NASA Exploration System Mission Directorate Higher Education Project

Final Design Report
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Lunar Regolith Excavator Student Competition
ME Team #8 / ECE Team #1

The ARTEMIS Project

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Executive Summary

In May of 2010, NASA will be holding the first annual Lunabotics Mining Competition at the Kennedy Space Center. The competition is designed to engage and retain undergraduate and graduate students in science, technology, engineering, and mathematics subjects in a competitive environment while also eliciting innovative ideas for lunar regolith excavation. Recently, NASA discovered that lunar regolith, or top soil, has solid water, or ice, in it. This discovery has shown that it would be feasible to build a lunar base in the near future. Other than water, lunar regolith can be used for construction material, shielding from radiation and micro-meteorites, blast burms for landing craft, and possibly even raw materials such as rocket fuel constituents. In the future of lunar exploration and colonization, regolith has an important role to play as well as the excavation of regolith.

The ARTEMIS Project, using a Systems Engineering methodology, has conceived and designed a robotic platform capable of excavating 10 kg of lunar regolith within 15 minutes. The design incorporates tracks, a conveyor paddle belt excavator, a bucket for regolith storage, and various components for control. The total budget allotted for the project is currently $6,500, the projected cost for the project is currently $6,195. The project is currently slated to be completed by mid Spring semester of 2010 for evaluation of excavation and redesign if needed.

Table of Contents

Appendices

1. Introduction

NASA is hosting the first annual Lunabotics Mining Competition in May 2010. This will be held at Kennedy Space Center and is geared towards undergraduate and graduate students. There is another similar competition entitled NASA Regolith Excavator Centennial Challenge, and has been previously held at the California Polytechnic State University in San Luis Obispo, California. In both cases NASA is hoping to find innovative ideas on how to excavate the surface of the moon. In the Lunabotics Mining Competition the primary goal is to educate students in engineering, math, sciences, and project management in a competitive setting.

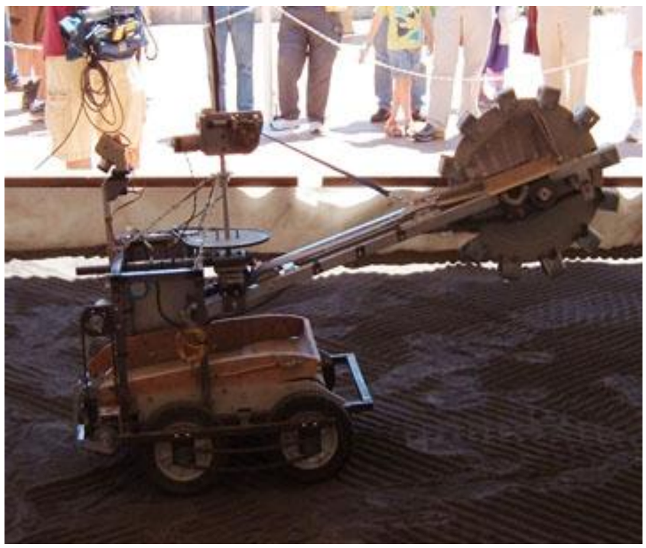

Figure 1a. A robot presented at the 2008 NASA Regolith Excavator Centennial Challenge [1].

Each team will be given thirty minutes to excavate as much regolith as possible. To be considered for placing in the competition the robot must excavate at least 10 kilograms of regolith in 15 minutes. The robot must have a mass of less than 80 kilograms, be no taller than 2.0 meters, no wider than 1.5 meters and no longer than 0.75 meters. Before and after the competition each team will have ten minutes to setup and take down the excavation equipment. After every team has competed a winner will be announced and receive $5,000 and VIP launch tickets. There are minor prizes given to teams that win other categories such as a system engineering paper, outreach to informal education, and the team spirit competition.

1.1 Background

Interest in lunar exploration began right before the 1960s. In 1959 the Soviets designed Luna 1, the first of the Luna series and the first spacecraft to fly by the moon. Luna 2 was the first spacecraft to impact the moon later that same year. Between then and 1966 both the United States and the Soviets had many missions that sent spacecrafts to the moon.

Figure 1.1a. Luna 1 was a spacecraft developed by the Soviet Union and the first to fly by the moon in January 1959 [2].

The first American missions were designed to test the technology and after a year of testing the goal shifted to landing on the moon. In many of these missions Soviet and American spacecrafts impacted the moon instead of a soft landing. Not until 1966 was there a soft landing. This is when Luna 9 landed on the moon. From this mission the first photographs of the moon's surface were achieved. Only two years later in 1968, the Apollo 8 mission had the first humans orbited the moon. The following year the first humans landed on the moon. The Apollo 11 mission was the first time lunar geologic samples were taken

Figure 1.1b. Artist's Conception of Lunar Mining [1].

Recently interest has shifted from short missions to the moon to longer, more permanent missions. Because of this, interest in excavation of the moon has increased. The reason behind these long-term projects is to perform longer supervised scientific studies. NASA hopes that by excavating the moon natural resources will be found and help make the moon a place where humans can survive. The reason NASA wishes to use the regolith to get these resources is because getting oxygen and other means to the moon can become very expensive. The main resource that can be used from the moon is the regolith, or lunar sand. Previous testing of the regolith has proven that it contains oxygen, silicon, aluminum, calcium, iron, and magnesium as well as very small amounts of titanium, sodium and sulfur. Besides extracting elements from the regolith it will be used to protect the astronauts from radiation as well as a building material for the lunar camp.

NASA has developed a product called JSC-1 that contains similar properties to regolith and can help in the development and testing of an excavator.

1.2 Problem Statement

The competition is designed to promote the development of mechanical designs to excavate lunar regolith. Each team that can, using telerobotic or autonomous operation, excavate the most lunar regolith stimulant (above the Minimum Excavation Requirement of 150.0 kg and within the Excavation Hardware mass limit of 80.0 kg) from a supplied quantity of regolith within a specified time limit of 30 minutes will win the competition.

1.3 Project Objectives

The motivation for the project is for lunar exploration and colonization. NASA's Constellation Mission Program is designed to return humans to the moon within the next 20 years. As part of the Constellation Program, human settlements will be set up creating a permanent moon base. Autonomous, telerobotic, and direct control excavation and construction vehicles will be necessary for moon colonization. Lunar regolith, or top soil, can be utilized for many uses including resources, construction, and protection.

The focus for a Lunar Excavating robot will be to excavate regolith for use in construction and resource mining. The construction of regolith over living quarters adds a layer of protection against solar radiation and micro-meteorites. Other construction uses for regolith include creating blast burms for landing pads. Lunar regolith also has a very important role in creating oxygen and water, as lunar regolith has a high percentage of oxides that can be extracted and converted to useable resources.
The primary objective of this project is to design and build a telerobotic system capable of exceeding competition requirements to allow a solid win at the Exploration Systems Mission Directorate Lunar Regolith Excavator Student Competition at Kennedy Space Center in May 2010. The secondary objective of the project is to create a useful robotic system that can easily be implemented for lunar excavation, exploration, and construction.

2. Systems Engineering Method and Concept Development

2.1 Systems Engineering Methodology

Systems engineering presents a useful method for accomplishing all tasks necessary in the design and manufacture of the Lunar Excavating Robot discussed above. Systems engineering focuses on identifying and analyzing customer needs early in the development process, documenting requirements, and then identifying necessary subsystems and proceeding with design synthesis [3]. In this project, systems engineering is an important aspect of the development of the robot due to the complexity of locomotion, excavation, control, and power. Each complex system is identified, and the team works to solve the technical challenges presented. Each system is developed to be integrated into one coherent product in the final manufacturing process.

In the development of the Lunar Excavating robot, 6 subsystems were identified as high priority design aspects. The subsystems are locomotion, excavation, navigation (now control), power, and micro-controllers & communications. These subsystems represent important facets of the final product, and thus warrant more detailed design.

The needs analysis flow diagram represents the needs of the customer, the project, and identifies specific elements and interfaces to address the needs. Figure 2.1a outlines the needs analysis for the ARTEMIS Project including a basis for the individual systems, interfaces within the systems, and the overall goals of the project (requirements).

The system requirements were identified by the customer, in this case they represent the rules outlined by NASA and the Exploration Systems Mission Directorate for the competition. The requirements were broken down into specific tasks that the robot needed to perform. These tasks included movement over a large area, excavation of regolith, material transport, obstable avoidance, power storage and power regulation, delivery of power, information relay, signal processing, and many more. Once the tasks were identified, they were grouped based on similarity and purpose. These groups were then identified as the specific subsystems of the ARTEMIS Project Robot and represent the categories necessary to fulfill all customer requirements.

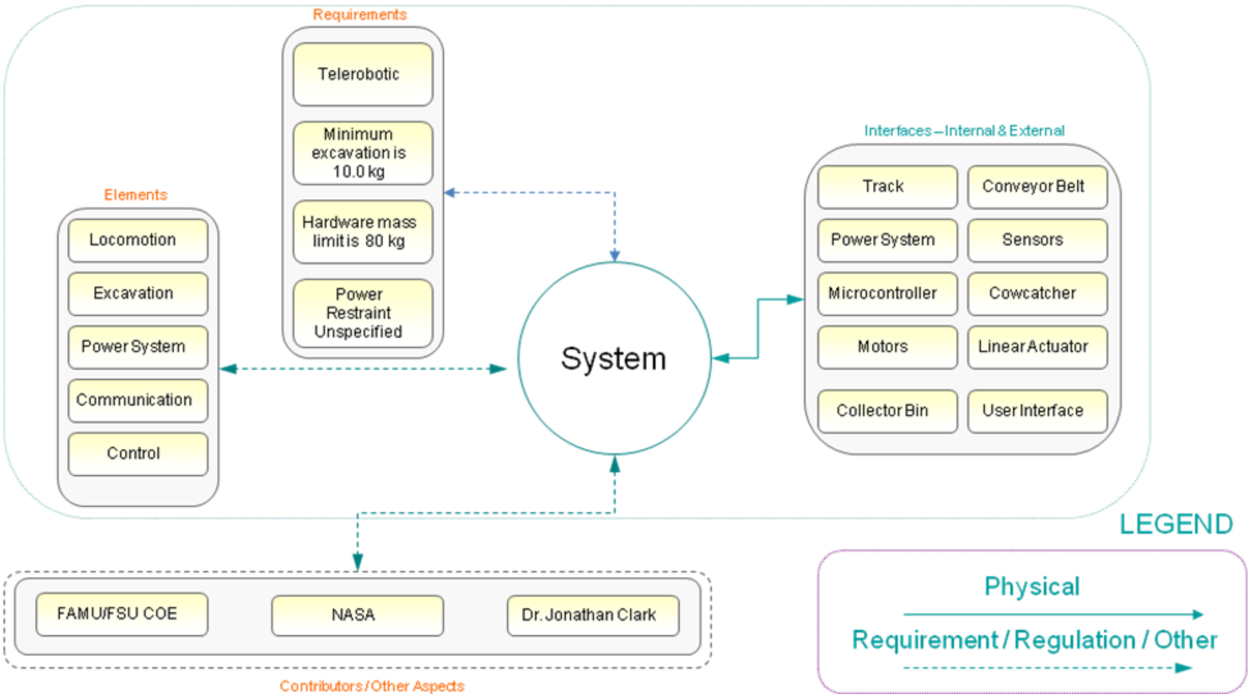

Figure 2.1a. Needs Analysis Flow Diagram for the ARTEMIS Project

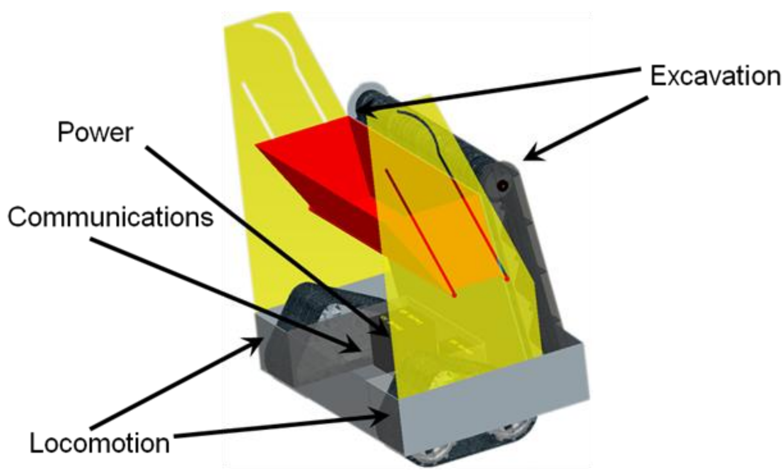

Figure 2.1b. Overall platform design with subsystems

Figure 2.1c represents the overall system, the subsystem, and the individual components or tasks as a block diagram hierarchy. Once each subsystem was identified, the team brainstormed overall designs capable of fulfilling part or all of the customer requirements. These overall designs were then dismantled into the representative subsystems for a host of possibilities to solve each subsystems individual problem.

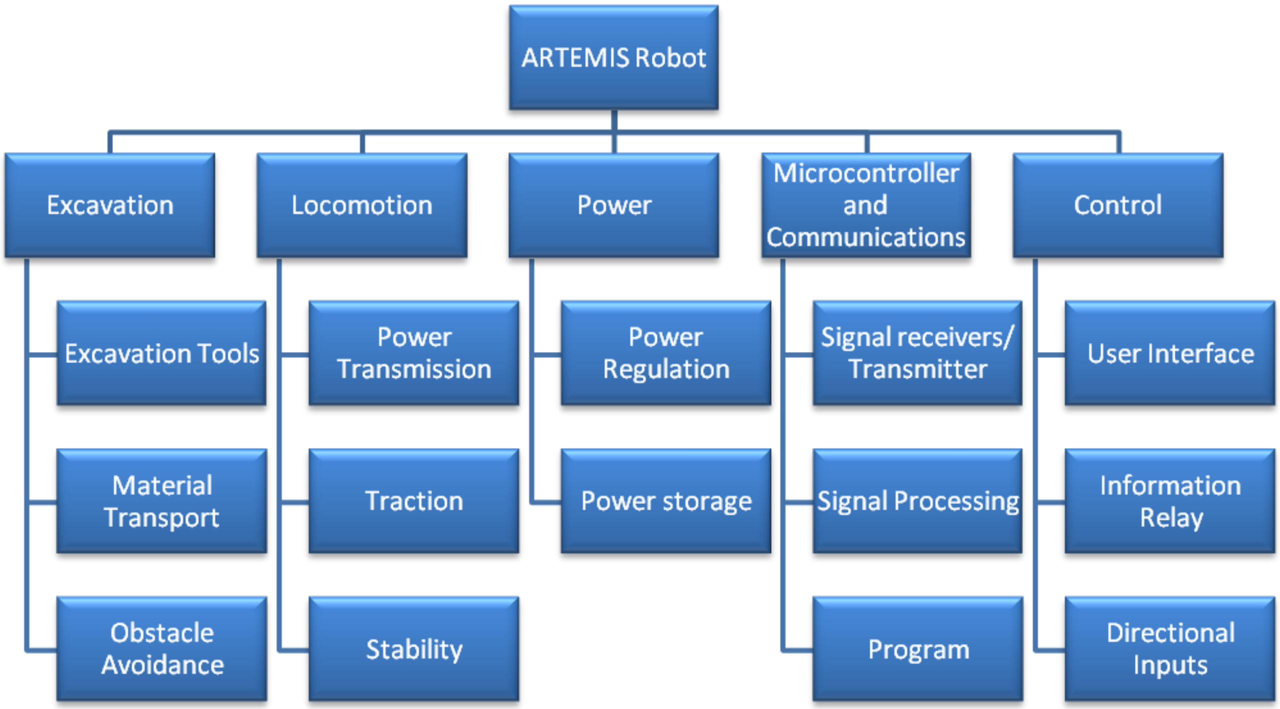

Figure 2.1b. Block Diagram Hierarchy of the ARTEMIS Project Robotic System

2.2 Excavation Subsystem Concepts

Bucket Chain

The bucket chain is a combination of the two primary functions of the excavation subsystem – excavation and transport to the holding bin. A conveyor belt with digging buckets removes material and carries it directly to the bin. The bucket chain in Figure 2.2a can excavate in a large swath below the level of the crawlers tracks. This is used to dredge canals and shape material stockpiles.

Figure 2.2a. Commercial bucket chain excavator [29].

The main advantage of this method is the immediate transport of removed material to the bin. There is no need to synchronize the excavating mechanism with a separate conveyor. Also, there is less material lost during transport to the bin. The disadvantages include high inertia and power requirements due to the number of buckets on the chain and the digging action of multiple buckets. The weight and power increase over a conveyor and digging system necessitate a much stronger chain and supporting framework.

<u>Clam Shell</u>

The clamshell is a pivoting split bucket that excavates and removes material by closing the bucket on the material to be removed. The bucket is then moved over a collection bin and opened to release the material. A common use of a clamshell is to excavate material from the bottom of a shaft or caisson.

Figure 2.2b. Clamshell attachment for backhoes [30].

Due to its split bucket design, the clamshell can develop high excavation force without a backward reaction force. As seen in Figure 2.2b, the clamshell has three moving parts – the shell halves and the hydraulic actuator. It is also highly maneuverable and can deposit the excavated material in a bin without an extra conveyance device. The main drawback to the clamshell is that it requires a rigid articulated arm to supply the downward force needed to penetrate the ground. This articulated arm is difficult to control remotely due to its many degrees of freedom.

Powered Brushes
This method is commonly seen in street sweepers. There are two different types of brushes used to move material, circular and cylindrical. The circular brushes (right side, Figure 2.2c) are spun at angles to bring material inward while the cylindrical brush (left side, Figure 2.2c) is used to pick the material up onto a conveyor.

Figure 2.2c. Elgin street sweeper [31].

The ease of implementation and control is the main selling point of this design. It also works very well when picking up loose debris from a hard surface. Unfortunately, the processes of spraying water and vacuuming to reduce the dust will not work in a lunar environment. This will lead to a large amount of material being lost before reaching the bin. Due to the origin and design of the sweeper, it has neither the capacity nor efficiency to serve as an excavator.

Boring
The most unconventional idea conceived was thought up in conjunction with the worm locomotion method. Taking cues from tunnel digging (Figure 2.2d), mechanically boring through the sand was proposed, since vacuum methods will not work on the atmosphereless moon. The ingestion of material would occur as the robot moved through the sand, clearing a path for the framework to follow. The material would be transported through the robot to a bin above the surface or directly deposited into the collection bin. It was decided that such a device would not be feasible within the scope and timeframe of this project.

Figure 2.2d. Microtunneling Boring Machine [32].

Bucket-wheel Excavator

The bucket-wheel excavator is one of the primary excavation tools used in surface mining. Figure 2.2e below is an example of a very large bucket-wheel excavator used in mining. A bucket-wheel consists of a large wheel fitted with digging buckets located around its circumferences. The bucket-wheel is connected to the main body via a large boom. Within this boom is a conveyor system which transports excavated material to the main body where it is collected.

Figure 2.2e. A giant bucket-wheel excavator [23]

The advantages of the bucket-wheel excavation method are that it is highly efficient, excavates uniformly, easily scalable, offers excellent controllability, and is a proven excavation method. The disadvantages of this excavation method are that there are very few off-the-shelf parts available on the scale we need to work with. This in turn makes this design more costly, and time consuming to develop when compared to some other proposed methods of excavation. Another disadvantage of this design is that it does not handle large object well. On the scale of the bucket-wheel excavator in figure 8 above, a large boulder could cause major damage to the mechanical components of the excavation system. On the scale in which we will be operating during competition, the rocks placed within the regolith box pose an equal threat to our vehicles excavation components.

Split V-plow

V-plows are primarily used in the removal of debris from roadways. An example of this application is shown in figure 2.2f below. Inward v-plows are far less common, since it focuses debris toward the middle of the plow as opposed to forcing debris off to the sides, which is generally considered more desirable.

Our design requires that debris be focused inward toward the centerline of the vehicle, as this is where the regolith will be collected. By separating the inward v-plow into two halves with ato be determined gap width, we are able to achieve this desired design characteristic. As the vehicle is moved forward, the regolith is funneled by the plow blades to the center mounted conveyor belt which transports the regolith to the collection bin.

Figure 2.2f. An adjustable v-plow in inward-v position [24].

The advantages of this excavation method are that it is a fairly simple design with few moving components, low cost, excavates uniformly, and ease of fabrication. The disadvantages of this design are that it is unproven, it places additional loads on the drive train, and its excavation effectiveness is directly correlated to the performance of the drive system. Through the use of a decision matrix we determined the split inward v-plow to be our best option for excavation.

Backhoe

The backhoe excavation method is one most people are familiar with. In figure 2.2g, a backhoe mechanism is attached to the rear of a tractor. It consists of a two-part articulating mechanical arm with an attached bucket at its end. Backhoes are commonly used in the construction industry and perform very well as hole diggers. They work by forcing the leading edge of the bucket into the ground and then drawing it toward the vehicle, effectively taking a “scoop” out of the soil.

Figure 2.2g. A standard backhoe mounted to a tractor [25].

The advantages of a backhoe are that it is a proven design, and low cost. The disadvantages of this design are that it has a low excavation rate, complicated controls, and a low volume bucket.

Paddle belt

Paddle belt excavation is very similar to bucket-chain excavation in that it excavates and transports the material in one process. The paddle belt excavator is essentially a paddle belt conveyor that is angled into the ground such that when in operation, the paddles on the belt scoop up the regolith and transport it to the collection bin. Pictured below in figure 2.2h is an example of a paddle belt conveyor that could be adapted to excavate regolith.

Figure 2.2h. A paddle belt conveyor [26].

One advantage of the paddle belt excavation method is that it eliminates the need for an additional means of material transport since the paddle belt acts as the excavator and material transport system. Other advantages attributed to this design are its simplicity, variable speed capability, few moving parts, and the need for only on motor drive. A disadvantage of this design is, that while very similar to the bucket-chain, the paddle belt is an unproven excavation method since it is not currently used as such in any industry. Another disadvantage of this design is that few off-the-shelf parts exist on the scale in which we will be operating.

Front loader

A front loader consists of a large bucket attached by mechanical arms to the main body of the vehicle. The front-loader is generally used in the loading of material onto dump trucks, railcars, etc, and is not usually considered excavation equipment. In our case, the front-loader system will be used to excavate regolith by positioning buckets' leading at ground level, and moving bucket through the regolith via the vehicles forward motion. Once the bucket is filled, it would be lifted up above the vehicle and dispense the regolith into collecting bin.

Figure 2.2i. A large excavation front loader from Caterpillar [27].

The advantages of using a front-loader for the excavation of regolith are that it is a proven, simple design, excavates a large volume of regolith per scoop, low cost, low maintenance, and offers good controllability. Two disadvantages of this design are that the rate of excavation is directly correlated to the performance of the drive system, and that few off-the-shelf parts exist outside of heavy machinery applications as seen above in figure 2.2i.

2.3 Obstacle Avoidance Subsystem Concepts

Bumper/Pilot/Angled Plow

This is the simplest method of protecting a device from damage due to collision. It is widely used in industrial robotics and automobiles. A wraparound bumper similar to the one in Figure 2.3a will allow the robot to excavate without having to worry about rock positioning or tracking. It is also easy to manufacture, low cost, and easy to implement. The major drawback to the plain bumper is the flat front. A rock could stay in front and contribute drag to the robot for a long period of time. This can be alleviated with the use of a pilot, colloquially known as a cowcatcher. The sloped and slanted front shown in Figure 2.3a would divert the rock to one side of the robot. In conjunction with a wraparound bumper protecting the locomotion system, the pilot would minimize contact time with the rock, reducing power loss. Manufacturing wise, a pilot is still inexpensive, but would require more fabrication time than a plain bumper. The angled plow is a combination of the bumper and the pilot, but only slanted in one direction. If programmed correctly, the known slant will allow the rocks to be moved in a specific direction, or even to a specific area of the regolith box. This can minimize subsequent contact with the rocks and allow the robot to maintain full excavation speed for a longer period of time. The angled plow is a minor variation on the plain bumper, thus sharing all of its benefits and lessening the severity of its major downside. These methods can be easily implemented for the limited movement excavation methods of the V-plow, front loader, bucket chain, paddle belt, and powered brushes.

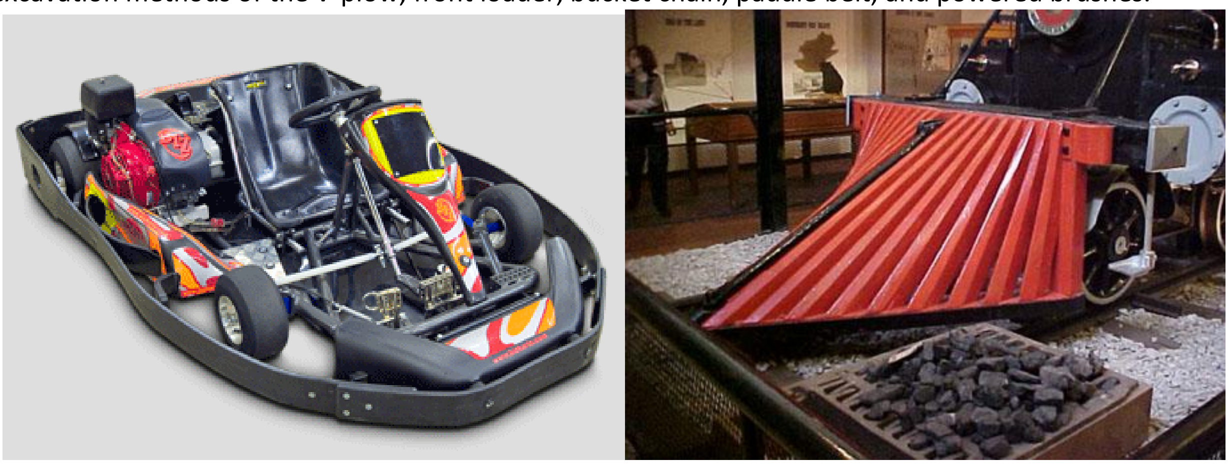

Figure 2.3a. (left) Wraparound bumper on go-kart. (right) Pilot (cowcatcher) on locomotive [33,34].

Post-excavation

In lieu of deflecting or avoiding the rocks, they can simply be picked up by the excavation method. The methods most suited to this approach are the V-plow and the paddle belt. One possibility is to ignore the rocks completely, allowing them to end up in the dump bin. This is the simplest method of dealing with the rocks. The drawback is that they take up space in the dump bin and do not count toward our excavated mass. Another variation on this method is to reject the rocks with an angled bumper or grate at the top of the conveyor. This will allow the excavation mechanism to work nonstop and the rocks will be rejected before they reach the bin. This method has the advantage of keeping unnecessary mass out of the dump bin and allowing the robot to collect only regolith.

Catapult

A Catapult is an example of the only active rock handling method devised. It involves using a catapult on the front of the robot to physically remove rocks from the competition area. Unfortunately, it was deemed unnecessarily complex and hazardous to be pursued any further.

Avoidance

The only non-physical method for dealing with rocks is avoidance. This relies on sensors and navigation commands to avoid both rocks and walls. As such, this concept will be covered in the sensor and navigation subsections.

2.4 Locomotion Subsystem Concepts

The locomotion subsystem presented technical challenges separate from the excavation and navigation subsystems. Six strategies were developed to meet the challenges presented, each implementing a different mode of locomotion. These strategies were compared through ranking with engineering quality characteristics. The requirements ranked include traction, stability, maneuverability, speed, power, cost, simplicity, maintenance, and dust resistance. The six ideas developed were wheels (4 and 6), tracks, C-legs, iSprawl legs, and a digging/locomotion system similar to a worm.

The ideas were created based on the strategy of using speed as a portion of the excavation system. Since the competition requires that 10 kg of regolith (JSC-1 regolith simulant) be excavated in 15 minutes, speed is extremely important to the development of the robotic platform. To maximize efficiency, cross development of sub-systems may be desirable. Matching a semi-passive excavation system, such as plows, with a faster and powerful locomotion system would reduce the amount of motors required in the system. This consideration, along with the above engineering quality characteristics, were used in comparing each locomotion subsystem.

The four wheels are the standard locomotion system employed by modern passenger vehicles and many military vehicles [2]. Equipped with proper off-road tires, and coupled with strong motors, the four wheel design presents a strong option for non-uniform surface operations in soft sand environments. The positives of the four wheel design include simplicity of form, stability, ease of control, smaller physical size, and lower cost. The cons of a four wheel design include lower traction, less stability than other options, and lower power to ground. Figure 2.4a shows an example of an off-road vehicle capable of traversing rough terrain and non-uniform surfaces.

Figure 2.4a. (left) A four wheeled, off-road, military vehicle used in the Afghanistan theatre of war by the United States Army [2]. (right) The Mars Rover Pathfinder, Sojourner developed by NASA [1].

The six wheel design is a standard locomotion system for larger vehicles including transport trucks, Martian rovers, and off-road vehicles. A six wheel design, with proper treaded wheels and a good suspension system, is a good option for off-road operation on surfaces that have large variations in topography [1]. The positives of a six wheel design include stability, traction, redundancy, and lower cost parts. The cons of a six wheel design include more parts, difficulty of control, and larger power requirements. Figure 2.4a shows an example of a six wheeled Martian rover known as Sojourner, capable of slow traversal of rough terrain.

Track designs have been utilized on off-road and all terrain vehicles including tanks and personnel carriers. A tracked system offers great off-road and sand traction performance as well as stability and ease of control. The positives of a tracked system include high traction, large power to ground ratio, ease of control.   The cons of a tracked system include more parts, complicated construction, and higher cost. Figure 2.4b shows a standard example of tracks implemented on a military tank as well as the adaptability of tracks for use on vehicles that typically use wheels.

Figure 2.4b. (left) Tracks have been implemented on military vehicles such as tanks for almost a century [4]. (right) Tracks have been adapted to a variety of vehicles and uses, as shown being utilized by a humvee for off-road, winter conditions [3].

Biomimetic robotics has developed two systems of legged locomotion recently. The first system, known as C-legs, was developed and implemented on a robot known as RHex, a rotary hexapod robot [6]. RHex offers a stable, tripod gait as well as speed and ability to adapt to different surface topographies [6]. The positives of a C-leg system would be stability, adaptability, speed, and dust resistance. The downside of a C-leg system would be complexity, cost, vertical perturbations due to gait changes, and reduced traction. Figure 2.4c illustrates the C-leg system as implement on the RHex robotic platform.

The second system developed through biomimetics is similar to a cockroach leg, first implemented on the Sprawl family of robots [5]. Sprawl legs are actuated using pistons pushing on compliant flexure legs, causing movement up and down [5]. These legs provide high speed, agility, adaptability, and high dust resistance. The cons of this design include difficulty with dynamic scaling, low payload capacity, low traction in sand, and difficulty adapting to excavation functions. Figure 2.4c shows the completed first generation Sprawl robot that uses prismatic actuators to flex compliant legs.

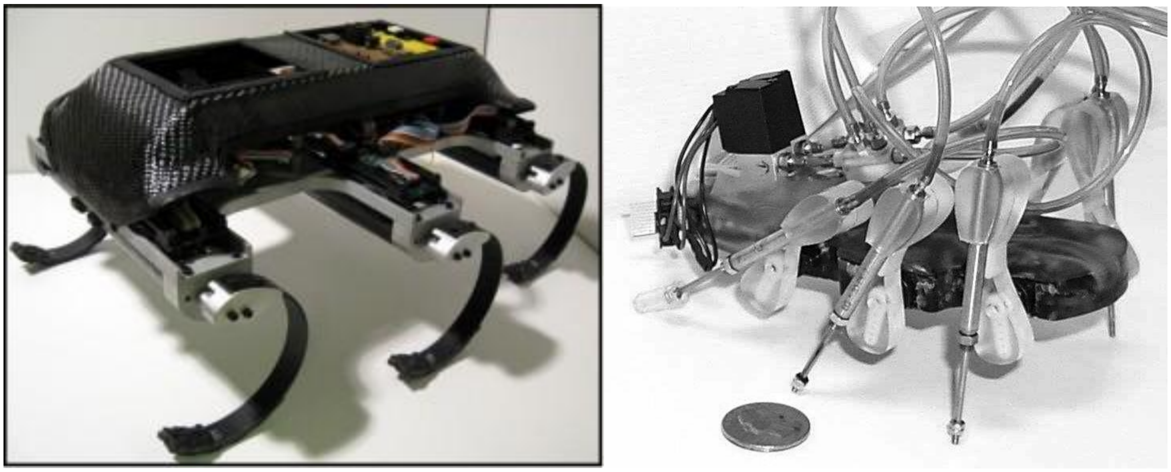

Figure 2.4c. (left) RHex, a rotary hexapod robot (shown here as the EduBot version), uses six c-legs with an alternating tripod gait for stable locomotion over rough terrain [6]. The Sprawl family of robots use 6 legs with prismatic actuation to move with speed and agility [5].

The final design considered has been dubbed the "worm" system. The worm moves in a similar fashion to its biological counterparts [7]. The primary purpose of such a system would be to propel the robot through the sand, under its surface, while using an excavation system that would funnel sand into the center of the robot. The positives of such a design would be that it could simplify the excavation process, combining locomotion and excavation. The cons, however, would include developing new technologies, low dust resistance, higher cost, extreme complexity, and time constraints. Figure 2.4d shows current research designs of robots that use snake and worm inspirations for locomotion.

Figure 2.4d. (left) Example of worm-like locomotion in SnakeBot [8]. (right) Another example of possible worm locomotion using multiple tiers of tracks on the OmniTread Serpentine Robot [7].

The six designs were compared in a selection matrix and a House of Quality. Each design was compared to the others by ranking each system on the above stated engineering quality characteristics. After careful consideration, the tracked system was the final choice for the locomotion subsystem due to its traction, stability, and ease of control characteristics. The next two choices were a four wheel system followed by a six wheel system for ease of control, dust resistance, and simplicity. Table 2 shows the selection matrix used for the decision of which design for locomotion would be the best choice. The relative ranks were chosen for importance to the overall project, including strategies for excavation as well as the competition scoring rubric.

		Concepts											
		Tracks		4 Wheels		6 Wheels		C-Legs		iSprawl Legs		Worm	
Specifications	**Importance Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Traction	20.00%	5	1	2	0.4	3	0.6	0	0	1	0.2	4	0.8
Stability	10.00%	5	0.5	3	0.3	4	0.4	1	0.1	2	0.2	0	0
Maneuverability	15.00%	4	0.6	3	0.45	2	0.3	1	0.15	5	0.75	0	0
Speed	15.00%	2	0.3	4	0.6	3	0.45	1	0.15	5	0.75	0	0
Power	10.00%	5	0.5	3	0.3	4	0.4	2	0.2	1	0.1	0	0
Cost	10.00%	3	0.3	5	0.5	4	0.4	2	0.2	1	0.1	0	0
Simplicity	10.00%	2	0.2	5	0.5	4	0.4	3	0.3	1	0.1	0	0
Low Maitenance	5.00%	2	0.1	4	0.2	3	0.15	5	0.25	1	0.05	0	0
Dust Resistance	5.00%	2	0.1	4	0.2	3	0.15	5	0.25	1	0.05	0	0
	Score		3.6		3.45		3.25		1.6		2.3		0.8
	Selection	1st		2nd		3rd		-		-		-	

Table 1. Selection Matrix used for determination of best designs for locomotion.

2.5 Power Subsystem Concepts

The purpose of a power regulation system is to supply power to all components of the system in the most efficient and reliable manner. Depending on specific circumstances, a power regulation system can be engineered with different objectives in mind. Several of these objectives are costs, reliability and weight.

In designing a robot with several different components with varying power requirements, a power source must be implemented to adequately power each or all components. The power distribution options available for this particular project is to use the 40V/15A power source available through tether, to implement a battery pack source on the robot itself, or to use a combination of the tether with an additional battery pack.

A source alone is not enough to satisfy the power requirements because the robot components will be rated at different voltages. A couple options to satisfy this demand are to design one power electronic circuit to deliver appropriate voltages to all devices, or, to use multiple power circuits with separate battery sources. If one circuit with one power source is desired, switching regulators must be implemented to step down the voltage to comply with the different devices. If multiple battery sources are to be utilized then the only requirement is to use an appropriate battery for each device.

The final set of options to consider is the exact type of battery source. The following list presents the top three types of batteries chosen for this project's specific purposes.

Lithium-Ion – Lightweight, comparatively expensive, fast charge with zero memory effect.
Lead Acid – Large and heavy, comparatively inexpensive, high current output.

Lithium-polymer –Similar to Lithium-Ion with higher current output but less energy density.

(Lead-acid) (Lithium-Ion) (lithium-Ploymer)

Power Source

The existence of a power source tether is ambiguous throughout different editions of the rule set. Due to the uncertainty of such a source, at this point in time it is sensible to pursue the battery pack source option.

Power Distribution

The optimal choice for reliability is to use a separate power source for the motors and a separate power source for the MCU and sensors. The optimal choice for a minimal weight and cost design would be to implement one power electronic circuit utilizing one or more switching regulators to step down the voltage.

Battery Option

The optimal choice for weight minimization is to use lithium-polymer or lithium-Ion Batteries. If cost is the largest limiting factor, Lead Acid batteries should be used. Lead Acid also has the greatest energy density and current output versus cost and will be the more effective choice so long as weight is not restricted.

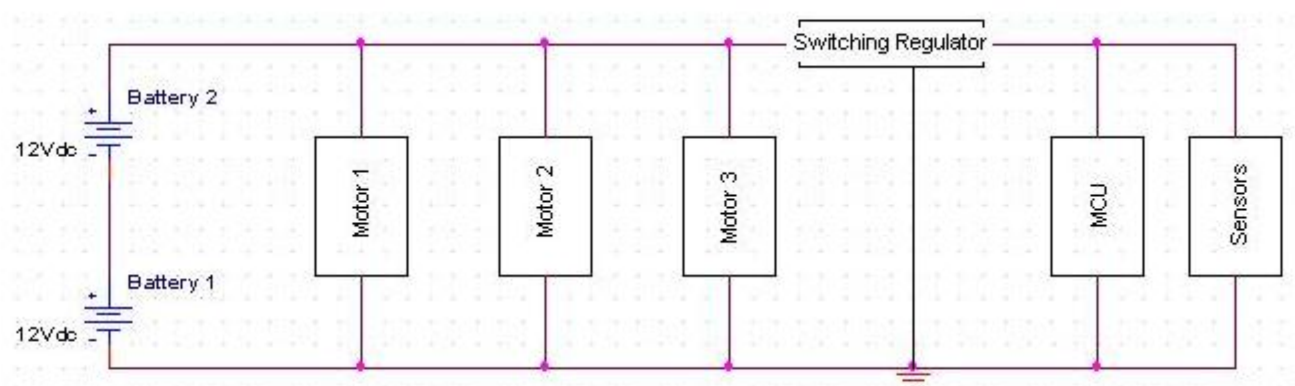

Figure 2.5a. Final Power subsystem design

This design consists of one or more Lead Acid batters connected in series to produce an appropriate voltage (this specific voltage will rely upon the torque requirements of the motors). The source is then connected in parallel with the motor controllers and in series with an adjustable switching regulator to output a lower voltage for the MCU and sensors.

It is currently decided upon that the greatest limiting factor for the design is going to be money. Therefore the power distribution method of lowest cost has been implemented while still retaining the ability to adapt into a more costly yet reliable system such as the multiple source/circuit concept.

2.6 Micro-controller & Communications Subsystem Concepts

The robot is useless without something to control all its various sensors and motors. The microcontroller is a chip with a processor, memory and I/O that can perform all these tasks. It needs to read in the data from all of the sensors and make sense of that data then use that to make decisions and drive the motors accordingly. The type of controller is heavily dependent on the sensors and motors that the robot uses but the general type at least can be selected.

First up are FPGAs. These are technically not microcontrollers but they can perform the same functions in a robot. An FPGA is purely hardware; It's a box of logic gates where the connections between gates can be programmed. There's no software so they are usually very fast and can even perform multiple operations at once. They typically have plenty of I/O pins and being hardware, are very good at performing the low level functions of sensor reading and motor control. There are plenty of downsides though. The biggest is that the programming is far more complicated than software programming. There's nothing prebuilt so everything that is already in a microcontroller has to be programmed from the ground up. There are also usually horrible timing issues that take forever to debug. If this weren't enough, they also have to be reprogrammed every time they're turned off, they don't have any analog inputs and don't have standard 5V I/O pins.

Getting to microcontrollers, they can be split up by bus size, 8-bit and 32-bit. 8-bit microcontrollers are what are typically used for robot control. They are very good at doing all the useful functions for interfacing with other components. Analog to digital converters for reading in analog sensors, pulse width modulation for various types of motor control, and plenty of timers and interrupts. The type currently being looked at is the AVR ATMEGA line. It is especially popular with hobbyist robotics so there is a wealth of information about using them for robot control. Because of this, they also have plenty of different easy to use development boards available for the microcontroller. The downsides are few and hopefully shouldn't be an issue. They are fairly slow at about only 16MHz and have very small amounts of memory. If some kind of complicated program is needed, using tons of floating point operations or too many variables, something more powerful would be needed. So far though, the control isn't being foreseen as being too complicated so these should be fine.

There is a fairly large gap between 8-bit and 32-bit microcontrollers. The 32-bit ones are more like small computers, the larger bus size and faster clock speed make them much faster, have more I/O pins and they typically even have their own operating system. This makes them more useful in areas needing more processing power like image and audio processing and typically show up in cell phones and the like. They aren't as popular for robotics because most projects don't need the extra power, so there's not as much in the way of resources available. The selection of development boards is also worse as they're usually packed with extra devices and buttons. The low level functions are also not as good and few boards are intended for robotics. The added difficulty and complexity doesn't seem worth it if we aren't even going to need the extra processing power.

Trying to decide which type to use is easy, 8-bit microcontrollers win out by a long shot. FPGAs are out right off the bat and weren't really considered. FPGAs are used more for digital signal processing where their high speed and parallelability is useful. That isn't as useful for a robot and the added complexity and time needed to program the device definitely isn't worth it. No one on the team is really good at VHDL anyway. 32-bit microcontrollers were also eliminated. The main advantage of more processing power shouldn't be needed and isn't worth the increased complexity and cost. They might be useful later on if it is found that more processing power is needed. Then the robot can have a low level 8-bit doing the low level control, and a 32-bit doing the high level calculations and decision making. Right now though, the plan is for a single 8-bit microcontroller and to add additional controllers if speed, memory or number of pins becomes an issue.

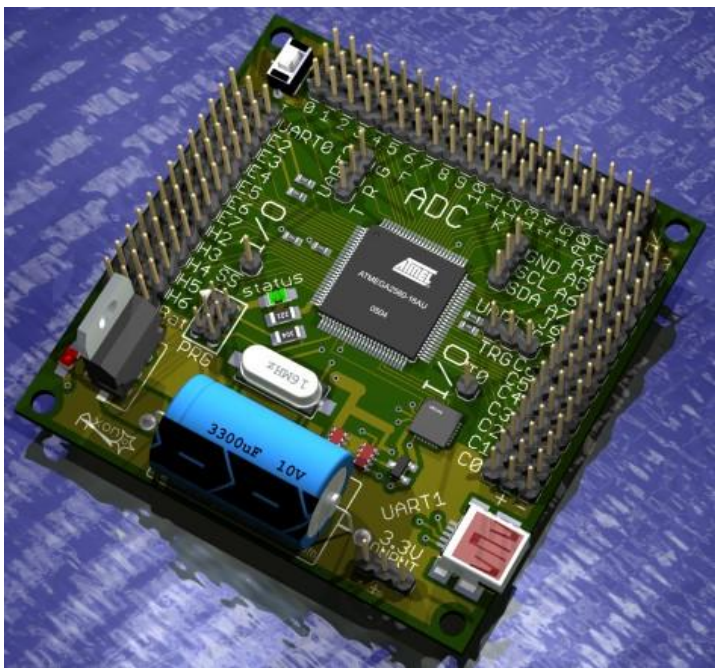

Figure 2.6a. Axon, development board for the AVR ATMEGA 640 [19].

Telerobotic Interface:
The robot needs to have some kind of remote control, even if that is just turning it on and off. Some way of communicating with the robot remotely is needed. Very little can be done with this because of the enforced 2s delay both ways on the line and the maximum bandwidth of 1Mb/s. This delay is provided by a computer provided at the contest which runs an emulated wide area network. The robot then must have a way of connecting to this network and somehow communicate with the operator on a computer on the other side of the network.

The first question is wired or wireless. A wired connection with Ethernet cable would be ideal, as wired connections are much simpler and faster than the equivalent wireless. This poses the obvious problem of dealing with the wire and avoiding getting it stuck or caught on anything. Originally, in the rules the robot was to be provided with a tether supplying power from an overhead scaffold. Then communications cable could then just use the same scaffold. It's unclear now if the robot gets a tether or not so some kind of wireless connection will most likely be needed. The three main wireless protocols available are Zigbee, Bluetooth and Wi-Fi and they all have various pros and cons.

Zigbee is fairly new, inexpensive and focuses mainly on connecting multiple remote sensors into a network. This means the speed isn't that great and maxes out at 250Kb/s ¼ of the maximum bandwidth. This and that they would have a hard time connecting to the WAN doesn't make them very promising.

The next option is Bluetooth which is the next step up from Zigbee in terms of speed and cost. Their maximum speed is 1-3Mb/s which is perfect given the maximum usable is 1Mb/s. Bluetooth is also set up to act similar to serial only wireless. This means the interface with the microcontroller should be simple and easy to use. The problem is interfacing with the WAN. Bluetooth is a personal area network so it will need some kind of router to connect to the WAN. This will likely be a laptop getting data from the robot via a Bluetooth USB dongle then acting as a server and relaying the data through the WAN.

Figure 2.6b. Modules for interfacing a microcontroller with Zigbee, Bluetooth and Wi-Fi respectively [20, 21, 22].

Most expensive and powerful is the standard Wi-Fi. It's incredibly fast compared to the other two at 56Mb/s but most of that is useless given the bandwidth limit. Even without the limit the bottleneck is the serial interface with the microcontroller which caps out at about 1Mb/s The interface is mostly the same as Bluetooth. Wi-Fi also uses the most power for its strong signal with is mostly a waste because all three have a range of at least 10 meters which is plenty for this robot. The one advantage is that Wi-Fi is already the same kind of protocol as the network and so should be able to connect directly to the WAN.

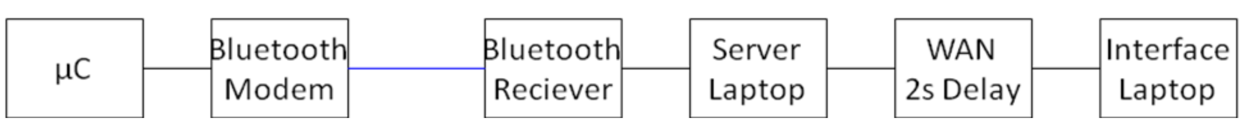

Figure 2.6c. Proposed communication system.

Zigbee is dropped right away as it's too slow and more suited for distributed networks rather than data transfer. So far both Wi-Fi and Bluetooth should work for the requirements but it's hard to tell this early which will be easiest to implement. This system though should work with both so all of this applies to both.

The microcontroller connects to a Bluetooth modem which sends data to a laptop outside of the collection area. That laptop then makes sense of the data and sends it through the network. 2 seconds later an operator controlling the robot receives that data at the interface laptop. This has the advantage of relying on laptops for the WAN connection because they're already built to do this and essentially free because the team already has laptops. Also, if needed, the server laptop could run code for the microcontroller if there is something computationally draining that it needs. It would be tricky working out the communication to do that but it's possible if we really need it. After all, a laptop is going to be more powerful than most affordable microcontrollers.

2.7 Navigation Sensor Subsystem

The purpose of the navigation system is to provide the robotic device with the means of making automatic decisions within their environment. In order to accomplish this goal the robotic device is going to require a collection of sensors. Without sensors, a robot could not react or respond to changes within their environment causing them to be considered a machine which is capable of moving only by predefined movements. A sensor is a device that measures physical quantities and converts it into a signal which can be read by an observer or by an instrument. For a sensor to sufficiently work it must measure for system errors; once an errors is found by the sensor the robot is able to correct them for the desired outcome. A sensor that is sensitive to the measured property, insensitive to any other property, and does not influence the measured property is consider as a good sensor.

Figure 2.7a. Example of Sensors used on a vehicle

In determining different methods for controlling the navigation of the robotic the following concept were generated:

- **Pre-programmed path** – deals with encoding the robotic device with a path which is already determined. The device should not deviate from the planned path.
- **Mapping** – deals with the ability to make a map of the present environment and make concentrated movements within it.
- **Random path** – the device will maneuver randomly within a fix area. The movements are recorded and calculated to prevent repetition to the same position.

To determine which method or collection of methods works best, the path planning must consider the following:

- **Work space:** The work space is the geometric space in which a robot operates. It consists of obstacles and empty space that may be occupied by the robot.
- **Configuration:** A configuration of the robot is a full description of the robot's state, including its position, orientation, and the states of any internal degrees of freedom (such as revolute joint angles).
- **Collision:** A configuration is said to be in collision if any part of the robot overlaps with either another part of the robot or with a work space obstacle.
- **Free:** A configuration is said to be free if it is not in collision.
- **Configuration space (C-space):** The space of all configurations of the robot annotated by whether the robot is in collision or free at each configuration.
- **Free space:** The space of all free configurations.

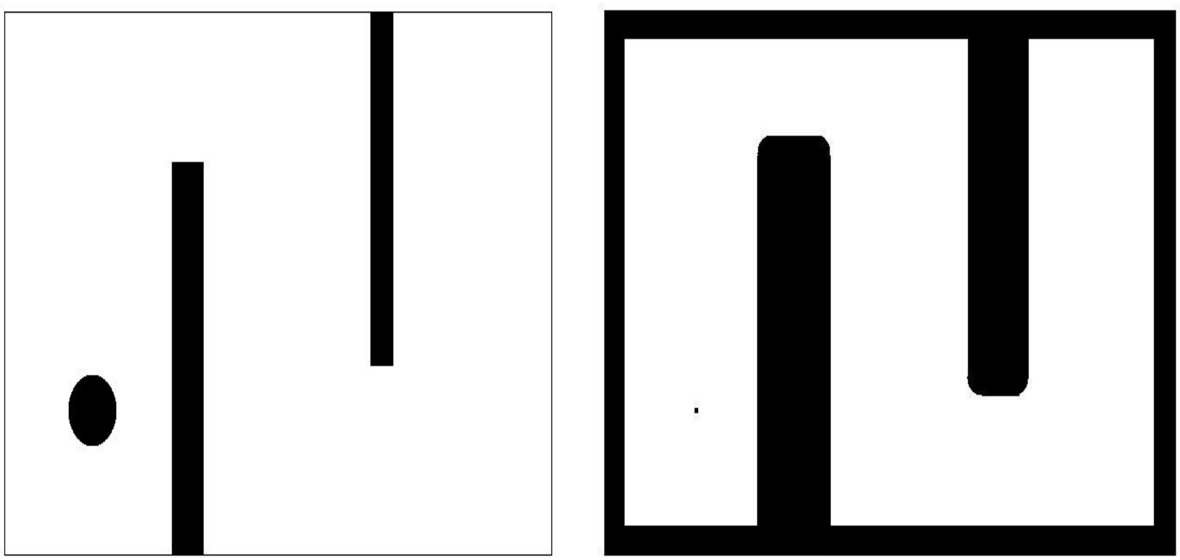

Figure 2.7b. (left) Work space which a robot can operate in. (right) Configuration space which a robot can operate in.

Now the method for navigating has been considered, determining what devices will be used to perform the desired designer's tasks; this leads to the type and functions of different sensors.

Types of Sensors

- Position, angle, displacement, distance, speed, acceleration
- Acoustic, sound, & vibration
- Navigation instruments
- Optical, light, imaging
- Proximity, presence
- Electric current, magnetic, radio, voltage
- Pressure, force, density, level

- Environment, weather
-

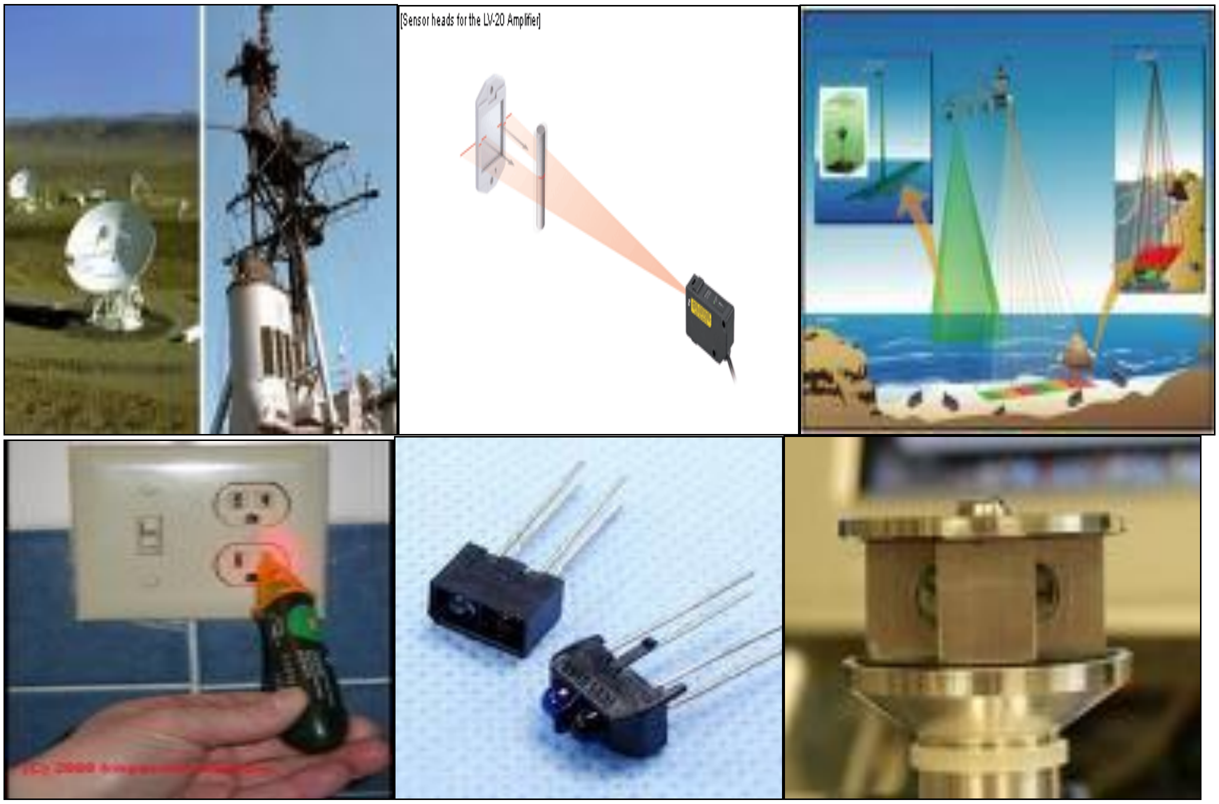

Figure 2.7c. Examples of sensors are shown: (top left) radar device, (top center) laser sensor, (top right) lidar sensor, (bottom left) voltage sensor, (bottom center) optical sensors, and (bottom right) beacon sensor.

The following sensors present themselves as the most beneficial for navigation, current control, weight control and positioning of the robot:
Inertial Sensor – used to measure the pitch, yaw and roll of the robot.
Digital Scale – used to measure the amount of regolith collected.
IR Beacon Sensor(s) - works by sending infrared light in all directions to a receiver(s).
Current Sensor(s) – used to control current used in the robot to prevent the damaging fuses.
Relative Sensor(s) – used to measure the absolute or relative location of the robot.

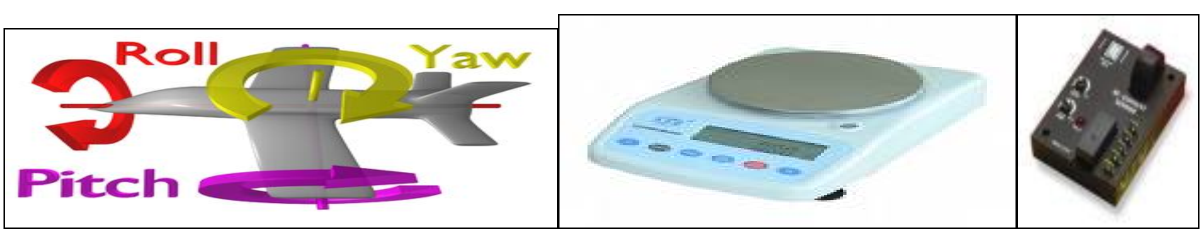

Figure 2.7d. (left) Spatial measurements calculated by INS, (center) Digital Scale, (right) Current Sensor

3. Design Changes

In mid November the rules for the first annual Lunabotics Mining Competition were revised to address problems raised by teams when attempting to interpret the rules. The revision of the rules not only changed the size of the competition box, but also the maximum dimensions of the excavators, amount of time to excavate, and minimum excavated material to qualify. These changes in the rules for the competition presented major challenges to the final design developed by the ARTEMIS Project.

3.1 Excavation Subsystem Changes

The rule redraft has required a change in the excavation system. The size of the sandbox has been reduced, thus leading the plow design to be inefficient. Since the robot cannot travel long distances in a straight line during the competition, the v-plow was dropped for a cleated belt system that can be moved up and down to excavate deeper trenches and move more regolith from a single position.

Due to the rule redraft, the bucket dimensions required alteration to integrate into the overall robot design. The bucket's height and length is smaller, but the width is larger. The angle of the front of the bucket directly relates to the angle of the conveyor belt because it will be connected and the front side of the bucket will be used as a means to hold the regolith in as it is being brought up to the top of the bucket.

To find out what angle the bucket needed to be tilted to so that the sand will fall off the team experiment with different materials. For all of the materials the angle the sand fell was less than thirty five degrees. Because of this it was decided that the bucket needed to be tilted so that the backside of the bucket will be at negative thirty five degrees.

With this in mind the design for the slots in the side plate were designed. The bucket first needed to be tilted so the backside is horizontal and then tilted the extra thirty-five degrees. This is the reason the back of the bucket is at an angle; if it was not the bucket would have to be tilted ninety degrees plus the thirty five to make the sand fall off. The backside of the bucket is about fifty-five degrees; thus the bucket needed to be tilted a total of ninety degrees. Before the bucket can begin to dump it needs to be raised and placed over the collector bin. This is why the slots first angle together then one stops and the other continues to allow the bucket to deposit the regolith.

3.2 Locomotion Subsystem Changes

The rules redraft required a change in the locomotion system due to a reduction in the length of the robot. The original design incorporated 80 cm long tracks for locomotion. The current rules draft, dated November 16th, requires the length of the robot to be under 75 cm. Due to this reduction, the tracks of the robot were reduced to a length of 50 cm. All other properties of the locomotion subsystem will remain the same except for this scaling.

3.3 Power Subsystem Changes

The most recent rule update did not specify any sort of power limitation. This means that a power supply can be of any voltage and no particular fuse level is required. The power system design will remain the same but allow much high currents to flow to the motors without the fuse. High current into the motors means that the robot will be able to move faster and thus be able to excavate more regolith.

If the rule changes back to a required fuse and it is noticed that there will not be enough current draw to move the robot at a desirable speed, the power system will be broken up into separate systems. This means that each motor will contain its own battery source and thus be able to draw higher currents. The final design of this power system cannot be complete until the rules are finalized.

3.4 Micro-Controller & Communications Subsystem Changes

The Micro-Controller will remain the same as the original design. The communications have now been altered to interface with the WAN network provided by NASA per the current rules redraft. The Micro-controller will interface with a WAN card and transmit the data over the WAN network.

3.5 Control (formerly Navigation) Subsystem Changes

Due to the rule change, many of the original functions of the robot changed. Originally the robot was designed to be almost entirely autonomous. Now, with the current rules draft, there is no time delay in communications between the robot and the control center. Due to this, it was decided remote control operation would be best. The switch to remote control operation meant the reduction of necessary sensors on the final design. Instead of the sensors outlined above in concept generation, only a handful are needed. These sensors include a three axis accelerometer, a bump sensor, a web camera, a current sensor, and a weight sensor. IR sharp sensors, leds, multiple accelerometers, and some other sensors are no longer necessary.

4. Final Design

The final ARTEMIS design incorporates a tracked locomotion system with a cleated belt excavation and regolith transportation system and a bucket. Electronics are integrated into the design to provide power and control necessary to control the robot. Figure 4a shows a diagram of the system overview with each subsystem pointed out.

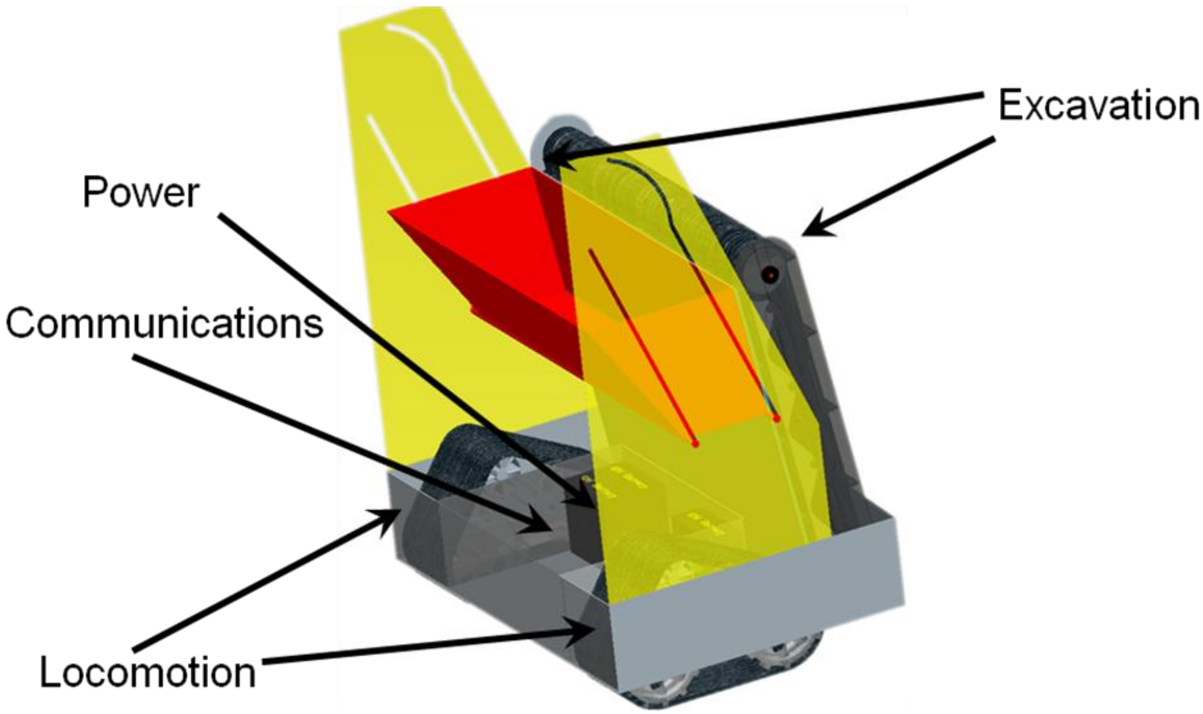

Figure 4a. Overall final design with each subsystem labeled

4.1 Excavation Subsystem Design

For excavation, we will be utilizing a single cleated conveyor belt system to scoop regolith simulant and transport it to the dumping bucket, where it will be held until unloading is necessary. The main components of the conveyor system consist of the two piece aluminum frame, belly pan, driven and idler roller, tensioning mechanisms, low drag sliders, and cleated conveyor belt. The design is such that an aluminum belly pan is mounted to the bottom of the frame rails forming a trough. As the cleated belt rotates, each cleat will take a scoop of regolith and force it up the trough and into the dumping bucket. To prevent belt deflection that could result in material losses, low friction sliders are placed in contact with the inner surface of the belt. To maximize the volume of regolith excavated per scoop, the belt was set to the maximum allowable width of 90 cm. Both the left and right side frame rails, contain a belt tensioning mechanism. The tensioning mechanism is essentially a prismatic joint with an integrated bearing housing. A single bolt is passed through a smooth hole in the end cap of the frame rail and into a threaded hole in the sliding block. As the bolt is threaded into the block, the block and idler roller is drawn toward the frame rail end cap, and as a result increases the tension in the belt. Likewise, if the bolt is reversed out of the sliding block, the tension is reduced.

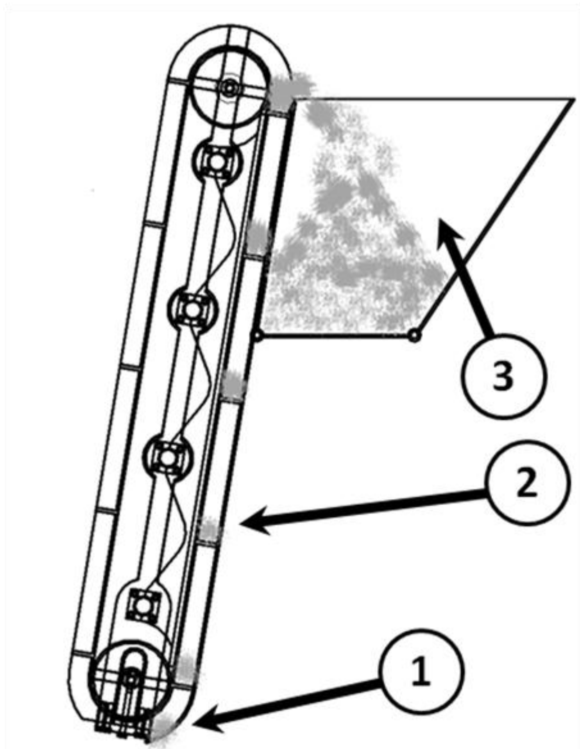

Figure 4.1a. Diagram of movement of regolith from regolith being excavated by cleated belt(1), transported up towards the bucket via the cleated belt(2), and dumped into the bucket for storage(3)

The bucket is designed to hold a specific amount of 0.075 cubic meters while also filling the space left between the conveyor components. The dumping mechanism will dump the bucket by using a linear actuator and a slot-and-groove mechanism that will guide the bucket back, then rotate 90 degrees to dump all of the regolith into the collector bin.

4.2 Locomotion Subsystem Design

Figure 4.2a. Final frame of locomotion system.

The final design of the locomotion subsystem incorporates 50 cm tracks that are 20 cm wide. The tracks use a torsional spring arm to tension the track links. The tracks are driven by a sprocket-gear design that "bite" into specific grooves in the tracks. The sprockets are driven by dedicated motors on each side outlined in the final power subsystem design.

Figure 4.2b. Example of treads wrapping around sprocket of locomotion system.

4.3 Power Subsystem Design

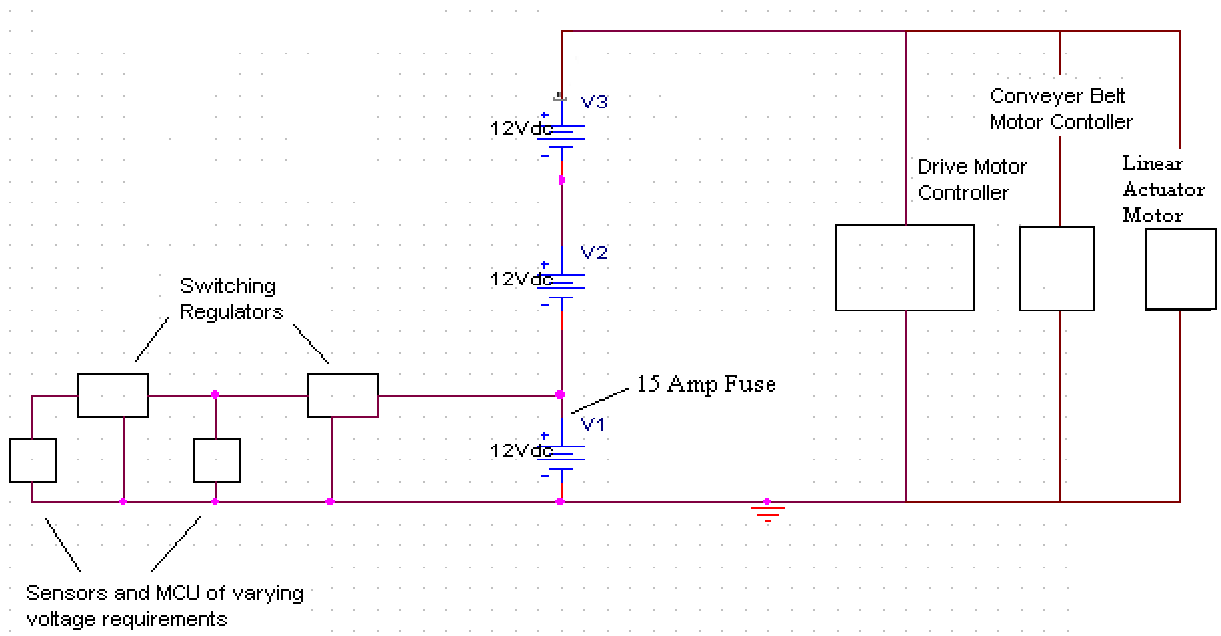

Figure 4.3a. Power schematic

In this design, the power system will be comprised of three 12V lead-acid batteries. The motors will be connected across all three batteries resulting in a total voltage of 36V across each motor. The sensors and MCU will be connected across one of the 12V with adjustable switching regulators to step down the voltage to the appropriate levels. The exact parts and weight can be viewed in the following table:

Artemis Power System Specifications		
Part	**Type**	**Weight**
Switching Regulator (2)	DE-SWADJ	N/A
Lead-Acid Batteries (3)	Powersonic 12V 18AH	5.94 kg
Accessories	Wires/Fuses/Switches/Capacitors	N/A
	Total:	17.82 kg

Figure 4.3b. Table of Power parts

A Pspice simulation was performed on this circuit to demonstrate that the voltages across the motors will be 36V and that the voltage across the MCU and sensors would be 12V prior to implementing the switching regualtors. This Pspice schematic and simulation is as follows:

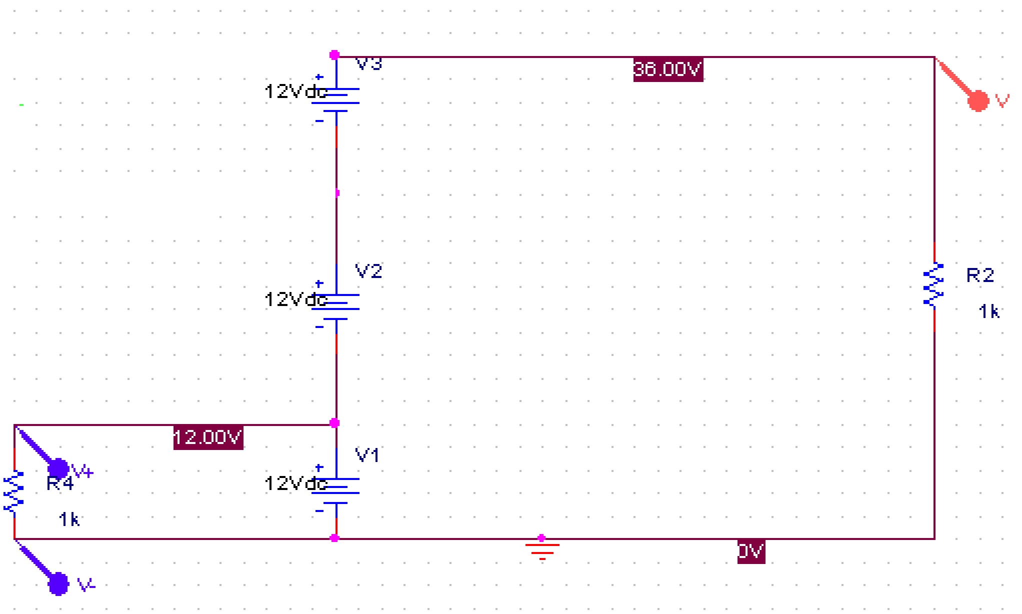

Figure 4.3c. Schematic of test of power system

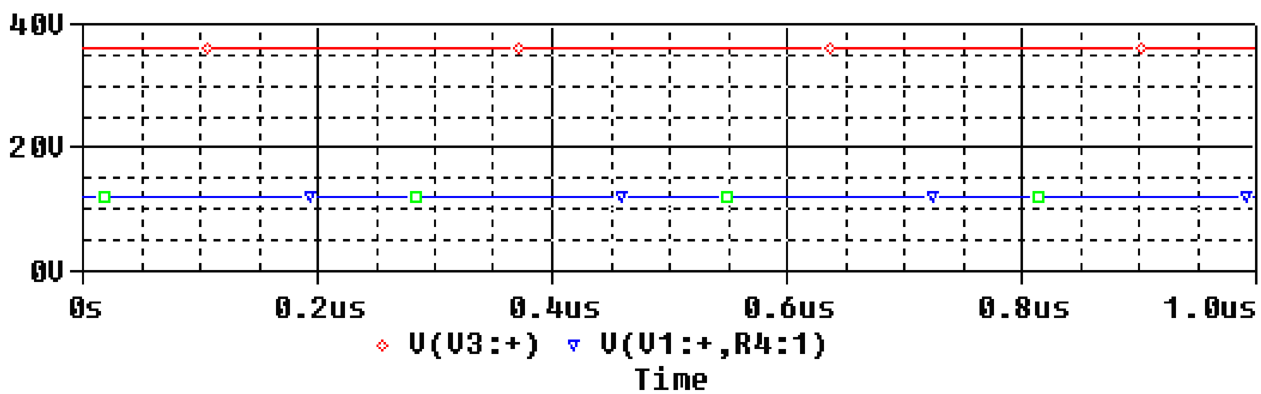

Figure 4.3d. Results of power system simulation

According to the rules of the competition, there will be a required fuse of 15A placed on the power supply. This fuse will have to be attached just above the "V1" battery in the above schematic. This means that the total current draw from all of the motors, plus the current draw of the sensors and MCU must never exceed 15A.

In calculating the maximum current draw of each component due to the current restriction, it is important to figure out which motors will be running simultaneously and which will not be. This was done by dividing the operation of the robot into two phases. These phases are regolith collection and regolith deposit. In regolith collection, the two drive motors as well as conveyor belt motor will all be operating, the linear actuator however, will be off. In the regolith deposit phase, the drive motors as well as conveyor motor will be off while the linear actuator will be on. The MCU and sensors will remain on throughout the entire operation. Using this phase analysis, the following charts were creating displaying the maximum current draw that the power system can supply for each component.

Device	PHASE 1	PHASE 2
Drive Motor 1	ON	OFF
Drive Motor 2	ON	OFF
Conveyor Motor	ON	OFF
Linear Actuator	OFF	ON
MCU/Sensors	ON	ON

Device	Maximum Allowable Current Draw	Maximum Power Draw
Drive Motor 1	5A	180W
Drive Motor 2	5A	180W
Conveyor Motor	2A	72W
Linear Actuator	12A	432W
MCU/Sensors	2A	12W

Figure 4.3e. Table of device phases for operation

4.4 Micro-Controller & Communications Subsystem Design

In selecting the microcontroller for our robot we eventually had to just pick one because of all the thousands of different models out there to choose from. Most microcontrollers have the same functions built into them. They have timers to perform regular timed actions and for pulse width modulation, UARTs for serial transmission and analog to digital converters to read in analog signals. The important parameters then are speed, number of pins, and cost. With so many to choose from we fortunately had a representative from ARM, a microcontroller company, come to the school and he donated a microcontroller to the project. This ended up being the MCBSTM32, a 32 bit 72MHz cortex M3 based microcontroller. This board comes with a development kit which includes an IDE to develop software for it and a hardware programmer to get the software onto the board. All of this usually goes for about $230 so getting it for free is a huge boon. The board is more than enough for our purposes having 48 pins and being plenty fast. Now especially with the rule changes because it doesn't need to be autonomous so there is much less demand on the microcontroller.

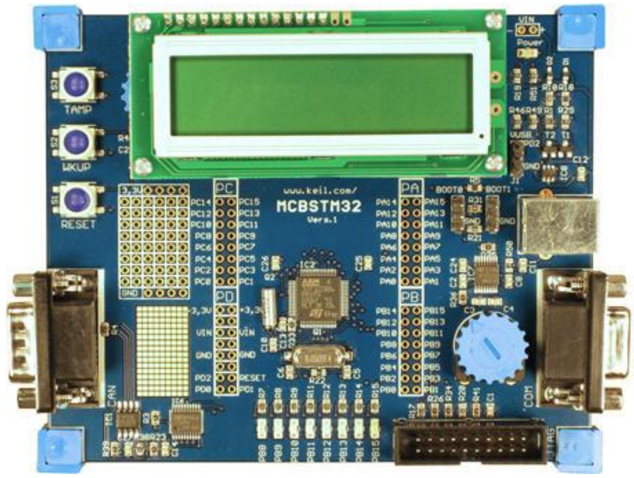

Figure 4.4a. Our Microcontroller MCBSTM32

The first thing needed from the microcontroller is a UART which will be used to connect to the serial to WiFi module. The board has three UARTs and they are all linked to ports on the board which are USB, RS-232 and CAN. Fortunately, the microcontroller and WiFi module both work at 3.3V so they will just be connected directly and the distance between them should be short enough that RS-232 shouldn't be needed. Next are the digital inputs from the two touch sensors. If these output 3.3V as high logic they will simply just be read in by two pins configured as input. If not some voltage drop will be needed to drop the voltage from the sensors to 3.3V. Then there are the analog inputs from the weight sensor, accelerometer and current sensor. These sensors all output an analog voltage ranging from 0 to 3.3v so they can be read in using the analog to digital pins on the microcontroller. Everything will be attached to the pins on the board labeled PA PB and PC. These pins are direct connections to the microcontroller and bypass any built in things on the board.

The programming requirements for the microcontroller are now much simpler because autonomous functions are no longer needed. It's going to be almost completely remote controlled so the microcontroller is only reacting to the commands received over the communication link. Periodically, the microcontroller needs to poll all of its sensors, send the values it reads over the communication link. The sensor data is used by the human operator and not the microcontroller. The microcontroller also needs to listen to the link and receive commands from it, decode the commands, and act on them by driving the right motors.

The motor control for the two main drive motors will be the only complicated programming requirement. The speed of these two motors needs to be controlled more accurately. If the robot wants to go straight, the two motors need to be turning at the same speed or else it will veer off course. The speed modulation of these motors will be done via pulse width modulation. The microcontroller will generate a signal that switches at a few kHz at a certain duty cycle. This will turn the motor on and off so it is only on a fraction of the time. So a 50% duty cycle drives the motor at half speed. This isn't ideal though, and all motors are different so an additional feedback loop will be used to control speed. The speed the hall effect sensors are changing will be used to detect the speed the motors are spinning and a simple PD loop will be used to keep the motors spinning at the desired speed.

The link to the robot isn't perfect and if the competition from this year was any indication it goes down fairly often. The robot then needs some way of coping with losing the connection to the control computer. It could always just keep executing the last command it received but that might be dangerous. There's no telling how long the break will last so it might just smash straight into a wall. The safest method is to just have the robot kill the drive motors when this happens. It's easy to implement but we waste time with the robot not doing anything. The robot could also take over with some autonomous function when this happens but that would be very complex to implement. The link shouldn't go down as much as the 2009 competition as there is now no delay so this will hopefully not be too much of an issue.

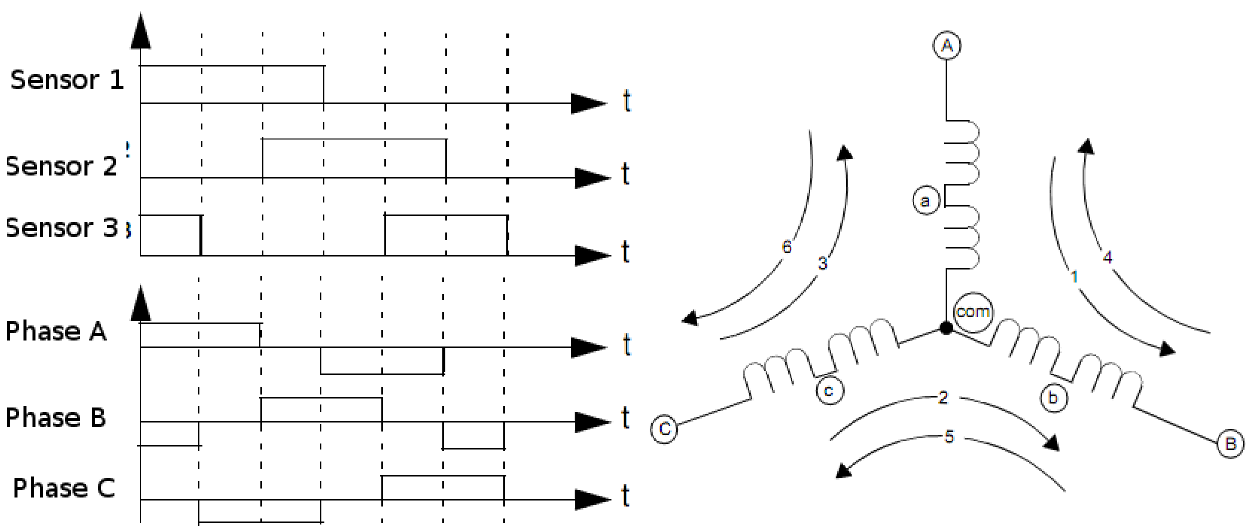

Figure 4.4b. Diagram showing motor, and outputs for sensor inputs

The two brushed DC motors that run the conveyor belt and linear actuators are easy to control. The conveyor belt only needs to run in one direction so a half bridge will be enough to run it. The linear actuator needs to run in both directions though, so it will need to be run with a full H bridge. These two should be low enough power that an IC can be used that contains all the drive circuitry. If not, we can get a full circuit board driver that will do everything needed and support higher currents. These will take in two signals, a pulse width modulated signal which controls the speed and a digital signal that controls direction.

The two drive motors however are far more complicated being brushless motors. These motors don't handle commutation automatically so it needs to be done manually. They're essentially AC motors driven with a DC current. The commutation is performed by determining the current position of the rotor of the motor using three hall effect sensors then changing which phases of the motor that are being driven to the next set as seen in the diagram. The full board motor controllers for brushless motors are horribly expensive so we're going to we're building it ourselves. This consists of two parts, the drive circuitry and commutation circuitry. There aren't chips available that do both parts because the current requirements of the motors is too high and they max out at about 2.5A.

The commutation part simplifies down to a 6 state finite state machine for the 6 phase combinations that the motor can be driven in. Each time one of the three position sensors on the motor shaft changes it switches to the next state. For example, if the sensors change and are now 101, phase A now needs to be driven high and B driven low. To go forward it progresses forward through these states and to go backwards it reverses the order. Because the microcontroller isn't going to be used for much anymore, it probably has enough resources left that this can be done in software with a few external interrupts. There are also chips available that perform all of this and also have safety features built in which would work much better. Unfortunately they're all surface mount so it would be a huge pain to make a circuit board to put them on.

The other section of the controller is the drive circuitry. This is the part that actually interfaces with the terminals of the motor and performs the high power switching needed. The motors are going to need far too much power to be able to use a chip to do this so it needs discrete power transistors instead. This will be three half bridge circuits, one for each phase, using MOSFETs. MOSFETs because they are very common for these low voltage applications and their isolated gate makes them easier to drive with a microcontroller compared to a BJT. The driver works by having 6 MOSFETs acting as switches. Turning on one of the high side switches connects that phase of the motor to VCC and turning on a low side switch connects that phase of the motor to ground. So one phase will be high and the other low and current will be driven through the motor. Turning on both high and low of the same phase will short the battery and be a very bad thing to happen so the commutation circuit will need to ensure that never happens.

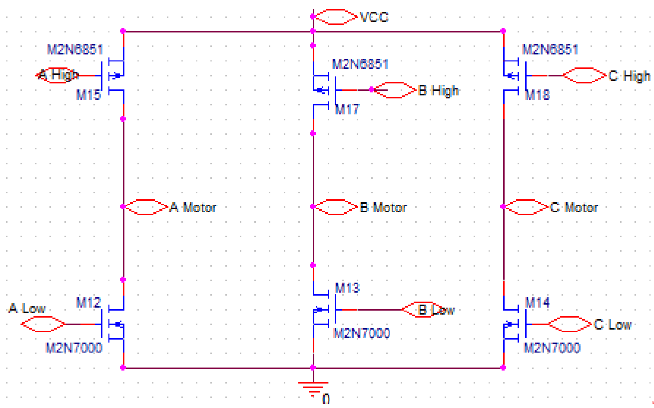

Figure 4.4c. Three half bridge motor driver for three phase Brushless DC motor.

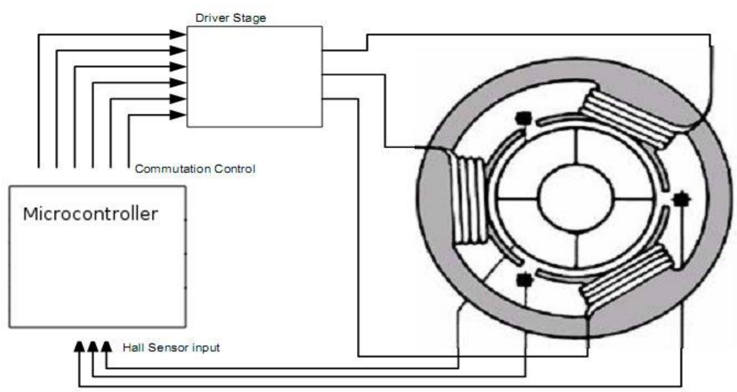

Figure 4.4d. Entire motor controller subsystem

With the change to remote control, the communication system has become far more important. Instead of just using it to tell the robot to start and stop operations, the robot now completely depends on remote commands. The old rules had a 2 second delay for all data sent through the network but that delay is now gone so there's not really any point anymore in making the robot autonomous. We can make use of the superior decision making abilities of the operator instead of trying to program all of that ourselves.

Figure 4.4e. Lantronix Matchport Serial to WiFi module

On the robots side of the link, the robot sends commands serially via one of its UARTs to a serial to WiFi module. This module will be a Lantronix Matchport which handles all of the networking automatically and relays all data sent to it over the network. It also has a bunch of other features which might come in handy like a built in web server and telnet access. It will connect to the provided network via a WiFi access point on it. The competition provides us with two IP addresses on their network and this will be using one of them.

The other side of the link will be in the control room where the operator will be. This will be run from one of the member's laptops or some other computer. This computer will connect to the network with a wired Ethernet connection and communicate with the robot via port redirection software that comes with the Matchport. The port redirection software creates a virtual serial port on the computer which redirects data sent to it to a member on the network. Using this, the entire network can be abstracted away and the connection from both ends will just look like a wired serial connection. This is very nice as serial connections are incredibly simple and we don't have to worry at all about the network.

The protocol for the serial connection making the communication link will be a standard 8 bits data, 1 end bit and 1 odd parity bit. The data will be transmitted in bytes as individual ASCII characters. Transmitting 5 bytes for each sensor reading will allow 0 to 99999 to be sent which should be enough to give a good representation of the sensor readings. Each packet sent on the robot's end will be 25 bytes or 250 bits after adding parity and end for each byte. A packet of sensor data will be sent 10 times a second giving a transfer rate of 2500 bits/s, well under our limit.

Accelerometer X	Accelerometer Y	Accelerometer Z	Weight	Current

Figure 4.4f. Packet of data sent by robot. 5 bytes ea.

On the control side of the link, the computer needs to send the speed and direction of the two drive motors and activation of the linear actuator and conveyor belt. The speed of the motor needs one byte which gives 256 divisions of speed, because the joystick used has 256 divisions, enough that the divisions are almost indistinguishable. The direction of the motor though, only needs one bit. 0 is forward and 1 is reverse. The conveyor belt only moves one direction so only one bit is needed. 0 for off and 1 for on. The linear actuator needs two bits, the first being 1 to move it up and the other 1 to move it down. This gives 5 bits for all of this so it can all be sent in one byte. This gives 3 bytes per motor data packet or 30 bits after adding parity and end bits. 25 of these packets will be sent per second for a data rate of 750 bit/s.

Left Motor Speed	Right Motor Speed	Other Motor Info

Figure 4.4g. Packet of data sent by control computer. 1 byte ea.

This bandwidth is much less than the limit from the competition of 5Mbit/s. That is a huge amount though and is about as much data transmission as a DVD movie. The Matchport can transmit data wirelessly at about 1Mbit/s which is still far more than is needed. The real bottleneck is the link though is the link between the microcontroller and the Matchport. That serial connection maxes out at about 115kbit/s. This is still plenty fast for just transmitting the types of simple commands that we're using. To make use of all the extra bandwidth not being used, it was thought to add a network camera that can connect directly to a wireless network to the robot. A first person view from the robot would be useful for control and it would be easy to add. It wouldn't need to interface with the microcontroller at all and could just be controlled completely over the network using the second IP address available to us.

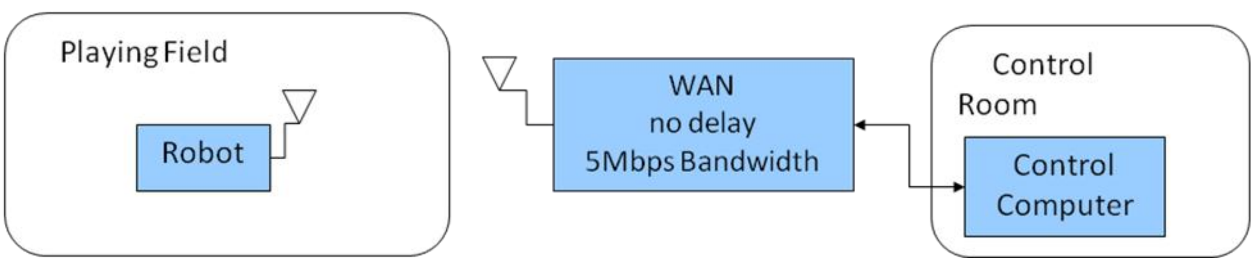

Figure 4.4h. Communications Diagram

3.5 Control Subsystem Design

The control system design will consist of using a PS2 Controller and adapting it to interface with the communications relay provided by the microcontroller and control computer. The web camera on the robot will transmit via the WAN images of the robots telemetry to the control room so that a human controller can guide the robot through the sandbox. The robot will include some autonomous features including a bump sensor that will stop the robot when triggered. The weight sensor will send data back to the human controller so that all decisions can be made by the controller during the competition.

5. Acknowledgements

The ARTEMIS Project senior design team would like to acknowledge the Scansorial and Terrestrial Robotics and Integrated Design Lab (STRIDe Lab) for its contribution of working space, tools, and storage. The team would also like to thank the FAMU-FSU College of Engineering and the NASA Space Grant Foundation for their contributions of funds for the team budget.

6. References

1. D. Beale. *Fundamentals of Lunar and Systems Engineering for Senior Project Teams, with application to a Lunar Excavator*, Auburn ESMD Course, <" http://education.ksc.nasa.gov/esmdspacegrant/LunarRegolithExcavatorCourse/index.htm">
2. Lunar and Planetary Institute. Lunar Mission Summaries, Lunar Science and Exploration, <"http://www.lpi.usra.edu/lunar/missions">
3. S. Ramo, and R. St.Clair. The Systems Approach: Fresh Solutions to Complex Problems Through Combining Science and Practical Common Sense, Anaheim, CA: KNI, Inc.
4. Rover Team. *Characterization of the Martian Surface Deposits by the Mars Pathfinder Rover, Sojourner*, Science, 5 December 1997.
5. J. Sheldon. Off-*Road Prototype Vehicles Test in Afghanistan*, Army.Mil/News, June 09, 2008.
6. J. Geiger. Auto Industry Insider: Hummer, Consumer Guide Automotive, <http://consumerguideauto.howstuffworks.com/industry-insider-hummer-cga.htm>.
7. Picture Dicitionary, dicts.info. Armored Combat Vehicle. <"www.dicts.info/picture-dictionary.php?w=army">.
8. J. Cham, S. Bailey, J. Clark, R. Full, and M. Cutkosky. *Fast and Robust: Hexapedal Robots via Shape Deposition Manufacturing*, International Journal of Robotics Research, 2002.
9. B. Potsaid, and J. Wen. *EduBot: a Reconfigurable Kit for Control Education – Part I: Mechanical Design*, IEEE International Conference on Control Applications, September, 2000.
10. G. Granosik, M. Hansen, and J. Borenstein. *The OmniTread Serpentine Robot for Industrial Inspection and Surveillance*, International Journal on Industrial Robots, Special Issue on Mobile Robotics, March 18th, 2005.
11. G. Miller. *Snake Robots*, SnakeRobots.com.
12. http://www.takraf.com/images/m-produkte/ers710_nochten_3_534px.jpg
13. http://www.grapples.us/_borders/cbucket1.jpg
14. http://upload.wikimedia.org/wikipedia/commons/thumb/2/23/Street_sweeping_machine.jpg/713px-Street_sweeping_machine.jpg
15. http://upload.wikimedia.org/wikipedia/en/c/ce/Sandwormmouth.jpg from the movie Dune
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17. http://www.locomotivegeneral.com/generalparts/images/CowCatcher.jpg
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27. http://www.passenlaw.com/blog/wp-content/uploads/2009/08/front-loader-death.jpg
28. K. Haddock. *The Earthmover Encyclopedia: The Complete guide to heavy equipment around the world*, 2002, Googlebooks.
29. http://www.takraf.com/images/m-produkte/ers710_nochten_3_534px.jpg
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34. http://www.locomotivegeneral.com/generalparts/images/CowCatcher.jpg
35. http://img.directindustry.com/images_di/photo-g/mobile-screen-387429.jpg

Appendix A. Spring Proposal

The Fall 2009 semester conceived and designed the components and overall system for the ARTEMIS Project robot. In the Spring 2010 semester, the ARTEMIS Project team proposes to prototype the designed parts, evaluate their performance, redesign if necessary and build the final product. The team attempted to use as many “off-the-shelf” parts as possible where feasible, but many parts are custom designed to meet the requirements set forth by the needs analysis.

Those parts that are pre-manufactured and easily obtained are listed, by subsystem, in table A.1. with description, supplier, quantity, and cost. For those parts that must be custom manufactured, the raw materials for them are also listed in table A.1. The engineering drawings for each part are attached following the table.

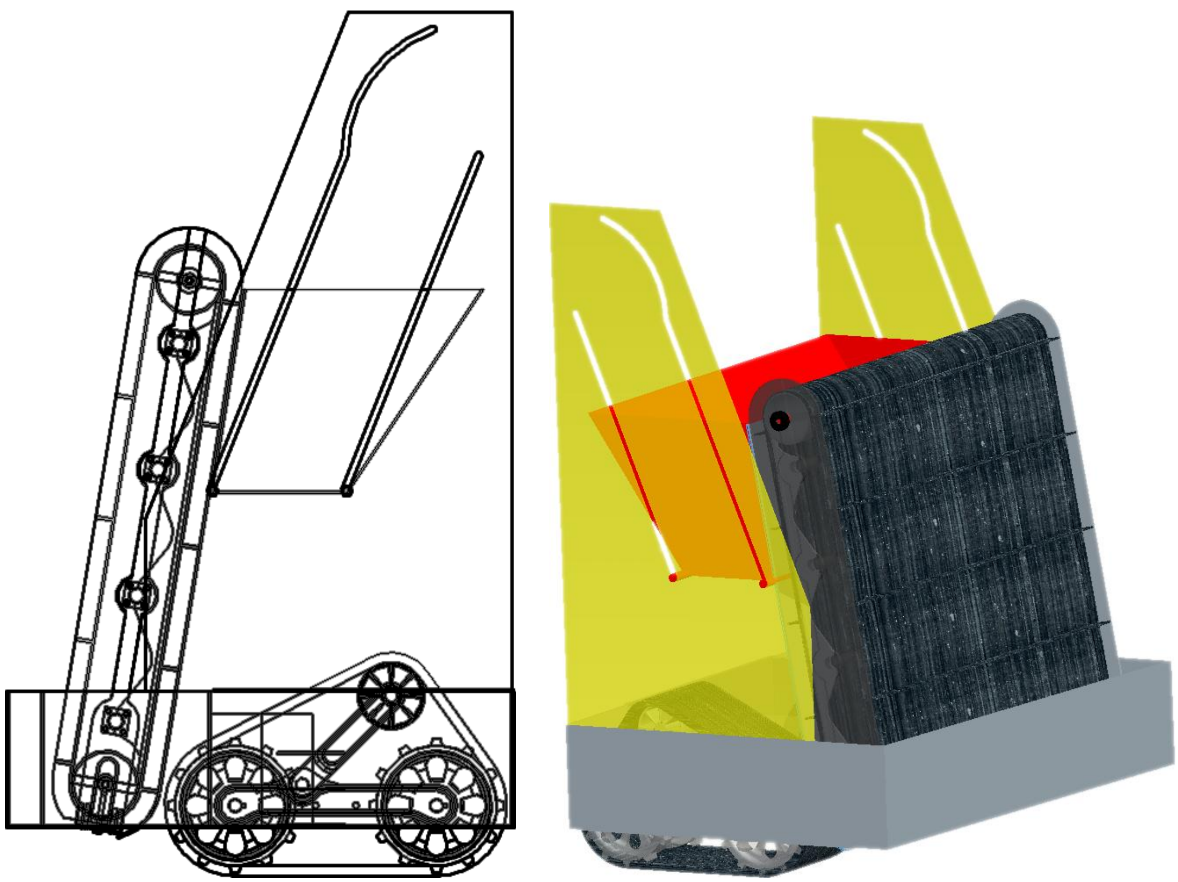
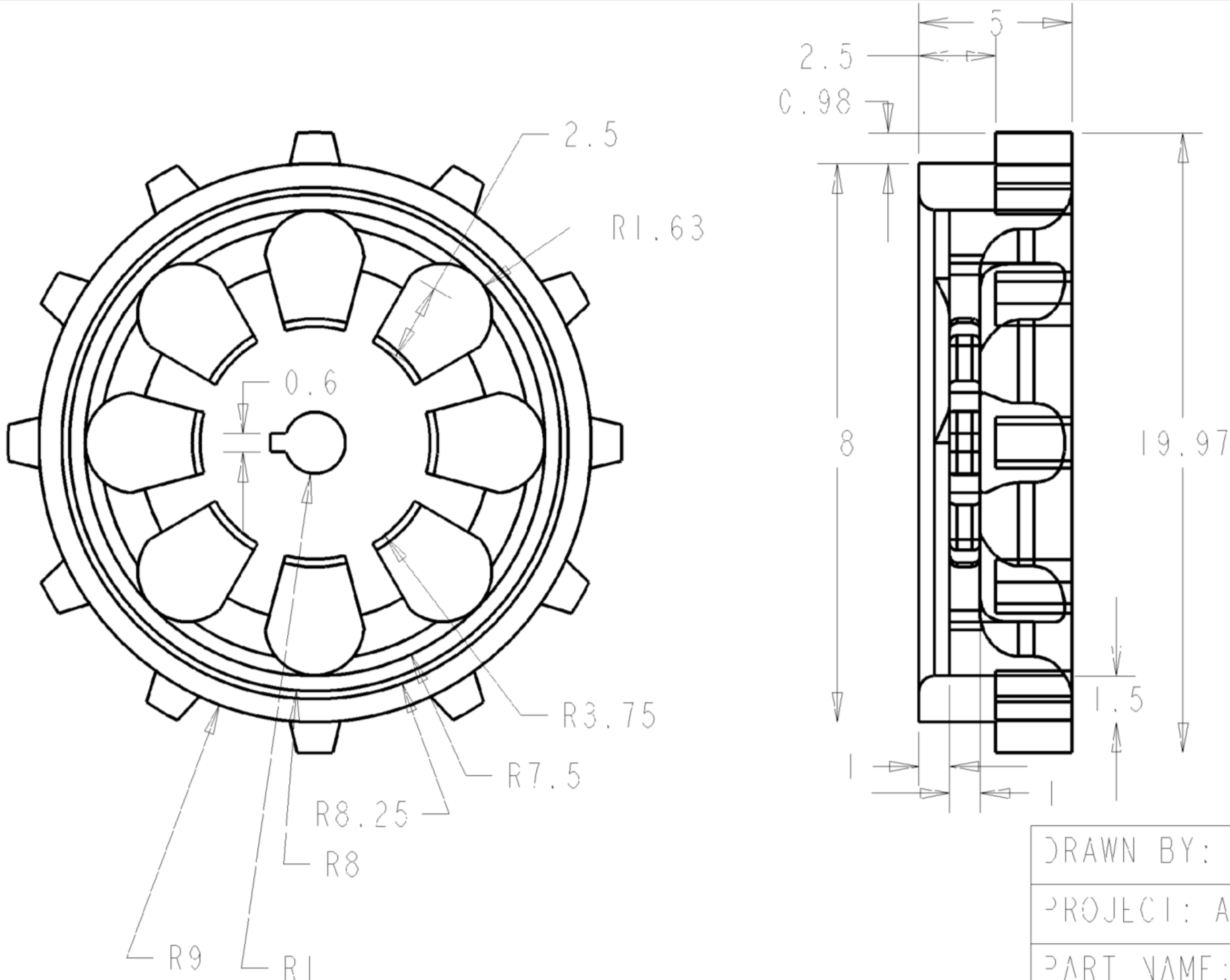


Figure A1. Final Full System Robot Design

	Part Description	Supplier	QTY	Cost	Total
Excavation System					$1,237.78
	Radial Ball bearings	Boca Bearing	1	$8.95	$8.95
	Tensioner Belt	Lowes'	1	$5.45	$5.45
	Washer	Lowes'	2	$0.35	$0.70
	Frame Mounting hardware	Pro-Bolt, USA	3	$5.78	$17.34
	Tensioner Mounting Bolts	Pro-Bolt, USA	1	$5.78	$5.78
	Sheet AL6061	McMaster-Carr	2	$46.28	$92.56
	AL 1.5" Tube	McMaster-Carr	1	$34.76	$34.76
	AL 3" Tube	McMaster-Carr	1	$28.94	$28.94
	AL 1" Tube	McMaster-Carr	1	$17.83	$17.83
	0.5" Square Al Sheet	McMaster-Carr	1	$26.28	$26.28
	Paddle belt	All-State Industries	1	$63.24	$63.24
	Radial gear	Boston Gears	1	$17.58	$17.58
	Teflon sheet	Teflon Sheet Stock	1	$47.56	$47.56
	Aluminum Sheet	McMaster-Carr	1	$61.81	$61.81
	Linear Actuator	Maxon Motors, Inc.	1	$809.00	$809.00
Locomotion System					$3,309.07
	Aluminum Block, 8"x8"12"	McMaster-Carr	1	$435.40	$435.40
	Aluminum Rectangular Tube, 2"x4"x72"	McMaster-Carr	3	$54.43	$163.29
	Aluminum Rod, 1"x60"	McMaster-Carr	1	$20.92	$20.92
	Aluminum Rod, 1/2"x72"	McMaster-Carr	4	$6.22	$24.88
	Bearings, 1"	Misumi, USA	8	$12.23	$97.84
	Rubber Sheet, 1-1/2"x24"x6'	McMaster-Carr	2	$71.10	$142.20
	Roller, 40mmx50mm	Misumi, USA	2	$31.90	$63.80
	Brass Flat plate, 3/32"x3/4"x72"	McMaster-Carr	2	$21.56	$43.12
	Maxon Motor Controller	Maxon Motors, Inc.	2	$497.09	$994.18
	Maxon DC Motor	Maxon Motors, Inc.	2	$661.72	$1,323.44
Power System					$229.85
	Switching Regulator		2	$12.00	$24.00
	Lead Acid Batteries		3	$51.95	$155.85
	Accessories (Wires, Fuses, etc)	-	1	$50.00	$50.00
Micro-Controller and Communications System					$110.00
	ARM Microcontroller*	ARM, Ltd	1	$0.00	$0.00
	Accessories (Wires, Breadboard, etc.)	-	1	$75.00	$75.00
	Bluetooth Adapters		1	$35.00	$35.00
Control System					$93.00
	3-Axis Accelerometer		1	$50.00	$50.00
	Bumper Sensor		2	$1.50	$3.00
	Weight Sensor	Wal-Mart	1	$40.00	$40.00
Miscellaneous Parts					$1,215.00
	Miscellaneous Costs (Shipping, etc)	-	1	$300.00	$300.00
	Regolith Simulant for evaulation	ORBITEC, Inc.	1-25Kg	$415.00	$415.00
	Lumber for Sandbox	Lowes'	-	$500.00	$500.00
Total Proposed Budget					**$6,194.70**

Table A.1. Proposed Budget for the Development of an Advanced Robotic extra-Terrestrial Excavating and Mining Integrated System (ARTEMIS)



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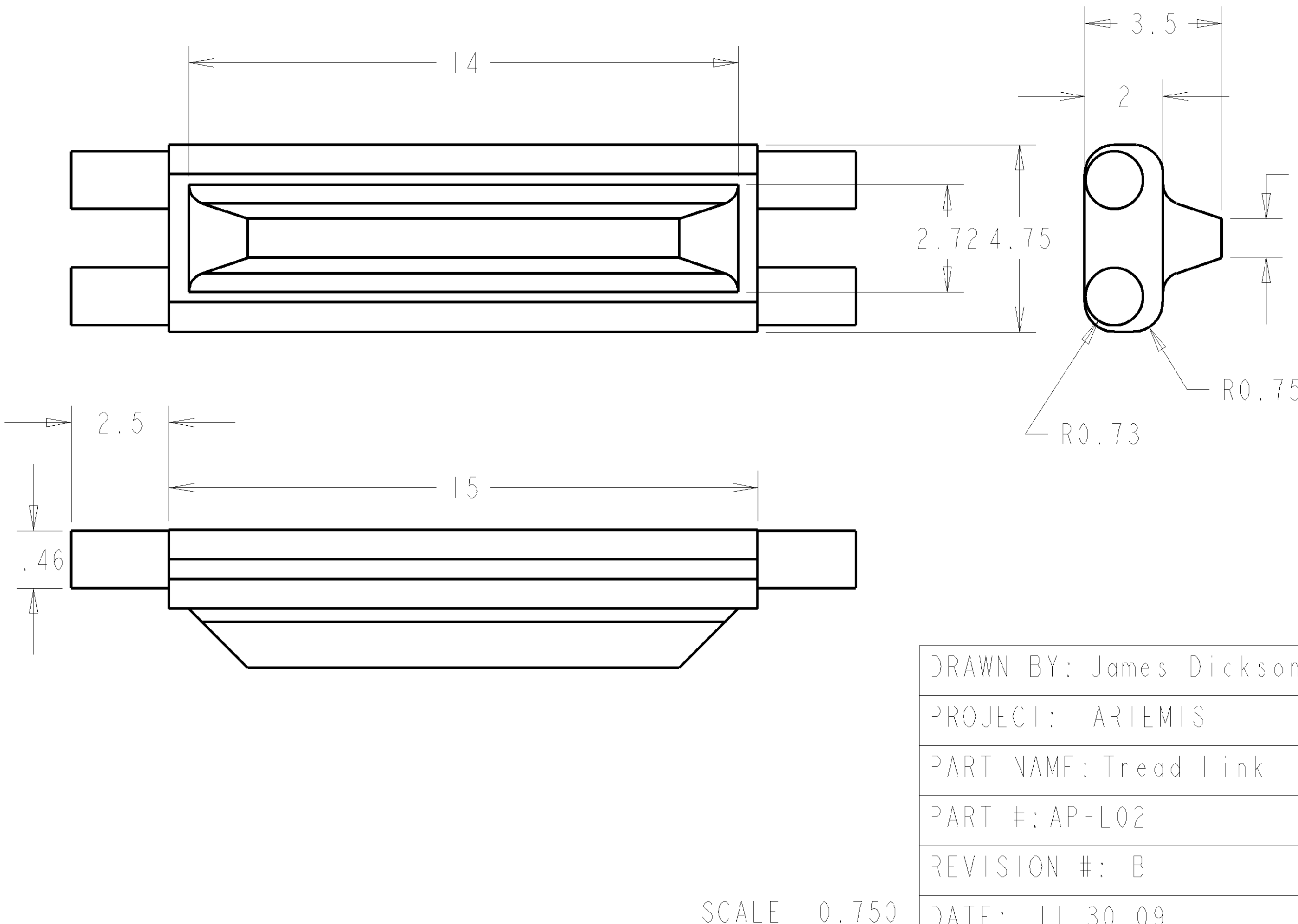
PART #: AP-L01	
REVISION #: A	
DATE: 11.30.09	



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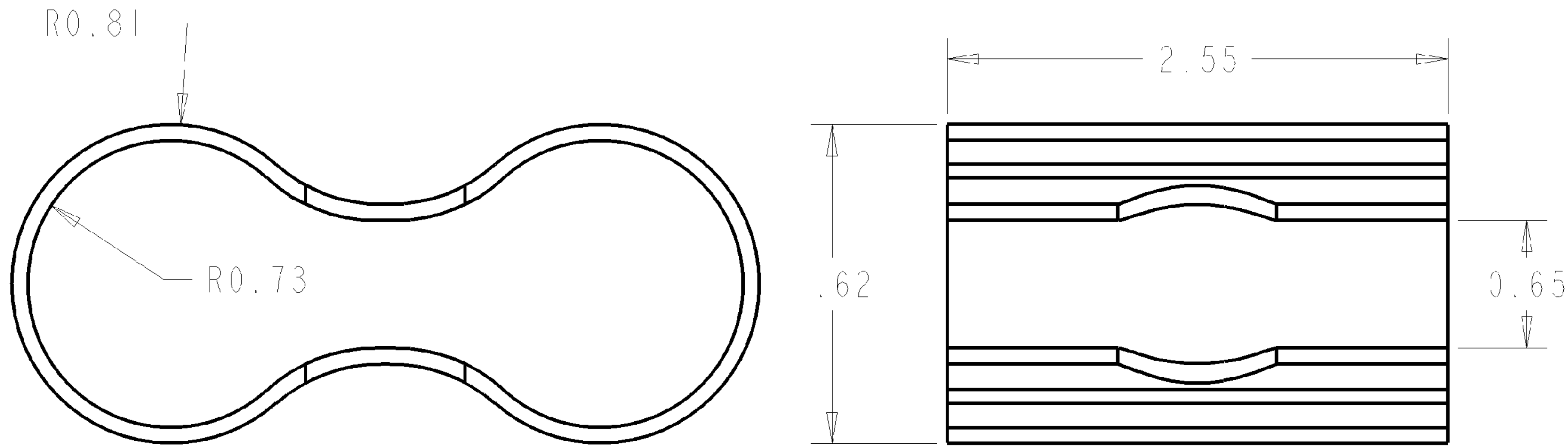
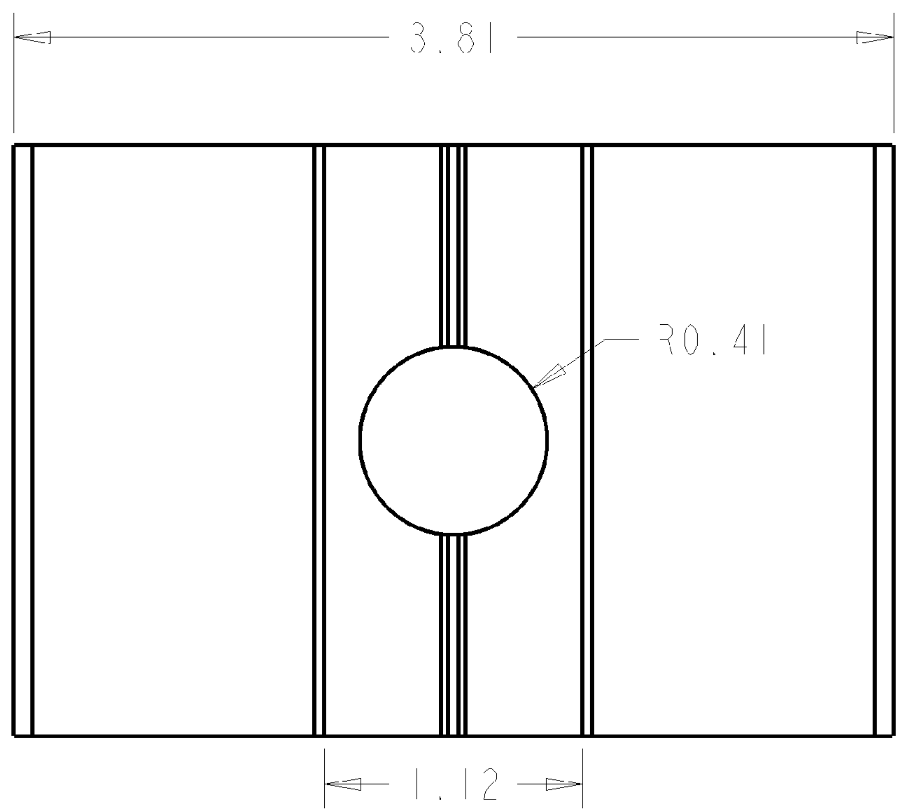
PROJECT: ARTEMIS	
PART NAME: Tread link	
PART #: AP-L02	
REVISION #: B	
DATE: 11.30.09	





SCALE 3.000

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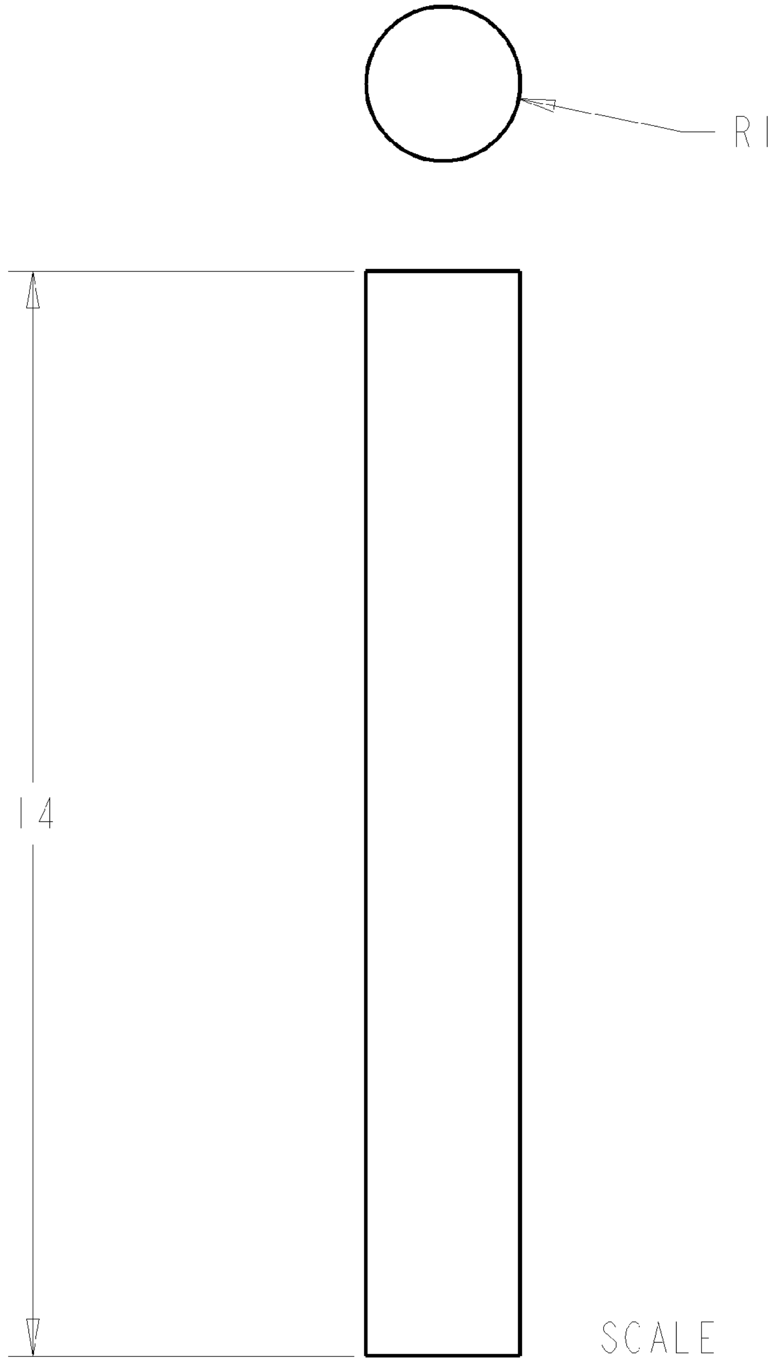
PROJECT: ARTEMIS
PART NAME: Connector
PART #: AP-L03
REVISION #: A
DATE: 11.30.09



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PART NAME: Shaft
PART #: AP-L01
REVISION #: A
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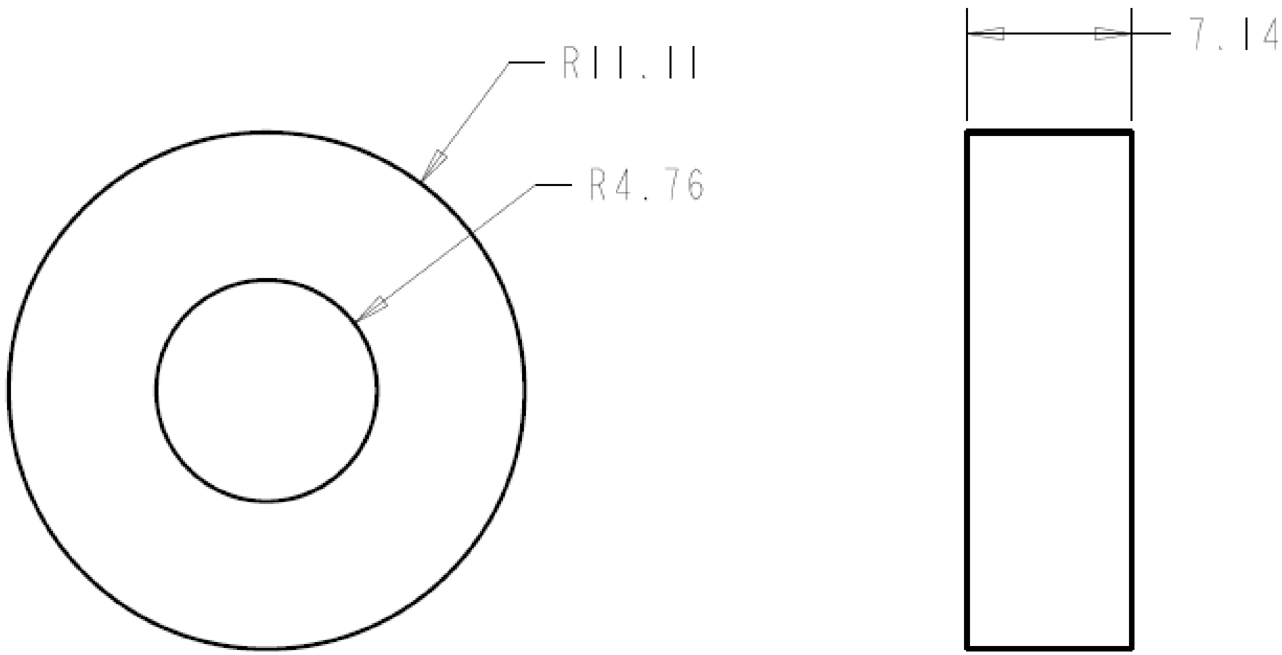

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DRAWN BY:	Alan Williams
PROJECT:	NASA
PART NAME:	Ball Bearing
PART #:	3
REVISION #:	1
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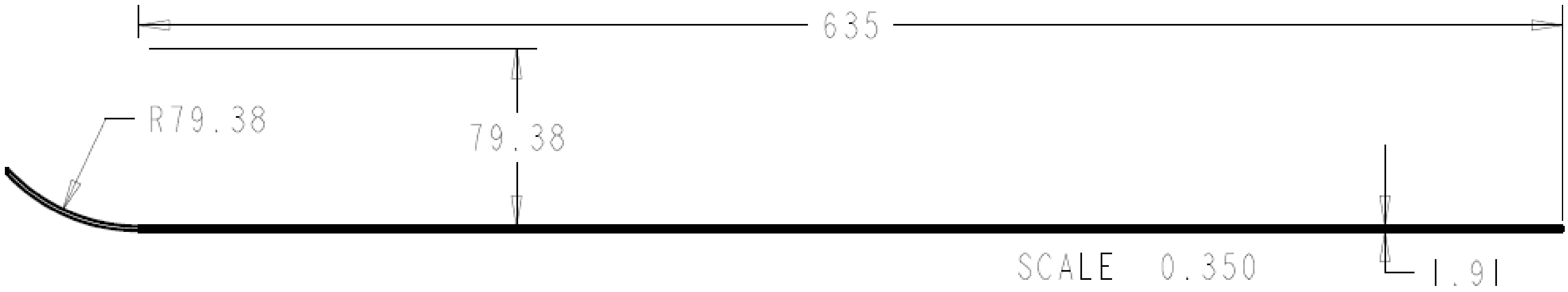

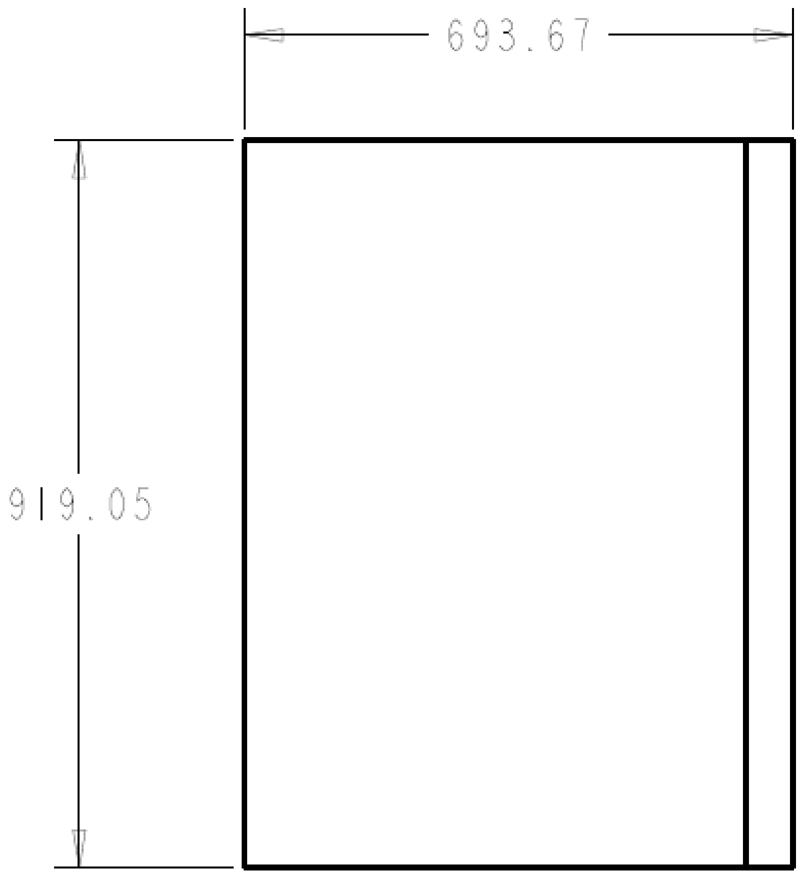

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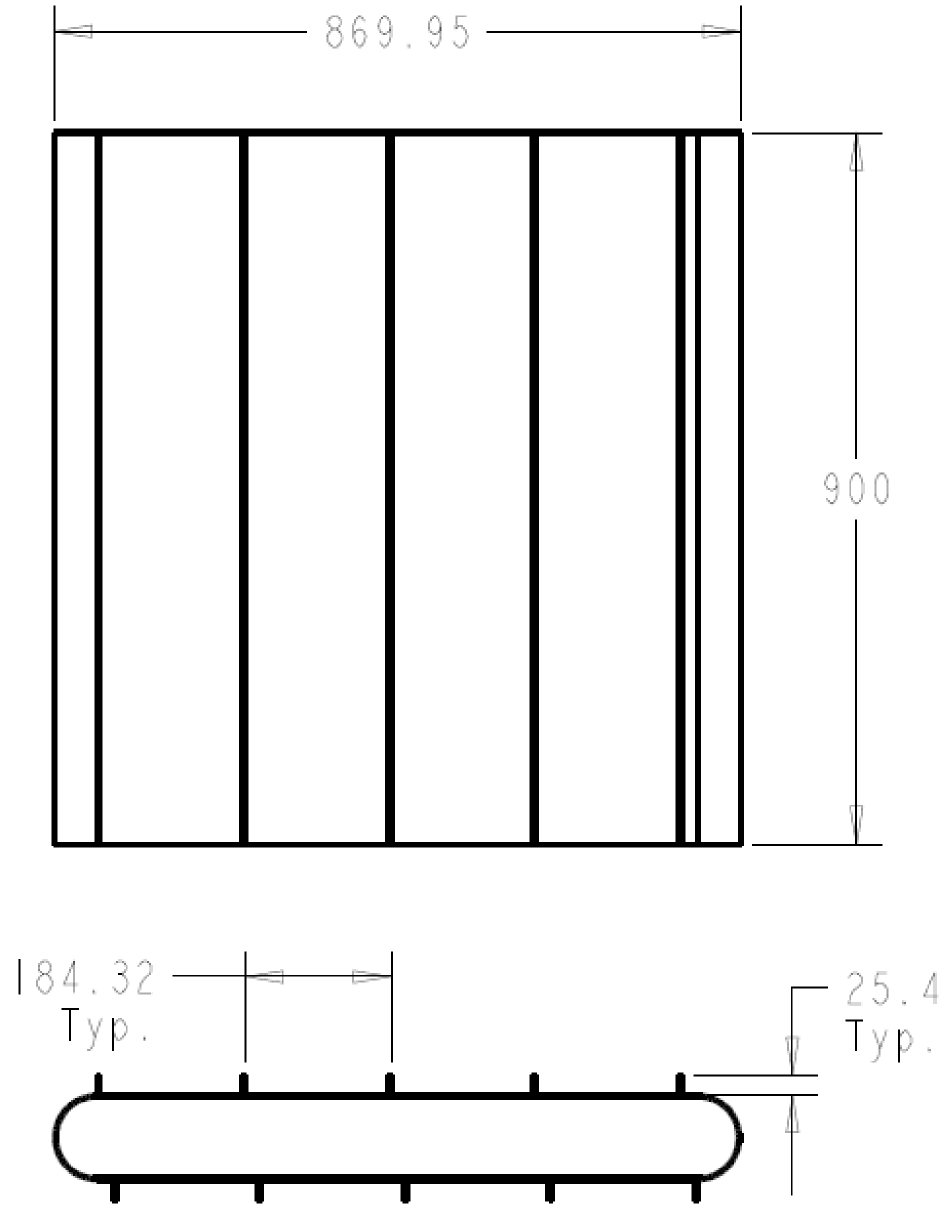

Material: PVC 120

DRAWN BY: Alan Williams	
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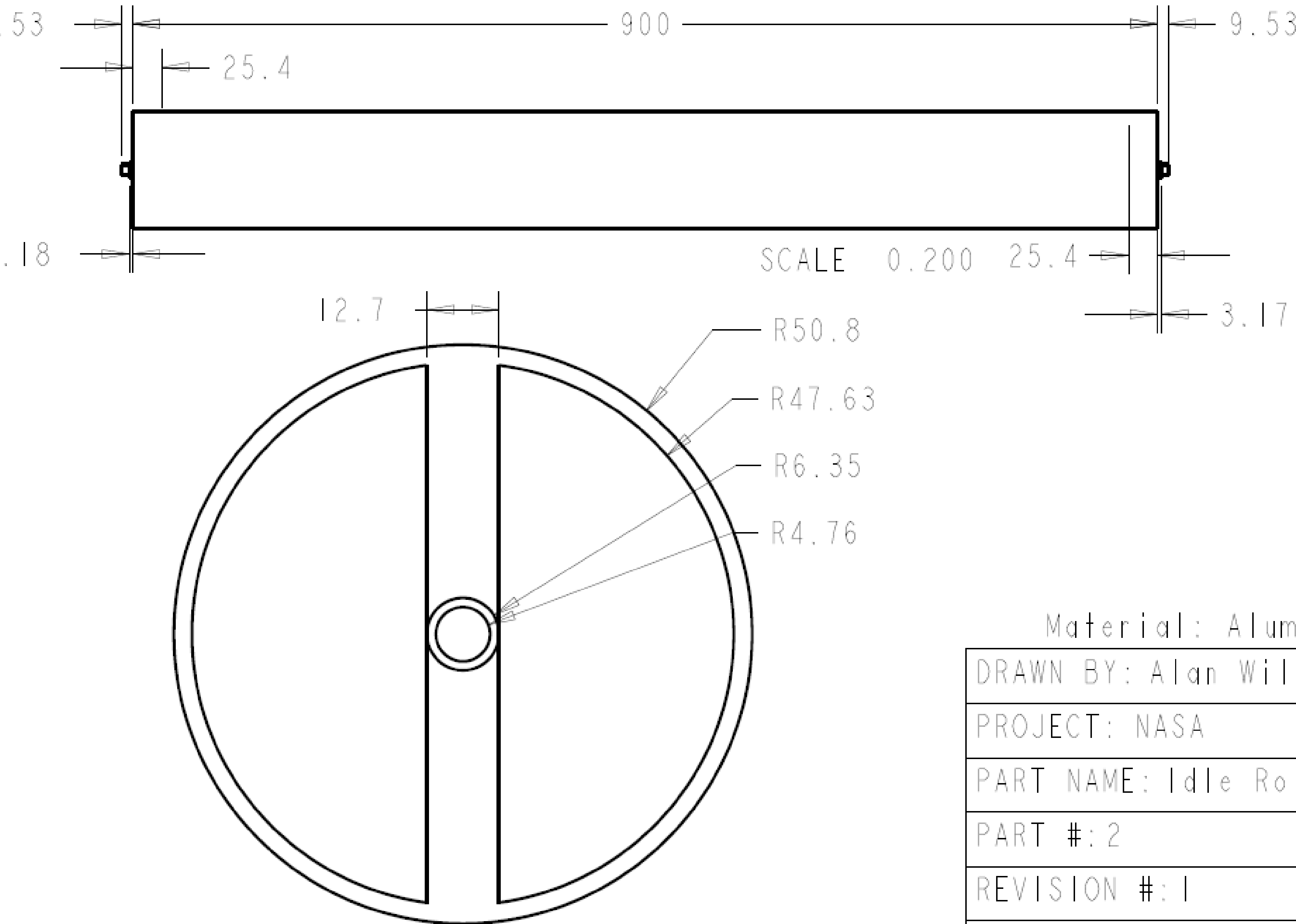

ALE 1.000 Note: All measurements are in millimeters

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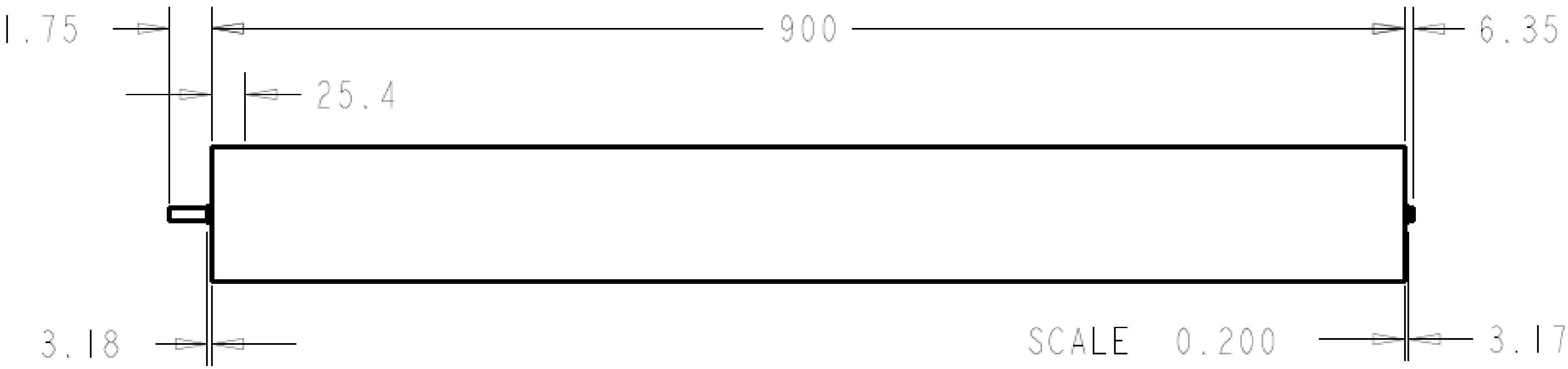

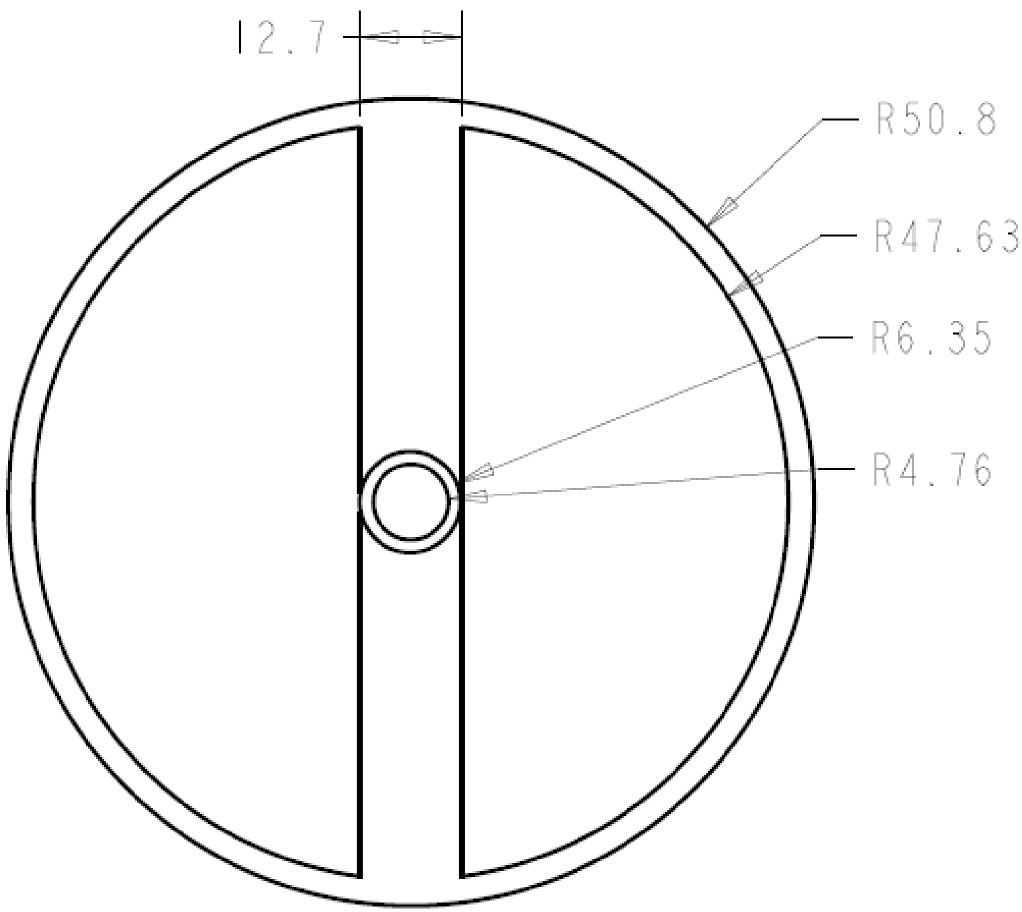

Material: Aluminum

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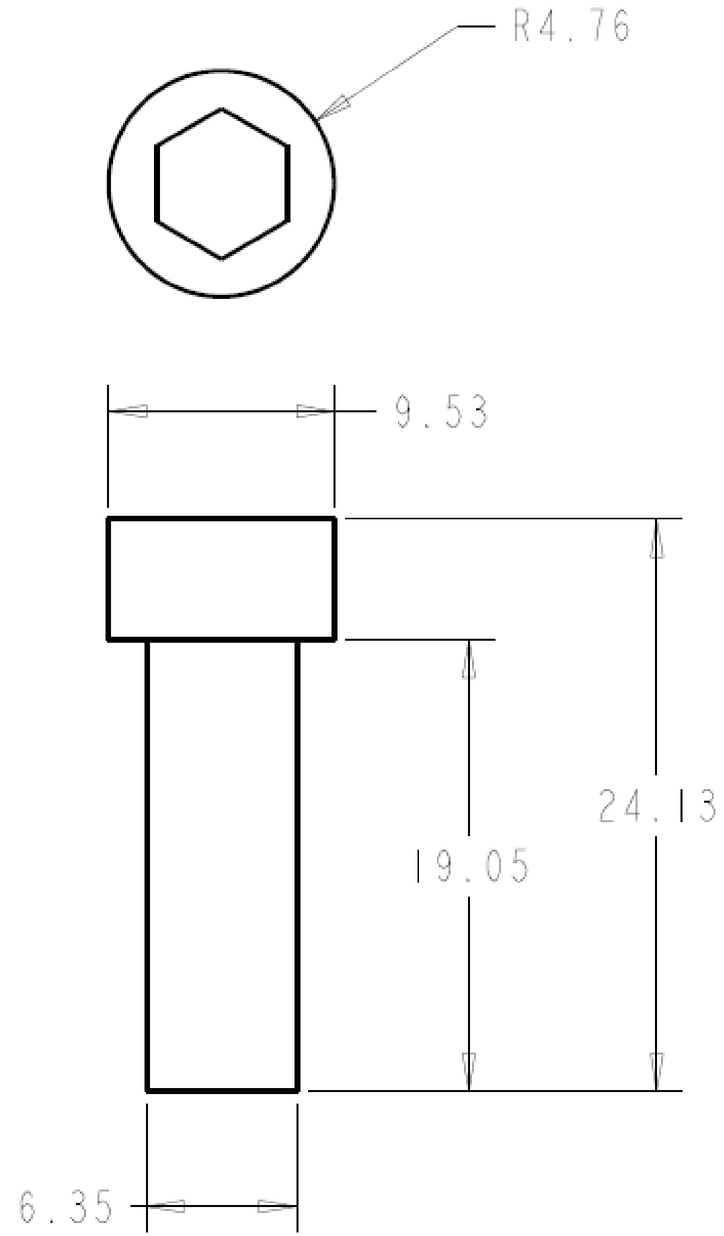
PROJECT: NASA
PART NAME: Driven Roller
PART #: 1
REVISION #: 1
DATE: 12/11/2009

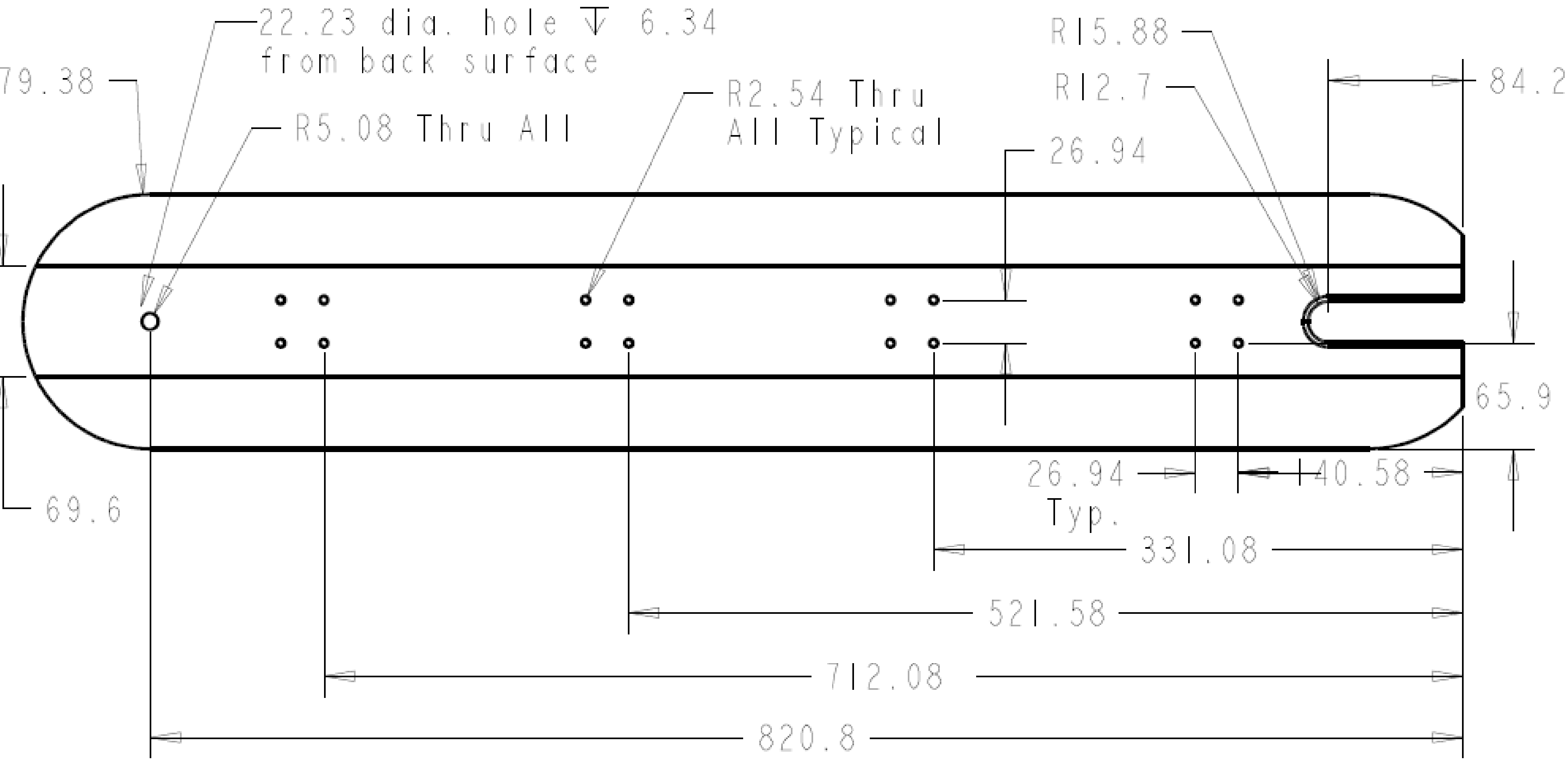
SCALE 1.000 Note: All measurements are in millimeters



Material: Aluminum

DRAWN BY: Alan Williams	
PROJECT: NASA	
PART NAME: F.M. Hardware	
PART #: 14	
REVISION #: 1	
DATE: 12/11/2009	

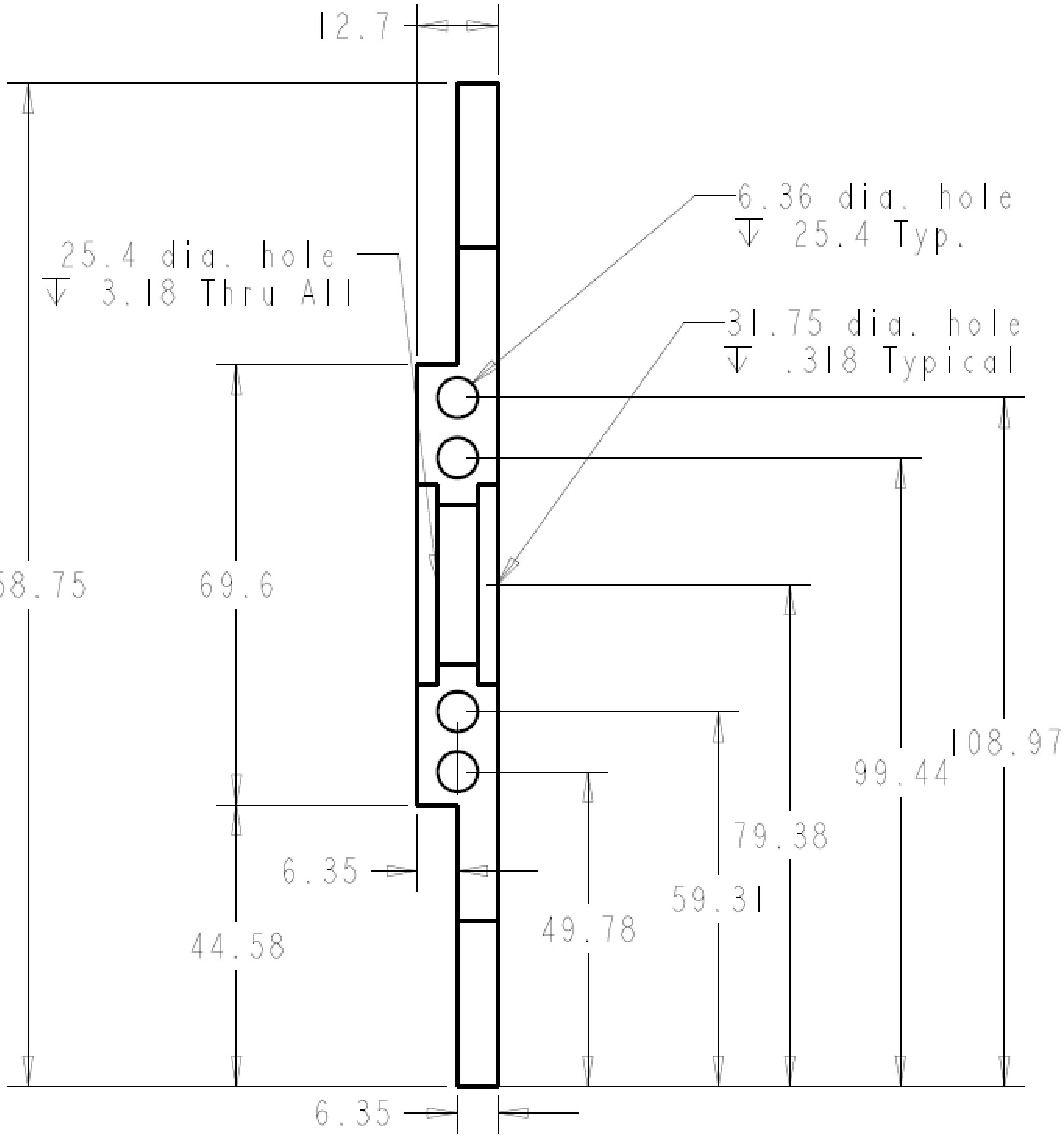
CALE 3.000 Note: All measurements are in millimeters



Material: Aluminum

DRAWN BY: Alan Williams	
PROJECT: NASA	
PART NAME: Left Shield	
PART #: 8	
REVISION #: 1	
DATE: 12/11/2009	

ALE 0.250 Note: All measurements are in millimeters



ALE 1.000 Note: All measurements are in millimeters

Material: Aluminum

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PROJECT: NASA
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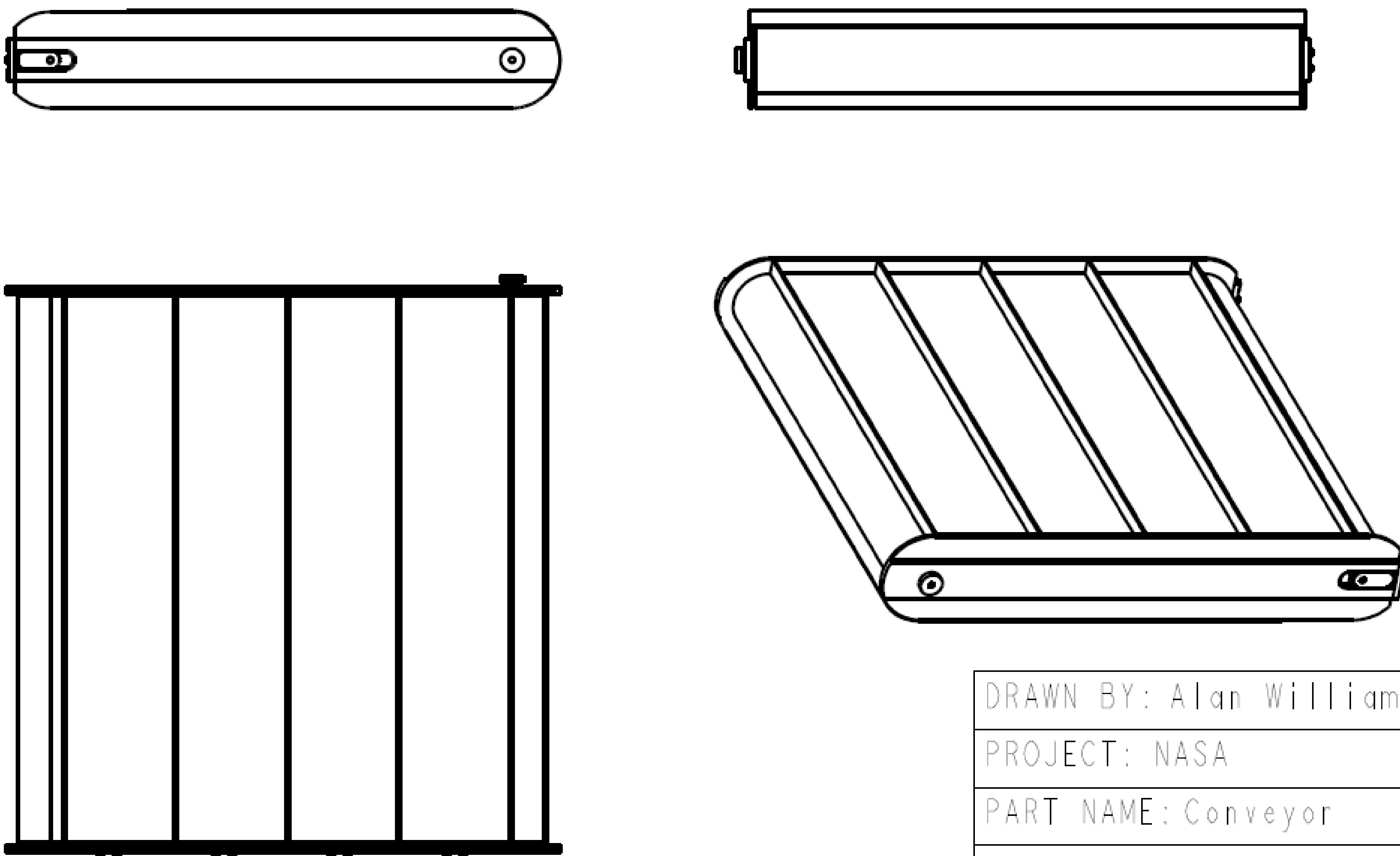
REVISION #: 1
DATE: 12/11/2009



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PART NAME: Conveyor	
PART #: Assembly View	
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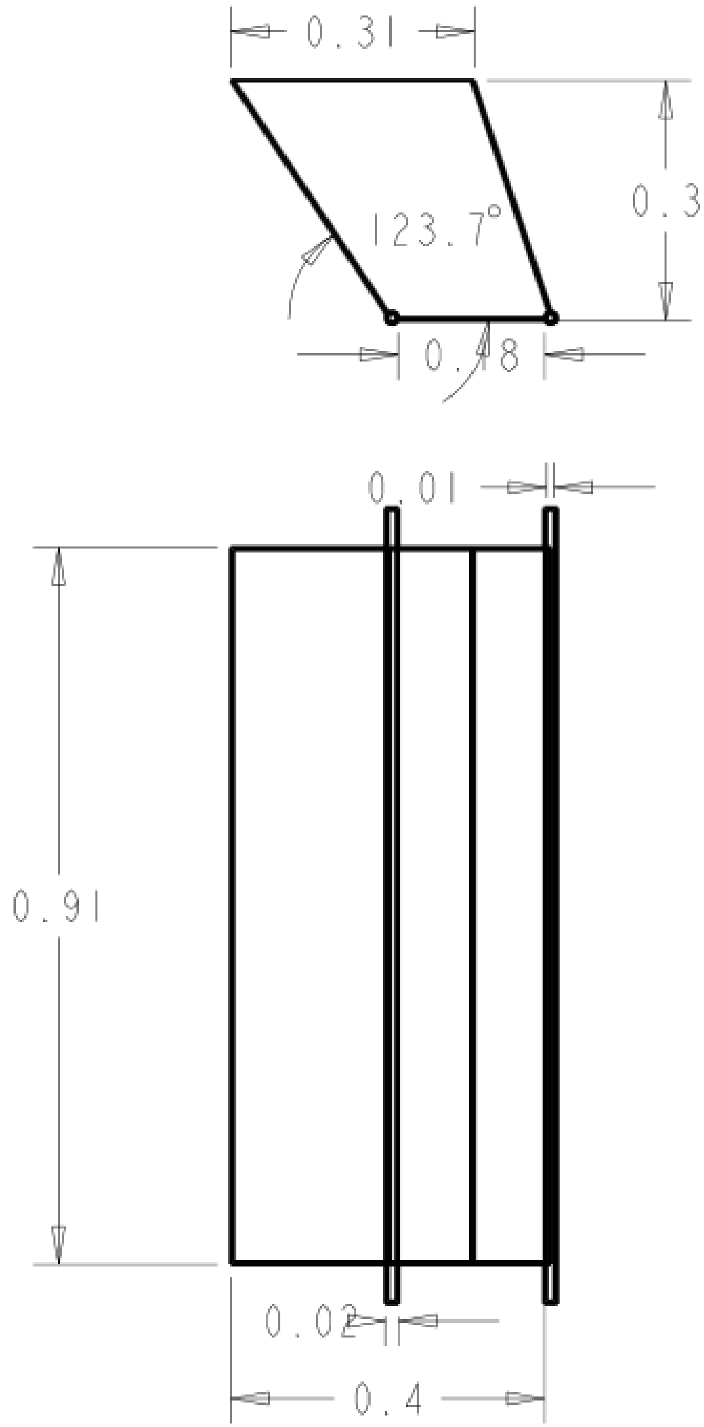
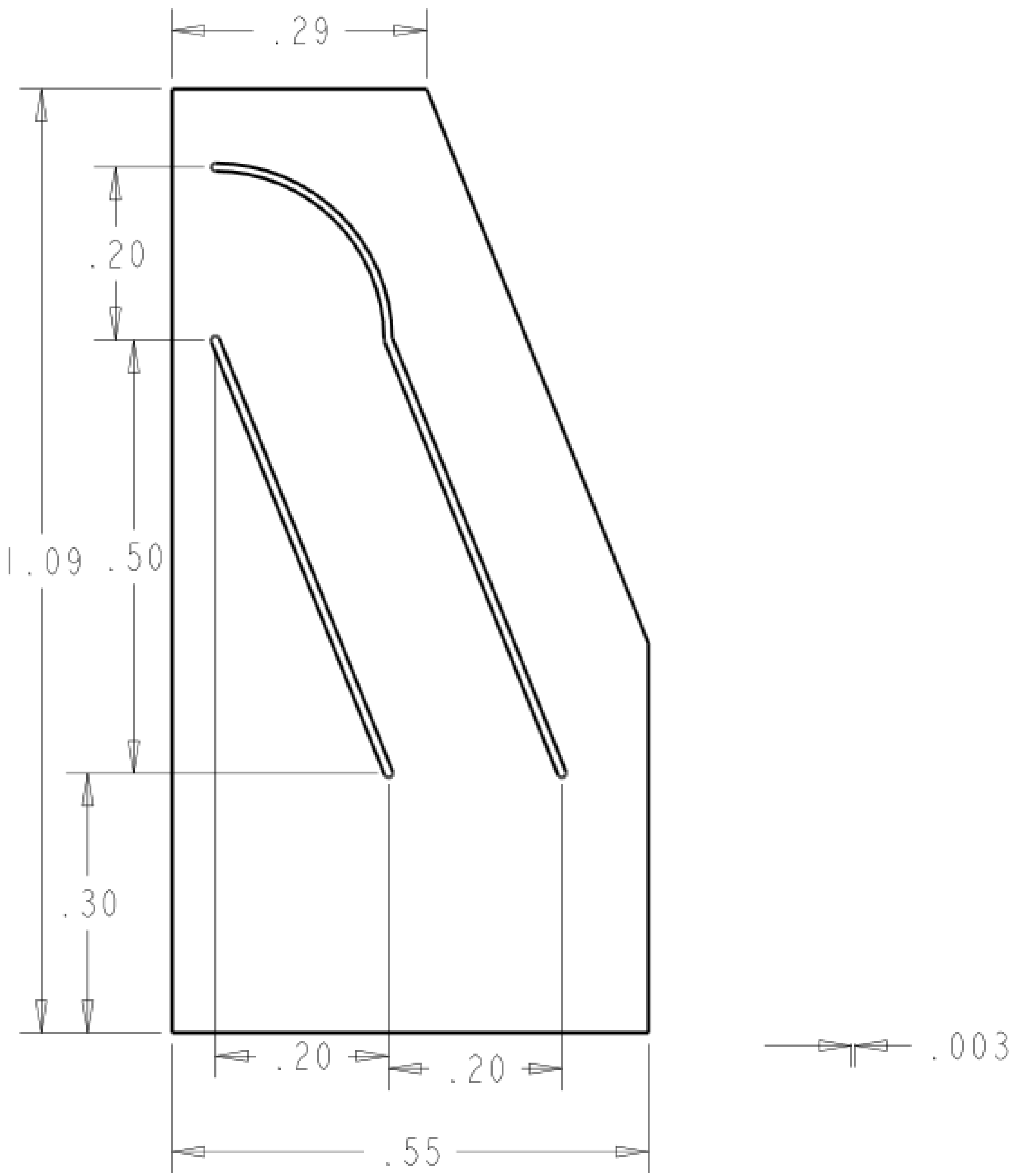
DATE: 12/11/2009	



PART:	BUCKET
DRAWN BY:	JENNIFER SCHRAGE
DATE:	12/8/09
PROJECT:	SENIOR DESIGN
SHEET:	
MATERIAL:	AL 6061 (1/8" SHEETS)
REVISION:	2
PART NUMBER:	



PART: Side Plate	
DRAWN BY: JENNIFER SCHRAGE	
DATE:	
PROJECT:	
SHEET:	
MATERIAL:	
REVISION:	
PART NUMBER:	

Appendix B. Rules Re-draft

Lunabotics Mining Competition

May 25-28, 2010

Kennedy Space Center

Astronaut Hall of Fame

Introduction

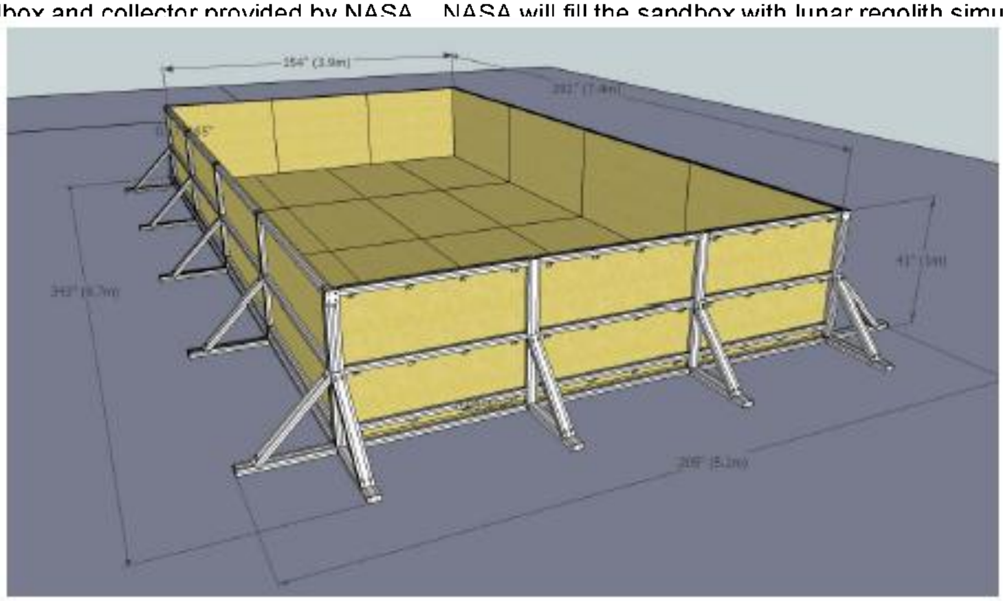
NASA's Lunabotics Mining Competition is designed to promote the development of interest in space activities and STEM (Science, Technology, Engineering, and Mathematics) fields. The competition uses excavation, a necessary first step towards extracting resources from the regolith and building bases on the moon. The unique physical properties of lunar regolith and the reduced 1/6th gravity, vacuum environment make excavation a difficult technical challenge. Advances in lunar regolith mining have the potential to significantly contribute to the Nation's Space Vision and space exploration operations.

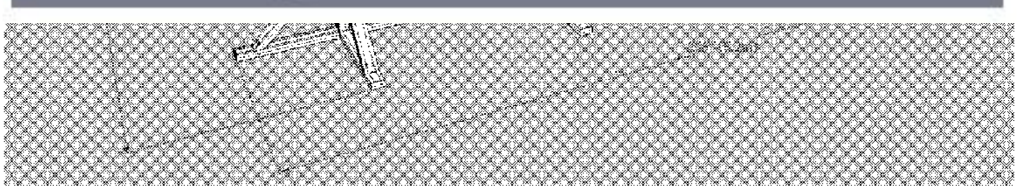
The competition will be conducted by NASA at Kennedy Space Center. The prize funding for the Lunabotics Student Mining Competition is provided by NASA. The teams that can use telerobotic or autonomous operation to excavate the most lunar regolith simulant within a 15-minute time limit will win the competition. The minimum excavation requirement is 10.0 kg, and the excavation hardware mass limit is 80.0 kg. Winners are eligible to receive first, second, or third prize of $5,000, $2,500, and $1,000, respectively. Rules for the competition are explained below.

Rules Draft 11/16/09

Game Play Rules

1) These rules and specifications may be subject to future updates by NASA at its sole discretion.
2) Teams will be required to perform one official competition attempt using lunar regolith simulant, sandbox and collector provided by NASA. NASA will fill the sandbox with lunar regolith simulant, com[...] eiken, D. T[...] tacles in th[...] ne. After [...] be retur[...]





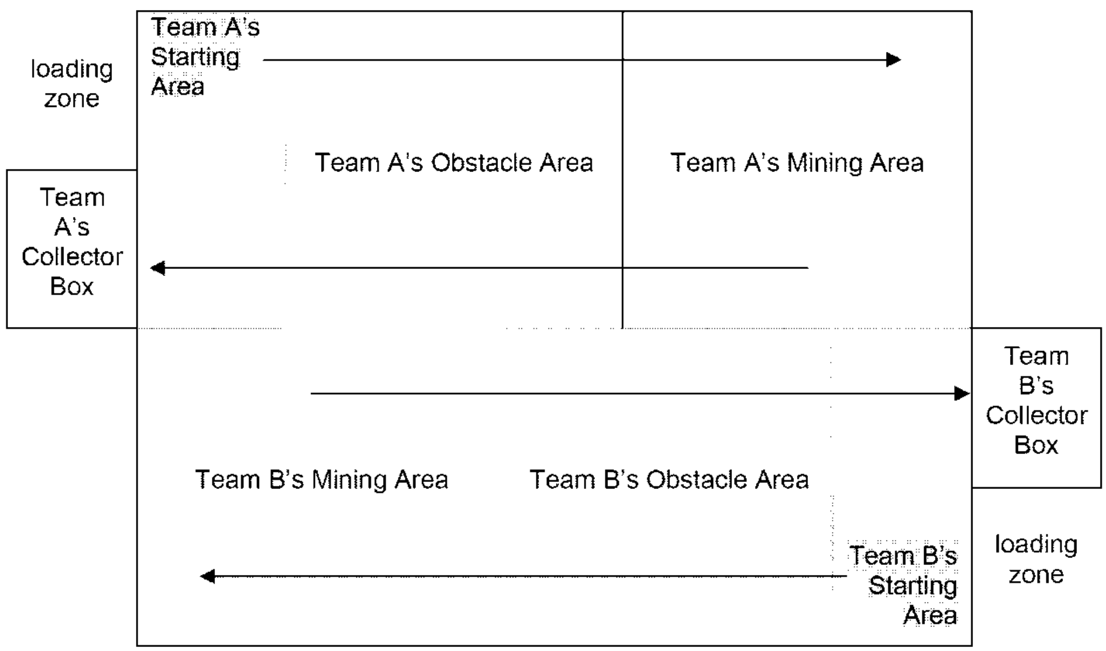
3) In the official competition attempt, the teams that acquire the first, second, and third most mass by excavating the lunar regolith simulant mass over the minimum excavation requirement (10 kg) within the time limit (15 minutes) will respectively win first, second, and third place prizes. In the case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

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

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

6) A team's excavation hardware shall only excavate lunar regolith simulant located in that team's respective mining area at the opposite end of the sandbox from the team's starting area.

7) The excavation hardware is required to move across the obstacle area to the mining area and then move back to the collector box as illustrated (not to scale) below. The dotted lines inside the sandbox are imaginary and may be crossed when safe to do so.



8) Each team is responsible for placement and removal of their excavation hardware onto the lunar regolith simulant surface without the use of a ramp. There must be one person per 23 kg of mass of the excavation hardware, requiring 4 people to carry the maximum allowed mass. Assistance will be provided if needed.

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

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

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

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

13) Each team will be permitted to repair or otherwise modify the excavation hardware after the team's practice time. The excavation hardware will be inspected the evening before the competition takes place and quarantined until just before the team's competition attempt.

Field Rules

14) At the start of the competition attempt, the excavation hardware may not occupy any location outside the footprint defined by the area of the starting area, the top surface of the sandbox and collector walls, and an 8 cm buffer around the inside surface of the sandbox. A target may be attached to the collector for navigation purposes only. This navigational aid must be attached during the setup time and removed afterwards during the removal time period.

15) The collector will be placed so that it is adjacent to the side walls of the sandbox without a gap.

16) There will be a variety of obstacles placed on top of the compressed lunar regolith simulant surface within the obstacle area before the competition attempt is made. The placement of the obstacles will be randomly selected before the start of the competition and will be identical for every competition attempt. Each rock will have a diameter of approximately 20 to 30 cm and an approximate mass of 7 to 10 kg. Rocks placed in the collector will not be counted as part of the excavated mass. Craters will be of varying depth and width, being no wider or deeper than 30cm.

17) Excavation hardware must operate within the sandbox: it is not permitted to pass beyond the confines of the outside wall of the sandbox and the collector during the competition attempt. The regolith simulant must be collected in the mining area allocated to each team and deposited in the collector. The team may only dig in its own mining area. The simulant must be carried from the mining area to the collector by any means as long as the team avoids the other team's excavator during the traverse through the rock field. The excavator can separate intentionally, if desired, but all parts of the excavator must be under the team's control at all times.

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

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

Technical Rules

20) During the competition attempt, excavation hardware is limited to autonomous and telerobotic operations only. No physical access to the excavation hardware will be allowed during the competition attempt. In addition, telerobotic operators are only allowed to use data and video originating from the excavation hardware. Visual and auditory isolation of the telerobotic operators from the excavation hardware in the Mission Control Room is required during the competition attempt. The Mission Control Room is approximately 12 meters from the sandbox. Telerobotic operators will be able to see the excavation hardware through fixed overhead cameras on monitors that will be provided by NASA in the Mission Control Room. The walls of the Mission Control Room are metal framed with 5/8" wall board on both sides of the framing.

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

22) The excavation hardware must be equipped with an easily accessible red emergency stop button on the surface of the excavator. This kill switch must require no steps to access.

23) The communications link used for telerobotic operations is required to have a total bandwidth of no more than 5.0 megabits/second. Teams will be required to demonstrate compliance prior to starting the competition attempt. Wi-Fi infrastructures will be provided and monitored by NASA: one for practice and one for the competition attempt. IP addresses will be provided and managed by NASA. Each team must request anticipated IP address requirements by January 15, 2010 by e-mailing

Definitions

Collector – A device provided by NASA for the competition attempt into which each team will deposit excavated regolith simulant. The collector will be large enough to accommodate each team's excavated regolith simulant. The collector will be stationary and located adjacent to the sandbox. Excavated regolith simulant mass will be measured after completion of the competition attempt. The collector mass will not be counted towards the excavated mass or the mass of the excavation hardware. The collector will be sized 1.65 meters long, and .48 meters wide. The collector walls will rise to an elevation about 1 meter above the average elevation of the regolith simulant surface closest to the collector.

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

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

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

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

Lunar regolith simulant – Specific lunar regolith simulant provided by NASA during the competition attempt is to be determined. Small samples will be provided to each registered team.

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

Power – All power shall be provided by a system onboard the excavator. No facility power will be provided to the excavator.

Practice time – Teams will be allowed to practice with their excavators in the sandbox on May 25 and 26, 2010. NASA technical experts will offer feedback on real-time networking performance during practice attempts.

Reference point – A fixed location on the excavation hardware that will serve to verify the starting location and traversal of the excavation hardware within the sandbox.

Sandbox – An open-topped container (i.e., a box with a bottom and four side walls only), containing regolith simulant, within which the excavation hardware will perform the competition attempt. The dimensions of the sandbox will be 3.9 meters wide and 7.4 meters long, and one meter in depth. The sandbox for the competition attempt will be provided.

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

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

Appendix C. Concept Selection Matrices

		Concepts											
		Tracks		4 Wheels		6 Wheels		C-Legs		iSprawl Legs		Worm	
Specifications	Importance Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Traction	20.00%	5	1	2	0.4	3	0.6	0	0	1	0.2	4	0.8
Stability	10.00%	5	0.5	3	0.3	4	0.4	1	0.1	2	0.2	0	0
Maneuverability	15.00%	4	0.6	3	0.45	2	0.3	1	0.15	5	0.75	0	0
Speed	15.00%	2	0.3	4	0.6	3	0.45	1	0.15	5	0.75	0	0
Power	10.00%	5	0.5	3	0.3	4	0.4	2	0.2	1	0.1	0	0
Cost	10.00%	3	0.3	5	0.5	4	0.4	2	0.2	1	0.1	0	0
Simplicity	10.00%	2	0.2	5	0.5	4	0.4	3	0.3	1	0.1	0	0
Low Maitenance	5.00%	2	0.1	4	0.2	3	0.15	5	0.25	1	0.05	0	0
Dust Resistance	5.00%	2	0.1	4	0.2	3	0.15	5	0.25	1	0.05	0	0
	Score		3.6		3.45		3.25		1.6		2.3		0.8
	Selection	1st		2nd		3rd		-		-		-	

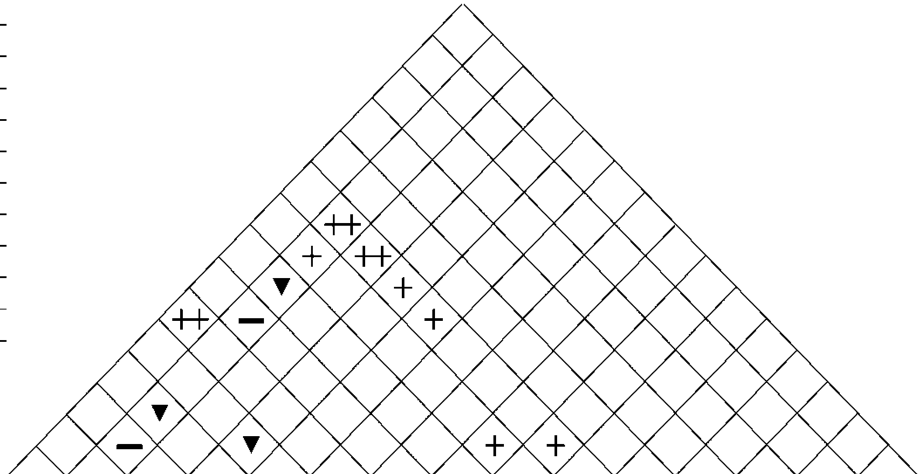
Title:

thor:

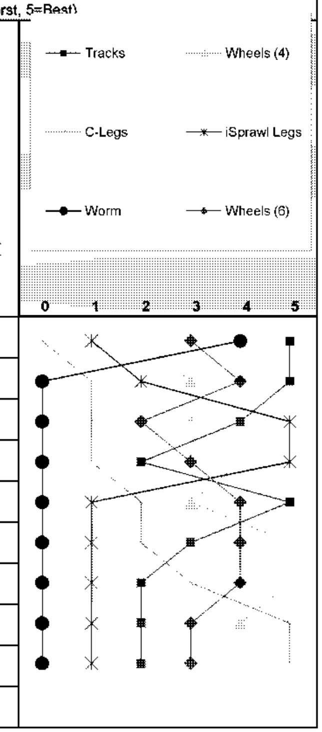
Date:

otes:

Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
−	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	



Max Relationship Value in Row	Relative Weight	Weight / Importance	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Competitive Analysis (0=Worst, 5=Best)					
			Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▼	▼	▼	x	▲	▲	x	x	▲	▲											
			Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Center of Gravity Height	Cost	Mass	Treads	Surface Contact	Track Width (Stance)	Independent Track Control	Standardized Parts	Environmentally Sealed	Motor Power						Tracks	Wheels (4)	C-Legs	iSprawl Legs	Worm	Wheels (6)
9	11.1	10.0	Traction	▲		O	Θ	Θ	▲				O						5	2	0	1	4	3
9	11.1	10.0	Stable	Θ					Θ										5	3	1	2	0	4
9	11.1	10.0	Manuverability	▲		O	Θ	O	O	Θ			O						4	3	1	5	0	2
9	11.1	10.0	Speed		O	O	Θ	O					Θ						2	4	1	5	0	3
9	11.1	10.0	Power		Θ	▲							Θ						5	3	2	1	0	4
9	11.1	10.0	Inexpensive		Θ	Θ				O	Θ	Θ	Θ						3	5	2	1	0	4
9	11.1	10.0	Simplicity		Θ		▲	▲		Θ	Θ	Θ							2	5	3	1	0	4
9	11.1	10.0	Low Maitenance		Θ		O			▲	Θ	Θ							2	4	5	1	0	3
9	11.1	10.0	Dust Resistance		Θ						▲	Θ							2	4	5	1	0	3
	0.0	0.0																						
			Target or Limit Value	20 cm	$1,500	10 kg	u=1.0	0.1 m^2	1 m	100%	75%	IP6X	2x100W											
			Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	3	8	6	7	3	0	7	4	9	1											
			Max Relationship Value in Column	9	9	9	9	9	9	9	9	9	9											
			Weight / Importance	122.2	533.3	211.1	344.4	177.8	144.4	244.4	311.1	400.0	366.7											
			Relative Weight	4.3	18.7	7.4	12.1	6.2	5.1	8.6	10.9	14.0	12.8											



Appendix D. Analysis

Conveyor Analysis

To perform analysis of the conveyor system, several key assumptions where necessary. First, it was assumed that the optimum belt velocity is one meter per second and that the belt would reach this velocity in a time of one and one half seconds. Secondly, it was assumed that the inclination angle of the conveyor system as measured from the horizontal is fifty-five degrees. Thirdly, it was assumed that the optimum belt tension during operation is equivalent to thirty newtons. The next assumption was that each belt cleat excavated a triangular volume of 580.64 centimeters cubed. Finally, before analysis could be performed, it was necessary to define a few key parameters. Through research we determined the coefficient of friction of a steel radial ball bearing, delrin slider, and PVC-120 belt to be .0015, .2, and .3 respectively. The maximum regolith stimulant density of 1.91 grams per centimeters is also used to determine the maximum load. Below are the steps, formulas, and values used to determine the required motor torque in order to operate under the conditions previously stated.

__Design Calculations__

Estimated Volume Calculation Per Scoop:

$$V_s = \frac{1}{2} \cdot h \cdot w \cdot b = \frac{1}{2} \cdot CleatHeight \cdot BeltWidth \cdot (2 \cdot CleatHeight)$$

$$= .5 \cdot 2.54cm \cdot 90cm \cdot 5.08cm = 580.644cm^3$$

Maximum Mass at an Instant:

$$eCleats \cdot RegolithDensity = 580.644cm^3 \cdot 5 \cdot 1.91\frac{g}{cm^3} = 5545.15g$$

$$ravity \cdot \sin(55^\circ) = 5.54525kg \cdot 9.81\frac{m}{s^2} \cdot \sin(55^\circ) = 44.5602N$$

Total Bearing Friction Force:

$$F_B = \left(\frac{BeltTension + WeightBelt + WeightRollers}{4Bearings} \right) \cdot 4Bearings \cdot \mu_B$$

$$= \left(\frac{30N + (7.87kg + 5.11kg) \cdot 9.81\frac{m}{s^2}}{4} \right) \cdot 4 \cdot .0015 = .236N$$

Total Slider Friction Force:

$$F_s = \mu_s \cdot F_n * 4Sliders = .2 \cdot 1N * 4 = .8N$$

Total Belt/Roller Friction Force:

$$F_r = 2Rollers \cdot BeltTension \cdot \mu_r = 2 \cdot 30N \cdot .3 = 18N$$

Angular Velocity and Angular Acceleration:

$$\omega = \frac{V}{r_{roller}} = \frac{1\frac{m}{s}}{.0508m} = 19.685\frac{rad}{s} \qquad \alpha = \frac{dw}{dt} = \frac{19.685\frac{rad}{s}}{1.5s} = 13.1234\frac{rad}{s^2}$$

Total Roller Moment of Inertia:

$$I_r = 2Rollers \cdot \frac{1}{2} \cdot m \cdot (R_r^2 + r_r^2) = 2.55kg \cdot [(.0508m)^2 + (.0476m)^2] = .0124kg \cdot m^2$$

Required Motor Torque:

$$T_m = I_r \cdot \alpha + F_r \cdot r_{roller} + F_s \cdot r + F_B \cdot r + F_{load} \cdot r$$

$$= \left(.0124kg \cdot m^2 \cdot 13.1234\frac{rad}{s^2} \right) + (18N \cdot .0508m) + (.8N \cdot .0508m) + (.236N \cdot .004763m)$$

$$+ (44.5602N \cdot .0508m) = 3.383N \cdot m$$

T_m = 3.383 N*m