Mech 4250 Operational Readiness Review (ORR)

NASA Robotic Mining Competition Design Team

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Abstract

The purpose of the NASA Robotic Mining project is to develop an autonomous Martian mining device which will be used in the 2015 NASA Robotic Mining competition. As the 2015 competition rules have not been released, the 2014 rules will be used to determine functional requirements for the project.

NASA has held the robotic mining competition for several years now. This year, the focus has been switched from a lunar mission to an asteroid or Martian mission. As very little is known about these surfaces, the surface is assumed to be similar to the moon. Thus, Black Point 1 (BP-1), a crushed lava basalt, will be the soil used at the competition to simulate lunar regolith.

Through the use of a systems engineering approach, the NASA robotic mining team has set out to develop a winning solution to solve the problem, exceed the sponsors' expectations and showcase Auburn University's Engineering College. Through the utilization of system engineering tools such as the Vee Chart, a Gantt Chart and the 11 System Engineering Functions; a methodical approach has been used to develop the design.

A wheeled digging device with an auger dump was selected as the leading concept after watching film, conducting trade studies, and testing. This device utilizes scoops mounted on two of the robot's four wheels. As these wheels turn, the scoops pick up BP-1. An inner wheel keeps the BP-1 from falling out until the scoops have reached the upper portion of the wheel. The BP-1 then slides down a shoot into the storage bin. A horizontal auger in the bin sends the BP-1 backward toward the dumping auger. The wheel digger/auger robotic mining system provides an optimal solution that can be easily controlled for autonomous operation. As well, this design has not been seen at the competition so it provides a good chance to win the ingenuity award.

However, the main focus of this project is to win the on-site mining competition portion of the 2015 NASA Robotic Mining Competition. Upon researching the point breakdown, it became evident that the ability to autonomously control the robot is much more important than the dry weight of the robot or the amount the robot can dig. The current design is estimated to earn 1420 points. In comparison, the 2013 winner had approximately 900 points. Information on the 2014 competition has not yet been analyzed.

The mechanical design on the robot was completed by late May 2014. This finalized mechanical design includes a Technical Data Package (TDP). Upon sponsor approval of the final mechanical design, fabrication began on the chassis, electrical, bin and auger subsystems. At current state, the chassis, bin and auger subsystems have been built according to the design. As well, a prototype electrical subsystem has been created to allow for testing.

Integration and testing have been done to ensure proper alignment and to begin to determine system functionality. The prototype consists of those subsystems mentioned above as well as stand-in wheels for testing. A prototype auger was tested to determine the load on the battery and to check for any design flaws. After building the subsystems, each auger was individually tested to ensure proper alignment. The electrical box was tested separately as well. After positive results, the subsystems were integrated and motors were attached. System testing then followed.

The Operational Readiness Report (ORR), testing results and other relevant information as specified in the Manager's Project Contact of Deliverables (MPCOD) will be handed over to the 2015 NASA Robotic Mining Competition team and/or the next design team once the prototype is validated and verified. The senior design team has begun to share ideas with the competition team in hopes to familiarize them with the design and get feedback.

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1.0 Introduction

The primary objective of this project is to determine a winning design for the NASA 2015 Robotic Mining competition. This competition is comprised of student teams from across the world. During the competition, each team has two mining competition runs of ten minutes to collect as much regolith as desired. A minimum of 10 kg must be collected to gain any points for the run however. Above the 10 kg minimum, 3 points are awarded per additional kg of BP-1. Likewise, 8 points are subtracted for each kg of dry robot mass with a maximum mass requirement of 80 kg. The total points for each one are averaged to give the final on-site mining competition score. Full autonomy during the runs is critical in that a majority of the points in the on-site mining competition are available here. A more detailed explanation of these requirements and point scoring opportunities is described in the requirements section below.

A systems engineering approach was used to systematically develop a design which, given customer approval, will be prototyped and tested. After determining the mission objective and reviewing the rules of the 2014 NASA Robotic Mining Competition, trade studies were done to develop concepts and see which of these concepts had worked in previous competitions. Teams like the University of North Dakota, Alabama, Iowa State, NYU-Poly and many other designs were compared with each other and the previous Auburn robot. Iowa State was studied carefully as they have been the competition winners the in 2012 and 2013 seasons. They were the only team to attempt an autonomous run in 2013 (though unsuccessful).

Due to the limited timeframe of this project, manufacturability was a significant concern to the design process. Thus, a modular design was chosen so that a change can be made in one subsystem without forcing a complete redesign of the system. As this project has a very expeditious timeline, a systems engineering approach was vital in that it provided a regimented approach to solve the problem. The 11 System Engineering Functions (as seen in Figure 1) were used to create the design, budget resources and provide ways to prove its functionality.

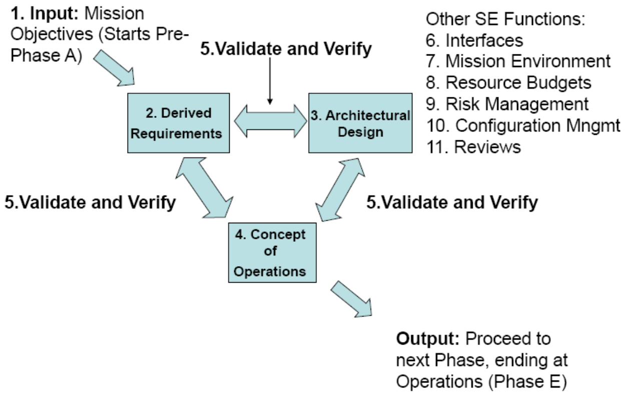


Figure 1: System Engineering Functions

Once a concept was developed, further research, MATLAB simulations and preliminary testing were used to further refine the design. Currently, the design utilizes 2 digging wheels with scoops to pick up the BP-1. This BP-1 then is sent down a shoot into a bin. The bin uses a horizontal auger to redistribute BP-1 in the bin towards an angled auger which in turn is used to dump into the final collection bin. This design will be discussed extensively in the following report.

At the CDR, Dr. Beale suggested a change from 1.5 inch OD 6061 aluminum tube for the frame to square tubing. Upon quick calculation, it was determined that 0.75 inch 1018 steel square tubing was sufficient for the design and allowed for much simpler manufacturing. Likewise, carbon fiber was chosen to replace the vertical auger tube which was once going to be heavy PVC. This change helped to reduce weight as well as tied the auger tube into the bin much more efficiently.

After the redesign, work began on the chassis, bin and a prototype auger which was used for testing. When it was determined that the complete design could not be manufactured by the end of the semester, adjustability became a main concern. Motor mounts were slotted to allow for potential changes in sprockets. As well, the axles were standardized to allow for interchangeability. Once the prototype was completed, testing, validation and verification occurred.

2.0 Mission Objective

The objective of this project is to create the mechanical portion of an autonomous system weighing less than 80 kg capable of surviving/navigating terrain representative of the Martian surface in order to retrieve and deposit Regolith. This system should be able to collect and deposit a minimum of 10 kg of Regolith in 10 minutes. At the end of the summer, a non-autonomous version was operational and tested. This prototype will be handed off to the next group to be modified as needed to meet the 2015 NASA Robotic Mining Competition rules and participate in the 2015 competition. A full list of objectives is defined in the MPCOD in Appendix A.

3.0 Environment

The NASA Robotics Competition has been designed to simulate a Martian or asteroid surface. As the actual completion will be held on earth, certain aspects of the design will vary from an actual Martian device. One such example is that the estimated gravity of Mars is 3/8 that of the earth. Equipment for the competition does not have to be rated for Martian atmospheric conditions. However, physical processes should be capable of being used in space. Since the competition will be at the Kennedy Space Center, the components must be capable of storage and operation in an average of 90 degrees Fahrenheit and high levels of humidity.

As not much information is known about the actual Martian soil, the soil has been assumed to be similar to lunar regolith. The soil in the competition will be Black Point 1 (BP-1) which is a noncommercially available crushed lava basalt. The BP-1 is an abrasive powder-like soil that is very similar to the regolith on the Earth's moon. The BP-1 also has some magnetic characteristics.

The actual competition will be inside an enclosed room with two pits side by side as shown in Figure 2. Throughout the competition, dust should be expected from either robot and must be taken into account.

The BP1 in the competition will have a density of approximately $0.75 g/cm^3$ for the top 2 cm and between $1.5 g/cm^3$ to $1.8 g/cm^3$ below (Appendix B). The mining area will be 3.78 m (width) x 2.94 m (length) x 0.5 m (depth). The coefficient of friction is not well known.

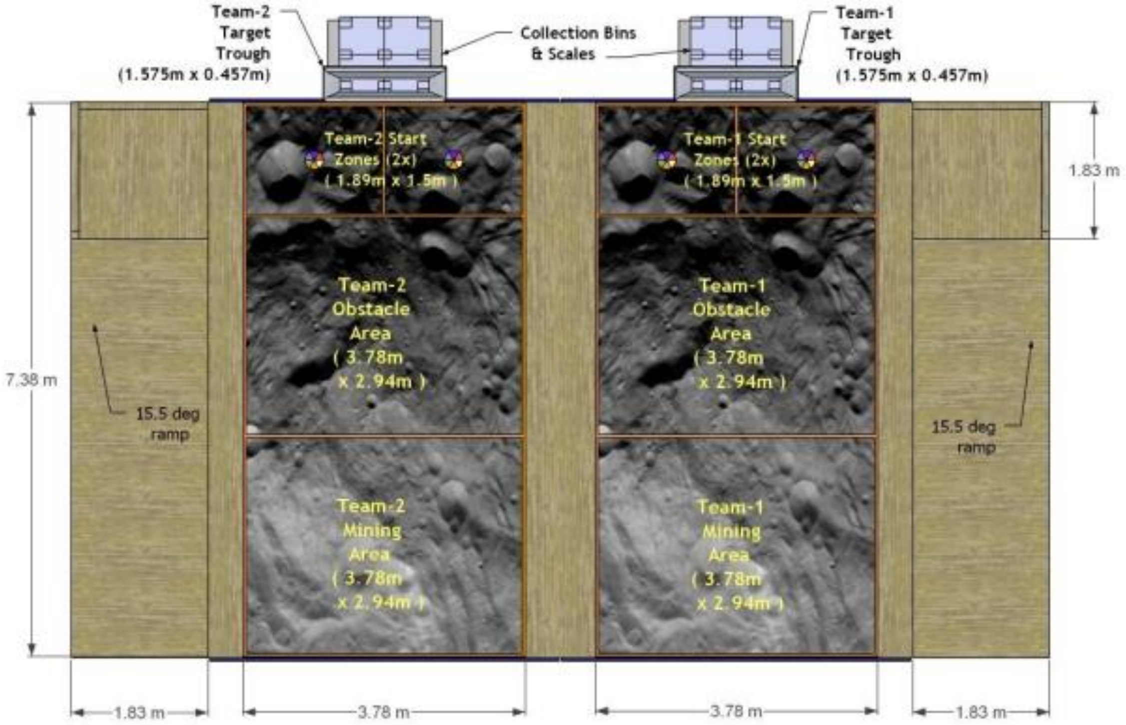


Figure 2: Competition Pit Dimensions

4.0 Requirements

The proposed system must adhere to the rules as specified in "NASA's Fifth Annual Robotic Mining Competition Rules and Rubrics 2014" as specified in Appendix B. This system must originally fit in a volume of 1.5 m (length) x 0.75 m (width) x 0.75 m (height). After the start of the competition, the height can be extended up to 1.5 m. The system must be able to deposit the regolith into the top of the collection system 0.5 m above the regolith's surface. The robot must have a dry mass of 80 kg or less.

The robot will be randomly orientated in the start zone shown in Figure 1 before each run of the competition. Then, the robot must traverse the obstacle area which will include three obstacles up to 30 cm in diameter and 10 kg in mass. As well, this area will have two craters up to 30 cm in depth and diameter. The robot must not "excavate" BP-1 until crossing the line into the mining area. Per the definition section of the competition rules (Appendix B), the excavated mass is defined as:

> *Excavated mass – Mass of the excavated BP-1 deposited to the Collector bin by the team's mining robot during each competition attempt, measured in kilograms (kg) with official result recorded to the nearest one tenth of a kilogram (0.1 kg).*

After a thorough correspondence with the 2014 NASA Robotic Mining Coordinator, a further clarification to the rule was made to determine the interpretation of the word "excavate". This correspondence can be seen in its entirety in Appendix C. The robotic device must mine a minimum of 10 kg in the 10 minute competition run to qualify. Teams will have two 10 minute runs in the competition. The average of the two runs will be the final score for the on-site mining portion of the competition. During each of the competition runs, the robot must be controlled remotely and/or be autonomous in function. The robot must also be capable of wired control for practice runs.

The design of the robot must be formulated in such a way to win the 2015 NASA Robotics Competition. As the 2014 rules indicate, the point breakdown for the on-site mining award has been documented in Table 1.

Table 1: Onsite Mining Competition Points

Element	Points
Pass Safety and Comm. Check	1000
BP-1 Excavated over 10kg	+3 per kg
Robot Weight	-8 per kg
Dust Tolerant Design	0-30 (Judge's discretion)
Dust Free Operation	0-70 (Judge's discretion)
Autonomous Operation	0, 50, 150, 250 or 500
Average Bandwidth	-1 per 50 kb/sec
Energy Consumption Reported	0 or 20

Autonomy has been divided up into sections based on the level of functions performed autonomously. Fifty points will be given for crossing the obstacle field. One hundred and fifty will be given for crossing and digging. Two hundred fifty will be rewarded for one full run including deposit. Five hundred will be rewarded for a full ten minute autonomous run.

As can be seen in Appendix B, the Joe Kosmo Award for Excellence (grand prize) is made up of several other categories including a presentation, systems engineering paper, team spirit and community involvement. As the current design team will not be attending the 2015 competition, the focus of this project will be on the on-site mining portion of the competition.

5.0 Architectural Design

After the competition rules were thoroughly examined, conceptual design began. The first steps were to performing trade studies on the previous competitions and comparing the leading competitors' designs with the current Auburn robot.

5.1 Trade Studies

Trade studies were completed by first watching several hours of YouTube videos of previous competitions. In the 2012 and 2013 competitions, Iowa State University won the on-sight mining award. The 2013 Iowa State University robot can be seen in Figure 3.

Figure 3: Iowa State University 2013 Robot

Upon the close examination of the Iowa State design, it was noticed that the tracks appeared to slow the robot down. Likewise, the fact that the collecting bin had to be raised to dump out the BP-1 caused a change in the center of gravity and made it prone to flip. The 2013 team attempted an autonomous run but was unable to complete it.

From examination of other teams, it became apparent that wide wheels helped the robot stay above the surface and thus improved mobility. NYU-Poly's 2012 robot was also analyzed due to its unusual front wheel and digging scoop designs. These front wheels used scoops to provide traction for the robot. The digging mechanism was a revolving drum with scoops that collected regolith.

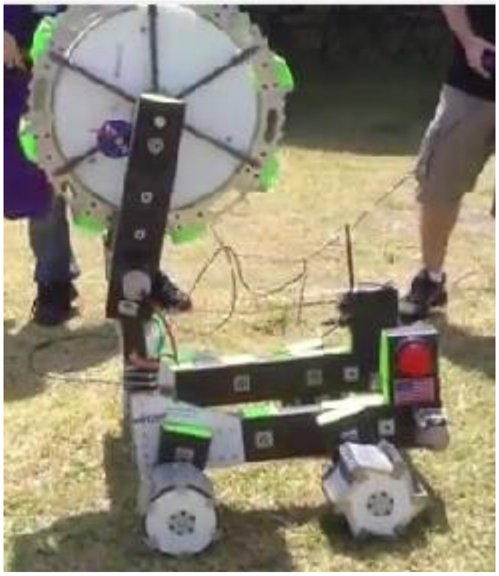


Figure 4: NYU-Poly 2012 Robot

Teams with revolving mining systems such as the conveyor seen in Figure 3 or the drum as seen on Figure 4 had better digging rates than traditional scoop designs. The drum designs however took a long time to dump.

The current Auburn robot as seen in Figure 5 was also examined. The Auburn robot has a single bucket and narrow wheels. Thus, after watching several hours of competition video, this design was quickly determined to not be an optimal solution.

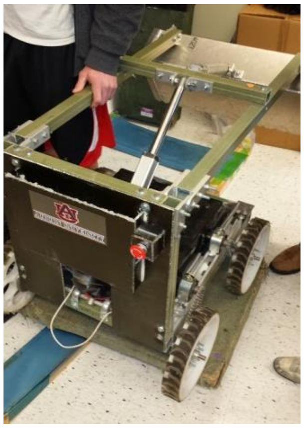


Figure 5: Current Auburn Robot

It was noticed that in general, teams that incorporated moving bins tended to lose stability. On the other hand, teams that incorporated a conveyor or auger system had slower dumps but were able to maximize stability. As the competition runs are averaged together, a robot prone to flipping is highly undesirable. Upon examination, one of the teams that used an auger was the University of North Dakota. Thus, the UND auger (Figure 6) was examined.

Figure 6: UND 2010 Auger

5.2 Decomposition

After a general trade study over old designs was completed, a functional decomposition was performed to look at each individual function and determine what factors would have a major impact on each function.

- Carry Dirt
  - Cannot tip
  - Support dirt weight
  - No spillage/low dust generation
- Dig Dirt
  - Target time for digging
  - Repeatability
  - Low dust generation
  - Placing dirt in carrying receptacle
- Mobility
  - Motion in cardinal direction (forward/reverse, left right)
  - Obstacle avoidance/survivability
  - Carry dirt load
  - Low dust generation
- Dump dirt
  - Hit target receptacle
  - Low dust
- Structural Support
  - Hold everything together
  - House “fragile” components
    - Prevent dust penetration
  - Lightweight
  - Robust

The design was then divided up into multiple subsystems including digging, drivetrain/steering, storage/dumping, electrical and communication systems. For the digging system, the following mechanisms were considered:

Scoop
Backhoe
Clamping jaw
Conveyer driven scoops
180 degree scraping
Vacuum
Drum scoop
Bucket wheel excavator
Bottom mount scoop
Electromagnetic
Auger.

For the drivetrain/steering system, the following mechanisms were considered:

Tracks
4 legs
4 wheels/4 motors
6 wheels
3 wheels
4 wheels/2 motors
Multi-leg (centipede).

For the Storage/Dumping systems, the following mechanisms were considered:

Auger(s)
Dump truck bucket
Conveyor belt
Shovel/mechanical push
Drum scoop.

5.3 Concept Generation

With the domain knowledge gained from the trade studies, evaluation on the practicality of designs and the estimated weight to digging capacity of designs; a few main concepts were developed. The first was a conveyor digger/dumping system as seen in Figure 7. Concept 1 was attractive because it utilized an on-off control system and could be run very quickly to dig and dump. However, this concept has a lot of moving parts and the dual conveyors add weight. This design (or portions of it) have been used by many past competition teams.

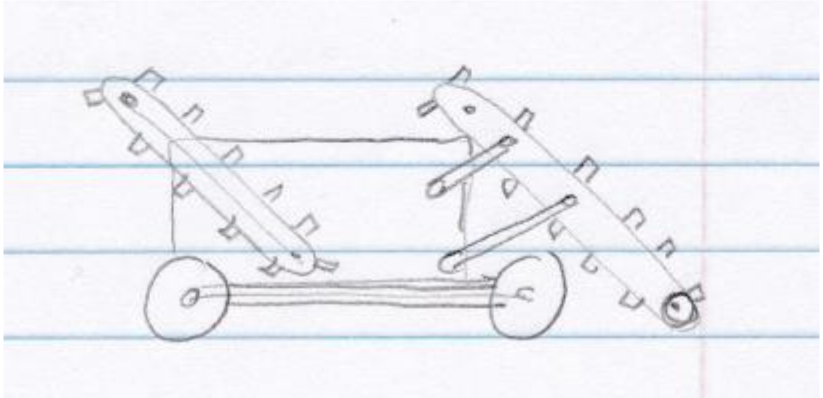


Figure 7: Concept 1 Dual Conveyor

Another concept was a bucket wheel connected to a conveyor with a dumping bucket as shown in Figure 8. Concept 2 used two strong scoop mechanisms that dumped onto lightweight conveyor in between to which transports the regolith to the bin. This design allowed for different motor sizes on the scoop wheels and conveyor which allowed for lower weight and faster digging. The dump bucket would be quick but transferred the center of gravity making the system less stable. Another issue was the complexity of the scoop and conveyor system.

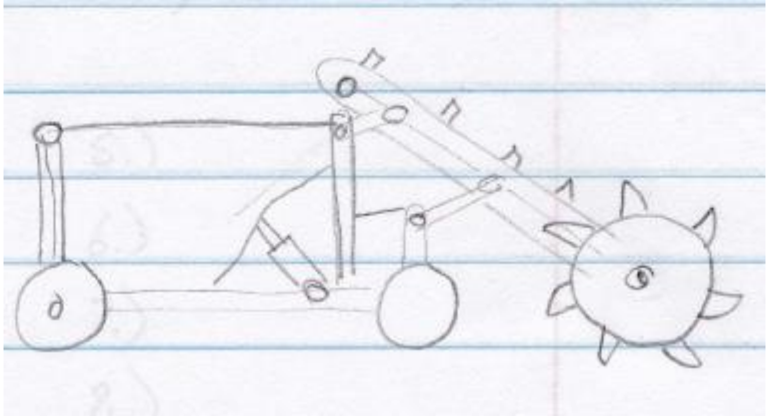


Figure 8: Concept 2 Bucket Scoop Conveyor Dump

A final concept was a digging device employing scoops on the wheel (Figure 9). Once the scoops dug up the dirt, the dirt would be channeled down a shoot into a bin and then an auger would deposit into the competition bin. This design cut down on possibility of the digging system not working. As two of the wheels would dig, if one were to jam the system could still work. A complication of this design was the fact that the device cannot excavate before reaching the mining area. A method to close off the shoot to the collection bin must be used to adhere to the rules. Likewise, the wheels would need to be strengthened adding some weight.

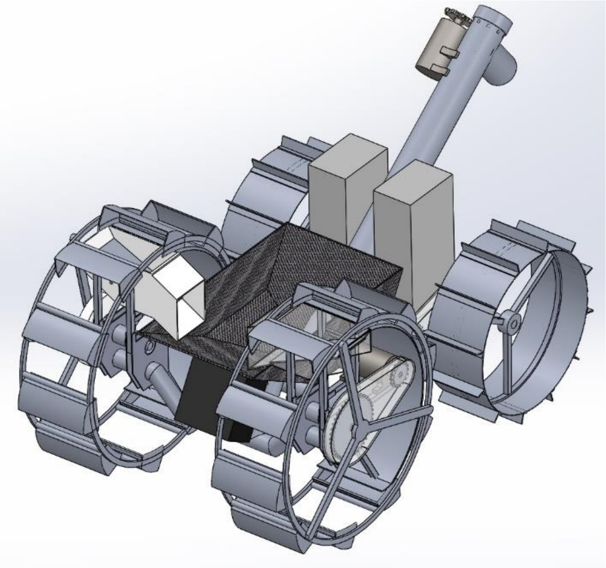


Figure 9: Concept 3 Wheel Digger to Auger

Given the digging ability, originality and robustness of the design; Concept 3 was chosen for further development. Several technical issues arose and thus were tested with prototypes. Concepts 1 and 2 were retained for a final leading concept determination after the preliminary testing on Concept 3 was finished.

5.4 Testing/Prototypes

In order to determine a leading concept, multiple tests were run. One test was conducted to determine what minimum angle was required for regolith to slide down an inclined plane. A prototype wheel/scoop assembly was created and tested as a proof of concept. This prototype also helped to optimize scoop geometry and power requirements. A third test was used to evaluate the effectiveness of an auger as a means of moving sand.

5.4.1 Slip Test

The Concept 3 utilized angled shoots to transport the BP-1 that was being collected from the wheels to the carrying bin. For this system to work properly the shoots needed to be at a large enough angle such that the BP-1 would side down. To determine this minimum angle, a slip test was done using sand as a BP-1 alternative. Damp and dry samples of sand were tested but it was determined that the difference was fairly negligible. In the dynamic tests, the wet samples tended to fall at very low angles so these results were thrown out. The density of both the damp and dry sands were both very near to 1400 kg/m^3. As the compacted BP-1 specification was close to this value, sand provided a reasonable approximation for this test. These samples of sand were tested on various plate materials under consideration for the shoots.

There were two main types of test carried out for every material. A static test where a volume of sand that was representative of the amount of BP-1 that one scoop should be able to gather was first placed in a linear fashion across the plate (much as the scoop would dump it) and then the material was slowly raised until almost all of the sand pile slid down. The second test was dynamic, where the material was held at some initial angle then a volume of sand was dropped down from a height representative of where the scoops would be dropping from, onto the material. The initial angle was adjusted until all the sand that was dropped would freely slide down the material. Figure 10 is representative of the two tests that were carried out. Results from the test are listed in Table 2.

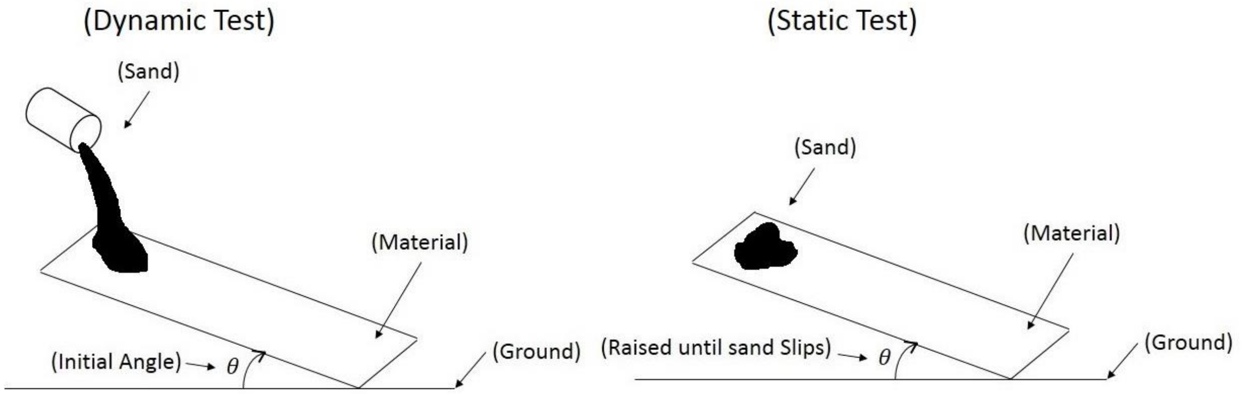


Figure 10: Slip Test

As can be seen in Table 2, the results from the slip angle tests showed that a minimum shoot angle of 30° to ensure that the BP-1 would flow freely. Smooth carbon fiber offers the best slip results. Thus, carbon fiber due to its light weight was chosen to be ideal.

Table 2: Slip Test Results

Test Type		Material				
		Carbon Fiber (Smooth)	Carbon Fiber (Rough)	Plastic	Steel	Aluminum
Static slip Angle (deg)	Damp	30	35	30	25	30
	Dry	25-30	35	30	25	30
Dynamic Slip Angle (deg)	Dry	20	30	25	25	25

5.4.2 Wheel Prototype and Scoop Test for the Digging Wheel

To determine the optimal scoop design and required torque to turn the digging wheels, a wheel prototype was built and set up to enable measurements of the torque required to turn the wheel when it was digging to be taken. The test was set up as seen in Figure 11. This configuration allowed us to place an analog torque wrench on the outer wheel axle and measure the torque as the wheel turned.

Figure 11: Wheel Torque Test

Tests were carried out using the prototype to simulate the wheel digging in order to evaluate how well the scoops were gathering sand. The tests helped determine the optimal entry angle and the height of the scoop above the wheel. For testing, weight was added to the wheel to simulate the weight of the robot that would be acting on it. From the CAD model, it was determined that the complete robot would weigh roughly 100 lbf, so it was estimated that each axle would see 25 lbf acting on it. This was accomplished by placing weight on the pivoting axle. Figure 12 shows the scoop design that was tested as well as the parameters that were varied.

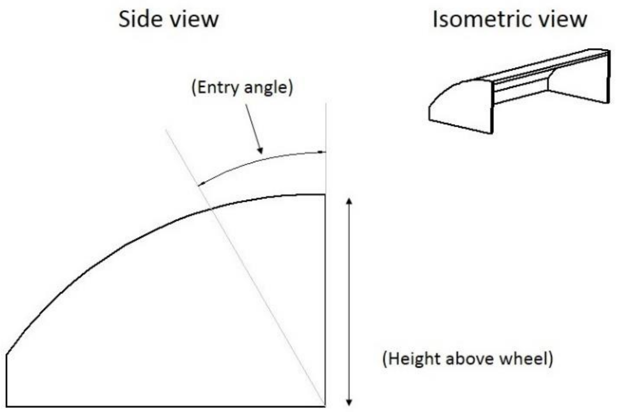


Figure 12: Scoop Design Testing

From the results it was determined that the height above the wheel played the biggest role in increasing the required torque to turn the wheel, and the entry angle played the dominating role in determining how much of the scoop was filled with sand. Table 3 summarizes the scoop designs that were tested and there results.

Table 3: Scoop Design Tests and Results

Scoop Design number	Height above the wheel [in]	Scoop entry angle [deg]	Weight added to wheel [lbs]	Amount of Sand Collected [% of scoop filled]	Torque required to turn wheel [ft-lbf]
1	2	0	25	Didn't Dig	4-5
2	2	10	25	60	12-14
3	1.25	0	10	Didn't Dig	3-5
4	1.25	30	10	100	5-7
4	1.25	30	25	100	5-7
4	1.25	30	50	100	5-7

After testing several configurations of height above the wheel and entry angles for the scoop, an entry angle of 30° and height above the wheel of 1 ¼ in. was found to be the optimal configuration for gathering dirt without requiring a ridiculous amount of torque to turn the wheel. The torque required to turn the scoop design that was chosen was measured to be 5-7 ft-lbf. This torque was used to size the electric drive motors for the digging wheels.

5.4.3 Auger Concept Validation

From the trade study, information found on UND's 2010 auger based system proved it was possible to move an extensive amount of sand using an auger. A helicoid was tested to further prove the validity of the concept. The helicoid was tested using wet sand to determine the general effectiveness of an auger at transporting particulate. The helicoid was a 2.5” outer diameter, 1.5” inner diameter, standard pitch (outer diameter = thread pitch) center-less auger with a helical angle of 22°. A 2 HP motor was used to turn the shaft at 348 RPM with 30 ft-lbs of torque provided to the screw. Since the goal of the tests was to determine the effectiveness of an auger at moving particulate, this helicoid was tested while oriented horizontally, as can be seen in Figure 13.

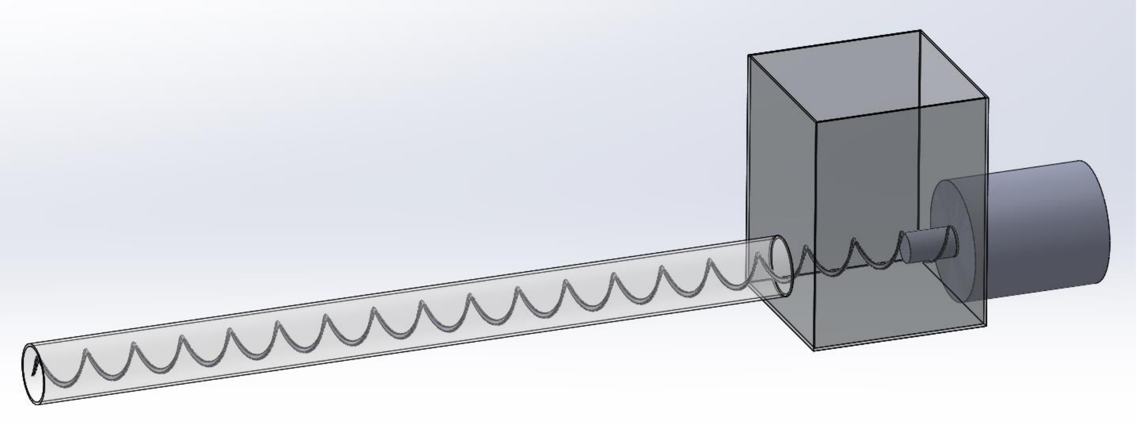


Figure 13: Auger Test Setup

Like in many of the other tests, wet sand was chosen as it has a similar density to packed BP-1 and its tendency to clump makes it a worst case scenario. It is important to note that the auger used in the test was not optimized for what is going to be used on the robot as it had a hollow core. This hollow core allowed particulate to fall out of the threads and not move as quickly down the length of the auger. Figure 14 shows this happening during testing. Testing revealed that the particular auger that was tested was able to move 7.9 kg of sand in 52 seconds. From the trade study and testing, it was concluded that the auger design could accomplish the task of moving the regolith in an accurate and timely manner.

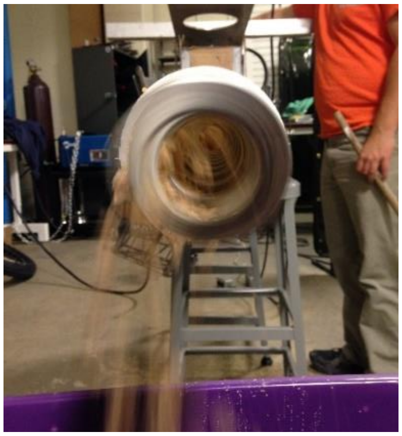


Figure 14: Sand Falling Out of Auger Threads During Testing

5.5 Leading Concept

Using the decision matrix seen below Table 4, the wheeled digging device was chosen as the leading concept. This device will have the ability to be easily controlled autonomously as every system can be controlled with a simple on/off controller.

Table 4: Decision Matrix

	Weight (- high)	Digging Capacity	Manuverability	Ease of Use	Manufactorability	Dust Generation	Originality	Total
Concept 1: Dual Conveyor	-	+	0	+	0	+	-	1
Concept 2: Bucket Scoop Conveyor	-	0	0	0	0	+	0	0
Concept 3: Wheel Digger to Auger	0	0	+	+	-	0	+	2
Exsisting Design: Front End Digger	+	-	-	-	+	+	-	-1

Rank	Points
-	-1
0	0
+	1

As well, the wheel based digging design has not yet been seen in the NASA competition so it will help to win the ingenuity award. This design was proven to be feasible through the testing and prototypes built as can be seen in Section 7.

A 3D model of the design has been made using SolidWorks; a Computer Aided Design (CAD) software. The design has been split into separate design groups for further definition of the wheel/digging device, the storage/dumping device and the electrical/motor components. The sensor and communications subsystems are in the process of being designed to such a point that a non-autonomous prototype can be tested by the end of the summer.

6.0 Post Concept Review Simulation/Calculations

After the concepts review, further development of the wheel based digging/auger dump setup was done to find an optimum design. Once clarification on the excavation rule (Appendix C) was received from NASA, design continued as such.

6.1 Virtual Test Run

After the concepts review, a virtual test run was developed to determine the capabilities of the robot. Through watching of past competition runs and determining the maximum speed allowed by the wheel motors, it was decided that the top speed for the robot should be set at 1 mph. The simulated run can be seen in Figure 15.

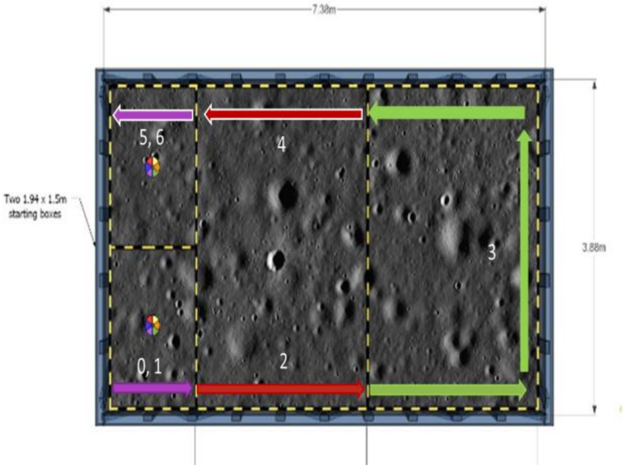


Figure 15: Virtual Competition Run

The following input parameters:

10 sec orient (0)
1 mph start(1)
(0.447 meters/sec)
0.25 mph (2)
0.25 mph (3)
0.1875 mph (4)
0.75 mph (5)
15 sec align (6.1)
Dump (6.2)
Scoop Efficiency 0.5
BP-1 density 750 kg/ m^3

Led to the determination of the following:

Volume of BP-1 Collected = 0.037 m^3
Mass of BP-1 Collected = 27.57 kg
Mass of BP-1 per scoop = 0.478 kg
Dig Time = 1.441 min
Travel time = 1.570 min
Max allowable dump time = 6.99 min

Seeing that the maximum allowable dump time was 7 minutes, it was determined that an analysis of the auger would be beneficial. Ideally, the goal was to find out if the dumping could be done in two minutes to provide time for another run.

The other main outcome from this simulated run was the realization that the design's limiting factor was the bin size. Relying solely on the stationary bin with 30 degree angle, the bin developed in the conceptual stage was slightly more than half the size of what was expected to be gathered. The full MATLAB code for the test run can be seen in Appendix D.

6.2 Auger Simulation

After the virtual test run data was compiled, an auger simulation was set up to determine the torque and RPM requirements needed to dump the amount of regolith in the bin in 2 minutes. Using auger volume and the number of turns in the auger, the amount of turns of the screw conveyor necessary to withdraw all of the regolith from the bin and into the collector bucket was determined. Since the sprocket ratio was known from the old robot's hardware, a calculation was done to find the rpm required to dump in 2 minutes. To find motor torque required, the potential energy stored in the total mass of regolith gave an energy number with a unit of Joules. The rate at which the energy is transmitted through the motor determines the power requirement of the motor. In order to find torque from that, the standard equation relating power, torque, and rpm was used. All equations used can be found in Appendix E. Friction observed by the motor was not included in the auger simulation. To compensate, a factor of safety was added to the motor torque and rpm to ensure it can overcome any friction restraints. The determined value of the rpm needed to completely empty the bin in 2 minutes was 80 rpm, and the torque necessary was low.

6.3 Horizontal Auger Simulation

Once it was determined that the dumping auger could deposit over the amount of the full bin in less than two minutes at a reasonable RPM and torque, the notion was brought up to flatten out the sloped sides of the bin in order to increase volume. However, if the slopes were to be removed, some sort of conveyor system would be needed to transport regolith from the back of the bin to the front. Therefore, it was decided to put a horizontal auger inside the bin to move the collected BP-1 to the dumping auger. This concept would allow for a much larger bin. A calculation (very similar to the other auger calculation) was done to determine the feasibility as well. A complete listing of the code used can be seen in Appendix F.

7.0 Subsystem Design

Further subsystem design was enabled with the post-Concepts Review simulation and calculations. Corporation 12's design structure was maintained from the Concepts Review stage and the newly added members from Corporation 4 were divided into the wheel/digging, storage/dumping and electrical/motor subsystems. David Faucett continued to be lead on the wheel/digging and chassis subsystems. Stewart Boyd continued to be lead of the storage/dumping subsystem. Will Flournoy was appointed to be the lead electrical/motor designer.

7.1 Wheels/Digging

To reduce weight, mechanical complexity and driving components; a decision was made to combine the digging and propulsion systems. This dual system allows the regolith to be gathered by the wheels while also allowing the robot to move. This was accomplished by having scoops attached to the exterior of the wheels. As the wheels rotate, regolith will be picked up, carried to the top of the wheel and then deposited into a chute that leads to the carrying bin. The complete wheel concept is shown in Figure 16 and an exploded view with the main components labeled is shown in Figure 17.

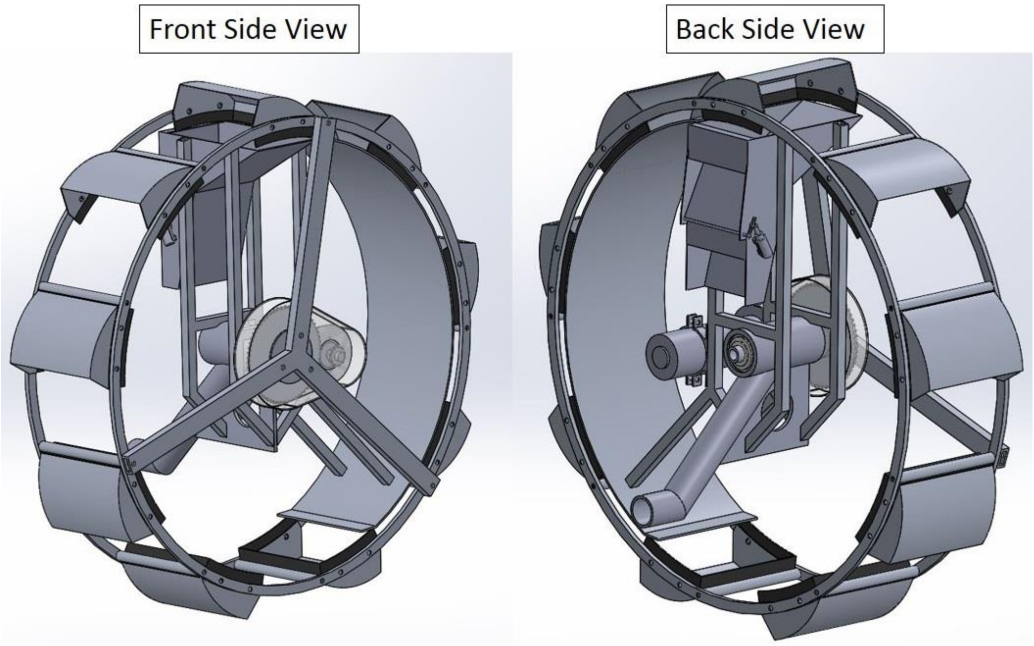


Figure 16: Wheel Concept

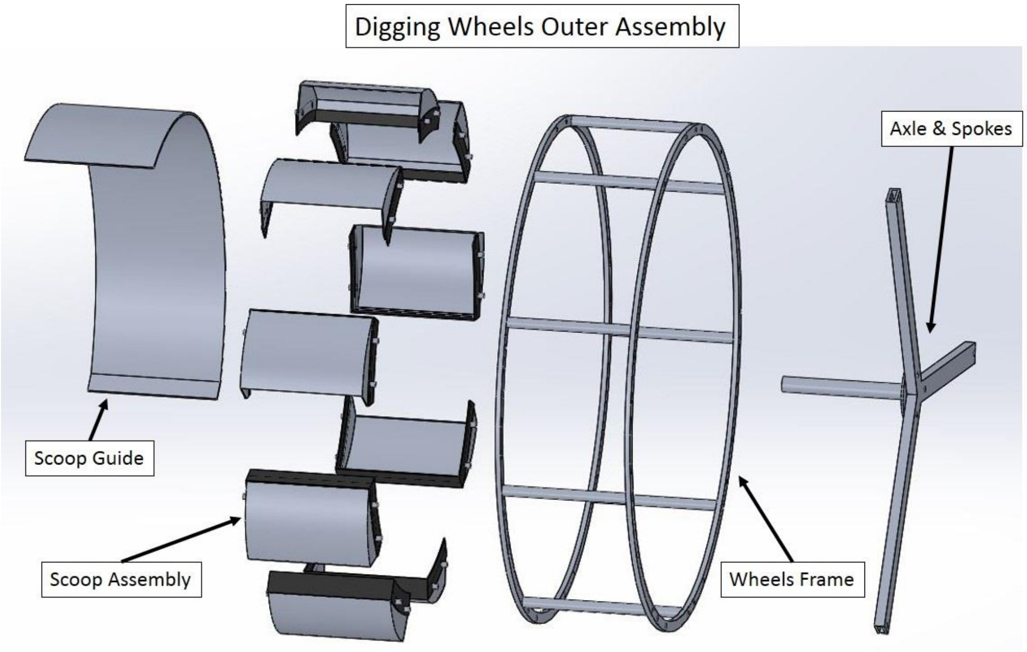


Figure 17: Exploded Wheel View

A chute was placed at the top of the wheel with a solenoid induced plate that can pivot between two positions to control whether or not the regolith is harvested. When the door is in the closed position, the BP-1 that is gathered by the wheels and deposited into the chute is routed into the lower portion of the chute that leads back to ground. The lower portion's purpose is to contain the BP-1 as it is routed back to ground to minimize dust generation. The solenoid controls whether the regolith is being deposited into the bin or back to the environment. This is shown in Figure 18.

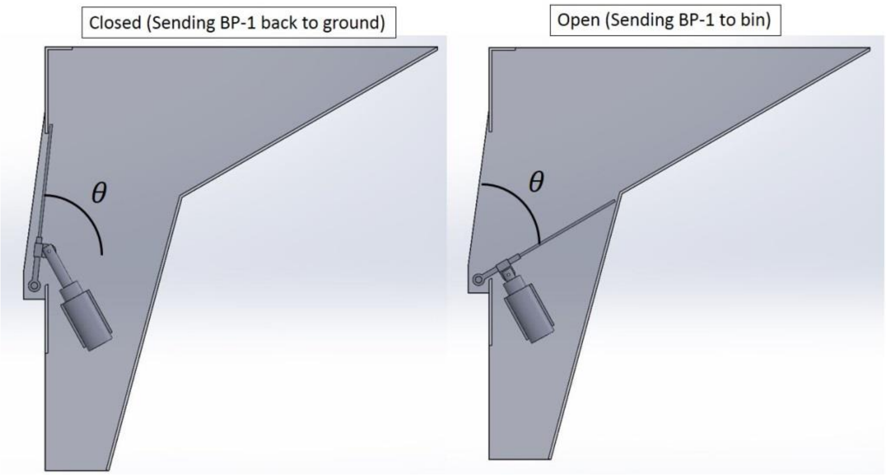


Figure 18: Shoot Concept

The wheel is driven by a single electric motor mounted to the inside of the wheel's fixed frame and attached to the drive axle through a chain and sprocket. The complete inner wheel hub assembly is shown with labeled components in Figure 19.

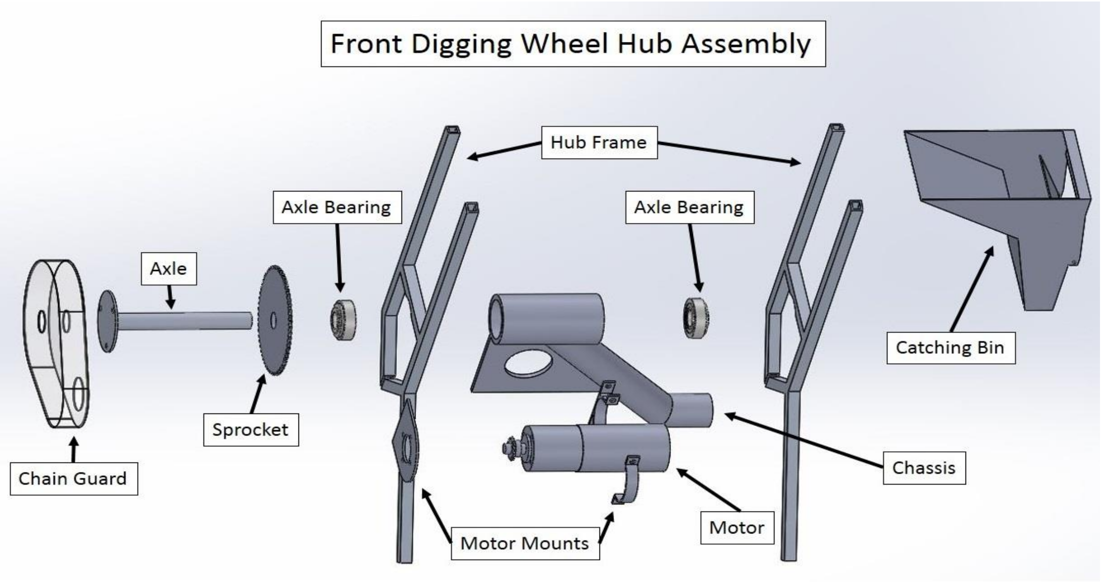


Figure 19: Motor Mount Concept

To keep the chain and sprockets from being contaminated with regolith, a guard was designed to enclose the chain and sprocket system. This has been shown in Figure 19.

Jamming concerns became an issue with the way the scoops slid on the guide as the BP-1 was carried to the top of the wheel. In order to minimize the amount of BP-1 that was lost during this process a rubber guard was implemented on the underside of the scoop. This would also allow excess BP-1 or rocks that were gathered from the scoop a way to squeeze under the scoop and fall back to the ground without causing the wheel to jam. This is shown in Figure 20.

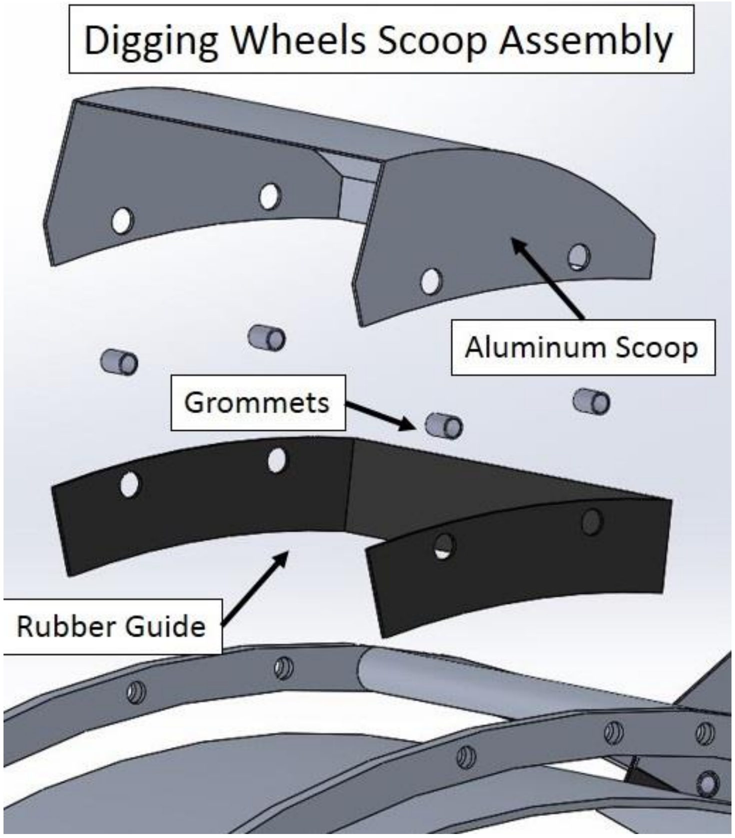


Figure 20: Scoop Design

The primary function of the rear wheels is to aid in the propulsion of the robot. As shown in Figure 21, the center of the driving wheels consists of a lightweight hub, while the outer tread provides the robot with additional traction.

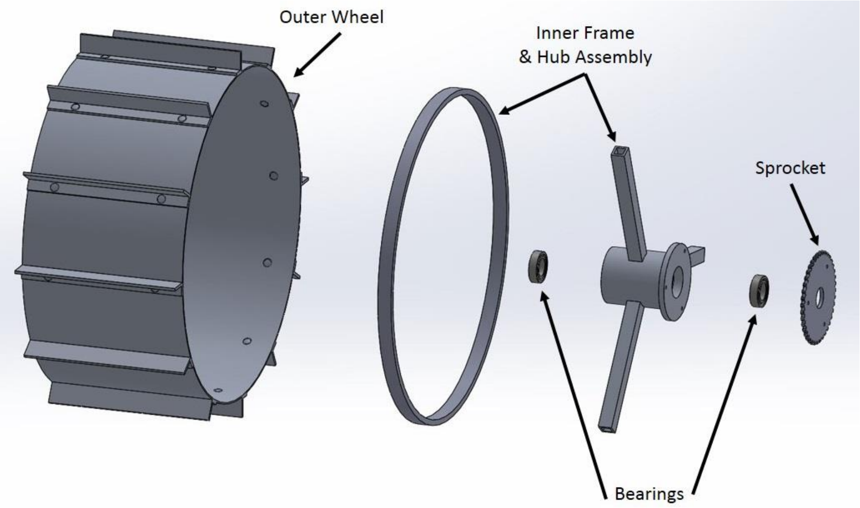


Figure 21: Exploded Driving Wheel View

7.2 Storage/Dumping

Previous designs from the trade study and data collected from the tests were taken into account when designing the storage and dumping system. Many teams that employed a dump truck approach to store and dump the regolith had problems with tipping over either while transporting the regolith or attempting to dump it into the target bin. The dump truck approach also led to teams, despite managing to successfully raise the bin, missing the target bin either partially or completely. Furthermore, it was decided that the number of individual moving parts required to operate the dumping mechanism needed to be kept at a minimum. Therefore, the design with a stationary storage bin utilizing an auger conveyor system was selected as shown in Figure 22. The stationary bin ensures that the center of gravity of the robotic miner remains relatively unchanged during mining, traveling, and dumping operations. The auger conveyor system minimizes the risk of missing the target bin as well as cuts down on the number of moving parts needed to operate the robotic miner.

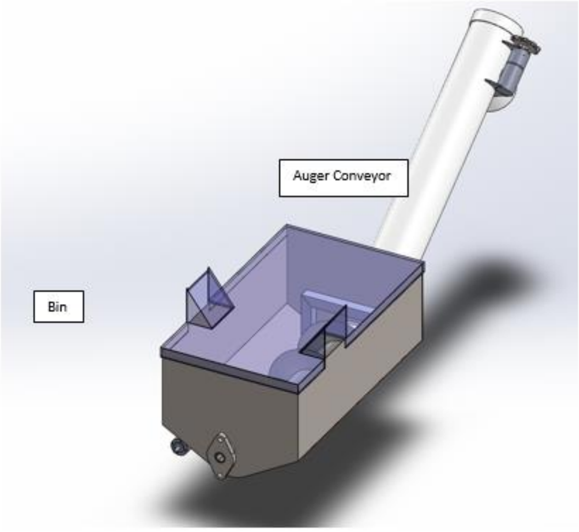


Figure 22: Storage/Dumping Assembly

The bin features a horizontal auger system in order to move all the regolith from the back portions of the bin to the front with relative ease. The estimated volume of the bin is 33,400 cubic centimeters, with a connection on one side to the diagonal auger. The horizontal auger has a 5 5/8" outer diameter and is 20 inches in length. It is attached to the bin with brackets and fasteners. A plastic top is attached to the top of the bin in order to prevent dust creation, with openings where the regolith will fall into the bin without creating dust.

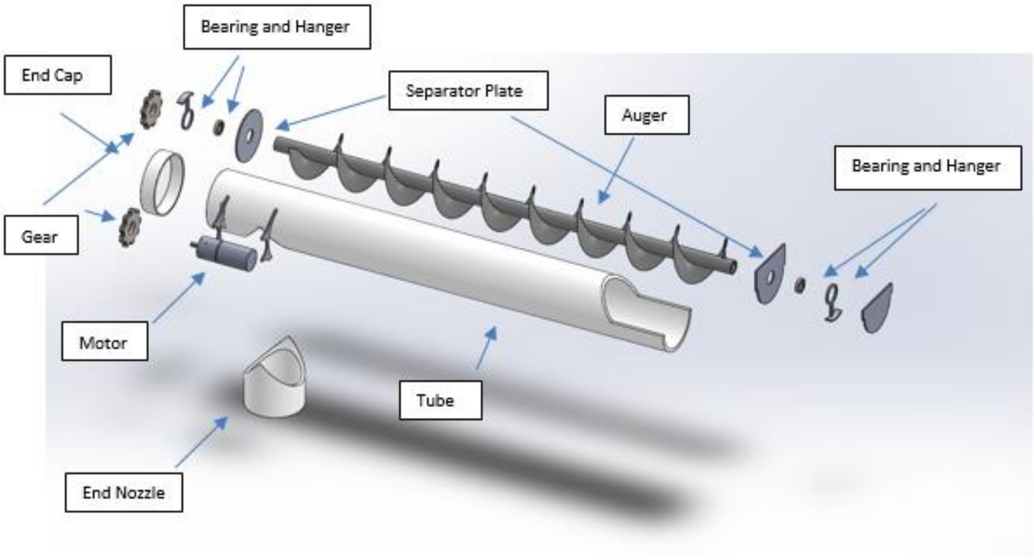


Figure 23: Auger Conveyor Subsystem

The auger conveyor subsystem will consist of a large screw encased in a tube that will be slightly larger than the thread diameter of the screw. Regolith will be lifted towards the target bin as it fills the intake and the auger is turned. As can be seen from Figure 23**,** the screw will be supported by two hangers and bearings at the ends of the auger. These bearings are protected from dust. A gear will be mounted to the center axle of the auger just past the final hanger and bearing. This gear will in turn be driven by an electric motor mounted on the outside of the tube. The auger has a diameter of 4” and is held at an angle of approximately 35 degrees, which gives it an efficiency of 65%. Auger systems that match the dimensions for both augers can be bought from Lindell Plastics as shown in the Bill of Materials.

7.3 Motor

The selection of motors for the NASA mining robot is broken down into two subsystems: the drive subsystem and the auger subsystem. The drive system will be discussed first. A calculated torque of roughly 7 ft-lbs was determined from the wheel prototype test to be the minimum amount of torque required for each drive motor. The IG52-04 24VDC 010 RPM Gear Motor was selected to be used as the motor for all four wheels (Appendix G). This motor is a brushed permanent magnet DC motor with variable speeds and reversibility. The motors have a mass of 1.80 kg each. These motors come with micro-gearing with a ratio of 1:43 and will be further geared using sprockets. The digging wheels will have a sprocket reduction ratio of 1:5 and the rear wheels will have a sprocket reduction ratio of 1:2.5. Using a torque and speed calculator that was offered by the motor manufacturer, the max speed was determined to be 1.17 mph and the total driveshaft torque was calculated to be 11.93 ft-lb. This calculated total output torque offers a factor of safety of 1.7. To further ensure the motors are sized correctly, the motors from the existing robot which offer lower outputs than the new motors will be implemented and tested first before ordering the new motors. Regarding the auger subsystem, the IG52-04 24VDC 285 RPM Gear Motor was selected for both the angled and horizontal auger as well (Appendix G). This motor is a brushed permanent magnet DC motor with variable speeds and reversibility. The motors have a mass of 1.80 kg each. The motors are manufactured with micro-gearing with a ratio of 1:12. The motors will have a sprocket reduction ratio of 1:5. The sprocket reduction ratio can be easily changed if the output requirements change. From the virtual run analysis, a required torque of roughly 0.20 ft-lb and 80 RPM was determined to be the minimum requirements for the vertical auger motors.

7.4 Power Consumption

The power consumption was broken into two different systems. First is the mechanical system which consists of the drive motors and the auger motors, and the second is the electrical system. The power consumed was found by:

$$Power\ consumed\ (W) = V(V) * I(A)$$

For the mechanical system the current for each motor was found to be linearly increasing with increasing torque, as seen on the graph in Appendixes F, G. Therefore the current for the motors was estimated to be:

$$I_{driving} = 5\ (A)$$

$$I_{auger} = 3.25\ (A)$$

These values were determined from the estimated consistent torque the motors are going to see. Since all the motors are 24 V motors then the power consumed by the mechanical system was found to be:

$$Power\ consumed_{driving}\ = 24\ (V) * 5(A) = 120\ (W)$$

$$Power\ Consumed_{auger} = 24\ (V) * 3.25\ (A) = 78\ (W)$$

Therefore:

$$Total\ Power = 4 * 120 + 2 * 78 = 636\ (W)$$

The power consumed for the electrical system was negligible compared to the motors.

7.5 Power Supply

Two 25.6 V LiFePO4 batteries were selected (Appendix H). These batteries were chosen because of their light weight and large amount of power. If the motors are all running in parallel then the estimated current being pulled from the battery is about 25 A. The battery can sustain this supply for about 24 minutes (Appendix H). Since the current was estimated on a desired consistent torque seen by the motors, if one motor increases torque, then the current will also increase. Due to this two batteries running in parallel was found to be better because it provides a factor of safety of two for the mechanical system.

A separate 12V battery will be used for the electrical system but due to not knowing all the electrical components that will be used in the final design, a specific battery has not been selected yet. The full design with integrated electronics can be seen in Figure 24.

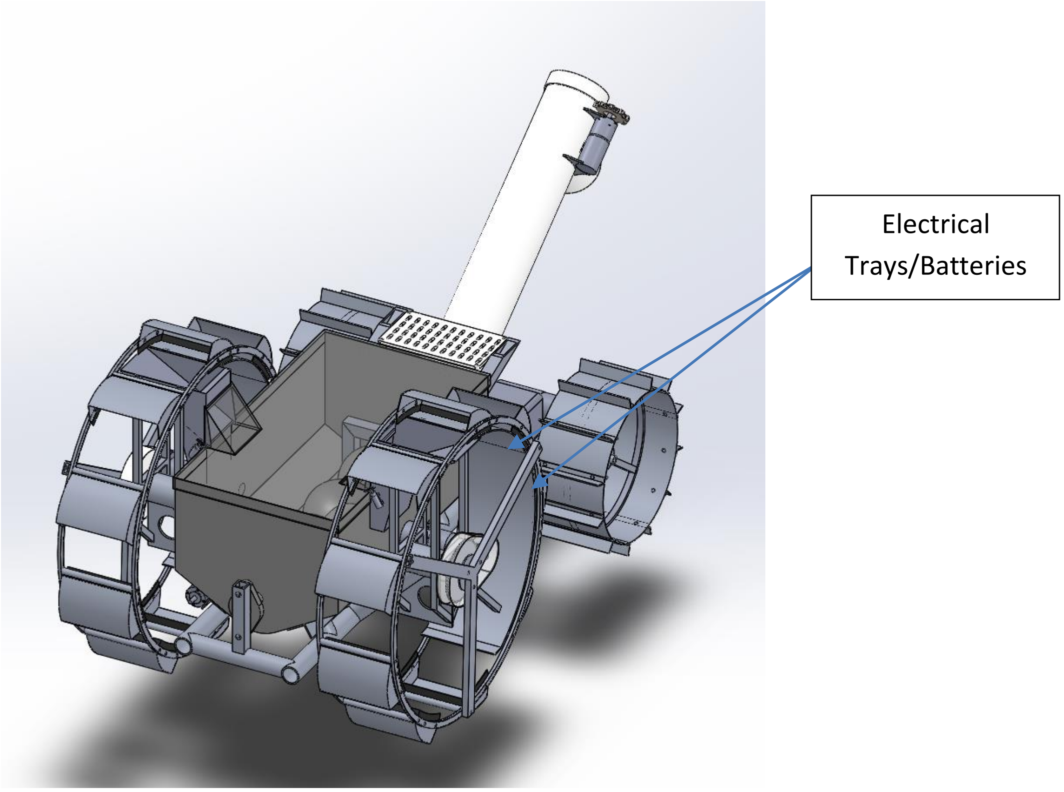


Figure 24: Full System with Electrical Components

7.6 Electrical/Controls

The team's goal for the end of the summer semester was to control the mining robot prototype with a remote control. Controlling the robot with a remote control entailed the use of a microcontroller, the appropriate DC motor drivers, a computer to compile code on, and a means of communicating the remote control commands to the microcontroller. It is assumed that all of the choices made in these areas may, and probably will, change as the incoming electrical/computer team works to incorporate autonomous operation.

In that regard, the intention of operating the robot completely autonomously will ultimately decide which microcontrollers and computer are used to interface with the robot's sensors. Sensors for the robot's autonomy have yet to be specified due to needed input from the electrical/computer group. Currently, the team has considered the use of lidar and radar for the robot's mapping and localization tasks. Per the 2014 NASA Robotics Mining Competition rules (Appendix B), a navigation aid system, not exceeding 9 kg in mass and self-powered, can be attached to the collection bin for navigating the rover. The following, rule 15 from the "On-Site Mining Category Rules," is provided below:

> “15) *The Collector Bin top edge will be placed so that it is adjacent to the side walls of the Caterpillar Mining Arena without a gap and the height will be approximately 0.5 meter from the top of the BP-1 surface directly below it. The Collector bin top opening will be 1.65 meters long and .48 meters wide. See Diagrams 1 –3. A target(s) or beacon(s) may be attached to the Collector Bin for navigation purposes only. This navigational aid system must be attached during the setup time and removed afterwards during the removal time period. If attached to the Collector Bin, it must not exceed the width of the Collector Bin and it must not weigh over 9 kg. The mass of the navigational aid system is included in the maximum mining robot mass limit of 80.0 kg and must be self-powered. The target/beacon may send a signal or light beam but lasers are not allowed for safety reasons except for Visible Class I or II lasers or low power lasers and laser based detection systems. Supporting documentation from the laser instrumentation vendor must be given to the inspection judge for “eye-safe” lasers. The Judges will inspect and verify that all laser devices are a class I or II product and they have not been modified (optics or power). Any objects placed on the Collector Bin cannot be more than 0.75 m above the BP-1 surface, and cannot be permanently attached or cause alterations (i.e. no drilling, nails, etc.).”*

Considering these parameters, a primary microcontroller and some supporting motor drivers were selected to control the currently specified motors.

When considering a microcontroller, it is mandatory to first analyze the motors and actuators that need to be controlled. Currently, only the DC motors for the two augers and four wheels have been selected. Initially, it was believed that the rover’s 6 separate DC motors would require at least 6 pulse-width modulation pins on the microcontroller to control them bi-directionally. However, research conducted by Cy Scott proved that a serial communication line would be easier to implement with the adopted motor drivers that will be powering the motors. The microcontroller should also provide enough inputs to accommodate the encoders on the motors, as well as the aforementioned sensors. Considering these parameters, the Arduino Mega 2560 rev3 microcontroller board was chosen. The Arduino platform of microcontrollers has intensive documentation online, and are by far the most widely used and supported microcontrollers on the market. And with the vast amount of Arduino code libraries available online, the selection of an Arduino microcontroller allowed the team to get started faster and more efficiently. Arduino boards also have a wide variety of compatible shields (hardware interfaces) already available for purchase.

The Arduino Mega 2560 rev3 is a new model of microcontroller from Arduino which offers the same amount of I/O pins as the old Mega, which was used on the previous NASA Robotics rover, yet couples this functionality with a 32-bit ARM core microcontroller. The Mega is based on the ATmega 2560 CPU, which makes this microcontroller powerful enough to implement memory intensive tasks with the motors. One important note: the Mega operates on 5V, unlike some Arduino models which operate on 3.3V. The board itself is presented below in Figure 25.

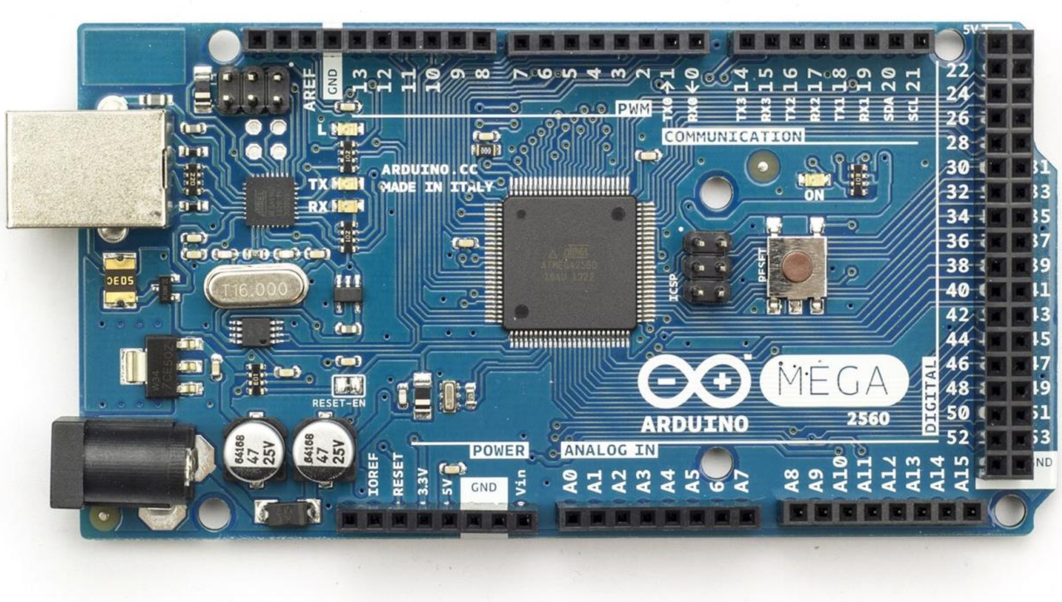


Figure 25: Arduino Mega 2560 Microcontroller

The following specs are provided from Arduino:

Microcontroller	ATmega2560
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	54 (of which 14 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	256 KB of which 8 KB used by bootloader
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz

Motor drivers are an integral piece to powering and controlling the motors. Given that all of the motors operate on 24VDC and up to 5 A, motor drivers were selected. The motor drivers selected are the Sabertooth 2 x 25 used from the previous robot. Each of the three Sabertooth drivers can control 2 motors. They are compatible with motors rated up to 24V. The driver itself is presented below in Figure 26.

Figure 26: Sabertooth 2 x 25 Motor Driver

Because the motors/actuators for controlling the trap door on the shoot have not been specified, a motor driver had not been selected for them. Currently, the team is considering using either stepper motors or servomotors to actuate the trap doors, in which case one Adafruit Motor Shield V2 or another Sabertooth driver could be used to control both of the motors.

A PlayStation 2 controller is being used for testing because to its ability to wirelessly sync up to the Arduino. PS2 controller is interfaced to the Arduino board through a simple shield that connects the controller to pins 10 – 13 on the Arduino via an analog signal. Once the electrical team begins working on the design, a completely different way of controlling the robot is expected to be implemented.

7.7 Specific Changes from CDR

At the CDR, a few issues were discussed and then modified before building. These changes are discussed on the next page. The final excavator assembly CAD with the changes discussed during the CDR is shown in Figure 27.

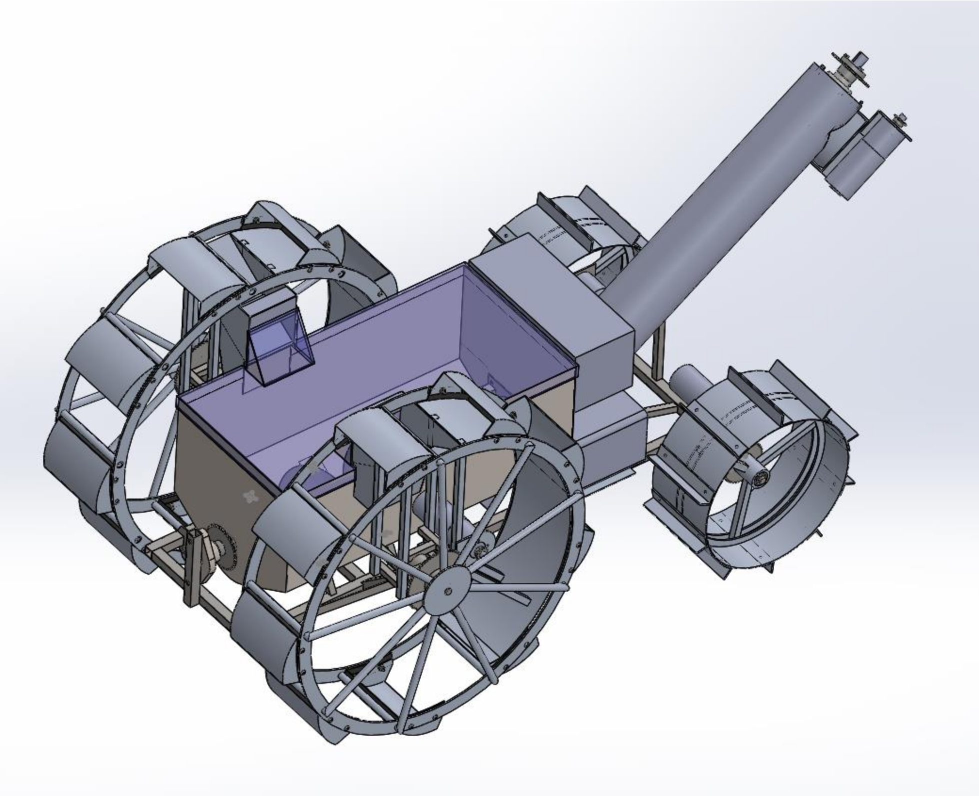


Figure 27: Final CAD Design

7.7.1 Chassis

The primary change from the CDR was the change from 1.50 in OD aluminum tube for the frame to 0.75 in square steel tube. This change allowed for easier manufacturability with negligible change in weight. This change allowed for better weldability between the chassis components and required less fitting of tubes. It also made measuring much easier. Figure 28 shows the redesigned chassis.

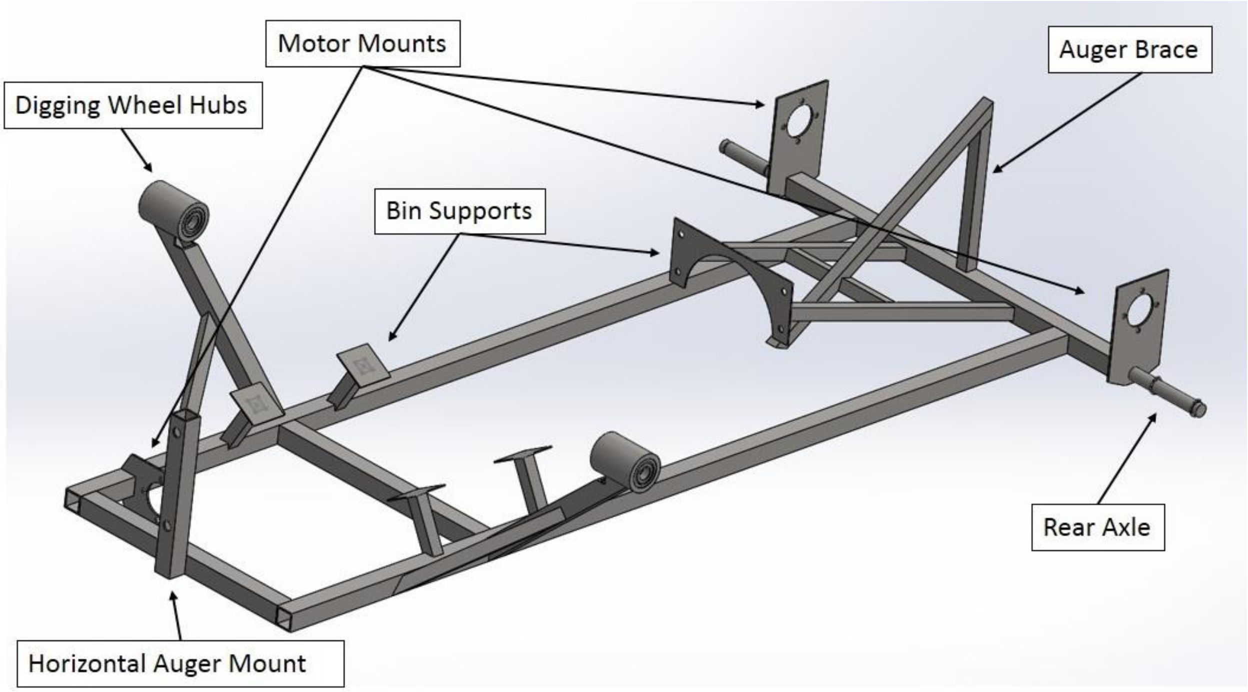


Figure 28: Redesigned Chassis

7.7.2 Vertical Auger

The vertical auger cap was determined to be unnecessary due to the separator plate so it was removed to save weight. Also to get the desired 1/16th inch auger clearance, a carbon fiber tube was selected to replace the PVC pipe. This change also helped save weight and allowed for a smooth transition between the bin and tube. Figure 29 show the redesigned auger end that was created after the CDR.

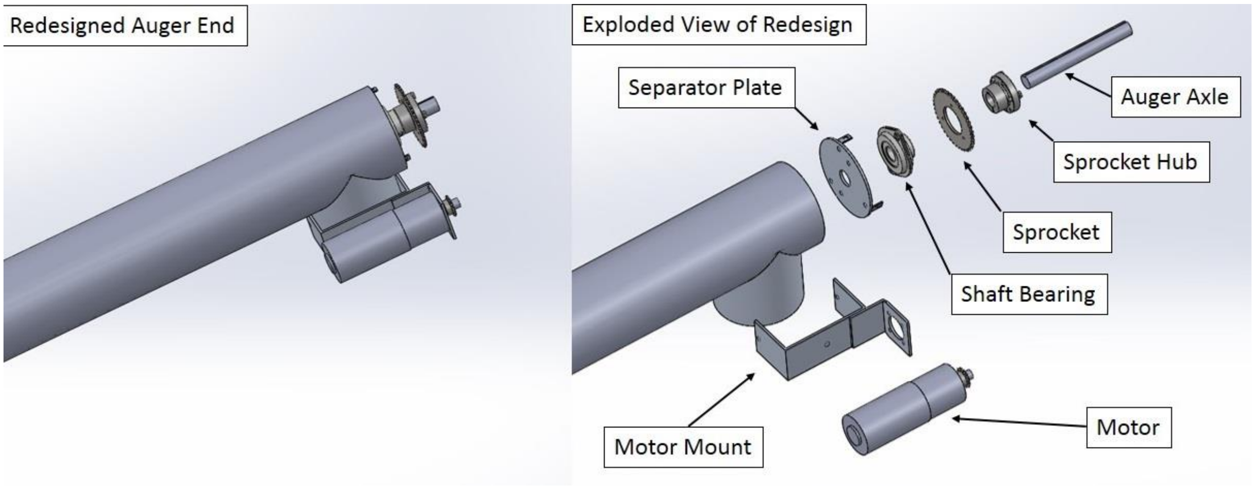


Figure 29: Redesigned Auger

7.7.3 Motor Mounts

The vertical auger motor mount was a concern at the CDR. Thus, it was significantly strengthened. As well, the distance between the motor and drive shaft sprockets was reduced. Additionally, all the motor mounts were slotted to allow for tensioning of the chain and adjustability to different sprocket sizes in the future. The current sprockets were scavenged from the old robot.

7.7.4 Electrical

The final electrical wiring was finalized after the CDR and involves a relay, a fuse protector, a single DC switch, an emergency stop, 3 Sabertooth drivers, and the Arduino package, which includes the aforementioned Arduino Mega2560, the Adafruit Proto-Screwshield, and the Dexter Industries PS2 interface shield. It should be noted that Dr. Roppel was a crucial player in designing and shaping the electrical portion the robot. His lab was used for soldering the Arduiino shields and it was under his guidance that the electronics were wired correctly. The electrical box was constructed from clear acrylic plastic and a Vex Robotics aluminum build kit. As per design, the wiring into and out of the electrical enclosure was fitted with quick disconnects so that the entire electrical/computing box could be removed if work were required. The enclosure is shown below in Figure 30.

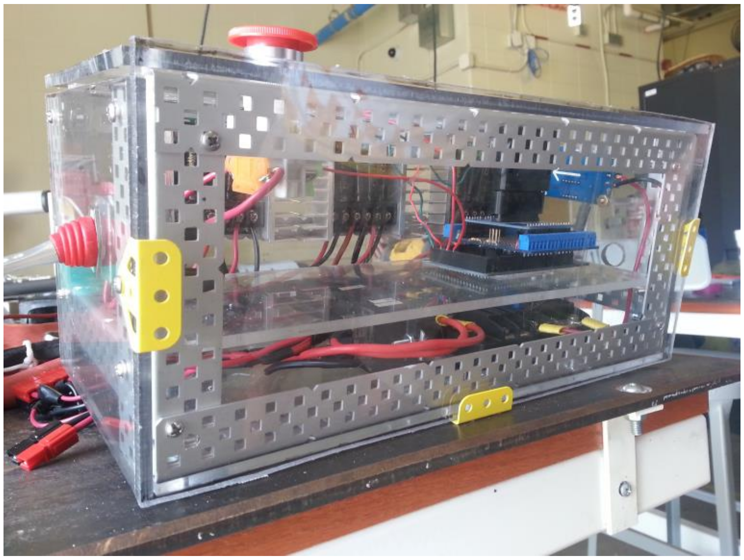


Figure 30: Electrical enclosure

8.0 Prototype Build

For the build process, the team was divided up into sub-teams. Once the subsystems got close to completion, the team came back together to assure all interfaces were properly constructed and that the subsystems worked as needed.

8.1 Chassis

As the chassis provides the central interface between all of the other subsystems, special attention was taken to make sure that it was manufactured as closely as possible to the design. Corresponding tubes were milled flat simultaneously to ensure that the tubes were the same length. Great care was also taken to ensure that components were held squarely during and after welding. Also, an adjustable jigging feature with spacers was created to ensure that the front wheel hubs were held level, square and in the correct location for welding as shown in Figure 31.

Figure 31: Chassis with Hub Alignment Fixture

Since the front motor mounts as designed were part of the inner wheel structure, a temporary way was needed to attach them. Thus, the aluminum channel from the old robot was used. The duel channel setup helps to support the motor and minimize any twisting. This mount required no permanent additions to the robot so it can be easily removed and the wheel can be built as designed. This mount can be seen in Figure 32.

Figure 32: Duel Channel Motor Mount

8.2 Bin

The team worked with Jeff Thompson in Poly-Fi to develop a method to vacuum bag the bin (Figure 33). Plywood ribs were cut out in the shape of the bin as specified by the design. These ribs were then attached to each other and a thin sheet metal was draped over it. The ends were then sealed off and the bin was laid up with 4 layers of carbon fiber. After the bin had been set up, the holes were cut into it.

Figure 33: Vacuum Bagging the Bin

8.3 Prototype Auger Test

A prototype vertical auger subassembly was created to determine if the IG52 motor was sufficient to move sand. When it was shown to be feasible, the draw from the motor was tested. The result confirmed the MATLAB simulations discussed earlier were fairly accurate. Exact details of the test were not recorded as the setup was not finalized and the tube did not have the needed clearance volume. More details of the final tube will be discussed in the testing section.

8.4 Augers

The vertical auger tube was made by using a 4.0 in ID PVC tube which was used as a mandrel. This tube was filled with expanding foam to increase its rigidity. Then, layers of unimpregnated carbon fiber were wrapped around it under the desired 4.125 in diameter was obtained. At this point, the actual tube was made on the mandrel using 4 layers of carbon fiber. Once the tube had set up, the tube was cut according to the design.

The top chute was then attached by using a 2 part epoxy and a wet lay of carbon fiber. The same process was used to attach the tube to the bin. In order to position the tube in the correct location in respect to the bin, measurements were made to ensure that the tube would clear the collection bin while still staying within the required length and height requirements. This process is shown in Figure 34.

Figure 34: Attaching the Auger Tube to the Bin

8.5 Wheels

Due to the time constraints, the wheels in the design were unable to be built. The rear wheels were designed to be 12 inches in diameter. The old Auburn robot had 11 inch wheels which were sufficient for testing and validation. The front wheels were designed to be 24 inches in diameter. Bicycle rims of 22in diameter were used on the front. A picture of the robot with the wheels attached can be seen in Figure 35 below.

Figure 35: Prototype with Wheels

9.0 Interfaces

The chassis to bin interfaces were of particular importance to the build to ensure that rigidity of the bin/auger as well as strengthening the whole robot in general. The bin itself is held by four bolts at the bottom which attach to the chassis via risers. The horizontal auger is mounted through the bin to the chassis to remove extra stress to the bin.

The interface between the bin and vertical auger tube was attached as discussed in the Prototype Section. The horizontal tube is also supported by a triangulated tube arrangement on the chassis to reduce the stresses on the tube.

The electrical box was created in such a way to create a compact enclosed space for the prototype electronics. The motor drivers were attached in back to get them as far away as possible from the Arduino board. The box was also large enough to provide for storage of the play station controller when not in use. If desired, enough room is available to install a filter and fan on the box at a later date if desired.

Future design/competitions teams should take the aforementioned interfaces into account. As well, the interface between the wheel design and the storage bin is critical to the functionality of the robot's design. Other interfaces of interest will be the new electrical and communications systems. Special attention must be taken to keep these areas dust free.

10.0 Testing

Auger and electronic testing were done to provide the following design team with a starting point. Each of these subsystem tests will be discussed below.

10.1 Auger testing

Initial testing of the augers was done by hooking up each to a power supply and spinning it to make sure that the auger spun freely. Once each auger was shown to spin without problems, both were hooked up to separate power supplies and sand was run through them (Figure 36). This initial test showed that the horizontal auger gear reduction was not sufficient to turn the auger when sand covered it. As well, it was noted that if the horizontal auger was spun at a faster rate than the vertical auger, sand packed the vertical auger stalling it. Both augers stalled at approximately 5 Amps at 24 volts. Both augers had more than enough speed. Thus, the conclusion of this test was that the concept was working but that the gear reduction (especially that of the horizontal auger) needed to be increased.

Figure 36: Auger Testing with Sand

10.2 Electronic Testing

The electronic box was initially tested separate from the robot. First, the box was connected to the 24V batteries. The output from the digital display on the Drok voltage regulator was compared to the multimeter to ensure the correct voltage was being read.

Next, the Arduino board was wired to one of the Sabertooth drivers. The Arduino was also connected to the computer for inputting code and power. The power was supplied by the computer at this point to make sure that no potential issues in the box could damage the Arduino. One of the motors was also connected to the driver. Code was run through the Arduino until the PlayStation controller could wirelessly control the motor as desired. This process can be seen in Figure 37.

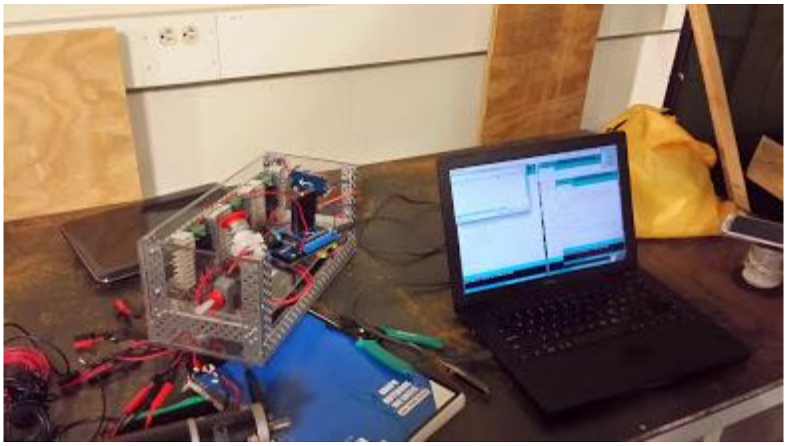


Figure 37: Electrical Systems Testing

10.3 Driving Test

Once the single motor testing was completed, coding was completed that allowed four motors to be controlled using two of the three Sabertooth drivers. The electronics box was attached to the robot and the four driving wheels were wired to the box. Each motor driver was controlled by one of the joysticks on the PlayStation controller. This allowed for skid steering of the robot. (Figure 38).

Figure 38: Skid Steer using Controller

The test proved the operability of the electrical systems. Issues arose with the wheels however. The smaller wheels (those used on the past robot) were found not to be concentric with the sprockets. Thus, the chain caused the back motors to bounce putting aditional stress on the motor mounts. Additionally, the bushings were a bit too tight on the shaft and came loose from the wheels.

Likewise, the front wheels were proven to be non-ideal. Traction was achieved by attaching 26 inch rubber tires to the front wheels. A single #10 bolt was used to hold each bicycle rim to the shaft. During an attempt to turn right, the bolt attaching the right front wheel sheared off and damaged the rim. Given the FEA done on the actual design, this issue does not appear to be a problem in the final wheel.

The robot, with the current sprocket reduction, is very fast. Given that initial calculations required a maximum speed of 1 mph, there is a large amount of adjustability in the reduction that will allow increased torque for digging in the front and lighter motors in the back. As all the driving motors have the same reduction currently, future tests will attempt to reduce slippage by pulsing the frequency of the voltage on the back wheels at a lower rate than the front.

Failure of the front right wheel was early on in the testing process and didn’t allow time for empirical data to be recorded. The primary goal of this test was to prove operability of the electronics as the wheels aren’t representative of the actual design. Thus, the test was determined to be a success.

After the test, the rear wheels were both replaced and the shaft was sanded to help the bushing slide on easier. The front wheel attachments to the shafts were beefed up by adding an additional #10 bolt. After these fixes, the robot was again tested. It easily did a zero turn on concrete during this test. As the batteries wore down, it became harder and harder to turn. The robot was also taken out to drive on the grass where it seemed to perform about the same. Even with a low battery, an obstacle of approximately 3 inches was traversed by the wheels. During this portion of the test, the robot was wirelessly controlled out to a range of 50+ feet with no noticeable degradation of control. An exact distance was not determined as the batteries died.

10.4 Full System Test

Once the batteries were recharged, the augers were wired up and full system testing began. The first portion of this testing involved determining the deposit rate of the augers. Forty eight pounds of sand (21.8 kg) was poured into the bin before each test. This 48 pounds of sand filled the bin approximately halfway to the top. Each test was run for a specified time and the amount of sand deposited was weighed. Between each run, as much sand as possible was removed from the auger tube to ensure accuracy of date. This data can be seen in Table 5. As the bin hasn't been clear coated yet, the surface doesn't allow the sand to slip as well as it will in the actual competition. However, an easy way to combat this was to shake the robot by quickly moving the wheels back and forth. It was also noted that new reduction ratio took care of any jamming issues.

Table 5: Full System Auger Test

Sand weight (kg)	21.8				
Run	Run Time (sec)	Sand deposited (kg)	% of original	Shake (Y/N)	Other Notes
1	44	19.1	88%	N	New sprocket had no problems with jamming
2	30	18.1	83%	N	
3	30	20.4	94%	Y	Bin almost empty by 15 sec
4	15	12.7	58%	N	
5	18	11.8	54%	Y	Piled in back of bin

Once auger testing was completed, the robot's speed was determined by recording its time to traverse 45 ft both with and without the 48 pounds of sand. As can be seen in Table 6, the difference in time was very small. Unloaded the robot traveled at approximately 2.19 mph. Loaded it traveled at 1.92 mph. Given that the desired maximum speed was 1 mph, the gear reductions can be adjusted to provide more torque to the digging wheels.

Unloaded and loaded, the robot had no problems completing a zero turn (even with a flat tire). The joystick controls were very straight forward and the robot responded very well to wireless operation.

Table 6: Speed Tests

45 foot run (13.7 m)	Time (sec)
w/o sand	14
w/ 21.8 kg of sand	16

The conclusion of the full system test was that the current setup over performed in all aspects. As designed, the augers were expected to dump 30 kg of regolith in two minutes. However, the testing showed over 20 kg can be dumped in approximately 30 seconds. Driving speeds were calculated to be around twice as fast as the desired maximum with and without a load. Thus, the next team will need to decide if they want to cut back the performance levels for weight savings or try for a third digging session.

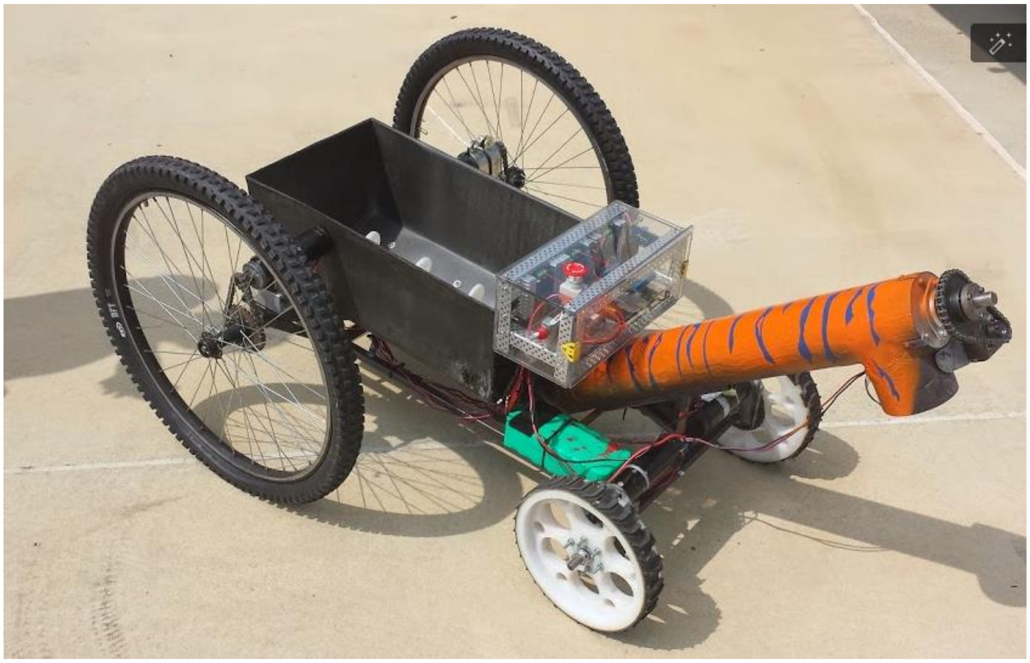


Figure 39: Finalized Prototype After Testing

11.0 Validation/Verification

Both augers and the electrical subsystem have been validated independently before being integrated into the assembly. Once the non-autonomous prototype was completed, the system was validated through testing (as discussed above) by showing that the systems are working together properly. Then, the full system will be verified to the sponsor and advisors through a series of field tests designed to showcase basic functions such as driving and dumping as defined by the testing/prototype engineer.

12.0 Economic Analysis

A first pass budget was formed with the help of a BOM as shown in Appendix N. The estimated total cost of materials for the project at the time of the CDR was $3000. This did not include any tooling costs.

The actual cost to build the prototype was just shy of $1000 per the teaching assistant's records. A full breakdown of purchases can be seen in Appendix O. Money was saved by reusing many of the materials from the old robot as well as using hardware and tooling available in the senior design project room. For example, two 24V batteries were found saving around $700. These batteries are just for testing and should be replaced with lighter ones by the next team. As well, the carbon fiber and epoxy used to create the bin and auger tube was donated by Mr. Thompson.

13.0 Mass

The mass of the robot is still expected to be approximately 40kg if completed as designed. The mass of the current prototype is 45.4 kg. However, this mass is not representative of the proposed design due to the temporary electronics, heavy batteries and different wheels. A general breakdown of masses can be seen below in Table 7. A piece by piece mass determination would be helpful in the future.

Table 7: Mass Breakdown

Component/System	Mass per (kg)	Quanity	Total Mass (kg)
Electrical Box	3.63	1	3.63
Battery	3.18	2	6.36
Motor	1.59	6	9.54
Chassis w/ Wheels	13.57	1	13.57
Horizontal Auger	3.63	1	3.63
Bin and Vertical Auger	8.62	1	8.62
		Sum	45.35

14.0 Risk Management

Potential issues that could arise have been noted and ranked in Appendix K. Solutions to these issues will be in the form of design, testing or inspection. A kill switch has been attached to power down all systems upon a malfunction. Special care should be taken to make sure that large objects do not come in contact with the augers. Future teams will also need to enclose the chains for safety.

15.0 Project Management

The NASA robotic mining team was divided into two separate groups for an internal competition to determine the best concept during the first 4 months of the project. Corporation 12 was a four member group of the original 8 person team. Corp 12 was managed by Matthew Jones. David Faucett was lead designer for the wheel/digging device. Stewart Boyd was the lead storage/deposition designer. Will Flournoy was the testing/prototype engineer.

After the Concepts Review, the other four members of the team joined with corporation 12 to form the NASA robotic mining team. Cy Scott assumed the position of electrical/controls subsystem lead and worked on the electrical closure. Bradley Kondrak helped Will with the motors and the carbon fiber bin. Jay Jeter worked with Stewart on the bin/dump system. Bo Thornton also worked on the bin design and helped with project management/paperwork. By the end of July 2014, a working non-autonomous prototype was built and tested. For a full timeline, refer to Appendix I: Gantt Chart.

Configuration management will managed by storing information on Dropbox. Before the CR and PDR, a full set of relevant information was saved in a file for storage. After ORR, the final data set will be handed off to the next team in a method to be determined by Dr. Beale.

16.0 Future Work

The team has designed the prototype of a very unique robotic mining system. During the summer, the actual wheels were not able to be manufactured. Finishing the build of those wheels (or a redesigned version) is the primary issue that needs to be addressed by the next design team. As designed, the wheel rims will likely need to be outsourced. Three separate companies provided quotes as can be found in the TDP. Once these wheels are built, the robot can be tested extensively to determine the best course of action for making the final battery selection and determining the best way to approach autonomy.

Thus, another issue is the design/integration of electrical systems capable of autonomous operation. This portion of the design will likely need to be handed to an electrical or computer team as it will involve very complex coding.

While not vital to the operation of the robot, weight savings is another area for future work. Weight can easily be saved by making the electronics box out of carbon fiber. Other weight savings could involve replacing the metal shafts in the augers, shortening of bolts and replacing the auger hubs. Much for ambitious changes might involve making the entire frame out of carbon fiber or shortening the entire robot. Overall, the design currently is still a prototype. Now that the concept has been proven to be possible, some refining touches can help make it into the winning 2015 design.

17.0 Conclusions

Through careful examination and testing, the wheeled digging device was determined to be the optimum solution to win the 2015 NASA Robotic Mining Competition. Systems engineering tools such as the Vee Chart and 11 System Engineering Functions helped to track progress and ensure proper care was used during the design process (Appendix J).

Using the wheeled digging device and two auger system, an estimated 1420 points can be earned per run. This value is much higher than the 2013 winner which was just above 900 points. Appendices L and M were used to determine a general point breakdown. As autonomy is one of the main sources of points, special attention was taken to ensure the system was designed in such a way to maximize the usage of on/off processes.

In late-May, a CDR was delivered. Final design changes were made and then fabrication commenced. A working non-autonomous prototype was created and tested by the end of the summer. A complete timeline can be seen in the Gantt Chart (I).

Overall, the current prototype is over built. It over performs in both the dumping and moving speeds. But it is also 5 kg over the projected weight. This testable prototype was designed to be vastly different than any other robot seen in the competition to this point. With that in mind, it was hard to tell how well it would work until the prototype was completed. The design process took 5 months. Then, the current prototype was built and tested in just under two months. The design is an excellent concept for the next team to build upon. With a little work, this concept has potential to be the 2015 winner.

Appendix A: Manager’s Project Contract of Deliverables

NASA Robotic Mining Competition Design Team

Manager: Matthew Jones

5/20/2014

The following Manager’s Project Contract of Deliverables (MPCOD) will serve as the definitive contract between the design team and the sponsor upon initial sponsor approval. This contract has had unanimous approval of the group. Any changes to the MPCOD will be subjected to a three quarter majority vote of the group and approval of the sponsor. These changes will be added to the original contract as an addendum. In a conflict, the latest addendum will supersede any previous agreements. The MPCOD and all the deliverables within will be handed over by COB of last day of finals for the summer of 2014.

The deliverables for this project are as follows:

1. Technical Data Package- The technical data package (TDP) will have a complete set of mechanical drawings detailing the manufacture/assembly of parts (not including purchased parts). These drawings will be sufficiently detailed to produce the mechanical/structural components of the design. A generalized electrical/wiring layout will also be included. Finite Element Analysis (FEA) done during the design portion will be included. Documentation of testing (if more than what is in design notebook is deemed necessary by the team) will be included. Specification sheets of purchased parts/materials will be included to the extent given by the manufactures. Last, a Bill of Materials (BOM) will be compiled.
2. Design Notebook- The design notebook will show the general design progress and enough detail on design/testing to ensure future team members can determine design intent. Through the usage of the design notebook and other documentation as specified in the MPCOD, a future mechanical team will be able to ascertain the concept, design specifics, production and testing of the robot. Using the same set of documents, an electrical team will be able to determine the current status of the electrical design and modify accordingly.
3. Physical Robotic Components- The team is responsible for the mechanical/structural portions of the robot (assembled) which meet the specifications as noted in the 2014 NASA Mining Competition Rules. The robot will include marginally operational electronic systems capable of allowing for mechanical system and/or subsystem testing and validation. The level of system and/or subsystem testing and validation that is finished may correlate to the amount of support that is provided by electrical professors and/or electrical students. If time, a controller such as an xbox or ps2 controller will be implemented to test the robot.
4. Systems Engineering Report- A systems engineering report will be developed using the Vee Chart and 11 Systems Engineering functions (as defined in class). This report will be up to date with the progress of the design when delivered.
5. Access to Full Set of Design Files- A complete set of design files will be turned over for use by future teams. This will include 2D mechanical drawings, 3D cad, data management information, design process information, contact info and reports. The TDP, as defined above, will be submitted in this information.

Addendum 1
6/14/2014

Addendum 1 has been agreed upon by the team and upon approval of the sponsor will supersede the MPCOD. This addendum has been written due to a major redesign of several of the components/subsystems after sponsor/advisor requests for changes at the Critical Design Review (CDR). As well, several unforeseeable delays have stretched the build process to such a point that it will be impossible to finish the physical robotics component section (#3) in the summer.

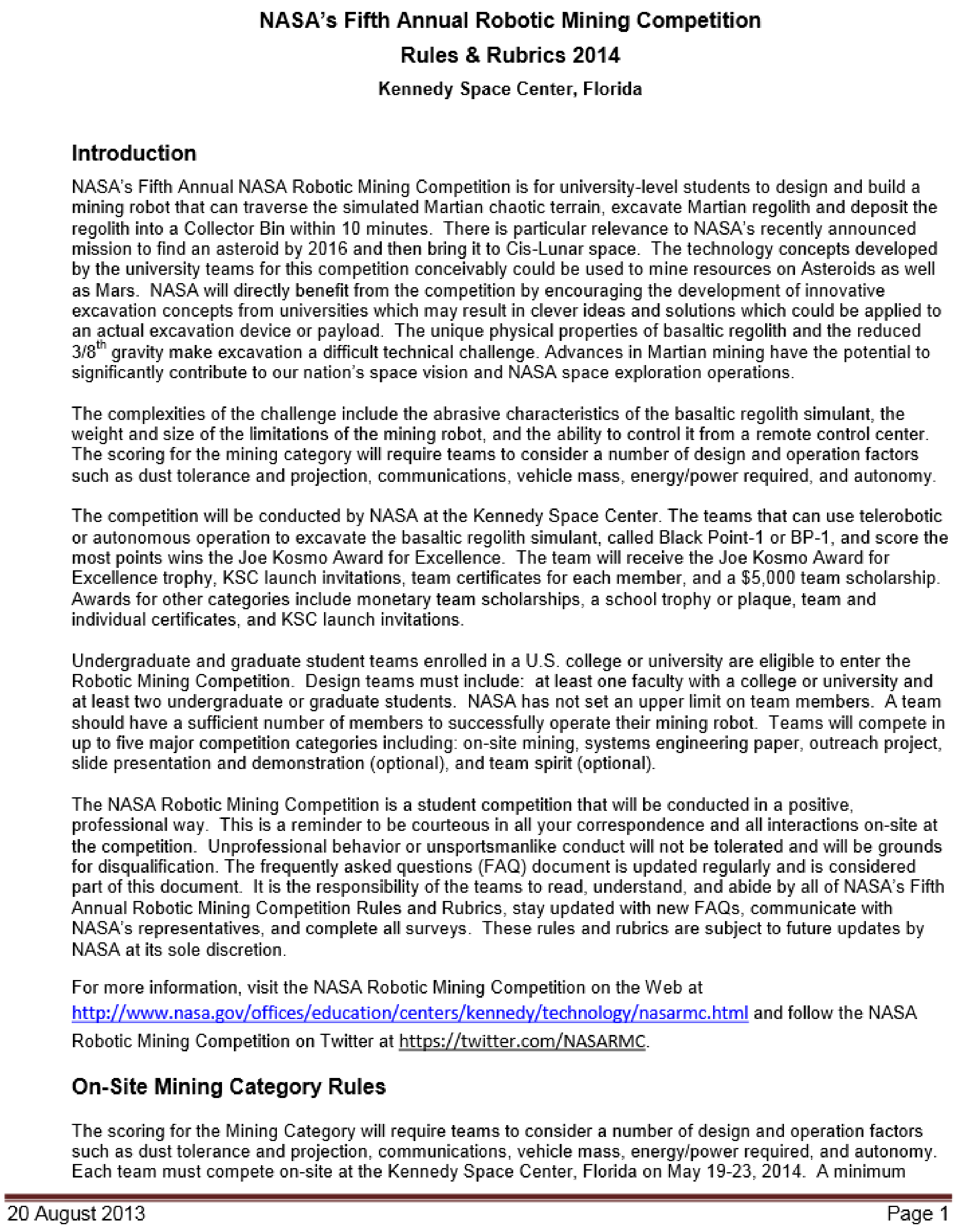
From the original MPCOD, numbers 1,2, 4,5 will remain intact and will be representative of the overall design which will be finished by the following senior design or competition team.

Number 3 will be modified to read:

> Physical Robotic Components- The team is responsible for the design and fabrication of the chassis, bin and augers which meet the specifications as noted in the 2014 NASA Mining Competition Rules. The robot will include wheels solely for testing per sponsor request. The robot will also include basic electronic systems capable of allowing for auger testing and validation.
>
> The level of system and/or subsystem testing and validation that is finished may correlate to the amount of support that is provided by electrical professors and/or electrical students and the ability to procure electronic components in a timely manner. A controller such as an xbox or ps2 controller will be implemented to test the robot's ability to roll and test the augers' functionalities. Roll testing may not be representative of the actual robots movement but will be used to showcase the electrical system concept.

Any later changes will be added in subsequent addendums using the process defined in the MPCOD. These future addendums will supersede old addendums and the original contract.

Appendix B: 2014 NASA Competition Rules



NASA's Fifth Annual Robotic Mining Competition

Rules & Rubrics 2014

Kennedy Space Center, Florida

Introduction

NASA's Fifth Annual NASA Robotic Mining Competition is for university-level students to design and build a mining robot that can traverse the simulated Martian chaotic terrain, excavate Martian regolith and deposit the regolith into a Collector Bin within 10 minutes. There is particular relevance to NASA's recently announced mission to find an asteroid by 2016 and then bring it to Cis-Lunar space. The technology concepts developed by the university teams for this competition conceivably could be used to mine resources on Asteroids as well as Mars. NASA will directly benefit from the competition by encouraging the development of innovative excavation concepts from universities which may result in clever ideas and solutions which could be applied to an actual excavation device or payload. The unique physical properties of basaltic regolith and the reduced 3/8th gravity make excavation a difficult technical challenge. Advances in Martian mining have the potential to significantly contribute to our nation's space vision and NASA space exploration operations.

The complexities of the challenge include the abrasive characteristics of the basaltic regolith simulant, the weight and size of the limitations of the mining robot, and the ability to control it from a remote control center. The scoring for the mining category will require teams to consider a number of design and operation factors such as dust tolerance and projection, communications, vehicle mass, energy/power required, and autonomy.

The competition will be conducted by NASA at the Kennedy Space Center. The teams that can use telerobotic or autonomous operation to excavate the basaltic regolith simulant, called Black Point-1 or BP-1, and score the most points wins the Joe Kosmo Award for Excellence. The team will receive the Joe Kosmo Award for Excellence trophy, KSC launch invitations, team certificates for each member, and a $5,000 team scholarship. Awards for other categories include monetary team scholarships, a school trophy or plaque, team and individual certificates, and KSC launch invitations.

Undergraduate and graduate student teams enrolled in a U.S. college or university are eligible to enter the Robotic Mining Competition. Design teams must include: at least one faculty with a college or university and at least two undergraduate or graduate students. NASA has not set an upper limit on team members. A team should have a sufficient number of members to successfully operate their mining robot. Teams will compete in up to five major competition categories including: on-site mining, systems engineering paper, outreach project, slide presentation and demonstration (optional), and team spirit (optional).

The NASA Robotic Mining Competition is a student competition that will be conducted in a positive, professional way. This is a reminder to be courteous in all your correspondence and all interactions on-site at the competition. Unprofessional behavior or unsportsmanlike conduct will not be tolerated and will be grounds for disqualification. The frequently asked questions (FAQ) document is updated regularly and is considered part of this document. It is the responsibility of the teams to read, understand, and abide by all of NASA's Fifth Annual Robotic Mining Competition Rules and Rubrics, stay updated with new FAQs, communicate with NASA's representatives, and complete all surveys. These rules and rubrics are subject to future updates by NASA at its sole discretion.

For more information, visit the NASA Robotic Mining Competition on the Web at http://www.nasa.gov/offices/education/centers/kennedy/technology/nasarmc.html and follow the NASA Robotic Mining Competition on Twitter at https://twitter.com/NASARMC.

On-Site Mining Category Rules

The scoring for the Mining Category will require teams to consider a number of design and operation factors such as dust tolerance and projection, communications, vehicle mass, energy/power required, and autonomy. Each team must compete on-site at the Kennedy Space Center, Florida on May 19-23, 2014. A minimum amount of 10 kg of BP-1 must be mined and deposited during either of two competition attempts according to the rules to qualify to win in this category. If the minimum amount of 10 kg of BP-1 is not met for an attempt, then the total score for that attempt will be 0. In the case of a tie, the teams will compete in a tie-breaking competition attempt. The judges' decisions are final in all disputes. The teams with the first, second, and third most Mining points averaged from both attempts will receive team plaques, individual team certificates, KSC launch invitations, $3,000, $2,000, and $1,000 scholarships and 25, 20, and 15 points toward the Joe Kosmo Award for Excellence, respectively. Teams not winning first, second, or third place in the mining category can earn one bonus point for each kilogram of BP-1 mined and deposited up to a maximum average of ten points toward the Joe Kosmo Award for Excellence. The most innovative design will receive the Judges' Innovation Award at the discretion of the mining judges.

1) Teams must arrive at the Robotic Mining Competition Check-In Tent in Parking Lot 4 of the Kennedy Space Center no later than 3:00 p.m. on Monday, May 19, 2014; but teams are encouraged to arrive earlier.
2) Teams will be required to perform two official competition attempts using BP-1 in the Caterpillar Mining Arena. NASA will fill the Caterpillar Mining Arena with compacted BP-1 that matches as closely as possible to basaltic Martian regolith. NASA will randomly place three obstacles and create two craters on each side of the Caterpillar Mining Arena. Each competition attempt will occur with two teams competing at the same time, one on each side of the Caterpillar Mining Arena. After each competition attempt, the obstacles will be removed, the BP-1 will be returned to a compacted state, if necessary, and the obstacles and craters will be returned to the Caterpillar Mining Arena. The order of teams for the competition attempts will be chosen at NASA's discretion. See Diagrams 1 and 2.
3) In each of the two official competition attempts, the teams will score cumulative Mining Points. See Table 1 for the Mining Category Scoring Example. The teams' ranking Mining Points will be the average of their two competition attempts.
    A) Each team will be awarded 1000 Mining points after passing the safety inspection and communications check.
    B) During each competition attempt, the team will earn 3 Mining points for each kilogram in excess of 10 kg of BP-1 deposited in the Collector Bin. (For example, 110 kg of BP-1 mined will earn 300 Mining points.)
    C) During each competition attempt, the team will lose 1 Mining Point for each 50 kilobits/second (kb/sec) of average data used throughout each competition attempt.
    D) During each competition attempt, the team will lose 8 Mining points for each kilogram of total mining robot mass. (For example, a mining robot that weighs 80 kg will lose 640 Mining points.)
    E) During each competition attempt, the team will earn 20 Mining points if the amount of energy consumed by the mining robot during the competition attempt is reported to the judges after each attempt. The amount of energy consumed will not be used for scoring; a team must only provide a legitimate method of measuring the energy consumed and be able to explain the method to the judges.
    F) During each competition attempt, the judges will award the team 0 to 100 Mining points for dust tolerant design features on the mining robot (up to 30 Mining points) and dust free operation (up to 70 Mining points). If the mining robot has exposed mechanisms where dust could accumulate during a Martian mission and degrade the performance or lifetime of the mechanisms, then fewer Mining points will be awarded in this category. If the mining robot raises a substantial amount of airborne dust or projects it due to its operations, then fewer Mining points will be awarded. Ideally, the mining robot will operate in a clean manner without dust projection, and all mechanisms and moving parts will be protected from dust intrusion. The mining robot will not be penalized for airborne dust while dumping into the Collector Bin. All decisions by the judges regarding dust tolerance and dust projection are final.

The 30 points for dust-tolerant design will be broken down in the following way:

1. Drive train components enclosed/protected and other component selection – 10 points
2. Custom dust sealing features (bellows, seals, etc.) –10 points
3. Active dust control (brushing, electrostatics, etc.) – 10 points

The 70 points for dust-free operation will be broken down in the following way:

1. Driving without dusting up crushed basalt – 20 points
2. Digging without dusting up crushed basalt – 30 points
3. Transferring crushed basalt without dumping the crushed basalt on your own Robot – 20 points

G) During each competition attempt, the team will earn up to 500 Mining points for autonomous operations. Mining points will be awarded for successfully completing the following activities autonomously:

1. Successfully crossing the obstacle field: 50 pts
2. Successfully crossing the obstacle field and excavating: 150 pts
3. Successfully crossing the obstacle field, excavating and depositing regolith, 1 time: 250 pts
4. Successful fully autonomous run for 10 minutes: 500 pts

For a team to earn mining points in the autonomous category, the team cannot touch the controls during the autonomous period. If the team touches the controls then the autonomy period for that run is over; however, the team may revert to manual control to complete that run. Start and stop commands are allowed at the beginning and end of the autonomous period. Orientation data cannot be transmitted to the mining robot in the autonomous period. Telemetry to monitor the health of the mining robot is allowed during the autonomous period. The mining robot must continue to operate for the entire 10 minutes to qualify for a fully autonomous run.

The teams with the first, second, and third most Autonomous points averaged from both attempts will receive the Caterpillar Autonomy Award and $1,500, $750, and $250 team scholarships respectively. Points will count toward the Caterpillar Autonomy Award even if no regolith is deposited. In the case of a tie, the team that deposits the most regolith will win. If no regolith deposited in the case of a tie, the judges will choose the winner. The judges' decision is final.

Mining Category Elements	Specific Points	Actual	Units	Mining points
Pass Inspections				1000
BP-1 over 10 kg	+3/kg	110	kg	+300
Average Bandwidth	-1/50kb/sec	5000	kb/sec	-100
Mining Robot Mass	-8/kg	80	kg	-640
Report Energy Consumed	+20	1	1= Achieved 0= Not Achieved	+20
Dust Tolerant Design (30%) & Dust Free Operation (70%)	0 to +100	70	Judges' Decision	+70
Autonomy	50, 150, 250 or 500	150		+150
Total				800

Table 1: Mining Category Scoring Example

4) All excavated mass deposited in the Collector Bin during each official competition attempt will be weighed after the completion of each competition attempt.

5) The mining robot will be placed in the randomly selected starting positions. See Diagrams 1 and 2.

6) A team's mining robot may only excavate BP-1 located in that team's respective mining area at the opposite end of the Caterpillar Mining Arena from the team's starting area. The team's starting direction will be randomly selected immediately before the competition attempt. Mining is allowed as soon as the mining line is crossed.

7) The mining robot is required to move across the obstacle area to the mining area and then move back to the Collector Bin to deposit the BP-1 into the Collector Bin. See Diagrams 1 and 2.

8) Each team is responsible for placement and removal of their mining robot onto the BP-1 surface. There must be one person per 23 kg of mass of the mining robot, requiring four 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 mining robot in its designated starting position within the Caterpillar Mining Arena and 5 minutes to remove the mining robot from the Caterpillar Mining Arena after the 10-minute competition attempt has concluded.

10) The mining robot operates during the 10-minute time limit of each competition attempt. The competition attempts for both teams in the Caterpillar Mining Arena will begin and end at the same time.

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

12) The mining robot cannot be anchored to the BP-1 surface prior to the beginning of each competition attempt.

13) The mining robot will be inspected during the practice days and right before each competition attempt. Teams will be permitted to repair or otherwise modify their mining robots anytime the Pits are open.

14) At the start of each competition attempt, the mining robot may not occupy any location outside the defined starting position in the Caterpillar Mining Arena. See Caterpillar Mining Arena definition for description of the competition field.

15) The Collector Bin top edge will be placed so that it is adjacent to the side walls of the Caterpillar Mining Arena without a gap and the height will be approximately 0.5 meter from the top of the BP-1 surface directly below it. The Collector bin top opening will be 1.65 meters long and .48 meters wide. See Diagrams 1 – 3. A target(s) or beacon(s) may be attached to the Collector Bin for navigation purposes only. This navigational aid system must be attached during the setup time and removed afterwards during the removal time period. If attached to the Collector Bin, it must not exceed the width of the Collector Bin and it must not weigh over 9 kg. The mass of the navigational aid system is included in the maximum mining robot mass limit of 80.0 kg and must be self-powered. The target/beacon may send a signal or light beam but lasers are not allowed for safety reasons except for Visible Class I or II lasers or low power lasers and laser based detection systems. Supporting documentation from the laser instrumentation vendor must be given to the inspection judge for "eye-safe" lasers. The Judges will inspect and verify that all laser devices are a class I or II product and they have not been modified (optics or power). Any objects placed on the Collector Bin cannot be more than 0.75 m above the BP-1 surface, and cannot be permanently attached or cause alterations (ie. no drilling, nails, etc).

16) There will be three obstacles placed on top of the compressed BP-1 surface within the obstacle area before each competition attempt is made. The placement of the obstacles will be randomly selected before the start of the competition. Each obstacle will have a diameter of approximately 10 to 30 cm and an approximate mass of 3 to 10 kg. There will be two craters of varying depth and width, being no wider or deeper than 30 cm. No obstacles will be intentionally buried in the BP-1 by NASA, however, BP-1 includes naturally occurring rocks.

17) The mining robot must operate within the Caterpillar Mining Arena: it is not permitted to pass beyond the confines of the outside wall of the Caterpillar Mining Arena and the Collector bin during each competition attempt. The BP-1 must be mined in the mining area and deposited in the Collector bin. A team that excavates any BP-1 from the starting or obstacle areas will be disqualified. The BP-1 must be carried from the mining area to the Collector bin by any means and be deposited in the Collector bin in its raw state. A secondary container like a bag or box may not be deposited inside the Collector bin. Depositing a

container in the Collector bin will result in disqualification of the team. The mining robot can separate intentionally, if desired, but all parts of the mining robot 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. The walls may be used for the purposes of mapping autonomous navigation and collision avoidance. Touching or having a switch sensor springwire that may brush on a wall as a collision avoidance sensor is allowed.

18) The mining robot must not use the wall as support or push/scoop BP-1 up against the wall to accumulate BP-1. If the mining robot exposes the Caterpillar Mining Arena bottom due to excavation, touching the bottom is permitted, but contact with the Caterpillar Mining Arena bottom or walls cannot be used at any time as a required support to the mining robot. Teams should be prepared for airborne dust raised by either team during each competition attempt.

19) During each competition attempt, the mining robot is limited to autonomous and telerobotic operations only. No physical access to the mining robot will be allowed during each competition attempt. In addition, telerobotic operators are only allowed to use data and video originating from the mining robot and the NASA video monitors. Visual and auditory isolation of the telerobotic operators from the mining robot in the Mission Control Center is required during each competition attempt. Telerobotic operators will be able to observe the Caterpillar Mining Arena through overhead cameras in the Caterpillar Mining Arena via monitors that will be provided by NASA in the Mission Control Center. These color monitors should be used for situational awareness only. No other outside communication via cell phones, radios, other team members, etc. is allowed in the Mission Control Center once each competition attempt begins. During the 10 minute setup period, a handheld radio link will be provided between the Mission Control Center team members and team members setting up the mining robot in the Caterpillar Mining Arena to facilitate voice communications during the setup phase only.

20) The mining robot mass is limited to a maximum of 80.0 kg. Subsystems on the mining robot used to transmit commands/data and video to the telerobotic operators are counted toward the 80.0 kg mass limit. Equipment not on the mining robot used to receive data from and send commands to the mining robot for telerobotic operations is excluded from the 80.0 kg mass limit.

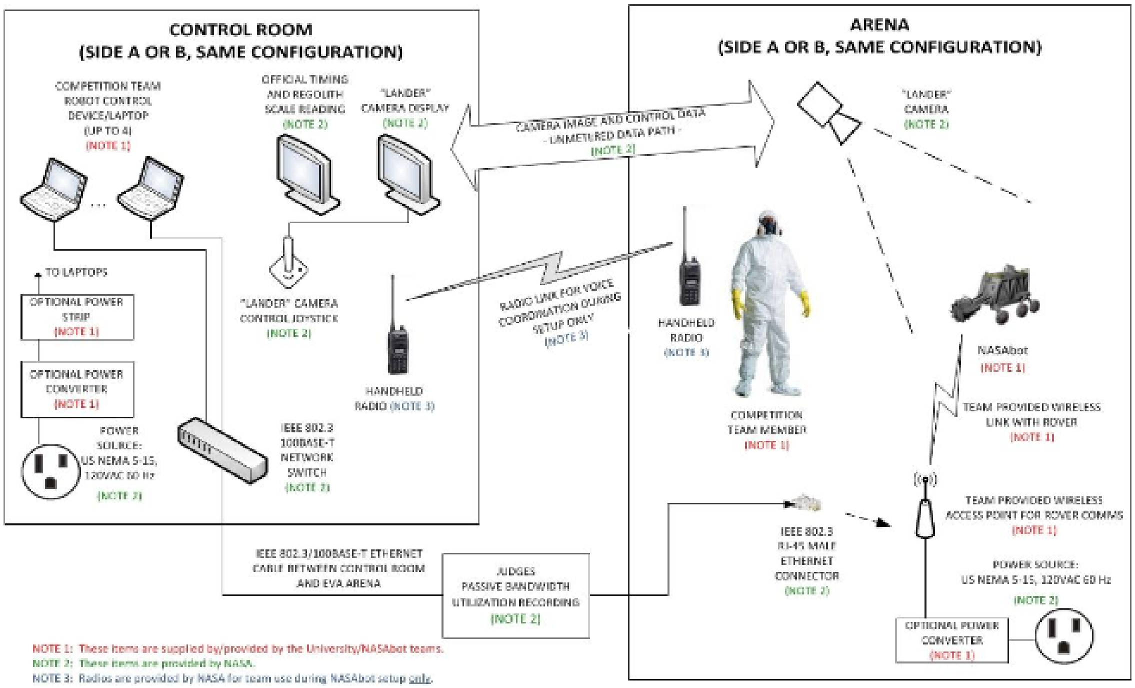
21) The mining robot must provide its own onboard power. No facility power will be provided to the mining robot. There are no power limitations except that the mining robot must be self-powered and included in the maximum mining robot mass limit of 80.0 kg.

22) The mining robot must be equipped with an easily accessible red emergency stop button (kill switch) of minimum diameter of 40 mm on the surface of the mining robot requiring no steps to access. The emergency stop button must stop the mining robot's motion and disable all power to the mining robot with one push motion on the button. It must be highly reliable and instantaneous. For these reasons an unmodified "Commercial Off-The-Shelf" (COTS) red button is required. A closed control signal to a mechanical relay is allowed as long as it stays open to disable the mining robot. The reason for this rule is to completely safe the mining robot in the event of a fire or other mishap. The button should disconnect the batteries from all controllers (high current, forklift type button) and it should isolate the batteries from the rest of the active sub-systems as well. Only laptop computers may stay powered on if powered by its internal battery.

23) The communications rules for telerobotic operations follow.

A. MINING ROBOT WIRELESS LINK

1. Each team is required to command and monitor their mining robot over the NASA-provided network infrastructure. Figure 1 shows
    a. the configuration provided to teams to communicate with their mining robot,
    b. the "Mars Lander" camera staged in the Caterpillar Mining Arena, and Mars Lander Control Joystick provided to the team in the Mission Control Center,
    c. the official timing display, which includes a real-time display of BP-1 collected during the match, and
    d. the handheld radios that will be provided to each team to link their Mission Control Center team members with their corresponding team members in the Caterpillar Mining Arena during setup.



NOTE 1: These items are supplied by/provided by the University/NASAbot teams.
NOTE 2: These items are provided by NASA.
NOTE 3: Radios are provided by NASA for team use during NASAbot setup <u>only</u>.

Figure 1

2. Each team will provide the wireless link (access point, bridge, or wireless device) to their mining robot, which means that each team will bring their own Wi-Fi equipment/router and any required power conversion devices. Teams must set their own network IP addresses to enable communication between their mining robot and their control computers, through their own wireless link hosted in the Caterpillar Mining Arena.
   a. In the Caterpillar Mining Arena, NASA will provide an elevated network drop (female RJ-45 Ethernet jack) that extends to the Mission Control Center, where NASA will provide a network switch for the teams to plug in their laptops.
      i. The network drop in the Caterpillar Mining Arena will be elevated high enough above the edge of the regolith bed wall to provide adequate radio frequency visibility of the Caterpillar Mining Arena.
      ii. A shelf will be set up next to the network drop, will be 4 to 6 feet off the ground, and will be no more than 50 feet from the mining robot. This shelf is where teams will place their Wireless Access Point (WAP) to communicate with their mining robot. The Caterpillar Mining Arena will be 150 to 200 feet from the Mission Control Center.
      iii. The WAP shelves for side A and side B of the Caterpillar Mining Arena will be at least 25 feet apart to prevent electromagnetic interference (EMI) between the units.
   b. Power interfaces:
      i) NASA will provide a standard US National Electrical Manufacturers Association (NEMA) 5-15 type, 110 VAC, 60 Hz electrical jack by the network drop. Both will be no more than 5 feet from the shelf.
      ii) NASA will provide a standard US NEMA 5-15 type, 110 VAC, 60 Hz electrical jack in the Mission Control Center for each team.
      iii) The team must provide any conversion devices needed to interface team access points or Mission Control Center computers or devices with the provided power sources.
   c. During the setup phase, the teams will set up their access point and verify communication with their mining robot from the Mission Control Center.

3. 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. Channels will be assigned when the teams check in with the Pit crew chief.
4. Each team will be assigned an SSID that they must use for their wireless equipment.
   a. SSID will be "Team_##."
   b. Teams will broadcast their SSID.
5. Bandwidth constraints:
   a. A team will be awarded the Efficient Use of Communications Power Award for using the lowest average bandwidth during the timed and NASA-monitored portion of the competition. Teams must collect the minimum 10 kg of BP-1 to qualify for this award.
   b. The communications link is required to have an average bandwidth of no more than 5 megabits per second. There will not be a peak bandwidth limit.

B. RF & COMMUNICATIONS APPROVAL

1. Each team must demonstrate to the communication judges that their mining robot and access point are operating only on their assigned channel. Each team will have approximately 15 minutes at the communication judges' station.
2. To successfully pass the communication judges' station, a team must drive their mining robot by commanding it from their mining robot driving/control laptop through their wireless access point. The judges will verify the course of travel and verify that the team is operating only on their assigned channel.
3. If a team cannot demonstrate the above tasks in the allotted time, the team will be disqualified from the competition.
4. On Monday, May 19, 2014, on a first-come, first-serve basis, the teams will be able to show the communication judges their compliance with the rules.
5. The NASA communications technical experts will be available to help teams make sure that they are ready for the communication judges' station on Monday, May 19, 2014, and Tuesday, May 20, 2014.
6. Once the team arrives at the communication judges' station, the team can no longer receive assistance from the NASA communications technical experts.
7. If a team is on the wrong channel during their competition attempts, the team will be disqualified and required to power down.

C. WIRELESS DEVICE OPERATION IN THE PITS

1. Teams will not be allowed to power up their transmitters on any frequency in the Pits during the practice matches or competition attempts. All teams must have a hard-wired connection for testing in the Pits.
2. Teams will have designated times to power up their transmitters when no matches are underway.

24) The mining robot must be contained within 1.5 m length x 0.75 m width x 0.75 m height. The mining robot may deploy or expand beyond the 1.5 m x 0.75 m footprint after the start of each competition attempt, but may not exceed a 1.5 meter height. The mining robot may not pass beyond the confines of the outside wall of the Caterpillar Mining Arena and the Collector Bin during each 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 Martian hardware requirements, no ramps of any kind will be provided or allowed. An arrow on the reference point must mark the forward direction of the mining robot in the starting position configuration. The judges will use this reference point and arrow to orient the mining robot in the randomly selected direction and position. A multiple mining robot system is allowed but the total mass and starting dimensions of the whole system must comply with the volumetric dimensions given in this rule.

25) To ensure that the mining robot is usable for an actual Martian mission, the mining robot cannot employ any fundamental physical processes, gases, fluids or consumables that would not work in the Martian

environment. For example, any dust removal from a lens or sensor must employ a physical process that would be suitable for the Martian 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 Martian environment and if such resources used by the mining robot are included in the mass of the mining robot. Closed pneumatic mining systems are allowed only if the gas is supplied by the mining robot itself. Note: the mining robot will be exposed to outside air temperatures averaging 90 degrees Fahrenheit during inspection and while waiting to enter the Caterpillar Mining Arena.

26) Components (i.e. electronic and mechanical) are not required to be space qualified for Martian atmospheric, electromagnetic, and thermal environments. Since budgets are limited, the competition rules are intended to require mining robots to show Martian plausible system functionality but the components do not have to be traceable to a Martian qualified component version. Examples of allowable components are: Sealed Lead-Acid (SLA) or Nickel Metal Hydride (NiMH) batteries; composite materials; rubber or plastic parts; actively fan cooled electronics; motors with brushes; infrared sensors, inertial measurement units, and proximity detectors and/or Hall Effect sensors, but proceed at your own risk since the BP-1 is very dusty. Teams may use honeycomb structures as long as they are strong enough to be safe. Teams may not use GPS, rubber pneumatic tires; air/foam filled tires; open or closed cell foam, ultrasonic proximity sensors; or hydraulics because NASA does not anticipate the use of these on a Mars mission.

27) The mining robot may not use any process that causes the physical or chemical properties of the BP-1 to be changed or otherwise endangers the uniformity between competition attempts.

28) The mining robot may not penetrate the BP-1 surface with more force than the weight of the mining robot before the start of each competition attempt.

29) No ordnance, projectile, far-reaching mechanism (adhering to Rule 24), etc. may be used. The mining robot must move on the BP-1 surface.

30) No team can intentionally harm another team's mining robot. This includes radio jamming, denial of service to network, BP-1 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 mining robot as determined by the judges will be cause for immediate disqualification. A judge may disable the mining robot by pushing the red emergency stop button at any time.

31) Teams must electronically submit documentation containing a description of their mining robot, its operation, potential safety hazards, a diagram, and basic parts list by April 30, 2014 at 12:00 p.m. (noon) eastern time.

32) Teams must electronically submit a **link** to their YouTube video documenting no less than 30 seconds but no more than 5 minutes of their mining robot in operation for at least one full cycle of operation by April 30, 2014 at 12:00 p.m. (noon) eastern time via e-mail to Bethanne.Hull@nasa.gov. One full cycle of operations includes excavation and depositing material. This video documentation is solely for technical evaluation of the mining robot.

Shipping

33) **Plan ahead for shipping your mining robot and its battery(s) as some batteries may not be allowed on board airplanes or in shipping containers.** Teams may ship their mining robots to **arrive no earlier than May 12, 2014**. The mining robots will be held in a safe, non air-conditioned area and be placed in each team's Space Pit by Monday, May 19, 2014. The **ship to** address is:

Transportation Officer, NASA
Central Supply, Bldg M6-744
Kennedy Space Center, FL 32899
M/F: KSC Visitor Complex, NASA's Robotic Mining Competition, M/C: DNPS

Note: Do not have the shipping company deliver the mining robot directly to the Kennedy Space Center Visitor Complex. They do not have facilities to store them until the Pits are set up. The shipper will come to the Pass & ID facility right before the Kennedy Space Center gate on State Road 405. Central Receiving will send an escort.

34) Return shipping arrangements must be made prior to the competition. All mining robots must be picked up from the Kennedy Space Center Visitor Complex **no later than 5:00 p.m. on Wednesday, May 28, 2014**. Any abandoned mining robots will be discarded after this date. The **return** shipping address is:

Kennedy Space Center Visitor Complex
Robotic Mining Shipping Area
Mail Code: DNPS
State Road 405
Kennedy Space Center, FL 32899

Caterpillar Mining Arena Diagrams

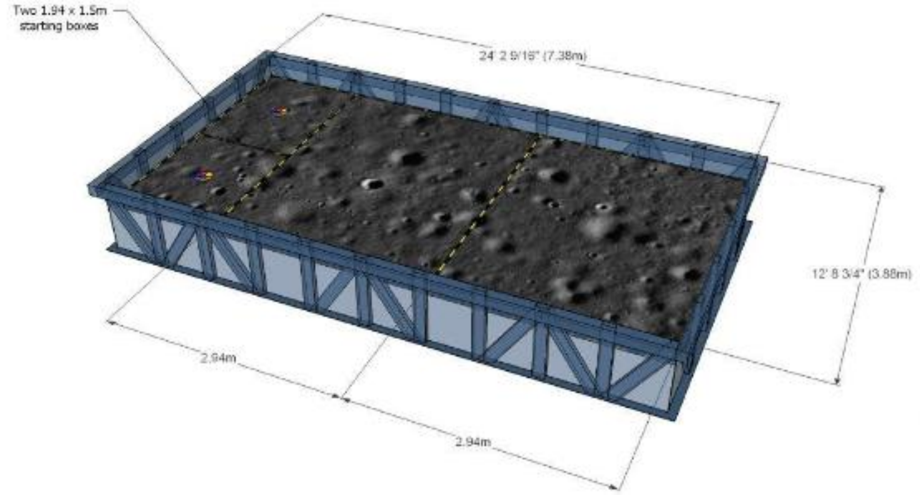


Diagram 1: Caterpillar Mining Arena (isometric view)

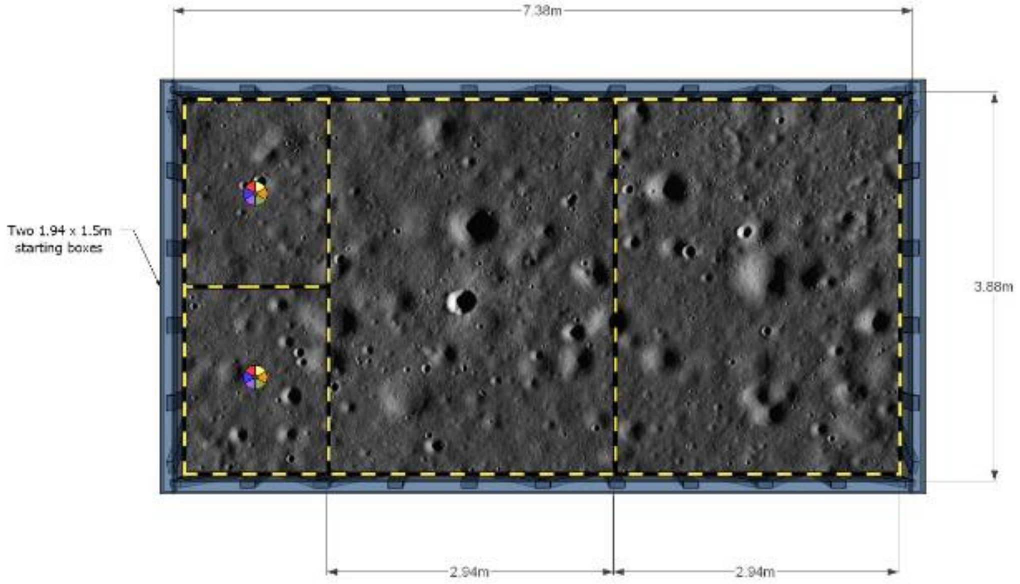


Diagram 2: Caterpillar Mining Arena (top view)

Collector bin Diagram

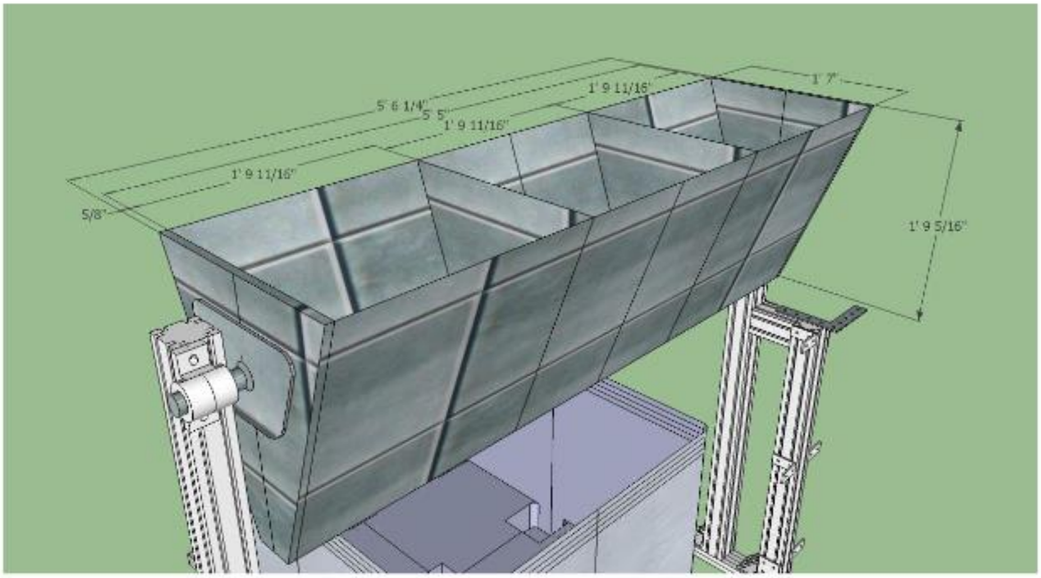


Diagram 3: Collector Bin

NASA's Robotic Mining Competition Systems Engineering Paper

Each team must submit a Systems Engineering Paper electronically in PDF by April 21, 2014 at 12:00 p.m. (noon) eastern time. Your paper should discuss the Systems Engineering methods used to design and build your mining robot. All pertinent information required in the rubric must be in the body of the paper. A minimum score of 16 out of 20 possible points must be achieved to qualify to win in this category. In the case of a tie, the judges will choose the winning Systems Engineering Paper. The judges' decision is final. The team with the winning Systems Engineering Paper will receive a team plaque, individual certificates, and a $500 team scholarship. Second and third place winners will receive certificates.

For reference, undergraduate course materials in NASA Systems Engineering, are available at www.spacese.spacegrant.org.

NASA's Robotic Mining Competition Systems Engineering Paper Scoring Rubric

Elements	Points
Content: • Formatted professionally, clearly organized, correct grammar and spelling, size 12 font; single spaced, maximum of 20 pages not including the cover, table of contents, and source pages. Appendices are allowed and limited to 5 pages, and should referenced in main body. Cover page must include: team name, title of paper, full names of all team members, university name, and faculty advisor's full name. • Title page must include the signature of the sponsoring faculty advisor and a statement that he/she has read and reviewed the paper prior to submission to NASA. • Purpose Statement must be included and related to the application of systems engineering to NASA's Robotic Mining Competition.	There are 3 points for 3 elements.
Intrinsic Merit: • Cost budget (estimated costs vs. actual costs) • Design philosophy in the context of systems engineering; discuss what your team is optimizing in your design approach (light weight? automation? BP-1 capacity? etc.) • Schedule of work from inception to arrival at competition • Major reviews: system requirements, preliminary design and critical design	There are 4 points for 4 elements. Up to 2 additional points may be awarded for exceptional work related to systems engineering intrinsic merit, for a total of 6 points.
Technical Merit: • Concept of operations • System hierarchy • Interfaces • Requirements • Technical budgets (mass, power & data allocated to components vs. actual mass, power, & data usage) • Trade-off assessments • Reliability • Verification of system meeting requirements	There are 8 points for 8 elements. Up to 3 additional points may be awarded for exceptional work related to systems engineering technical merit, for a total of 11 points.

NASA's Robotic Mining Competition Outreach Project Report

Each team must participate in an educational outreach project in their local community. Outreach examples include actively participating in school career days, science fairs, technology fairs, extracurricular science or robotics clubs, or setting up exhibits in local science museums or a local library. Other ideas include organizing a program with a Boys and Girls Club, Girl Scouts, Boy Scouts, etc. Teams are encouraged to have fun with the outreach project and share knowledge of NASA's Robotic Mining Competition, engineering or Martian activities with the local community.

Each team must submit a report of the Outreach Project electronically in PDF by April 21, 2014 at 12:00 p.m. (noon) eastern time. A minimum score of 16 out of 20 possible points must be achieved to qualify to win in this category. In the case of a tie, the judges will choose the winning outreach project. The judges' decision is final. The team with the winning outreach project report will receive a team plaque, individual certificates, and a $500 team scholarship. Second and third place winners will receive certificates.

NASA's Robotic Mining Competition Outreach Project Report Scoring Rubric

Elements	Points
Structure, Content and Intrinsic Merit: • Formatted professionally, clearly organized, correct grammar and spelling, size 12 font; single spaced, maximum of 5 pages not including the cover. Appendices are not allowed, however, a link in the body of the report to a multimedia site with additional photos or videos is allowed. Cover page must include: team name, title of paper, full names of all team members, university name and faculty advisor's full name. • Purpose for this outreach project, identify outreach recipient group(s). • Illustrations must appropriately demonstrate the outreach project.	There are 3 points for 3 elements. Up to 2 additional points may be awarded for exceptional work related to outreach intrinsic merit, for a total of 5 points.
Educational Outreach Merit: • The report must effectively describe what the outreach activity(s) was. • The report must describe exactly how the Robotic Mining Competition team participated. • The report must reflect how the outreach project inspired others to learn about robotics, engineering or Martian activities. • The report must demonstrate the quality of the outreach including how hands-on activities were used to engage the audience at their level of understanding. • The report must show statistics on the participants. Examples include an in-depth or long term outreach project or follow-up with the participants.	There are 10 points for 5 elements. Up to 5 additional points may be awarded for exceptional work related to educational outreach merit, for a total of 15 points.

NASA's Robotic Mining Competition Slide Presentation and Demonstration

The Robotic Mining Slide Presentation and Demonstration is an optional category in the overall competition. The presentation and demonstration must be no more than 20 minutes with an additional 5 minutes for questions and answers. It will be judged at the competition in front of an audience including NASA and private industry judges. The presentations must be submitted electronically in PDF by April 21, 2014 at 12:00 p.m. (noon) eastern time. Teams **MUST** present the slides turned in on April 21st. Visual aids, such as videos and handouts, may be used during the presentation but videos must be presented using the team's own laptop. You may NOT update/modify your slide presentation and present it from your laptop. A minimum score of 16 out of 20 possible points must be achieved to qualify to win in this category. The content, formatting and illustration portion of the score will be judged prior to the live presentation and scored based on the presentation turned in on April 21st. In the case of a tie, the judges will choose the winning presentation. The judges' decision is final. The team with the winning presentation will receive a team plaque, individual team certificates, and a $500 team scholarship. Second and third place winners will receive certificates.

NASA's Robotic Mining Competition Slide Presentation and Demonstration Scoring Rubric	
Elements	**Points**
Content, formatting, and illustrations: • Content includes a cover slide (with team name, presentation title, names of team members, university name, and faculty advisor's name). Also includes an introduction slide and referenced sources. • Formatting is readable and aesthetically pleasing with proper grammar and spelling. • Illustrations support the technical content • Illustrations show progression of the project and final design	There are 4 points for 4 elements. Up to 2 additional points may be awarded for exceptional slides, for a total of 6 points.
Technical Merit: • Design Process • Design Decisions • Final Design • Mining robot functionality • Special features - highlight what makes the mining robot unique or innovative	There are 5 points for 5 elements. Up to 2 additional points may be awarded for exceptional work related to technical merit, for a total of 7 points.
Presentation: • Handles slides and equipment professionally • Engages audience and infuses personality • Creative and inspirational • Demonstrates Robot • Answers questions	There are 5 points for 5 elements. Up to 2 additional points may be awarded for an exceptional presentation, for a total of 7 points.

NASA's Robotic Mining Competition Team Spirit

NASA's Robotic Mining Competition Team Spirit is an optional category in the overall competition. A minimum score of 12 out of 15 possible points must be achieved to qualify to win in this category. In the case of a tie, the judges will choose the winning team. The judges' decision is final. The team winning the Team Spirit Award at the competition will receive a team plaque, individual certificates, and a $500 team scholarship. Second and third place winners will receive certificates.

NASA's Robotic Mining Competition Team Spirit Competition Scoring Rubric

Elements	3	2	1	0
Teamwork: • Exhibits teamwork in and out of the Caterpillar Mining Arena • Exhibits a strong sense of collaboration within the team • Supports other teams with a healthy sense of competition	All three elements are exceptionally demonstrated	Three elements are clearly demonstrated	Two or less elements are clearly demonstrated	Zero elements are clearly demonstrated
Attitude: • Exudes a positive attitude in all interactions, not limited to competition attempt • Demonstrates an infectious energy by engaging others in team activities • Motivates and encourages own team • Motivates and encourages other teams • Keeps pit clean and tidy at all times	All five elements are exceptionally demonstrated	Four elements are exceptionally demonstrated	Three or less elements are clearly demonstrated	Zero elements are clearly demonstrated
Creativity & Originality: • Demonstrates creativity and originality in team activities, name, and logo • Wears distinctive team identifiers • Decorates team's Pit to reflect school/team spirit	All three elements are exceptionally demonstrated	Three elements are clearly demonstrated	Two or less elements are clearly demonstrated	Zero elements are clearly demonstrated
Sportsmanship: • Demonstrates fairness • Shows respect for both authority and opponents • Promotes specific cultural and/or regional pride • Demonstrates fellowship with competitors	All four elements are exceptionally demonstrated	Three elements are clearly demonstrated	Two or less elements are clearly demonstrated	Zero elements are clearly demonstrated
Feedback at Competition	Up to three points for compliment cards collected at the Competition.			

Categories & Awards

In addition to the awards listed below, school plaques and/or individual team certificates will be awarded for exemplary performance in the following categories:

Category	Required/ Optional	Due Dates	Award	Maximum Points toward Joe Kosmo Award for Excellence
On-site Mining in the Caterpillar Mining Arena	Required	May 21-23, 2014	First place $3,000 team scholarship and Kennedy launch invitations	25
			Second place $2,000 team scholarship and Kennedy launch invitations	20
			Third place $1,000 team scholarship and Kennedy launch invitations	15
			Teams not placing 1st, 2nd, or 3rd will receive one point per kilogram mined and deposited up to 10 points	Up to 10
Systems Engineering Paper	Required	April 21, 2014	$500 team scholarship	Up to 20
Outreach Project Report	Required	April 21, 2014	$500 team scholarship	Up to 20
Slide Presentation and Demonstration	Optional	April 21, 2014 and On-Site on May 21-23, 2014	$500 team scholarship	Up to 20
Team Spirit Competition	Optional	All Year	$500 team scholarship	Up to 15
Joe Kosmo Award for Excellence	Grand Prize for Most Points	All Year	A school trophy, $5,000 team scholarship and KSC launch invitations	Total of above points, maximum of 100 points possible
Judges' Innovation Award	Optional	May 21-23, 2014	A school trophy	
Efficient Use of Communications Power Award	Optional	May 21-23, 2014	A school trophy	
Caterpillar's Autonomy Award	Optional	May 21-23, 2014	First place $1,500 team scholarship Second place $750 team scholarship Third place $250 team scholarship	

NASA’s Robotic Mining Competition Checklist

All documents are due by 12:00 p.m. (noon) eastern time.

Required Competition Elements

If required elements are not received by the due dates, then the team is not eligible to compete in any part of the competition (NO EXCEPTIONS).

Registration Application*	50 teams are registered
Systems Engineering Paper	April 21, 2014
Outreach Project Report	April 21, 2014
On-site Mining	May 21-23, 2014
○ Team Check-in, Unload/Uncrate mining robot	May 19, 2014 by 3:00 p.m.
○ Practice Days	May 19-20, 2014
○ Competition Days	May 21-23, 2014
○ Awards Ceremony	May 23, 2014 (evening)

Optional Competition Elements

Presentation File	April 21, 2014
Team Spirit	All year

Required Documentation

Letter of Support from lead university’s Faculty Advisor	With Complete Application
Letter of Support from lead university’s Dean of Engineering	January 20, 2014
Team Roster	January 20, 2014
Student Participant Form	January 20, 2014
Faculty Participation Form	January 20, 2014
Transcripts (unofficial copy is acceptable)**	January 20, 2014
Signed Media Release Form	January 20, 2014
Corrections to NASA generated Team Roster	February 24, 2014
Team Photo including faculty (high resolution .jpg format preferred)	March 24, 2014
Team Biography (200 words maximum)	March 24, 2014
Head Count Form	March 24, 2014
Revised Team Roster (no changes accepted after this date)	March 24, 2014
Rule 31 documentation	April 30, 2014
Rule 32 video	April 30, 2014
Shipping Bill of Lading/Commercial Invoice	April 30, 2014

Optional Documentation

Student Resume (optional)	December 2, 2013

* Registration is limited to the first 50 approved U.S. teams. Registration is limited to one team per university campus. Registration will end when NASA approves 50 applications.

** Each student’s Transcript must be from the university and show:

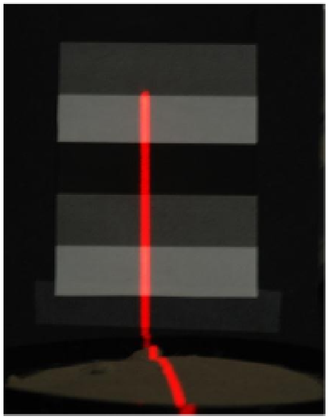
- name of university
- name of student
- current student status within the 2013-2014 academic year
- coursework taken and grades

Definitions

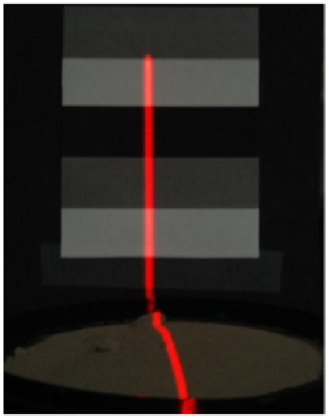
Autonomous – The operation of a team’s mining robot with no human interaction.

Black Point-1 (BP-1) – A crushed lava basalt aggregate which is similar to Mars Volcanic Ash. The BP-1 will be compacted with a fluffy top layer similar to the Martian surface. However, it does not behave like sand. The study on BP-1 is available on http://www.nasa.gov/offices/education/centers/kennedy/technology/nasarmc.html. Also, watch the Lunabotics Webcast where Dr. Philip Metzger, a NASA Physicist, describes BP-1 and its behavior. It is available at http://youtu.be/hMfrv7mlxbE. The density of the compacted BP-1 aggregate will be between 1.5 g/cm^3 and 1.8 g/cm^3. The top 2 cm will be raked to a fluffy condition of approximately .75 g/cm^3. There are naturally occurring rocks in the BP-1 aggregate. The coefficient of friction has not been measured for BP-1. BP-1 behaves like a silty powder soil and most particles are under 100 microns diameter. The coefficient of friction and the cohesion of Martian soil have not been precisely measured due to a lack of scientific data from Mars. Instead, they have been estimated via a variety of techniques. Both parameters (coefficient of friction and cohesion) are highly dependent on the compaction (bulk density, porosity) of the Martian soil. Since the properties of Mars regolith vary and are not well known, this competition will assume that Martian basaltic regolith properties are 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 basaltic minerals and lunar surface regolith particle size, shape, and distribution. BP-1 is not commercially available and it is made from crushed basalt fines. However, JSC-1A is available from Orbital Technologies at: http://www.orbitec.com/store/simulant.html and NU-LHT is commercially available from Zybek Advanced Products (ZAP) at: http://www.zybekap.com/.

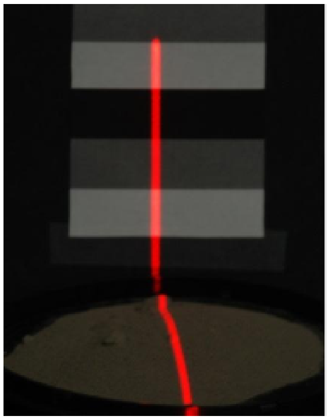
BP-1 reflectivity – NASA performed tests to answer questions about BP-1 reflectivity for LIDAR (or other LASER-based) navigation systems. The laser is not a beam – it is spread out as a sheet that is oriented in the vertical direction, so it is draped across the BP-1 and across a white/gray/black target that is standing up behind the BP-1 in the images. The BP-1 is the mound at the bottom of each image. Teams can get the reflectivity of the BP-1 by comparing the brightness of the laser sheet seen reflected from the BP-1 with the brightness of the same sheet reflected from the white and black portions of the target. The three images are for the three angles of the laser. Note the BP-1 is mounded so they need to account for the fact that it is not a flat surface if they choose to analyze the brightness in the images. The three pictures below were shot with the camera at 10, 16, and 21 degrees relative to the surface. The laser was at an angle of 15 degrees. The camera speed and aperture were set to (manual mode): 1/8 s, f/4.5.



10 degree



16 degree



21 degree

Caterpillar Mining Arena – An open-topped container (i.e., a box with a bottom and 4 side walls), containing BP-1, within which the mining robot will perform each competition attempt. The inside dimensions of the each side of the Caterpillar Mining Arena will be 7.38 meters long and 3.88 meters wide, and 1 meter in depth. The BP-1 aggregate will be approximately .5 meters in depth and approximately .5 meters from the top of the walls to the surface. The Caterpillar Mining Arena for the practice days and official competition will be provided by NASA. The Caterpillar Mining Arena will be outside in an enclosed tent. The Caterpillar Mining Arena lighting will consist of high intensity discharge (HID) lights such as metal halide lights inside a tent structure with clear sides, which is not quite as bright as outdoor daylight conditions. The atmosphere will be an air-conditioned tent without significant air currents and cooled to approximately 77 degrees Fahrenheit. See Diagrams 1 – 3. The Caterpillar Mining Arena steel, primer and paint specifications are as follows:

1. Steel: A-36(walls) & A-992(I-beams) structural steel
2. Primer: Devran 201 epoxy primer, 2.0 to 3.0 mils, Dry Film Thickness (DFT)
3. Paint: Blue Devthane 379 polyurethane enamel, 2.0 to 3.0 mils, DFT (per coat)

Collector Bin – A Collector Bin in the Caterpillar Mining Arena for each competition attempt into which each team will deposit excavated BP-1. The Collector Bin will be large enough to accommodate each team's excavated BP-1. The Collector Bin will be stationary and located adjacent to the Caterpillar Mining Arena. See Diagram 3.

Competition attempt – The operation of a team's mining robot intended to meet all the requirements for winning the mining category by performing the functional task. The duration of each competition attempt is 10-minutes.

Excavated mass – Mass of the excavated BP-1 deposited to the Collector bin by the team's mining robot during each competition attempt, measured in kilograms (kg) with official result recorded to the nearest one tenth of a kilogram (0.1 kg).

Functional task – The excavation of BP-1 from the Caterpillar Mining Arena by the mining robot and deposit of BP-1 from the mining robot into the Collector Bin.

Martian like – Basis of merit associated with feasibility of:

1. Packaging into a small stowed volume for transportation to Mars (1.5 m x .75 m x .75 m)
2. Low mass - it costs $5,000 per kg to send mass to Low Earth Orbit and about 2.5 Million per kg to the Martian surface (based on NASA Mars Science Lab).
3. Simple and reliable – able to operate for 5 years without maintenance on the Martian surface
4. Martian dust tolerant
5. Easy to teleoperate
6. Able to survive a Martian winter

Mining robot – A teleoperated or autonomous robotic excavator in the Robotic Mining Competition including mechanical and electrical equipment, batteries, gases, fluids and consumables delivered by a team to compete in the competition.

Mining points – Points earned from the two competition attempts in the Robotic Mining Competition will be averaged to determine ranking in the on-site mining category.

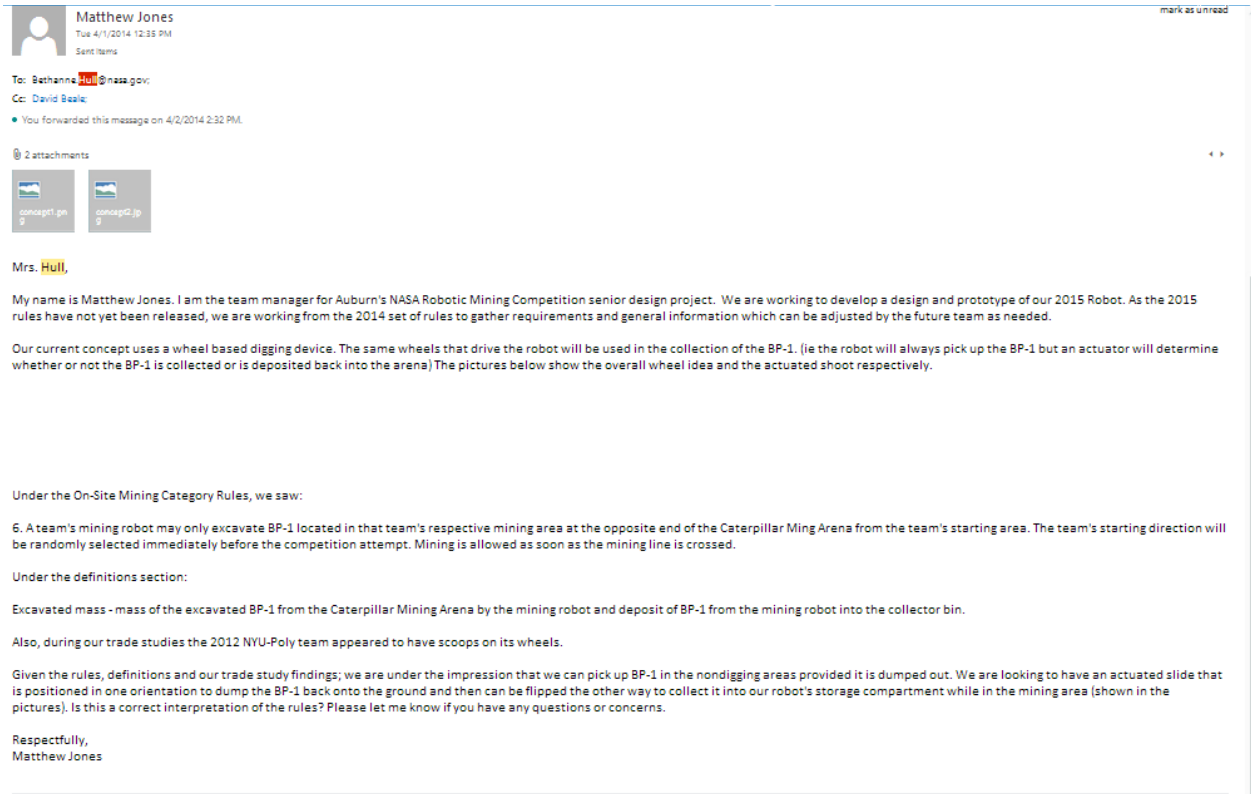
Practice time – Teams will be allowed to practice with their mining robots in the Caterpillar Mining Arena. NASA technical experts will offer feedback on real-time networking performance during practice attempt. A maximum of two practice attempts will be allowed, but not guaranteed.

Reference point – A fixed location signified by an arrow showing the forward direction on the mining robot that will serve to verify the starting orientation of the mining robot within the Caterpillar Mining Arena.

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

Time Limit – 10 minutes to set up the mining robot in the Caterpillar Mining Arena, 10 minutes for the mining robot to perform the functional task, and 5 minutes to remove the mining robot.

Appendix C: Rule Clarification Correspondence



mark as unread

Matthew Jones
Tue 4/1/2014 12:35 PM
Sent Items

To: Bethanne.Hull@nasa.gov;
Cc: David Beale;

- You forwarded this message on 4/2/2014 2:32 PM.

2 attachments

Mrs. Hull,

My name is Matthew Jones. I am the team manager for Auburn's NASA Robotic Mining Competition senior design project. We are working to develop a design and prototype of our 2015 Robot. As the 2015 rules have not yet been released, we are working from the 2014 set of rules to gather requirements and general information which can be adjusted by the future team as needed.

Our current concept uses a wheel based digging device. The same wheels that drive the robot will be used in the collection of the BP-1. (ie the robot will always pick up the BP-1 but an actuator will determine whether or not the BP-1 is collected or is deposited back into the arena) The pictures below show the overall wheel idea and the actuated shoot respectively.

Under the On-Site Mining Category Rules, we saw:

6. A team's mining robot may only excavate BP-1 located in that team's respective mining area at the opposite end of the Caterpillar Ming Arena from the team's starting area. The team's starting direction will be randomly selected immediately before the competition attempt. Mining is allowed as soon as the mining line is crossed.

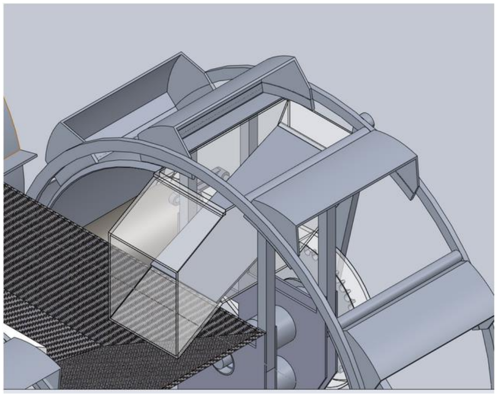
Under the definitions section:

Excavated mass - mass of the excavated BP-1 from the Caterpillar Mining Arena by the mining robot and deposit of BP-1 from the mining robot into the collector bin.

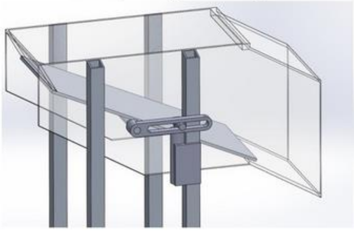
Also, during our trade studies the 2012 NYU-Poly team appeared to have scoops on its wheels.

Given the rules, definitions and our trade study findings; we are under the impression that we can pick up BP-1 in the nondigging areas provided it is dumped out. We are looking to have an actuated slide that is positioned in one orientation to dump the BP-1 back onto the ground and then can be flipped the other way to collect it into our robot's storage compartment while in the mining area (shown in the pictures). Is this a correct interpretation of the rules? Please let me know if you have any questions or concerns.

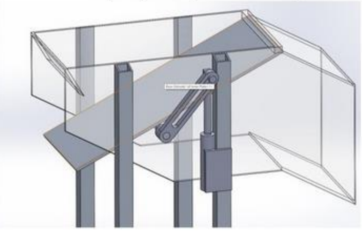
Respectfully,
Matthew Jones

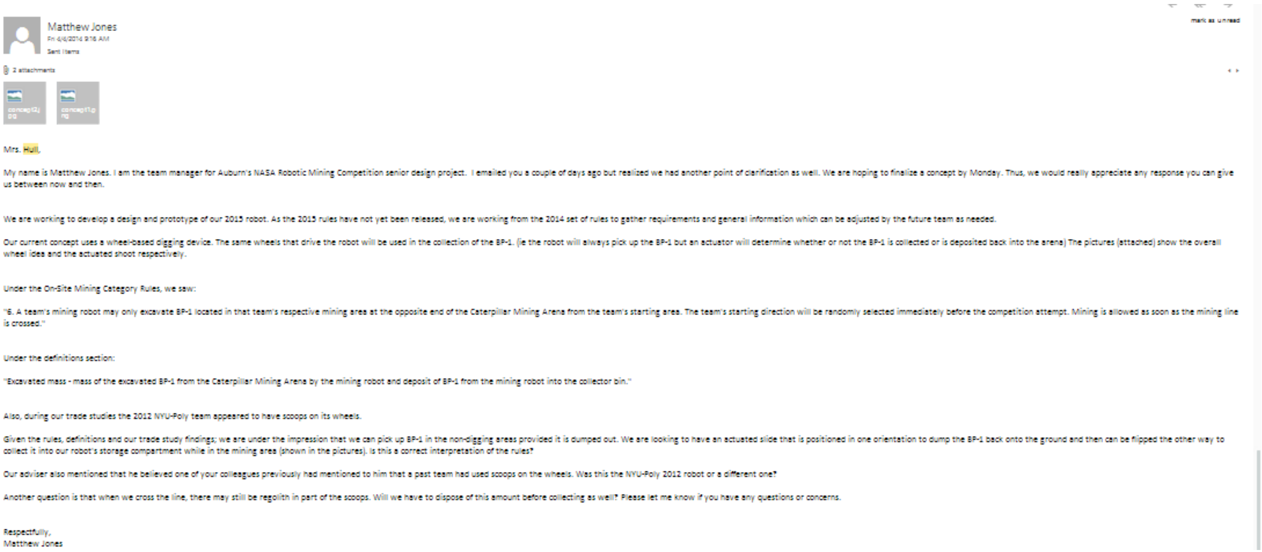


Closed (Sending BP-1 to Bin)



Open (Sending BP-1 back out)





Matthew Jones
Fri 4/4/2014 9:16 AM
Sent Items

Mrs. Hull,

My name is Matthew Jones. I am the team manager for Auburn's NASA Robotic Mining Competition senior design project. I emailed you a couple of days ago but realized we had another point of clarification as well. We are hoping to finalize a concept by Monday. Thus, we would really appreciate any response you can give us between now and then.

We are working to develop a design and prototype of our 2015 robot. As the 2015 rules have not yet been released, we are working from the 2014 set of rules to gather requirements and general information which can be adjusted by the future team as needed.

Our current concept uses a wheel-based digging device. The same wheels that drive the robot will be used in the collection of the BP-1. (ie the robot will always pick up the BP-1 but an actuator will determine whether or not the BP-1 is collected or is deposited back into the arena) The pictures (attached) show the overall wheel idea and the actuated shoot respectively.

Under the On-Site Mining Category Rules, we saw:

"6. A team's mining robot may only excavate BP-1 located in that team's respective mining area at the opposite end of the Caterpillar Mining Arena from the team's starting area. The team's starting direction will be randomly selected immediately before the competition attempt. Mining is allowed as soon as the mining line is crossed."

Under the definitions section:

"Excavated mass - mass of the excavated BP-1 from the Caterpillar Mining Arena by the mining robot and deposit of BP-1 from the mining robot into the collector bin."

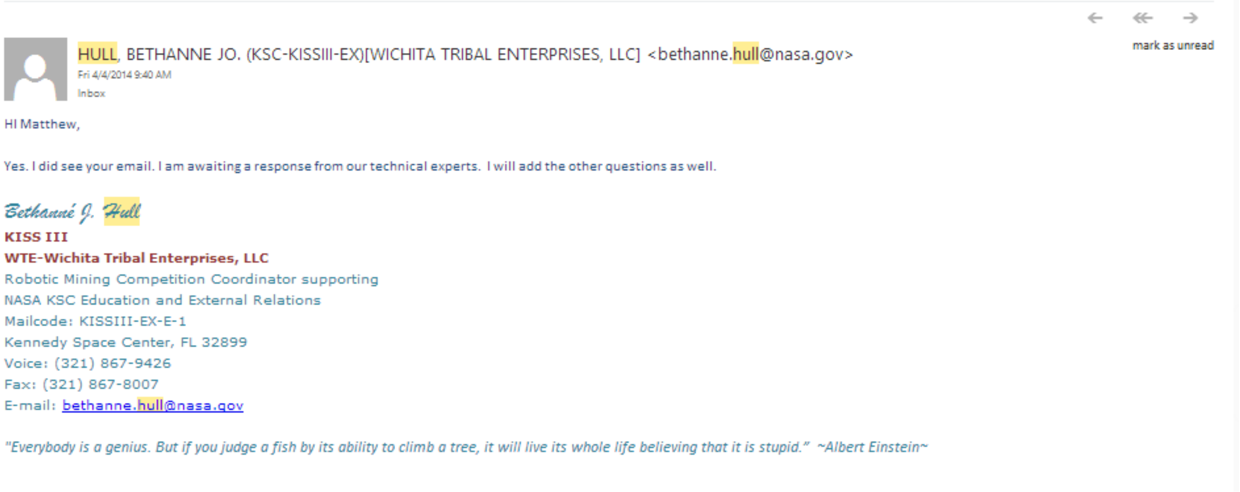
Also, during our trade studies the 2012 NYU-Poly team appeared to have scoops on its wheels.

Given the rules, definitions and our trade study findings; we are under the impression that we can pick up BP-1 in the non-digging areas provided it is dumped out. We are looking to have an actuated slide that is positioned in one orientation to dump the BP-1 back onto the ground and then can be flipped the other way to collect it into our robot's storage compartment while in the mining area (shown in the pictures). Is this a correct interpretation of the rules?

Our adviser also mentioned that he believed one of your colleagues previously had mentioned to him that a past team had used scoops on the wheels. Was this the NYU-Poly 2012 robot or a different one?

Another question is that when we cross the line, there may still be regolith in part of the scoops. Will we have to dispose of this amount before collecting as well? Please let me know if you have any questions or concerns.

Respectfully,
Matthew Jones



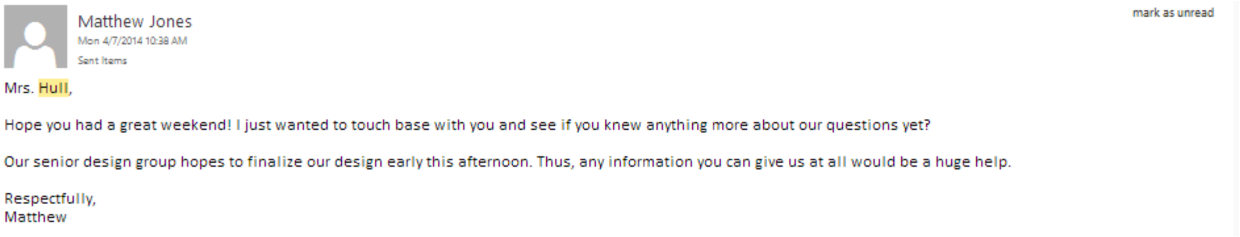
HULL, BETHANNE JO. (KSC-KISSIII-EX)[WICHITA TRIBAL ENTERPRISES, LLC] <bethanne.hull@nasa.gov>
Fri 4/4/2014 9:40 AM
Inbox

HI Matthew,

Yes. I did see your email. I am awaiting a response from our technical experts. I will add the other questions as well.

Bethanné J. Hull
KISS III
WTE-Wichita Tribal Enterprises, LLC
Robotic Mining Competition Coordinator supporting
NASA KSC Education and External Relations
Mailcode: KISSIII-EX-E-1
Kennedy Space Center, FL 32899
Voice: (321) 867-9426
Fax: (321) 867-8007
E-mail: bethanne.hull@nasa.gov

"Everybody is a genius. But if you judge a fish by its ability to climb a tree, it will live its whole life believing that it is stupid." ~Albert Einstein~



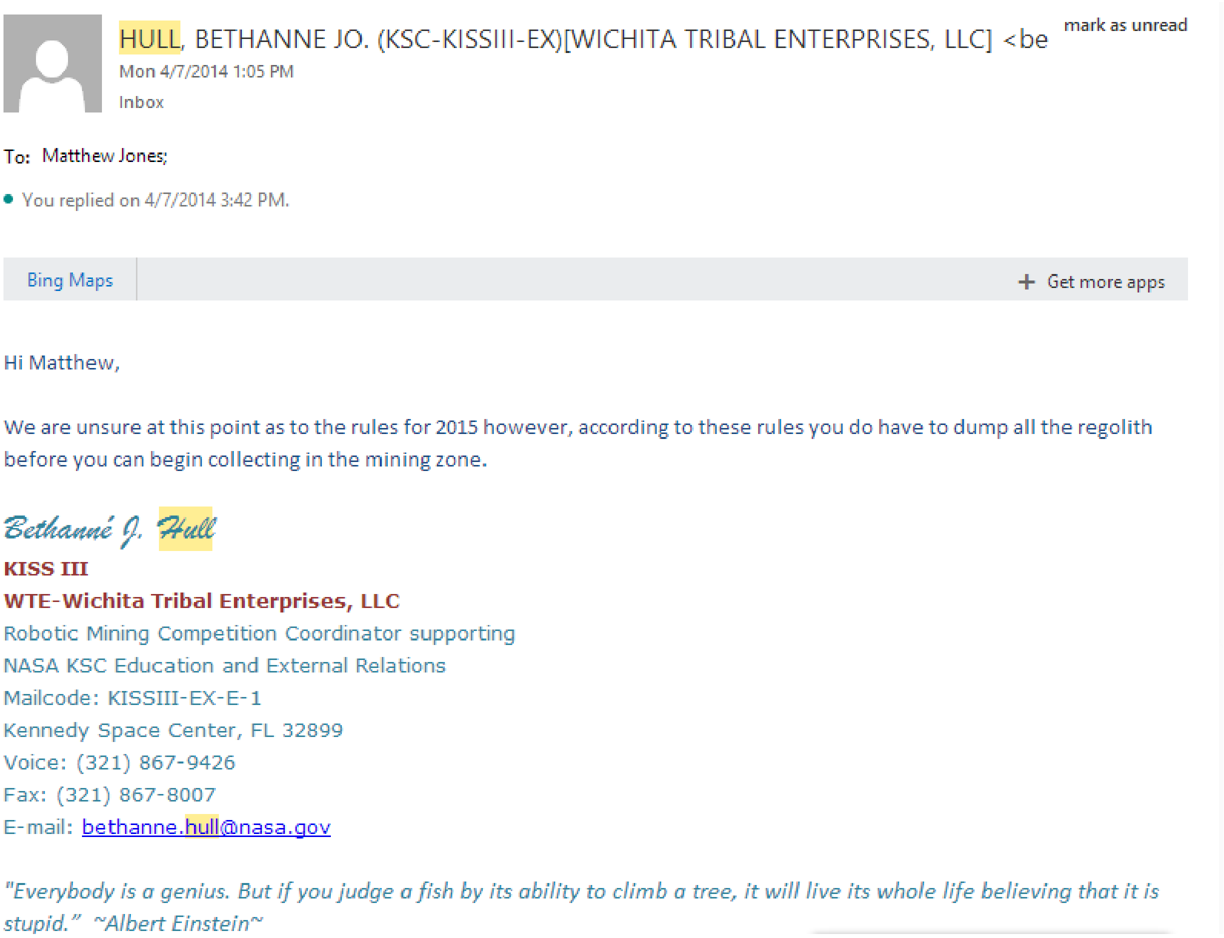
Matthew Jones
Mon 4/7/2014 10:38 AM
Sent Items

Mrs. Hull,

Hope you had a great weekend! I just wanted to touch base with you and see if you knew anything more about our questions yet?

Our senior design group hopes to finalize our design early this afternoon. Thus, any information you can give us at all would be a huge help.

Respectfully,
Matthew



HULL, BETHANNE JO. (KSC-KISSIII-EX)[WICHITA TRIBAL ENTERPRISES, LLC] <be

Mon 4/7/2014 1:05 PM

Inbox

To: Matthew Jones;

- You replied on 4/7/2014 3:42 PM.

Hi Matthew,

We are unsure at this point as to the rules for 2015 however, according to these rules you do have to dump all the regolith before you can begin collecting in the mining zone.

Bethanné J. Hull

KISS III

WTE-Wichita Tribal Enterprises, LLC

Robotic Mining Competition Coordinator supporting
NASA KSC Education and External Relations
Mailcode: KISSIII-EX-E-1
Kennedy Space Center, FL 32899
Voice: (321) 867-9426
Fax: (321) 867-8007
E-mail: bethanne.hull@nasa.gov

"Everybody is a genius. But if you judge a fish by its ability to climb a tree, it will live its whole life believing that it is stupid." ~Albert Einstein~

Appendix D: Virtual Test Run

```
%%%Code for calculating expected course travel during 10 minute run
%NASA Robot Senior Design Spring 2014

clc
clear all

mph=input('Enter wheel speed in miles per hour: '); %most teams run from .25
to .5 mph
meterph= 1609.34*mph; %meters per hour
meterps= meterph/3600; %meter per sec

timemax=10; %10 minutes
timemaxsec=timemax*60; %competition time in seconds

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Competiiton bin size
%%%overall 7.38m x 3.78m

    %Start zone 2x (1.89m x 1.5m)
    Lst=1.5; %length in start zone

    %Obsticle area (3.78m x 2.94m)
    Lobs=2.94;

    %Digging area (3.78m x 2.94m)
    Ldigmax=2.94;
    Wdigmax=3.78;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%Time to cross start (assuming turned around backwards)
orienttime=10; %time to orient robot (sec)

traveltimest=Lst/meterps; %traveling time across start zone
timestartzone=orienttime+traveltimest; %total time in start zone

%%%Time across obstacle zone
alpha=.25; %percentange of full speed through the obstacles
traveltimeobs=Lobs/(alpha*meterps);

%%%Digging time
beta=.25; %percent full speed due to turning and/or digging retardation.
nL=2; %number of length passes
nW=1; %number of width passes
Ldig=nL*Ldigmax+nW*Wdigmax; %length traveled while digging
digtime=(Ldig)/(beta*meterps);
digtimemin=digtime/60; %dig time in minutes

%%%Amount Dug
BP_1denlbin=.027095469; %lb/in^3
%BP_1denlbin=0.05; %ish to check max
BP_1den=BP_1denlbin*27679.9047; %kg/m^3
Nscoops=10; %number of scoops per wheel
wheeldiain=21; %wheel diameter (not including scoop dia) (in)
```

```
wheeldia=wheeldiain*0.0254; %dia in meters
volscoopinch3=38.918;  %volume of one scoop (in^3)
volscoop=volscoopinch3*1.63871e-5; %converted to m^3
sfill=.50; %amount of scoop filled
cir=pi*wheeldia;
digvol=2*(Ldig/cir*Nscoops*sfill*volscoop); %amount dug with 2 digging wheels
BP_1weight=BP_1den*digvol;%weight of BP-1 dug (kg)

%%%%%
%weight per scoop
weightscoopdig=volscoop*BP_1den;
%%%%%

%%Return time
gamma=.75; %retardation due to weight (precent of max speed)
traveltimeobsret= 1/gamma*(traveltimeobs+traveltimest); %time to get back to
collector bin

%%Allign time
tallign=15; %time to allign to collector bin (sec)

%Dump time
timedump=timemaxsec-
(timestartzone+traveltimeobs+digtime+traveltimeobsret+tallign); %maximum
allowed time to dump given other inputs
timedumpmin=timedump/60; %dump time in minutes

%Non-digging and dumping time (Travel time)
traveltimemin= timemax-(timedumpmin+digtimemin); %time not spent digging or
dumping in minutes

%Output
fprintf('\nThe digging distance traveled was %2.3f meters. \n', Ldig)
fprintf('The volume of BP-1 collected was %2.3f meters^3. \n', digvol)
fprintf('The weight of BP-1 collected was %2.3f kg. \n\n', BP_1weight)
fprintf('The weight of BP-1 collected per scoop per rev was %2.3f kg. \n\n',
weightscoopdig)
fprintf('The digging time was %2.3f minutes. \n', digtimemin)
fprintf('The travel time was %2.3f minutes. \n', traveltimemin)
fprintf('The max dumping time was %2.3f minutes. \n\n', timedumpmin)
```

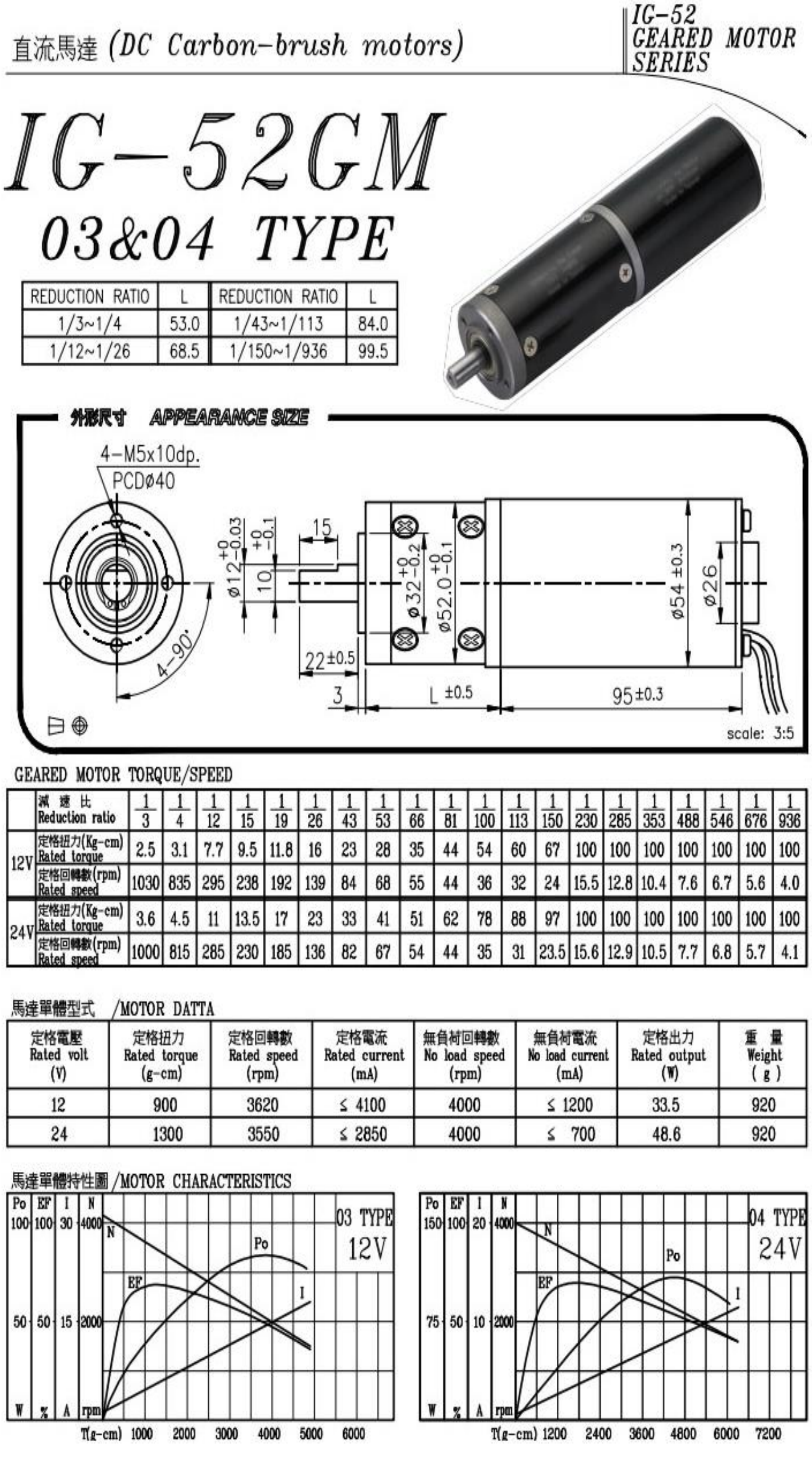
Appendix E: Dumping Auger Simulation

```
%Dumping Auger Analysis and Motor Sizing
%Jay Jeter and Stew Baloo Boyd

clc; clear all;

%___________Auger characteristics
od = 4; %in
id = 1.5; %in
pitch = 2/3*od; %in
length = 36; %in
length_m = length*.0254; %meters
N = length/pitch; %number of turns in auger
theta = 35; %degrees
e = .6; %Efficiency of auger at 35 degree incline

%___________Regolith Characteristics
den_g = 0.75; %g/cm^3
den_kg = 0.75*1000000/1000; %kg/m^3
total_mass = 27.6*3; %kg Total mass to be unloaded
t_mins = 2.5; %min Time available to complete operation
t_secs = t_mins*60;
%___________Volume Equations
V = e*(pi*(od^2-id^2)/4)*pitch*N; %in^3
V_ft3 = V/(12^3); %ft^3
V_m3 = V_ft3*.0283; %m^3
V_act = V_m3; %m^3

%___________Mass Equations
M = V_act*den_kg; %kg Mass contained in one full auger load
m = M/N; %kg Mass of one rotation of screw

%___________RPM Equations
flow = total_mass/t_mins; %kg/min Target Mass Flow Rate
rots_needed = (total_mass/m) + M/N; %turns needed to remove all material
rpm = rots_needed/t_mins; %target motor rpm
rpm_rads = rpm*0.1047; %rad/s
%___________Energy Equations
g = 9.81; %m/s^2
Ixx = 0.0319; %kg-m^2
PE = total_mass*g*length_m*sind(theta) + Ixx*rpm_rads^2; %J potential energy
P_watts = PE/t_secs; %W Power
P_hp = P_watts*0.001341; %hp Power in horsepower
T = (P_hp*5252)/rpm; %Torque in lb-ft
```

Appendix F: Horizontal Auger Simulation

```matlab
%Bin Auger Analysis and Motor Sizing
%Jay Jeter and Stew Baloo Boyd

clc; clear all;

%___________Auger characteristics
od = 6; %in
od_m = od*.0254;
id = 1.5; %in
id_m = id*.0254;
pitch = od; %in
length = 20; %in
length_m = length*.0254; %meters
N = length/pitch; %number of turns in auger
theta = 0; %degrees
e = 1; %Efficiency of auger at 35 degree incline

%___________Regolith Characteristics
den_g = 0.75; %g/cm^3
den_kg = 0.75*1000000/1000; %kg/m^3
total_mass = 27.6*3; %kg Total mass to be unloaded
t_mins = 2.5; %min Time available to complete operation
t_secs = t_mins*60;
%___________Volume Equations
V = e*(pi*(od^2-id^2)/4)*pitch*N; %in^3
V_ft3 = V/(12^3); %ft^3
V_m3 = V_ft3*.0283; %m^3
V_act = V_m3; %m^3
V_flow = V_act/t_secs; %m^3/s

%___________Mass Equations
M = V_act*den_kg; %kg Mass contained in one full auger load
m = M/N; %kg Mass of one rotation of screw

Vel = V_flow/(pi*(od_m^2-id_m^2)/4); %m/s


%___________RPM Equations
flow = total_mass/t_mins; %kg/min Target Mass Flow Rate
rots_needed = (total_mass/m) + M/N; %turns needed to remove all material
rpm = rots_needed/t_mins; %target motor rpm
rpm_rads = rpm*0.1047; %rad/s

%___________Energy Equations
g = 9.81; %m/s^2
Ixx = 0.00572; %kg-m^2
KE = 0.5*total_mass*Vel^2 + Ixx*rpm_rads^2; %J Kinetic Energy
P_watts = KE/t_secs; %W Power
P_hp = P_watts*0.001341; %hp Power in horsepower
T = (P_hp*5252)/rpm; %Torque in lb-ft
```

Appendix G: Motors



直流馬達 *(DC Carbon-brush motors)*

IG-52
GEARED MOTOR
SERIES

IG-52GM

03&04 TYPE

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

外形尺寸 **APPEARANCE SIZE**

GEARED MOTOR TORQUE/SPEED

	減速比 Reduction ratio	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
12V	定格扭力(Kg-cm) Rated torque	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
	定格回轉數(rpm) Rated speed	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	定格扭力(Kg-cm) Rated torque	3.6	4.5	11	13.5	17	23	33	41	51	62	78	88	97	100	100	100	100	100	100	100
	定格回轉數(rpm) Rated speed	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

馬達單體型式 /MOTOR DATTA

定格電壓 Rated volt (V)	定格扭力 Rated torque (g-cm)	定格回轉數 Rated speed (rpm)	定格電流 Rated current (mA)	無負荷回轉數 No load speed (rpm)	無負荷電流 No load current (mA)	定格出力 Rated output (W)	重量 Weight (g)
12	900	3620	≤ 4100	4000	≤ 1200	33.5	920
24	1300	3550	≤ 2850	4000	≤ 700	48.6	920

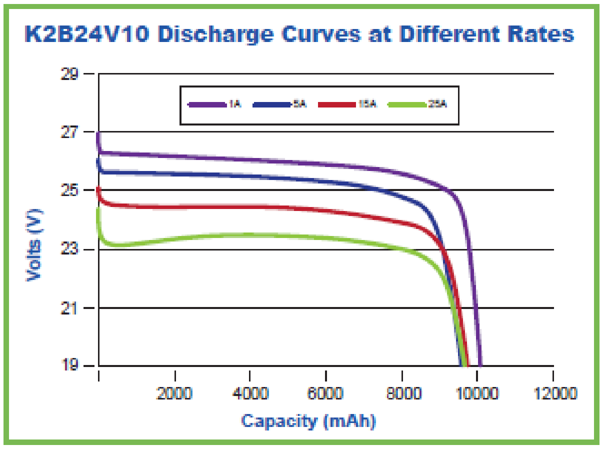
馬達單體特性圖 /MOTOR CHARACTERISTICS

Appendix H: Battery

K2 Energy®

Executing Engineering Excellence

HIGH CAPACITY K2B24V10EB ENERGY MODULE DATA


K2B24V10 Discharge Curves at Different Rates

SPECIFICATIONS:

Nominal Capacity @ C/5 (Ahr)	9.6
Average Operating Voltage @ C/5	25.6
Weight (kg)	2.5
Height (mm)	165.0
Width (mm)	89.5
Length (mm)	115.0

RECOMMENDED OPERATING CONDITIONS:

Continuous Discharge (A)	≤9.6
Pulse Discharge (A) 30 seconds	25
Charge Current (A)	≤4.8
Charge Voltage Cutoff (V)	29.2
Discharge Voltage Cutoff (V)	20.0
High Temp Operating Temp (°C)	60
Low Temp Operating Temp (°C)	-20

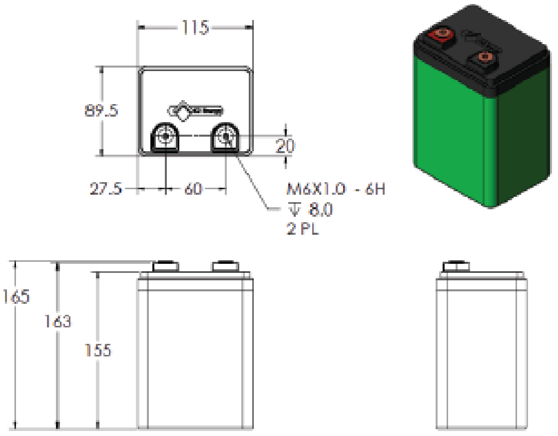
MAXIMUM OPERATING CONDITIONS:

Continuous Discharge (A)	≤24
Pulse Discharge (A) ≤2 seconds	40
Charge Current (A)	≤9.6
Charge Voltage Cutoff (V)	32.8
Discharge Voltage Cutoff (V)	16.0
Max Module In Series	1

Performance may vary depending on application. All specifications and operation conditions are subject to change without notice. This data is for evaluation purposes only. No guarantee is intended or implied by this data.

K2B24V10 Constant Current Time Profile @ 25°C				
C/20 (0.48 A)	C/2 (4.8 A)	1C (9.6 A)	2C (19.2 A)	2.6C (25 A)
20 hrs	2 hrs	60 min	29 min	24 min
ADVANCED FEATURES				
Short Circuit Protection	High Voltage Cut Off	Low Voltage Cut Off	Cell Balancing	Compatible With Most 24V Lead Acid Chargers

DIMENSIONS:



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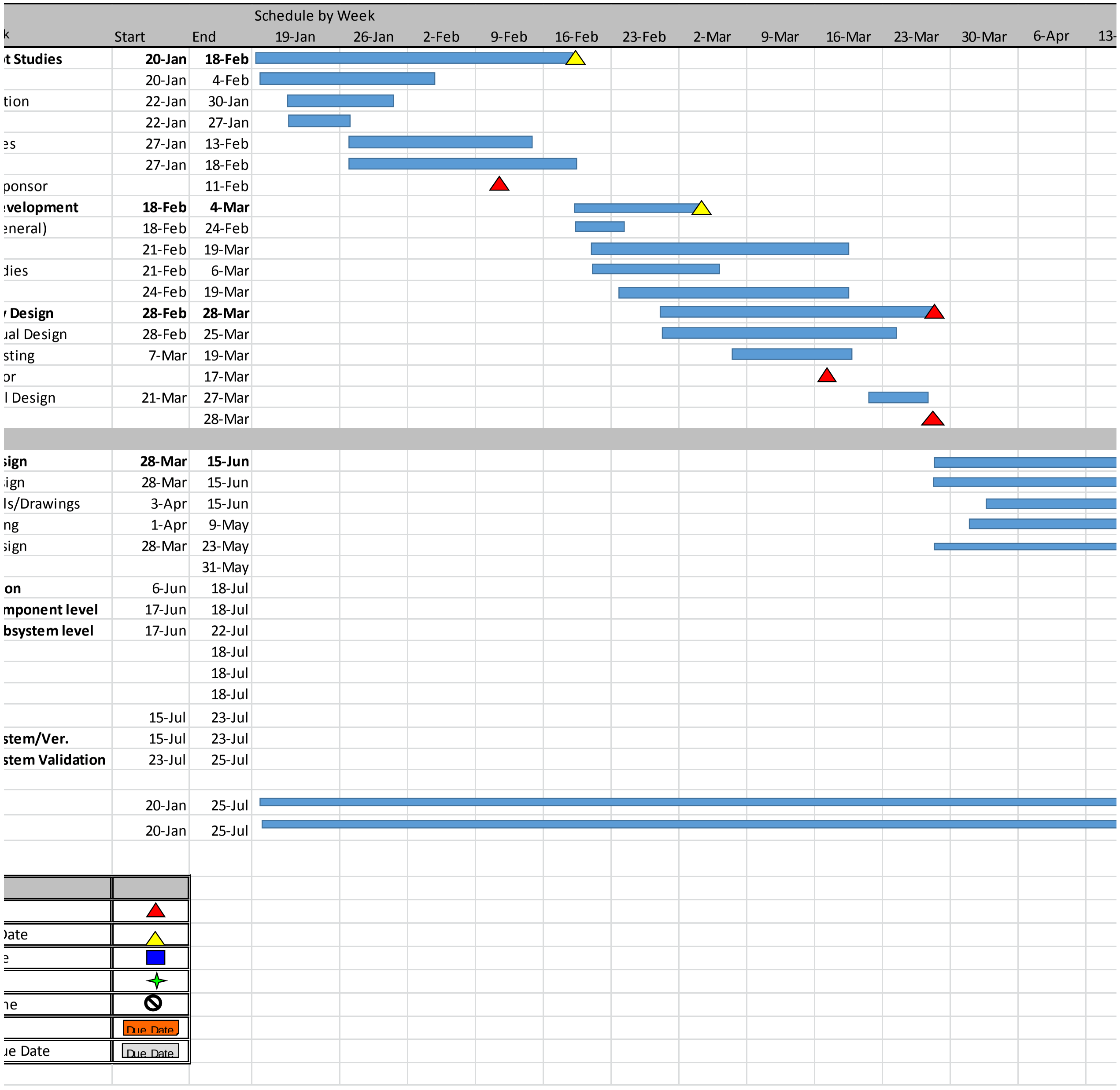
Appendix I: Gantt Chart



k	Start	End
t Studies	**20-Jan**	**18-Feb**
	20-Jan	4-Feb
tion	22-Jan	30-Jan
	22-Jan	27-Jan
es	27-Jan	13-Feb
	27-Jan	18-Feb
ponsor		11-Feb
evelopment	**18-Feb**	**4-Mar**
eneral)	18-Feb	24-Feb
	21-Feb	19-Mar
dies	21-Feb	6-Mar
	24-Feb	19-Mar
Design	**28-Feb**	**28-Mar**
ual Design	28-Feb	25-Mar
sting	7-Mar	19-Mar
or		17-Mar
l Design	21-Mar	27-Mar
		28-Mar
sign	**28-Mar**	**15-Jun**
ign	28-Mar	15-Jun
ls/Drawings	3-Apr	15-Jun
ng	1-Apr	9-May
sign	28-Mar	23-May
		31-May
on	6-Jun	18-Jul
mponent level	17-Jun	18-Jul
bsystem level	17-Jun	22-Jul
		18-Jul
		18-Jul
		18-Jul
	15-Jul	23-Jul
stem/Ver.	15-Jul	23-Jul
stem Validation	23-Jul	25-Jul
	20-Jan	25-Jul
	20-Jan	25-Jul

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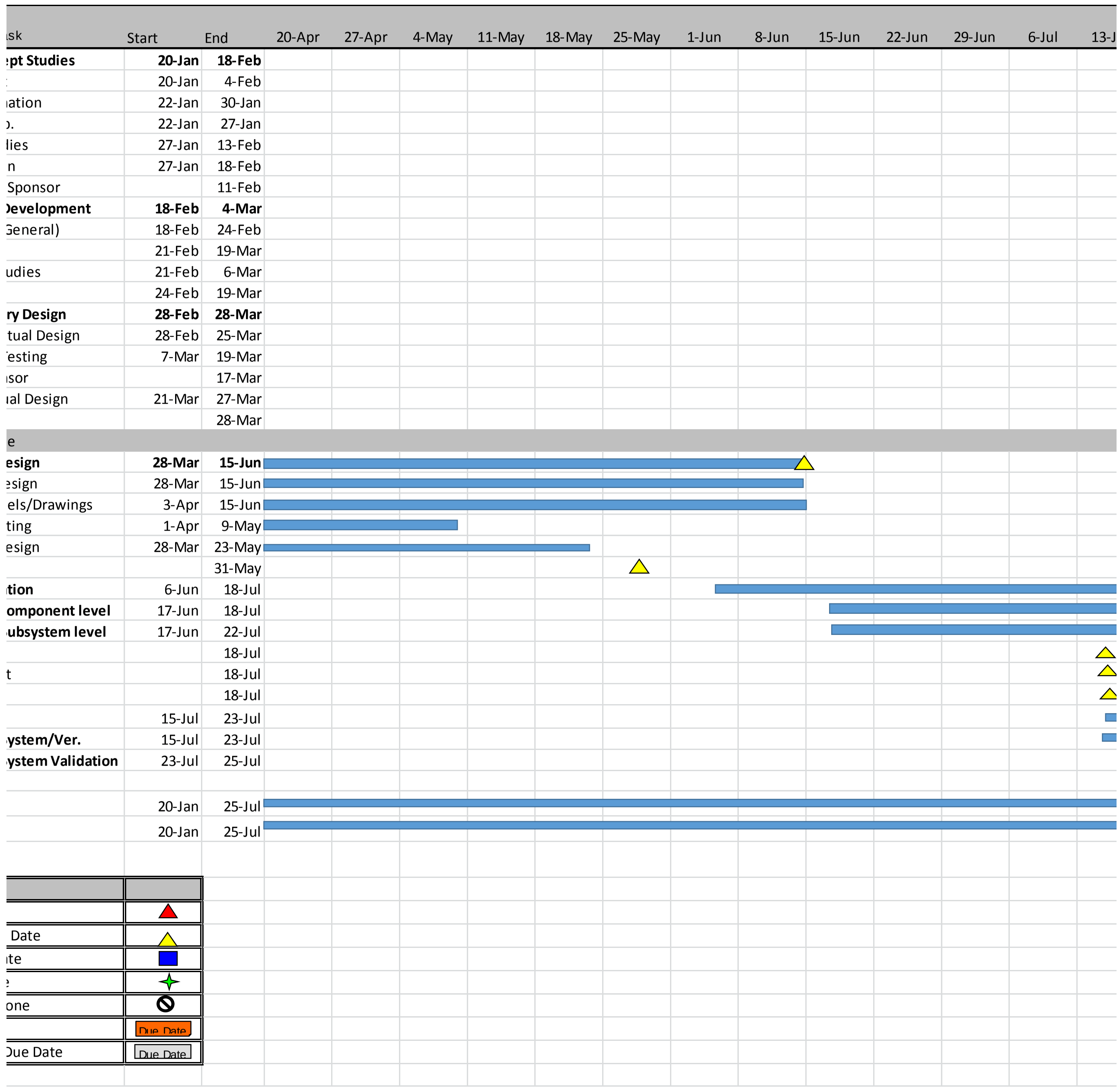
Gantt Chart (continued)



sk	Start	End
pt Studies	**20-Jan**	**18-Feb**
	20-Jan	4-Feb
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.	22-Jan	27-Jan
lies	27-Jan	13-Feb
n	27-Jan	18-Feb
Sponsor		11-Feb
evelopment	**18-Feb**	**4-Mar**
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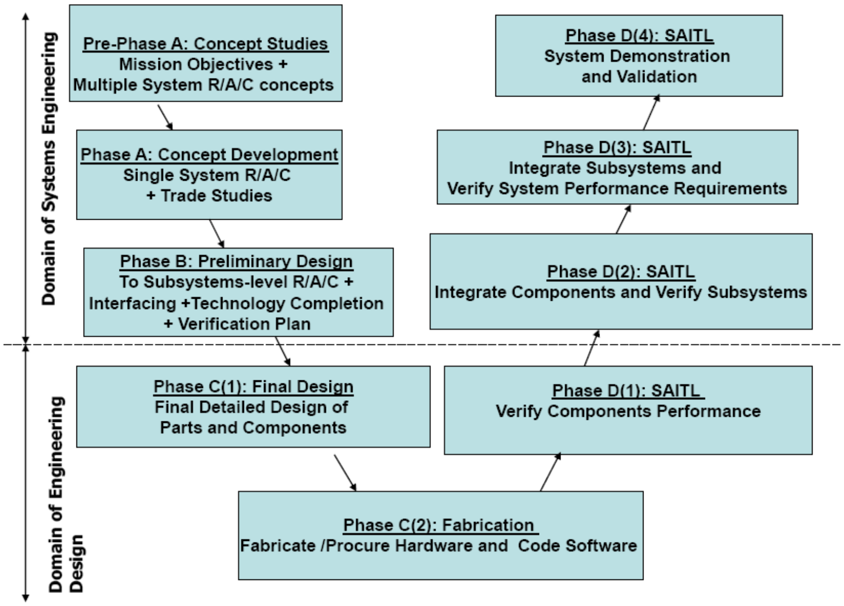
Appendix J: Vee Chart



Appendix K: Risk Management Chart

Priority	Description	Risk Expectation	Required Follow-up	Type	Required Action/Status
1	Wheel Jammed	Likelihood: Low Consequence: Failure to dig and/or drive (Mod)	Research/Testing	Technical	Determine method to ensure jams don't happen
2	BP-1 Not Sliding into Bin	Likelihood: Mod Consequence: Buildup of BP-1 on ramp (Mod)	Testing/Watch	Technical	Initial tests say 30 degrees is sufficient. Follow-up tests when fabricating
3	Auger(s) Jammed	Likelihood: Mod Consequence: Buildup of BP-1 in bin/no dumping ability (Hi)	Research/Testing	Technical	Test when fabricating
4	Dirt in Drivetrain	Likelihood: Mod Consequence: Malfunction/failure (Mod)	Testing/Watch	Technical	Test to ensure dust cover provides sufficient cover/clean between runs
5	Linear Actuator in Wheel Fails	Likelihood: Low Consequence: No digging or disqualified run (Hi)	Watch	Technical	Examine during test runs and before each competition run
6	Loss of Comm System	Likelihood: High, Lo Consequence: Loss of control -Temporary (Lo) -Permanent (Hi)	Research/Testing	Technical	Ensure ability to reconnect, allow autonomous operations to take over
7	Malfunction in Autonomy	Likelihood: Mod Consequence: Loss of autonomy points (Lo)	Research/Testing	Technical	Introduce redundancy in autonomous sensors, provide checks in software
8	Electrical Short	Likelihood: Low Consequence: Loss of control/fire (Hi)	Watch	Safety/Technical	Ensure kill switches work before each run
9	Robot Tips Over	Likelihood: Low Consequence: Loss of control (Hi)	Testing/Watch	Technical	Make sure weight of BP-1 dug is centered between wheels

Appendix L: Scoop Gathering Rate

```
%NASA Mining Robot

clear,clc
% Parameters                            % Units
BP1_Density=0.0406432;                     % lb/in^3
%%%%%%%%%%%%%%%%%%%%% Design Parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Efficiency = 0.10;                      % Volume Dirt/Volume Scoop
diaWheel=20;                            % in
scoopVolume=29.376;                          % in^3
numScoops=10;                             %
AngularSpeed=.5;                          % rad/s
RPM = AngularSpeed*(60/(2*pi));                   % rpm
NumOfWheels=2;                             % number of wheels that dig

%%%%%%%%%%%%%%%%%%%% Simulation Parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
RunTime=60;                             % s

%%%%%%%%%%%%%%%%%%%% Calculations
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
perimeter=pi*diaWheel;                       % in
spacing=perimeter/numScoops;                     % in/scoop
Velocity=(diaWheel/2)*AngularSpeed;                  % in/s
DumpRate=Velocity/spacing;                      % scoops /second
% Amount of BP1 per scoop
AmountBP1=scoopVolume*BP1_Density*Efficiency;          %lbs/scoop
% Harvest Rate BP1 Per Seconds
BP1HarvestRate=AmountBP1*DumpRate*NumOfWheels;          % lbs/s

% Total BP1 harvested
TotalBP1=BP1HarvestRate*RunTime;                    % lbs

%%%%%%%%%%%%%%%%%% Printing to terminal
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fprintf('\tTarget BP1 To Harvest\n')
fprintf('\t10kg = 22.05lbs\n\n')
fprintf('\tSimulation Results\n')
fprintf('\tRun Time [s]\tDump Rate [lbs/s]\tAmount BP1 [lbs]\n')
fprintf('\t%11.2f\t\t%16.2f\t\t%11.2f\n\n',RunTime,BP1HarvestRate,TotalBP1)

fprintf('\tIndividual Wheel Excavating Spec\n')
fprintf('\tWheel speed [rpm]\tAmount/Scoop [lbs]\tEfficiency [%%]\n')
fprintf('\t%16.2f\t\t%13.2f\t\t%9.2f\n',RPM,AmountBP1,Efficiency*100)
fprintf('\tTotal Amount/Wheel [lbs]\n')
fprintf('\t%23.2f\t\t\n',AmountBP1*DumpRate*RunTime)
```

Appendix M: NASA Lunabot Scoring MATLAB Code

```
%%%NASA LUNABOT SCORING
%%%Matthew Jones, David Faucett, Stewart Boyd, Will Flournoy
%%%Spring 2014

%%This file is intended to estimate the amount of points received per "NASA's Fifth Annual
Robotic Mining Competition Rules and
%%Rubrics 2014."

clc
clear all

%%%Inputs
SafeandCommCheck=input('Pass safety and comm check? (yes=1 n=0) ');
KG=input('Amount of BP1 dug(kg) ');
DATA=input('Amount of kilobits/second average data(kb/sec) ');
WEIGHT=input('Weight of robot (kg) ');
engycon=input('Was energy consumption reported after run (yes=1,  no=0) ');

%%%Dust inputs - (judge's discretion)
dustdrive=input('Enter number from 0 to 10 for points for drivetrain components
enclosed/protected and other component selection ');
   if dustdrive <0 | dustdrive>10
      error('Check input for drivetrain dust.')
   end
dustsealing=input('Enter number from 0 to 10 for points for custom dust sealing features
(bellows,seals,etc.) ');
   if dustsealing <0 | dustsealing>10
      error('Check input for dust sealing features.')
   end
actdust=input('Enter number from 0 to 10 for active dust control (brushing, electrostatics,etc.) ');
   if actdust <0 | actdust>10
      error('Check input for active dust control.')
   end
dustmove=input('enter number from 0 to 20 for driving without dusting up crushed basalt ');
   if dustmove <0 | dustmove>20
      error('Check input for driving without dust.')
   end
dustdig=input('enter number from 0 to 30 for digging without dusting up crushed basalt ');
   if dustdig <0 | dustdig>30
      error('Check input for digging dust.')
   end
dusttransf=input('Enter from 0 to 20 points for transferring crushed basalt without dumping on
robot ');
   if dusttransf <0 | dusttransf>20
      error('Check input for transfer dust.')
```

```
    end

%%%Autonomy Inputs
    autoindex=input('What did robot autonomously robot do? (No autonomy=0  Cross field=1
Cross and excavate=2  Deposit once=3   Full 10 min=4) ');

%%%Start of main code
maxweight=80; %maximum dry weight of robot per rules
if WEIGHT > maxweight
    error('Robot too heavy')
else
    %%%Pass Saftey and comm check
    if SafeandCommCheck == 1
    SafeComm=1000;
    elseif SafeandCommCheck == 0
        error('Must pass safety and comm check to compete.')
    else
        error('Please enter a 1 or 0 for saftey and comm check.')
    end

    %%%Points per kg dug
        initial=10; %10kg to qualify
    if  KG<initial
        DigPoints=0;
        totalpoints=0;
    else
        pointsperkg=3; %points per kg Bp-1 dug over qualifying value
        DigPoints=pointsperkg*(KG-initial);

        %%%Points per 50kb/sec avg data
        datadeduct=(-1/50); %points per kb/sec
        DataPoints= datadeduct*DATA;

        %%%Points per kg mining robot weight
        weightdeduct=-8; %points per kg of robot dry weight
        WeightPoints= weightdeduct*WEIGHT;

        %%%Points for stating energy consumption after run
        if engycon==0 %not stated
            engyconpoints=0;
        elseif engycon==1 %stated
            engyconpoints=20;
        else
            error('Please enter a 1 or 0 for energy consumption reported.');
        end
```

```
        %%%Points for dust free operation
        dustpoints=dustdrive+dustsealing+actdust+dustmove+dustdig+dusttransf;

        %%%Autonomy
        if autoindex == 0 %No autonomy
            autopoints=0;
        elseif autoindex == 1 %Cross field
            autopoints=50;
        elseif autoindex == 2 %Cross field and dig
            autopoints=150;
        elseif autoindex == 3 %One complete run
            autopoints=250;
        elseif autoindex == 4 %Full 10 minutes
            autopoints=500;
        else
            error('Check autonomous input.')
        end

        %%%Total points calc

totalpoints=SafeComm+DigPoints+DataPoints+WeightPoints+engyconpoints+dustpoints+autop
oints

    end
end
```

Appendix N: Bill of Materials (At the time of CDR)

Bill of Materials

2 Digging Wheels and 2 Non Digging Wheels			
Material	Amount	Cost per [$]	Total [$]
6061 Aluminum Tube 1.5" OD 1.25" ID Tube	1	45.72	45.72
6061 Aluminum Tube OD 2.25" ID 1.25" Tube	1	18	18
6061 Aluminum Plate 0.188" Thick	1	15.03	15.03
6061 Aluminum Square Tube 0.5"X0.5" 1/16" wall thickness	1	18.72	18.72
6061 Aluminum Rec. Tube 0.5"X1.0" 1/16" wall thickness	1	21.6	21.6
6061 Aluminum Rec. Tube 0.25"x0.5" 1/16" wall thickness	1	40.84	40.84
6061 Aluminum Tube OD 0.5" ID 0.402"	1	18.2	18.2
6061 Aluminum Tube OD 0.75" ID 0.5"	1	7.2	7.2
6061 Aluminum Sheet Metal 0.090" thick sheet	1	34.64	34.64
6061 Aluminum Sheet Metal 0.063" thick	1	96	96
6061 Aluminum Sheet Metal 0.09" thick	1	42.56	42.56
6061 Aluminum Bar 0.188"x0.50"	1	14.08	14.08
Rubber sheet 0.050" Thick	1	30.43	30.43
IG52-04 24 VDC 82 RPM	4	135	540
Steel Roller Chain Sprocket for #25 Pitch Chain - 09 Teeth	4	9.67	38.68
Steel Roller Chain Sprocket for #25 Pitch Chain - 45 Teeth	2	29.18	58.36
Steel Roller Chain Sprocket for #25 Pitch Chain - 60 Teeth	2	36.62	73.24
Continuous pull solenoid. Holding force 12.8 N, Voltage 24 VDC	2	20.42	40.84
Bearing Shaft Dia 0.75" OD 1.781"	4	11.87	47.48
Bearing Shaft Dia 5/8" OD 1.125"	4	8.62	34.48
	22	0.88	19.36
	Total (wheels)		1255.46

Auger/Bin/Chassis			
Material	Amount	Cost per [$]	Total [$]
IG42-04 24 VDC 340 RPM	2	55	110
4" on Stainless Steel Center Tube	3	21.17	63.51
5 5/8" on Stainless Steel Center Tube	1.67	25.45	42.50
1" Pillow Block Bearing	1	14.97	14.97
1" Flange Bearing	1	9.18	9.18
PVC End Cap	1	7.71	7.71
PVC 38"L 4"D	1	12.17	12.17
EconomyPlate Carbon Fiber 8 ft^2	1	190.00	190.00
Plaskolite Corrugated Sheet	1	8.49	8.49
1"x1" Aluminum Square Tube 6 ft	1	20.58	20.58
Aluminum Angle Bar 4 ft	1	12.60	12.60
Aluminum 1"D 8 ft	1	56.16	56.16
1/8" Aluminum Sheet 2 ft^2	1	27.50	27.50
1" Bearing	1	17.99	17.99
	Total Auger/Bin/Chassis		593.3615

Electronics			
Material	Amount	Cost per [$]	Total [$]
Arduino Due	1	49.95	49.95
DC Motor Driver 20A RKI-1340	6	10.78	64.68
Adafruit Motor/Stepper/Servo Shield v2	1	19.95	19.95
K2 25.6V LiFePO4 Battery Pack 9.6Ahr	2	359.00	718.00
	Total (Electronics)		852.58

Hardware			
1/4 X 20 X 1.25 LG HHCS 100 PACK	1	7.760	7.760
1/4 x 20 LOCKNUT 100 PACK	1	7.950	7.950
Grommets			
1/4 WASHER 100 PACK	2	3.300	6.600
	Total Hardware		22.310
	Total (Overall)		2723.712

Appendix O: Purchases for the Prototype

Date	Vendor	Item	Unit Price	Quantity	Price	Shipping	Total
06/06/2014.	Metals Depot	T21121 1-1/2 OD x .250 wall x 1.00 ID 1020 DOM Structural Round Steel Tube	$20.02	1	$20.02	$19.08	$90.76
		T13416 3/4 X 3/4 X 16 GA (.065 wall) A513 Steel Structural Square Tube	$28.96	1	$28.96		
		S214 14 GA. (.079 thick) Steel Sheet Galvanized Steel Sheet	$19.76	1	$19.76		
		T11216 1/2 X 1/2 X 16 GA (.065 wall) A513 Steel Structural Square Tube	$5.10	1	$5.10		
		R112 1/2 inch Dia. Round Bar Hot Rolled A-36 Steel Round	$2.20	1	$2.20		
		S218 18 GA. (.052 thick) Steel Sheet Galvanized Steel Sheet	$14.72	1	$14.72		
6/18/2014	McMaster	6384K49 Steel Ball Bearing, Plain Double Sealed for 1/2" Shaft Diameter, 1-1/8" OD	$9.86	8	$78.88	$5.10	$83.98
7/1/2014	McMaster	1497K61 Fully Keyed 1045 Steel Drive Shaft, 3/4" OD, 3/16" Keyway Width, 24" Length	$33.23	1	$33.23	$5.69	$38.92
		1610T37 Multipurpose 6061 Aluminum, 4" Diameter, 1/2" Long	$7.64	2	$15.28	$18.98	$81.07
		6068K19 Split-Tapered Bushing, Style H, 3/4" Bore	$14.70	2	$29.40		
		6527K114 Low-Carbon Steel Square Tube, 1/2" W, 1/2" H, .060" Wall Thickness, 6' Length	$8.72	1	$8.72		
		6389K434 Nylon Bearing, Flanged, for 3/4" Shaft Diameter, 1" OD, 3/4" L, 5/32" Thickness, Packs	$8.69	1	$8.69		
7/3/2014	McMaster	1610T38 Multipurpose 6061 Aluminum, 4-1/4" Diameter, 1/2" Long	$8.72	2	$17.44	$5.42	$22.86
7/8/2014	Tindie	Arduino PlayStation DualShock Shield	$18.00	1	$18.00	$5.50	$23.50
7/9/2014	McMaster	1610T39 Multipurpose 6061 Aluminum, 4-1/2" Diameter, 1" Long	$14.84	1	$14.84	$5.69	$68.13
		5913K73 Stamped-Steel Mounted Ball Bearing--ABEC-1, 2-Bolt Flange Mount, for 3/4" Shaft Diam	$11.90	4	$47.60		
7/10/2014	McMaster	3113K69 SAE 841 Bronze Flanged Sleeve Bearing with Certificate, for 3/4" Shaft Diameter, 7/8" C	$2.44	2	$4.88	$5.33	$37.46
		6086K113 Quick-Disconnect (QD) Bushing, Style JA, 3/4" Bore, 3/16" X 3/32" Keyway	$12.24	2	$24.48		
		98535A140 Spring Steel Standard Key Stock, 3/16" X 3/16", 12" Length	$2.11	1	$2.77		
7/14/2014	McMaster	3113K26 SAE 841 Bronze Flanged Sleeve Bearing with Certificate, for 3/4" Shaft Diameter, 7/8" C	$2.44	2	$4.88	$4.86	$31.46
		680K321 Steel Finished-Bore Roller Chain Sprocket, for #35 Chain, 3/8" Pitch, 10 Teeth, 3/8" Bore	$10.86	2	$21.72		
7/15/2014	McMaster	62375K18 Quick-Disconnect Bushing-Bore Sprocket, for #35, 3/8" Pitch Chain, 30 Teeth, JA Bush	$34.00	2	$68.00	$5.33	$73.33
6/27/2014	Amazon	DROK Adjustable 4.0-40V to 1.25-37V 5/12V DC LM2596 Voltage Regulator Experimental Power E	$8.93	2	$17.86	$0.00	$17.86
6/30/2014	SuperDroid Robots	TD-045-285 IG52-04 24VDC 285 RPM Gear Motor with Encoder	$141.43	1	$141.43	$8.37	$149.80
7/14/2014	SuperDroid Robots	TD-045-285 IG52-04 24VDC 285 RPM Gear Motor with Encoder	$141.43	1	$141.43	$8.37	$149.80
7/17/2014	Tractor Supply Company	Roller Chain Size 35 10ft.	17.99	1	17.99	$0.00	$17.99
		16 Gauge Wire	$6.99	2	$13.98	$0.00	$13.98
		10-24 x 1 SHCS	$1.29	1	$1.29	$0.00	$1.29
		Chain Link Connectors Size 35	$2.99	1	$2.99	$0.00	$2.99
		Black Electrical Tape	$6.99	1	$6.99	$0.00	$6.99
		6-32 x 3/8 PHMS	$1.29	2	$2.58	$0.00	$2.58
		6-32 x 3/4 PHMS	$1.49	4	$5.96	$0.00	$5.96
		M5-80 SHCS	$0.99	4	$3.96	$0.00	$3.96
		6-32 Hex Nut	$1.29	4	$5.16	$0.00	$5.16
7/22/2014	McMaster	Part # 62375K19 # 35 Chain, 40 Tooth Quick Disconnect Sprocket	$37.41	1	$37.41	$5.00	$42.41
		Part #6086K213 Quick Disconnect Bushing Stle SH for 3/4" Bore	$16.73	1	$16.73	$5.00	$21.73
						Sum	$993.97

Appendix P: References

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