Mech 4240 Preliminary Design Review (PDR)

NASA Robotic Mining Competition Design Team - Corp 5

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Abstract

The goal of Corporation Five's senior design project was to alter and improve the 2014 NASA Robotic Mining robot developed at Auburn, with the goal of producing an autonomous and lightweight robot for the 2015 NASA Robotic Mining Competition. The 2015 NASA competition rules, previous design specifications and research, as well as testing and experimentation were used to develop a functional and competitive design.

NASA's robotic mining competition has several parameters that have been constant for the last several years in addition to two new developments published in the 2015 regulations. Black Point 1 (BP-1) constitutes the soil on the competition track, with a newly added simulant for the icy gravel expected on Mars. A new restriction for autonomy is also included disallowing contact with the edges of the competition arena for navigation.

Through the use of such engineering tools as the Vee Chart, the 11 system engineering functions, and detailed trade studies, an innovative and competitive design was developed. A conveyor digging system in combination with an auger delivery system and an innovative wheel-leg locomotion system were selected for the robot. The conveyor is a subsystem proven effective by several years of legacy in the competition, shown in the trade study, and the auger system underwent extensive testing last semester to verify its effectiveness. Gravel tests on the auger indicated that a wide inlet was necessary to prevent gravel from jamming in the mouth, and corrections have been made. The Conveyor/auger system provides an efficient solution with simple functions for autonomous control. The wheel-leg system has never been used in this competition before and was designed by Auburn engineering students for this purpose. It is an innovative and unique system, which places Auburn's Robotics team in an advantageous position for winning the NASA ingenuity award. To achieve the goal of making the Robot lightweight, the frame has been designed in carbon fiber, and the bucket dimensioned in such a way as to permit the use of gravity in place of a mechanism to load regolith into the auger.

Review of the competition point structure showed that the most effective way to win the on-site mining portion of the competition is to complete the competition run autonomously. The ability to run the robot autonomously combined with the low weight of the current robot design exceeds the point gain that might be possible with a design focused on heavy digging and collection of large amounts of regolith.

This design is to be completed by February of 2015 and will include dimensioned drawings of manufactured parts, a bill of materials, any necessary records of testing and prototyping, and a complete technical resource budget. By the end of spring 2015 this design will be manufactured and in competition. Autonomous function for the robot will be achieved by the end of spring 2015 through the the Space Club team and an electrical senior design team.

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1.0 Introduction

The objective of this semester is to design the systems necessary to complete a functioning robotic miner to take to the NASA competition in May of 2015. The problems associated with completing this objective are the strict adherence to the NASA competition rules (attached in Appendix A) and building a robust, reliable robot that is lightweight, autonomous, and simplistic. Auburn University has not been able to field a successful mining robot within the past three competition years, so it is important that the robot currently being designed be a strong contender for the 2015 competition as well as provide a platform for future design teams to optimize and improve.

The current design team has received data from previous design teams in order to expedite the design process and eliminate poor design concepts. Research of previous competition winners yielded a better understanding of what concepts work and what to reject. The mechanical design team has collaborated closely with the Auburn Space Club to split up work tasks, garner expert advice on unfamiliar systems, and ensure interfacing different subsystems is as smooth as possible.

This report will cover a design breakdown of the robotic subsystems, explanations on why different concepts were chosen or rejected, validation tests for critical subsystems, and a rough budget analysis for overall robot cost.

2.0 Mission Objective

The object of this project is to design the mechanical systems of an excavation robot capable of autonomously navigating and digging in a simulated Martian environment. The robot should be as lightweight as possible while also digging as much as possible. The robot should also include simple subsystems in order to achieve autonomy.

3.0 Environment

The NASA Robotics Competition has be designed to simulate a Martian or asteroid surface. The soil used to simulate the Martian surface is called Black Point 1 (BP-1). The BP-1 will be on the top 30 cm of the surface. Gravel will be used to simulate icy regolith below the 30 cm of BP-1. This gravel may be mixed in with the BP-1 and is not necessarily just below 30 cm. The gravel will be a minimum of 2 cm in diameter with some larger particle sizes mixed into the gravel.

The pit in which the robot will be placed will be 7.38 meters long and 3.88 meters wide and 1 meter in depth. The arena will consist of two pits contained inside an air-conditioned tent without significant air currents and cooled to approximately 77 degrees Fahrenheit. Each pit will have three zones designated Start (1.89 x 1.5m), Obstacle Area (3.78x 2.94m), and Mining Area (3.78 x 2.94m). A collection bin will be placed at the Starting zone .5 m above the BP-1 surface. Figure 1 shows the whole arena as well as the three zones of each pit.

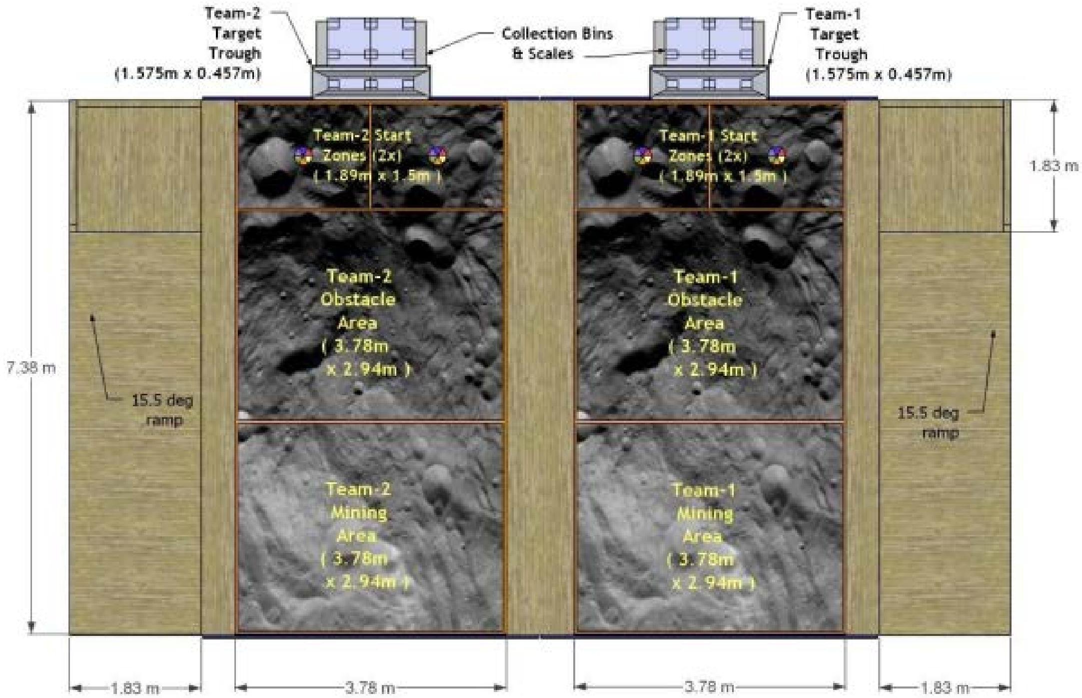


Figure 1: Competition Pit Dimensions

4.0 Project Management

The mechanical design team is managed by Chris Oliver. Clark Williams is the lead designer for the digging subsystem. Elizabeth Swaim is leading the delivery subsystem and co-leading storage design. Sukrit Kumar is the lead for frame subsystem design and also a co-lead for the storage system.

5.0 Requirements

As the team came up with concepts for the design of the robot, the rules for the NASA Robotic Mining Competition as shown in Appendix A. The system must fit in a volume of 1.5 m (length) x 0.75 m (width) x 0.75 m (height). The robot may extend up to 1.5 m. The design must be able to deposit regolith at a height of .5 m into a collection bin in the start zone. The weight of the robot will be measured prior to the competition and it must be no more than 80 kg.

For the competition, the robot will be oriented in the start zone in a random direction. The robot must then be controlled from a remote location and traverse the obstacle zone. Once past the obstacle zone, the robot will move into the mining zone and then be able to dig into the BP-1. Excavation can only occur once the robot is in the mining zone.

After digging, the robot will return to the start zone and deposit its excavated mass into the collection bin. Excavated mass is defined by:

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).

A minimum of 10 kg of BP-1 must be deposited in the collection bin in order for the run to qualify. Teams will get two, 10-minute runs during the competition. The average of the two runs together will determine the mining portion of the competition. In order to win the competition, the team must have the most points of any team coming from several point categories. The mining portion is just one category in the competition. These categories are outlined in the rules in Appendix A.

6.0 Architectural Design

The first step to the team's architectural design was to perform trade studies on previous winners to the competition as well as analyzing the old robot to get a list of concepts to move forward with.

6.1 Trade Studies

Trade studies of the top three onsite mining winners from the past four years consisted of pulling the winners from NASA's previous winners table and scouring the Internet for information on the robots. An Excel spreadsheet (found in Appendix D) was created that has fields for the main subsystems of each robot. The spreadsheet also contains notes describing interesting features or concerns as well as where the information was found.

Analyses of the data concluded that wide footprint wheels were by far the most popular choice for movement, with all but two robots using wheels. Conveyor systems were the most popular for excavating regolith. A wide variety of different systems were used for depositing regolith into the bin. Important observations include ensuring the geometry of the digging and dumping systems are correct so regolith is not deposited incorrectly and to keep the lightweight theme with reliable composite materials.

6.2 Concept Generation

After evaluating the success and methods of previous competition winners, as well as determining a preferred approach to getting points, several interchangeable subsystem concepts emerged as most practical. The first digging/delivery system considered was a conveyor system. This type of conveyor system was popular among previous competition winners, as demonstrated in the trade study (Appendix A), and had several advantages as either a digging device or a delivery system. It was simple to automate, being a basic on-off function, was compact, would not throw off the balance of the machine, and the conveyor speed could be easily adjusted to allow for rapid and efficient digging. Also, the extension system for the conveyor would be separate from the digging or delivery function so that the conveyor could be lifted and the robot free to travel in the event that the conveyor jammed. The drawbacks of this system were its weight, conveyors are notoriously heavy, the number of moving parts, and this systems inability to dig deeply into the regolith, making it unlikely that the miner would pick up the more valuable gravel under the regolith. Relevant only to delivery, the conveyor system also had the drawback of having a wide spread flow, having the tendency to waste regolith around the competition bin, and having a flow too wide to be easily directed into the bin. In figure 2 the conveyor lift system is operated by a linear actuator and motor attached to a crossbar on the conveyor frame and fastened to the robot frame with a pin joint, allowing for rotation of the actuator itself to accommodate the rising and falling motion of the conveyor. The conveyor itself will rotate over the two drums shown, driven by a motor mounted inside the frame and gear meshed with the upper drum.

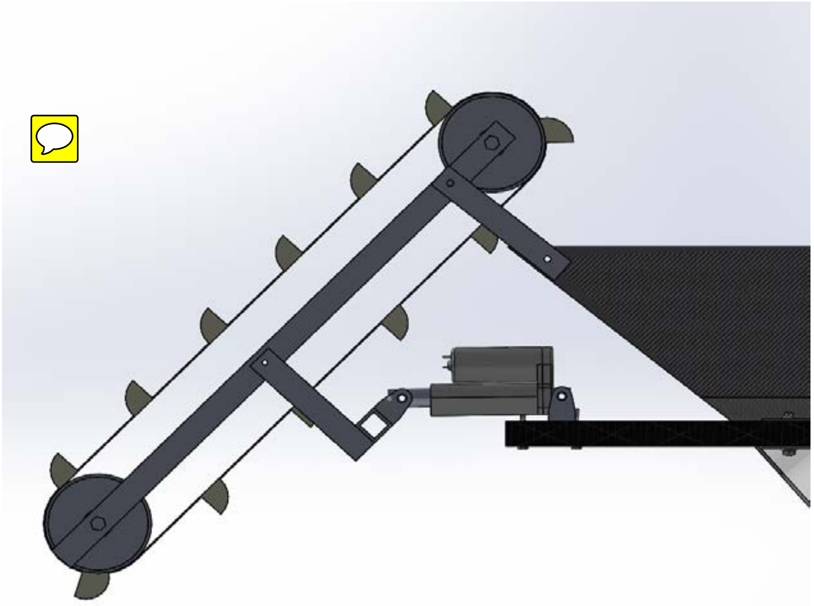


Figure 2: Conveyor

The second digging and delivery possibility was an auger. The auger would have a simple on-off control system, it was compact and would not upset the balance of the machine, and could move regolith quickly with little dust. The auger digger was also the only concept that could feasibly be designed to reach the gravel under the regolith and so gain extra points. However, research into the history of the use of augers in industry revealed that using an auger like a drill would require a large amount of torque and put very high stress on the auger itself, risking snapping. In addition, if the auger were to malfunction while extended into the regolith, the robot would be unable to move from its position to deliver what regolith was gained. As a delivery system, the auger was much more attractive. The narrow, circular mouth of the auger would eliminate the tendency to spill regolith over the robot itself as well as provide a greater range of positions from which the robot could deliver regolith, rather than having to maneuver into an exact position. Figure three demonstrates the design of the auger, a plastic screw inside a carbon fiber tube. It is driven by a motor mounted on the side of the casing and attached to the head of the auger by a chain.

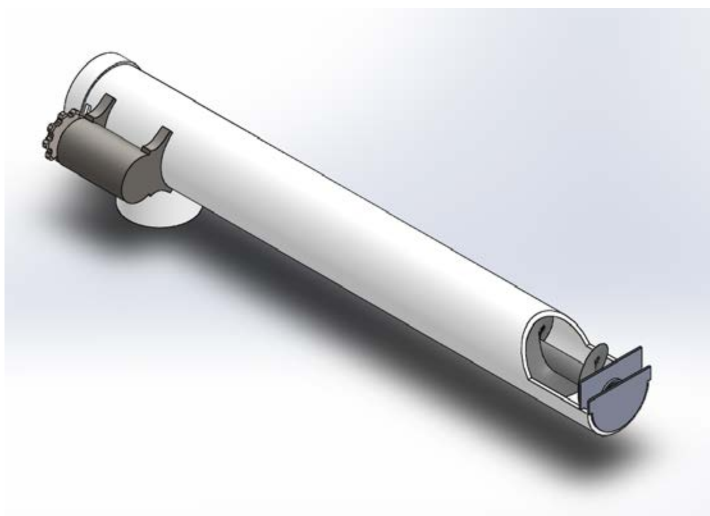


Figure 3: Auger [1]

A final design, this one specifically for delivery, was developed in the form of a dumping bucket. The dumping bucket would be simple to operate, again an on-off function, and reduce the weight of the machine by eliminating the need for some form of separate delivery system, like another conveyor. The dumping bucket also would require a large amount of power to function, place a great amount of stress on whatever actuator was used to move it, and be slower than other options. This design would also share the conveyors lack of precision in delivery, wasting gravel over the sides and possibly over the robot itself in the act of dumping. The act of dumping also throws off the balance of the machine and past competitions have a shown this design to have a high rate of failure by tipping. This design used a linear, vertical actuator mounted to the frame on a pin joint to lift the bucket. Tipping was forced by keeping one end of the bucket fixed to vertical frame elements by the upper corners. In order to actuate this the design the digging apparatus would either have to be attached solely to the bucket itself and lifted along with it, or to the frame and capable of moving clear of the bucket's lifting track. Figure four demonstrates the basic structure of this design.

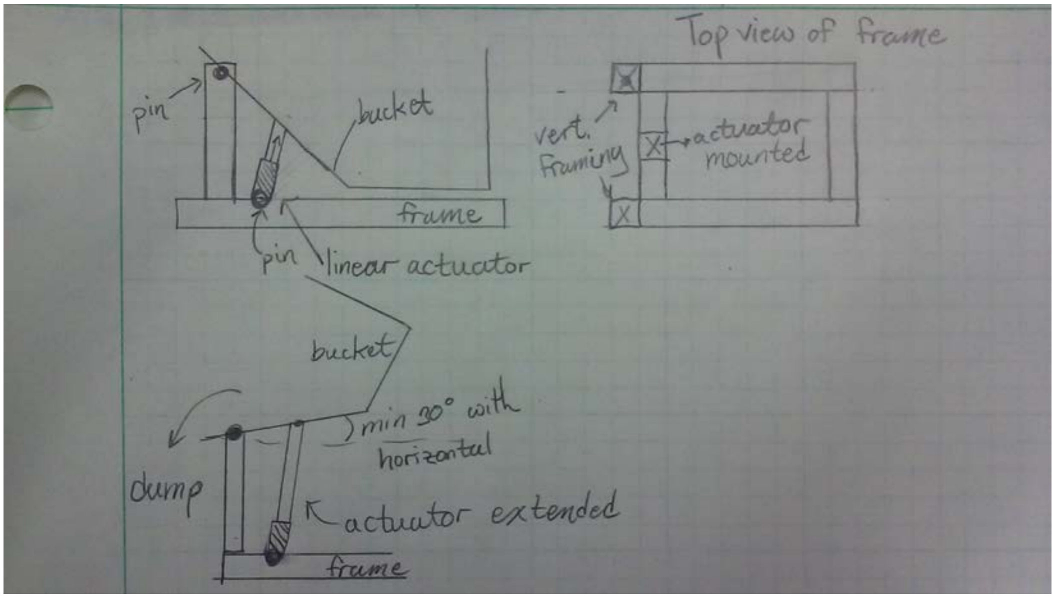


Figure 4: Dumping Bucket

Several interchangeable transportation methods were also considered for this robot. The first possibility was the use of continuous track with grips to ensure stability. This option was inviting for its increased stability and capacity to scale obstacles smoothly. However, continuous track is very heavy and Auburn teams who have used it in the past have found that it has a high risk of slipping off while running. In the figure below, the continuous track runs over five rollers. The two upper rollers would be sprockets fitting into corresponding chain links or gaps in the tread in order to prevent it from slipping off. One of these sprockets would also be geared to the motor and form the single driver of each tread. This would allow the use of two motors rather than four in the drive train, lowering the weight, but also causing the motors to become a single point vulnerability. The three lower rollers would be pinned to the frame at an angle with a rigid rod and a spring, forming independent suspension for each roller. This would permit the robot to essentially crawl over obstacles without a large degree of tipping or jarring.

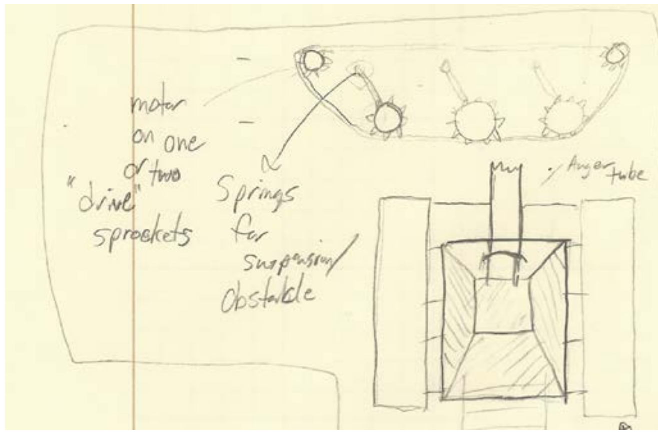


Figure 5: Continuous Track

Simple wheels were also considered, valuable for their ease of manufacture, simplicity, and reasonable weight. This has been one of the most popular modes of transportation in previous competition and would involve the least extra labor from robot designers. However, wheels would still have considerable weight and the lack of suspension would lead to a high degree of shock to the robot as it crosses obstacles. This, in turn, would necessitate that the frame of the robot be hardier and therefore heavier. As shown below, the wheels would be of large diameter for stability and fitted with sharp tracks to prevent slipping. Each wheel would have its own motor and be mounted to a shaft directly connected to the frame.

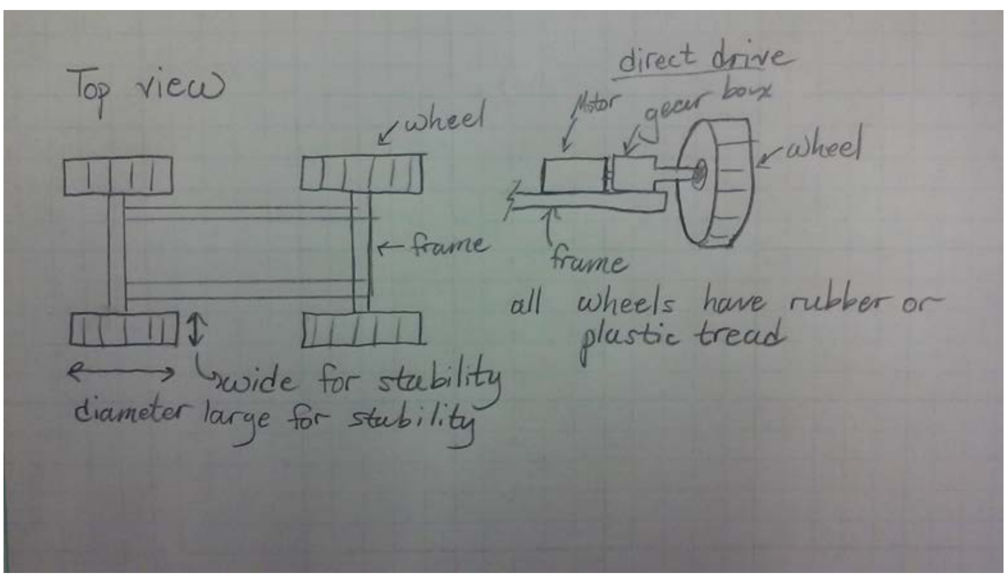


Figure 6: Simple Wheels

The concept of reducing the surface area of a wheel into a series of padded legs, as depicted below, was put forward by the club team. This design had the advantages of reducing the weight of a full wheel while introducing mild suspension to the system. The structure of the wheel-leg system required careful design, placing high stress on each leg and creating the risk of sinking into and getting stuck in the regolith. In addition, this method of support has not been seen in any previous competition, making this a good candidate design for the innovation award. Each leg consists of two aluminum tubes, the lower telescoped into the upper. Inside these tubes is a simple suspension system protected from dust by its position inside the legs, and on the end of each leg is a wrapped carbon fiber foot with paper honeycomb core. These feet will be attached to each wheg by being screwed into a threaded insert pressure fitted to the inside of each tube.

Figure 7: Wheel-leg

The final transportation concept was chosen for its originality, low weight, and built in suspension. This was combined with an auger for delivery and a conveyor for digging, for further development. The delivery auger provided the advantage of a precisely directed flow and can be calculated to deliver regolith at the rate desired by altering the gearing and changing the torque applied to the spinning screw. However, the conveyor proved more advantageous than the auger for digging since the digging operation and lifting mechanism would be separate and not become a single point vulnerability.

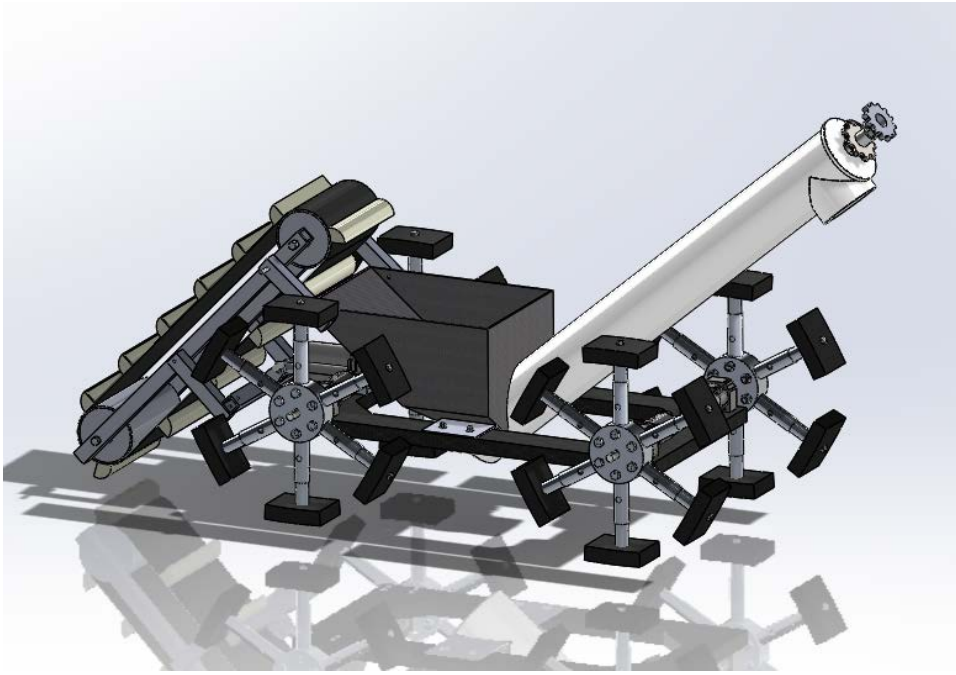


Figure 8: Final Concept

6.3 Testing/Prototypes

In order to determine the best concept, several tests were run and reviewed, including several tests performed by the previous design team. One such previously recorded test was conducted by the Summer team to determine the minimum angle required for regolith to slide down an incline plane. The second test performed by the previous team was used to determine the effectiveness of an auger for moving sand. Two more tests were conducted this semester, one to determine the effectiveness of the auger to move gravel, the other to test a possible solution to the problems discovered in the gravel test.

6.3.1 Slip Test

Several concepts required the sides of the bucket to be angled in such a way that regolith would slide freely down into the mouth of the auger. The minimum angle necessary for free sliding was determined by the previous design team through a series of tests using sand. The two thousand and fourteen senior design team's midterm report states as follows.

> "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/m3. 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 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 material (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 [9] is representative of the two test that were carried out. "[1]

Results from this test are listed in Table 1. The results of this tests indicated to the current team that, in order to avoid the use of a mechanism to move regolith from one end of the bucket to the other, the sides and bottom of the bucket should be at an angle of no less than 30° with the horizontal, angled into the delivery mechanism. The necessity of using these angles would play a large part in determining the maximum possible size of such a bucket. In addition, this test indicated that the inside walls of the bucket should be a smooth as possible to minimize friction resistance between the regolith and bucket.

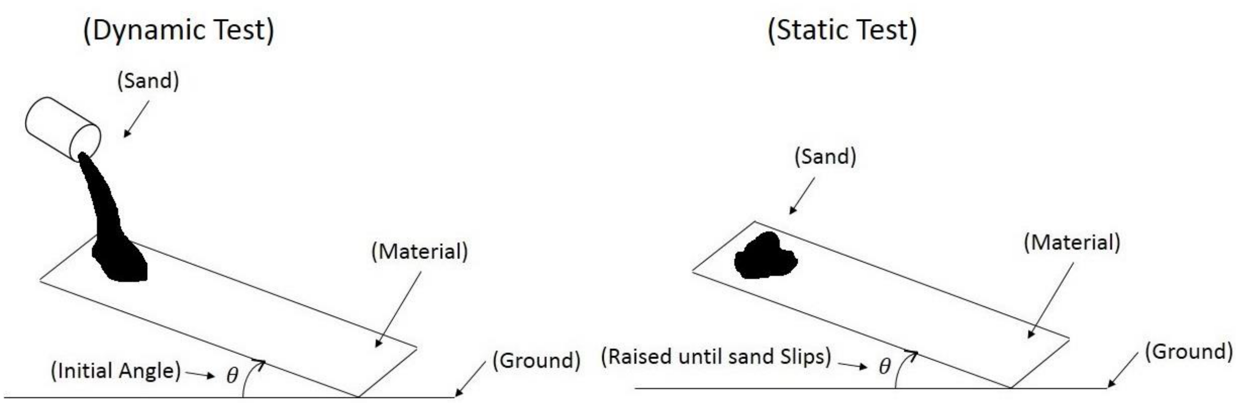


Figure 9: Slip Test Configuration [1]

Table 1: Slip Test [1]

Test Type		Material				
		Carbon Fiber (Smooth)	Carbon Fiber (Rough)	Plastic	Steel	Aluminum
	Damp	30	35	30	25	30

Static slip Angle (deg)	Dry	25-30	35	30	25	30
Dynamic Slip Angle (deg)	Dry	20	30	25	25	25

6.3.2 Auger Test

The last design team also tested the viability of an auger as a delivery mechanism. “The auger was tested using wet sand to determine the general effectiveness of an auger at transporting particulate. 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. 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.”[1] An auger was chosen for the current robot based off of this test. It verified that the flow of regolith through an auger can be directed with accuracy and that an auger can be designed as an efficient delivery system.

6.3.3 Gravel Test

After the new rules were published indicating that gravel of an average two centimeters diameter would be placed under the regolith at the start of the competition, it was determined that regardless of whether collecting gravel was a goal or not some gravel would get mixed into the regolith over the course of the competition and the robot needed to be able to process it. Delivery concepts two and three both used an auger, which would be enclosed in a casing, meaning that an auger of the wrong size or shape would be unable to process large gravel. In order to determine whether an auger could be designed to accommodate the gravel and what steps would have to be taken to optimize such a design a simple test was performed. Basic garden gravel was loaded into last semester’s robot and run through in an attempt to determine how much gravel the auger could process over a period of time. However, the auger jammed immediately. Upon inspection it was discovered that the gravel would catch on the sharp angle of the circular opening from the bucket to the auger. Gravel was then inserted directly into the auger past his opening. Once inside the auger, gravel ran through smoothly and was deposited with the sand it was mixed with. The figure below shows a piece of gravel stuck in the sharp lip of the auger mouth. This test demonstrated that an auger would be appropriate for use in delivering regolith mixed with gravel, but further testing had to be done to determine the type of opening necessary to accommodate the entrance of gravel into the auger. It was found, based on this test that the currently built auger could be modified to serve the new robot in competition.

Figure 10: Gravel Test

6.3.4 Follow-up Gravel Test

With gravel getting caught between the auger screw and the bucket opening, a change to the opening was necessary to test. Parts of the previous year's robot had to be reassembled in order to accomplish testing. The bucket was re-bolted back onto the old chassis and the auger screw was inserted back into its tube. It was noted that the auger assembly lacked the rigidity necessary for smooth operation. The testing setup can be seen below in Figure 11.

Figure 11: Follow-up Gravel Test

A cut-to-form wooden ply board piece was used to replicate the angles of the new bucket design. A drill motor was then connected to the auger shaft to power the screw and preliminary testing was conducted. It was found that the gravel would get stuck at the auger-bucket junction and jam the auger. The test thus yielded mostly negative results. In order to iron out the construction flaws of the junction, a Dremel was used to remove the excess carbon fiber and epoxy resin. Care was taken so as to prevent the Dremel from roughing or piercing the tube.

The auger was tested for a second time. This test yielded positive results, with the auger effectively pulling a sand and gravel mixture from the bucket. The jamming of the auger was attributed to the following factors:

- Inadequate torque from the drill motor used for the experiments
- Shifting of the auger of screw in the tube, which created gaps between the tube and screw edges in which gravel could get stuck
- Broken links at the bottom of the auger tube, which allowed sand to leak from the tube
- Tilting and bending of the connecting shaft attached to the drill motor

- Presence of excess epoxy at the auger-bucket junction

In order to avoid further complications, the following design characteristics of the auger should be met:

- The construction of the auger and tube must be a rigid assembly to prevent the shifting of the screw inside the tube
- The motor employed to run the auger must be able to provide a large amount of torque to remove stuck gravel in the auger, should gravel become stuck
- The auger-bucket junction must be smooth

6.4 Leading Concept

The conveyor-auger design with a basic ladder frame and angled bucket was chosen as the leading concept due to the following reasons. Conveyors have been used successfully by many teams. Augers are efficient and a precise dumping mechanisms. The digging and dumping mechanisms are both on/off mechanisms for ease of automation. There are fewer concerns for the robot tipping over. In addition, the wheel-leg or 'wheg' design aims to win the ingenuity award, as it has not been used in the competition before. This design could also prove to be a better alternative to wheels on rocky terrain due to its ability to climb over obstacles. The angled sides of the bucket eliminate the need for a second heavy auger and the carbon fiber frame provides an extremely lightweight platform for auger, conveyor, and bucket.

7.0 Subsystem Design

Once the team's leading concept was chosen, subsystems were divided among team members for development.

7.1 Storage and Delivery

Data collected through trade studies indicated that teams which used a dump trunk style delivery system encountered problems with the balance of the robot, often tipping it over. This approach, and the frequently seen conveyor delivery system also demonstrated a tendency to miss the competition bin or waste material onto the ground while in the process of aligning with the bin. In the interests of pursuing autonomous motion simplicity of actuation was prioritized, as was reduction of moving parts. The choice of an augur connected to an angled bin proved to fit the requirements most expediently. The auger required a simple on-off control mechanism, its circular mouth allowed more precise delivery of regolith, and it required minimal moving parts. Having a bucket with sides and bottom at angles of no less than thirty degrees to horizontal eliminated the need for some mechanism to move regolith from the front of the bucket to the mouth of the auger. The regolith collected would slide naturally to the lowest point of the bucket, the auger mouth. In order to gain as many points as possible on top of autonomy and low weight, the size of this bucket was maximized as much as possible while still fitting within design parameters and the position requirements for the auger and conveyor. Volume calculations for the bucket can be found in appendix H, showing a maximum internal volume of 767 cubic inches and capable of holding 21.4 kg of regolith if filled to the brim. The dimensions of the bin were limited by the need to have a few inches of ground clearance and fit the entire robot into a length of less than 1.5 meters. Drawings and dimensions for the bin can be found in appendix H.

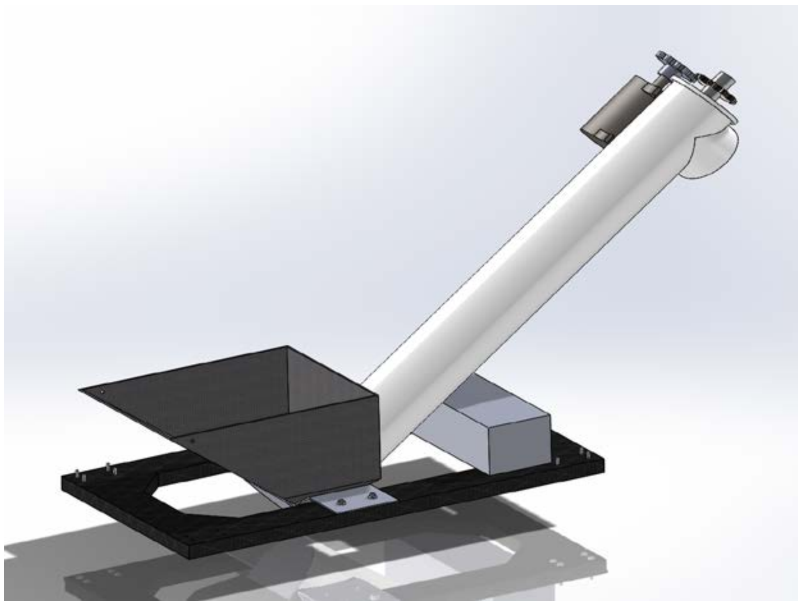


Figure 12: Storage/Dumping Assembly

This auger system consisted of a single long screw encased inside of a tube. As regolith fell into the mouth of this device the turning of the auger would draw it up and deposit it through the end nozzle into the delivery bin. The turning of the auger would be driven by an electric motor mounted to the outside of the auger casing, connected to a chain, which would drive a gear mounted to the axle of the auger screw. In order to accommodate larger gravel as well as sand, the auger was designed with a slightly larger, smoother opening to the bin than that of the previous auger, on which tests were conducted. This larger opening prevents gravel from catching on the rough lip of the opening.

7.2 <u>Frame</u>

The steel frame and wheel design of the previous team was recorded to have a weight of thirteen kilograms with its bike wheels attached.[2] Research into the typical weight of a mountain bike wheel suggested that these wheel contributed a rough estimate of four kilograms of the frame's total mass. This means that the frame itself weighed approximately nine kilograms. In hopes of cutting down this weight a basic ladder style frame consisting of carbon fiber was proposed for this project. The final design of this carbon fiber frame was estimated to weigh less than half a kilogram based on the material properties defined by carbon fiber production company VectorPly, a significant reduction from the weight of the steel frame. With such a large weight difference between steel and carbon fiber, it was decided to move forward with a carbon fiber frame. Carbon fiber is more difficult to machine or alter, but it is incredibly lightweight and the simplicity of the frame structure allows it to be made in one piece. As shown in the figure below, this frame consists of a single piece paper honeycomb cutout wrapped in a single layer of carbon fiber. Making the frame a single unit reduces stress concentration at the corners and simplifies the construction process. The frame was dimensioned to fit around the bucket, be long enough to provide a support platform for both the auger and the Conveyor, while remaining short enough to not exceed the 1.5 meter length limit of the robot. In addition, the corners were angled to provide a greater platform for the wheel driving motors and further strengthen the corners where stress might concentrate. This design was then validated using software developed by VectorPly which can be found in section 9, validation and verification.

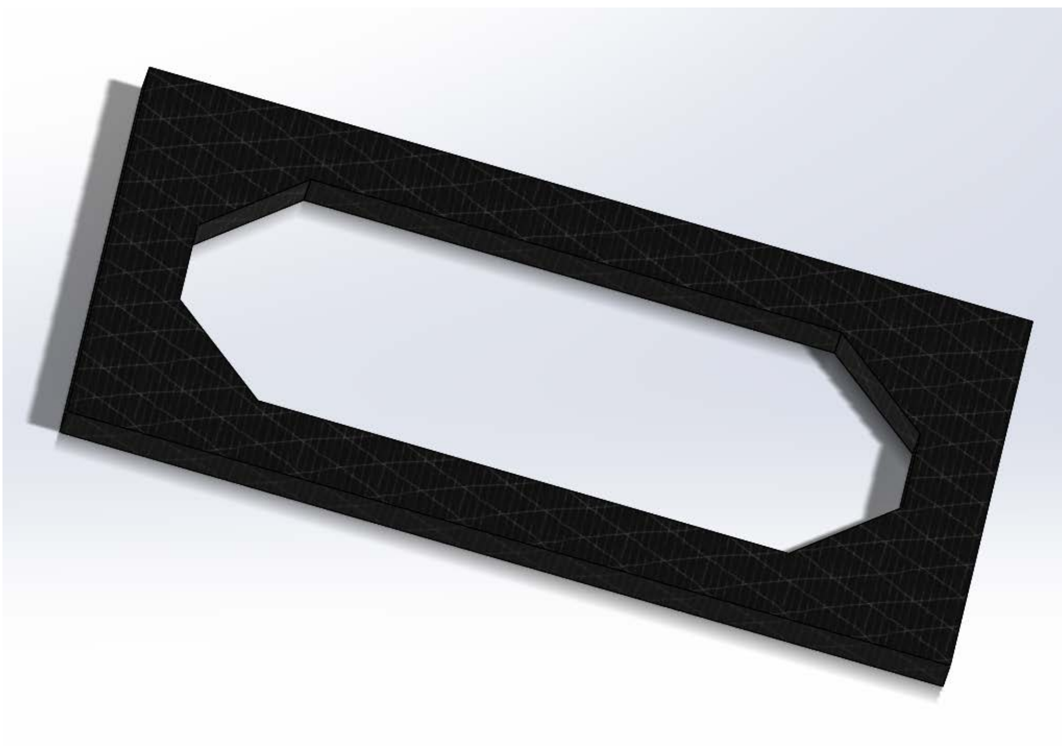


Figure 13: Frame

7.3 Conveyor

A tilting conveyor system was changed over the previous retractable design for the digging of BP-1 regolith after in-depth research of previous competition winners and analyses of different digging systems. A legacy exists for the reliability and power of conveyors, as three of the past four on-site digging winners have used them. Conveyors are capable of digging large amounts of regolith in very short periods of time, leading to more runs during the ten minute time given for each attempt, more regolith being deposited, and therefore, more points toward winning the competition.

In order to reduce the number of parts, the complexity of the system, and the weight, a tilting actuator system has been devised for deploying the conveyor for excavation and raising up when the robot must move. The tilting mechanism was chosen over the previous retractable design since it lessens the amount of moving parts, conserves space, and is easier to manufacture. A basic view of the conveyor system can be seen below in Figure 14 that reflects the geometry and how the conveyor will move.

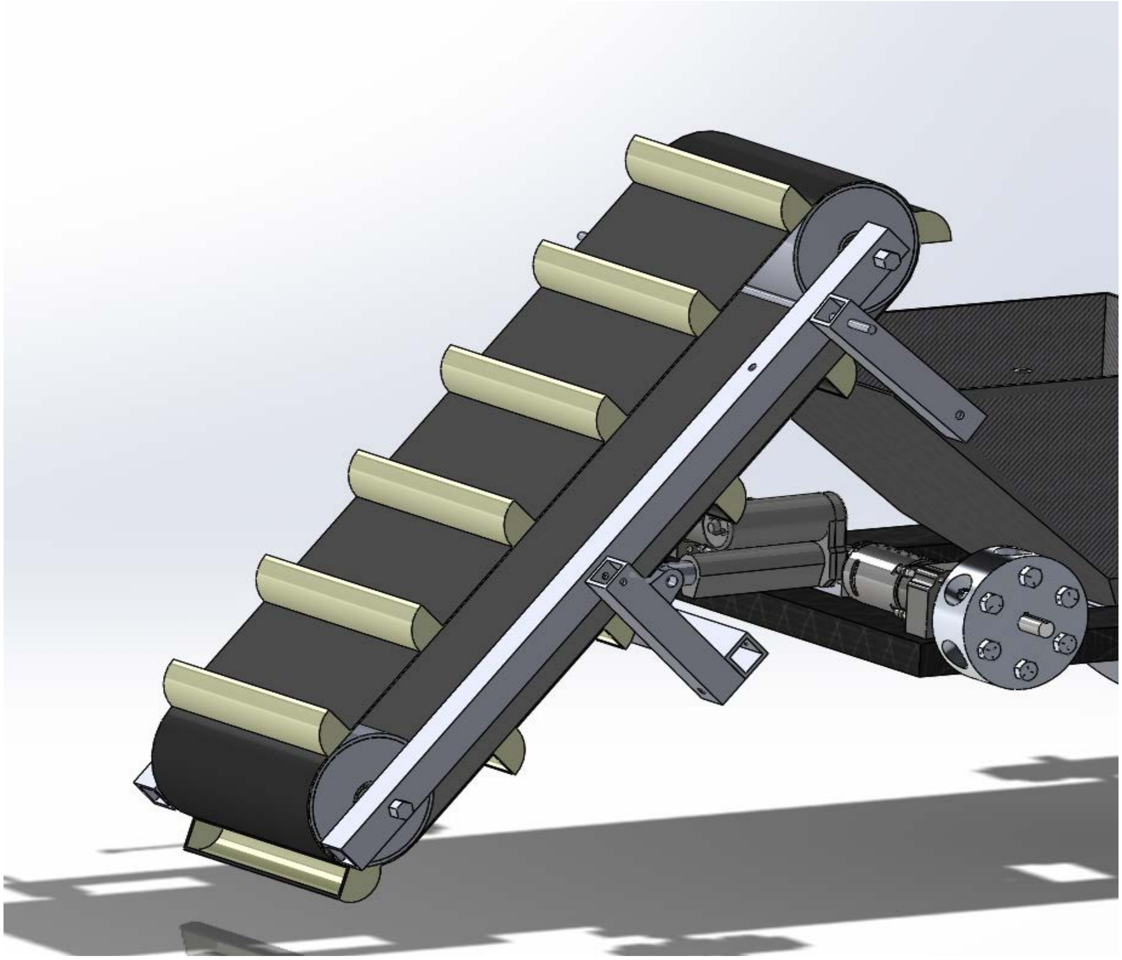


Figure 14: Conveyor System

A three inch stroke actuator capable of lifting 200 pounds will be perfect for raising the conveyor enough so that it does not strike any obstacles while traversing across the course. The pivot point of the system will be at the end of the bars that protrude from the bucket. The actuator will be mounted on both sides by brackets that allow angular rotation in one direction. Further details on the actuator can be found in the appendix.

8.0 Interfaces

The mechanical subsystems will all work together in order to move the robot as well and dig and deposit regolith. These subsystems will be controlled by the systems the electrical design team as well as the club team comes up with.

The conveyor interfaces with three different subsystems, which include the chassis, bin, and electrical systems. Interfacing with the chassis is incredibly important since the chassis will be supporting most of the stress from the conveyor. With the chassis made of carbon fiber, the exact connection points between the chassis and conveyor must be known before the chassis is manufactured so epoxy can be injected at those points.

The conveyor interface with the bin is just as important since the conveyor's pivot point is at that interface. Therefore, the bin requires additional support structures in order to handle the stress. Ensuring precise connections and a robust structure will lead to a reliably functioning pivot point and minimal stress at the bin connection points. The electrical interfaces should be fairly simplistic, consisting of wiring up the actuator and motor with the electrical box and arduino.

Additionally, the bin interface with the auger should be similarly reinforced and provides the limiting factor for the ground clearance of the robot. The lowest point of the auger has the lowest clearance on the robot and requires at least three to four inches to prevent it from catching in the sand as the robot moves.

As stated previously with regards to the carbon fiber frame, epoxy injections are necessary at all connection and mounting points, of the whegs to the frame. A specialized gearbox-bearing hybrid is being used in conjunction with the motor to drive the whegs. The gearbox will attach with four mounting points to the frame and will also serve to hold the motor in place. A keyed shaft will extend directly from the gearbox into the center of the whegs, which will have a matching keyed hole. Two keyed cylinders with set screws on either side of the wheg hub will hold the wheg in place so it does not slip from the shaft end.

The relationship of the wheel "foot" to the rest of the wheel is a critical interface. The load of the robot will be rested entirely on the feet of the robot. The foot must be securely fastened to the spokes on the wheg.

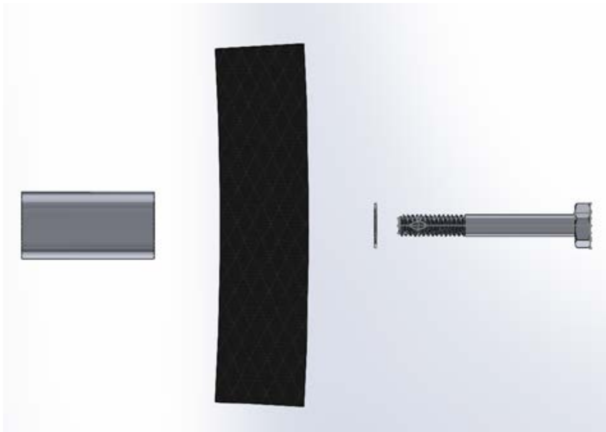


Figure 15: Wheg Interface

Figure 15 shows how the carbon fiber foot will be attached to the wheg's spoke. An insert with a threaded hole in the middle (pictured left) will be pressed into the spoke tube. A hole will then be drilled through the, epoxy filled, carbon fiber. The bolt will be threaded through the foot into the threaded insert with a washer placed on the bolt. The washer will be inserted to ensure the bolt does not damage the carbon fiber.

Figure 16: Bin to Frame Interface

The bin/frame connection is important because it provides support for the middle of the frame as well as holds the bin in place. Brackets will be constructed to fit the thickness of the frame and bolted through. Holes will also go through the angled portion of the bin to attach the bin to the brackets.

9.0 Concept of Operations

The very simplified goal of the robotic miner is to dig regolith. The electrical design team is in charge of designing the computing nerve center of the robot, which will run all systems autonomously, distribute power, and navigate the terrain. The robot will move around on wheel-legs, each of which will be direct driven by motors. Once it reaches the mining area, the conveyor will lower using an actuator mechanism and commence digging using the conveyor belt system driven by another motor. The regolith will be deposited into a sloped bin that siphons into an auger. When the bin is full, the robot will return to NASA's collector receptacle and position the auger opening over the receptacle. When positioned, the auger will activate and the screw inside the auger will be driven by another motor attached to the outside of the auger. The auger will continue running until the robot's bin is empty, after which the robot will proceed with another regolith gathering run.

10.0 Validation/Verification

All the subsystems will be independently verified to determine whether they meet the team's engineering requirements. This will be done before the systems are implemented into the working prototype. Each team member leading each subsystem will bring verification to the team manager before it will be implemented to be sure the subsystems meet the team's requirements.

10.1. Conveyor

In order to ensure that the conveyor design outlined in section 7.3 functions without unforeseen failures, parts were ordered so that a prototype could be built. The prototype was designed to ensure that the frame geometry meshes successfully with all moving parts and that the concepts with the timing belt/timing pulley/conveyor belt are sound and can dig regolith without failing. The prototype will be driven by a motor scavenged from the old robot. Once motors are selected for the new robot, these motors will be exchanged.

Testing of the conveyor prototype will be a basic test consisting of rigidly mounting the conveyor frame to a cart that can be pushed as the conveyor digs. The previous team's scoop design, shown below in Figure 17 will also be validated and changed if not optimal.

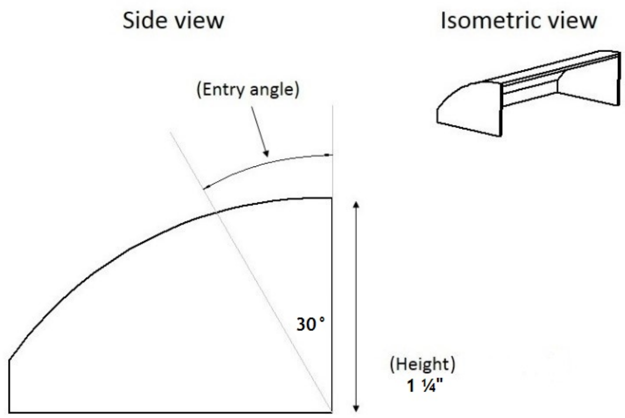


Figure 17: Scoop Design Testing

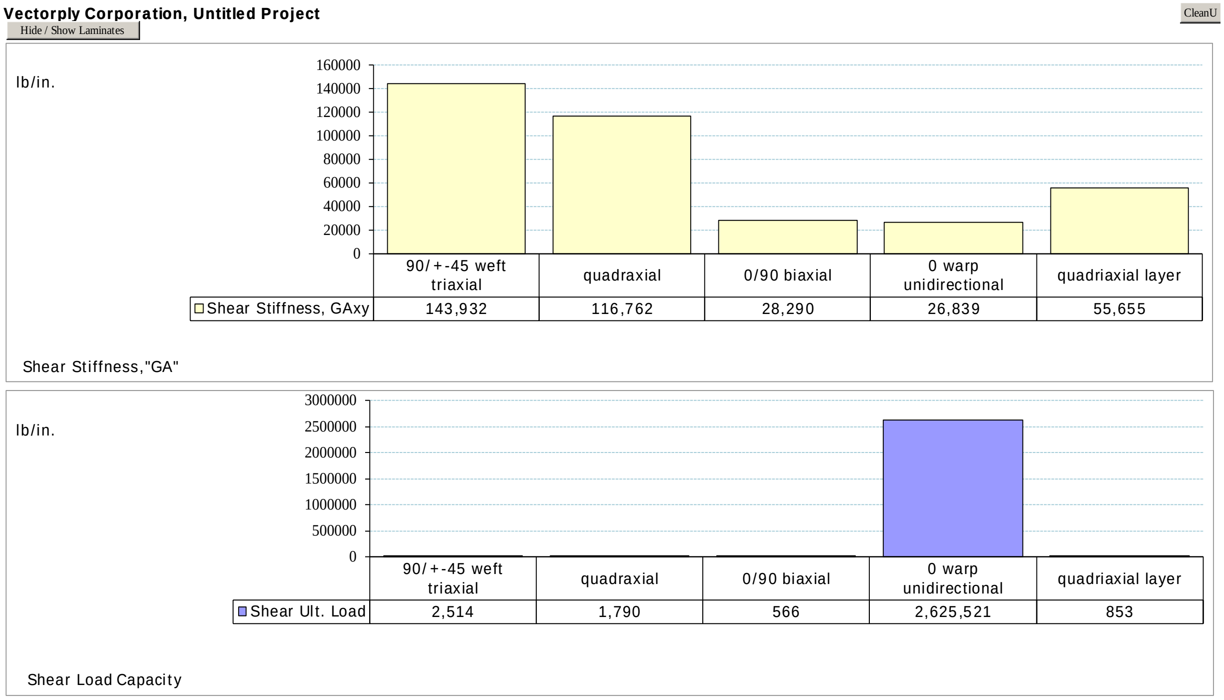
The full sized conveyor will be built using identical concepts and material from the prototype should the prototype accomplish the following testing criteria:

- Five minutes of continuous digging without failure
- Thirteen kilos or more of regolith dug in one minute
- Minor wear on conveyor components during testing

The optimal digging depth into the regolith will also be determined during testing so that the actuator can be programmed correctly by the electrical and computer design teams.

10.2. Frame

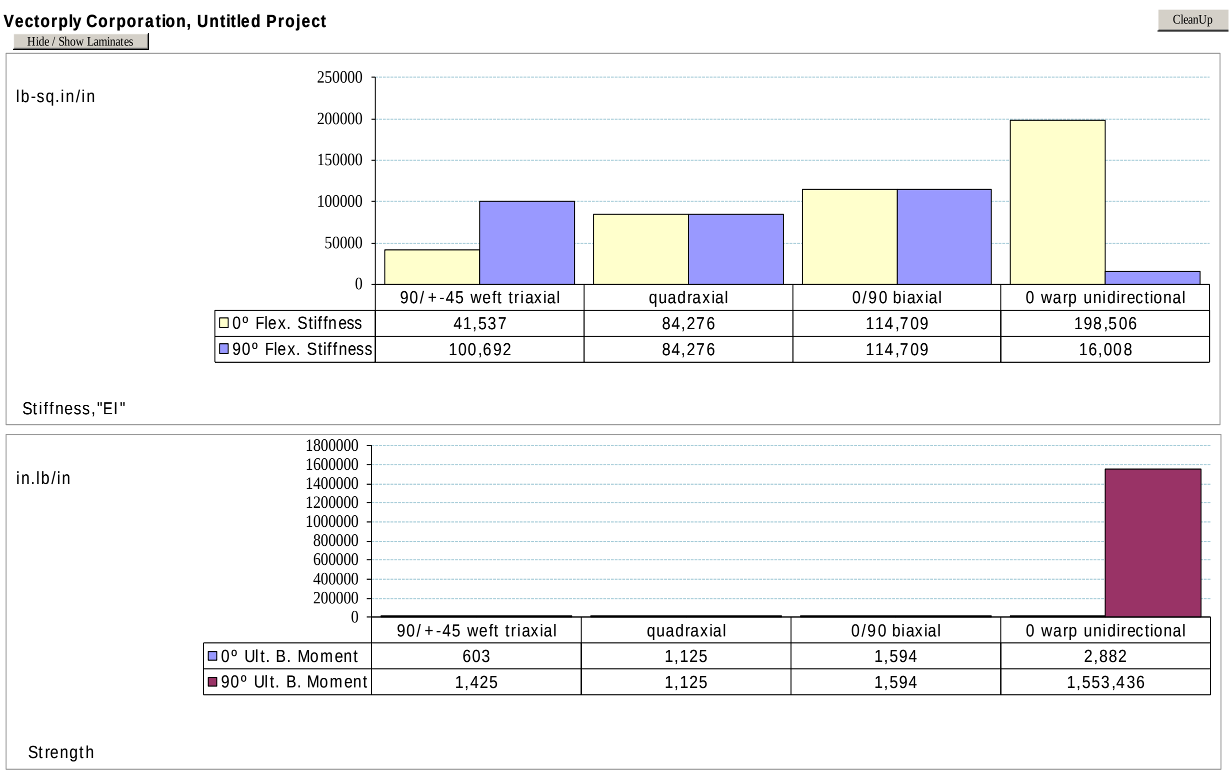
A program called VectorLam, developed by the company VectorPly and used in industry to compare the strengths of carbon fiber structural designs, was used in order to evaluate the strength of the carbon fiber frame. This analysis was done for a worst case scenario, using a beam structure. The honeycomb core of the frame adds a small amount of stiffness, but the key to the structural strength is the distance between carbon fiber layers. The honeycomb was used as a core to form a mold for the non-traditional shape of the frame and allow it to be constructed in one piece. VectorLam[3] indicated the material stiffness and strength for a single carbon fiber layer wrapped around a paper honeycomb core, shown in figures 18 and 19 below.



	90/+-45 weft triaxial	quadraxial	0/90 biaxial	0 warp unidirectional	quadriaxial layer
Shear Stiffness, GAxy	143,932	116,762	28,290	26,839	55,655

	90/+-45 weft triaxial	quadraxial	0/90 biaxial	0 warp unidirectional	quadriaxial layer
Shear Ult. Load	2,514	1,790	566	2,625,521	853

Figure 18: Shear properties



	90/+-45 weft triaxial	quadraxial	0/90 biaxial	0 warp unidirectional
0º Flex. Stiffness	41,537	84,276	114,709	198,506
90º Flex. Stiffness	100,692	84,276	114,709	16,008

	90/+-45 weft triaxial	quadraxial	0/90 biaxial	0 warp unidirectional
0º Ult. B. Moment	603	1,125	1,594	2,882
90º Ult. B. Moment	1,425	1,125	1,594	1,553,436

Figure 19: Bending properties

Based on these material properties the program was used to run a beam analysis verifying that design loads would not exceed material ultimate strength and bending moments. This analysis was conducted based on the unsupported lengths of the robot's frame elements, using the reaction forces of the wheels as simple supports. The image below demonstrates the position and value of forces on each beam.

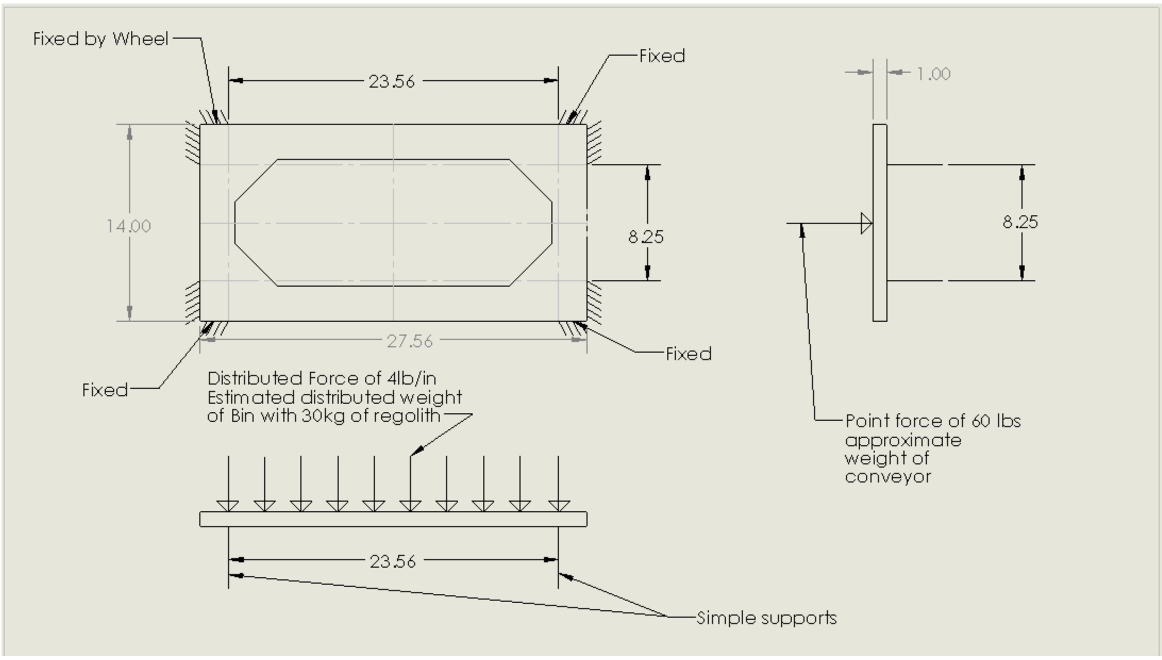


Figure 20: Force Placement on Frame

The beam analysis report, found in appendix E, showed factors of safety for both bending and shear given in table 2 below.

Table 2: Results of VectorPly Beam Analysis

Type	23" Beam (in*lb)	8" Beam (in*lb)
Max Moment	277.5	123.8
Factor of Safety for Max bending moment	14.5	32.5
Factor of Safety for Web Shear	49	76.9

Given that this worst-case-scenario analysis proved successful, the carbon fiber frame design for this robot will be more than adequate.

10.0 Technical Resource Budget Tracking

Weight is a high priority in the design of the robot as adding 1 kg of weight loses 8 points in the mining category. Also, cost should be minimized since this project has limited budget.

10.1 Weight

This robot was estimated to weigh approximately 25 kg without the addition of the electronic components which have not yet been define. The club team has set an upper limit weight of eight kilograms for the four innovative whegs being designed. The previous senior design team recorded the weight of the auger in their report, which will be used for the current design. [2] The following table was developed to indicate an estimated spread of weight.

Table 3: Weight Breakdown

Subsystem	Item	Mass	Quantity	Total Mass (kg)
Wheels	Motor	0.9781 lbs	4	0.44
	Wheel-leg		4	8.00
	Carbon Foot		24	
		Subsystem Total		8.44
Chassis	Carbon sheet	17.37 oz/sq. yd	/	0.20
	honeycomb	27.1 oz/sq. yd	/	0.12
		Subsystem Total		0.32
Electrical	Battery		1	
	Electronics		1	
		Subsystem Total		0.00
Storage and Delivery	Auger and Bucket	8.02 kg	1	8.02
	Motor	0.9781 lbs	1	0.44
		Subsystem Total		8.46
Conveyor	Steel Bearing for Roller	0.105 lbs	4	0.19
	Long Aluminum Tubing Supports	0.408 lbs	2	0.37
	Short Aluminum Tubing Supports	0.239 lbs	2	0.48
	ABS Plastic Scoops	0.25 lbs	12	1.36
	Aluminum Roller Supports	1.22 lbs	4	2.21
	Conveyor Belt	0.84 lbs	4	1.52
	Timing Belt Pulley	0.83 lbs	1	0.38
	Fasteners	1 lbs	1	0.45
	Motor	0.9781 lbs	1	0.44
	PVC Roller Tubes	0.291 lbs	2	0.26
		Subsystem Total		7.67
		Total Mass (kg)		24.90

Estimates for the mass of the frame were calculated using the Vectorlam software and can be found recorded in appendix G. All other masses are manufacturers' values.

10.2 Cost

A rough cost estimate had been developed for the major expenses of each system. This estimate is incomplete, but does include a high view assessment of currently selected system components.

Table 4: Cost Overview

Chassis/Auger/Bin			
Matl	QTY	$ per	total $
Carbon Fiber (Bin and Chassis)	1	donated	free
Paper Honeycomb	1	donated	free
Auger	1	existing	free
Motor	1	52.99	52.99
		Subsystem Total	52.99
Wheels			
Matl	QTY	$ per	total $
4" ODx1.5" thick Aluminum Hub	4	20	80
.75"x4" Aluminum Tube	20	2	40
1"x4" Aluminum Tube	20	2.2	44
Motor	4	52.99	211.96
Feet	24	donated	free
		Subsystem Total	375.96
Conveyor			
Matl	QTY	$ per	total $
Conveyor Belt	4	22.18	88.72
1" x 1" x 2' Aluminum Tubing	5	12.01	60.05
Steel Bearing	4	8.69	34.76
ABS Plastic Sheeting	2	14.43	28.86
Aluminum Rod, 1' x 4"	1	86.02	86.02
Aluminum Hex Bar, 1'	1	5.54	5.54
Alligator Belt Lacing	1	28.05	28.05
Timing Belt	1	44.2	44.20
Timing Belt Pulley	1	45.95	45.95
Bolts for Frame 1-1/2" long	1	10.98	10.98
Bolts for Frame 2-1/4" long	1	7.58	7.58
Hex Nuts for Bolts	1	2.97	2.97
Motor	1	52.99	52.99
		Subsystem Total	496.67

Electronics			
Matl	QTY	$ per	total $
Battery	2		
NI myRio Enclosed Device	1	500	500
Box elctronics	1		
	Su+bsystem Total		500
	Total	1425.62	

11.0 Risk Management

Risks and potential failures for the chosen design were tabulated in the following table, with emphasis on planned corrective action. Further evaluation is necessary for most of these issues and will be detailed in the final design report. Many of these corrective actions will take the form of testing and design validation after the prototype is constructed. The damage that might be caused by the failure is listed from zero (no damage), to five (catastrophic failure).

Table 5: Risk Management

Risk	Failure Type	Risk level	Probability	Corrective Action
Auger Failure	Technical	Loss of delivery (4)	Mod	Prototype testing
Conveyor Lift Failure	Technical	In raised position: Loss of digging (3) In lowered position: Loss of mobility and digging (4)	Mod	Prototype testing for durability and power
Conveyor Belt Slip	Technical	Loss of digging (3)	Low	Test conveyor prototype to evaluate need for guides. Develop dust control method
Conveyor Belt Drive Failure	Technical	Loss of digging (3)	Mod	Prototype testing. Examine before each run to determine functionality
Structural Wheel Failure	Technical	Loss of mobility (4)	Mod	Wheel prototype has been constructed and will be tested under to stress to determine structural strength
Loss of Comm	Technical	Loss of control, Temporary (1) Permanent (3)		Ensure reboot and reconnect capability
Electrical Short	Safety/ Technical	Loss of Control/Fire (5)	Low	Regular check of emergence shut off switch
Loss of balance	Technical	Loss of mobility (4)	Low	Verify that prototype center of gravity is low and between the wheels
Foreign Material invasion	Technical	Loss of mechanical function (4)	Low	Design covers for gears and develop dust control method
Camera Malfunction	Technical	Loss of Autonomy (1)	Mod	Introduce system redundancy
Dust on Camera	Technical	Loss of Visibility/Autonomy (1)	High	Dust control method is in development by the electrical team

12.0 Conclusions

Although no complete prototype has been built yet, the auger has been independently tested with satisfactory results. The wheel-leg will be tested and optimized to reduce weight. Carbon fiber components will be manufactured and tested under the supervision of the Polymer and Fiber Engineering Department.

A preliminary design has been developed. Subsystem design will be optimized and tested. The major concerns at the moment are the weight and automation. A solution to these issues will be developed through prototyping.

Prototyping is underway by the Electrical design team in order to develop autonomous navigation and location tracking, and by the mechanical team to optimize the function of the conveyor belt. Mechanical subsystems will continue to be developed with autonomous operation in mind.

The design will be optimized and fabrication will commence once the results are deemed satisfactory. Although the major subsystem break-down and subsystem design is likely to remain unchanged, changes to the system architecture and arrangement may be needed to meet the competition criteria.

Appendix A: 2015 NASA Competition Rules

NASA's Sixth Annual Robotic Mining Competition

Rules & Rubrics 2015

Kennedy Space Center, Florida

Introduction

NASA's Sixth 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 mission of pioneering a human presence on Mars through resource mining and utilization. A critical resource on Mars is water ice which can be found buried in the regolith where it is well insulated. The technology concepts developed by the university teams for this competition conceivably could be used to robotically mine regolith resources on Mars. NASA will directly benefit from the competition by encouraging the development of innovative robotic 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 of Earth 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 limitations of the mining robot, and the ability to tele-operate it from a remote mission 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 dust projection, communications, vehicle mass, energy/power required, and autonomy.

The competition will be conducted by NASA at the Kennedy Space Center in Florida. 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 Sixth 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/nasarmc 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 18-22, 2015. A minimum amount of 10kg of BP-1 and/or icy regolith simulant (gravel) 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 10kg of BP-1 and/or icy regolith simulant (gravel) 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 and/or icy regolith simulant (gravel) 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 18, 2015; 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 approximates basaltic Martian regolith. The mining area will contain BP-1 regolith simulant up to a depth of approximately 30 cm. Below the BP-1 there will be approximately 30 cm depth of gravel with a mean particle size diameter of ~ 2 cm which simulates icy regolith buried in the Martian regolith. Larger rocks may also be mixed in with the gravel and BP-1 in a random manner. Note that gravel may be mixed in with the BP-1, but the bulk of it will be in the bottom 30 cm of the mining area only. 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 gravel will be returned to the lower 30 cm of the mining area and the BP-1 will be returned to the top 30 cm in a compacted state, and the obstacles and craters will be re-set in 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 earn 6 Mining points for each kilogram of simulated icy regolith (gravel) deposited in the Collector Bin. The gravel will be sieved out at the Collector Bin and weighed separately from the BP-1.

   D) 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.

   E) 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.)

   F) During each competition attempt, the team will lose 1 Mining point for each watt-hour of energy consumed. The electrical energy consumed must be displayed by an electronic data logger and verified by a judge.

G) 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

H) 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 (two times only – outbound and back)
2. Successfully crossing the obstacle field, excavating and returning to the collection bin: 150 pts
3. Successfully crossing the obstacle field, excavating and depositing regolith, 2 times: 250 pts
4. Successful fully autonomous run for 10 minutes: 500 pts

The points earned for autonomy are not cumulative. Levels 1 through 4 points will be incrementally achieved. For example if level 2 is achieved then the points for level 1 are not counted. The autonomy points are awarded for the whole competition attempt and not for each run across the obstacle zone. If the robot fails to achieve autonomy during the competition attempt, and manual control is regained, then only autonomy points achieved to that point in time will be allowed.

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 walls of the Caterpillar Mining Arena cannot be used for sensing by the robot to achieve autonomy. The team must explain to the inspection judges how their autonomous systems work and prove that the autonomy sensors do not use the walls. There are no walls on Mars and the teams are expected to operate as closely as possible to a Mars scenario of operations. Honesty will be expected from all team members and their faculty coaches. Failure to clearly divulge the method of autonomy sensing will result in disqualification from the competition.

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	0 or 1000	1		1000
BP-1 over 10 kg	+3/kg	110	kg	+300
Gravel (Icy Regolith Simulant)	+6/kg	10	kg	+60
Average Bandwidth	-1/50kb/sec	5000	kb/sec	-100
Mining Robot Mass	-8/kg	80	kg	-640
Report Energy Consumed	-1/Watt-hour	-35	Watt-hour	-35
Dust Tolerant Design (30%) & Dust Free Operation (70%)	0 to +100	70		+70
Autonomy	50, 150, 250 or 500	150		+150
Total				805

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. All gravel will be sieved out from the BP-1 at the collector bin and weighed separately.

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 and gravel 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 by the front end of the robot.

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 and gravel 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 +/- 0.2 m 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. The

Collector bin will include a gravel sieve screen suspended above the existing bin. See Diagram 3. This sieve screen frame will have the same opening dimensions and internal slope angles as the bin but will be suspended above it. This effectively raises the lip of the collector bin by 3.8 cm. The Collector bin sieve top opening dimensions are 1.575 m long by 0.457 m deep with the same slope angles and the bin below of 44 degrees long side and 51 degrees and the ends. The sieve screen is 6.4 cm below the frame lip. 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 navigational aid system may not be higher than 0.25 m above the Collector Bin, and cannot be permanently attached or cause alterations (ie. no drilling, nails, etc). 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).

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 and/or gravel 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 and/or gravel 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 not 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 not allowed.

18) The mining robot must not use the wall as support or push/scoop BP-1 and/or gravel 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. The energy consumed must be recorded with an electronic data logger device. Actual energy consumed during each competition run must be shown to the judges on the data logger immediately after the competition attempt

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 SYSTEMS REQUIREMENTS

1. Each team is required to command and monitor their mining robot over the NASA-provided network infrastructure shown in Figure 1.

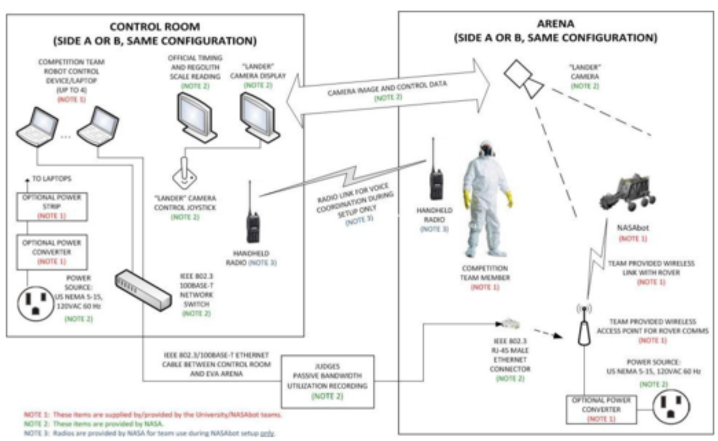


Figure 1: NASA Provided Network

a. This configuration must be used for teams to communicate with their mining robot.
b. The "Mars Lander" camera is staged in the Caterpillar Mining Arena, and Mars Lander Control Joystick and camera display will be located with the team in the Mission Control Center (MCC)
c. The MCC will have an official timing display, which includes a real-time display of BP-1 collected during the match
d. Handheld radios 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.

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 (male RJ-45 Ethernet plug) that extends to the Mission Control Center, where NASA will provide a network switch for the teams to plug in their laptops.
   b. 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.
   c. A shelf will be set up next to the network drop at a height 0 to 2 feet above the walls of the Arena, and will be placed in a corner area on the same side as the collection bin. During robot system operations during the competition, there may be some dust accumulation in this area. This shelf is where teams will place their Wireless Access Point (WAP) to communicate with their mining robot.
   d. Teams are STRONGLY encouraged to develop a dust protection cover for their wireless access point (WAP) that does not interfere with the radiofrequency signal performance.
   e. 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.
3. Power interfaces:
   a. NASA will provide a standard US National Electrical Manufacturers Association (NEMA) 5-15 type, 110 VAC, 60 Hz electrical jack by the network drop. This will be no more than 5 feet from the shelf.
   b. NASA will provide standard US NEMA 5-15 type, 110 VAC, 60 Hz electrical connections in the Mission Control Center for each team.
   c. 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.
4. During the setup phase, the teams will set up their access point and verify communication with their mining robot from the Mission Control Center.
5. The teams must use the USA IEEE 802.11b, 802.11g, or 802.11n standards for their wireless connection (WAP and rover client).
   a. Teams cannot use multiple channels for data transmission, meeting this rule will require a spectral mask or "maximum bandwidth setting" of 20MHz bandwidth for all 2.4 GHz transmission equipment.
   b. Encryption is not required, but it is highly encouraged to prevent unexpected problems with team links.
   c. During a match, one team will operate on channel 1 and the other team will operate on channel 11. See Figure 2. These channels will be monitored during the competition by NASA to assure there are no other teams transmitting on the assigned team frequency.
6. Channels will be assigned via email prior to the competition or when the teams check in with the Pit crew chief.
7. Each team will be assigned an SSID that they must use for the wireless equipment for channels 1 and 11.
   a. SSID will be "Team_##."
   b. Teams are required to broadcast their SSID.

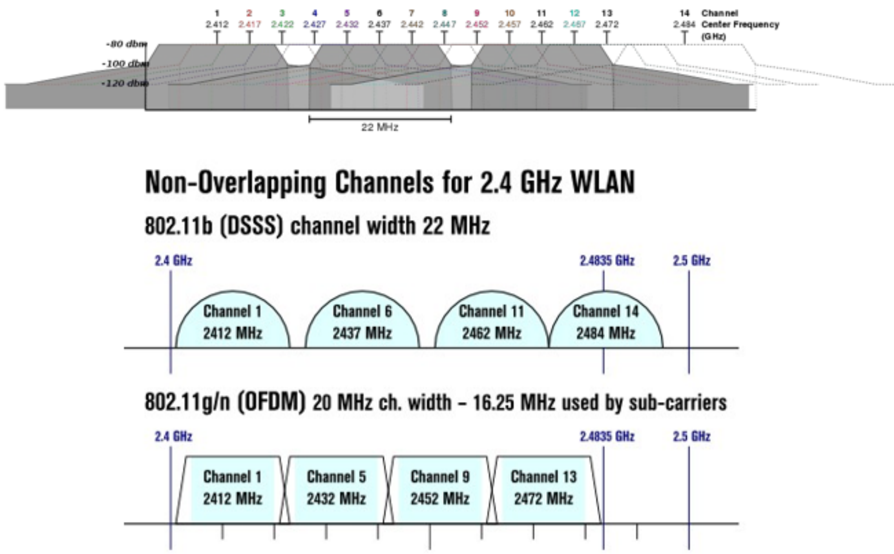


Figure 2: 802.11 n channels

8. The use of specific low power Bluetooth transmission equipment in the 2.4 GHz range is allowed for sensors and other robot communications. Bluetooth is allowed only at power levels of Classes 2 3, and are limited to a maximum transmit power of 2.5 mW EIRP. Class 1 Bluetooth devices are not allowed.
9. The use of 2.4 GHz ZigBee technology is prohibited because of the possibility of interference with the competition wireless transmissions.
10. Technology that uses other ISM non-licensed radio frequencies outside of the 2.4 GHz range, such as 900 MHz and 5 GHz, are ALLOWED to be used for any robot or sensor systems, but these frequencies will NOT be monitored during the competition. Interference avoidance will be the responsibility of the Team and will not be grounds for protest by any team.
11. Radio frequency power:
    a. All Team provided wireless equipment shall operate legally within the power requirements power levels set by the FCC for Unlicensed Wireless equipment operating in the ISM radio band. The FCC Federal Regulations are specified in the Electronic Code of Federal Regulations, Title 47, Telecommunication, Part 15, and must be followed if any commercial equipment is modified. All unmodified commercial off the shelf access point equipment and computers already meet this requirement.
    b. If a team inserts any type of power amplification device into the wireless transmission system, this will likely create a violation of FCC rules and is NOT allowed in the competition.
    c. This radio frequency power requirement applies to all wireless transmission devices at any ISM frequency.

B. BANDWIDTH CONSTRAINTS: 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 BP-1 and/or icy regolith simulant (gravel) to qualify for this award.

1. Use of the NASA provided Situational Awareness Camera in the control room will add 120 Megabits (Mb) of data use for all teams. If a team elects to turn off the joystick controlled situational awareness camera during the entire match, they will not be charged for the 120 Mb of data use. If the team elects to turn on the camera during the match, they will be charged for the full 120 MB of data use.
2. 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.

C. 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. The teams must identify and show to the judges all the wireless emission equipment on the robot, including amplifiers and antennas. If the team has added an amplifier, written documentation shall be submitted to the judges demonstrating that the limits as designated in these rules for power transmission levels are not being exceeded.
4. If the team robot is transmitting low power Bluetooth, or is using any non-2.4 GHz frequency equipment, the following information must be provided to the judges during the communications checkout.
    a. Printed documentation from the manufacture with part numbers of all wireless transmission equipment. This printout must be from the manufacturer's data sheet or manual, and will designate the technology, frequency, and power levels in use by this type of equipment.
5. If a team cannot demonstrate the above tasks in the allotted time, the team will be disqualified from the competition.
6. On Monday, May 18, 2015, on a first-come, first-serve basis, the teams will be able to show the communication judges their compliance with the rules.
7. 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 18, 2015, and Tuesday, May 19, 2015.
8. Once the team arrives at the communication judges' station, the team can no longer receive assistance from the NASA communications technical experts.
9. If a team is on the wrong channel during their competition attempts, the team will be disqualified and required to power down.

D. 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. During regolith simulant dumping operations only, the mining robot may deploy itself and exceed 1.5 m in height, but must be lower than the height of the ceiling of the tent, which is less than 2.5 m above the surface of the regolith. 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. Pneumatic mining systems are permitted if the gas is supplied by the robot and self-contained. 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 and/or gravel 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, 2015 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, 2015 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 11, 2015**. 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 18, 2015. 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. Teams must submit their Shipping Bill of Lading/Commercial Invoice by April 30, 2015. All mining robots must be picked up from the Kennedy Space Center Visitor Complex **no later than 5:00 p.m. on Wednesday, May 27, 2015**. 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

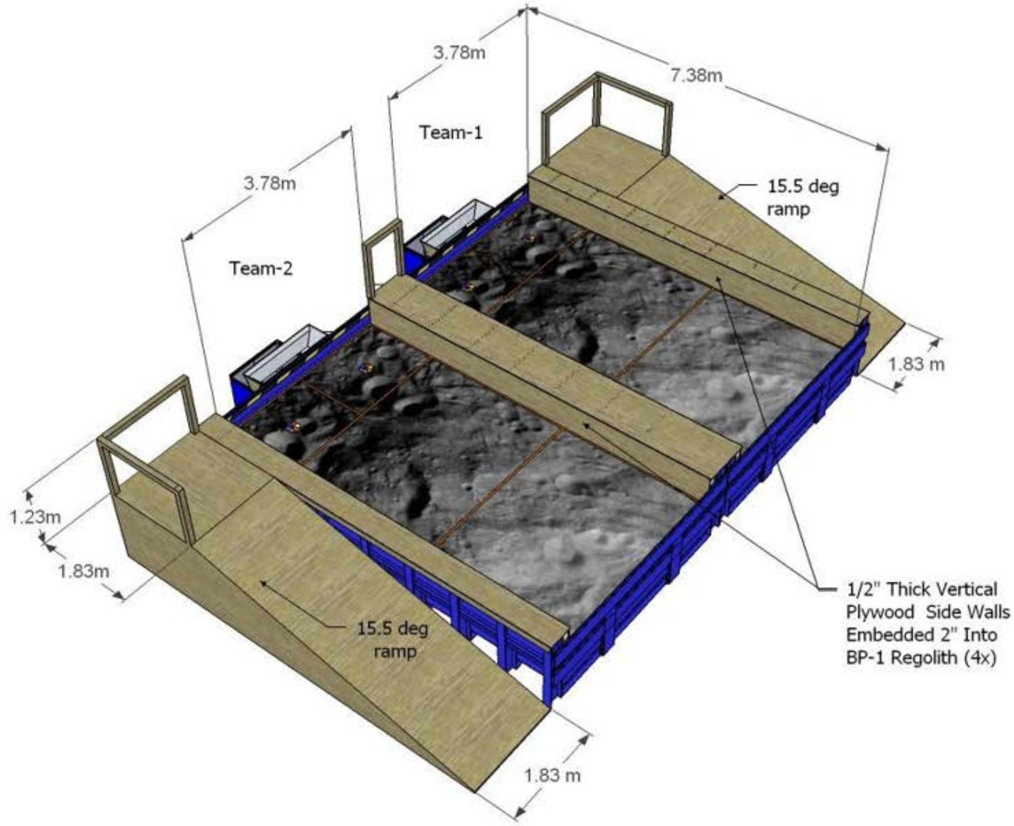


Diagram 1: Caterpillar Mining Arena (isometric view)

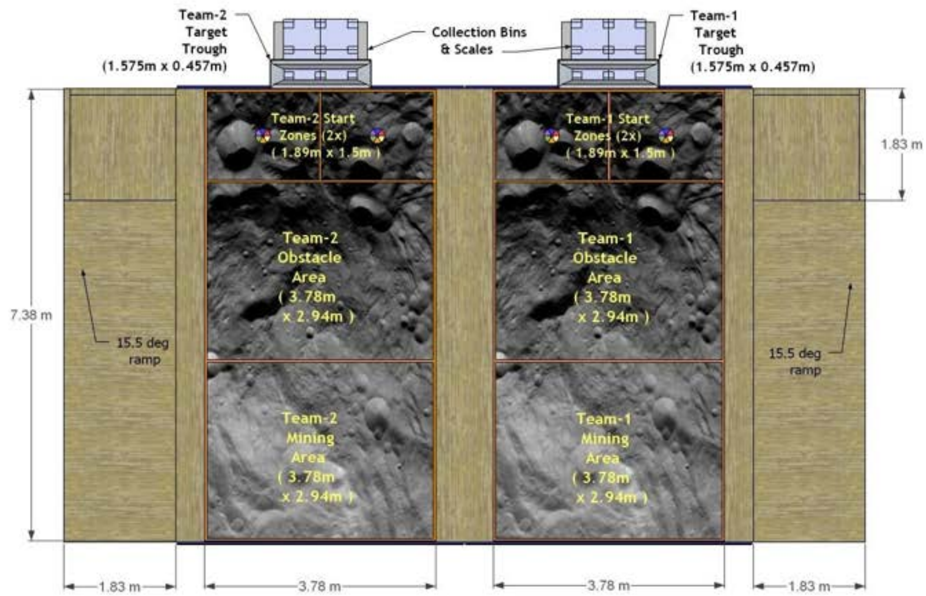


Diagram 2: Caterpillar Mining Arena (top view)

Collector Bin Diagram

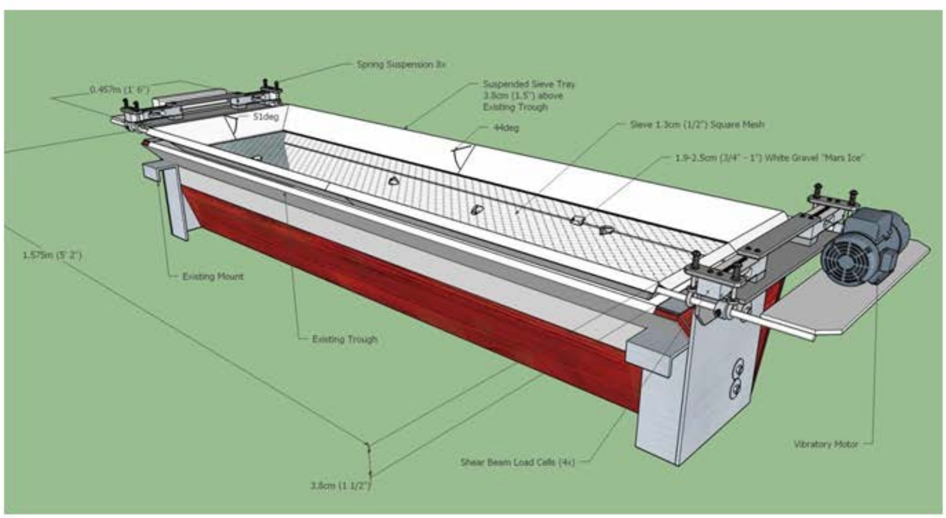


Diagram 3: Collector Bin

NASA's Robotic Mining Competition Systems Engineering Paper

Each team must submit a Systems Engineering Paper electronically in PDF by April 13, 2015 at 12:00 p.m. (noon) eastern time. Your paper should discuss the Systems Engineering methods used to design and build your mining robot. The purpose of the systems engineering paper is to encourage the teams to use the systems engineering process while designing, building and testing their robot as opposed to writing a paper after the fact. 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? ice simulant, 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 13, 2015 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 13, 2015 at 12:00 p.m. (noon) eastern time. Teams **MUST** present the slides turned in on April 13th. 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 13th. 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 the Caterpillar Mining Arena, Sandbox, and Pits • Exhibits a strong sense of collaboration within the team • Supports other teams	Three elements are clearly demonstrated	Two elements are clearly demonstrated	One element is clearly demonstrated	Zero elements are demonstrated
Attitude: • Exudes a positive attitude in all interactions • Demonstrates an infectious energy by engaging others in group activities • Keeps pit clean and tidy at all times	Three elements are clearly demonstrated	Two elements are clearly demonstrated	One element is clearly demonstrated	Zero elements are demonstrated
Creativity & Originality: • Demonstrates creativity and originality in team activities, name, and logo • Wears distinctive team identifiers • Creatively promotes specific cultural and/or regional pride	Three elements are clearly demonstrated	Two elements are clearly demonstrated	One element is clearly demonstrated	Zero elements are demonstrated
Sportsmanship: • Demonstrates courtesy with authority & competitors • Demonstrates respect • Conducts themselves as positive role models	Three elements are clearly demonstrated	Two elements are clearly demonstrated	One element is clearly demonstrated	Zero elements are demonstrated

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 20-22, 2015	First place $3,000 team scholarship and Kennedy launch invitations Second place $2,000 team scholarship and Kennedy launch invitations Third place $1,000 team scholarship and Kennedy launch invitations Teams not placing 1st, 2nd, or 3rd will receive one point per kilogram of BP-1 and/or icy regolith simulant (gravel) mined and deposited up to 10 points	25 20 15 Up to 10
Systems Engineering Paper	Required	April 13, 2015	$500 team scholarship	Up to 20
Outreach Project Report	Required	April 13, 2015	$500 team scholarship	Up to 20
Slide Presentation and Demonstration	Optional	April 13, 2015 and On-Site on May 20-22, 2015	$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 20-22, 2015	A school trophy	
Efficient Use of Communications Power Award	Optional	May 20-22, 2015	A school trophy	
Caterpillar's Autonomy Award	Optional	May 20-22, 2015	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	Noon, April 13, 2015
☐ Outreach Project Report	Noon, April 13, 2015
☐ On-site Mining	May 20-22, 2015
○ Team Check-in, Unload/Uncrate mining robot	May 18, 2015 by 3:00 p.m.
○ Practice Days	May 18-19, 2015
○ Competition Days	May 20-22, 2015
○ Awards Ceremony	May 22, 2015 (evening)

Optional Competition Elements

☐ Presentation File	Noon, April 13, 2015
☐ Team Spirit	All year

Required Documentation

☐ Letter of Support from lead university's Faculty Advisor	With Competition Application
☐ Letter of Support from lead university's Dean of Engineering	December 1, 2014
☐ Team Roster	December 1, 2014
☐ Student Participant Form	December 1, 2014
☐ Faculty Participation Form	December 1, 2014
☐ Transcripts (unofficial copy is acceptable)**	December 1, 2014
☐ Signed Media Release Form	December 1, 2014
☐ Team Photo including faculty (high resolution .jpg format preferred)	January 19, 2015
☐ Team Biography (200 words maximum)	January 19, 2015
☐ Corrections to NASA generated Team Roster	February 24, 2015
☐ Head Count Form	February 24, 2015
☐ Revised Team Roster (no changes accepted after this date)	March 24, 2015
☐ Rule 31 documentation	April 30, 2015
☐ Rule 32 video	April 30, 2015
☐ Rule 34 Shipping Bill of Lading/Commercial Invoice	April 30, 2015

* 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:

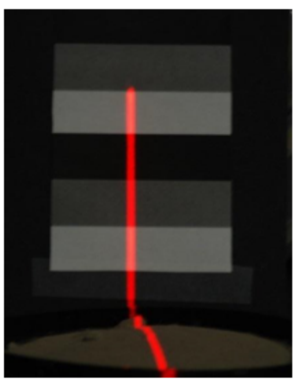
- name of university
- name of student
- current student status within the 2014-2015 academic year
- coursework taken and grades

Definitions

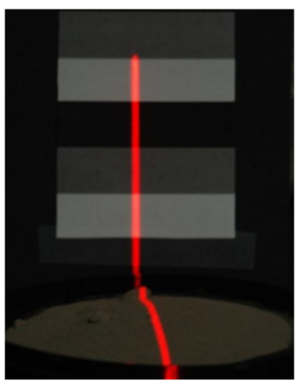
Autonomous – The operation of a team's mining robot with no human interaction.

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/nasarmc. 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 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/.

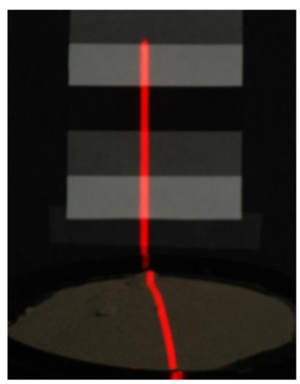
BP-1 reflectivity – NASA performed tests to answer questions about BP-1 reflectivity for LIDAR (or other LASER-based) navigation systems. The laser is not a beam – it is spread out as a sheet that is oriented in the vertical direction, so it is draped across the BP-1 and across a white/gray/black target 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 .3 meters in depth and approximately .5 meters from the top of the walls to the surface. There is no guarantee that the BP-1 in the mining arena will have a level surface, since planetary surfaces are random and chaotic. Be prepared for slopes, irregularities and small rocks in the BP-1 simulant 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 and/or icy regolith simulant from the Caterpillar Mining Arena by the mining robot and deposit of BP-1 icy regolith simulant from the mining robot into the Collector Bin.

Gravel - This is intended to simulate icy-regolith buried on Mars. The gravel will be approximately 2 cm in diameter (minimum size) but will have random particle sizes larger than that also mixed into the gravel. The gravel may be mixed in with the BP-1 in small quantities, but the majority of the gravel will be on the approximately lower 30 cm of the mining area regolith depth only. The gravel will be made of a hard rock material, and will not have a specific color.

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.

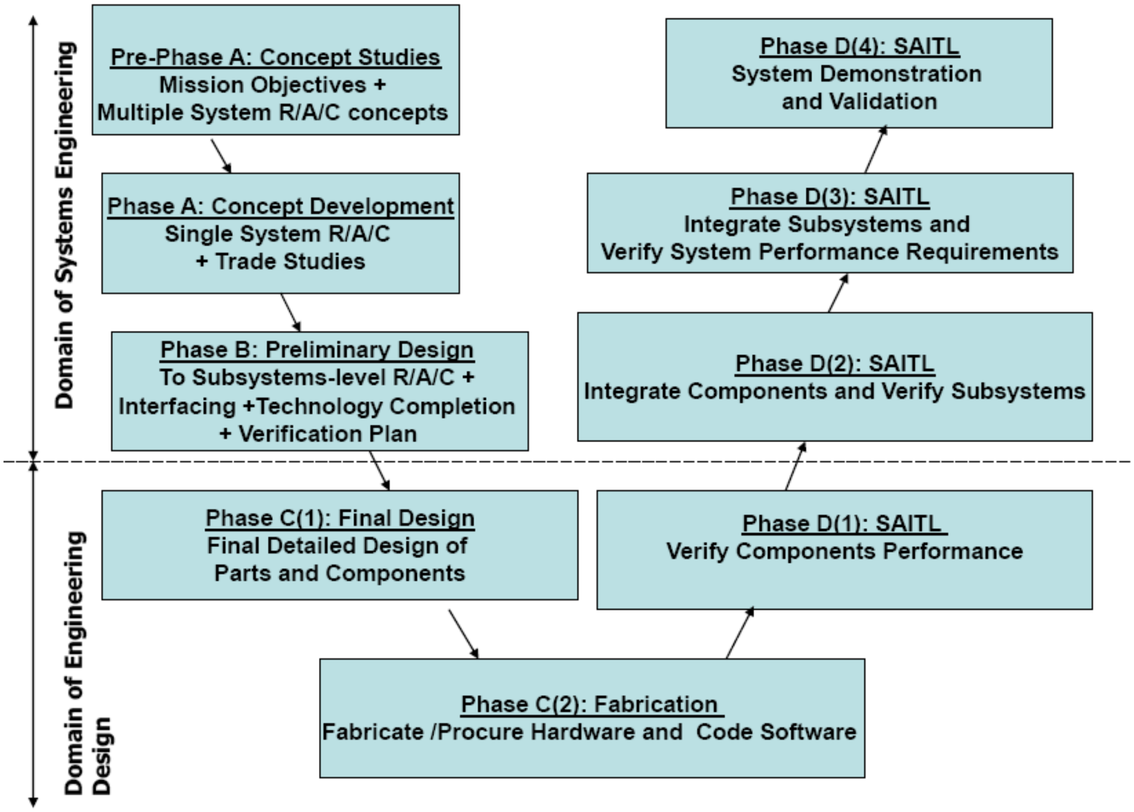
Practice time – Teams will be allowed to practice with their mining robots in the Caterpillar Mining Arena. NASA technical experts will offer feedback on real-time networking performance during practice attempt. A maximum of two practice attempts will be allowed, but not guaranteed.

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 B: Vee Chart



Appendix C: Trade Study Spreadsheet

	Trade Study-Previous On-Site Mining Winners 2011-2014					
	Clark Williams, Chris Oliver, Liz Swaim, Sukrit Kumar					
	2011 On-Site Winners	**Movement**	**Storage/Dumping**	**Digging**	**Source**	**Notes**
1st	Laurentian University	Wheels	Bucket with conveyor	Conveyor	Youtube	Looks heavy. Has trouble moving on small wheels.
2nd	University of North Dakota	Wheels	Bobcat scoop	Bobcat scoop	School Site	Basic bobcat design.
3rd	West Virginia University	Wheels	Dumpable bucket	Conveyor	Facebook page	Poor geometry led to half of dirt being dumped on robot.
	2012 On-Site Winners					
1st	Iowa State University	Treads	Bucket integrated with conveyor	Conveyor	Facebook page	Nice design. Lightweight and nice use of bucket/conveyor combo.
2nd	University of Alabama	Wheels	Bucket with conveyor and horizontal auger	Conveyor/scoop combo	Facebook page	Wheels are actuated and rotate 90 degrees. Robot looks heavy.
3rd	Milwaukee School of Engineering	Wheels	Bucket	Conveyor	Facebook page/ustream	Very lightweight design.
	2013 On-Site Winners					
1st	Iowa State University	Treads	Bucket integrated with conveyor	Conveyor	Facebook page	Same robot as 2012 except with larger bucket.
2nd	University of North Dakota	Wheels	Drum	Drum	Ustream site, search "2013 RMC part 1"	Drum on arm to dig, worrisome that arm might snap off
3rd	University of New Hampshire	Wheels	Bobcat scoop	Bobcat scoop	Facebook page	Basic bobcat design. Lightweight and reliable.
	2014 On-Site Winners					
1st	West Virginia University	Wheels	Dumpable bucket	Bobcat scoop	Facebook page	Bucket with bobcat scoop can continuously dig before having to dump. Wheel design allows for good traction.
2nd	Florida Institute of Technology	Actuated wheels	Conveyor track system	Sideways drum	http://www.ustrea	Conveyor dumping system is horizontal, so regolith sits on top of conveyor before being deposited.
3rd	University of Alabama	Wheels	Dumpable bucket	Conveyor	Facebook page	Lightweight and reliable system of digging and dumping.

Appendix D: NASA Lunabot Scoring MATLAB Code (Updated)

Matlab code from the previous semester has been updated with sections for scoring gravel, a new option in this year's competition with twice the point value of regolith.

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

%Updated For 2015 Competition by Clark Williams, Fall 2014

%This file is intended to estimate the amount of points received per "NASA's
Fifth Annual Robotic Mining Competition Rules and
%Rubrics 2015."

clc
clear all

%% Inputs
SafeandCommCheck=input('Pass safety and comm check? (yes=1 n=0) ');
KG=input('Amount of BP1 dug (kg) ');
KG2=input('Amount of gravel 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, excavate, and deposit=2  Cross, excavate, and deposit
twice=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 Safety 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
        pointspergravel=6; %points per kg gravel dug
        DigPoints=pointsperkg*(KG-initial)+pointspergravel*(KG2);

        %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, excavate, and return
            autopoints=150;
        elseif autoindex == 3 %Cross field, excavate, and return twice
            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+dustpoin
ts+autopoints

    end
end
```

Appendix E: VectorPly Analysis[3]

Laminates were defined with a top layer of carbon fiber, a center core of paper honeycomb, and a bottom layer of carbon fiber. Material properties are shown below.

Laminate	90/+-45 weft triaxial	quadraxial	0/90 biaxial	0 warp unidirectional	
Thickness	1.048	1.049	1.051	1.048	in.
Mf	65.98 %	65.98 %	65.98 %	65.98 %	by Wt.
Density	6.3	6.5	6.6	6.4	lb/cu.ft
Fiber Wt.	0.24	0.25	0.26	0.24	lb/sq.ft
Resin Wt.	0.12	0.13	0.13	0.12	lb/sq.ft
Laminate Wt.	0.55	0.57	0.58	0.55	lb/sq.ft
Vf	54.24 %	54.24 %	54.24 %	54.24 %	by Vol.
0º Modulus, Ex	0.13	0.31	0.45	0.77	MSI
90º Modulus, Ey	0.31	0.31	0.45	0.08	MSI
Poisson Ratio, PRxy	0.31	0.29	0.03	0.31	
Shear Modulus, Gxy	0.14	0.11	0.03	0.03	MSI
0º Ten. Ult. Stress	1.3	3.7	5.0	9.2	KSI
0º Comp. Ult. Stress	1.3	2.4	3.5	5.9	KSI
90º Ten. Ult. Stress	2.9	3.7	5.0	3683.0	KSI
90º Comp. Ult Stress	2.7	2.4	3.5	3683.0	KSI
Shear Ult. Stress	2.4	1.7	0.5	2506.2	KSI
0º Flex. Ult. Stress	3.3	6.1	8.7	15.8	KSI
90º Flex. Ult. Stress	7.8	6.1	8.7	8493.0	KSI

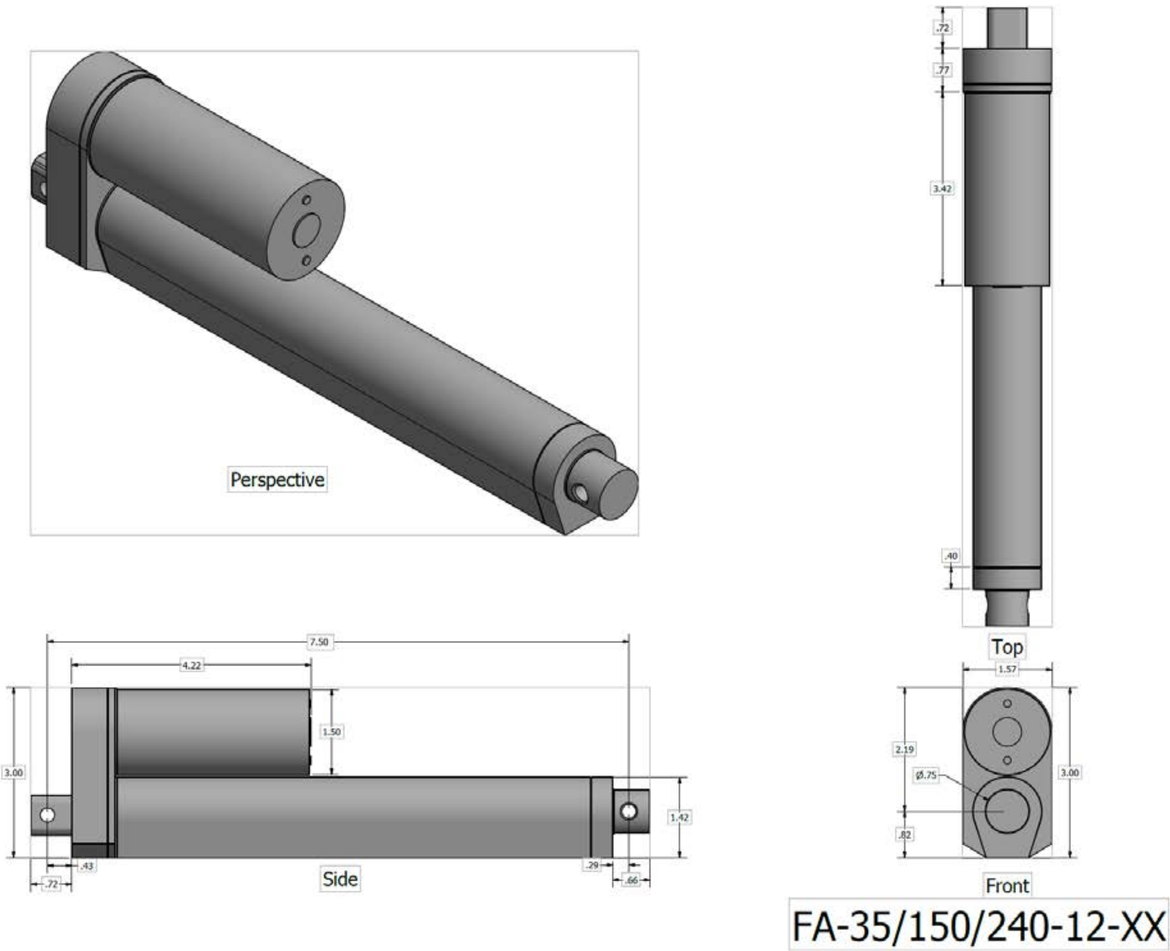
The beam analysis performed was based on the above material properties for a triaxial weave and the dimensions of the proposed frame. This analysis is shown in full below.

Load, Span & End Conditions			
Beam Unsupported Length :	8.3	23.6	in.
End Conditions :	Simple	Simple	
Type of Beam :	Box Beam	Box Beam	
Type of Load :	Point Load	Distributed Load	
Point Load :	60.0		lbf
Point Load Location from end with most fixity:	4.1		in.
Distributed Load :		4.0	lb/in
Beam Geometery			
Beam Height, h :	1.00	1.00	in.
Cap Width, b :	2.50	2.50	in.
Laminates			
Top Cap Laminate	triaxial Carbon fiber layer	triaxial Carbon fiber layer	
= Thickness of	0.024	0.024	in.
Web Laminate (per web)	triaxial Carbon fiber layer	triaxial Carbon fiber layer	
x multiplier	2.00	2.00	in.
= Total Web Thickness of	0.048	0.048	

Bottom Cap Laminate	triaxial Carbon fiber layer	triaxial Carbon fiber layer	
= Thickness of	0.024	0.024	in.
Weight			
Top Cap	0.04	0.04	lb/ft
Web	0.03	0.03	lb/ft
Bottom Cap	0.04	0.04	lb/ft
Per Length	0.11	0.11	lb/ft
Deflection	0.01	0.20	in.
= Span /	944	118	> 100
Bending Stiffness, EI =	80,320	80,320	lb-sq.in
Bending Moments			
Total Design Load	60.0	94.2	lbf
Moment at ends for distributed load	-	-	in-lb
Moment at mid-span for distributed load	-	277.5	in-lb
Max moment at ends for point load	-	-	in-lb

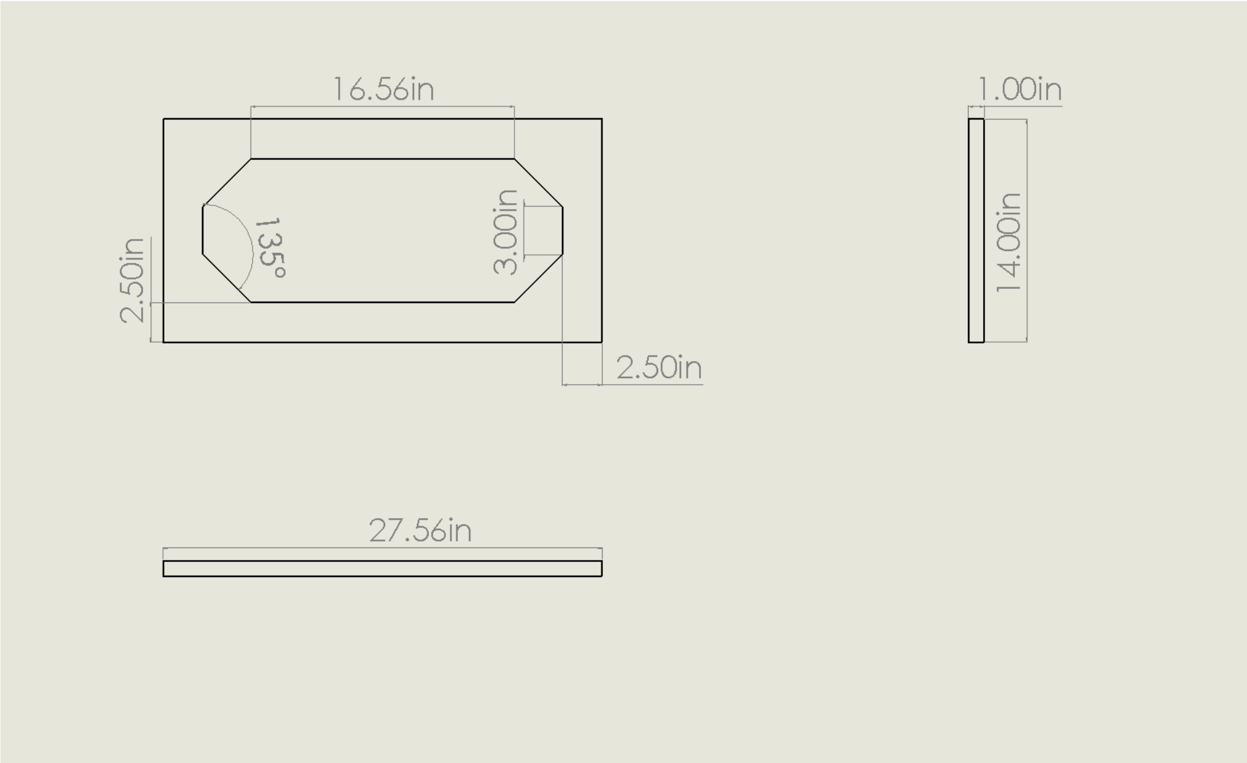
Moment at point load	123.8	-	in-lb
Max Moment at Ends	-	-	in-lb
Mom. at Mid-span of Distributed Load or Point Load	123.8	277.5	in-lb
Max Shear	30.0	47.1	lbf
Safety Factors			
Moment @ Ends	**n/a**	**n/a**	>= 3.33
Moment @ Middle of Distributed Load	**n/a**	**14.5**	>= 3.33
Moment @ Point Load	**32.5**	**n/a**	>= 3.33
Web Shear	**76.9**	**49.0**	>= 4.0

Appendix F: Conveyor Actuator Specifications



Firgelli Light Duty Rod Actuators	
Model	FA-240-S-12-XX
Dynamic Force	200 lb
Static Force	400 lb
Speed ("/s)	0.3
Duty Cycle	20%
IP Rating	54
Input	12 VDC
Max Draw	5.0 A
Operation Temperature	-26°C/65°C (-15°F/150°)
Stroke	3"
Retracted Length	7.5"
Extended Length	10.5"
Weight	2.15 lb

Appendix G: Frame Dimensions and Mass



Carbon sheet $17.37 \frac{oz}{yd^2}$

surface A of frame (in^2)

outside

$2(27.56 \cdot 1) + 2(14 \cdot 1) \rightarrow 83.12$

Top

$2(27.56 \cdot 2.5) + 2(9 \cdot 2.5) + 4(\frac{1}{2} 3 \cdot 3) \rightarrow 200.8$

inside

$2(16.56 \cdot 1) + 4(4.24 \cdot 1) + 2(3 \cdot 1) \rightarrow 56.08$

bottom

$2(27.56 \cdot 2.5) + 2(9 \cdot 2.5) + 4(\frac{1}{2} \cdot 3 \cdot 3) \rightarrow 200.8$

Total A = $540.8 \ in^2$

$$\text{mass (kg)} = \left(\frac{1 yd}{36 in}\right)^2 (540.8 \ in^2)\left(17.37 \frac{oz}{yd^2}\right)\left(\frac{1 kg}{35.274 oz}\right)$$

mass of carbon = **0.2 kg**

Honeycomb $27.1 \frac{oz}{yd^2}$ + 1 in thick

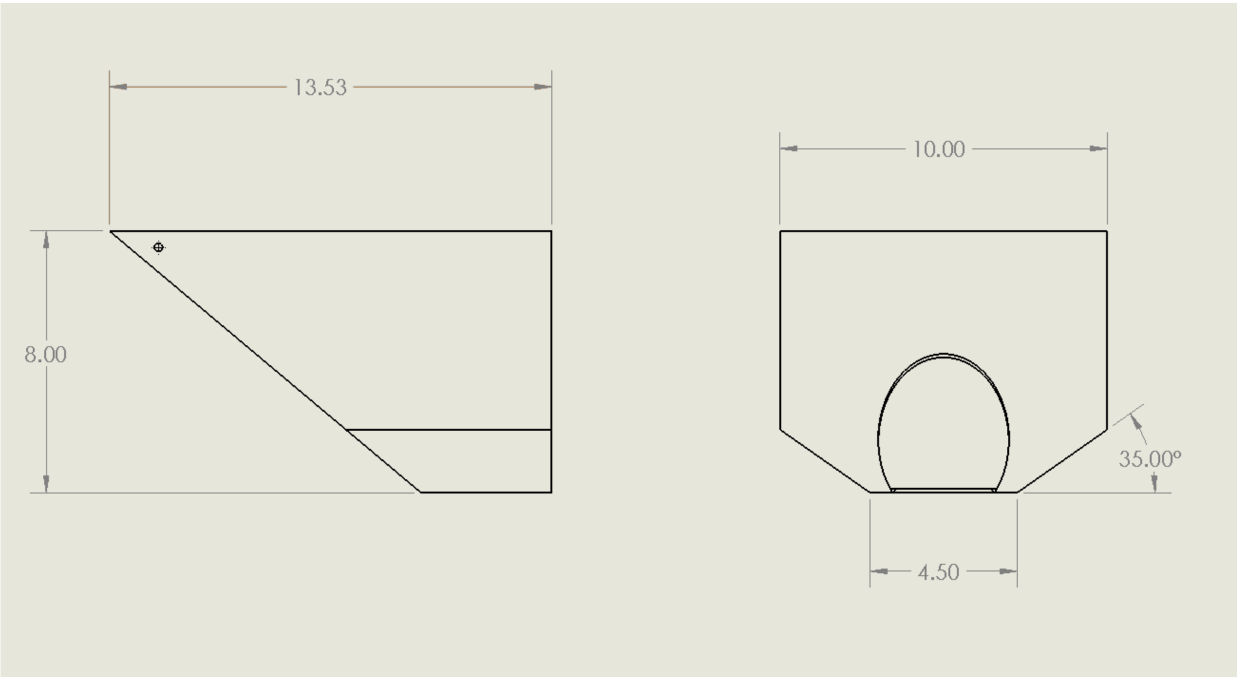
Area = Top area above

$200.8 \ in^2$

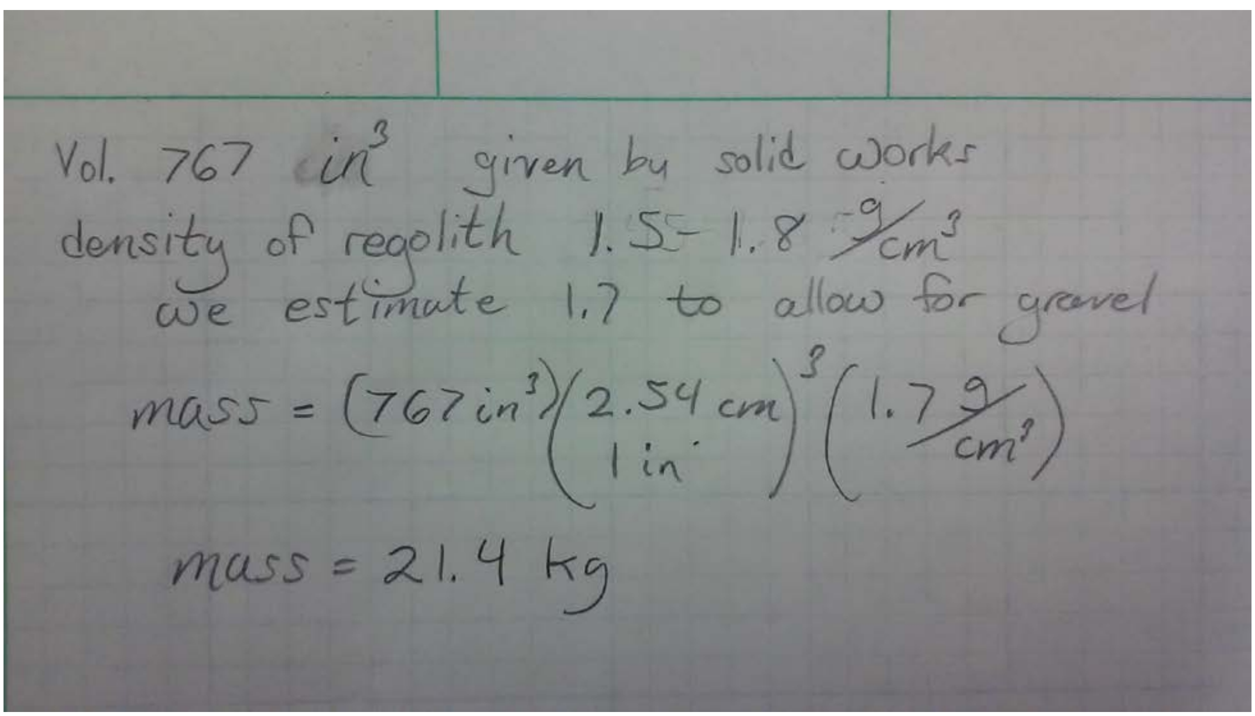
$$\text{mass (kg)} = \left(\frac{1 yd}{36 in}\right)^2 (200.8 \ in^2)\left(27.1 \frac{oz}{yd^2}\right)\left(\frac{1 kg}{35.274 oz}\right)$$

= 0.119 kg

Appendix H: Bin Dimensions and Volume



The mass of regolith which the bin is capable of holding was calculated based on the densities of lunar regolith given in a NASA lunar regolith study. [4]



Appendix I: References

[1] Mech 4240 Preliminary Design Review, Matthew Jones, David Faucet, Stewart Boyd, Will Flournoy. 2014.

[2] Mech 4240 Final Review, Matthew Jones, David Faucet, Stewart Boyd, Will Flournoy. 2014.

[3] VectorPly.com\vectorlam

[4] Rahmatian, Laila A, Philip T. Metzger. "Soil Test Apparatus for Lunar Surfaces." Earth and Space 2010: Engineering, Science, Construction, and Operations in Challenging Environments. 2010