"MECH 4240 Critical Design Review"

Summer 2011

Corp_2 – Lunar Excavator

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NASA

Group Members

Anna Holland

Kyle Otte

Cody Salmon

Alex Hollis

Han Cho

Faculty Advisor

Dr. David Beale

Sponsors

Dr. Nels Madsen

Dr. Lloyd Riggs

Dr. J-M Wersinger

Summary

The purpose of this senior design project is to develop a remotely controlled lunar excavator that can be used to collect 300 kilograms of lunar regolith in 15 minutes. The finished lunar excavator will take part in a NASA sponsored competition in 2012. The design stage of the project began with watching numerous videos of past competitions and researching and debating about which designs were the best. A lot of time was also spent talking to former Auburn students who worked on Auburn's previous version of the lunar excavator. Three good designs were developed and debated in greater detail. All three designs feature six wheels, and a large hopper that is emptied into the collection bin. The three designs included a design using a belt with small buckets that scooped regolith into a hopper, and a design featuring a small bucket that dumped into a hopper, which was then emptied via an auger. A plus-minus system was utilized to select a design that incorporates one small bucket to scoop regolith and then dump it into a larger hopper on the back of the excavator. When the large hopper is full, the excavator is driven to the collection bin and the hopper is emptied. Work has been completed on CAD drawings, Working Model simulation, Finite Element Analysis, and aluminum angle testing for the excavator. Parts will be obtained at the beginning of the fall semester and the excavator will be built by the midterm. All subsystems will be operated independently, or verified, before being integrated into the total system. This will ensure that all components will work as specified. After numerous tests are ran the excavator will be ready to compete in the 2012 competition.

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1.0 Introduction

NASA's Lunabotics Mining Competition is held once a year to encourage development of innovative lunar excavation concepts that could be used in real world application. The design problem is to design and build a remote controlled or autonomous excavator that can collect and deposit lunar stimulant. The project is assumed to have the same requirements as the 2011 competition. The excavator has to weigh no more than 80 kg, be no taller than 2 m at any point in the competition, and be no longer than 1.5 m and no wider than 0.75 m at the start of the competition. A full list of the rules and requirements are attached in Appendix A. Last year's competition winners were Laurentian University with a mini scoop conveyor design that gathered 237 kg of regolith. Second place winners were University of North Dakota with a hopper design that gathered 172 kg of regolith. Third place winners were University of West Virginia with a rotating barrel with pockets design that collected 106 kg of regolith.

The systems engineering approach, including the use of the Vee Chart and the 11 Systems Engineering Functions, was used to take the lunar excavator design from a list of given requirements and constraints to a finalized concept. This report details the steps taken to reach the final design concept, including defining a mission objective, formulating multiple design concepts, and creating a decision matrix. The decision matrix takes into affect advantages and disadvantages to each concept along with the probability of failure. From this matrix, hours of research and discussion, and from studying previous competition videos a finalized concept was chosen. This finalized concept will be discussed in further detail in the following sections of the report breaking the system down into 3 main subsystems: scoop system, drive system, and dump system. The electrical and frame subsystems are also discussed in limited detail.

This report details how the finalized concept was chosen and provides an overview of the concept of operation of the system. A complete detailed design of the excavator has been complete and the parts are ready to be ordered.

2.0 Project Management

The lunar excavator senior design project team consists of an instructor, three sponsors, one project manager, and four system engineers, one of which acts as the scribe for the project. The breakdown of the management structure is shown in Figure 1.

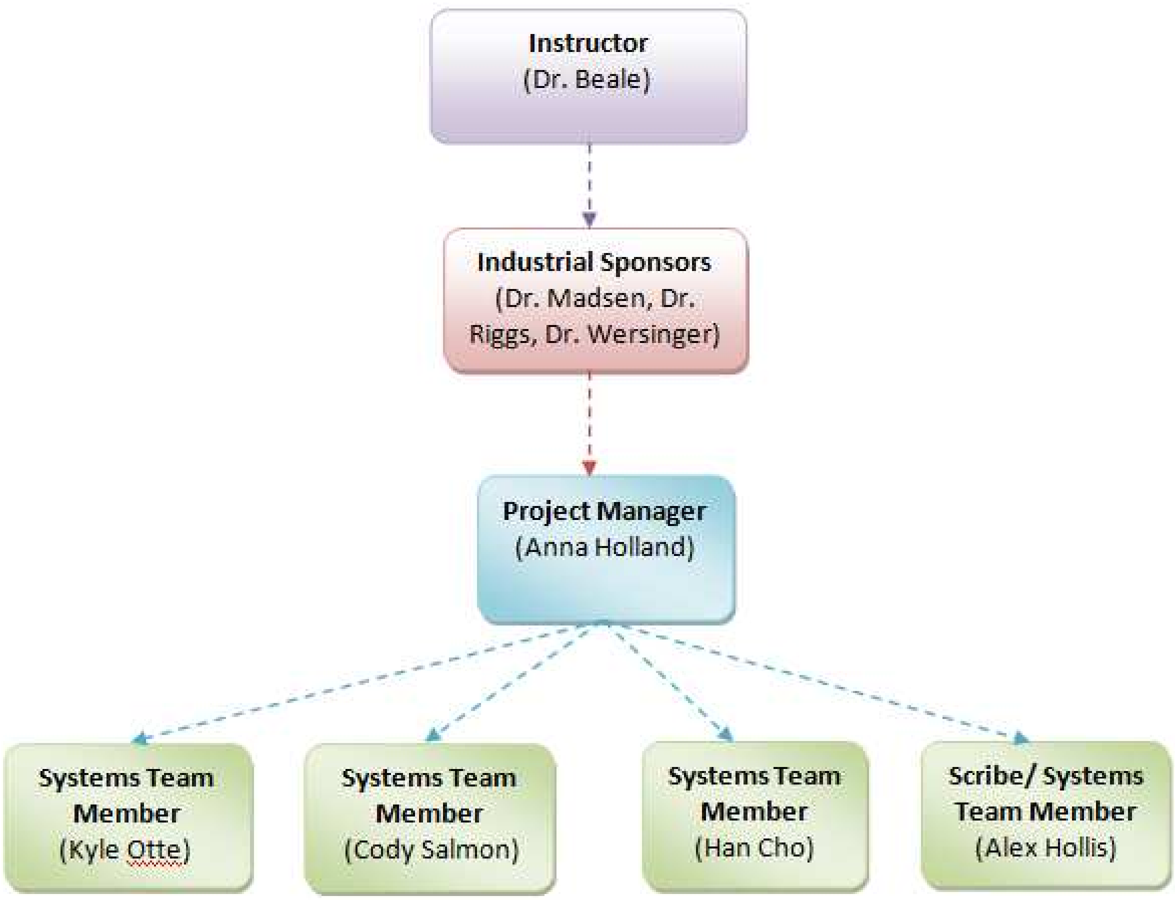


Figure 1: Project Management

Over half of the time breakdown was spent on concept generation and the other part spent on concept analysis and verification. The complete work breakdown for summer semester is shown in Figure 2.

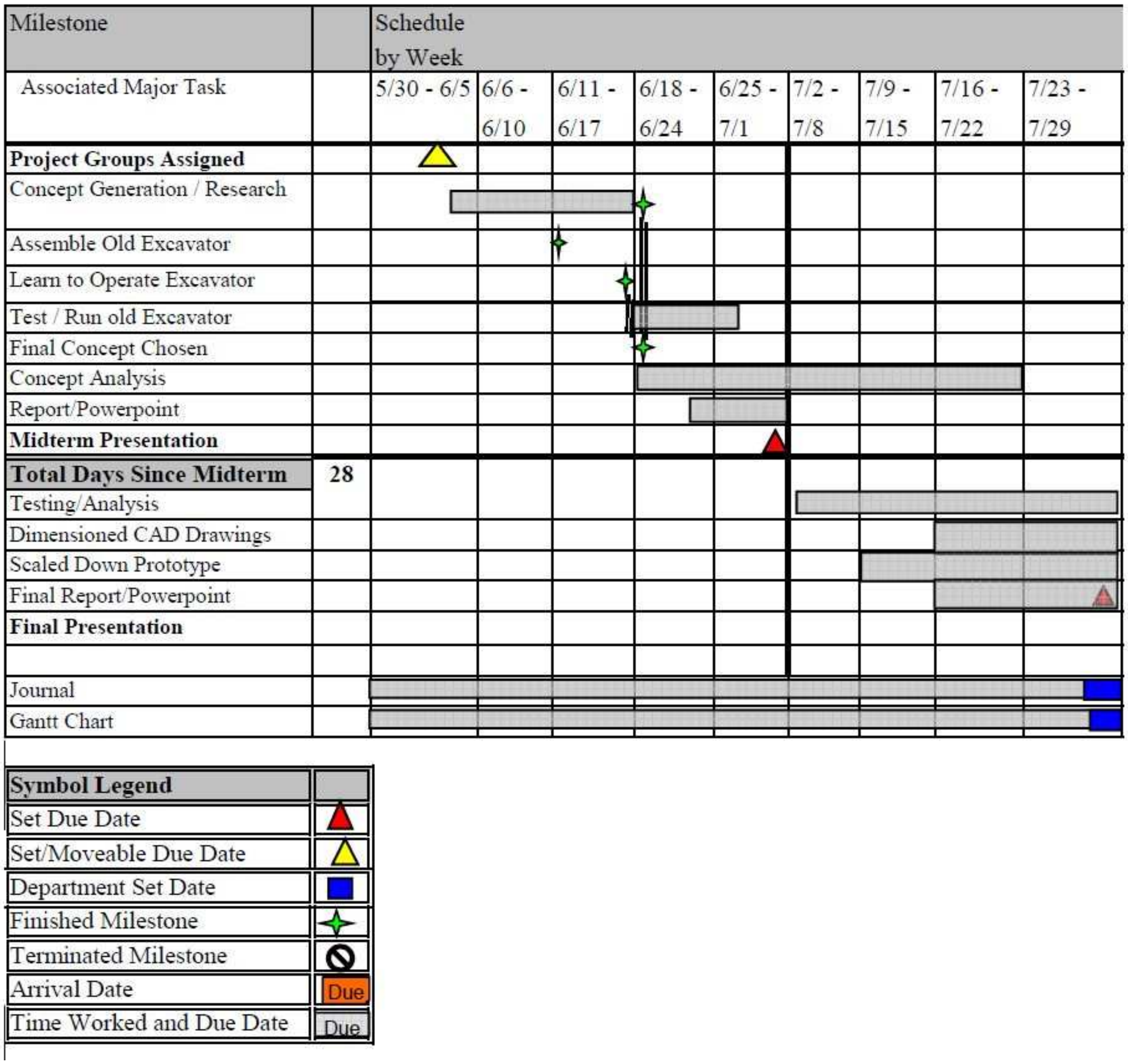


Figure 2: Summer 2011 Gantt Chart

3.0 Mission Objective

The Mission Objective is to create a remotely controlled excavator that weighs less than 80 kg, can collect and deposit at least 300 kg of lunar regolith within the 15 minute time limit, and that will win the 2012 Lunabotics Mining Competition. The overall size cannot exceed 0.75 m width x 1.5 m length x 2 m height at the start of the competition. However, the length and width constraints may be exceeded once the competition starts.

4.0 Mission Environment

The mission environment is an Earth representation of the Moon's lunar surface. The testing environment at NASA's Kennedy Space Center will use Black Point-1 (BP-1) which is a nearly exact replica of lunar regolith. Lunar regolith stimulant is a very fine powder with a particle size between than 60 and 80 micrometers. The regolith has a tendency to cling to everything it touches. The "lunarena" will have two teams competing at one time in parallel areas. The areas will be separated by a wall but the dust the other team kicks up will travel into the other arena. In the pictures of last year's competition the arena appeared to be open to the environment which would allow for humidity to enter the competition area. The lunarena will be 3.88 m wide by 7.38 m long and 1 m deep as shown in Figure 3.

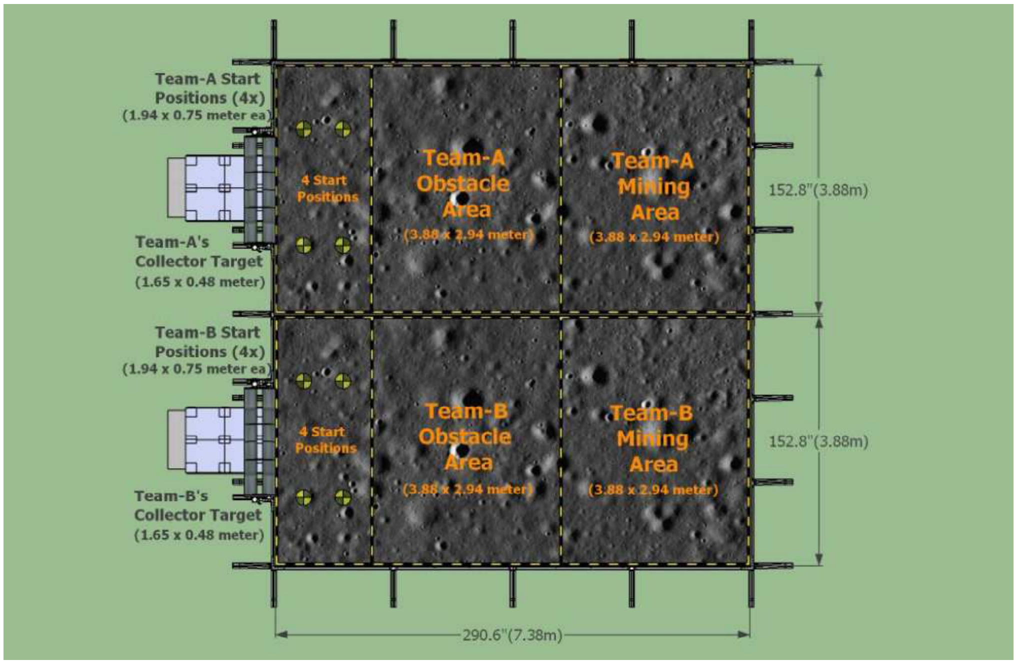


Figure 3 : Lunarena Diagram

The collection bin is 1.65 m wide by .48 m deep. There are two craters placed that are no more than 30 cm in depth or width. Three obstacles will be placed in the arena with diameters between 20 and 30 cm and masses between 7 and 10 kg. The dust will be a significant factor since the robot will be operated by cameras that need a clean lens to work efficiently. The dust could also affect the electronics if they get coated during the competition.

On the actual Moon the environment is much different from the simulation on earth. The gravity on the moon is 1.6 m/s^2. Due to the lack of an atmosphere the surface is in a total vacuum with the temperature ranging from 300˚F in the sun to -250˚F in the shade. The Moon's surface is littered with large craters much larger than the 30 cm craters in the competition. These factors are too difficult to reproduce on Earth and are excluded from the competition environment.

5.0 Architectural Design Development

The systems engineering approach, including the use of the Vee Chart and the 11 Systems Engineering Functions, was used to take the lunar excavator design from a list of given requirements and constraints to a finalized concept. The functional decomposition for the lunar excavator is broken down in Figure 4.

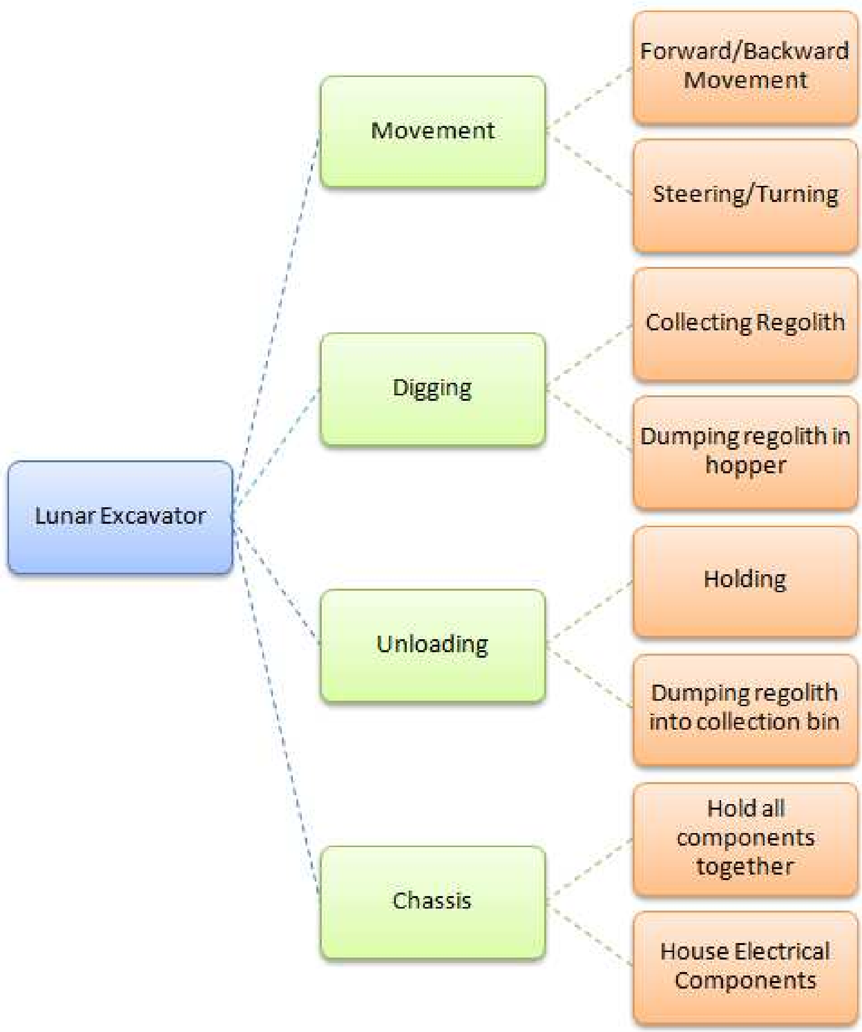


Figure 4: Functional Decomposition

From this functional decomposition, weeks of research and discussion, studying numerous previous competition videos, speaking with former Auburn competition attendees, and from formulating a decision matrix, a finalized concept was chosen. This concept generation process and the finalized concept will be discussed in further detail in the following sections of the report breaking the system down into five subsystems: electrical system, frame system, scoop system, drive system, and dump system.

5.1 Concept Generation

The Lunar Excavator project has five separate subsystems: electrical system, drive system, frame system, scoop system, and dump system   The concept generation for the lunar excavator project was initially broken into three main subsystems: drive system, scoop system, and dump system. Figure 5 shows the concepts that were generated for the subsystems.

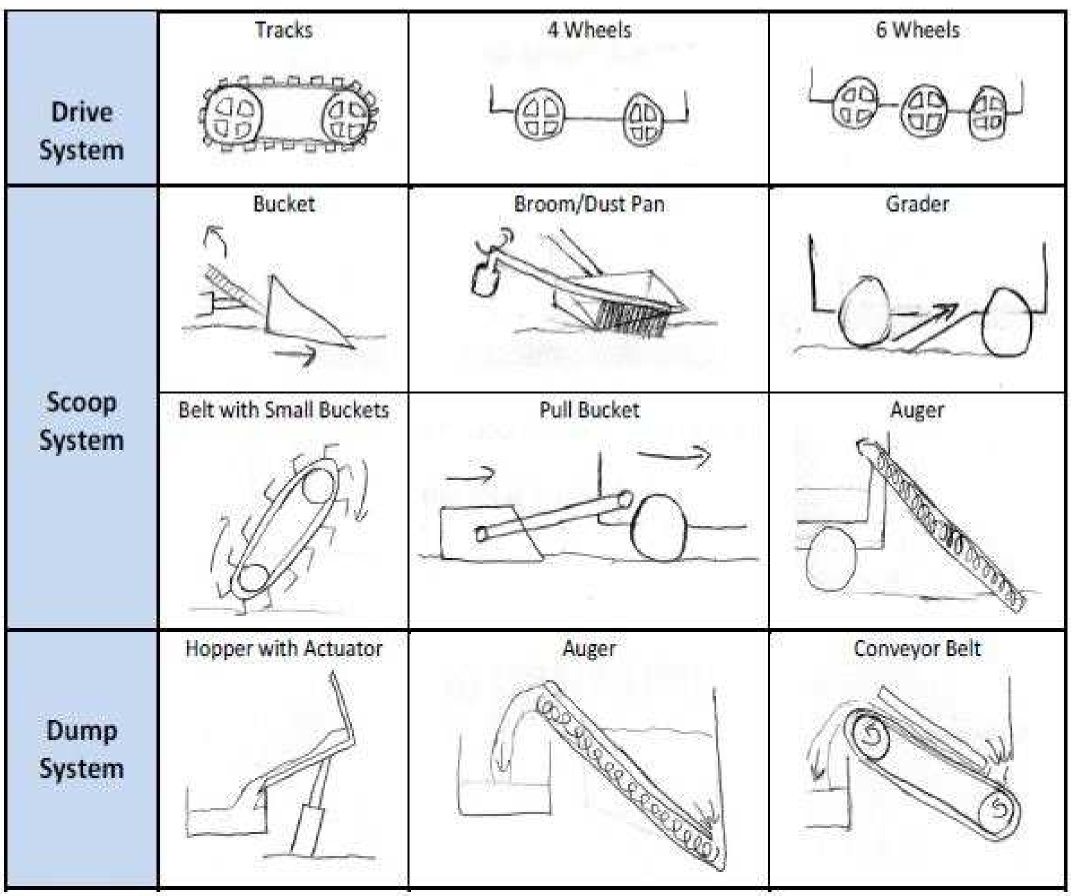


Figure 5 : Subsystem Concept Table

5.1.1 Electrical Subsystem

The electrical system has not been analyzed thoroughly to date due to the lack of knowledge of needs for the subsystem. The drive, scoop, and dump systems will all utilize electrical components, so each of these subsystems must be analyzed prior to alteration of the electrical system. Although a lot of the electrical system will be incorporated into the design, an electrical senior design group will be assigned to the lunar excavator project in the fall to help with and complete work on the electrical subsystem.

5.1.2 Drive Subsystem

Functional Requirement

1. Shall be able to transfer the regolith to the desired position
2. Shall be able to pass 30cm crater

Performance Requirement

1. Shall transfer maximum 150kg of regolith

For the drive system, the decision lay between whether to use tracks or wheels. If wheels were chosen, the decision between whether to use four or six wheels had to be made. The three main deciding factors for the drive system were traction, power, and failure prevention. Traction is determined by the tread pattern of the drive device and the surface area in contact with the ground. Tread pattern can be matched on any of the drive options, but the track and six wheeled options hold obvious advantages in surface area. The six wheel option has the power advantage due to the use of six motors to drive the vehicle rather than four, but will have to include the addition of a more complex electrical control. The four wheel option was disregarded after falling last in the previous two factors that were analyzed. Since the six wheels and track were almost even in advantages a failure prevention analysis was performed. As seen from the previous competition, the track system can become loose and detach from the drive system. If the tracks fail, there is no way to reassemble the track system, and the excavator would be left with four wheels not designed for traction in regolith. The likelihood of failure with the six wheel design is less likely, but even if a wheel fails, the excavator is left with working wheels designed to have traction on the regolith surface.

5.1.3 Frame Subsystem

Functional Requirement

1. Shall be able to provide rigidity on which the bucket and mechanical linkage can fasten
2. Shall be designed to provide easy interfacing to the bucket and mechanical linkage
3. Shall provide wheels to support bucket in all three mechanical positions
4. Shall interface with the provided interfacing plate

Performance Requirement

1. Shall hold maximum 150kg of regolith

The frame subsystem design depends on the needs of the drive, scoop, and dump subsystems, but the choice of frame material to use had to be made. The three options for frame materials were square aluminum tubing, square fiberglass tubing, or square carbon fiber tubing. The deciding factors for the materials were strength and weight. The carbon fiber excelled in weight followed by the fiberglass tubing. The aluminum had the highest strength, but it was followed closely by the fiberglass. The decision was made to go with the fiberglass tubing to have both strength and weight advantages. This was the same frame material used by the previous team as well.

5.1.4 Scoop Subsystem

Functional Requirement

1. Shall be designed to provide enough angle to accommodate excavating and dumping
2. Shall be designed to accommodate flow of regolith during dumping

Performance Requirement

1. Shall scoop and dump into the hopper 300kg of regolith in 15 minutes using 10 kg per scoop

The scoop and dump subsystem were the two most important designs to select. The scoop design determines how much and how quickly the excavator can extract regolith from the surface. From researching video, it was clear that there were two main designs utilized most in competition. The winning design last year consisted of many smaller buckets mounted in a belt type system for continuous removal of regolith. An advantage to this system is that the excavator will continuously remove regolith with no breaks as long and the buckets are kept buried in the top layer. Disadvantages to the belt type system were the small size of the buckets and the difficulty in keeping the buckets buried in the top layer of regolith. The second place excavator used the same type of scoop design as auburn's previous teams. This "bobcat" design used and single large forward mounted bucket which is pushed by the excavator to remove regolith. The advantages to the bucket are the ability to mine large amounts of regolith with each scoop, the ability to mine the more dense material below the raked top surface, and the simple design has few parts making system failure less likely than with the belt system. The disadvantage of the "bobcat" design is the lack in continuous soil removal. Through video research, our team determined that the single large bucket was able to remove more regolith in a shorter period of time than the small bucket/belt system. The limiting factor for the large bucket design in the previous competition was the inability to store regolith. The large bucket excavators were forced to travel to the collection bin after a single scoop was made wasting precious minutes of digging time. The single large bucket scoop was selected as the design to move forward due to the ability to mine the most regolith within the shortest period of time. This design also prevents total mission failure if the dump subsystem fails.

5.1.5 Dump Subsystem

Functional Requirement

1. Shall provide a method of keeping regolith from spilling during transport
2. Shall be designed to accommodate flow of regolith during dumping

Performance Requirement

1. Shall hold maximum 150kg of regolith

The dump subsystem design was met with many different initial ideas. The winning team from the previous year's competition used a hopper design paired with a belt/bucket unloader. The second place team used a completely different design utilizing the scoop/dump system as a single unit. As stated earlier, the single unit scoop/dump system wasted large amounts of time maneuvering between the mining area and the collection bin. A large hopper design was chosen to prevent the need to make so many trips to and from the collection bin. A design for the mechanism to be used to empty the hopper then had to be chosen. Three main design options were considered for emptying the hopper: an auger system, a belt system, and the actual hopper as the dump system. An auger would continuously remove the regolith from the hopper as long as loose material was entering the auger screw, but the material properties of the regolith cause it to clump together. One of these clumps could lodge itself over the auger screw entrance preventing the auger from removing any regolith from the hopper. The belt dump system allows for continuous removal of regolith from the hopper. However, the material entrance is not required to be enclosed as an auger entrance would be solving the regolith clumping problem. The final design option was to have the entire hopper be lifted by an actuator and pivot around the top rear of the excavator. This design was selected due to the ability to dump the entire load all at once. The chances of system failure are lower than that of the other two subsystems with the actuator being the only component that could cause the system to fail.

Figure 6 shows the decision matrix used in the analysis and choice of each subsystem design.

	Weight	Strength	Cost	Complexity	Effectiveness	Risk of Failure	Speed	Total
Drive System								
6 Wheels	-	+	-	+	+	+	+	3
4 Wheels	0	0	0	+	-	+	+	2
Tracks	-	+	-	-	+	-	0	-2
Scoop System								
Bucket with actuator	0	0	+	+	+	+	0	4
Grader	+	-	+	+	-	0	-	0
Conveyer Belt	-	-	-	-	+	-	+	-3
Broom and Dust Pan	0	0	-	-	0	0	0	-2
Pull Bucket	-	-	-	0	+	0	0	-2
Auger	+	+	-	-	-	0	+	0
Dump System								
Dump hopper	0	+	+	+	+	0	-	3
Auger	+	+	-	-	+	-	-	-1
Material								
Fiberglass	0	+	+	0	+	0	0	3
Aluminum	-	+	0	+	+	0	0	2
Carbon fiber	+	-	-	0	+	-	0	-1

+ Accomplishes Well
- Accomplishes Poorly
0 Indifferent

Figure 6 : Decision Matrix

5.2 Subsystem Design Engineering:

The final concept chosen is a 6 wheel, scoop bucket, dump hopper design. Figure 7 shows a screen shot from the 3D Solid Edge assembly of the excavator concept.

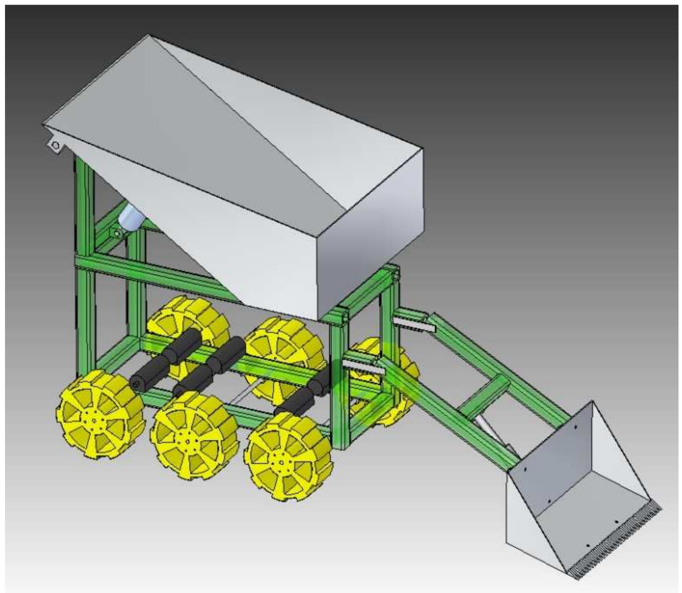


Figure 7 : 3D Model of Final Concept

The Lunar Excavator project was initially broken into five separate subsystems: electrical system, drive system, frame system, scoop system, and dump system. Concept of operation, details of the work done to date for each subsystem, and the test plan to validate and verify the system are discussed below.

5.2.1 Concept of Operations

The developed lunar excavator must operate precisely in a dusty and dirty environment. It needs to be able to scoop, transport, and dump as much regolith as it can in 15 minutes. The concept of operations is meant to show how the excavator will meet the system requirements. Operations are given in a timeline.

Time-ordered sequence of events:

1) Two Netbooks are booted up and the onboard Netbook connects and runs software automatically
2) The control module is opened on the control Netbook using Python software
3) The router power is connected and both Netbooks are connected to the team's network
4) The Xbox 360 controller is connected to the control Netbook
5) The connect button and remote start button are pressed on the control module, which is on the control Netbook
6) The Xbox 360 controller is used to control the excavator through the following steps
7) Bucket is pushed along surface of regolith until it reaches maximum capacity as shown in Figure 8

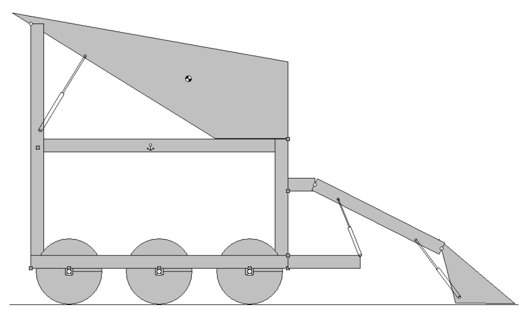


Figure 8 : Excavation Process

8) Bucket is rotated upward so that bucket dumps into large hopper on vehicle as shown in Figure 9

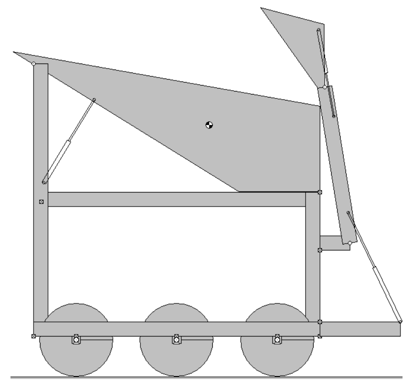


Figure 9 : Filling Storage Hopper

9) When hopper reaches capacity, vehicle is backed up to collection bin

10) Hopper is dumped into collection bin, and vehicle is moved back to digging section as shown in Figure 10

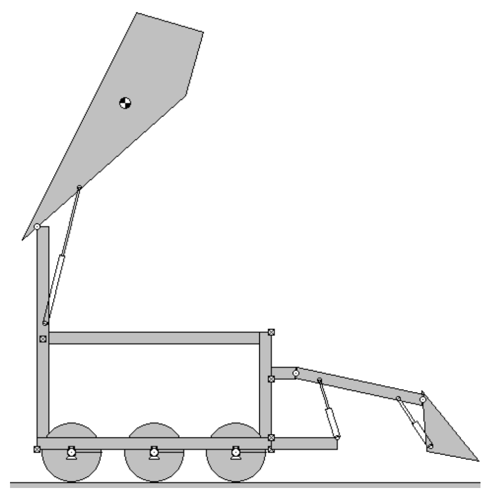


Figure 10 : Dumping the Hopper

5.2.2 Electrical Subsystem

The electrical system has not been analyzed thoroughly to date due to the lack of knowledge of needs for the subsystem. An electrical engineering senior design team will be assigned to the lunar excavator project in the fall semester. The group will help design and build the electrical system for the lunar excavator. The drive, scoop, and dump systems will all utilize electrical components, so each of these subsystems must be analyzed prior to alteration of the electrical system. The electrical system from last year's excavator will be incorporated into this year's design. The current electrical diagram is shown in Appendix E. Testing of the old excavator and electrical system was performed at the National Soil Dynamics Research Laboratory. The electrical system performance proved satisfactory. The only issues were with the battery and Netbook housing. Battery connection was lost because of lack of constraint. As of now the battery and Netbook are just placed in the frame with no constraints. The new design will incorporate specific housing for each to eliminate this issue and to protect/cushion the Netbook from vibration damage. The current electrical system is connected to the frame with Velcro. This electrical system will be taken out of the old excavator and attached to the new excavator's frame in the same fashion.

5.2.3 Drive Subsystem

The drive system chosen for the excavator is a six wheel option; each wheel is powered by a motor, as shown in Figure 11.

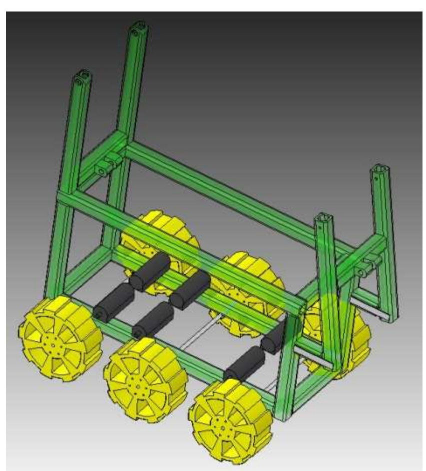


Figure 11 : Drive/Frame Subsystem

The motor specifications for the current motors are attached in Appendix F. By adding two more motors and improving the gear ratio, the current motors will be strong enough to move the lunar excavator at an acceptable speed. Speed data for the current motors with different gear ratios is given in Table 1.

Table 1- Speed Data

Mass (kg)	Distance (m)	Time (s)	velocity (m/s)	Wheel (Rps)	Wheel Rpm (78:1 gear ratio)	Motor Rpm (Geared) (26:1 gear ratio)	Rpm (with no Geared) (1:1 gear ratio)
0	5	7	0.714	1.007	60.42	181.26	4712
95	5	8	0.625	0.8815	52.89	158.67	4125
195	5	10.3	0.485	0.684	41.04	123.12	3201

Having a small bucket dumping into a bigger hopper, being able to transport a significant amount of weight was a concern. Speed tests were performed at the National Soil Dynamics Research Laboratory using last year's excavator. Table 2 shows the data that was gathered from testing.

Table 2 : USDA Speed Testing

Speed Test Results			
Weight Added	**Distance**	**Time**	**Avg. Velocity**
0 kg	5 m	7.0 sec	0.714 m/s
95 kg	5 m	8.0 sec	0.625 m/s
196 kg	5 m	10.3 sec	0.485 m/s

The motor's performance was not affected much by the added weight. The loss of velocity was due mostly to the fact the test was done with the old excavator which has four small wheels and minimal ground clearance. So with the six wheels that are bigger in diameter and wider on the final concept, these test results can be considered worst case scenario. This test proves that our design should be able to carry the 150 kg max load.

Finite Element Analysis was performed on the wheels that were developed for the lunar excavator. The analysis was done using SolidEdge software, and a medium-sized tetrahedral mesh was used. The wheels are made of ultra-high molecular weight polyethylene, for which SolidEdge contains built-in properties. The wheels have an outer diameter of ten in., and are four in. thick. For the analysis, the 0.5 in. center cylinder in the wheels was fixed in all directions. This is the center cylinder that the axle will pass through. 2450 N of force was applied to approximately fifteen degrees of the wheels directly between two spokes. This corresponds to about 250 kg resting on $1/24^{th}$ of the circumference of the wheel. The lunar excavator will weigh no more than eighty kg, and will be capable of hauling about 150 kg. Therefore the total maximum weight will be about 230 kg. Under ideal terrain conditions the weight will be dispersed relatively evenly between six wheels. This means that our analysis is a worst case scenario in which the excavator is balancing on one wheel with an overflowing hopper. Even under such unrealistic conditions, the total deflection at the end of the wheel is only 2.25 mm. The maximum Von Misses stress is about 9.5 MPa, as shown in Figure 12, and the yield strength of ultra-high molecular weight polyethylene is 19.5 MPa. Therefore the factor of safety for the wheels is about 2.05.

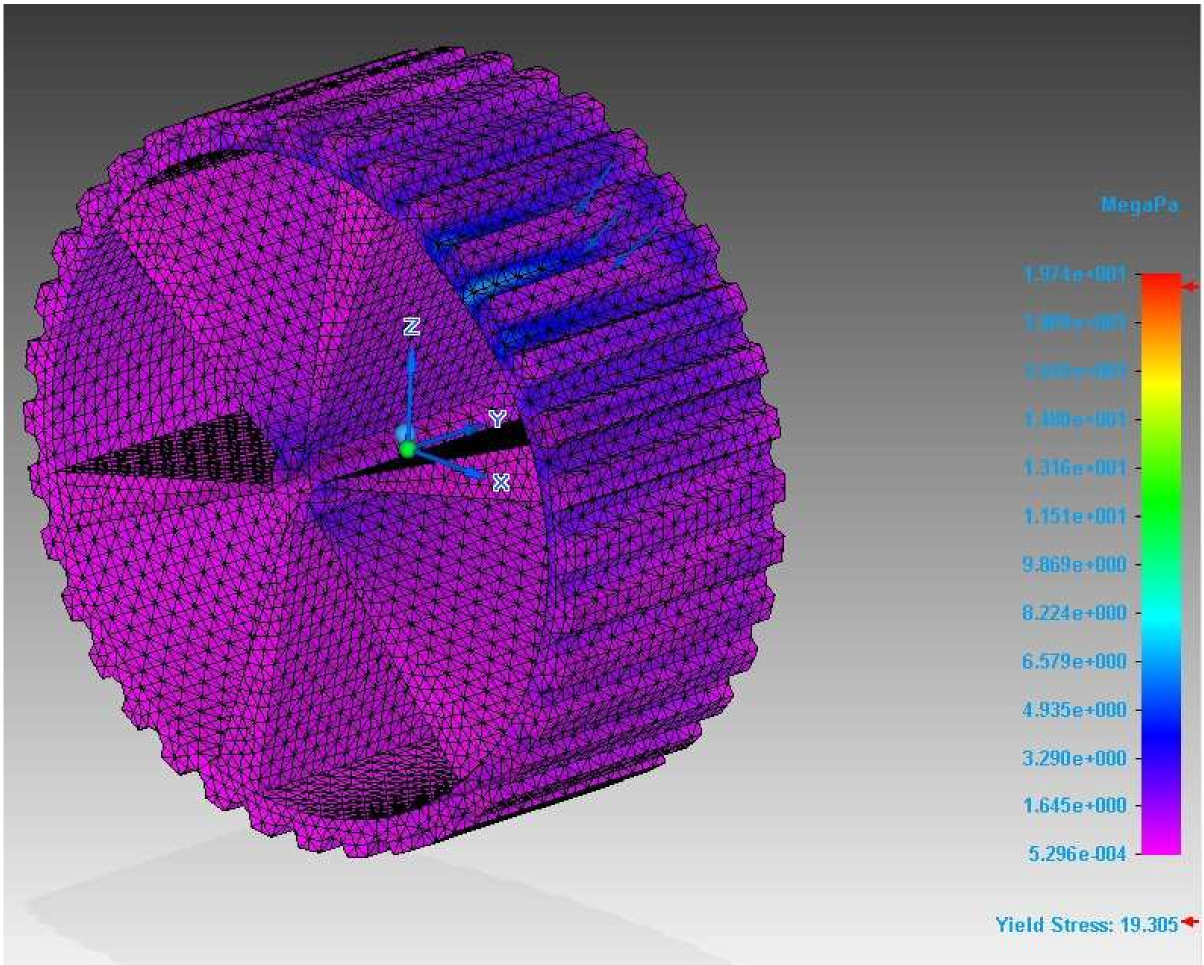


Figure 12 - Wheel FEA

5.2.4 Frame Subsystem

The frame of the excavator will be similar to the previous year's frame design. The fiberglass square tubing will be used for the frame material. The fiberglass material is lighter than aluminum, and the material has been proven through testing to be strong enough to handle the loads exerted on the excavator. A central box of tubing with paneling will be used to house the electronics. All of the other subsystems will extend from the central box. CAD analysis in Solid Edge, shown in Appendix G, validates that the frame geometry setup has no conflicts with the other subsystems as currently designed. The CAD drawing of the Drive/Frame System is shown in Appendix G.

` Finite Element Analysis was performed on the fiberglass tubing that will be used for the frame of the lunar excavator. The analysis was done using SolidEdge software, and a medium-sized tetrahedral mesh was used. The fiberglass tubing has outside dimensions of 1.5 in by 1.5 in., and the tubing is 0.125 in thick. The tubing was ordered from McMaster-Carr and the specification sheet shown in Appendix F states that the modulus of elasticity ranges from 2.8-5.5 x 10^6 psi. When the two numbers are averaged, the modulus of elasticity is approximately 4.15 x 10^6 psi, or 28,613 MPa. A new material was created in SolidEdge using 28,613 MPa as the modulus of elasticity, and the other material properties were input into SolidEdge using the same averaging system. After creating the new material, a three point bending test was performed using a four foot long piece of tubing. The tube was fixed in all directions in the middle of the tube, and a force of 2000 N was applied to each end in the vertical direction. This test corresponds to about 204 kg being placed at each end of a very long piece of tubing, which is beyond the expected load that will be placed on the frame.

After performing the test, the maximum deflection at each end was 56.4 mm. The maximum Von Misses stress occurred on the top and bottom of the tube, above and below the fixed center point, and was 266.7 MPa, as shown in Figure 13. The top of the tube was in tension, while the bottom was in compression. This stress and displacement were deemed too large for a 2000 N force, even though it was applied through a two foot moment arm. To remedy this problem, a piece of untreated pine wood was created in SolidEdge using the properties found at matbase.com (Appendix F). A piece of pine wood was created that fits inside the four foot length of fiberglass tubing. The same position was fixed and the same load was applied at each end. The maximum deflection at each end was reduced to 8.7 mm, and the maximum Von Misses stress occurred in the same position, but was reduced to about 4.5 MPa. After studying this analysis, it was deemed necessary to use pine wood block inserts in areas of the frame that will be stressed with a large bending force, such as any tube that an actuator will be mounted to. The yield strength of the fiberglass tubing is reported to be 162 MPa. Therefore, a tube that is not reinforced with wood would break if placed under the simulated load. However, one reinforced with wood would not break.

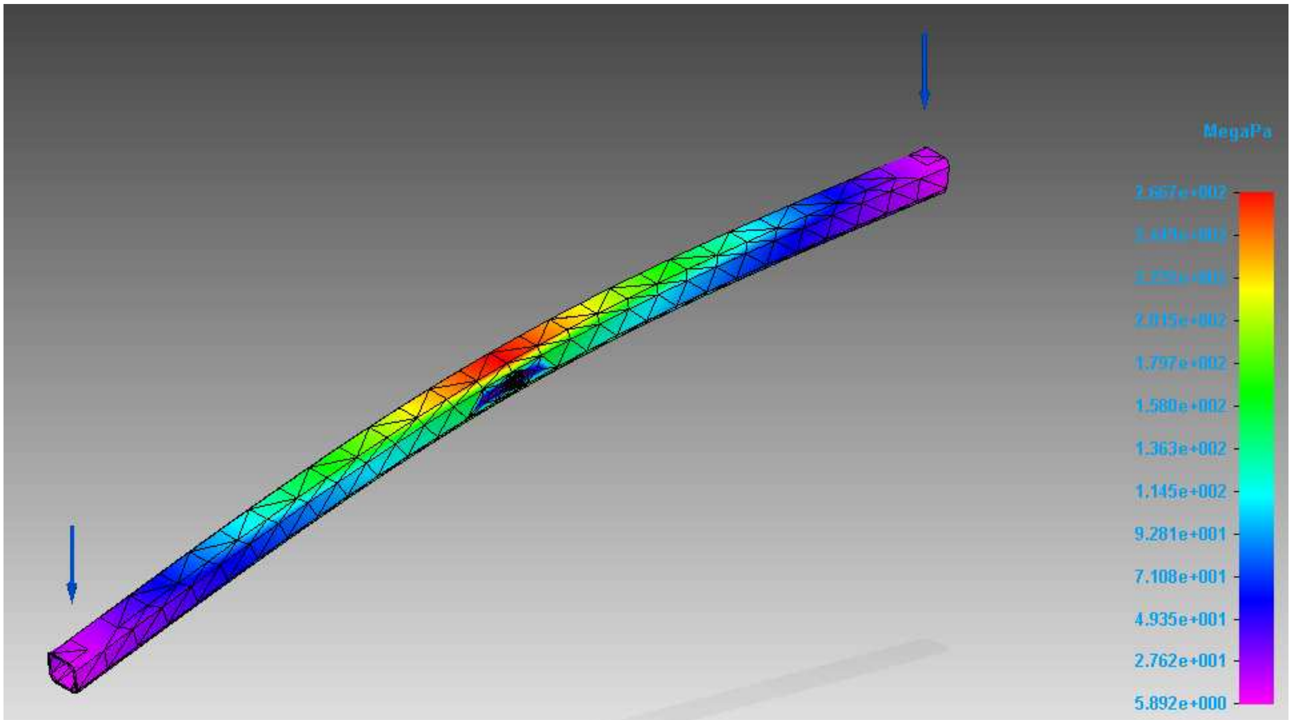


Figure 13 - 3 pt. bend test without wood

5.2.5 Scoop Subsystem

The scoop system chosen for the excavator utilizes an arm and two actuators to operate a large bucket as shown in Figure 14.

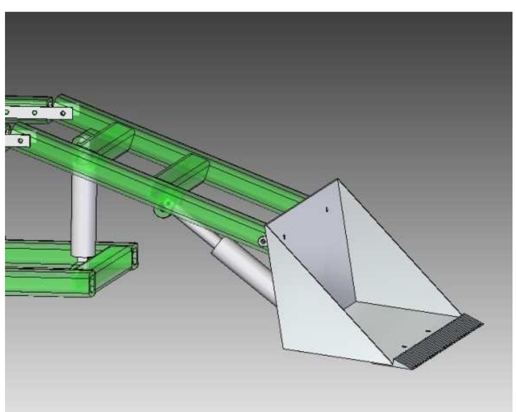


Figure 14 : Scoop Subsystem

This design is similar to the design of the previous year's excavator. After watching many competition videos, a conclusion was drawn that the large bucket system could remove the greatest amount of regolith for a given time period. After calculating the maximum volume of regolith the bucket could hold and using an average density of one g/cm^3, the maximum weight the bucket and arm would need to support is eighteen kilograms. Finite element analysis while applying uniform pressure equal to having a full load proved that the bucket and arm could handle the maximum stress. The initial design of this system used a motor to rotate the base of the arm for motion control, but the torque needed to overcome the moment was determined to be unrealistic by working model analysis. A revised design using an actuator mounted in front of the arm/frame pivot point applying a linear force to the arm was devised. Also, the excavator bucket differs from the previous year's design. The current bucket will be smooth on all interior surfaces allowing regolith to slide in and out with a minimum dumping angle. To allow the bucket to gather more regolith with each scoop, the width of the bucket was decreased in comparison to the previous year's bucket. This allows the excavator drive system to have enough power to not bog down while driving the scoop into the regolith.

Bucket analysis of preformed using Solid Edge, Working Model, and manual calculations. The goal of the analysis was to determine the mass of regolith collected in a single scoop and analyze the bucket arms if they are strong enough to carry the load. Brackets will be tested to find the correct number and strength to with stand the force of lifting a full load.

Knowing the density of lunar regolith and the volume of the bucket the total mass of one scoop can be derived. The volume of the bucket measured 23916 cm^3 which when multiplied by the density of regolith comes out to be approximately 23.9 kg of regolith per scoop. In reality the bucket cannot be filled completely and the regolith may be less dense than the 1 gm/cm^3 so a estimation of 10 to 15 kg per scoop was made. During testing between 10 and 15 kg was used as the force pressing against the inside of the bucket. Finite element modeling was used to quickly test various configurations of hinges, arms, and weights.

FEM testing was performed using the simulation solver in Solid Edge. In the first test the bucket was initially pinned at the top 2 hinges with a 15 kg load in the bucket. A force of 7000 N was applied to the bracket where the actuator will mount. The goal of the test was to estimate whether the hinges would be strong enough to support the lifting bucket. The analysis showed a maximum stress of 404.7 MPa which was centered holes in the hinges. The yield strength of the 6061-T6 aluminum is 276 MPa which indicates there will be yielding. Deflection was negligible during this test. The test results with locations of loading are shown in Figure 15

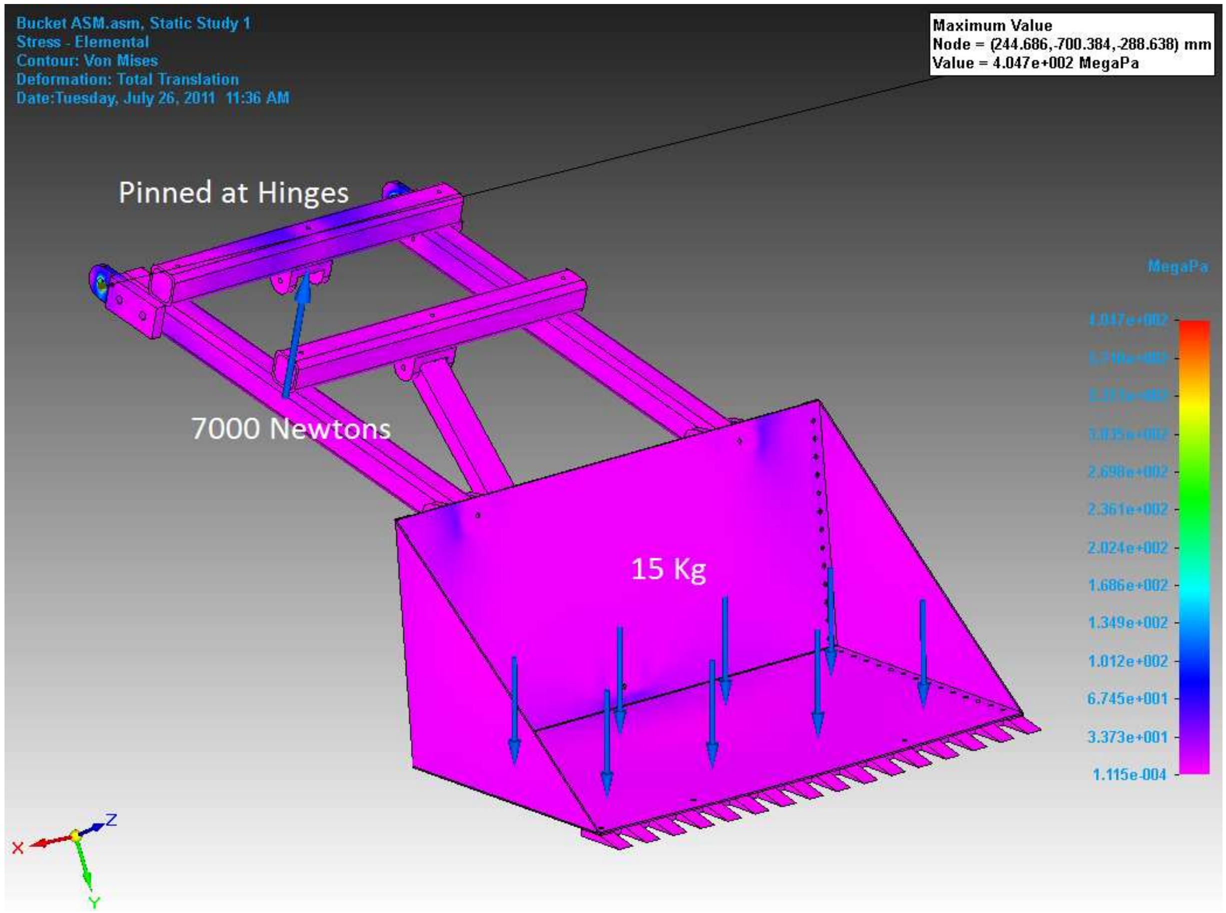


Figure 15 - Test 1, 2 hinges

In the second test two more hinges were added at the top to better distribute the load. The actuator force was decreased to a more reasonable 3500 N while the mass in the bucket was decreased to 10kg. The Maximum stress was still at the holes in the hinges but decreased to 237 MPa which is well under the yield strength of the 6061 Al. In conclusion the four hinges will provide more than enough strength to support the bucket at full load while being lifted. Figure16 shows the test setup along with relevant stresses.

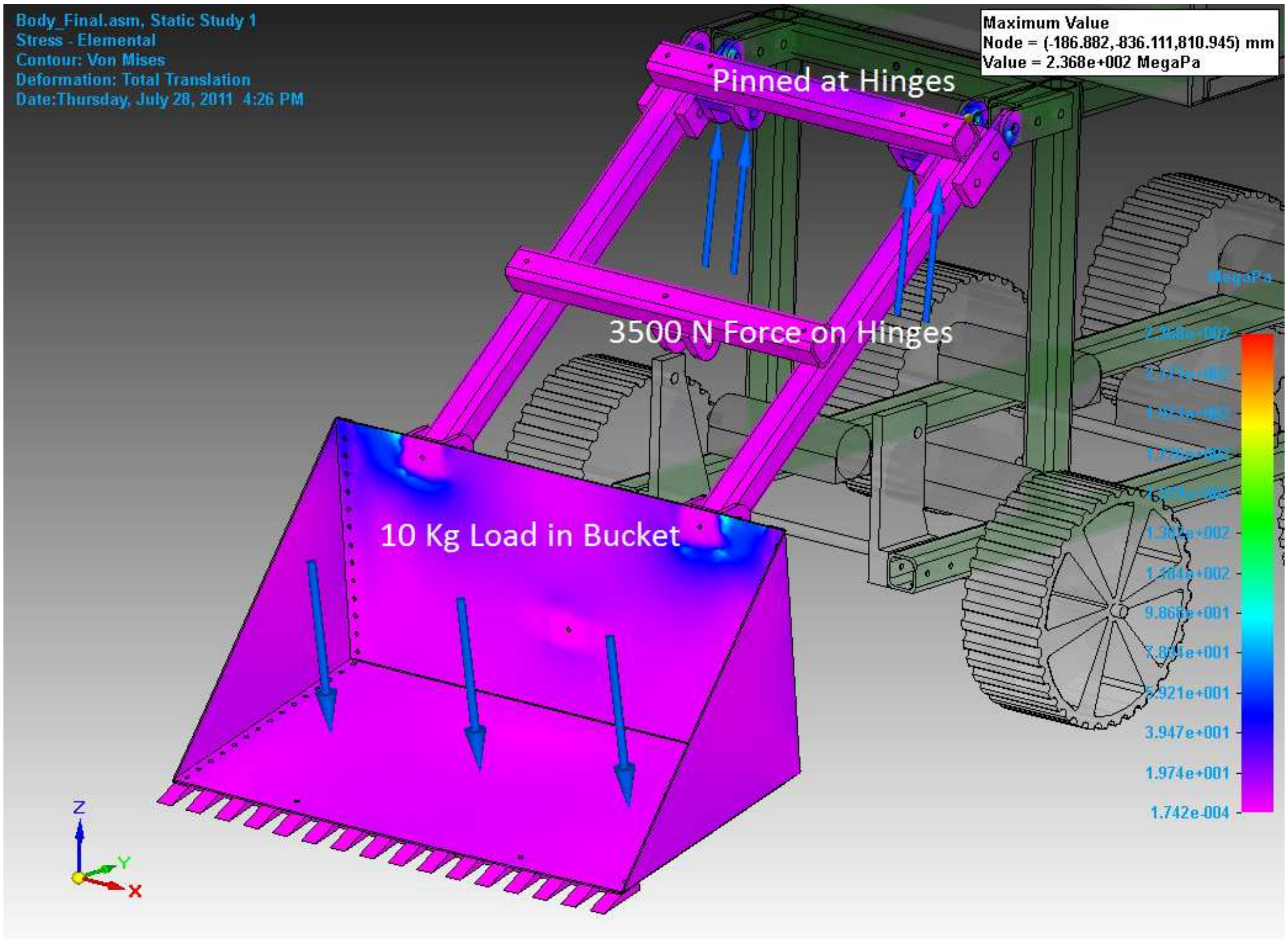


Figure 16 - Test 2, 4 hinges

Testing was performed on the mounts that hold the other side of the large bucket actuator. These mounts are made of one half inch thick 6061 aluminum to ensure zero deflection. The testing set up is the mounts attached rigidly to the frame with 4500 newtons applied down ward. The results of the test show a maximum of 170 Mpa which is well below the yield strength of the 6061 aluminum. Figure 4 shows the locations of the force and the test results.

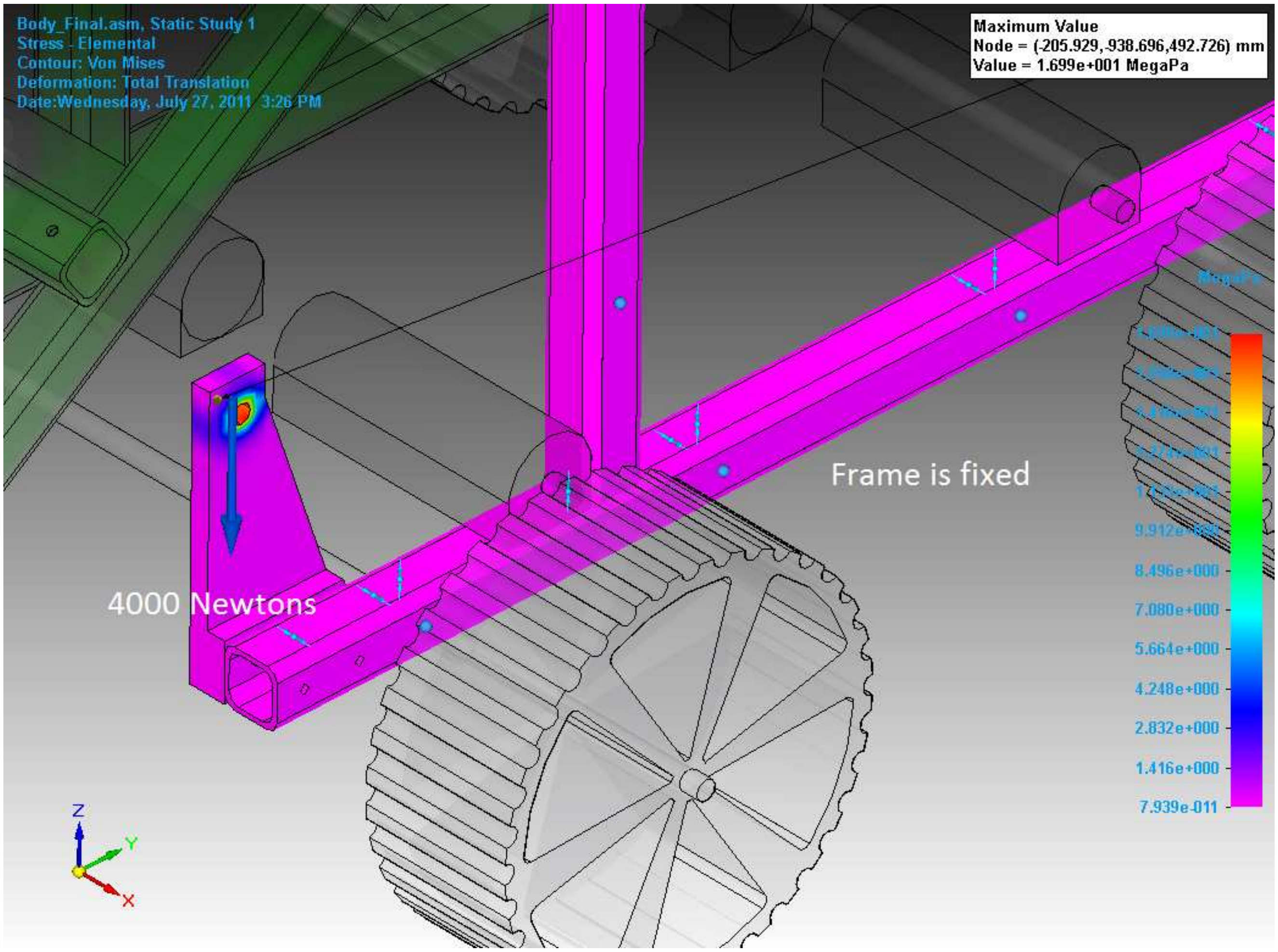


Figure 17 - Bottom Bracket Test

Working Model was used to determine the minimum amount of force required to lift the bucket at full load. Through trial and error the location along with the strength of the actuators was found. Each actuator tested had different compressed lengths and strokes, so individual testing were required for each actuator. Figure 17 shows the final large bucket actuator design along with forces.

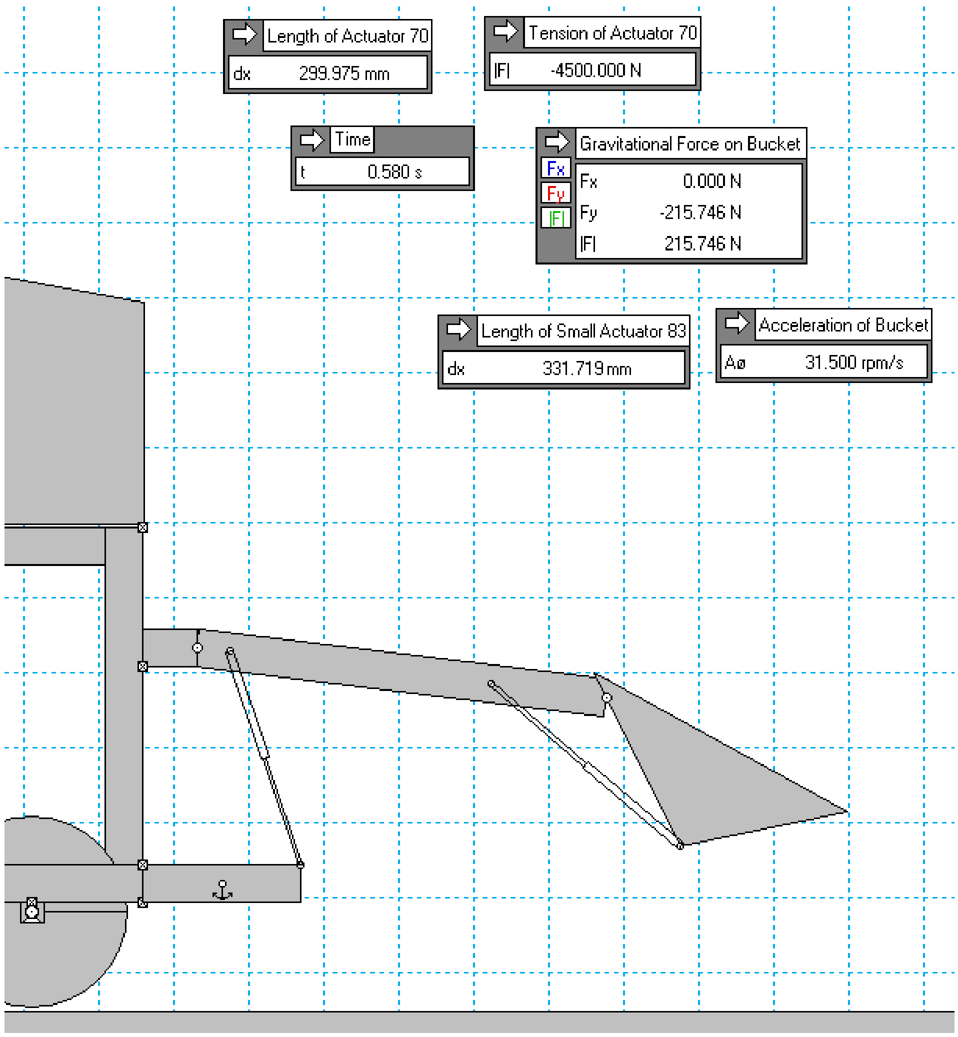


Figure 18 - Front Bucket Simulation

The minimum required force to move a 20 kg bucket is about 4500 N when the actuator is placed in the optimal position. If the mass of the bucket is decreased to 10 kg the force required by the actuators is reduced to about 3500 N.

On the front bucket a large actuator is required to flip the whole front assembly up to dump into the hopper. The actuator chosen is a Nook Industries CCHD-8532. It is rated for 28 mm/s at full load so the time from digging to dumping should take about 3.6 seconds. The actuator's lifting capacity is 3330 N so two actuators will have to run in parallel to lift the full bucket. The locations of the hinges was made as precisely as possible for maximum speed while staying within the limits of the materials strength. The full spec sheet for the larges actuator is found in Appendix 1.

The small actuator on the bucket is mainly used to hold the bucket steady and in position when the digging is occurring. The static load for the small actuator is 4459 N which is more than enough to hold back the bucket. The dynamic load for tilting the bucket back while dumping is 2230 N, which is an ample force to flip back the 20 kg bucket. The actuator is rated for 18 mm/s which will take about 2 seconds to flip the bucket back when dumping. The 2 second time is accounting for the actuator being mounted where the required stroke is only about 1.7 inches. The full spec sheet the small bucket actuator is found in Appendix H.

5.2.6 Dump Subsystem

Finite Element Analysis was performed on the Hopper Subsystem of the lunar excavator utilizing the simulation solver tool in solid edge. The body of the hopper was constructed using two millimeter thick sheets of 6061-T6 aluminum. The hopper has six pieces of fiberglass tubing strategically mounted to the bottom of the main plate for added support. A 3/8" aluminum plate was placed in position below the bearings mounted to the actuator shaft to dissipate the large force over a bigger surface area. Finally, aluminum blocks were added beneath the frame bearings to extend the hopper above the tops of the frame mounts.

To perform the Finite Element Analysis, a force equivalent to 110 kg was applied to the bottom plate of the hopper and a force equivalent to 40 kg was applied to the main plate. The maximum weight that the hopper would hold was calculated to be 150 kg of lunar regolith. A 4000 Newton force was also applied to the hopper to simulate the actuator lifting a fully loaded hopper. The only motion constraints applied for the analysis were pinning the frame bearings. This prevented the bearings movement in the three linear degrees of freedom but allowed rotation.

The simulation yielded a maximum Von Misses stress of 97.5 MPa as shown in Figure 19 and Figure 20. The yield strength of 6061-T6 aluminum is 275.8 MPa providing a factor of safety of about 2.83. The maximum deflection of the hopper was approximately 2.7 millimeters, as shown in Figure 21, with the maximum loads applied.

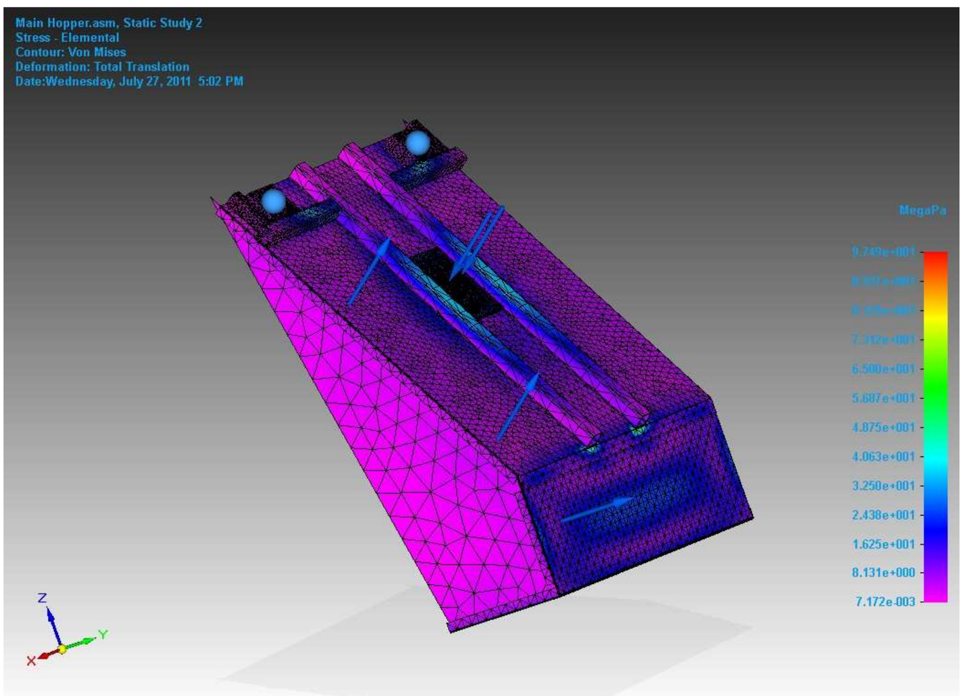


Figure 19: Hopper FEA Bottom View

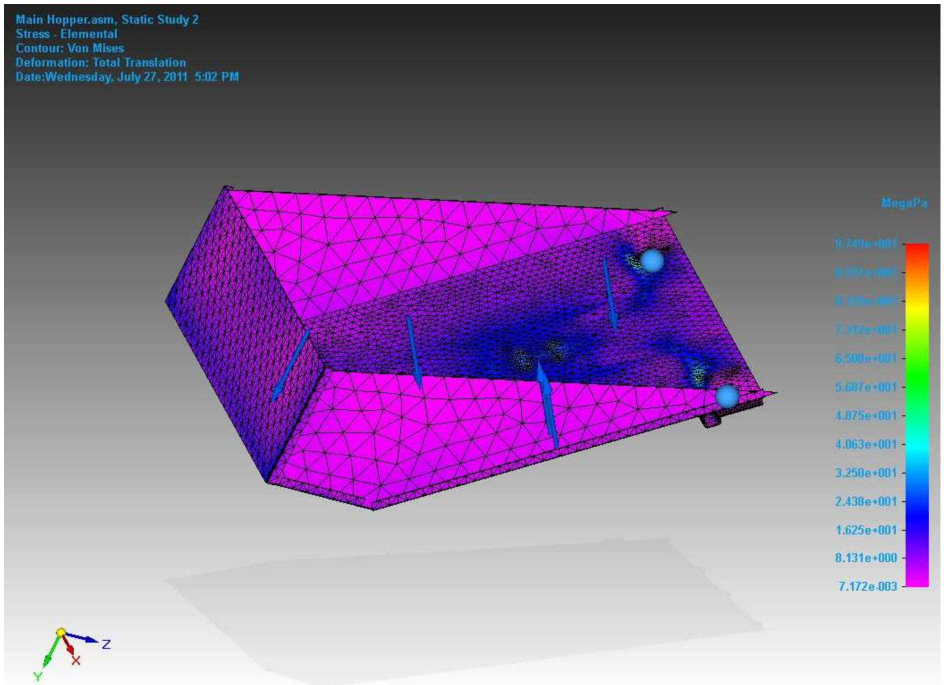


Figure 20: Hopper FEA Side/Top View

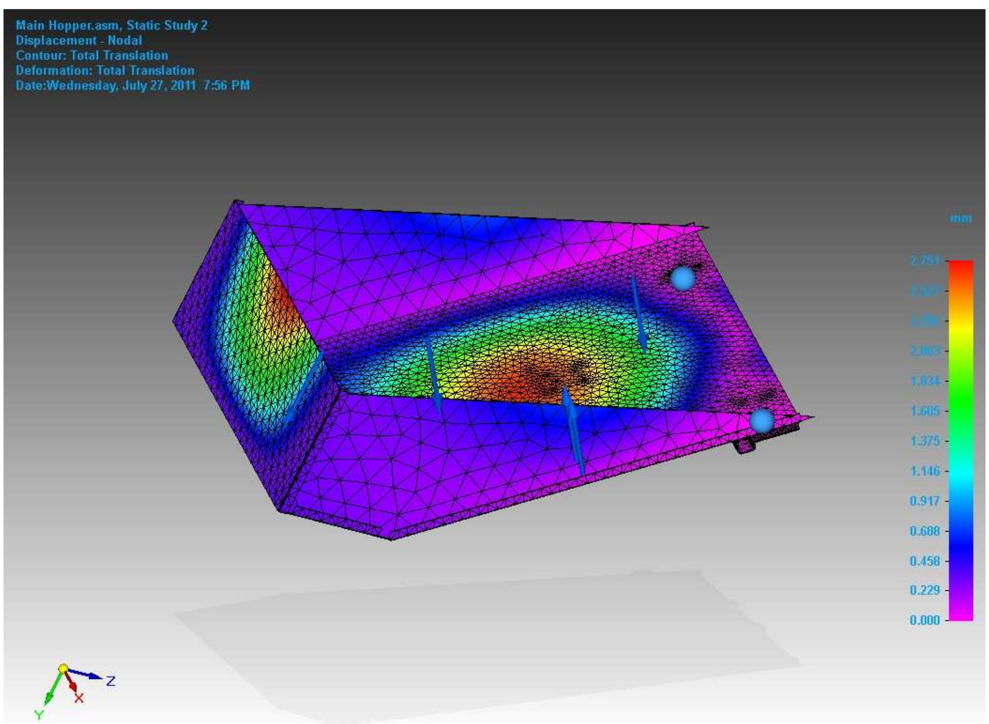


Figure 21: Hopper FEA Displacement

On the final design, when the hopper dumps the regolith into the collection bin it hits 45 ° when it reaches the maximum allowable height of 2m. An aluminum angle test was conducted to find out at which what angle regolith slides off of a piece of aluminum sheet as shown in Figure 22. Concrete mix, acting as lunar regolith stimulant, was placed onto a piece of aluminum plate with a protractor used for reading the angle. The plate was slowly lifted, starting at 0°, until all of the concrete mix slid off of the plate. Numerous tests were conducted. The lowest angle at which all of the lunar stimulant slid off of the plate was 31° and the highest angle was 36°. The testing verifies that 45° is a sufficient angle for the hopper to dump the regolith into the collection bin.

Figure 22: Aluminum Angle Test

5.3 Validate and Verify

Through the entire systems engineering process it is important to make sure that the system will meet all requirements once completed. A large part of making sure that the design is on track is validation and verification. Validation for this senior design project will be done using mostly Portland cement mix to represent lunar regolith. The first test that was conducted showed the required angle of the hopper in order to dump a load of regolith. A sheet of aluminum representing the hopper bottom was laid flat and covered with the Portland cement and then lifted until all of the cement slides off. The angle of the aluminum was calculated, and the 55° angle of the hopper was determined sufficient.

An actual size prototype of the lunar excavator was built for the final presentation. The fiberglass frame for the actual excavator is about 80% complete and was used for the prototype. The frame was built to CAD drawings out of the fiberglass tubing. The hopper, bucket, and the wheels were made out of plywood. The main reasons for building a prototype was to get ahead on building the excavator frame and to verify the Solid Edge assembly. The prototype was verification that our design will work. It also proved that the excavator has sufficient ground clearance Figure shows a picture of the finalized prototype.

Figure 23: Prototype

Also, CAD drawings and finite element analysis verified correct operation of the design. Verification of Auburn's old lunar excavator was done at the National Soil Dynamics Research Laboratory, since most of the electronics from the old excavator will be used in the new excavator. Results from the test showed some flaws in the old design, but also proved that the current electric motors are sufficient for use on the new excavator. Testing was done of acceleration using various loads. With no external load on the old excavator it was able to travel five meters in 7.0 seconds. Under an external load of ninety-five kilograms the old excavator was able to travel five meters in 8.0 seconds. Under an external load of 196 kilograms the old excavator was able to travel five meters in 10.3 seconds. This was deemed an acceptable acceleration if at least 300 kilograms of regolith is to be gathered in fifteen minutes.

All subsystems will be operated independently, or verified, before being integrated into the total system. This will ensure that all components will work as specified. The first half of fall will consist of building the excavator and the second half will consists of numerous testing of the subsystems and system. All subsystems will be operated independently, or verified, before being integrated into the total system. This will ensure that all components will work as specified.

6.0 Interfaces

Mechanical interfaces of the bucket, arm, and hopper subassemblies to the frame and also actuator interfaces are all supported by pin joints. The electrical to mechanical interfaces will utilize the same Sabertooth Motor Controllers as the previous year's excavator. Further interface details will be discussed in the critical design report.

7.0 CDR Economic Analysis

Figure 1 shows the critical design review bill of materials. Quotes were obtained for the majority of the items in the breakdown. For the items that will be reused from last year's excavator, prices were taken from the previous year's bill of material list. Total estimated costs for parts that will be reused in the design were set to $0.00. The total estimated cost at this point in the design process is $3,668.53. This price assumes the old batteries, motors, and hopper actuator will be reused. At this point, the budget is unknown. If the budget ends up being $5000.00 there will be room to increase speed and power. Next semester, a finalized cost breakdown will be created after all of the materials for the excavator are purchased.

Table 3: CDR Economic Analysis

CDR Economic Analysis							
Item	Description	Supplier	Supplier Part #	Lead Time	Original Unit Cost	Qty	Total Estimated Cost
1	6061 Aluminum 36"x48" sheet, 0.08" thick	Metals by the Inch		2-3 days	$79.17	4	$316.68
2	2x6x8' Untreated Pine Wood	Home Depot		1 day	$2.40	1	$2.40
3	Bucket Tilt Actuator	Moteck	ID10-12-20-A-100	2 weeks	$108.00	1	$108.00
4	Bucket Lift Actuator	Nook Ind.	CC-18	3-4 weeks	$600.00	2	$1,200.00
	Hopper Actuator (reuse)			-		1	$0.00
5	Fiberglass Tubing 1-1/2" x 1-1/2" 10' Section	McMaster-Carr	8548K32	1 day	$63.41	3	$190.23
6	UHMW Polyethylene 10" Diameter 4" Cut to Length	Eplastics		3-5 days	$167.46	6	$1,004.76
7	Motor	?			?	6	$0.00
8	Electrical Circuit System (reuse)	Sparkfun Electronics		-	$70.00	1	$0.00
9	Batteries (reuse)	10 Ah, 24V			$130.00	2	$0.00
10	Netbook (reuse)	Netbook Samsung NF310-A01		-	$400.00	1	$0.00
11	Cameras (reuse)	Newegg.com/		-	$40.00	3	$0.00
12	Fasteners	McMaster-Carr	1558A21	1 day	$100.00	1	$100.00
13	Router (reuse)	Newegg.com/ ASUS Router			$65.00	1	$0.00
14	Axle	McMaster-Carr	8974K113	1 day	$12.82	3	$38.46
15	Sabertooth Motor Controllers	Trossen Robotics	126233		$125.00	2	$250.00
16	Extra Electrical Components	Sparkfun Electronics			$50.00	1	$50.00
17	94 lb Portland Concrete Mix	Home Depot		1 day	$9.85	20	$197.00
18	Report Copies for all 4 Presentations	Copy Cat			$100.00	1	$100.00
19	Plywood for Mock up	Home Depot		1 day	$11.00	1	$11.00
20	Tools for DML	Sparkfun Electronics			$100.00	1	$100.00

TOTAL ESTIMATED COST	$3,668.53

8.0 Mass Budget Tracking

Tracking resource budgets is necessary for this project to ensure the weight limitation of 80 kg is met. A rough estimate of the system mass breakdown is shown in Appendix J. The estimated weight at this point in the design process is 73.4 kg. This mass budget is only an estimate and will be detailed more accurately in the critical design review that follows further in the design process.

9.0 Conclusions

For designing the excavator, the mission objective of the NASA's competition is collecting 10kg of regolith in 15 minutes. To win the competition, the team made the goal to collect 500 kg of regolith in 15 minutes. Before selecting the final design, the team had 3 alternative systems (bucket, 6 wheels, and auger), (bucket, 6 wheels, hopper), and (belt with small buckets, 6 wheels, hopper). To select the final design, the team evaluated the ideas and picked the best designs, and got the best scores for the bucket, 6 wheels, and hopper system. The design needed to be simple and have less complicated components to avoid braking. The excavator mass requirement is less than 80kg so to make the excavator light the team selected fiberglass for the material. Fiberglass is hard enough to handle 200kg of the regolith to carry.

For the next review, the team will complete the set of dimensioned part and assembly drawings, of details with the solid edge program, so that team could build the device from the drawing set.

Appendix A: 2011 Lunabotics Mining Competition Rules and Rubrics

NASA's Lunabotics Mining Competition
2011 Rules & Rubrics
November 23, 2010
Kennedy Space Center, Florida

Introduction

NASA's Lunabotics Mining Competition is designed to promote the development of interest in space activities and STEM (Science, Technology, Engineering, and Mathematics) fields. The competition uses excavation, a necessary first step towards extracting resources from the regolith and building bases on the moon. The unique physical properties of lunar regolith and the reduced 1/6th gravity, vacuum environment make excavation a difficult technical challenge. Advances in lunar regolith mining have the potential to significantly contribute to our nation's space vision and NASA space exploration operations. The competition will be conducted by NASA at Kennedy Space Center. The teams that can use telerobotic or autonomous operation to excavate the most lunar regolith simulant within a 15-minute time limit will win the competition. The minimum excavation requirement is 10.0 kg, and the excavation hardware mass limit is 80.0 kg. Winners are eligible to receive first, second, or third place awards of $5,000, $2,500, and $1,000, respectively.

Undergraduate and graduate student teams enrolled in a U.S. or international college or university are eligible to enter the Lunabotics Mining Competition. Design teams must include: at least one faculty with a college or university and two or more undergraduate or graduate students. Teams will compete in up to five categories including: on-site mining, systems engineering paper, outreach project, slide presentation (optional), and team spirit (optional). Additionally, teams can earn bonus points toward the Joe Kosmo Award for Excellence multidisciplinary teams and collaboration between a majority and U.S. minority serving institutions earn. All documents must be submitted in English.

Awards include monetary scholarships, a school trophy or plaque, individual certificates, KSC launch invitations, and up to $1,500 travel expenses for each team member and one faculty advisor to participate with the NASA Desert RATS as the winners of the Joe Kosmo Award for Excellence. Award details are available at www.nasa.gov/lunabotics.

The Lunabotics Mining Competition is a student competition that will be conducted in a positive professional way. So this is a reminder to be courteous in your correspondence and on-site at the competition because unprofessional behavior or unsportsmanlike conduct will not be tolerated and will be grounds for disqualification.

Game Play Rules

1) These rules and specifications may be subject to future updates by NASA at its sole discretion.

2) Teams will be required to perform 1 official competition attempt using lunar regolith simulant, Lunarena and collector provided by NASA. NASA will fill the Lunarena with compacted lunar regolith simulant that matches as closely as possible to the lunar regolith described in the Lunar Sourcebook: A User's Guide to the Moon, edited by G. H. Heiken, D. T. Vaniman, and B. M. French, copyright 1991, Cambridge University Press. NASA will randomly place 3 obstacles and create 2 craters on each side of the Lunarena. Each competition attempt will occur with 2 teams competing at the same time, 1 on each side of the Lunarena. After each competition attempt, the obstacles will be removed, the lunar regolith simulant will be returned to a compacted state, and the obstacles will be returned to the Lunarena. See the Lunarena Diagrams on page 7.

3) In the official competition attempt, the teams that acquire (and deliver into the collector container) the first, second, and third most mass by excavating lunar regolith simulant over the minimum excavation requirement (10 kg) within the time limit (15 minutes) will respectively win first, second, and third place awards. In the case of a tie, the teams will compete in a head-to-head round, where the team that acquires the most lunar regolith simulant in that round wins.

4) All excavated mass deposited in the collector during the official competition attempt will be weighed after completion of the competition attempt. Any obstacles deposited in the collector will be removed from the lunar regolith simulant collected.

5) The excavation hardware shall be placed in the randomly designated starting zones. The order of teams will be randomly chosen throughout the competition.

6) A team's excavation hardware shall only excavate lunar regolith simulant located in that team's respective mining zone at the opposite end of the Lunarena from the team's starting zone. The team's exact starting point and traversal direction will be randomly selected immediately before the competition attempt.

7) The excavation hardware is required to move across the obstacle zone to the mining zone and then move back to the collector box to deliver the simulant into the collector box. See the Lunarena Diagrams on page 7.

8) Each team is responsible for placement and removal of their excavation hardware onto the lunar regolith simulant surface. There must be 1 person per 23 kg of mass of the excavation hardware, requiring 4 people to carry the maximum allowed mass. Assistance will be provided if needed.

9) Each team is allotted a maximum of 10 minutes to place the excavation hardware in its designated starting position within the Lunarena and 5 minutes to remove the excavation hardware from the Lunarena after the 15-minute competition attempt has concluded.

10) The excavation hardware operates during the 15-minute time limit of the competition attempt. The 15-minute time limit will be reduced if a team is not ready at the team's competition attempt start time. Time will start even if a team is still setting up their excavator after the 10 minute setup time period has elapsed. The competition attempt for both teams in the Lunarena will end at the same time.

11) The excavation hardware will end operation immediately when the power-off command is sent, as instructed by the competition judges.

12) The excavation hardware cannot be anchored to the lunar regolith simulant surface prior to the beginning of the competition attempt.

13) Each team will be permitted to repair or otherwise modify the excavation hardware after the team's practice time. The excavation hardware will be inspected the evening before the competition takes place and quarantined until just before the team's competition attempt. Batteries will not be quarantined and may continue to charge.

Field Rules

14) At the start of the competition attempt, the excavation hardware may not occupy any location outside the defined starting zone. At the start of each competition attempt the starting location and direction will be randomly determined.

15) The collector box top edge will be placed so that it is adjacent to the side walls of the Lunarena without a gap and the height will be approximately 1 meter from the top of the simulant surface directly below it. The collector top opening will be 1.65 meters long and .48 meters wide. See the Lunarena Diagrams on page 7. A target may be attached to the collector for navigation purposes only. This navigational aid must be attached during the setup time and removed afterwards during the removal time period. The mass of the navigational aid is included in the maximum excavation hardware mass limit of 80.0 kg and must be self-powered.

16) There will be 3 obstacles placed on top of the compressed lunar regolith simulant surface within the obstacle zone before the competition attempt is made. The placement of the obstacles will be randomly selected before the start of the competition attempt. Each obstacle will have a diameter of approximately 20 to 30 cm and an approximate mass of 7 to 10 kg. Obstacles placed in the collector will not be counted as part of the excavated mass. There will be 2 craters of varying depth and width, being no wider or deeper than 30cm. No obstacles will be intentionally buried in the simulant by NASA, however, simulant includes naturally occurring rocks.

17) Excavation hardware must operate within the Lunarena: it is not permitted to pass beyond the confines of the outside wall of the Lunarena and the collector during the competition attempt. The regolith simulant must be collected in the mining zone allocated to each team and deposited in the collector. The team may only dig in its own mining zone. The simulant must be carried from the mining zone to the collector by any means. The excavator can separate intentionally, if desired, but all parts of the excavator must be under the team's control at all times. Any ramming of the wall may result in a safety disqualification at the discretion of the judges. A judge may disable the excavator by pushing the red emergency stop button at any time.

18) The excavation hardware must not push lunar regolith simulant up against the wall to accumulate lunar regolith simulant.

19) If the excavation hardware exposes the Lunarena bottom due to excavation, touching the bottom is permitted, but contact with the Lunarena bottom or walls cannot be used at any time as a required support to the excavation hardware. Teams should be prepared for airborne dust raised by either team during the competition attempt.

Technical Rules

20) During the competition attempt, excavation hardware is limited to autonomous and telerobotic operations only. No physical access to the excavation hardware will be allowed during the competition attempt. In addition, telerobotic operators are only allowed to use data and video originating from the excavation hardware. Visual and auditory isolation of the telerobotic operators from the excavation hardware in the Mission Control Room is required during the competition attempt. Telerobotic operators will be able to observe the Lunarena through fixed overhead cameras on the Lunarena through monitors that will be provided by NASA in the Mission Control Room. These monitors should be used for situational awareness only. The Lunarena will be outside in an enclosed tent.

21) Mass of the excavation hardware shall not exceed 80.0 kg. Subsystems on the excavator used to transmit commands/data and video to the telerobotic operators are counted towards the 80.0 kg mass limit. Equipment not on the excavator used to receive commands from and send commands to the excavation hardware for telerobotic operations is excluded from the 80.0 kg mass limit.

22) The excavation hardware must be equipped with an easily accessible red emergency stop button (kill switch) of minimum diameter 5 cm on the surface of the excavator requiring no steps to access. The emergency stop button must stop excavator motion and disable all power to the excavator with 1 push motion on the button.

23) The communications rules used for telerobotic operations follow:

A. LUNABOT WIRELESS LINK

1. Each team will provide the wireless link (access point, bridge, or wireless device) to their Lunabot
   a. KSC will provide an elevated network drop (Female RJ-45 Ethernet jack) in the Lunarena that extends to the control room, where we will have a network switch for the teams to plug in their laptops
      i. The network drop in the Lunarena will be elevated high enough above the edge of the regolith bed wall to provide adequate radiofrequency visibility of the competition pit.
      ii. A shelf will be setup next to the network drop and located 4 to 6 feet off the ground and will be no more than 50 feet from the Lunabot. This shelf is where teams will place their Wireless Access Point (WAP) to communicate with their rover.
      iii. The WAP shelves for side A and side B of the regolith pit will be no closer than 25' from each other to prevent electromagnetic interference (EMI) between the units.
   b. NASA will provide a standard 110VAC outlet by the network drop. Both will be no more than 2 feet from the shelf.
   c. During setup time before the match starts the teams will be responsible for setting up their access point.
2. The teams must use the USA IEEE 802.11 b/g standard for their wireless connection (WAP and rover client) Teams cannot use multiple channels for data transmission. Encryption is not required but it is highly encouraged to prevent unexpected problems with team links.
   a. During a match, one team will operate on channel 1 and the other team will operate on channel 11.
   b. The channel assignments will be made either upon check-in or a few weeks prior to the event.
3. Each team will be assigned an SSID that they must use for their wireless equipment.
   a. SSID will be "Team_##"
   b. Teams shall broadcast their SSID
4. Bandwidth constraints:
   a. There will not be a peak bandwidth limit.
   b. Teams will be awarded in some way for using the least amount of total bandwidth during the timed and NASA monitored portion of the competition.
   c. The communications link is required to have an average bandwidth of no more than 5 megabits per second.

B. RF & COMMUNICATIONS APPROVAL

1. There will be a communications judge's station where each team will have approximately 15 minutes to show the judges that their Lunabot & access point is operating only on their assigned channel.
2. To successfully pass the communications judge's station a team must be able to command their Lunabot (by driving a short distance) from their Lunabot driving/control laptop through their wireless access point. The judges will verify this and use the appropriate monitoring tools to verify that the teams are operating only on their assigned channel.
3. If a team cannot demonstrate the above tasks in the allotted time, they will be disqualified from the competition.
4. Each team will have an assigned time on Monday or Tuesday to show the judges their compliance with the rules.
5. The NASA communications team will be available to help teams make sure that they are ready for the judging station on Monday and Tuesday.
6. Once the team arrives at the judge's station, they can no longer receive assistance from the NASA communications team.
7. If a team is on the wrong channel during a match, they will be required to power down and be disqualified from that match.

C. WIRELESS DEVICE OPERATION IN THE PITS

1. Teams will not be allowed to power up their transmitters on any frequency in the pits once the practice matches begin. All teams shall have a hard-wired connection for testing in the pits.
2. There will be designated times for teams to power up their transmitters when there are no matches underway.

24) The excavation hardware must be contained within 1.5m width x .75m length x 2m height. The hardware may deploy beyond the 1.5 m x .75 m footprint after the start of the competition attempt, but may not exceed a 2 meter height. The excavation hardware may not pass beyond the confines of the outside wall of the Lunarena and the collector during the competition attempt to avoid potential interference with the surrounding tent. The team must declare the orientation of length and width to the inspection judge. Because of actual lunar hardware requirements, no ramps of any kind will be provided or allowed.

25) To ensure that the excavation hardware is usable for an actual lunar mission, the excavation hardware cannot employ any fundamental physical processes (e.g., suction or water cooling in the open lunar environment), gases, fluids or consumables that would not work in the lunar environment. For example, any dust removal from a lens or sensor must employ a physical process that would be suitable for the lunar surface. Teams may use processes that require an Earth-like environment (e.g., oxygen, water) only if the system using the processes is designed to work in a lunar environment and if such resources used by the excavation hardware are included in the mass of the excavation hardware.

26) Components (i.e. electronic and mechanical) are not required to be space qualified for the lunar vacuum, electromagnetic, and thermal environments.

27) The excavation hardware may not use any process that causes the physical or chemical properties of the lunar regolith simulant to be changed or otherwise endangers the uniformity between competition attempts.

28) The excavation hardware may not penetrate the lunar regolith simulant surface with more force than the weight of the excavation hardware before the start of the competition attempt.

29) No ordnance, projectile, far-reaching mechanism, etc. may be used (excavator must move on the lunar regolith simulant).

30) No excavation hardware can intentionally harm another team's hardware. This includes radio jamming, denial of service to network, regolith simulant manipulation, ramming, flipping, pinning, conveyance of current, or other forms of damage as decided upon by the judges. Immediate disqualification will result if judges deem any maneuvers by a team as being offensive in nature. Erratic behavior or loss of control of the excavation hardware as determined by the judges will be cause for immediate disqualification.

31) Teams must electronically submit documentation containing a description of the excavation hardware, its operation, potential safety hazards, a diagram, and basic parts list.

32) Teams must electronically submit video documentation containing no less than 30 seconds of excavation hardware operation and at least 1 full cycle of operation. One full cycle of operations includes excavation and depositing material. This video documentation is solely for technical evaluation of the team's excavation hardware.

Video specifications:

Formats/Containers: .avi, .mpg, .mpeg, .ogg, .mp4, .mkv, .m2t, .mov; Codecs: MPEG-1, MPEG-2, MPEG-4 (including AVC/h.264), ogg theora; Minimum frame rate: 24 fps; Minimum resolution: 320 x 240 pixels

Definitions

Black Point-1 (BP-1) – A crushed lava aggregate with a natural particle size distribution similar to that of lunar soil. The aggregate will have a particle size and distribution similar to the lunar regolith as stated in the Lunar Sourcebook: A User's Guide to the Moon, edited by G. H. Heiken, D. T. Vaniman, and B. M. French, copyright 1991, Cambridge University Press. Teams are encouraged to develop or procure simulants based on lunar type of minerals and lunar regolith particle size, shape, and distribution.

Collector – A device provided by NASA for the competition attempt into which each team will deposit excavated regolith simulant. The collector will be large enough to accommodate each team's excavated regolith simulant. The collector will be stationary and located adjacent to the Lunarena. Excavated regolith simulant mass will be measured after completion of the competition attempt. The collector mass will not be counted towards the excavated mass or the mass of the excavation hardware. The collector will be 1.65 meters long and .48 meters wide. The collector walls will rise to an elevation of approximately 1 meter above the BP-1 surface directly below the collector. See the Lunarena Diagrams on page 7.

Competition attempt – The operation of a team's excavation hardware intended to meet all the requirements for winning the competition by performing the functional task. The duration of the competition attempt is 15-minutes.

Excavated mass – Mass of the excavated lunar regolith simulant delivered to the collector by the team's excavation hardware during the competition attempt, measured in kilograms (kg) with official result recorded to the nearest one tenth of a kilogram (0.1 kg).

Excavation hardware – Mechanical and electrical equipment, including any batteries, gases, fluids and consumables delivered by a team to compete in the competition.

Functional task – The excavation of regolith simulant from the Lunarena by the excavation hardware and deposit from the excavation hardware into the collector box.

Minimum excavation requirement – 10.0 kg is the minimum excavated mass which must be met in order to qualify to win the competition.

Power – All power shall be provided by a system onboard the excavator. No facility power will be provided to the excavator. There are no power limitations except that the excavator must be self-powered and included in the maximum excavation hardware mass limit of 80.0 kg.

Practice time – Teams will be allowed to practice with their excavators in the Lunarena. NASA technical experts will offer feedback on real-time networking performance during practice attempts.

Reference point – A fixed location on the excavation hardware that will serve to verify the starting location and traversal of the excavation hardware within the Lunarena. An arrow on the reference point must mark the forward direction of the excavator in the starting position configuration. The judges will use this reference point and arrow to orient the excavator in the randomly selected direction and position.

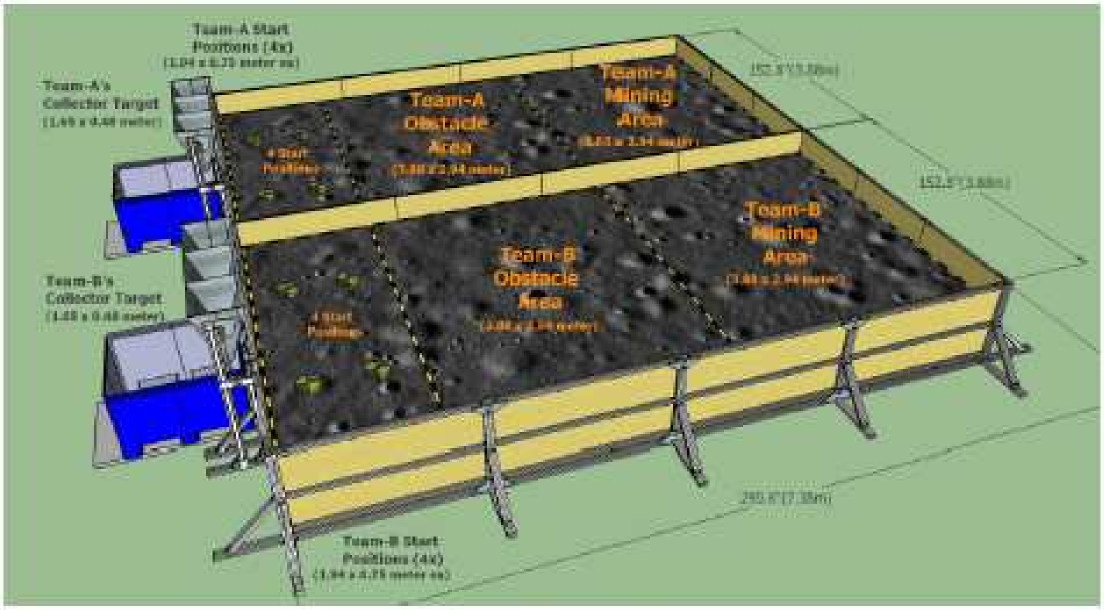
Lunabot – A teleoperated robotic excavator in NASA's Lunabotics Mining Competition.

Lunarena – An open-topped container (i.e., a box with a bottom and 4 side walls only), containing regolith simulant, within which the excavation hardware will perform the competition attempt. The inside dimensions of the each side of the Lunarena will be 7.38 meters long and 3.88 meters wide, and 1 meter in depth. A dividing wall will be in the center of the Lunarena. The Lunarena for the official practice days and competition will be provided by NASA. See the Lunarena Diagrams on page 7.

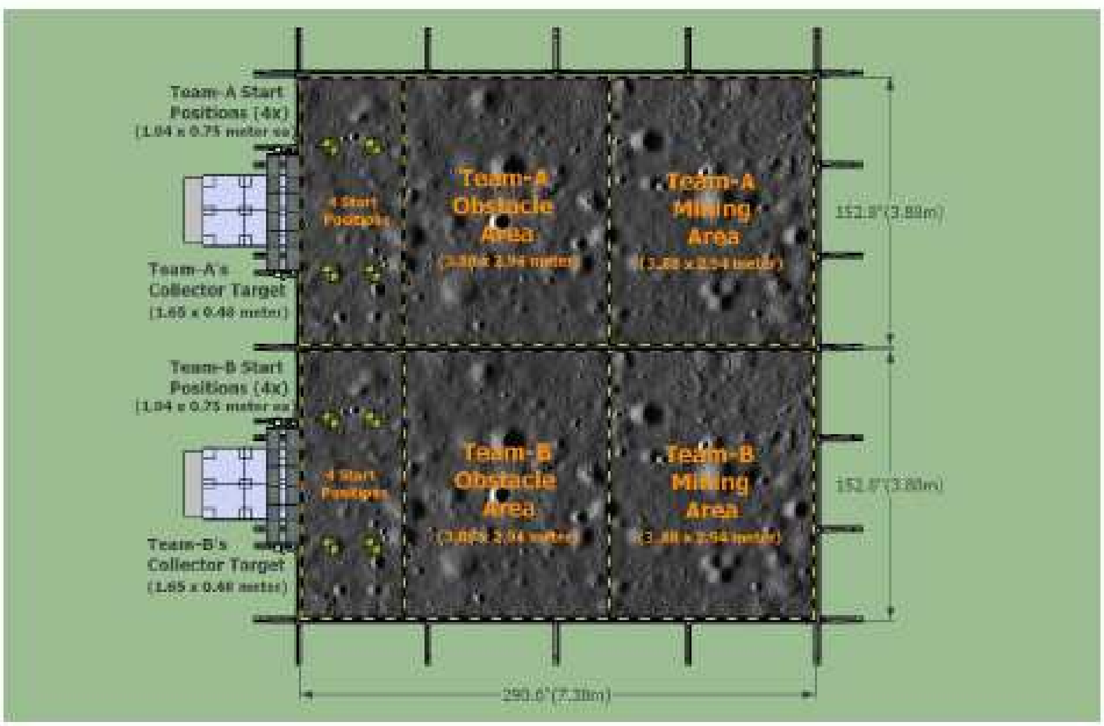
Telerobotic – Communication with and control of the excavation hardware during the competition attempt must be performed solely through the provided communications link which is required to have a total bandwidth of no more than 5.0 megabits/second on all data and video sent to and received from the excavation hardware.

Time Limit – The amount of time within which the excavation hardware must perform the functional task, set at 15 minutes; set up excavation hardware, set at 10 minutes; and removal of excavation hardware, set at 5 minutes.

Lunarena Diagrams

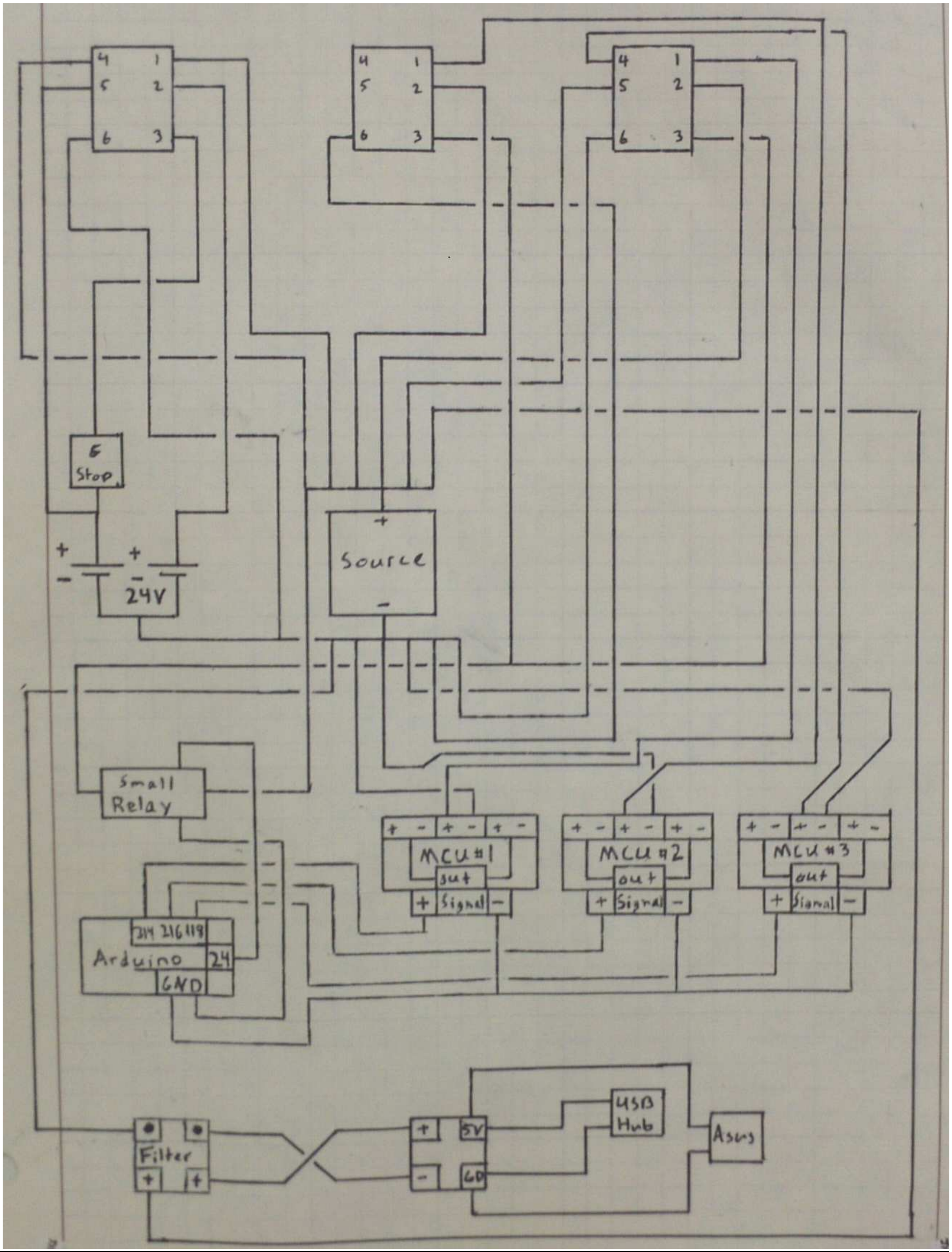


Lunarena Diagram (side view)



Lunarena Diagram (top view)

Appendix E: Electrical Diagram



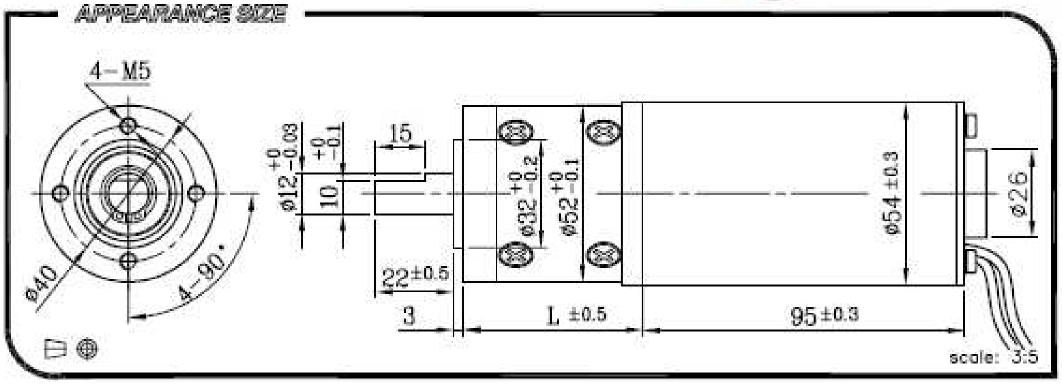
Appendix F: Wheel Motor Specification Sheet

IG-52GM (DC Carbon-brush motors)

03&04 TYPE

REDUCTION RATIO	L	REDUCTION RATIO	L
1/3~1/4	53.0	1/150~1/936	99.5
1/12~1/26	68.5		
1/43~1/113	84.0		

IG-52 GEARHEAD SERIES



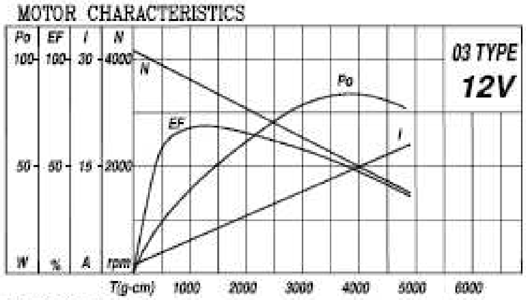
GEARED MOTOR TORQUE/SPEED

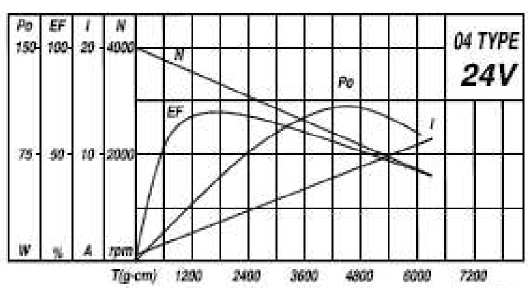
		1/3	1/4	1/12	1/15	1/19	1/26	1/43	1/53	1/66	1/81	1/100	1/113	1/150	1/230	1/285	1/353	1/488	1/546	1/676	1/936
	Reduction ratio																				
12V	Rated torque (Kg-cm)	2.5	3.1	7.7	9.5	11.8	16	23	28	35	44	54	60	67	100	100	100	100	100	100	100
12V	Rated speed (rpm)	1030	835	295	238	192	139	84	68	55	44	36	32	24	15.5	12.8	10.4	7.6	6.7	5.6	4.0
24V	Rated torque (Kg-cm)	3.6	4.5	11	13.5	17	23	33	41	51	62	78	88	97	100	100	100	100	100	100	100
24V	Rated speed (rpm)	1000	815	285	230	185	136	82	67	54	44	35	31	23.5	15.6	12.9	10.5	7.7	6.8	5.7	4.1

MOTOR DATTA

Rated volt (V)	Rated torque (g-cm)	Rated speed (rpm)	Rated current (mA)	No load speed (rpm)	No load current (mA)	Rated output (W)	Weight (g)
12	900	3620	≤ 4100	4000	≤ 1200	33.5	920
24	1300	3550	≤ 2850	4000	≤ 700	48.6	920

MOTOR CHARACTERISTICS





September 2006

More About Hard Fiber, Fiberglass, and Garolite

Tensile Strength—The maximum pulling force a material can withstand without breaking. It is usually measured in pounds per square inch (psi). A larger number indicates a stronger material.

Impact Strength—The ability of a material to withstand shock loading. Determined by the notched Izod test, which measures the effect on a material when it is suddenly impacted by a swinging pendulum. A larger number signifies greater impact resistance.

Flexural Modulus of Elasticity—The stiffness of a material. The higher the number, the stiffer the material; the lower the number, the more flexible it is.

Short-Term Dielectric Strength—The maximum voltage a material can withstand without rupture, measured as volts per millimeter of thickness. This is an indication of how effective the material is as an electrical insulator. A higher value signifies a better insulator.

Coefficient of Thermal Expansion—The amount a material increases in volume as the temperature rises. A smaller coefficient is an indicator of less thermal expansion.

Warning: Mechanical properties are not guaranteed and are intended only as a basis for comparison. Data is not for design purposes.

Material	Nominal Density, lbs./cu. in.	Tensile Strength, psi	Impact Strength, lbs./in.	Compressive Strength, psi	Flexural Strength, psi	Modulus of Elasticity, psi	Dielectric Strength, volts/mil.■	Coefficient of Thermal Expansion, in./°F	Thermal Conductivity BTU/hr. × sq. ft.	Water Absorption, %
Hard Fiber	0.043	9,000-21,000	1.8-2.5	35,000	16,000-29,000	$8\text{-}12 \times 10^5$	200-215	1.1×10^5	0.168	63-66
Fiberglass (FRP)	0.062-0.072	7,000-40,000	4-40	15,000-65,000	10,000-30,000	$2.8\text{-}5.5 \times 10^6$	200	$3.3\text{-}4.4 \times 10^6$	4	0.45
Fiberglass (GP03)	0.067	10,000-12,000	8.2-12	32,000-32,800	23,200-31,000	1.2×10^6	400-600	1.11×10^5	1.9	0.2
Garolite XX	0.05	8,000-23,900	0.35-1.3	15,000-35,000	14,000-29,000	Not rated	350-700	Not rated	Not rated	0.57-1.3
Garolite LE	0.048-0.051	6,000-15,300	0.8-1.3	22,600-36,000	15,400-19,700	Not rated	140-625	Not rated	Not rated	0.47-1.9
Garolite CE	0.05	6,000-15,100	Not rated	18,000-37,000	15,000-27,100	Not rated	120-550	Not rated	Not rated	1.6
Garolite G-9	0.074	39,000	5.5-7	23,900-70,000	55,000-60,400	1.7×10^6	370-450	Not rated	Not rated	0.5-0.6
Garolite G-10	0.069	15,000	Not rated	25,000	Not rated	Not rated	250-300	Not rated	Not rated	0.09-0.013
Garolite G-10/FR4	0.069	38,000-50,000	5.5-12	35,000-66,000	45,000-60,000	$2.2\text{-}3.3 \times 10^3$	400-800	Not rated	Not rated	0.10-0.25
Garolite G-11	0.069	37,000-56,600	Not rated	32,900-63,000	59,600-76,700	Not rated	521-900	Not rated	Not rated	0.15-0.20
Garolite G-7	0.068	18,000-27,700	Not rated	8,625-45,000	20,900-25,800	Not rated	400-465	Not rated	Not rated	0.6-0.12
Graphite-Impregnated Garolite	0.05	7,000	1.08	26,000	13,000	6.2×10^5	Not rated	Not rated	Not rated	0.7-2.05

■ 1 mil=0.001"

DATA TABLE FOR: Wood: Wood Class III (10-15y): Oregon Pine

Mechanical Properties

Quantity	Value	Unit
Young's modulus	11500 - 13500	MPa
Tensile strength	0 - 105	MPa
Compressive strength	43 - 52	MPa
Bending strength	68 - 82	MPa

Physical Properties

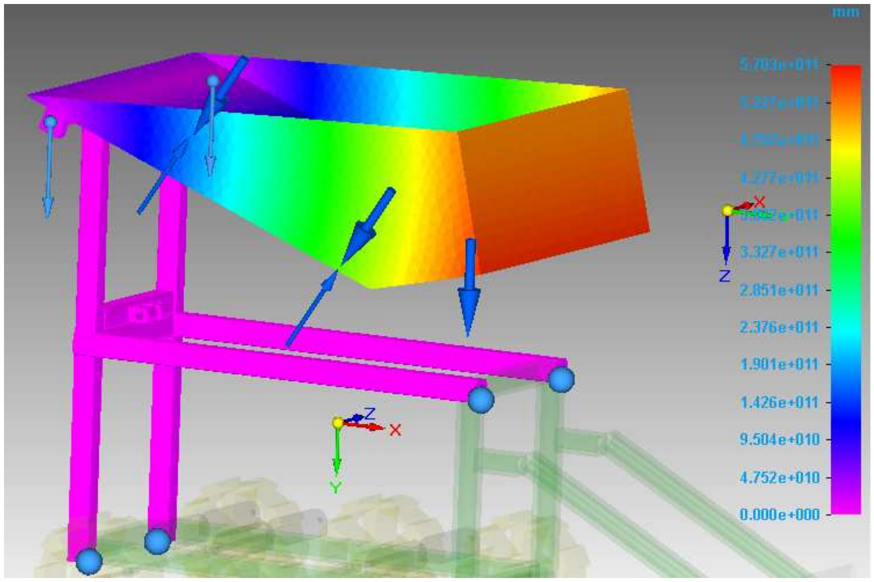
Quantity	Value	Unit
Thermal conductivity	0.17 - 0.17	W/m.K
Density	0 - 470	kg/m^3
Shrinkage	1.4 - 2.1	%

Environmental Data

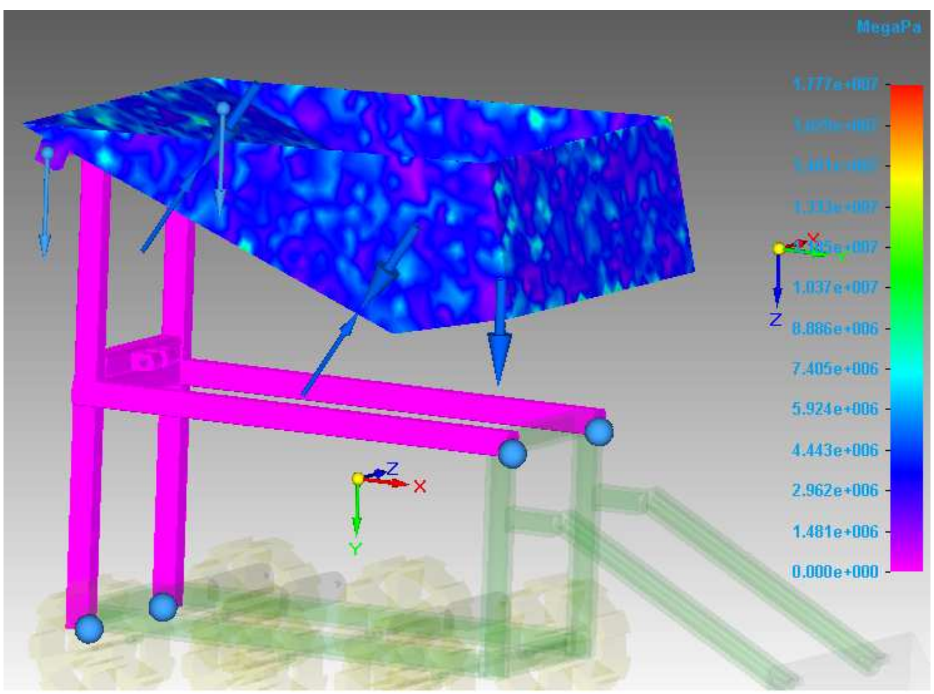
Quantity	Value	Unit
Eco indicator 95	1.79	mPt
EPS	152	mELU
Ex (in) / Ex (out)	1.47122692725299	MJ/MJ
GER	38	MJ
Raw materials input	2.1369075101726	kg
Solid	0.101251638313	kg
Eco indicator 99	0.388	Pt
Environmental remarks	Oregon pine is imported from the US (40%), France (30%) and the remaining from a varity of countries (Belgium.... Russia). It is cultured. Processing to beams is for 72% done in the producing country. 28% is processed in the Netherlands. Transport distance from plantage to factory 2 times 150km by trailers and 3020km to Rotterdam by ship. The annual production in culture is between 6 - 16 m3/ha/y, with an average of 11, depending on and region, at a growth cycle of 50 years.	
Author:	Idemat 1998	

<u>**Appendix G: Solid Edge**</u>

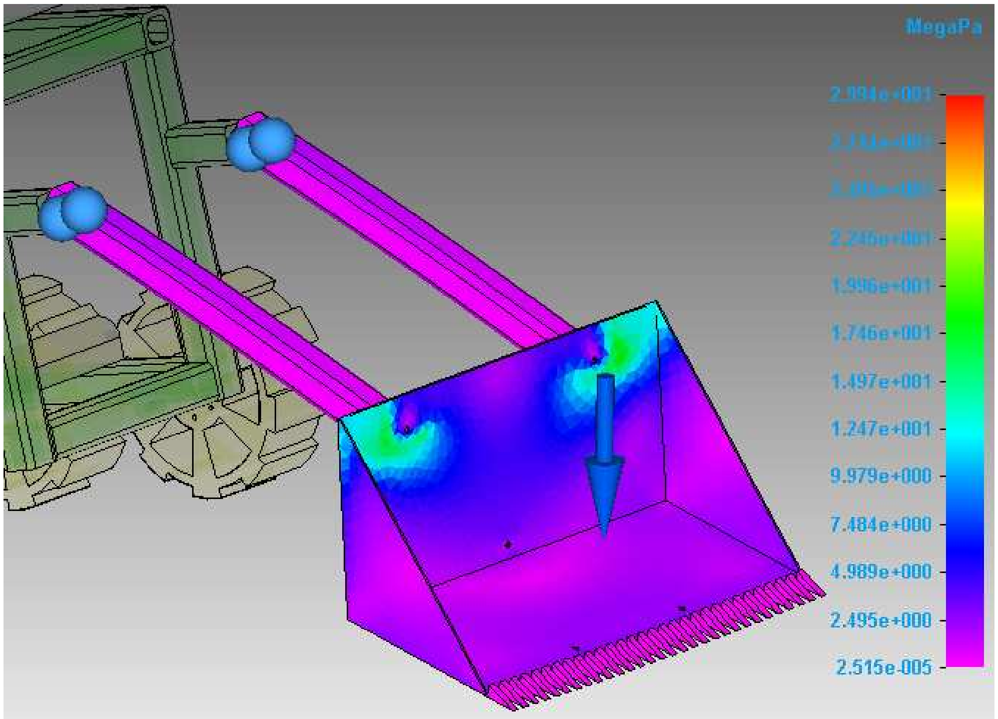
Appendix G.1:Solid Edge Finite Analysis



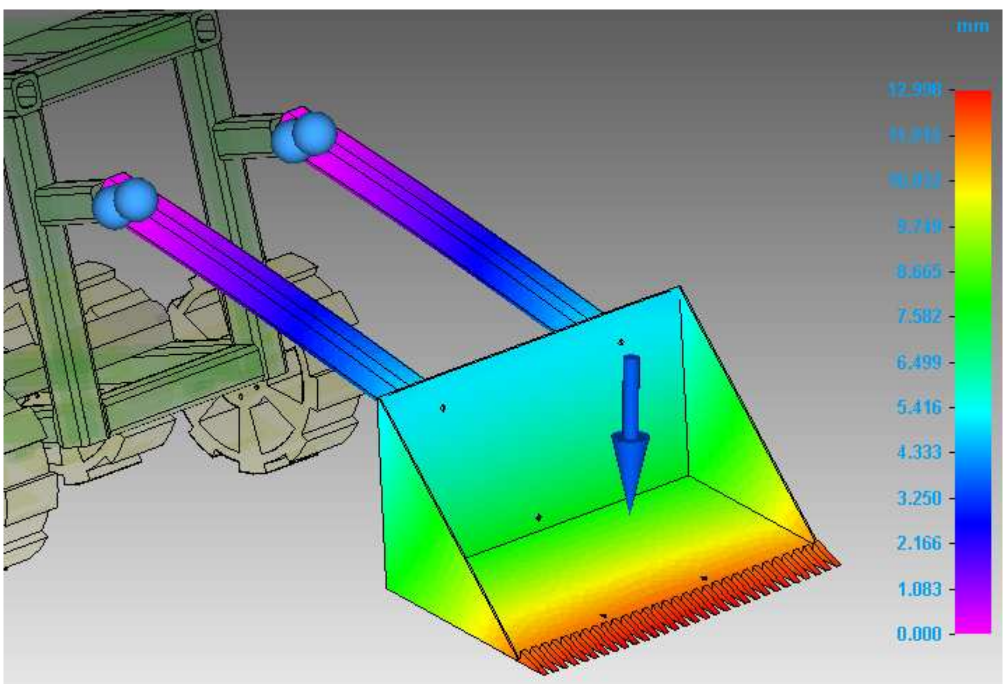
Hopper Bending Displacement



Hopper Von Mises



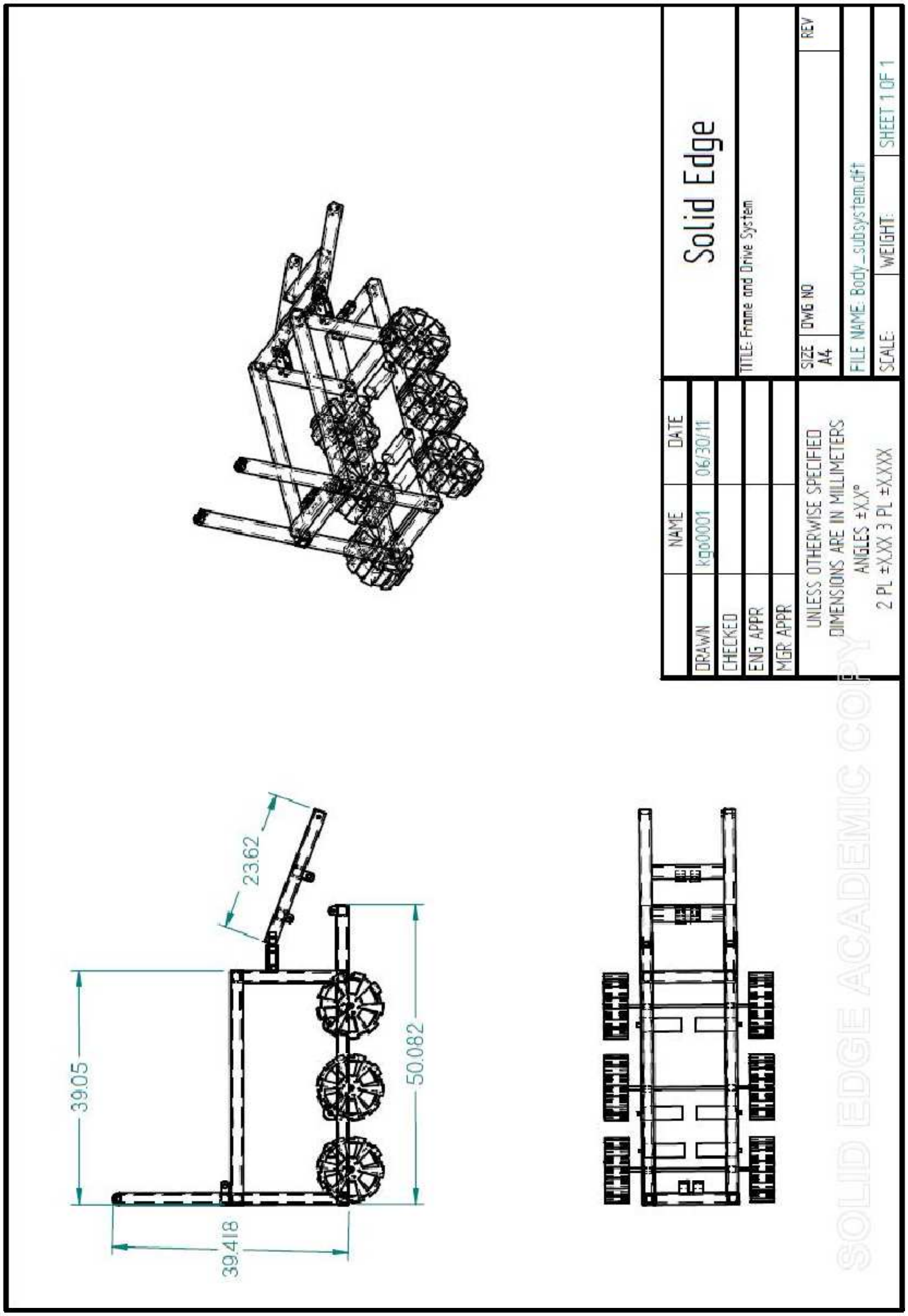
Bucket Von Mises Stress



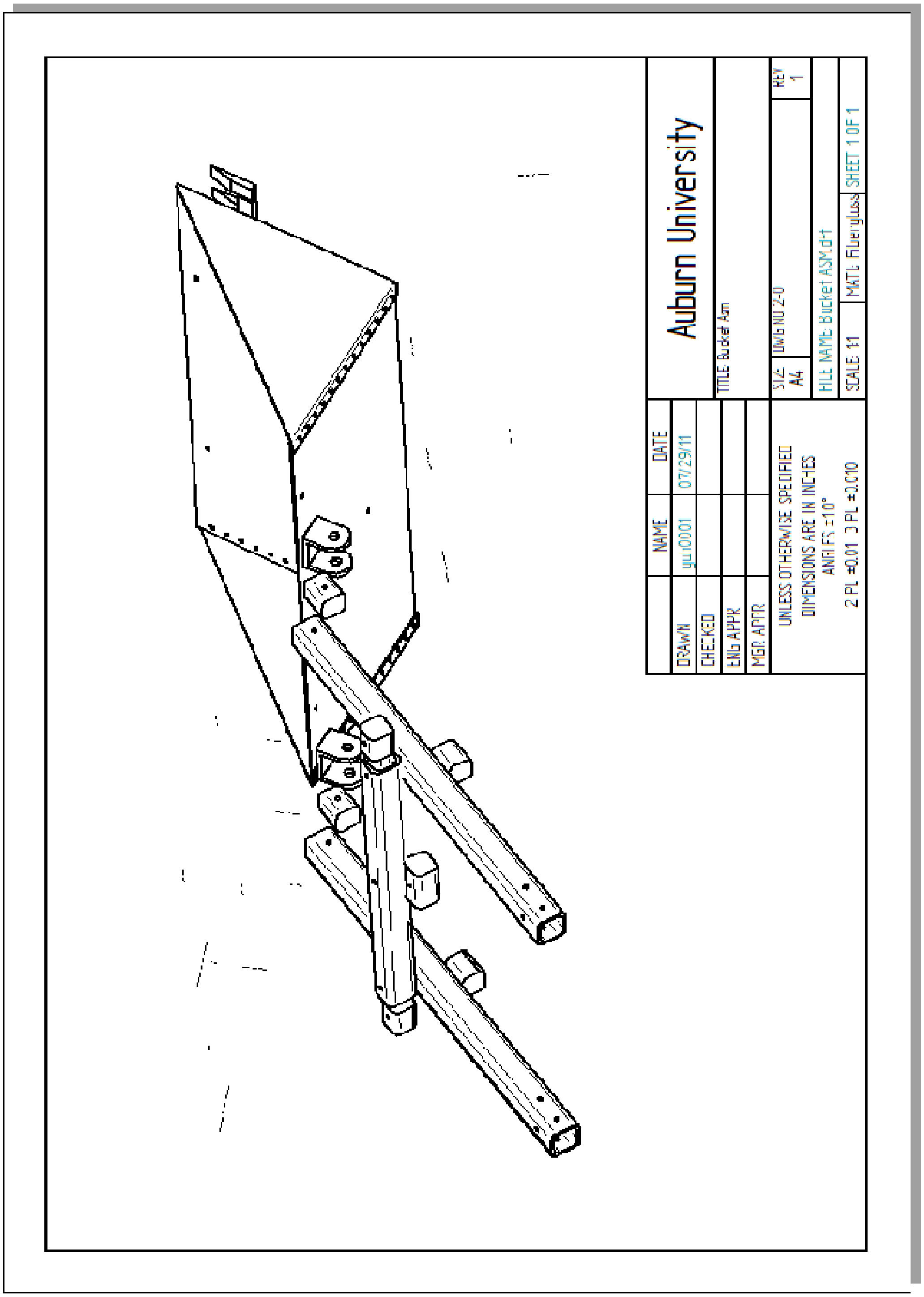
Bucket Bending Displacement

Appendix G.2: CAD Drawings

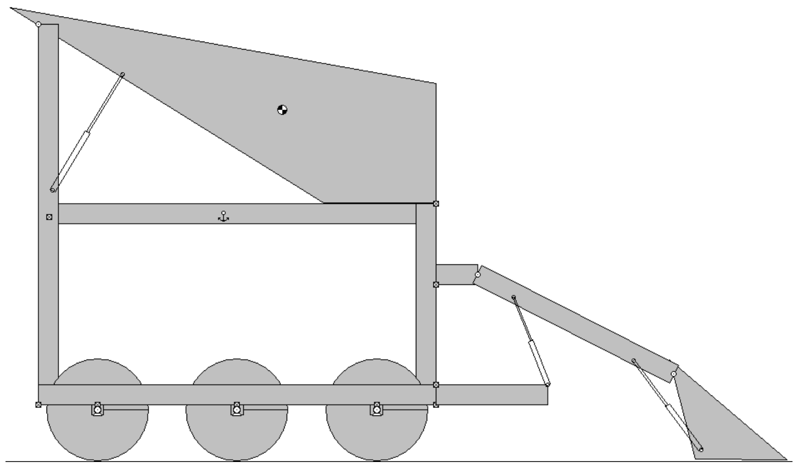
Drive System/Frame CAD Drawing



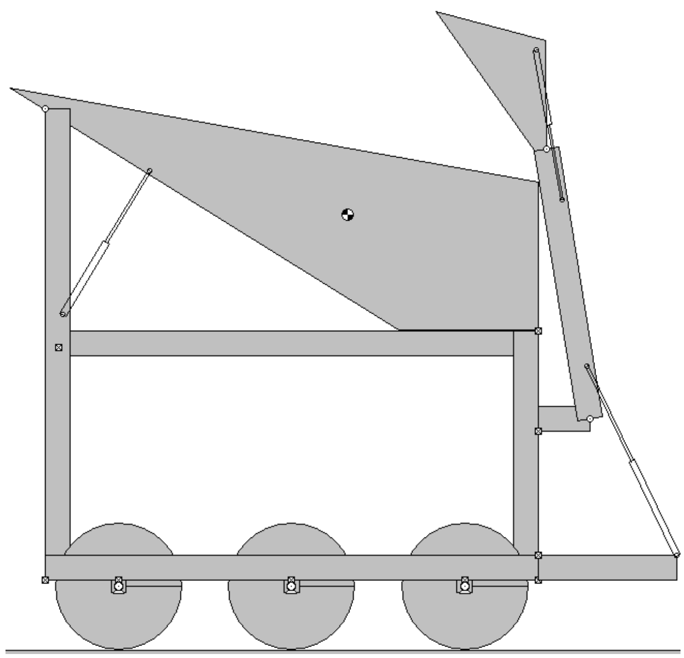
Scoop System CAD Drawing



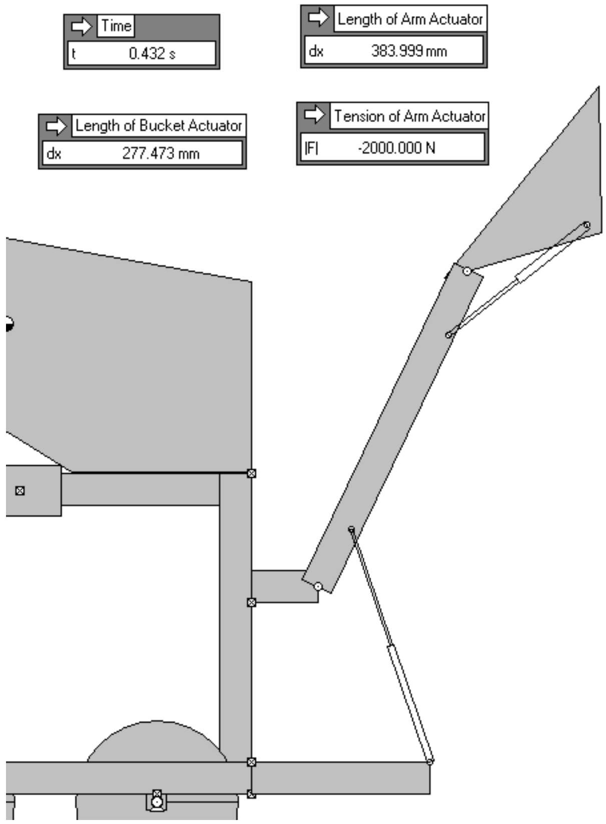
Appendix H: Working Model Analysis



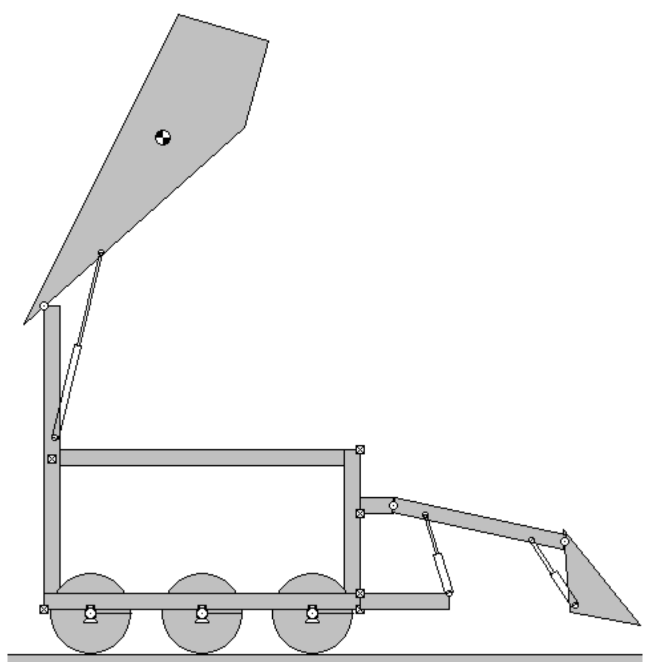
Full Excavator



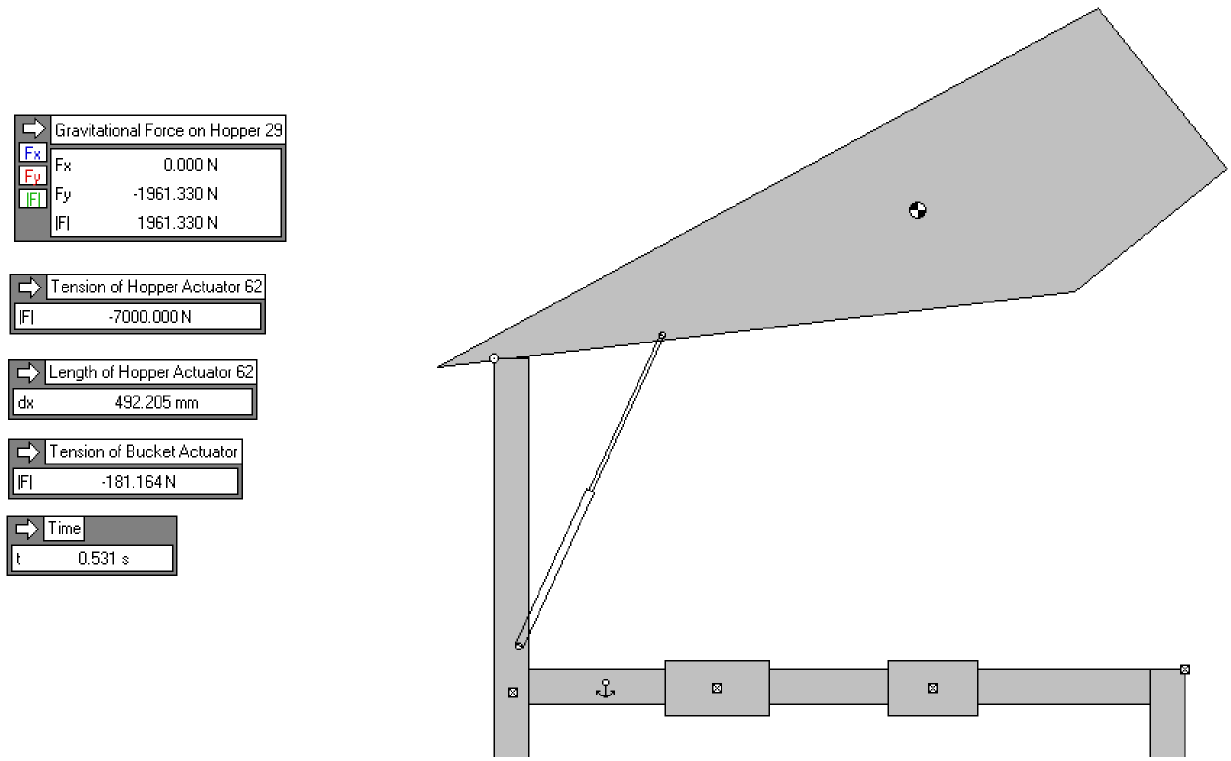
Front Actuator Fully Extended



Front Arm Actuator Extended



Full Range on Hopper Actuator



Hopper Actuator Extending