular Velocity - Low (RPM)	41.3
Angular Velocity – 0.9 ft (RPM)	22.55
Motor Efficiency	85%

Using this data, the torque and horse power per motor was calculated as shown below.

$$HP = \frac{V * I * Efficiency}{746}$$

Where HP is the horsepower, V is the voltage and I is the current. HP was found to be 0.160 hp (120 W). The power in foot time pound per second equals 48.65. Torque is found below:

$$T = \frac{HP * 5252}{RPM}$$

The maximum calculated torque drawn from one motor was found to be 50.82 Nm. Thus, the use of two motors is more than enough for the mobility of this system.

Lastly, using the forth mentioned weights, the contacts pressures are calculated using the total contact area. According to the Lunar and Planetary Institute, rovers designed for lunar exploration should have a contract pressure up to 10 kPa. Note the obtained value for the lunar contact pressure is way below that.

Table 25: Contact Pressures without Fins

Earth Contact Pressure	1.73 psi (11.92 kPa)
Lunar Contact Pressure	0.27 psi (1.853 kPa)

5.6 Structural Design

In order to complete a successful prototype, computer models of the principal components must be made. The appendix contains the engineering drawing subtracted from SolidWorks of the design. These drawing depict crucial the different components used, and how they come together with in the assembly.

These models are then tested using SolidWorks simulation software. These simulations allow the team to determine the effectiveness of the design, and how to further improve it. Below are CAD drawings of each part of the Lunabot, as well as the final assembly.

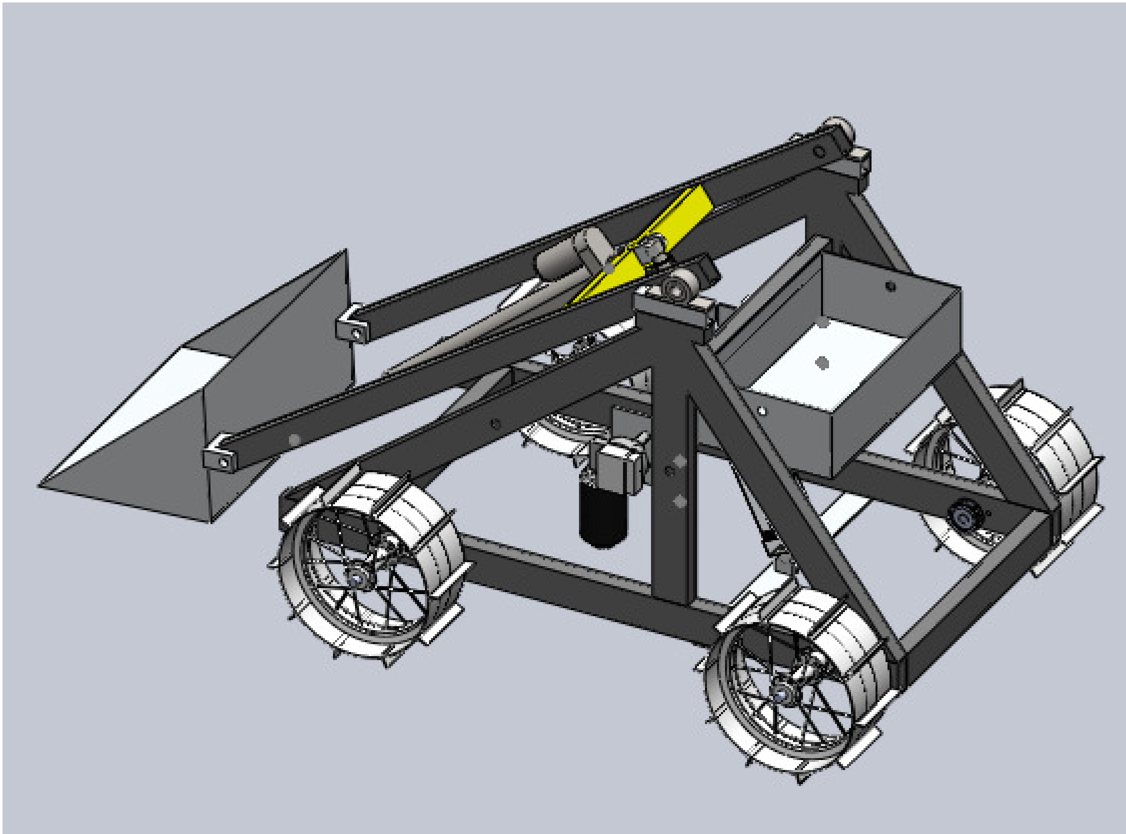

Figure 49: Final Lunabot Assembly

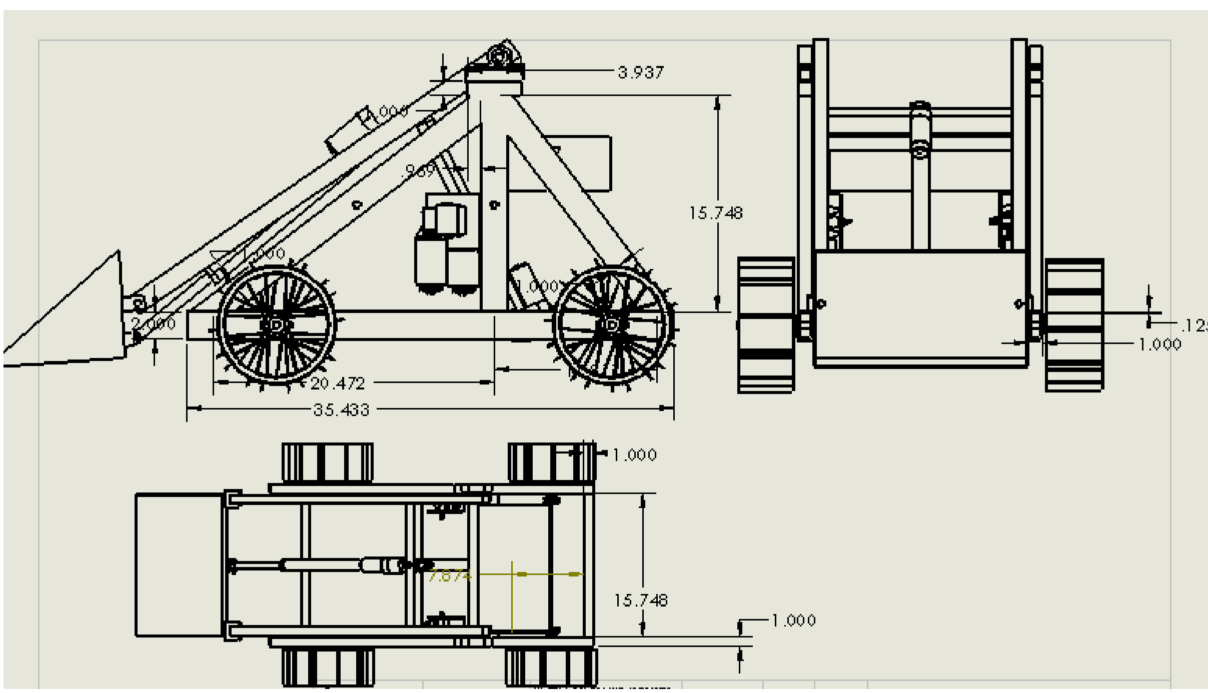

Figure 50: Lunabot Assembly Drawing

After the design was modeled and tested parts were ordered, and manufacturing began.

5.7 Component Design/Selection

Careful consideration was taken when deciding which components to use for the manufacturing process of the robot. Cost, availability, mechanical properties, and feasibility of integration were characteristics which were given priority.

The figures below show in detail the CAD generated components that were used on the design and construction of the Lunabot.

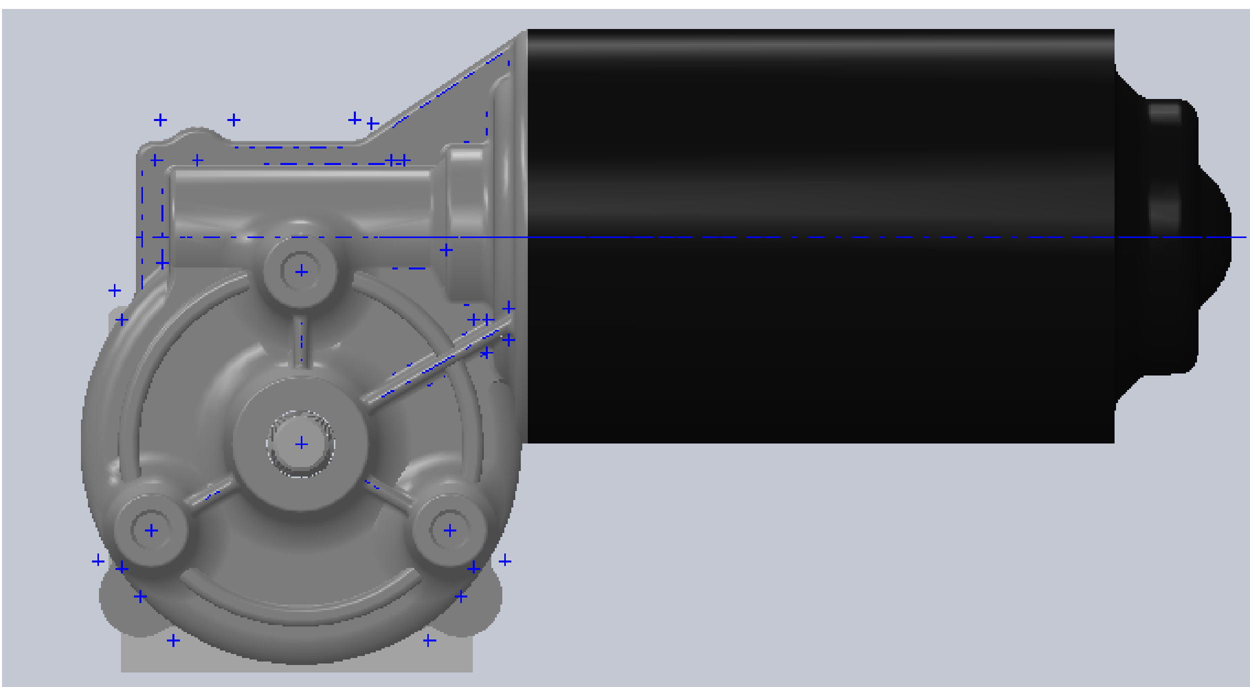

Figure 51: Wiper Motor

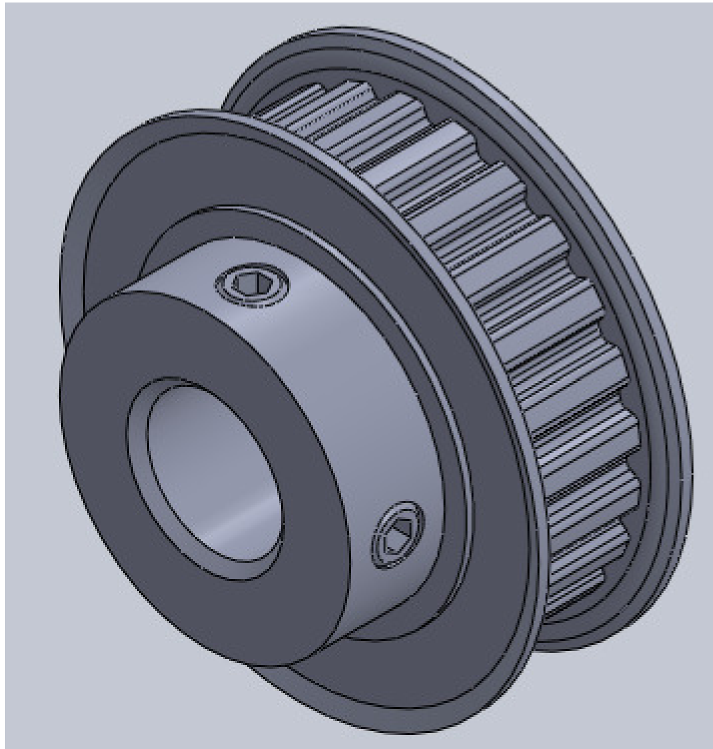

Figure 52: Timing Pulley

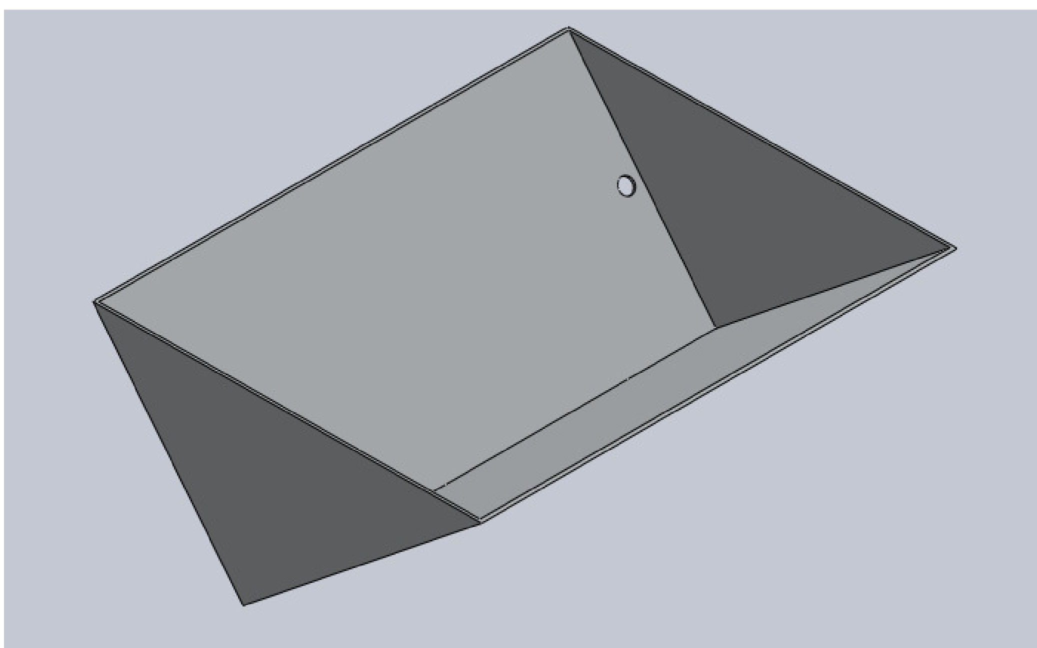

Figure 53: Bucket

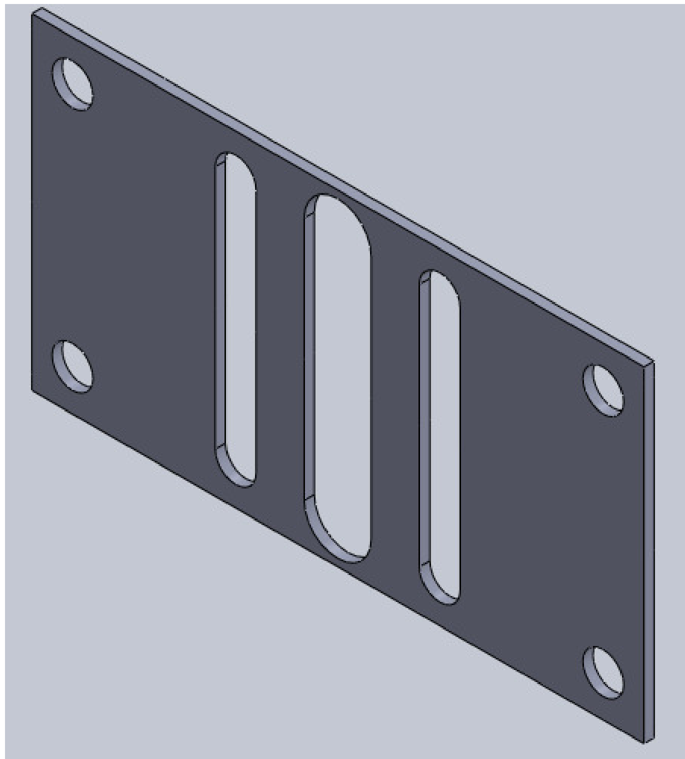

Figure 54: Motor Bracket

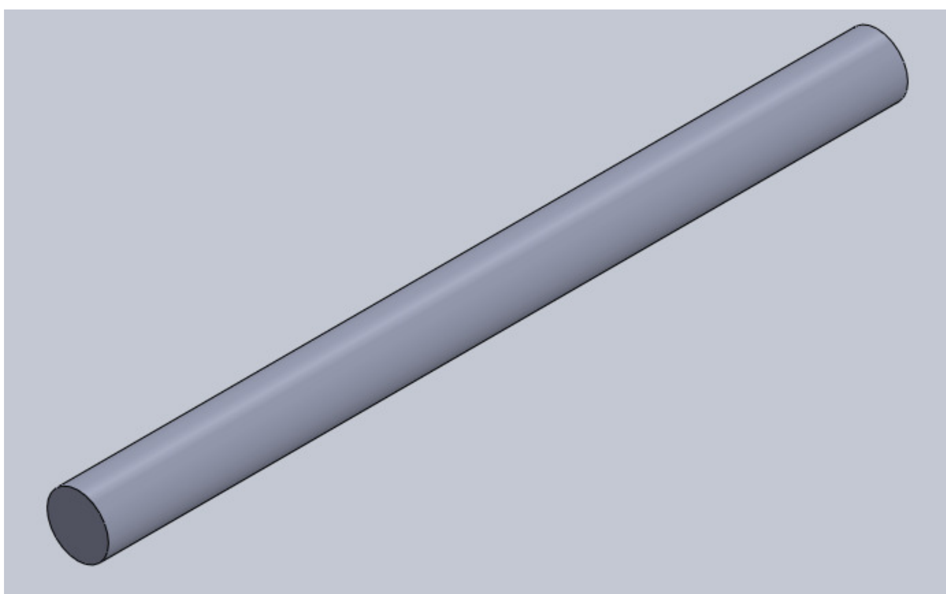

Figure 55: Shaft

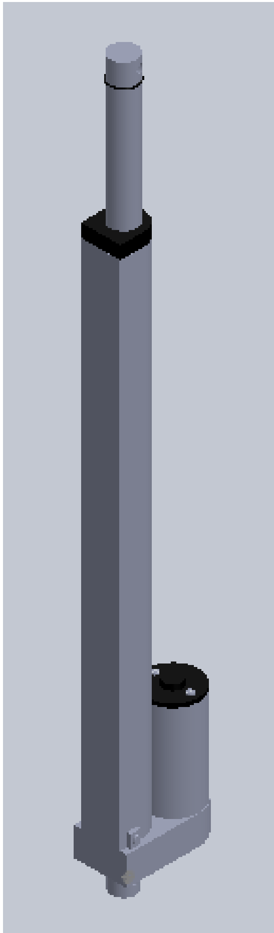

Figure 56: Actuator

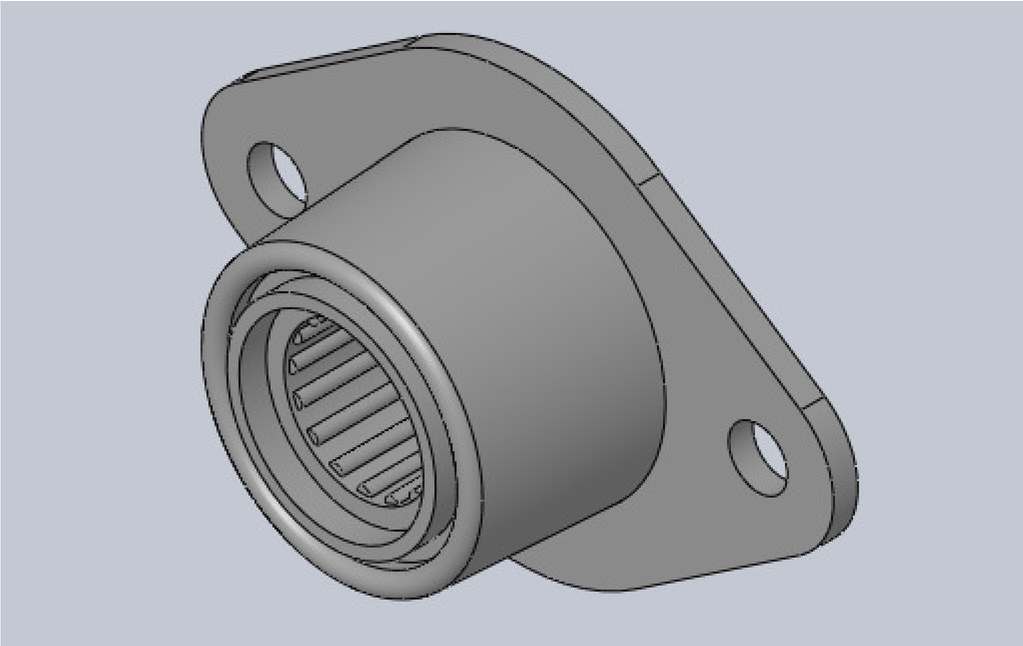

Figure 57: Flanged Bearing

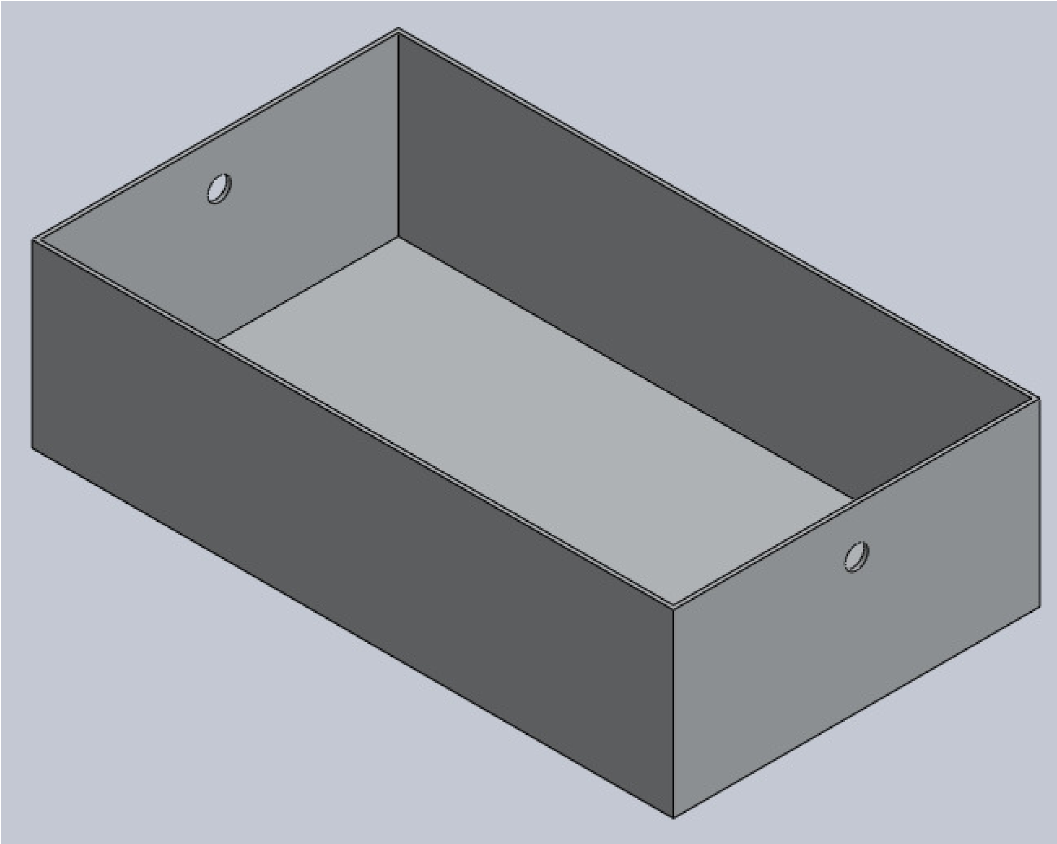

Figure 58: Basket

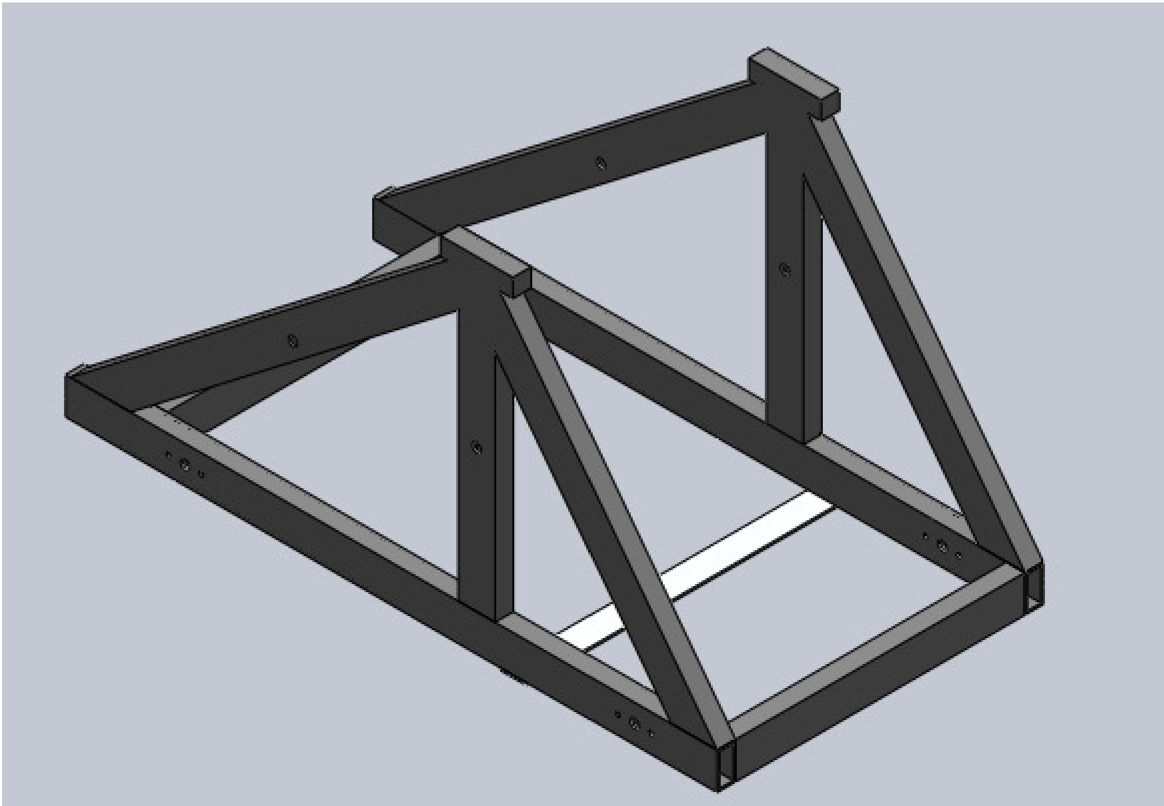

Figure 59: Frame

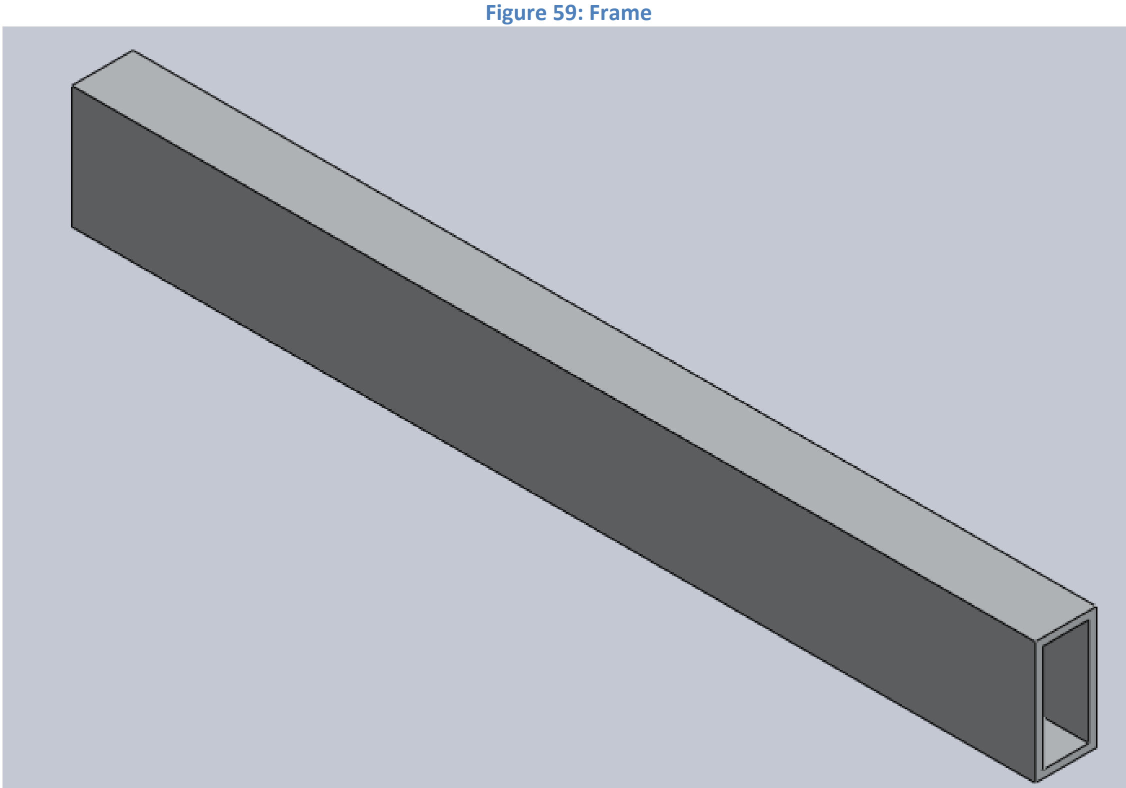

Figure 60: Back Bar

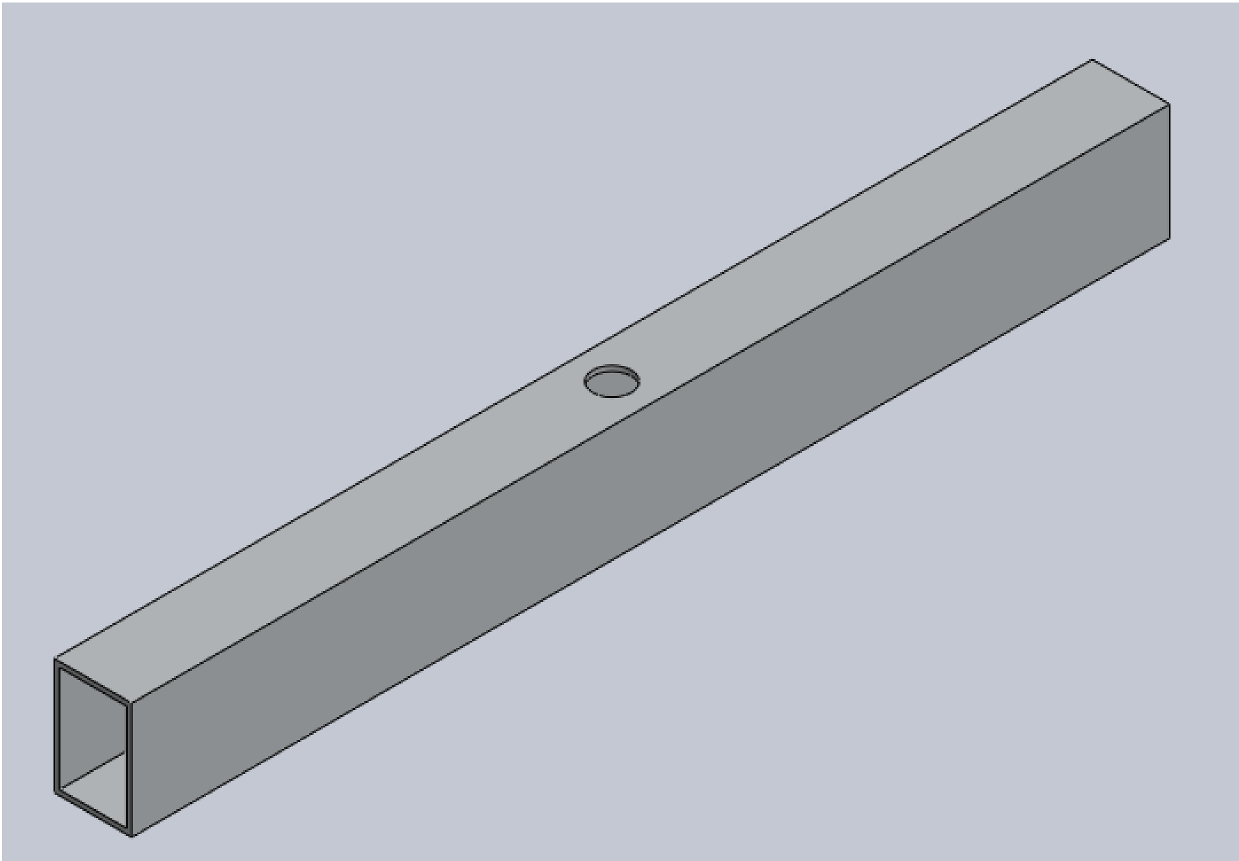

Figure 61: Arm Brace

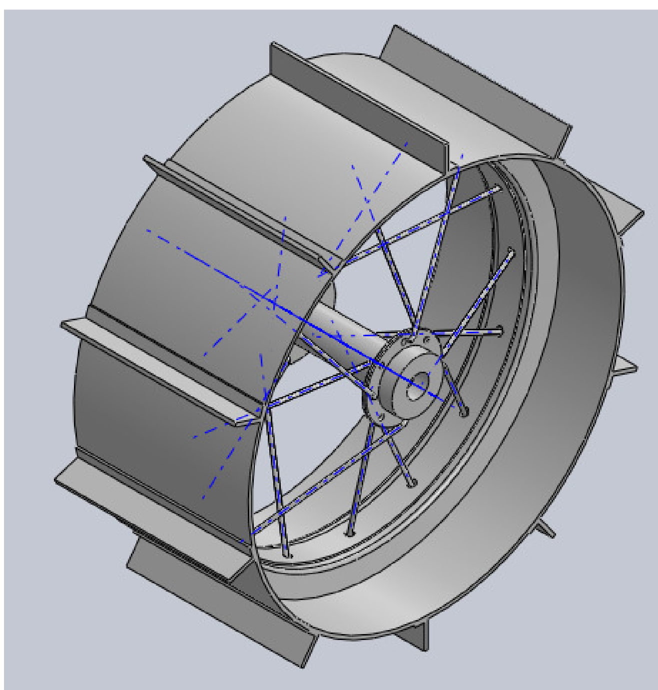

Figure 62: Wheel

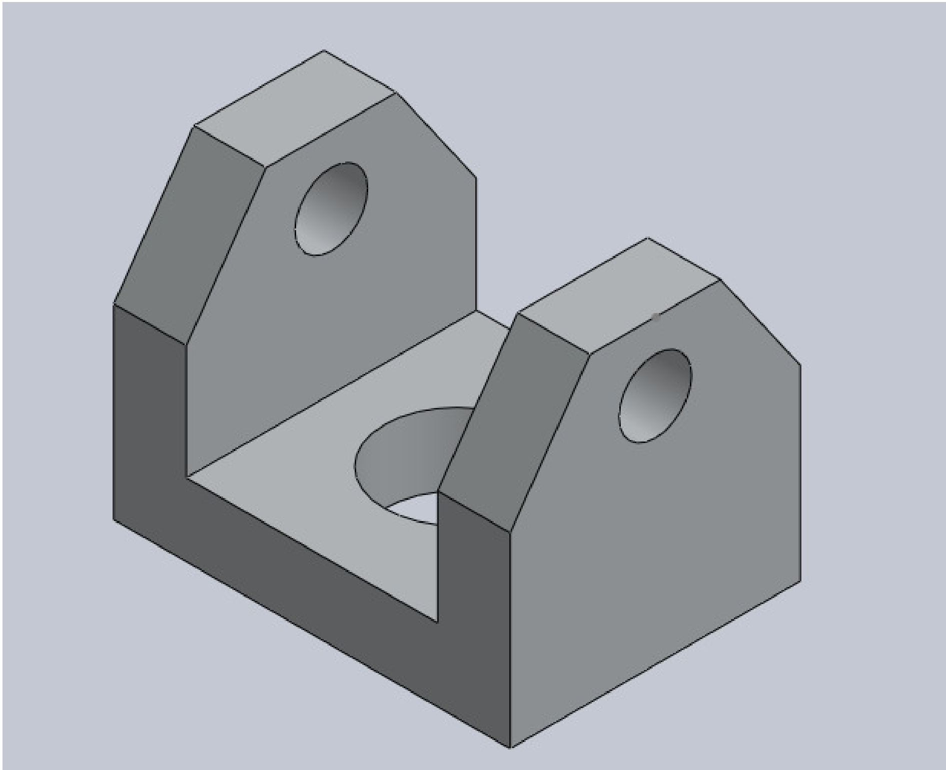

Figure 63: Actuator Bracket

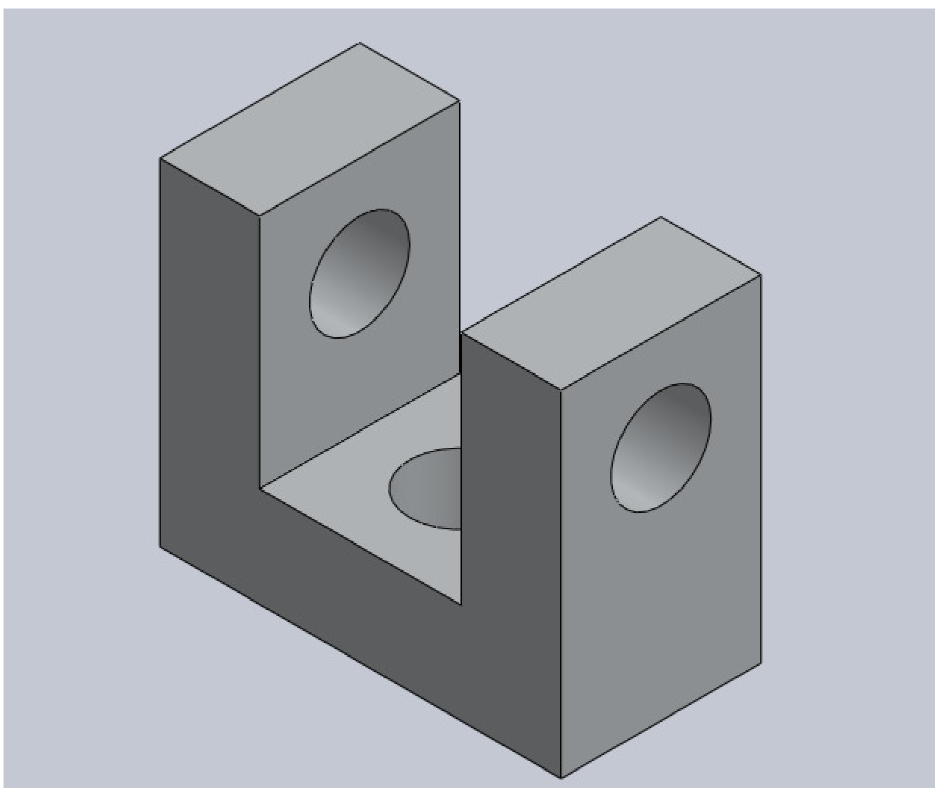

Figure 64: Bucket Bracket

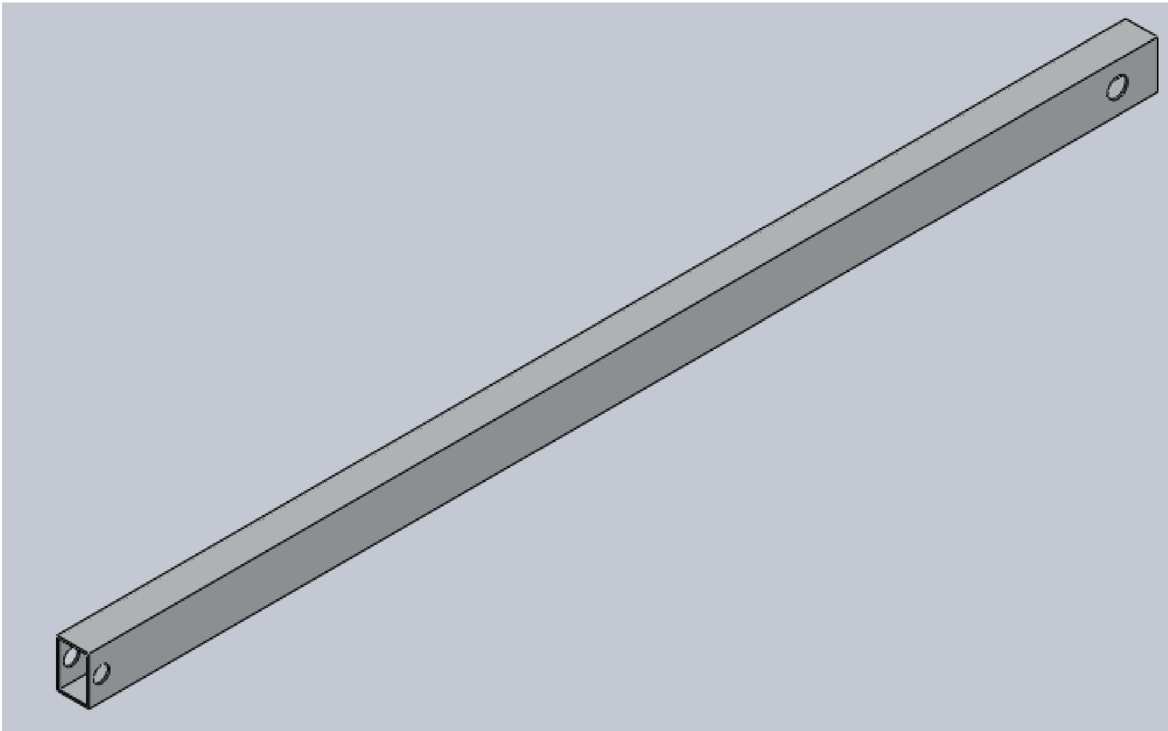

Figure 65: Arm

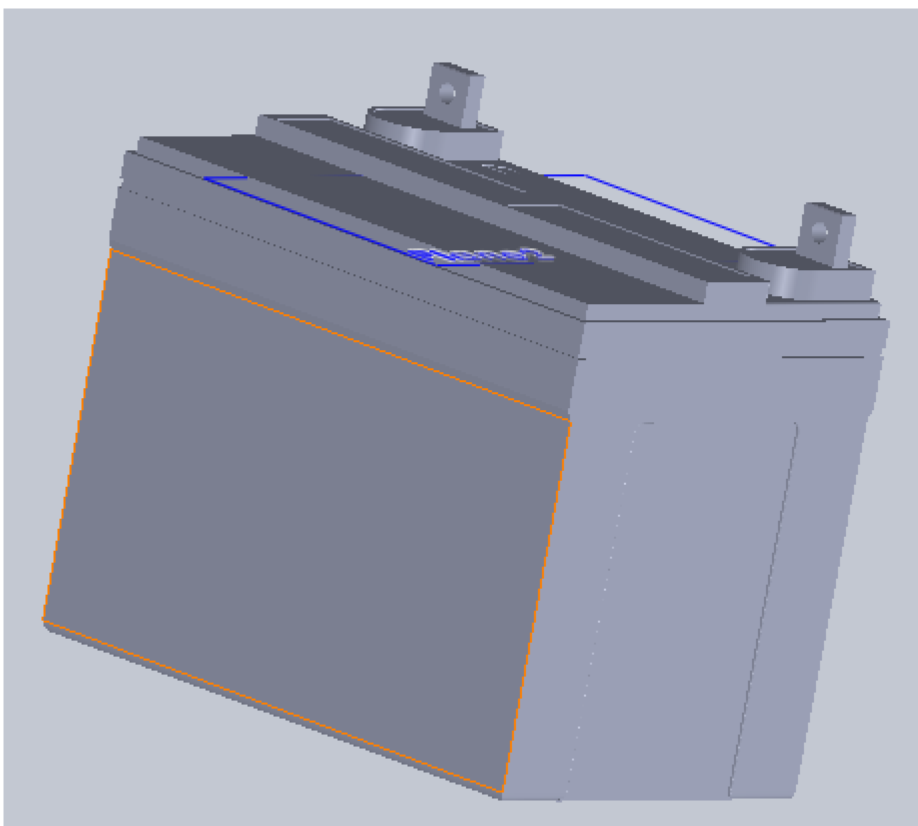

Figure 66: Battery

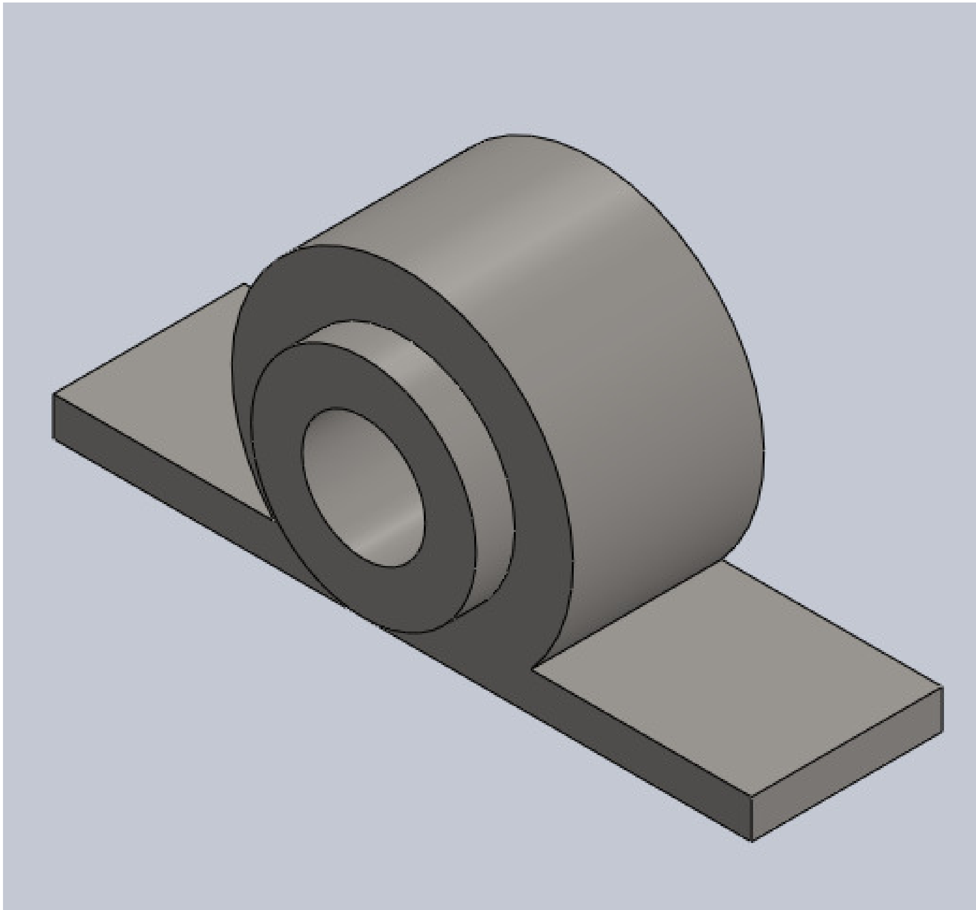

Figure 67: Rolling Bearing

5.8 Design Overview

Recall that from three proposed designs, one final design was chosen. This design falls fulfills all the requirements given by the Lunabotics Mining competition. This final design was manufactured to perform the tasks mentioned at the beginning of this thesis. Note that special attention was given to the effects of BP-1 on the robot. Also, the weight, resistance to fatigue, and mobility of the robot were topics whose importance was accentuated throughout the design process. Different forms of computer analysis were performed to ensure the success of the robot once manufactured. Also, critical calculations regarding the torque and power of the robot aided in the design process, ensuring that the Lunabot will be able to perform all the tasks required.

5.9 Cost Analysis

Table 26: Cost Analysis

Quantity	Element	Price ($)	Total ($)	Quantity	Element	Price ($)	Total ($)
2	Linear Actuators	$80.00	$180.00	4	8" Plastic Wheels	$10.99	$43.96
2	Wiper Motors	$30.00	$60.00	1	Pre-Cut Basket Aluminum	$19.77	$19.77
3	Belt (Pair)	$13.00	$39.00	1	Pre-Cut Bucket Aluminum	$20.30	$20.30
1	1’x2’ Aluminum Sheet	$23.22	$23.22	2	Dual Motor Driver	$125.99	$251.98
1	Arduino UNO	$60.00	$60.00	2	0.5" SS Bar (16" Long)	$8.99	$17.98
6	Timing Pulleys	$13.40	$80.40	3	Electrical Cables	$5.99	$17.97
4	10” Bike Rim	$17.99	$71.96	2	LiPo Batteries	$59.99	$119.98
8	Flanged Bearings	$5.76	$46.08	2	1"x2" Bars (Arms)	$18.47	$36.93
1	Xbee Kit	$90.00	$90.00	Total			$1,159.53

5.10 Discussion

This project is of a lengthy nature. It is extremely involved and required more than a lot of commitment from team in order to be followed to completion. After modeling was completed, several forms of analysis were performed to ensure the final product would not fail. Materials and component selection were put to the test and necessary changes were made. The team reached out to faculty members when they needed guidance regarding the manufacturability of the chosen components and the validity of the modeled analysis. In order to save time, the team opted to use as many prefabricated parts as possible as opposed to manufacturing everything from scratch. This was typically more costly than the forth mentioned option; however it saves time and minimized possibilities for error.

6. Prototype Construction

6.1 Description of Prototype

The production of a final prototype will be done with the purpose of it entering the Lunabotics competition. The prototype will be constructed based off the proposed design. Then, based on the test data, changes to the robot will be done in order to improve the design quality and its chances as a competitive entrée in the competition. Afterwards, the finalized version of the Lunabot will be constructed and entered to compete.

In building the Lunabot, several types of machines where used, such as a milling machine, a plasma cutter, and a welder. Furthermore, the steps for constructing this robot arranged in a logical manner. First, the wheels and chassis were assembled separately. Next, they were put together and the required electronics were attached (motors, batteries, etc.). The arm and collecting bin were the last parts to be assembled on to the robot.

6.2 Prototype Design and Construction

As previously noted, the prototype design is based off the proposed design. The team began constructing by welding the frame together. Next the wheels were manufactured and assembled on to the frame along with the motors. The scoop was the last part to be added to the robot assembly. The scoop was welded as a separate piece, while the wheels where bolted on to the frame. After all the mechanical aspects of the robot were completed, the programing was done to allow for the robot to complete the required task of mining.

6.3 Part List

When selecting the parts to be used for the prototype construction, the engineering approach was taken. Furthermore, for the purpose of time management and cost effectiveness, a great emphasis was placed on manufacturing. Parts which met all the criteria and also could be bought without the need to make any modifications to it were preferred over those that needed to be manufactured from scratch.

The engineering design process begins with the identification of a problem and its constraints, generation and selection of an idea, building and analyzing a prototype, and then improving on said idea based on test results.

The parts manufactured are listed below along with their perspective specifications.

- Wheels (4): Manufactured using 10” rims, and aluminum sheet metal.

Figure 68: Wheels

- Chassis (1): Manufactured using 2 by 1 inch hollowed out metal beams.

Figure 69: Chassis

- Windshield Wiper Motors (2):

Figure 70: Wiper Motor

- Stainless Steel Shaft (2)
- Assorted Nuts and Bolts (multiple)
- Batteries (1)

Table 27: Universal Battery

- 12" Linear Actuators (2)
- Arduino Uno Microcontroller (1)
- Sabertooth Dual Motor Driver (25 A) (2)
- XBee Arduino Shield and antenna kit (1)
- Pulleys (6)
- Belts (2)
- Wheel Shafts (4)
- Roller Bearing Shafts (2)
- Roller bearings (2)
- Motor Brackets (2)
- Flanged bearings (6):

Figure 71: Flanged Bearing

6.4 Construction

The frame of the Lunabot was built using aluminum 6061 bars. The bars were of a rectangular, hollowed out, cross section with dimensions of one by two inches. Aluminum was chosen because of its high strength and low mass (see literature survey for specifications). This satisfied the need to a light frame that is also durable and strong enough to lift and carry the required loads. Furthermore, the shape of the beam made the manufacturing process easier. A high moment of inertia occurs for the beam due to it being hollowed out (see calculations). As a result, the beam has a great resistance to bending. This increases the overall strength of the frame. The beams where individually cut and then welded together. Since this was done by hand, error with in the designated tolerances may have occurred. The final product can be seen below:

Figure 72: Final Chassis

Next, two pairs of wholes were made on each side of the frame to allow for the wheels to be placed. The holes were drilled in the middle of bottom bar, unlike in the original design, to allow for bigger clearance between the bottom of the Lunabot and the floor. The bearings where then bolted on to the frame. Four ribbed shafts were cut and mounted on to the frame. Nuts where used to tighten the wheels onto the shaft. The final product can be seen below.

Figure 73: Frame and Wheel (Side View)

Figure 74: Wheels and Frame (From View)

Pulleys were added to the shaft and tighten. This robot employs a two by two wheel drive, thus each side will have one motor corresponding to two wheels.

Figure 75: Pulleys

Figure 76: Motor with Pulley

Above is the figure showing the driving pulley attached to the motor, employing a stainless steel shaft. Motor brackets were fabricated using aluminum sheets. The windshield wiper motors were then mounted on to the motors and later on added to the chassis. The brackets were attached using self-aligning screws.

The wheels were created using ten inch aluminum bicycle rims. First, the rubber tires were removed from the rims. Four sheets of aluminum metal was cut according to the design specifications and then cut using the plasma cutter. Then each one was rolled individually and welded to the each rim. Next, a total of forty fins were cut and welded to the wheels, each wheel having a total of ten fins. The figures below pre-manufactured wheels and the final product.

Figure 77: Pre-Manufactured Wheel

Figure 78: Wheel (Final Product)

Next a pair of roller bearings were acquired and bolted on to the top of the frame. The acquired bearings were too larger than anticipated, thus an extra bar of aluminum was added between the top of the frame and the bottom of the bearing in order for them to sit correctly. The extra bars of aluminum were welded on to the frame and the bearings were bolted on to the bar. The result is shown below.

Figure 79: Rolling Bearings on Frame

Next, the shafts where added. The team selected to use hex bolts for the shafts since no changes needed to be made to them in order to fasten the arms on to the robot. Only the addition of nuts was required.

Figure 80: Bearing Shaft

Two arms were cut at the predefined length (see appendix for detailed drawings). Holes were made on opposite ends. On one end, the holes were made in order to allow for the arms to be mounted on to the rolling bearings on the frame. On the other end, hinges were installed with the use of another hex nut (1/4”). Later on, the edges of the arms facing the hinge were filed off to allow for full rotation of the bucket.

Figure 81: Hinge and Arm

Next, the arms were installed.

Figure 82: Lunabot with Arms

Next, the bucket was built. Four sheet of aluminum were cut using the plasma cutter: two in rectangular form and two in triangular for. They were welded together and the excess weld was buffered down as shown below.

Figure 83: Bucket

Holes were added to the bucket in order to be connected to the hinges on the arms via screws. Once placed, the bucket was secured using nuts.

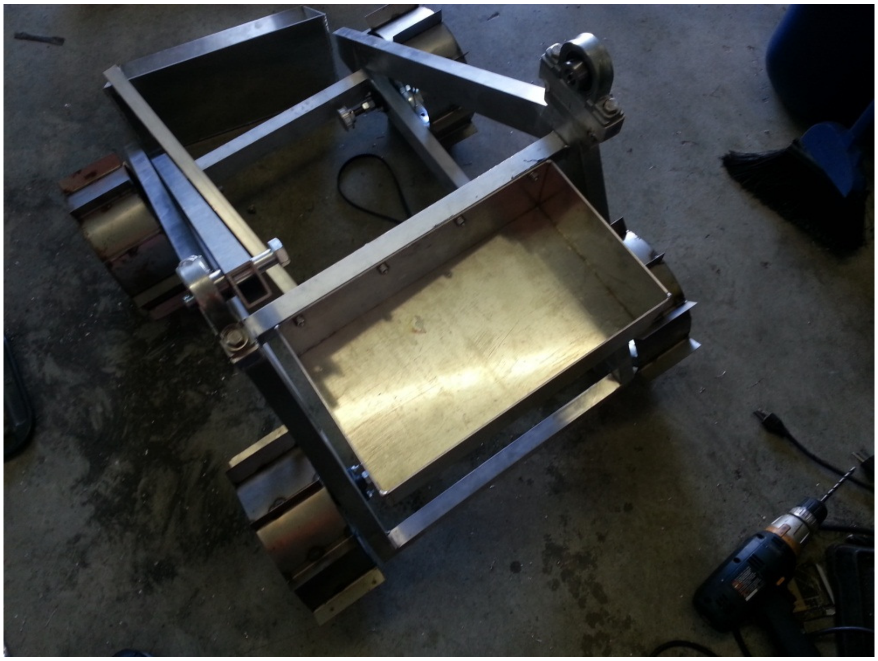

Figure 84: Pre-Installation Bucket

Figure 85: Pre-Installation Bucket (2)

Next, the motors were added. The brackets containing the rotating motors were mounted on to the Lunabot. A bar was added to the bottom of the Lunabot to provide a base for the bottom linear actuator. Another bar was welded between the arms. This second bar holds the linear motor responsible for rotating the bucket.

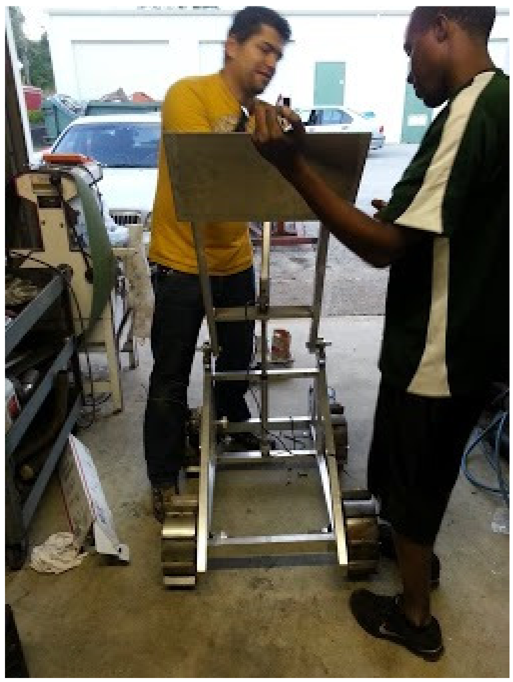

Figure 86: Completed Lunabot

Figure 87: Completed Lunabot (2)

The second part of the project consists of the electrical aspects. Two dual motor drivers were attached on to the system. Each motor driver was responsible for a rotating motor and a linear actuator. A PWM filter was created as indicated by the SaberTooth manual, and attached to the dual motor drivers. From there, the drivers were connected to the arduino microcontroller, which would connect to the computer (controller) via antenna XBee. Programing the microcontroller was done using the arduino compiller.

6.5 Discussion

It is critical to document the construction process of the robot in order to obtain a full understanding of the project. Throughout construction, the team ran into new issues that had not been considered, despite rigorous efforts to eliminate setbacks. For example, when adding the wheels, it was found that the bottom of the frame was too close to the ground. This arose great concern. The small clearance meant it was possible for the ground to cause interference with the bottom part of the frame Lunabot, impeding the Lunabot from advancing. This issue was fixed by moving the placement of wheels to the middle of the bottom beam, giving the Lunabot an extra inch of clearance.

7. Testing and Evaluation

7.1 Overview

Below is a list detailing the plans for testing once the design is completed.

- Computer models will be tested using SolidWorks
- Prototype's drive system will be examined through different sandy terrains
- Strength and functionality of prototype will be tested through mock mine runs
- Communication system will be used over a distance of 150 ft. (45.72 m)

Furthermore, each of the electrical components were tested individually to ensure functionality, and to obtain crucial data regarding their functionality (voltage, amperage, etc). Additionally, the CAD studies performed earlier sometimes proved to be not always accurate, usually due to alterations in the design. Often, this was a result of the manufacturing process. Lastly, the robot must meet the complete criterion laid out by NASA's Lunabotics panel of judges in order to qualify and be allowed to compete.

7.2 Test Results and Evaluation

First, NASA set 80 kg as the maximum weight allowed for each Lunabot. Also, point deduction for the mass begins at 10 kg, where 10 points are deducted for every 10 kg. After measuring the mass of the Lunabot using different scales, a total average mass of 31.30 kg was reached as the total mass of the robot (excluding the 7 kg batteries that will be replaced by LiPo batteries for the competition). The height, extended height, and width of the Lunabot also must fall below predefined parameters in order for the robot to continue on to the competition. For the height, the Lunabot can measure up to 0.75 m when entering the arena, and can extend to measure up to 1.5 m. The width must remain a constant of 0.75 m. The Lunabot designed by FIU's senior design team for the competition measured 1.26 m when extended. Once the linear actuator had been lowered, it measured 0.625 m. The width of the Lunabot was measured to be 0.673 m. The length of the Lunabot is also limited to 1.5 m according to regulations. The measured length of the Lunabot was 1.30 m.

Next, the design's lifting capabilities were tested. This was done by placing 13.61 kg on the bucket and lifting it via the linear actuator. Once again, the results showed to be successful.

Figure 88: Strength Testing

Figure 89: Strenght Testing Results

7.3 Discussion

In order to improve the design of the Lunar Excavator more testing will need to ensue to test the communications, traction, and velocity. Based on these results, changes on the feature of the robot will be planned and completed previous to the competition. Additionally, these changes will also need to be tested to ensure proper functionality.

Based on the testing that has already taken place, however, it can be concluded that the robot is in full conditions to qualify. It meets all the requirements set up by the Lunabotics board. The robot was designed so that there was flexibility with in terms of the height, width, and length measurements. Had the robot been designed to measure the same as the limit set by the rules, the team ran a high risk of not being able to compete. Furthermore, based on the gathered data, there are few key improvements that can be made. The first is to perform a weight reduction on the robot. While the mass of the Lunabot measured much below the specified limits, it would be to the advantage of the team to perform a mass reduction, since points are taken off for every 10 kg. This can be done by replacing metal with material of lesser density. For example, the back basket used to carry electronics is made of thick aluminum sheets. The only function of this basket is to hold the electronics in place. Since the load the carry is very small, another material can be used in the place of aluminum. Plexy glass, for example, would be an ideal replacement candidate.

8. Design Considerations

8.1 Assembly and Disassembly

Transporting the prototype via air or ground will be necessary in order to compete in NASA's Lunabotics competition. For this reason, the assembly and disassembly process played a key role in the design process. The Lunabot was designed in a way that makes disassembly for it easy. The arms, the bucket, the wiper motors, and both actuators are removable. This makes transportation of the Lunabot easy. Also, the possible need to replace parts of the robot, such as the motors or arms, was taken into consideration when constructing the design. For this reason, the metal brackets which hold the motors are removable, as well as all the moving mechanical parts.

Furthermore, during the competition the teams must complete two rounds of the material collection at the LunArena in order to qualify. Each team is also allowed to complete practice rounds. It is possible that failure may occur. Due to this, the Lunabot was designed to be easily assembled and disassembled. This makes troubleshooting of the robot easy. If replacement of a part is needed, then said part can be removed and replaced.

All the tools needed for reassembly can be found in an average tool box. The image below gives a graphical representation of all the parts on the Lunabot that may be removed.

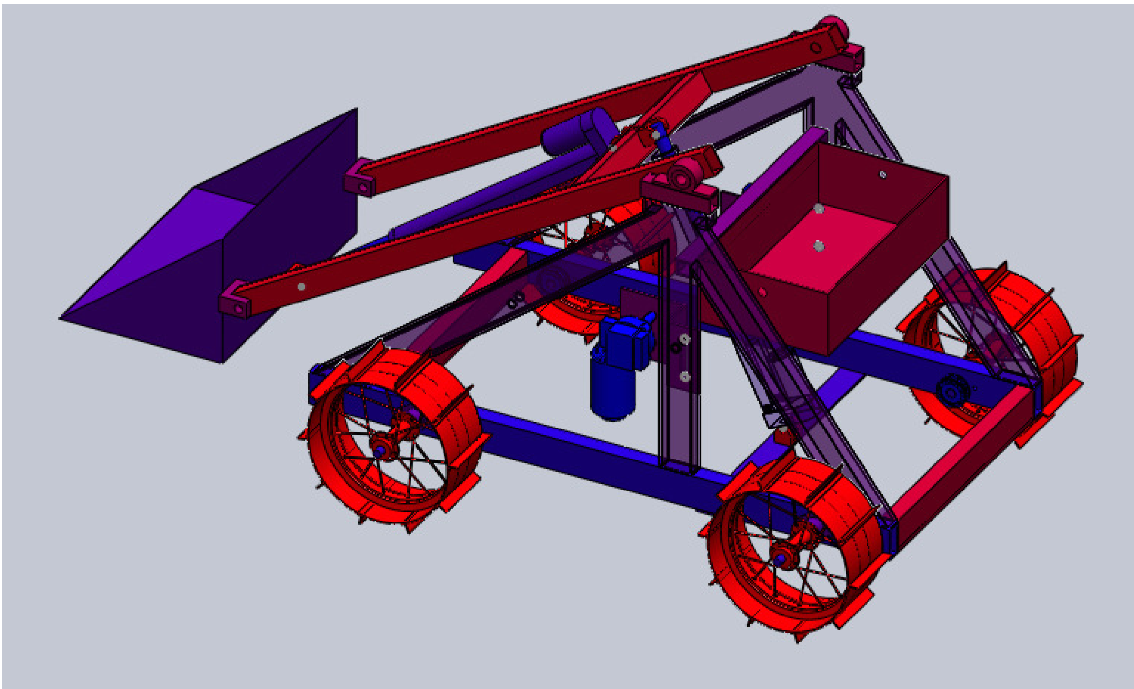

Figure 90: Lunabot Assembly

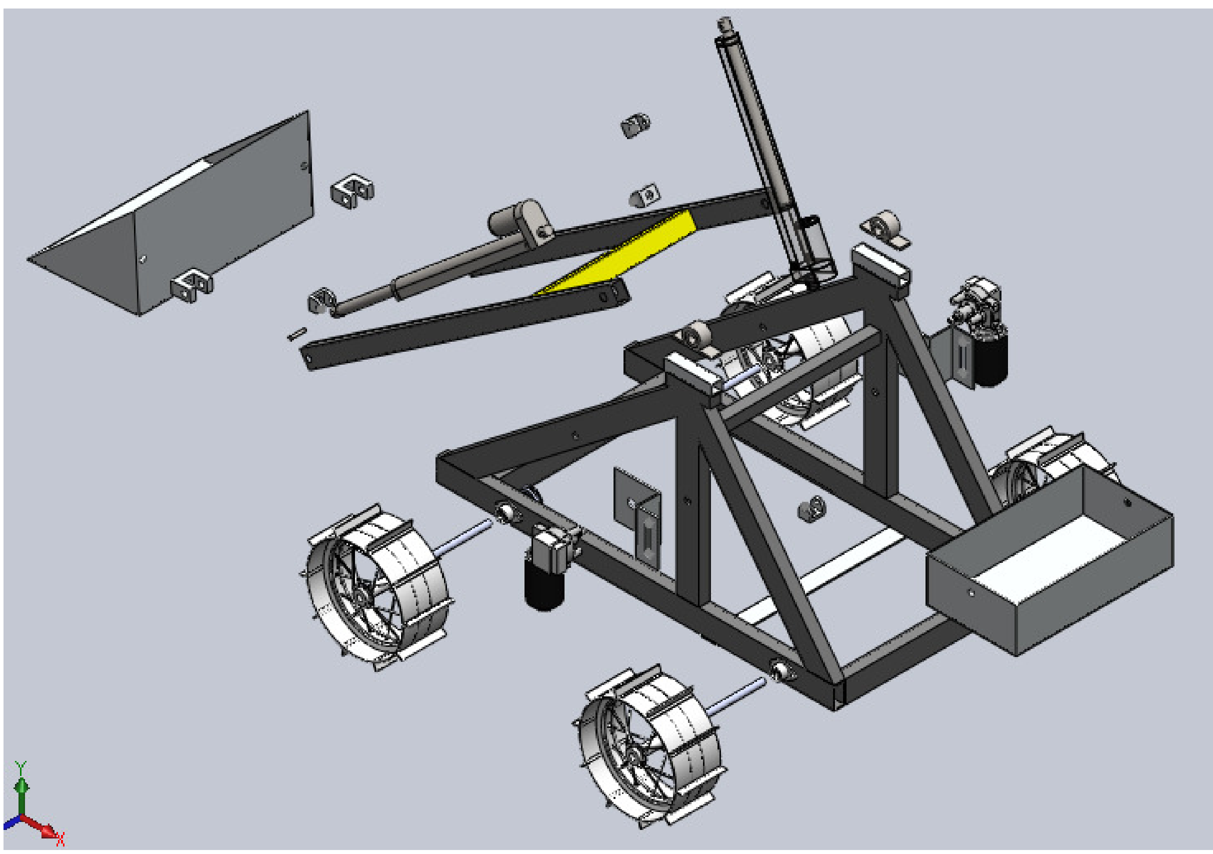

Figure 91: Lunabot Exploited View

The wheels, the bucket, the arms, the bearings, the basket, and all the motors are removable. Only the frame is to remain as one solid piece.

8.2 Maintenance of the System

Like all pieces of equipment, the Lunabot requires maintenance in order to maintain proper function. Maintenance is required regularly for small scale, and larger scale maintenance is recommended for the failure of major components.

8.2.1 Regular Maintenance

After every run of the Lunabot, it is recommended to perform a visual inspection on all the components. Visual inspection of the motors, belts, and shafts is recommended, as well as all the electrical components.

8.2.2 Major Maintenance

Like in every design, there always exists the possibility of failure. The wheel and motor shafts are especially susceptible to stress failures due to the high stress they are under. If this occurs, all that is needed is to replace the shaft to one with the same size and bolt it in place for the wheels. For the motors, the shafts were individually manufactured, thus it is necessary to use the measurements indicated on the appendix section of the report to create a new shaft.

Also, battery replacement is another procedure which will have to take place eventually since all batteries have a set life.

8.3 Risk Assessment

Safety risks are involved with the manufactured prototype, as with any other robotic platform. The wheels manufactured for the Lunabot have sharp edges which can easily cut through soft materials. Also, the batteries electrical system, in specific the LiPo batteries, are known to be fire hazardous if damaged. The large mass of the Lunabot can provide a great amount of momentum, and may easily hurt users. The area under the robotic arm should be kept clear at all times. Furthermore, the material mined, BP-1 can cause a lot of health related issues if inhaled. For this reason, competitors are required to wear a bunny suit at all times during the competition.

9. Conclusion

9.1 Conclusion and Discussion

The Lunabotics Competition allowed Team 7 to realize the thought and complexity that is put by NASA into space projects. Enlisting on this competition allowed students to comprehend the importance of team chemistry and gave them important insight into the processes of design, development, and manufacturing of a product. Furthermore, this project tied in all the skills the team gathered over the years as students at Florida International University. Financial availability also showed to be equally as important as any technical quality for completing this project.

Additionally, students developed a greater interest in NASA and its future projects. Thus, it is safe to say that the competition's goal to attract and retain science, engineering, math, and technology students into their perspective fields is reached amongst competitors. The continuation of this project will not only allow for a greater number of students to take interest into these fields, but also will influence NASA into their future ordeals.

9.2 Future Work

The Lunabotics Competition occurs every year, thus the design could be used as reference for future competitors. Additionally, the next generation of FIU Lunabotics may use the robot and further optimize it based on the competition results.

10. Reference

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11. Appendices

Appendix A. Detailed Engineering Drawings of All Parts

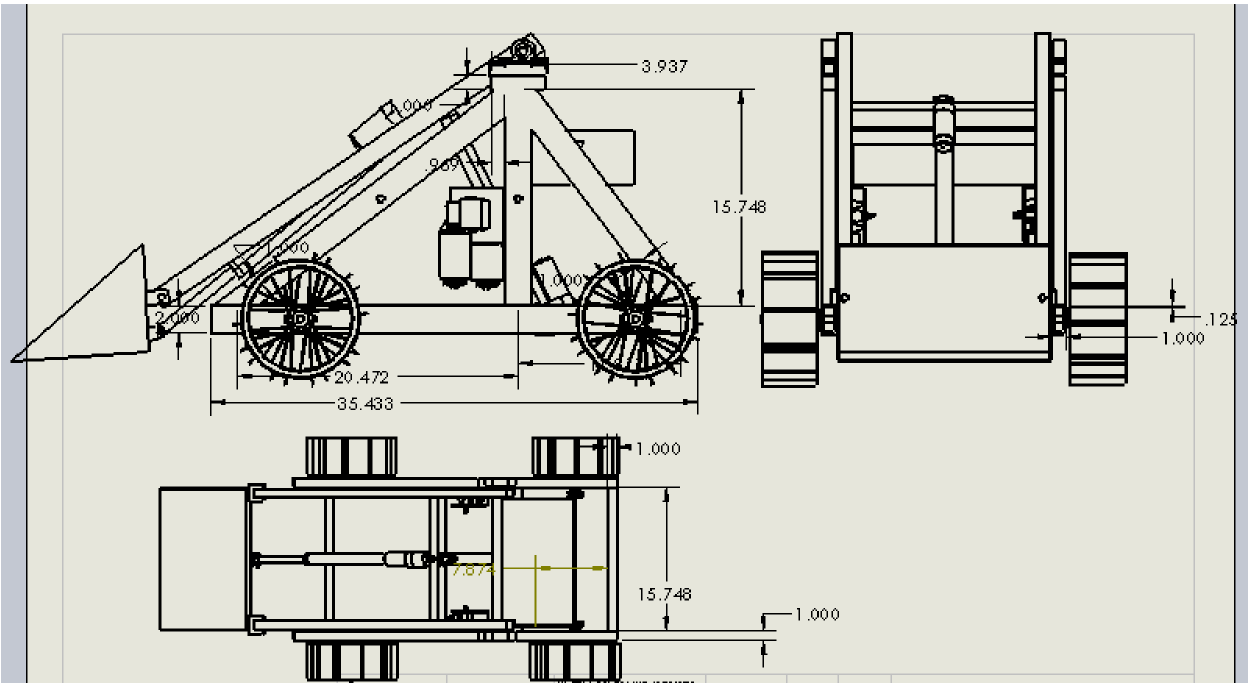

Figure 92: Assembly Drawing

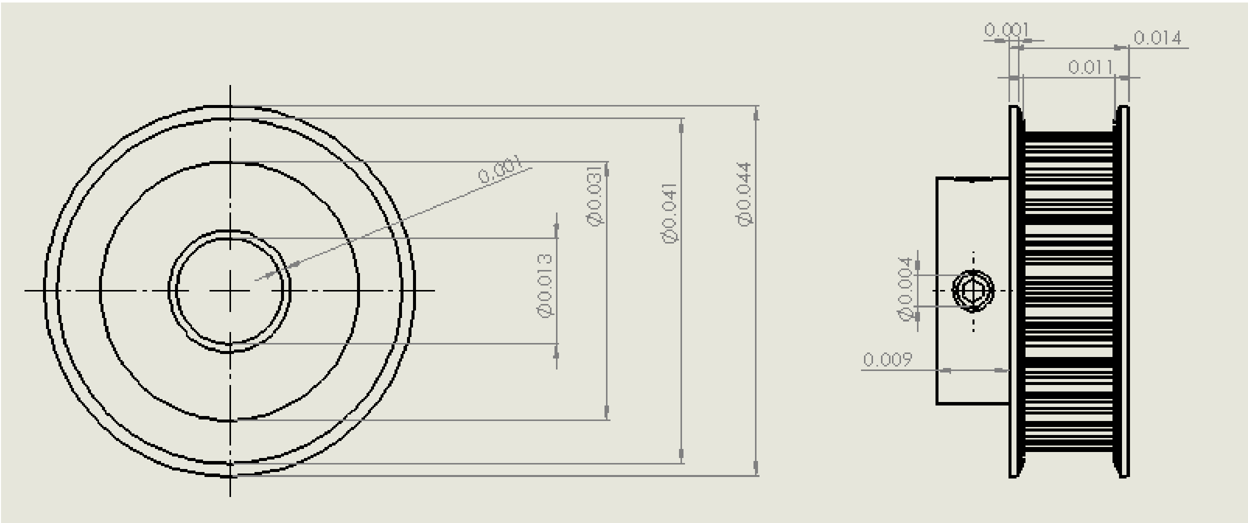

Figure 93: Timing Pulley

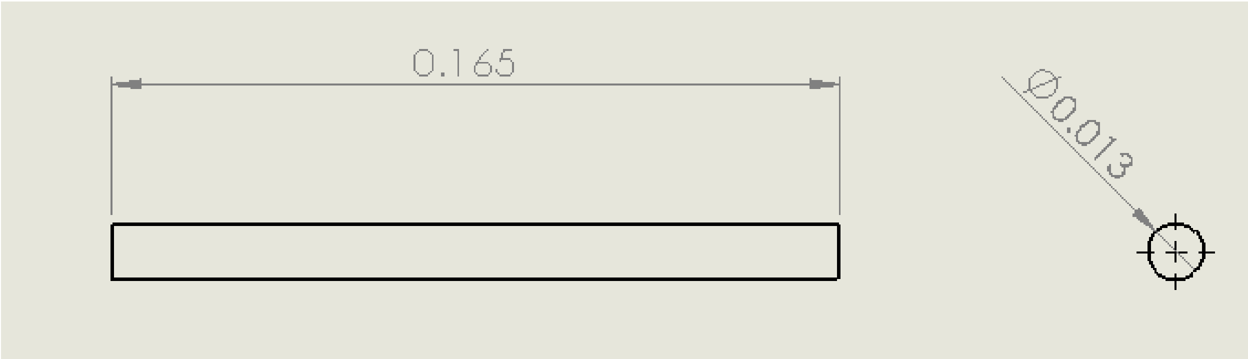

Figure 94: Shaft

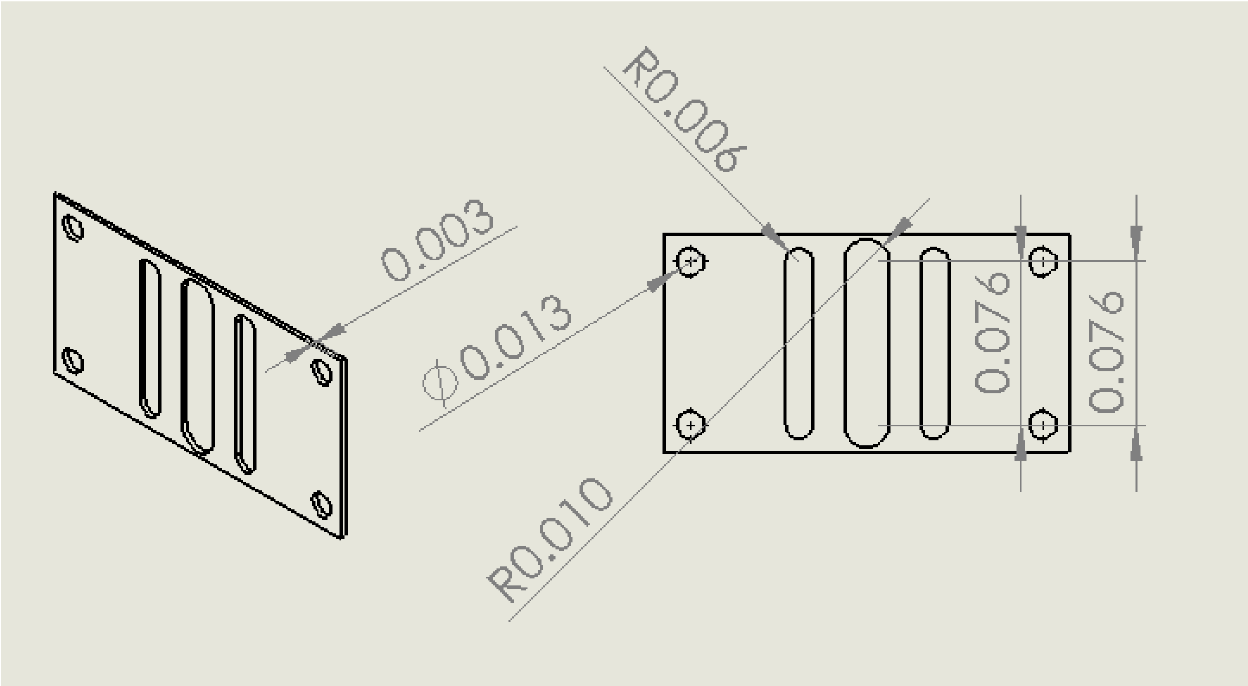

Figure 95: Bracket

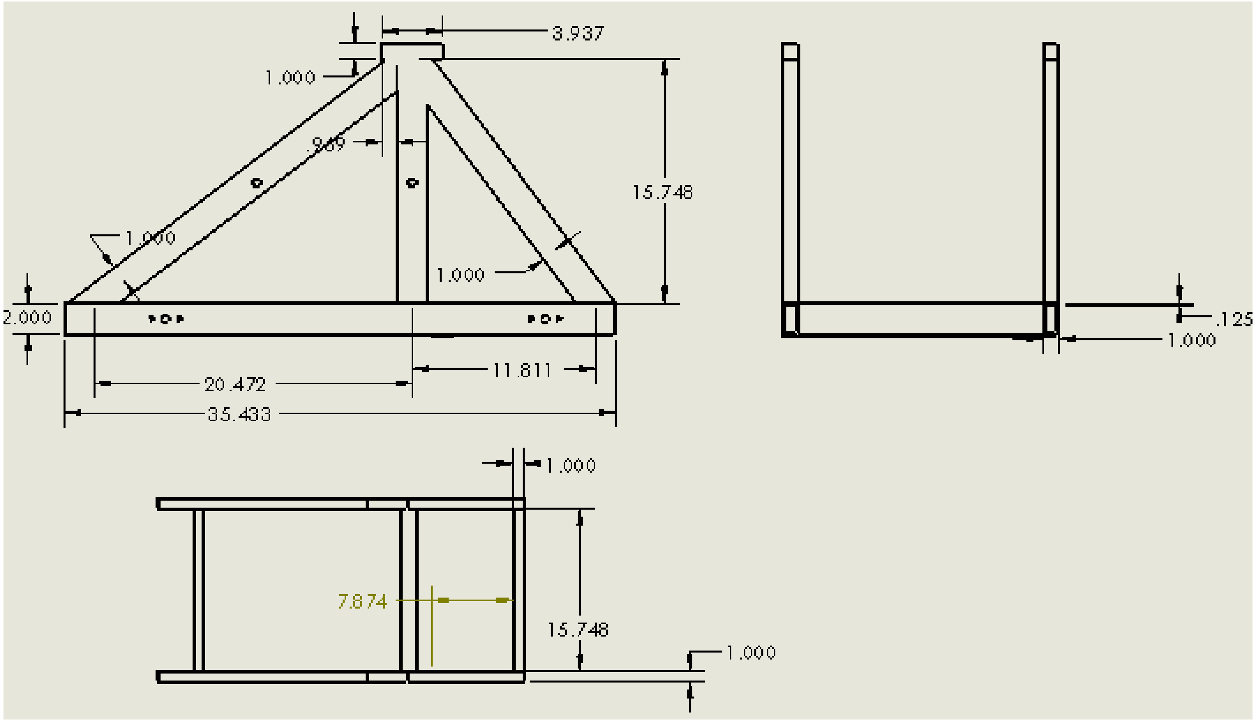

Figure 96: Frame

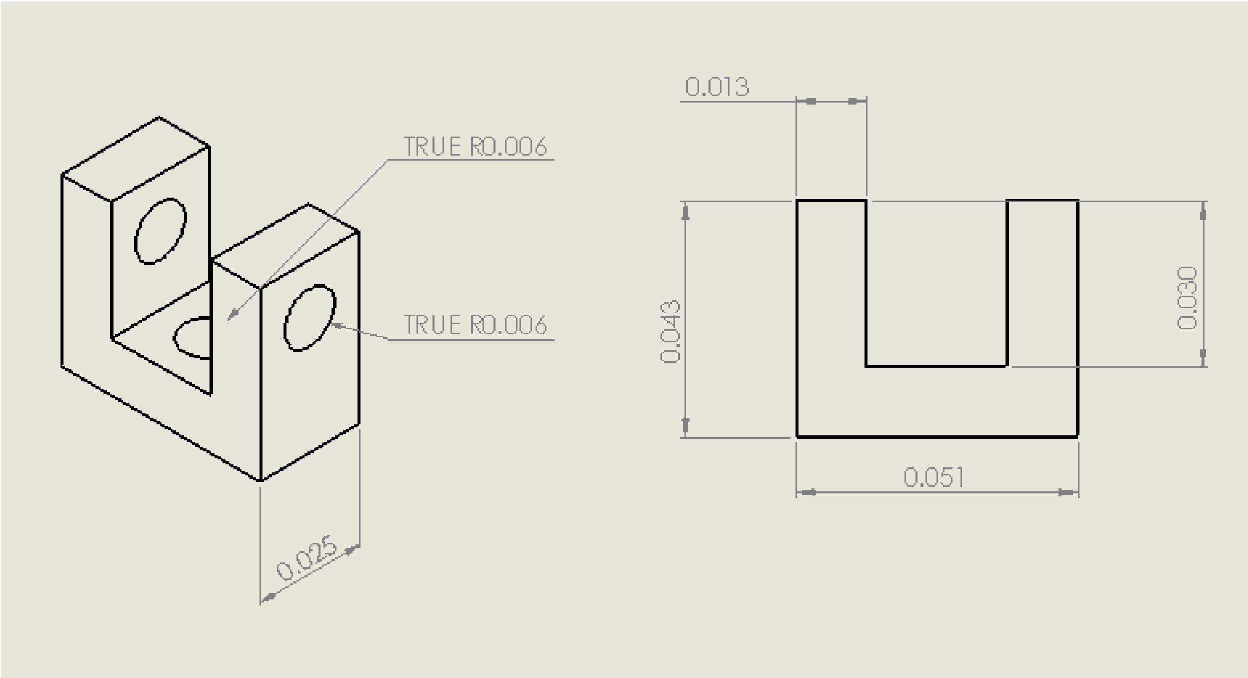

Figure 97: Arm Brackets

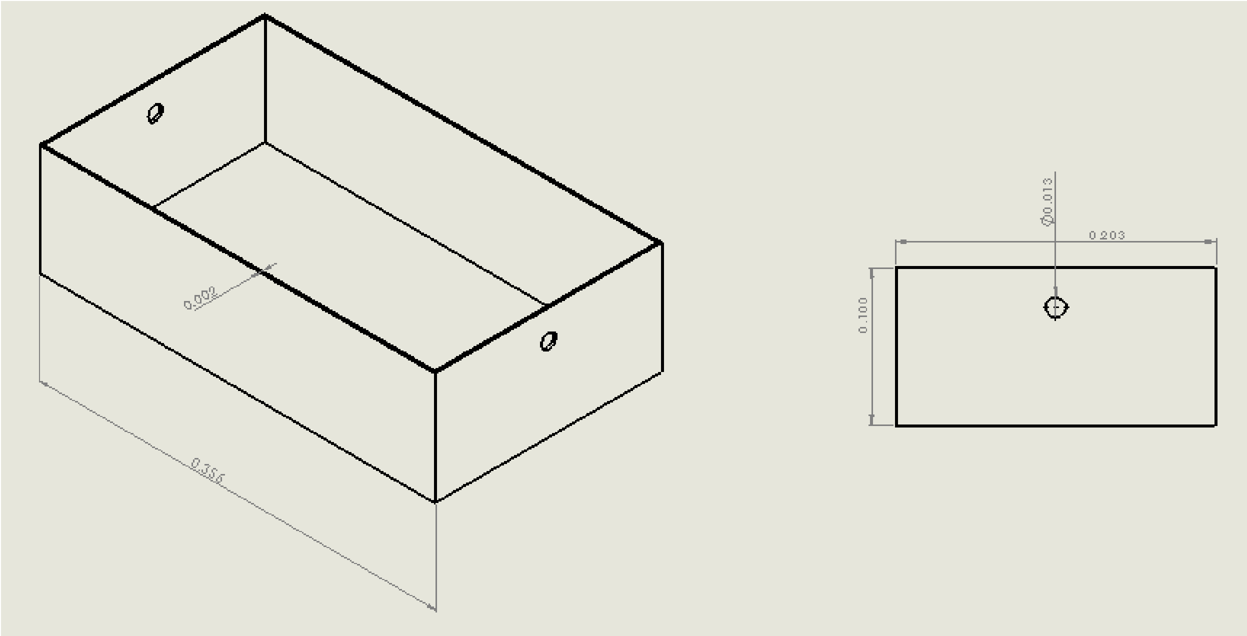

Figure 98: Basket

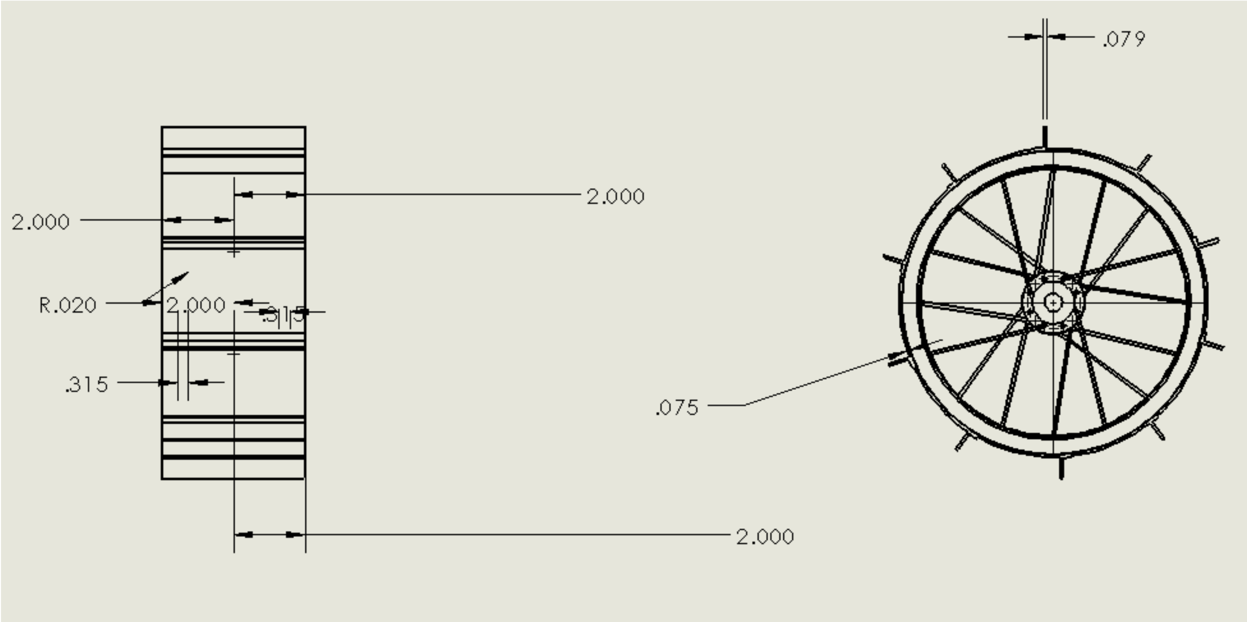

Figure 99: Wheels

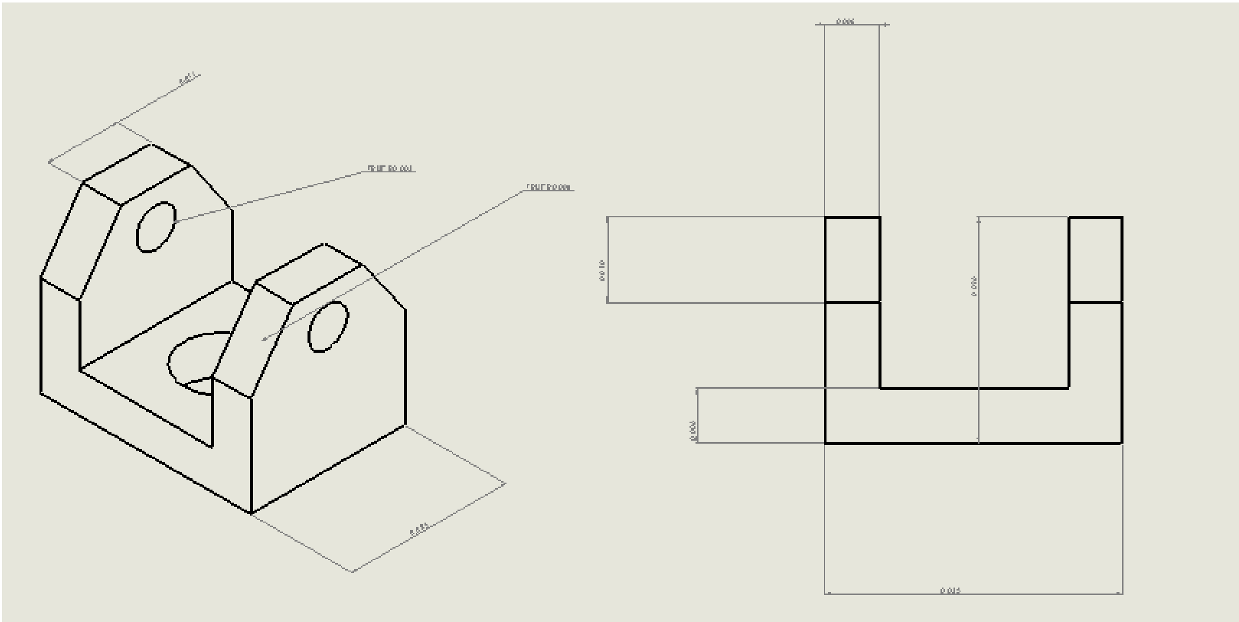

Figure 100: Actuator Bracket

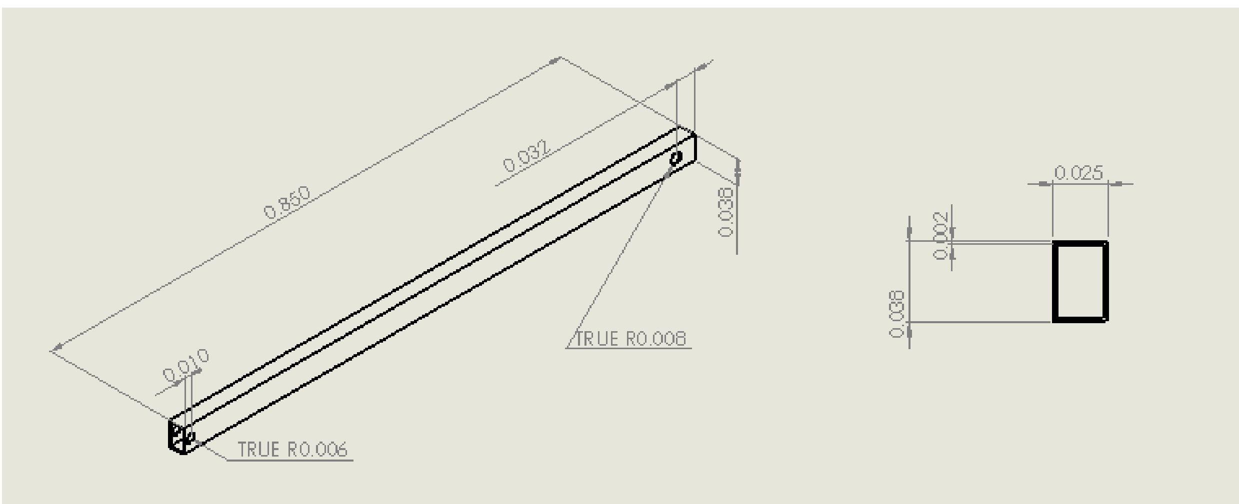

Figure 101: Arms

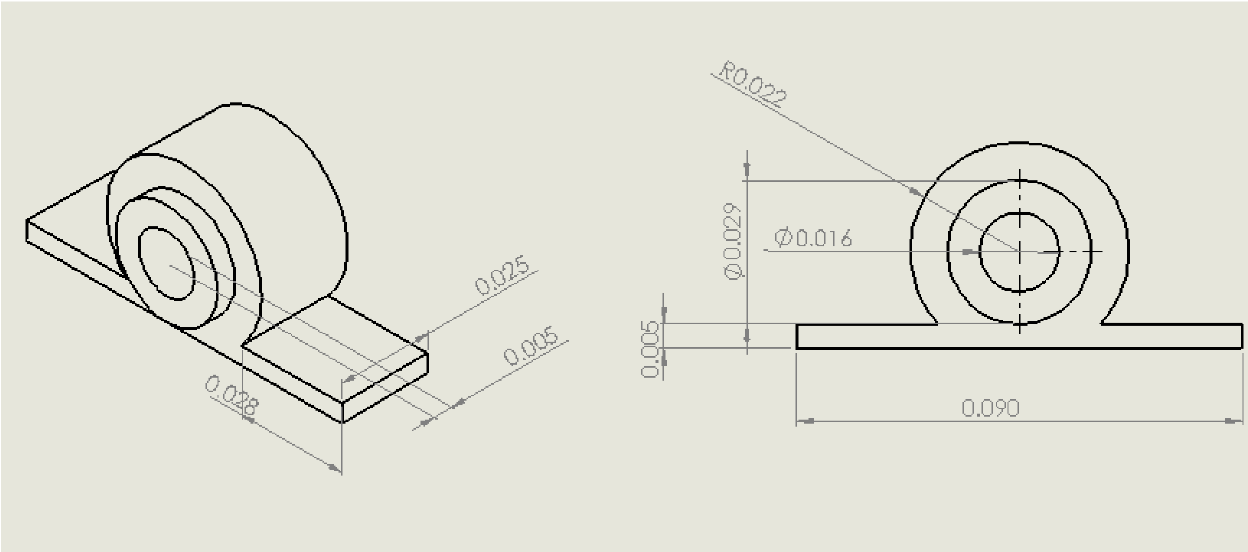

Figure 102: Roller Bearing

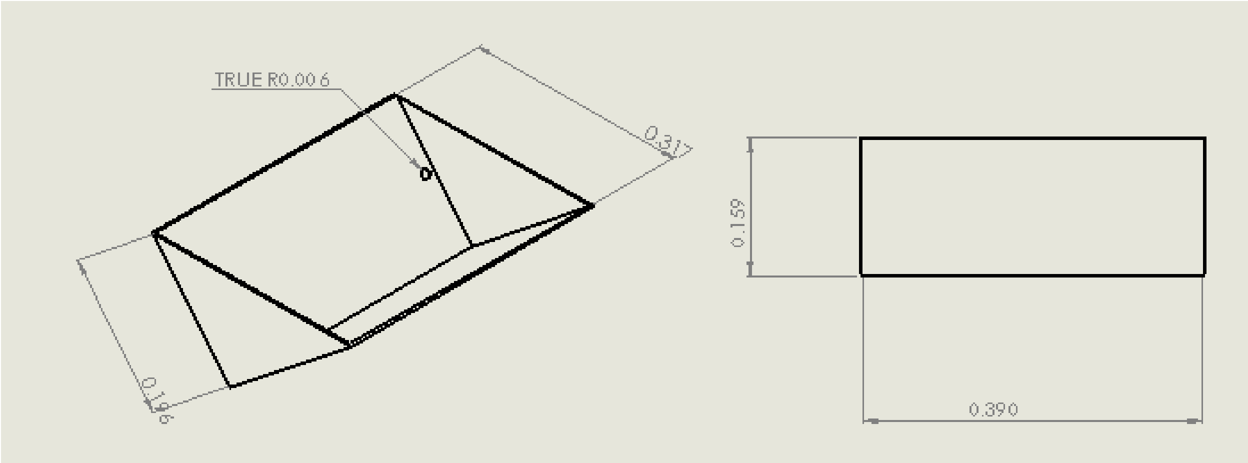

Figure 103: Bucket