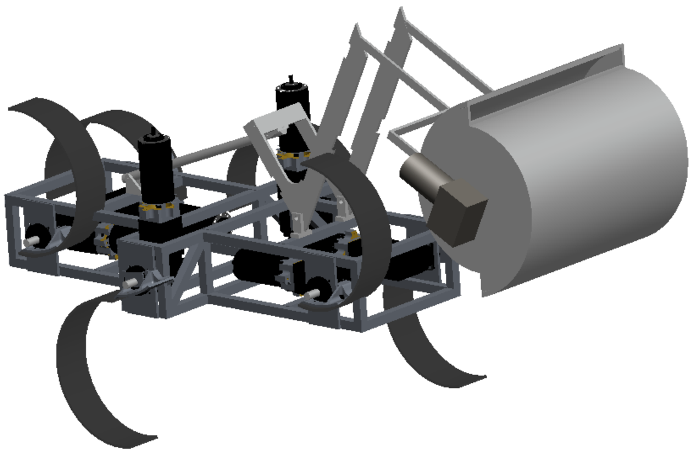
Hexcavator: NASA Lunabotics Competition

Senior Design Final Report – April 2012

By
C. Robert Sistare[2], Devin Walden[2], James Fadool[1], McKenzie Reed[1], Seth Murphy[2], and Shannon Berger[1]
[1]*Department of Mechanical Engineering*
[2]*Department of Electrical and Computer Engineering*



Project Sponsor
Dr. Jonathan Clark, *Assistant Professor*

Department of Mechanical Engineering
FAMU-FSU College of Engineering
2525 Pottsdamer St, Tallahassee, FL 32310

Contents

List of Figures

List of Tables

I. **Abstract**

The 2011-2012 Lunabotics Competition Senior Design group, named Hexcavator, built and tested a robotic platform to compete in the Third Annual NASA Lunabotics Mining Competition. The previous year's senior design team was unable to compete in the competition but made a frame, purchased batteries, motors, gear boxes, fuses and an emergency stop button. This year's team utilized all of these compenents but also designed, manufactured, and assembled an excavation system to mount directly to the robotic platform. This included much planning, preparation and execution over the course of two semesters. The team split themselves into three subgroups to focus attention on the three major areas of the project: locomotion, wireless communication, and excavation. These three parameters were developed and tested separate of each other to avoid further complicating testing and improving each system. After initial testing was completed and complications were defined and remedied, the wireless communication system and locomotion system were implemented into one testing application on the frame of the robot. The excavation system underwent a redesign which required further testing on a platform built to the same scale as the actual robotic frame. Testing is still underway of these two systems individually. Final implementation of a complete system will begin within the immediate future, after which initial testing will be completed for the integrated robotic system. The Hexcavator team will then travel to the Kennedy Space Center in Titusville, FL. The competition will take place from May 21st through May 26th. In that time, the team will be allowed to do final testing at the competition area to make sure the robotic platform is performing correctly. They will then have two ten minute attempts to extract as much lunar regolith from the competition area as possible, while being judged on a range of different parameters and specifications that are defined by NASA.

Overall we feel our project was a success because we implemented an excavation system that met the specifications of the NASA competition. We also believe that prior to the competition we will have a fully functional robotic system once the control law has been implemented for locomotion.

II. Introduction

This senior design project's purpose is to be entered into the Third Annual NASA Lunabotics Competition, which occurs from May 21st to 26th, 2012. This competition goal is to create a robot capable of operating in a lunar environment, including traversing rough terrain, communicating wirelessly with a simulated delay and collecting lunar soil. After the soil is collected, it will be deposited into the LunaBin. This LunaBin will be located 0.5m from the top of the lunar surface. Research on regolith would help determine the feasibility of lunar inhabitance, which could lead to future scientific breakthroughs. The competition will simulate the lunar environment and the accompanying hazards found on the moon, including craters and obstacles for the robot to traverse. Previous competition teams have succeeded with more traditional wheel based design, but have struggled with navigating the obstacles. This year's team will complete with a hexapedal robot based on the RHex family of robots. The main benefit of this design is the ability to easily overcome various obstacles such as rocks and craters via C-shaped legs. Last year's senior design team began building the Hexcavator platform, but was unable to complete the design. The completed portion of the platform is shown below in Figure 1; the platform had a frame, motors, legs, leg attachments and a few other minor components. It had no control system, power system, wireless communication system or excavation system. These systems have been designed, implemented and are outlined in detail later in this document.

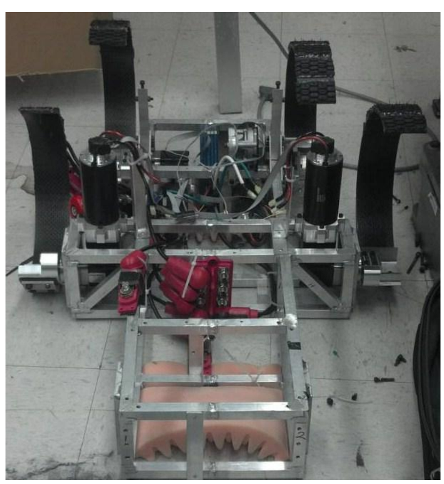


Figure 1: The 2010-2011 FAMU/FSU College of Engineering Lunabot that was developed for the NASA competition. Due to unfortunate circumstances, this robot was not able to compete in the Second Annual NASA Lunabotics Mining Competition.

II.1 List of Constraints

The design requirements of the robot are dictated by NASA's Third Annual Lunabotics Mining Competition Rules and Rubrics [3]. Below is a synopsis of these rules, the complete set can be found in the Appendix.

- The competition will take place on May 21-26, 2012. All teams must arrive at the Competition by noon on May 22, 2012.
- The team will be required to complete two, ten-minute competition attempts using the defined competition area provided by NASA.
- The NASA judges need to be able to send an immediate power-off command to the robot at the end of the ten minute competition attempts.
- The robot must excavate at least 10kg of regolith and deposit it into the LunaBin.
    - The LunaBin will be 0.5m tall and have an opening 1.65m long and 0.48m wide.
- The robot must be able to start from any start position dictated by the judges.
- The robot has a weight maximum of 80kg.
- The robot has a starting height maximum of 0.75m.
- The robot has a starting length maximum of 1.5m.
- The robot has a starting width maximum of 0.75m.
- The complete system must be self-powered.
- The team must have one person on the competition team per 23kg of mass of the robot.
- The team must be capable of setting up the robot in the competition area within ten minutes.
- The robot cannot be anchored to the Luna Surface prior to the competition attempt.
- The robot cannot use the walls as support, or use them to push/scoop regolith.
- The robot is limited to autonomous and telerobotic operations only.
- A red emergency stop button of 5cm diameter is required on the exterior of the robot. IT must act as a kill switch and be a commercially bought product.
- The robot is not allowed to use any fundamental physical processes (e.g. suction or water cooling in the open lunar environment), gases, fluids, or consumables that will not work in a lunar environment.

- The robot cannot cause the regolith to undergo any physical or chemical changes, and it may not be treated as a projectile.
- The robot must be able to overcome simulations of obstacles and craters during locomotion.

II.2. Buehler Clock

One of the primary challenges encountered on the moon is the terrain, which is full of craters, rocks and other challenging obstacles. The benefit of the RHex platform is its ability to climb over most obstacles instead of avoiding them. All of the obstacles that will be present in the competition will be easily manageable because of the large C-leg design of Hexcavator. However, locomotion for a RHex platform is not as simple as it would be for a traditional wheeled vehicle. The leg rotates about its center axis, creating a circular path. Since this robot is a walking robot, there must be three legs in contact with the ground at all times (this will be discussed in further detail in a later section). As such, the leg must be in contact with the ground for the same amount of time it is in the air. However, the amount of distance the leg must travel in the air is much greater than the distance it must travel when the leg is in contact with the ground. This discrepancy is demonstrated by Figure 2.

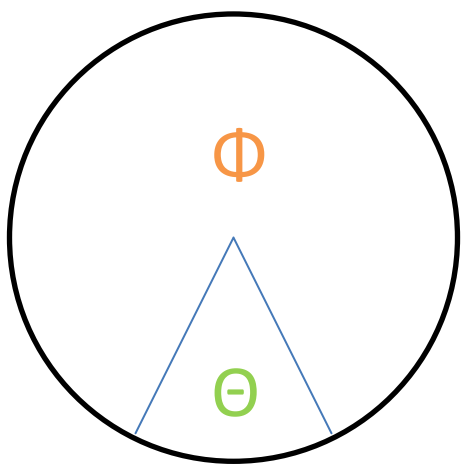


Figure 2: A circle demonstrating the path the leg must cover, and how it is done by a Buehler Clock.

To correct for this discrepancy, the velocity of the leg cannot be the same for the phases indicated by Figure 2. The velocity of leg as it travels through section Θ must be proportionally smaller than the velocity of the leg as it travels through section Φ in order for the time elapse in both states to be equal. As such, a Buheler Clock is used for locomotion. A Buehler Clock is a way of setting speed depending on the position of the motor. Since both angles Θ and Φ will be both known, the factors to adjust the speed, n and m, can be calculated by using the following equation:

$$t(\theta) = n * \theta = m * \Phi = t(\Phi)$$

In order to implement this, a motor with an encoder is required so that the position can be detected. Once the position is read, the speed of the motor can be adjusted appropriately.

In the current simulations for the robot, a value of 60° and 300° were used for Θ and Φ, respectively. That means that the angular velocity in the Φ sector is five times faster than when in the Θ sector. These degrees may slightly change when implemented on the robot, but should be very close to these values.

II.3 Goal Statement

The goal for this project is to be able to traverse the simulated moon environment while overcoming obstacles with a robotic platform. Upon reaching the opposite end of the course, the robot will excavate the regolith, store it onboard the robot, and traverse back across the simulated moon environment. Once the robot reaches the Lunabin it will deposit the regolith into the repository; the competition requires that least 10kg of regolith needs to be deposited. During this project we will design a hexapedal robot, named Hexcavator, capable of performing all of the aforementioned tasks while maintaining locomotion. The competition for this robot is May 21-26th 2012, and the first undertaking is to make the robotic platform stand and walk. While this is being done, we will design and implement an excavation system. After all the systems are integrated and fully functional, we will also develop a wireless communications system as well as make modifications to the frame so that we can make the robot as light as possible. After the robot has been completed, a body will also be designed so that the robot will be dust resistant, lightweight and still sturdy.

II.4 List of Objectives

The objectives for this project are to:

- Design a robot to traverse the lunar terrain and navigate the obstacles that are present.
- Design a robot that is regolith resistant while also following the NASA limitations for mass, length, width, and height.
- Design an excavation system to transport the maximum amount of excavated regolith as possible within the specified time frame.
- Remotely operate the robot with the possibility of autonomy.
- Consume a minimal amount of energy and power while competing.
- Communicate with robot wirelessly.
- Operate the robot in a safe manner with an emergency stop apparatus if there is a loss of control at any point.

II.5 Testing Environment

Initially, once the designs are completed and parts are manufactured and assembled, testing began in the STRIDe lab. The robot platform is tested in the lab without the excavation system mounted to ensure that the all of the electronics are performing correctly. The robot is currently standing on a platform so that its legs can spin freely in the air, as shown in Figure 3.

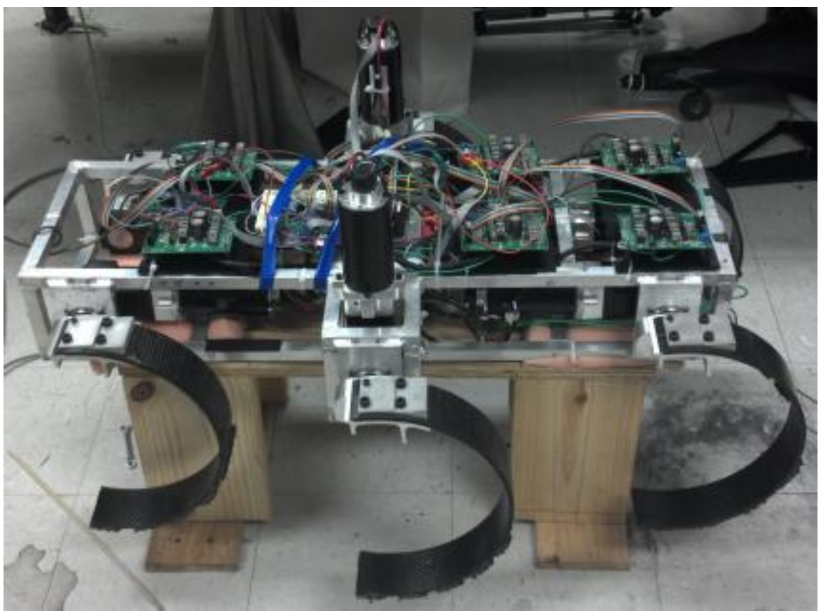


Figure 3: Hexcavator mounted on its wooden stand so that the legs can spin freely.

When the robot is ready, it will be tested by walking around on the flat, hard surfaces such as tile and cement. After it is determined ready, Hexcavator will be taken to the sandpits so that its control system can be tuned. Simulated obstacles will also be added to the sandpit for Hexcavator to overcome.

The excavation system is tested on a wooden platform to scale of the actual Hexcavator platform. First, it was tested on the wooden platform in the STRIDe lab, and when it was deemed ready, it was tested in the sand pits at the FAMU-FSU College of Engineering to ensure that it traverses through its entire range of motion and excavates correctly, shown in Figure 4.

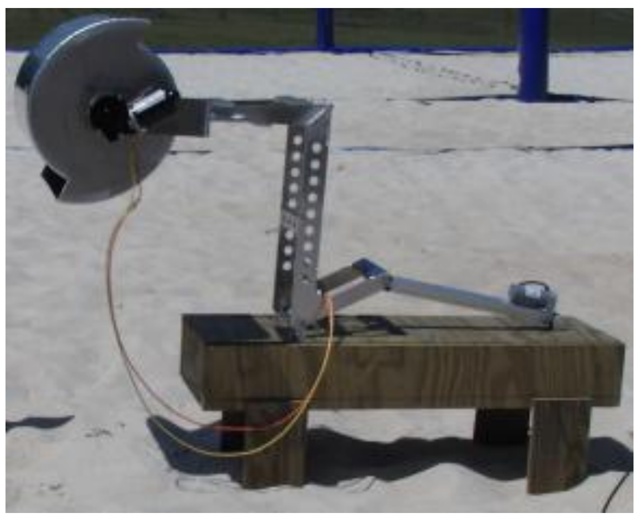


Figure 4: The excavation system being tested in a sand pit to ensure it performs its correct range of motion.

Once both the excavation system and controls are completed, the excavation system will be mounted to the actual robotic platform and the entire system will be tested in the sandpit together to ensure the integrated system performs correctly. Additionally, two days prior to the competition the actual testing area for the competition will be open for practice. The team will be arriving early to take full advantage of this testing fix period and fix any last minute issues.

II. 6 Functional Diagram

Below in Figure 5, is the functional diagram describing how Hexcavator's subsystems integrate. Since this is a hexapedal robot this process will be iterated in each leg.

There is a mechanical connection from the legs to the gear box, the gearbox to the motor, and the motor to the encoder. The encoder then sends data to the decoder, which sends data to sends data to the excavation system. Batteries send electrical power to the motor driver, micro controller, communication system and excavation system. The excavation system mechanically acquires regolith. The communication system feeds data back to the Micro operator. The motor driver sends electrical power to the motor.

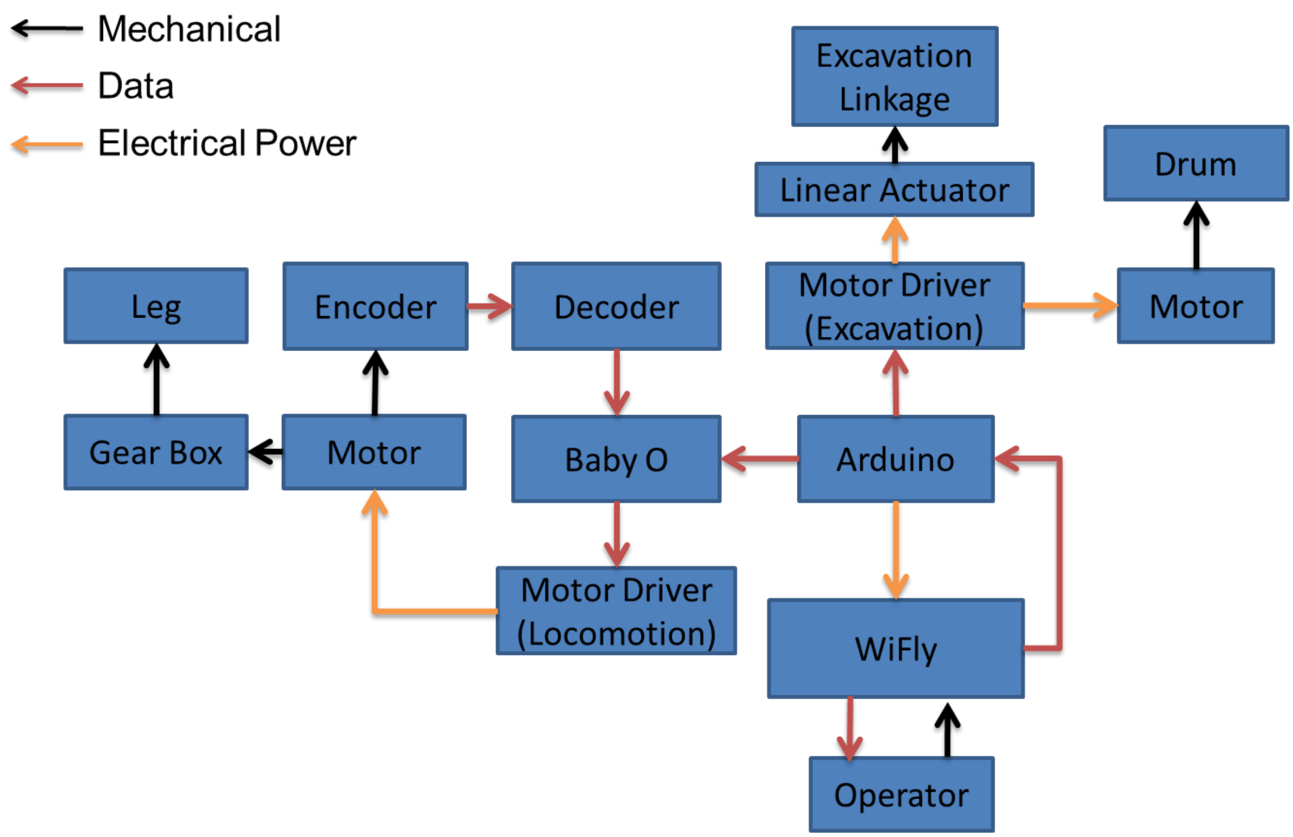


Figure 5: Functional diagram of Hexcavator.

II.7 Quality Function Deployment

For quality function deployment, NASA has given specific guidelines and parameters for each team to follow. These specifics can be seen below in tabular format, followed by a House of Quality in Figure 6 which lists each design parameter, how they relate to each other, and their importance to the project as a whole.

Design Parameters:

- Mass not to exceed 80kg.
- Self propulsion.
- Ability to stay within competition area.
- Robotic control at all times.
- Ability to transport at least 10kg of regolith.
- Ability to navigate all obstacles.
- Equipment of red emergency stop button.
- Wireless communication system.
- Capability to quantify the total amount of energy used.
- School Spirit.

Quality Parameters:

- Completely functional robotic locomotion.
- Control first with hard wiring followed by wireless control.
- Apparatus resistance to regolith.
- Excavation design and execution of design.
- Complete autonomy.
- Cost.
- Aesthetics.

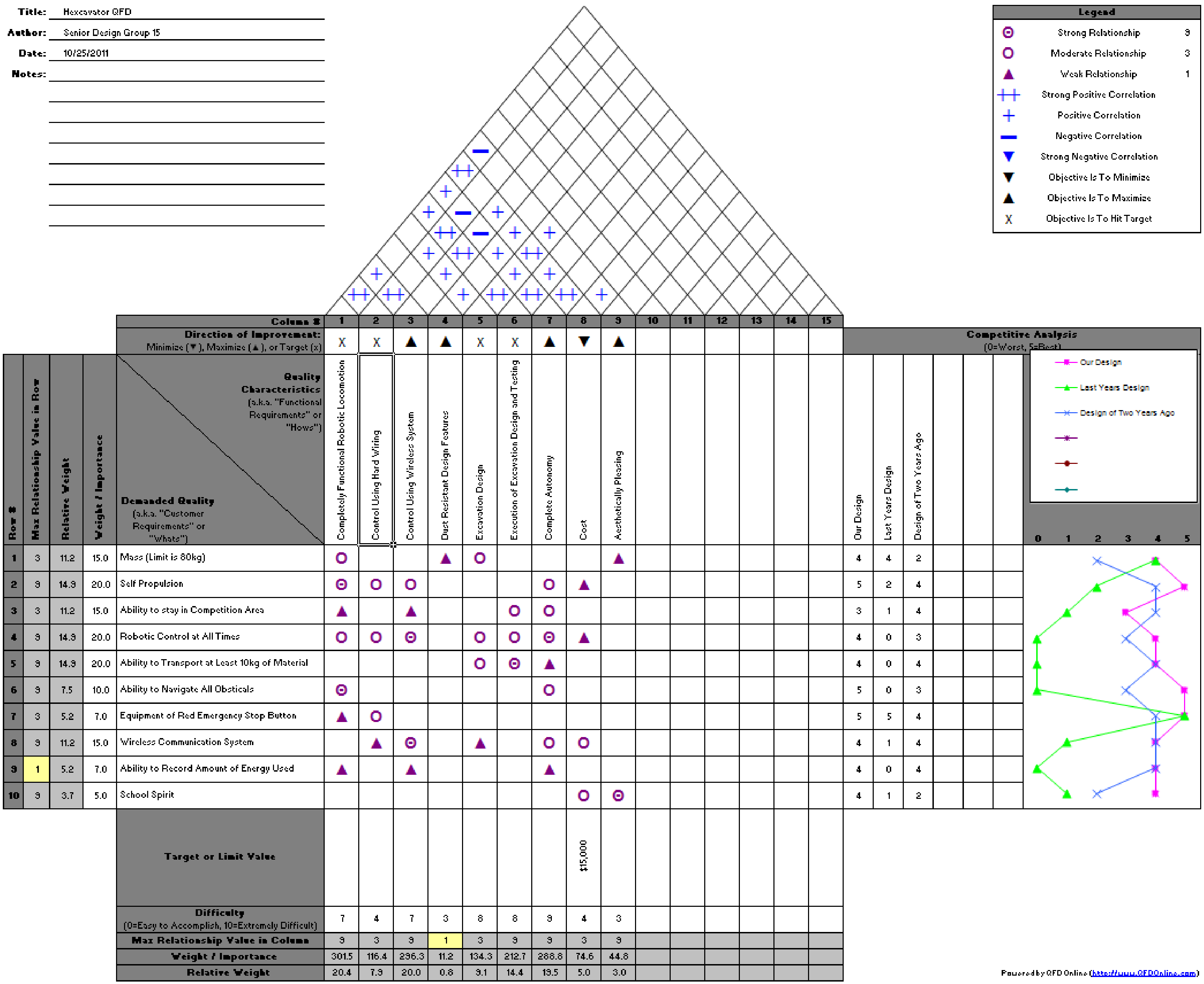


Figure 6: House of Quality.

II.8. Project Plan

The team's timeline is outlined in the Gantt Chart in Figure 7. The major goals are highlighted in gray and have been detailed below. The completed goals have a white X through them.

Research

Completion: Week 5

The team has performed an in-depth analysis of the former year's robot to determine which components can be utilized again for this year (discussed above in the budgeting section). Locomotion schemes, controls and different methods of excavation were researched. The team agreed on a micro controller and motor controllers, and met with a technical expert, Dr. Camillo Ordonez, to verify that our selected components were suitable.

Prototype 1a: Walking Platform

Intended Completion: Week 17

Current Status: In Progress

The goal is to have a functional walking hexapedal platform capable of walking on flat surfaces forwards, backwards and perform turns. This entails ordering and custom making electrical components, installing, programming and testing of the system. Currently the motor controls are undergoing troubleshooting. During testing they appear to have been damaged or wired incorrectly. However, the robot is capable of turning two legs is a Buheler clock motion.

Initial Prototype of Excavation

Completion: Week 12.

The production of the excavation system was a multistep process involving design, integration, and improvement. The team developed a six-bar linkage for mounted on the existing frame and an excavating drum for collecting, carrying and unloading the regolith. This design will be prototyped was from ABS plastic and mounted on the frame, and appeared to be adequate.

Prototype 1b: Excavation Design

Intended Completion Date: Week 17

Current Status: In Progress

After the prototype was mounted and tested, the six-bar configuration for the excavation system was cut from Al6061. It was mounted and tested on the existing Hexcavator frame using the mounts constructed by last year's team. After testing it was determined that the design was too unstable and the four bar design was designed and cut from Al6061 and assembled. This system was mounted the wooden mock-up of the Hexcavator body. Both actuators preformed their functions appropriately, and the linkage went through all the appropriate motions. The drum was tested in sand and was capable of collecting and unloading the regolith as it should. The next step is to implement a motor driver to control the excavation system.

Prototype 2: Wireless Walking Robot with Excavation

Intended Completion: Week 22

Current Status: In Progress

The Hexcavator will have considerably more mass above the top of the robot when the excavation system is attached, so Hexcavator will need to undergo testing and control refinement to maintain its locomotion capabilities. The system will also need to be tested to see if it is still capable of picking up soil. Additional testing will be performed to see how Hexcavator's locomotion is impacted when the excavation system is carrying the regolith. Depositing the regolith simulant will also need to be tested so that the maximum amount will be deposited. Navigating over obstacles will also need to be tested with the additional weight of the excavation system, with and without regolith. Currently, with the microcontroller but is unable to wirelessly control the legs.

Prototype 3: Walking Robot in Rough Terrain

Intended Completion: Week 29

The final steps that will be tested and practiced on the Hexcavator system will to make sure that the complete system is working correctly and efficiently. This will include navigating all obstacles, such as rocks, craters, and rough terrain. Also, the entire system will need to be capable of collecting soil and traversing a practice course to deposit into a practice bin. The excavation system at this point should be collecting the simulated regolith without hindering locomotion. It will then traverse the practice course to successfully deposit said substitute material into a practice bin that will simulate the LunaBin that will be used during competition. At the end of this deliverable, the team will participate in NASA's competition at Kennedy Space Center on May 23.

	October					November				Dec.		January					February				March				April				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Research																													
Determine which previous components can be utilized.	X	X																											
Locomotion Schemes and Controls.	X	X																											
Design excavation system.		X	X	X																									
Spec out Controllers and Motor Drivers.	X	X																											
Prototype 1a: Walking Platform																													
Purchase motor controllers, microcontrollers and decoders.										X																			
Program controllers.														X	X	X													
Test walking indoors.																													
Test walking on flat ground outside.																													
Test walking in sand pit.																													
Test turning in confined environments.																													
Initial Prototype of Excavation																													
Design Iterations.				X	X	X																							
Find stimulant for excavation.				X	X	X																							
Laser cut prototype from plastic.										X	X	X																	
Determine if existing frame will be used.										X	X																		
If necessary, redesign frame.											X																		
Prototype 1b: Excavation Design																													
Build first functional prototype.												X	X																
Testing getting soil from loosely compacted ground.														X															
Test getting soil from compacted ground.															X	X													
Develop and test a dumping mechanism.														X	X	X	X												
Design control system for excavation system.																													

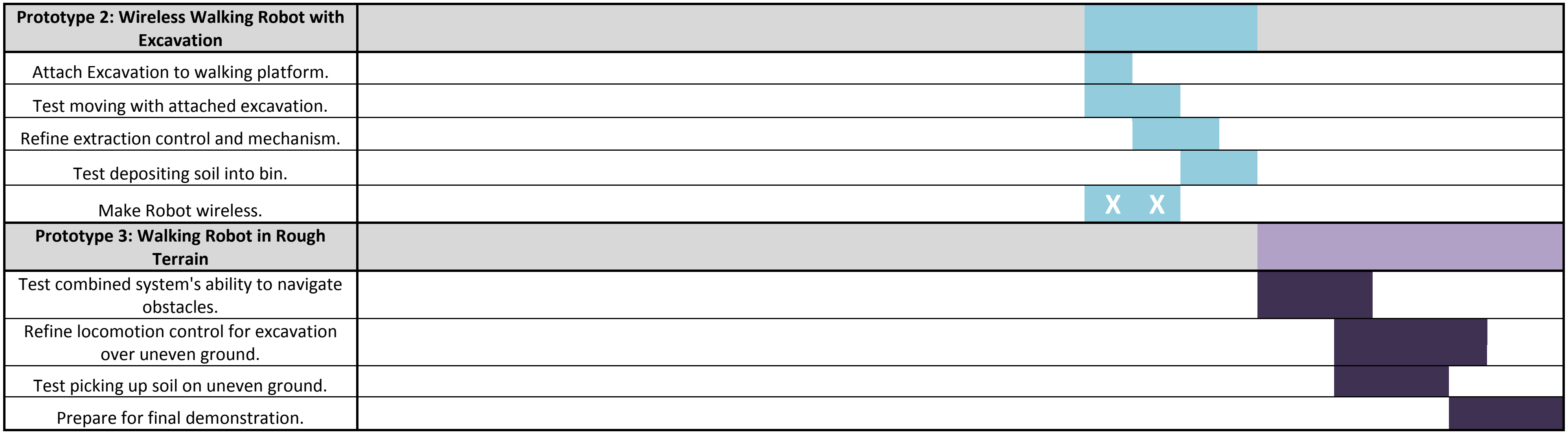


Figure 7: Gantt chart for developing the Hexcavator Platform.

III. Concept Generation and Final Design Selection

III.1. Wireless Communication

To simulate controlling a robot which is located on the moon, NASA uses a control center and provides a wireless signal with a realistic delay. Teams are required to bring their own router and be capable of communicating wirelessly. To complete this task the robot must be capable of receiving wireless signals and subsequently interpreting them. There are several WiFi communication devices available on the market; however few met the specifications necessary for our robotic system. Since the selected microcontroller will have serial ports, a device capable of serial communication is desirable. The STRIDe Lab, an advisor of this project, has several research assistants who have built robots which communicate wirelessly. These researchers recommended the use of a Spark Fun's WiFly module. Due to our limited connector options and the resources which are available for assistance, Spark Fun's WRL-10050 WiFly module was selected.

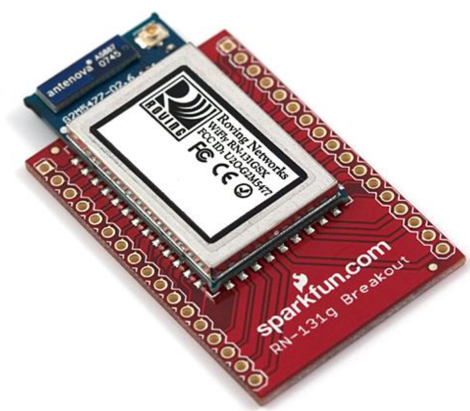


Figure 8: The Spark Fun's WRL-10050 WiFly module that will be used to communicate wirelessly with the robot.

The WiFly is a standalone wireless networking module; this means that it can both receive and transmit data. A flow chart of the information flow can be seen below in Figure 8. Bi-directional data flow is crucial since commands are going to be sent to the robot and the status will be received from the robot. The main functionality of the WiFly will be to take the user's commands and distribute them to the robot. The user will instruct the robot to either move forward, backward, turn left or turn right. If there is some failure on the robot, the WiFly will transmit back to the user, informing them of the error. Since the WiFly is only a standalone serial module, accessing the ports is difficult. However, Spark Fun has a WiFly breakout board, WiFly GSX Breakout, which will make connecting to the chip easier. This breakout board comes with the WiFly attached, so no soldering will be required. The device communicates using a UART port. It can transmit and receive data at speeds up to 1MBps, which will be more than enough for the competition. It uses 33.3 mA at 3V when both transmitting and receiving. The dimensions are 30.48 x 45.72 x 3.5mm. The price of the WiFly with the breakout board is $84.95[6].The WiFly can currently control the microcontroller, but has not yet been set up to simulate locomotion.

Figure 9: A flow chart demonstrating how the WiFly sends communications from the User in the command center to the Hexcavator and back.

III.2. Power System

The power system components were selected by the previous year's design. The 37V batteries output approximately 42V when fully charged, these are run in parallel to double the output current. These batteries will power the voltage regulators, motor drivers, microcontroller, Baby O and the motors, demonstrated by Figure 10. The red lines indicate constant voltage supply. The blue lines leading from the motor driver to the motors indicate that the motors will be receiving variable voltage to affect the speeds they turn at. Also, there are actually three motor drivers which control three motors each. This will be discussed in further detail in the controls section of this paper. There are no negative or ground terminals because everything on the robot can use the frame as a common ground.

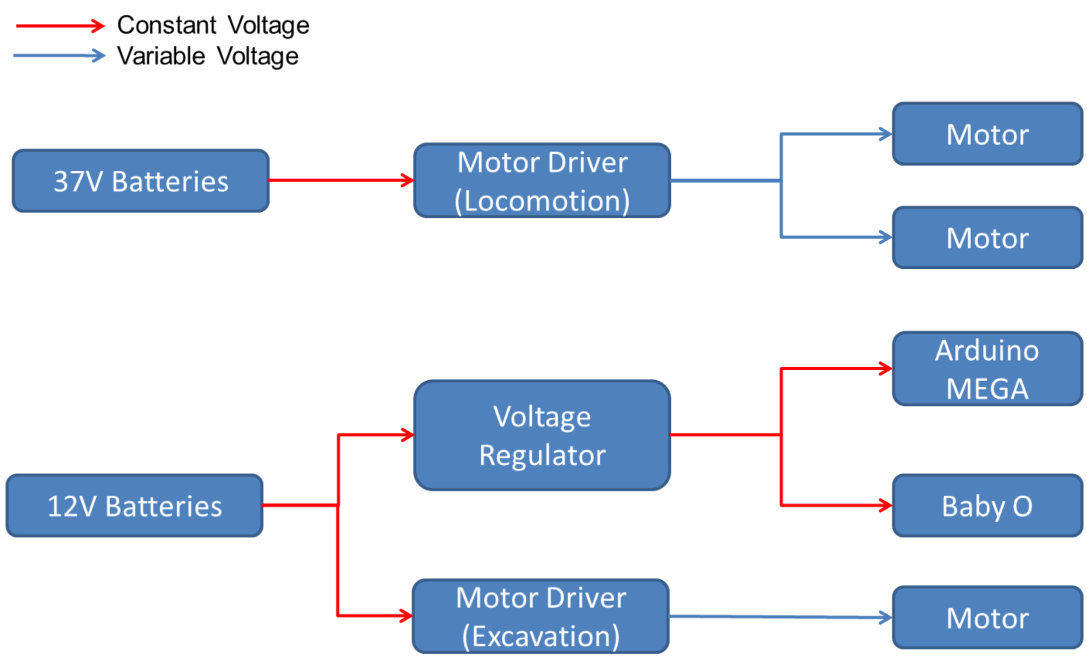


Figure 10: Flow of Positive voltage from batteries to subsystems.

To provide power to the onboard electronics the voltage is suppressed to 5V using a voltage regulator, shown in Figure 11. As an added bonus, the power consumption of our robot can be computed in real time. Since the resistance of the circuit is known a current meter will be placed on one side of the batteries, so the power consumption can be accurately measured. If these points are added together the total power consumed by the robot can be determined. This measurement is significant because teams are rewarded with points for providing real-time power consumption values and for transmitting the used power data back to base.

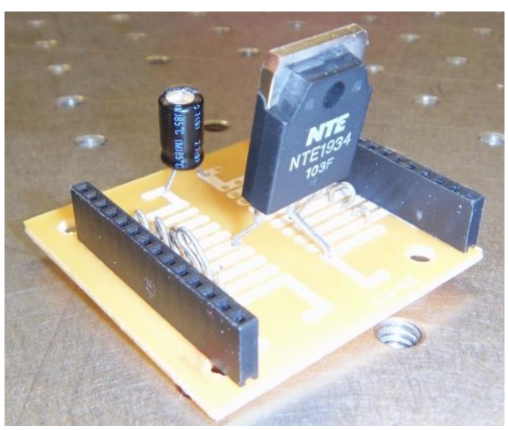


Figure 11: The voltage regulator used to suppress the voltage to 5V to run the smaller subsystems.

The Motor drivers selected are H-Bridge motor drivers capable of providing more than enough current to the motors, which are Maxon RE-65 motors, which are rated for 18V and 296A starting current [5]. These also have an attached gear box with a ratio of 50:1. The H-Bridge motor drivers supply the motors with a variable. The ability for the motor drivers to control voltage will be key to controlling the motors speed. Some safety measures have been implemented including a red safety button that will provide the competition referees with the ability to instantly shut off the robot in the case of an emergency. As per NASA requirements this is an off-the-shelf, unmodified, red, safety switch hardwired which is capable of terminating the robot's power supply with one push. There are also a multiple fuses which will limit the amount of current that is drawn by our motors. If the robot attempts to draw more than 100A, the fuse will blow which will mean all the energy utilized to move a leg will be disconnected.

III.3. Intra-Robotic Communication

III.3.A Motor Controller

To implement a Buhler clock on Hexcavtor's legs, a control law is implemented via a motor controller. Since there are currently no commercially available motor controllers that are capable of implementing a Buheler clock, a custom one was made for Hexcavator. The design for this motor controller contains four main components: a microcontroller, a motor driver, an encoded motor and a decoder.

The microcontroller communicates with the Pololu Baby Orangutan to implement the control law, as demonstrated below in Figure 12. It also sends signals to the decoder to gain information from it about the position and angular velocity of the leg. This information is then fed through the control law to control the speed of the motor.

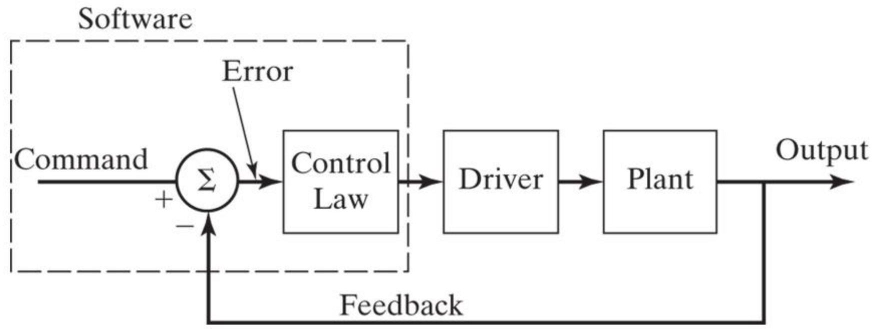


Figure 12: Model of the how the control system will be implemented.

The motor drivers will use an Intersil HIP4081A bridge driver, made by OSMC. It is a dual channel voltage control driver which amplifies the 0V – 5V PWM (Pulse-Width Modulation) signal from the micro-processor to a 36V signal. Pulse-Width Modulation, or PWM, is a way to apply variable voltage to the motor so as to allow for the motor to turn at variable speeds. The driver is capable of supplying 150A continuously to two different motors and a maximum short term range of 300A. The current is also reversible so the robot will be able to walk backwards. The lower level control of the legs will be done by the ATmega328P micro-processor mounted in a Pololu Baby Orangutan B-328 (Baby O), shown in Figure 13. Each micro-processor will be utilized to communicate to the motor drivers of two legs, meaning three will be necessary for the operation of the legs of the robot. The micro-processor outputs a 5V PWM signal, which is then used as the input to the motor drivers.

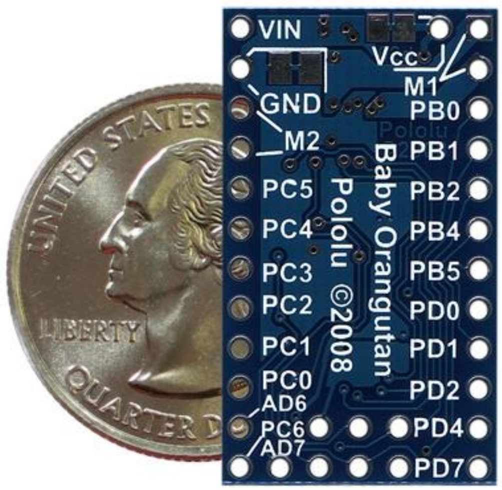


Figure 13: Pololu Baby Orangutan B-328 (Baby O) compared to the size of a quarter.

		BYTE SELECTED			
SEL1	SEL2	MSB	2ND	3RD	LSB
0	1	D4			
1	1		D3		
0	0			D2	
1	0				D1

Figure 14: Byte Selection from the Baby O to the decoder.

Each of the motors is connected to an incremental 512 count per revolution quadrature encoder. Between the leg and the motor there is a 50:1 speed reduction gear box. This gives an overall total of 102,400 counts per revolution of the leg. The encoder is read by an Avago HCTL2023-SC decoder chip. This chip reads up to a 32 bit count at 32MHz, which is more than adequate for the needs of the robot. The Baby O communicates with the decoder chip using twelve different analog control lines. Since there are four bytes that need to be read, two lines are used to select what byte will be read. As shown in Figure 13, one line is used to control what the motor's position is. The decoder is a dual channel decoder so it is capable of reading both motors that the Baby O will be controlling. A final line is used to tell the decoder to reset. Eight lines are used to as an output from the decoder. They are the lines that are held high or low to determine each of the 4 bites. These lines are then interpreted by the Baby O to find the current position of the motor. The decoder chip requires an external clock source capable of handle a frequency of 32 kHz.

Using the position of the motor a control law is enacted. The control law will control the speed of the motor based on the position of the leg. It will also enact a Buhler clock on each of the legs. A Buhler clock is used when the speed of the leg throughout the stride is not constant.

The final motor controller was first implemented using a breadboard, after the wiring was verified three protoboard versions were made for use during the competition. The final product can be seen in Figure 15, with all of the specified components: a microcontroller, a motor driver, and a decoder.

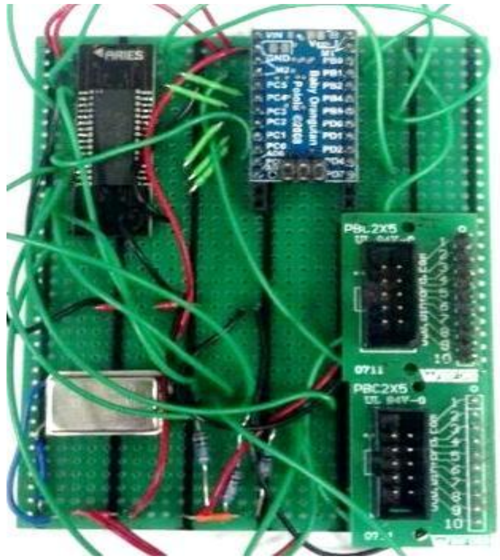


Figure 15: The custom made motor controller.

III.3.B Microcontroller

The microcontroller acts as the liaison between the user and the robot. The user sends commands to the robot to move, stop, excavate, and dump, etc. through the WiFly module. This command is interpreted by the microcontroller. Once the microcontroller has the user's command, it commands the motor communication system with what speed to obtain. In the unfortunate situation in which there is a malfunction with one of the legs, the motor-communications system informs the microcontroller, which will then tell the user of the error. This communications system can be seen in Figure 16:

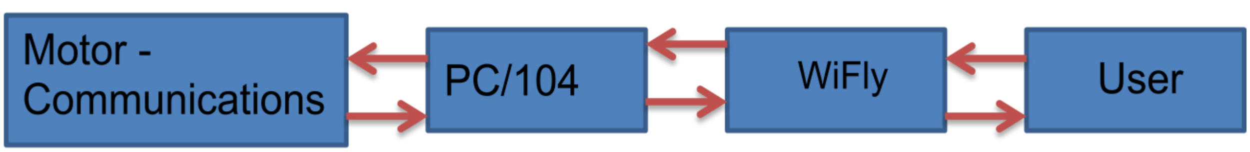


Figure 16: Basic Setup of the Communications System.

<u>Concept #1: Netbook</u>

A netbook is easy to interface, but it does not have any serial connections which are an essential for communication with the other parts of the robot. Though USB to RS232 connectors exist, netbooks typically come with two to three USB ports. Each set of legs is going to require a RS232 port to communicate with the netbook. While there would be enough ports for each of the legs, this leaves no way to communicate with the excavation or any other additional system that may be added. If a USB hub was added to the netbook, this would increase the number of USB ports, but communicating becomes less trivial. This extra work required to go through the USB Hub offsets the initial perk. Additionally, the reliability of USB to RS232 connectors is questionable at best. Lamment Bies, a Software Managing Director, said this about the potential downfalls of the converters, "This non-standard behavior of RS232 inputs makes it even more difficult to select the right RS232 to USB converter. If you connect and test an RS232 to USB converter over a serial line with another device, it might work with some devices, but not with others[SM1]."

Concept #2: PC/104:

A PC/104 allows low level communication through serial ports, but will be labor intensive to program. However, the vendor from which the PC/104 is being purchased, Advantech, supplies their own version of Windows XP for the micro-controller. This will cut down the amount of time required to learn how to interface with the PC/104 and will provide us with a resource when problems arise. Not only does the vendor supply an operating system for the board, but they also supply drivers for the various stacks that will be used with the robot. This decreases the interfacing issue with the PC/104.

The PC/104 has three separate modules: the main micro-controller, the additional serial port module and a digital I/O module. The micro-controller that was selected was the Advantech PCM-3355. It features an AMD Geode LX 800 processor, which has a frequency of 500MHz. The operating system for our robot will be Windows Embedded CE 6.0. It requires 2GB of storage space to install. Since the memory comes in either 1GB, 2GB, 4GB or 8 GB, a 4GB hard disk was selected. Since the only thing that will be on the PC/104 is the operating system, drivers for the other modules and the code to run the PC/104, 4 GB will be more than sufficient. It comes with 512MB of RAM but is capable of being expanded to 1GB. Both the hard drive and RAM will be comprised of flash memory. A hard disk drive would be undesirable for this application, due to the potential of regolith getting inside of the moving parts. The module typically draws 1.45A at +5V. The main micro-controller comes with one RS485 connector, which is sufficient for communication with the WiFly. It also has two RS232 connectors, which means an additional serial module is required for complete communication with the robot. The Advantech PCM-3644 has four RS232 slots and four RS485 slots. The additional serial ports will allow communication with the other motor control systems. The digital I/O module that has been selected is the Advantech PCM 3724, which has a total of 48 channels. The ports operate using TTL of 5V. These digital I/O ports will be used to control the excavation system and may be useful in the future development of the robot. The typical power consumption of the PCM-3644 is 400mA at +5V. The micro-controller, PCM-3355, has physical dimensions of 96 x 90 x 19.3 mm and a weight of 0.097kg. The serial extension, PCM-3644, has physical dimensions of 96 x 90 x 18.9 mm and a weight of 0.084kg. Finally, the PCM- 3724 has dimensions of 96 x 90 x 19.1 mm and weighs 0.073 kg. Since the three modules are meant to stack upon one another, the final dimensions, when assembled, are 96 x 90 x 57.3mm and a weight of 0.254kg. The cost of the micro-controller, PCM-3355, with the operating system is $365. The cost of the serial module, PCM-3644, is $144. The cost of the digital I/O module, PCM-3724, is $79. The total cost of these modules is $691.

Final Design Concept: Ardunio Mega 2650

Ultimately, an Aurdino Mega 2650 was selected for the microcontroller because it has four UART RS232 serial connections, which is how many Hexcavator requires during operation. The Arudino will send PWM signals to the motor drivers, which will communicate with the microcontrollers which will control the rotation of the motor. The Arduino will also send PWM signals to a Sabertooth motor driver will control the excavation system. The completed electronic system is shown below in Figure 17. Currently the electronics are mounted on plastic bottoms which are held on the top of the robot frame. Ultimately, the electronics will be mounted in boxes with small electronic fans which encourage circular flow. The bottom of the boxes will be plastic for eases of mounting the electronics, and the sides and top of the boxes will be 1/16” Aluminum to encourage heat transfer.

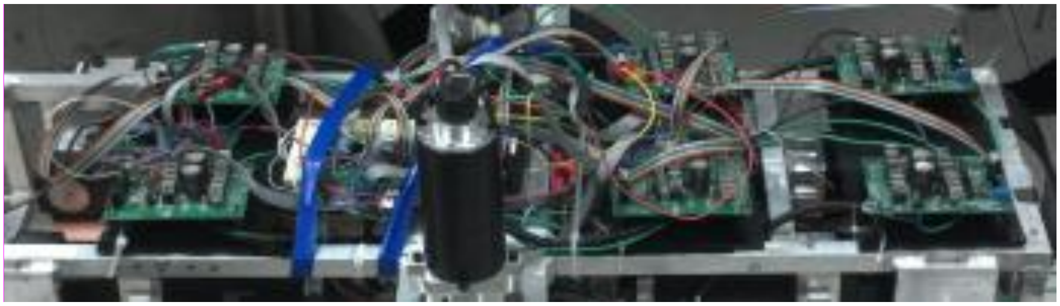


Figure 17: The electronics on the top of the robot frame.

The main issue with the controls portion of the project is trouble shooting the custom made motor control circuits. There are currently two fully functional circuits, and one that is undergoing trouble shooting. Wireless communication has been established using the WiFly module and the Arduino MEGA. Once we have three working motor controllers, we can control the motors wirelessly. After wireless control has been completed, we will develop a user interface to make using the robot more intuitive.

Due to the concern of the regolith interfering with the electronics, boxes were designed to be contained within the robot and be sealed. This is also to ensure that nothing was loosened during testing or competition, and to keep the lunar regolith from affecting them in any way. These were manufactured out of ABS plastic and are currently mounted to the Hexcavator frame, as can be seen in Figure 17.

III.4. Excavation

The purpose of the competition is to excavate at least 10kg of regolith from the excavation area and deposit it in the LunaBin at the opposite end of the competition area, depicted in Figure 18. The LunaBin and its dimensions are shown in more detail in Figure 19.

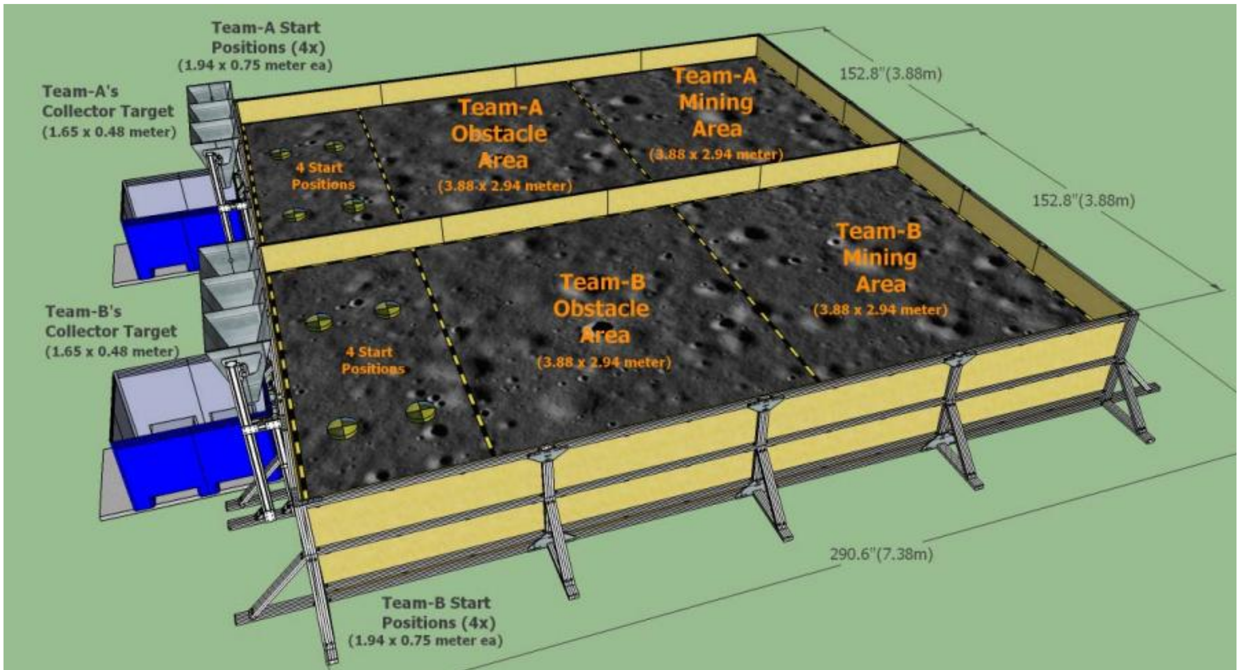


Figure 18: The competition area the robot will be competing in[3].

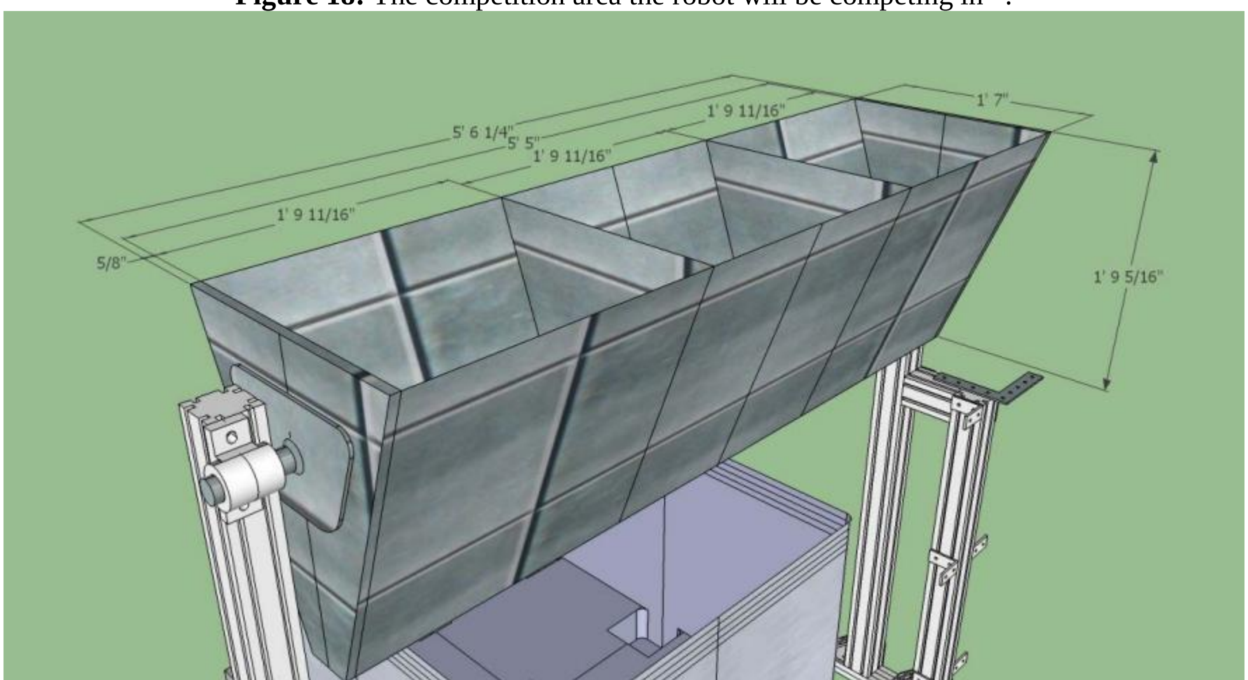


Figure 19: The LunaBin the regolith will be deposited in[3].

III.5. Center of Mass

The Hexcavator walks using an alternating tripod gait, which is based on how cockroaches walk. It is demonstrated in Figure 20; the left image uses red and blue dots to indicate a set of legs that move together, the right image is a ProEngineer depiction of a tri-pod gait. Essentially, there are two sets of three legs. The legs in the set all move together. When the first set (red dots) are touching the ground, the second set is in the air. When the first set of legs lift off the ground, the second set will come down so there will always be at least three legs on the ground. This means the Hexcavator will never enter an aerial phase, since it would always be touching the ground during locomotion. The control of the legs will be discussed in a later section.

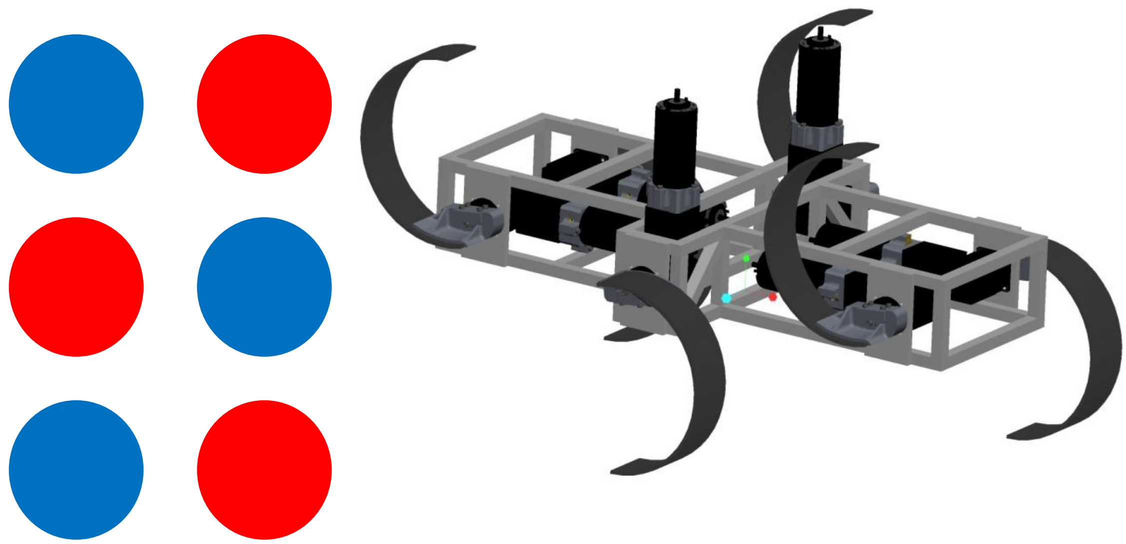


Figure 20: (Left): The dots depict what which legs move together during an alternating tri-pod gait. When the first set of legs is touching the ground (red dots) the second set (blue dots) are in the air. When the first set lifts off the ground the second set will touch the ground. (Right): A ProEngineer rendering of what the robot will look like while walking.

Since the robot will never be in an aerial phase the center of mass will be triangulated using the legs. When one set of legs is touching the ground, the center of mass must be contained in the purple triangle shown below in Figure 21. When the other set of legs is touching the ground the center of mass must be contained within the red triangle. Therefore the center of mass must be contained within the blue hexagon to satisfy the gait.

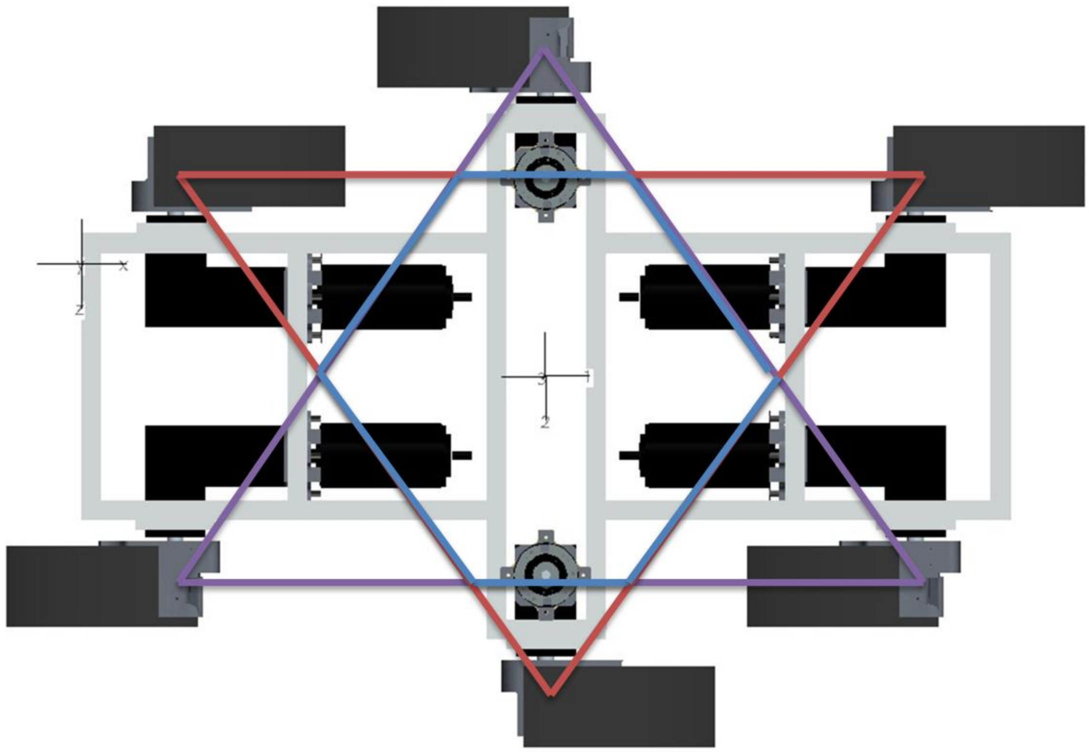


Figure 21: When one set of legs is touching the ground, the center of mass must be contained in the purple triangle. When the other set of legs is touching the ground the center of mass must be contained within the red triangle. As such the center of mass must be contained within the blue hexagon.

III.5.A Concept #1: Rotating Drum Excavation

Figure 22 is a rendering of an excavation design that will use a rotating drum with cutouts that will both dislodge and collect the regolith. The regolith will then be stored in the drum for transportation across the lunar competition arena. While the drum is rotating forward it will collect the regolith and when the rotation is reversed it will empty. The drum will be mounted on a four-bar linkage that will be used to lower the drum to the lunar surface, and then the four-bar will be used to raise the drum to the level of the collection area.

This design is appealing because it is relatively simple in operation. The drum would not require an encoder to determine its position because it is just a simple on off operation. The four-bar that the drum is mounted on to would also not need an encoder, this is because of the cameras monitoring the competition are available to the operator of the robot. The draw backs of the system would be in manufacturing. It would be difficult to make the drum due to its complex shape. The four-bar is considerably easier to produce.

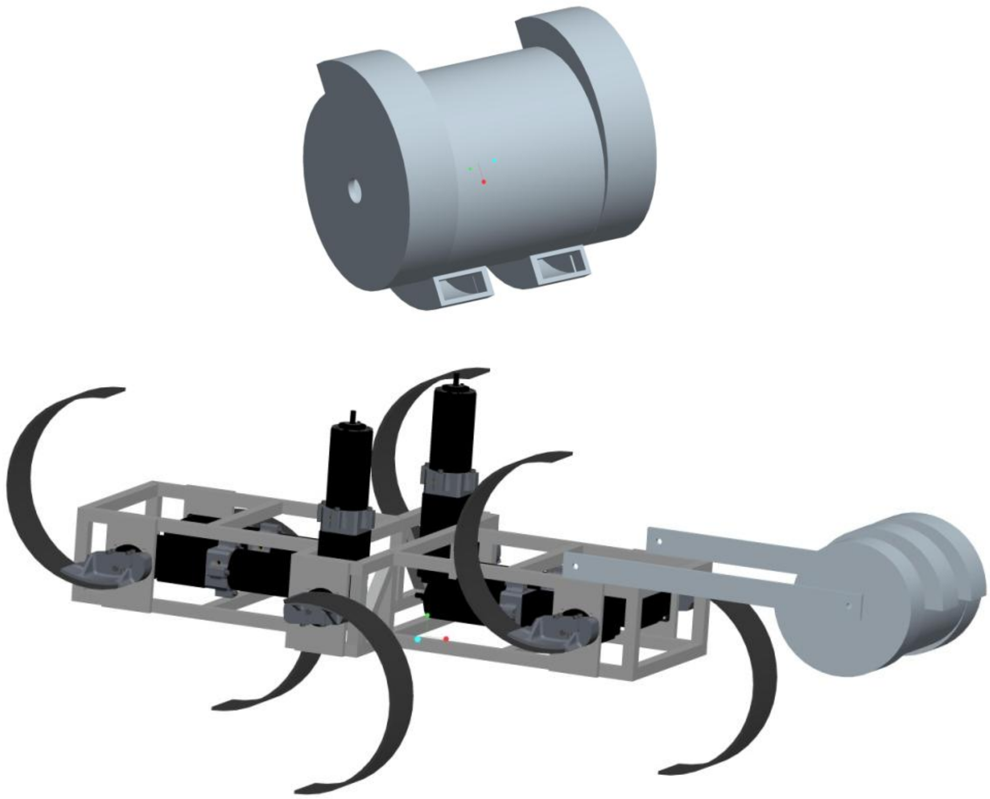


Figure 22: The top picture shows a close-up image of the excavation mechanism. It is a rotating drum that collects regolith when positioned on the ground. Then it rotates the opposite way to release the regolith into the LunaBin. It would be narrow enough to carry in between the legs, and will be capable of being lifted up to the center of the robot when containing regolith so it will not alter the center of mass outside of the vertical plane.

III.5.B. Concept #2: Screw Jack

The second design which will be considered for implementation on the current Hexcavator is a relatively simple design involving a shovel head and extending mechanism, a prototype is shown below in Figure 8. This shovel can either be bought or manufactured in house, and will then be welded to an arm attachment. This arm attachment will be a two part system. The instrument in which the shovel head will be attached will be called the “inner arm” because it will be able to translate in and out of a slightly bigger, longer part called the “outer arm.” This smaller arm attachment will be half the length of the piece that it will be translate in and out of. Attached to the other side of the “inner arm” will be a worm gear that will act as the extender for the inner arm. This will be fixed to a gear that will turn via motor actuation to either make the inner arm extend out or contract in. The worm gear length will be no longer than half of the length of the outer arm. This will be done to ensure that all moving parts stay housed within the other arm attachment to decrease the likelihood of problems due to regolith material build up. The entire arm mechanism will have one-dimensional rotational mobility via another actuator that will translate the system upwards and downwards. This will allow Hexcavator to be able to pick up and deposit the regolith material. The arm will be translated downward to some predetermined length so that the robot will be able to excavate from the test section surface. The upward actuation of the arm will be used to bring the shovel head to a horizontal equilibrium as well as deposit the material into the testing LunaBin. An additional actuator may need to be used to dump the material. However the preferred method would be to disturb the material using the motion of the other actuators.

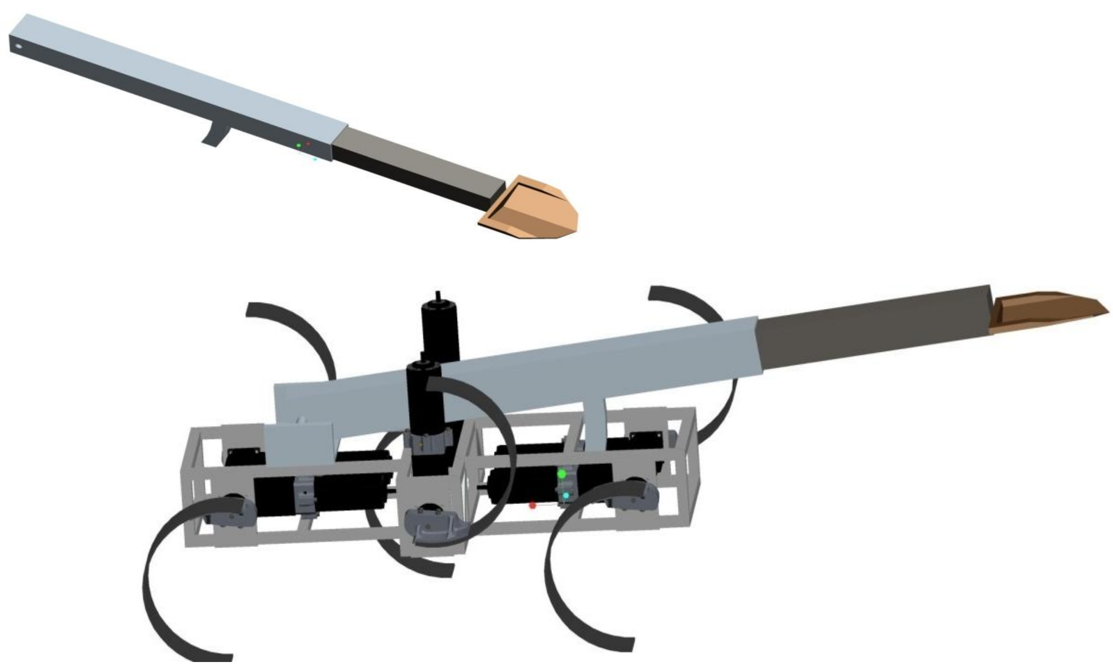


Figure 23: The top image is a close up of the excavation mechanism. It utilizes a shovel to cut thought the compacted regolith. Since it has an extendable arm it can reach both the ground and the LunaBin.

III.5.C. Concept #3: Auger

Figure 9 demonstrates a design that would use an auger to collect the lunar regolith, and release it into a bucket. When the augur rotates, it would circulate regolith into the collection bin. After the robot is done excavating, it would carry the regolith in this bin. When the robot reaches the LunaBin, the collection bin would raise up and deposit the regolith by inverting the collection bin. The bin would be connected to the frame using a four bar mechanism. However, the collection bin would not be capable of a large payload capacity because it would significantly affect the locomotion of the robot. The four bar mechanism would also have to be very long because the LunaBin is 1.65m from the ground, and the Hexcavator currently stands at 0.75m. However this system would be very complicated to build. Additionally, an auger mechanism is unprecedented in lunar excavation. Since regolith is a very dense, adhesive substrate, the effectiveness of the auger for collecting material is unknown. This system is would be very simple from an electronics stand point. It would not require an encoder or position control, it would simply need a motor to drive the four bar and the auger.

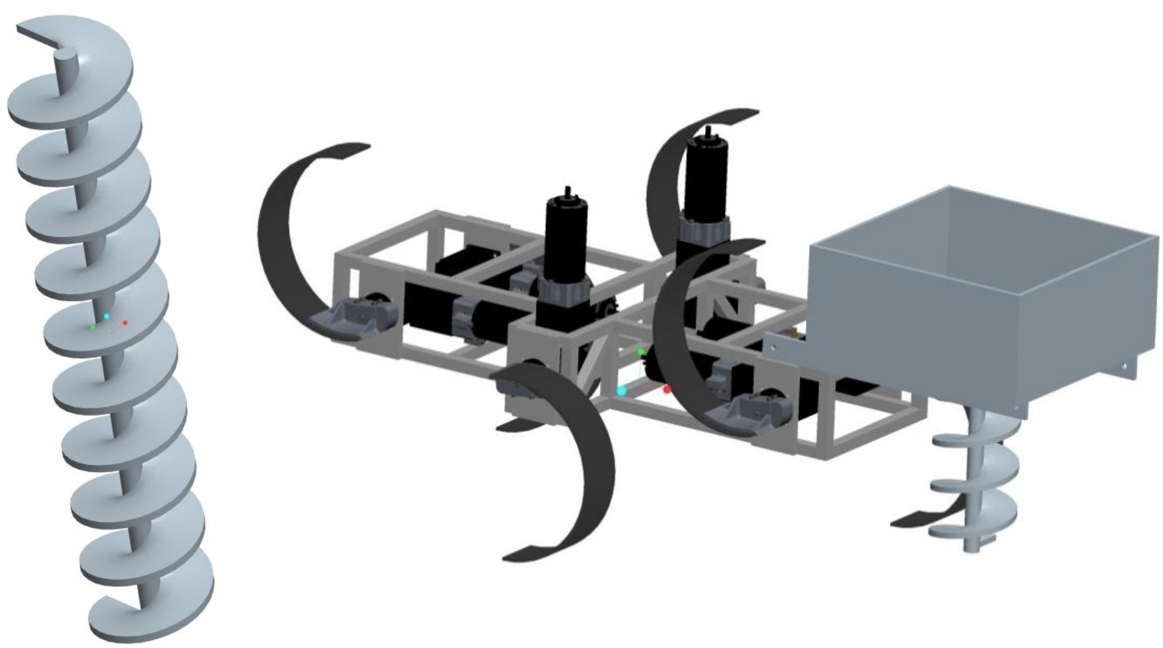


Figure 24: (Left) A close up image of an Auger design. It would rotate in order to collect regolith. (Right) The collection bin would retain the excavated regolith. The auger would directly transmit the excavated regolith in this bin. The design is attached with a four bar mechanism.

III.5.D. Concept #4: Shovel and Dump Bucket

This concept is based off last year's design for an excavation system, shown in Figure 10. It utilizes a belt driven shovel to excavate the regolith. Then the shovel will put the sand into the dump bucket, which uses pulleys to guide it up the height of the Lunabin. Then the dump bucket deposits the excavated regolith into the Lunabin. The advantages of this design are that it is fairly simple to attach to the existing frame. Also, pulleys and belts are commercially available in a variety of sizes, making it simple to purchase materials. The attachment mechanisms are very simplistic in design and would be very easy to construct. The disadvantages are that it will be costly to integrate the drive mechanisms for these pulleys. Additionally, the cost of materials will be very high, and probably add a significant amount of weight. The pulleys would also be a challenge because previous year's experience has indicated that the regolith can get into the cracks and hinder the performance of the pulleys. Finally, the linkage would need to be able to fold down onto the robot when not in use since there are starting height restrictions on the robot.

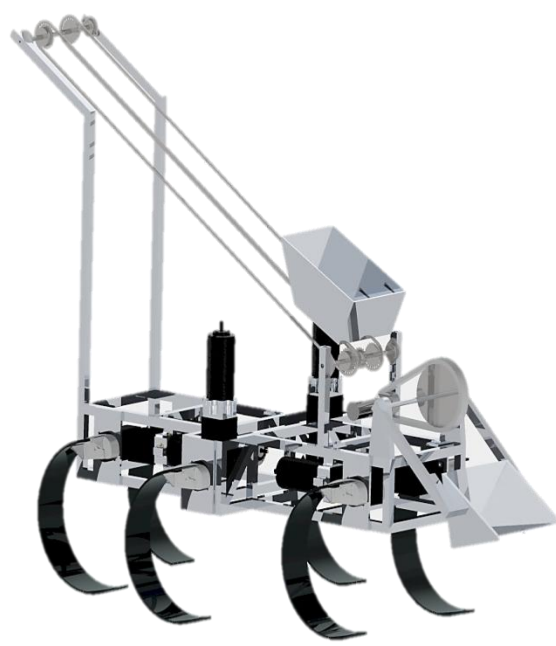


Figure 25: This design uses two pulley systems. The front one drives the excavation shovel which would cut into the compacted regolith. When it excavates some, it then deposits the collected regolith into the bin. When the robot reaches the collection bin, the bucket raises up (using the pulley system on the top left of the diagram) to release the regolith.

III.5.E. Concept #5: Six-bar Linkage and Drum

Regolith is notoriously a very dense, sticky material which becomes compacted and gets into all crevices. To mitigate this concern the excavator will be a rotating drum with slits on each end which will cut into the excavating surface, shown in Figure 27. The drum can hold a maximum of 9.8 kg regolith and will be made of Aluminum 6061 (a detailed drawing of it can be found in the Appendix).Since the minimum amount of regolith that needs to be excavated and deposited in the LunaBin is 10kg, the robot will be easily able to complete its required task. Aluminum 6061 was chosen because of its low density compared to other metals, while maintaining and the necessary hardness. The diameter of the rotating drum is 9inch and it is 18inch wide. When the robot is walking the linkage will hold the excavation system in such a position that the center of mass of mass will be within the necessary bounds, as indicated in Figure 26. When the robot is in excavating the robot will kneel down on its front legs to enhance stability. The rotating drum will be lowered to the surface and it will rotate so it will break the compacted surface and scoop the regolith into the drum. Then the robot will stand back up and navigate to the LunaBin. When it gets to the Lunabin, the robot will bring the excavation drum over the LunaBin,. Then the drum will then counter rotate and release the regolith into the LunaBin. Then the linkage will guide the excavation system back over the center of mass and the Hexcavator will stand back up and repeat the process.

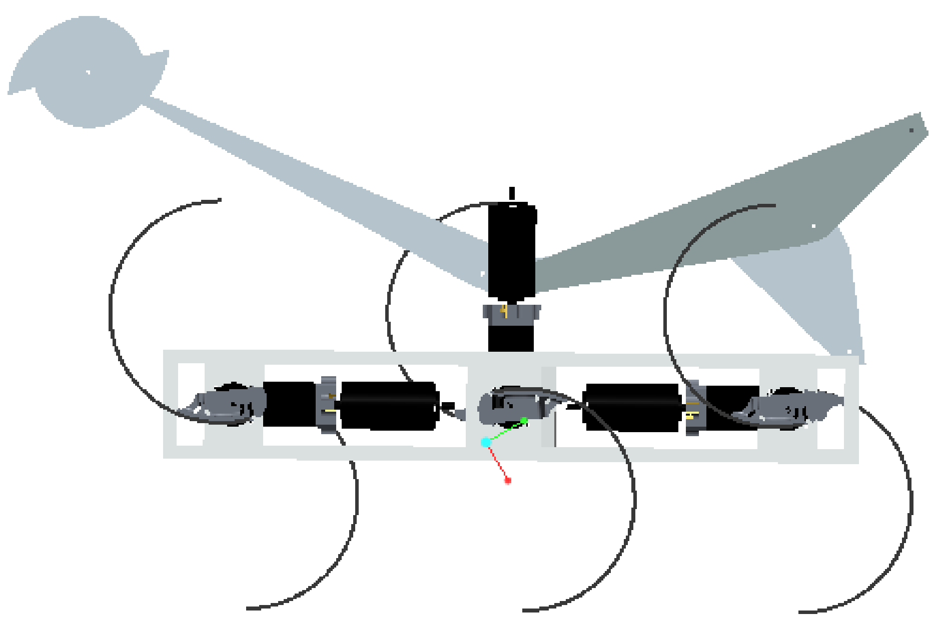


Figure 26: Hexcavator in its walking position with its drum held in the walking or unloading position.

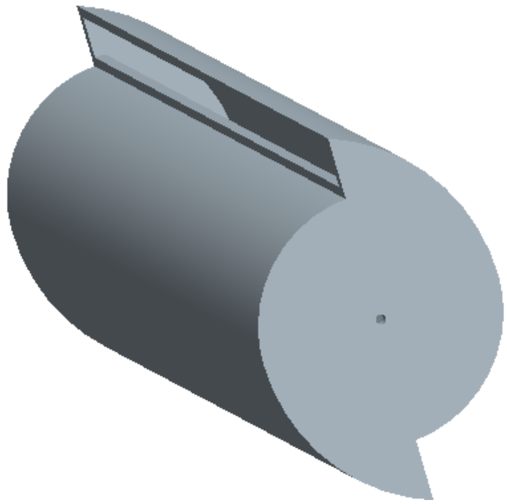


Figure 27: The rotating drum which will be used to excavate lunar regolith. It can hold a maximum of 9.764 regolith.

III.5.F. Final Design: Four-bar Linkage and Drum

Initially the six-bar design was selected for excavation, however after testing it was discovered to be too unstable to be a workable system. This design is a simple four bar mechanism that goes through all the necessary requirements, and uses the drum described in Concept #5. Figure 28 shows Hexcavator in the excavating and walking position. The drum is capable of dumping the regolith into the Lunabin while in the walking position. To enhance the stability of the four bar linkage there are multiple braces running across the third link as indicated in Figure 29. The link farthest left on the excavation system in Figure 28 is actually a linear actuator used to drive the system up and down. This motor has a displacement capability of 12inches and a load capacity of 200lbs (more than substantial for our design) and the motor used to drive the drum is capable of 36.7Nm.

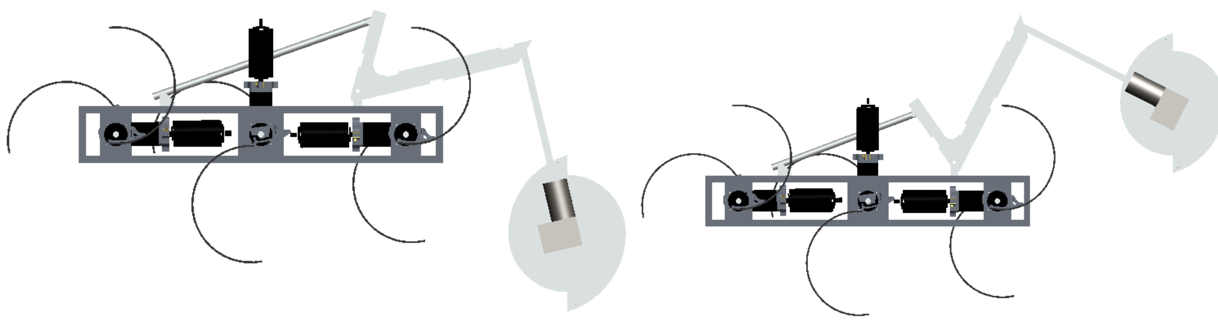


Figure 28: (Left) Hexcavator in excavating position. (Right) Hexcavator in walking position.

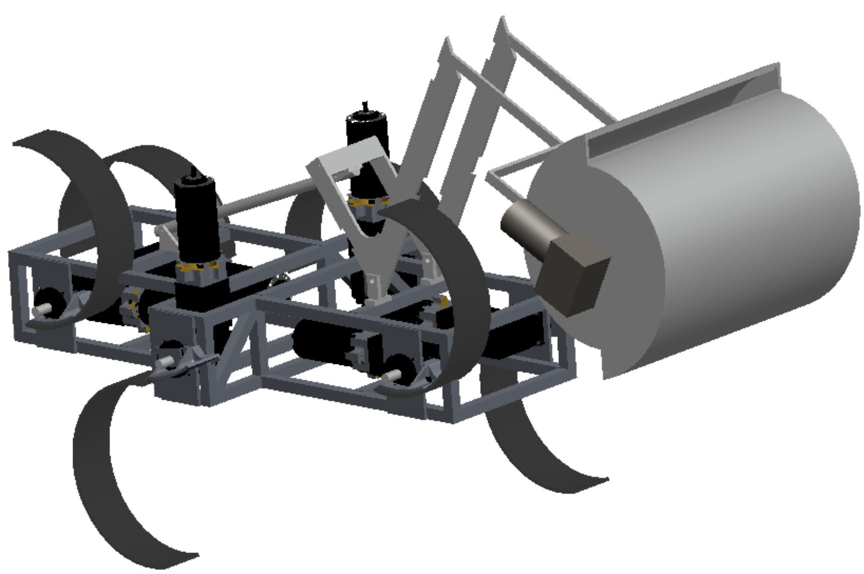


Figure 29: Hexcavator in the walking position as viewed in three dimensions.

The motor mount is shown in Figure 30, it a press fit for the motor shaft and bolts directly to the outside of the drum. The 'T' shaped piece fits into the motor mount and clamps down via screws to tightly hold the shaft in place and keep it rigidly affixed to the drum. The motor itself is connected to the outside of the forked links to enhance stability, a close up image of this is shown in Figure 31.

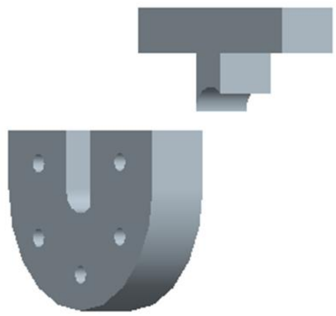


Figure 30: The motor mount used to clamp the motor shaft and rotate the drum.

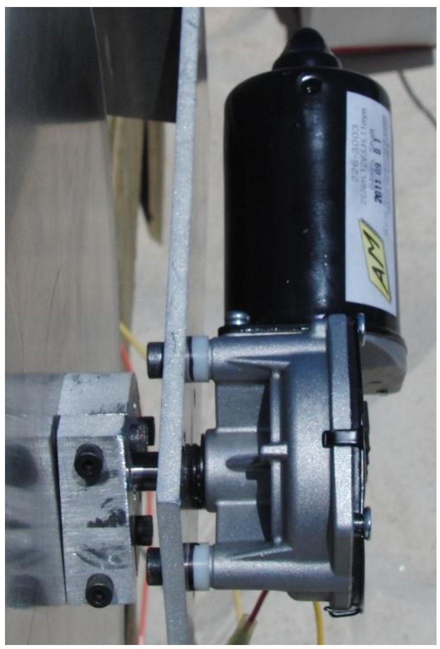


Figure 31: Close up image of drum motor mounting system.

Some improvements that could be made to improve the assembly of the excavation system are to bring the right link closer to the center of the robot by 0.25" so the necessity of a bushing between the link and drum is mitigated. The clearance between the forked link and the longer edge of the drum needs to be increased by 0.25" to prevent a scraping concern, shown in Figure 32. The link does not currently scrape, however more clearance would be beneficial.

Figure 32: The edge of the drum and forked arm where more clearance could be added to mitigate a scraping concern.

The system has been mounted to a wooden platform and tested. It goes through all the appropriate motions, and the motors move appropriately. It is also capable of excavating sand and dumping it at the appropriate height as indicated in the pictures in Figure 33. During the competition the drum will actually excavate while walking because experience from previous competitions indicates that the top layer of the regolith is the easiest to excavate. Lower than four inches is typically too dense to collect. To mitigate the center of mass issue, in particular because the drum is capable of holding 9.8kg of regolith, the batteries, two of which weigh 4.65kg combined to balance the weight of the robot. According to our moment balance equations and our center of mass analysis this should make the robot well within its restrictions.

Design, Manufacturing, and Assembly

During the manufacturing and assembly stages, small changes were made to the final design of the excavation system to ensure a proper fit and function. These changes included making the forked arms, which hold the excavation drum and to which the drum's motor is attached, wider and reinforced with an angled plate, which can be seen in Figure 33 below. This made the system both stable and strong. Also, cross members were added to the excavation linkages for stability purposes. In addition, a cross member was added to the Hexcavator frame to mount the linear actuator to. In the CAD model, it was seen that the actuator could have been mounted to one of the members already on the frame, but once installed on the mock up, it was decided that mounting the actuator further back was desired to increase the excavation systems range of motion to excavate and clear the 0.5 meter tall Lunabin. The Lunabin is represented below in Figure 33 by the two wooden planks on the left of the image, as the bottom picture shows, in the dumping position the robot is capable of dumping in to Lunabin.

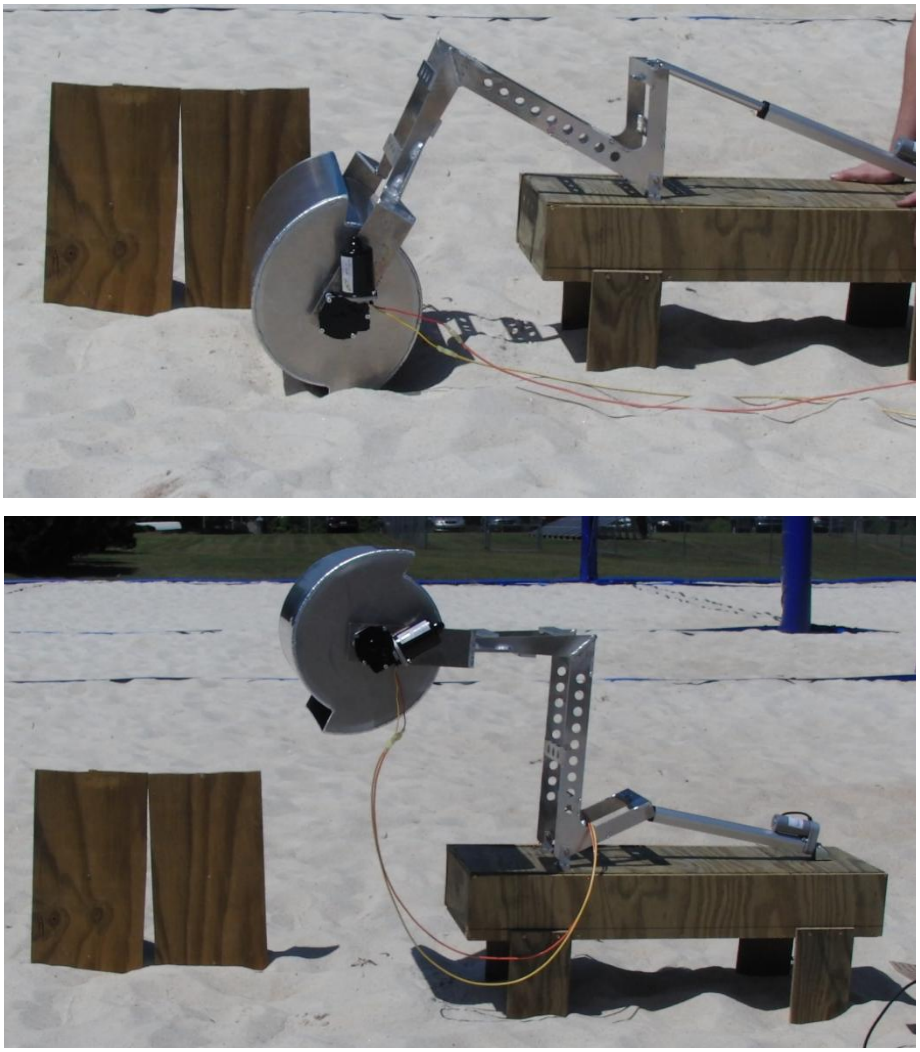


Figure 33: Images from the testing of the excavation system.

IV. Engineering Economics

The NASA Lunabotics senior design team received funding from three different sources, which are listed below in a tabular format.

- $5,000 donation by NASA
- $3,000 donation by Northrop Grumman

- $2,000 provided by the Mechanical Engineering department at the FAMU-FSU College of Engineering

Table 1 shows a breakdown of all of the materials acquired for the design competition, as well as the total amount of funding spent.

Excavation Total	**$1,536.74**
Linkage Aluminum	$842.71
Linkage ABS Plastic	$42.43
Steel Shaft	$41.60
Linear Actuator	$109.99
Drum Motor	$499.98
Hardware Total	**$274.81**
Circlips	$42.50
Bushings	$121.00
Spacers	$52.32
Copper Sheet	$58.99
Electronics Total	**$2,802.13**
WiFly	$424.75
BabyO	$95.00
Voltage Regulators	$67.45
Motor Drivers	$880.00
Decoders	$65.50
Clocks	$38.43
PC104	$691.00
Encoders	$350.00
Fans	$110.00
Misc Small Components	$80.00
Travel Expenses	**$1,880.85**
Final Total:	**$6,494.53**

Table 1: Budget breakdown

All spending in regard to excavation was necessary for the construction of the six bar linkage as well as the revisions into the four bar linkage with linear actuator. All aluminum was used in the manufacturing process. Also, ABS plastic was required to ensure that the excavation system would fit onto the Hexcavator platform as well as rotate through its entire range of motion. The steel shaft was purchased to engineer pins for the linkages and mount the drum to the forked linkage. Both the linear actuator and drum motor are required for the excavation system linkage to run and for the drum to excavate regolith.

The hardware purchases were essential in the assembly of the excavation system and electronics building. The circlips, bushings, and bearings were all used in the excavation system construction and serve to hold the shafts in the correct positions and in place. The copper sheet was going to be used to print circuits, but we found that using the protoboards made development and future additions easier.

All electronics purchases were necessary on many different Hexcavator apparatus. The motor drivers, decoders, encoders, Arduino Mega, BabyOs and clocks were all needed for a correct locomotion scheme. Without the use of any one of these components, the system would not operate so therefore it was not an option to do without them. In addition, the WiFly is completely necessary if wireless communication is to be achieved, which is one of the parameters set by NASA. Fans will be used to cool all electronic components so that the robot does not experience overheating, damage, or even fire. The small components, such as ribbon cables and wiring, are needed to construct the specific electronic components.

Overall, the team was efficient in ordering parts and materials to make the Hexcavator robot a success and compete well in the competition. Most of the parts and materials that encompass the robot's platform are being used from last year. Examples of this include the frame, leg motors, gearboxes, batteries, and carbon fiber legs. These components saved the team thousands of dollars and ensured that we would have more than enough money to get to the competition in May and be able to rent hotel rooms for the team for almost a week, which has also been included in the overall expenditures table, labeled above.

V. Results and Discussion

The Hexcavator platform required thorough testing of many different components which were conducted in their separate subsystems. Prior to the competition the subsystems will be merged into the singular platform to verify that integrating the systems still provides a robots platform.

Early testing included getting individual carbon fiber legs to run the Buehler rotation without the use of a control scheme, whilst mounted on the edge of the table. From there, all of the electronic components were added and the resulting tests were conducted to verify that multiple legs could run separate Buehler clocks both forwards and backwards. We are currently able to successfully use a Buehler clock with two legs. However, due to our lack of motor controllers, we have not been able to synchronize all six legs.

Wireless communication was tested and troubleshot by individually testing the WiFly and Arduino. They were tested to ensure that they were communicating and receiving any data initially, which was then modified to test if the correct data was being transferred. Once this was completed, the two were integrated and were able to communicate back and forth. Ultimately these have been applied to the robot and Hexcavator is able to communicate wirelessly to run all of its components, including rotating the legs. We have established control of the Baby O wirelessly, through the Mega, but have not set it up to control the motors. Once all of our motor control circuits are functional, this will be the next test.

The excavation system went through numerous tests throughout the course of completing the project. Initial tests included CAD analysis of the original six-bar linkage that was chosen to be the excavation system of the Hexcavator. This was done to rate what types of motor apparatus would be required to run the six-bar linkage and, additionally, the excavating drum. The analysis for the drum is shown in Figure 34. Once manufacturing of the six-bar linkage was completed, testing of the assembly began on a wooden mock up that is to scale of the Hexcavator design. These tests produced many issues with the current design. Such issues included lateral stability, long moment arm movement, mounting bracket redesign and placement, and motor ability to retract the system to the excavating position. The lateral instability issue was due to the two six-bar linkages inclination to deviate from side to side due to being long lengths and not secured to each other with cross members which would have added stiffness. This was further complicated by the length of the moment arms that were holding the drum in place. They had to be lengthened after the initial manufacturing to clear both the robot's frame and the other linkages. Mounting brackets were made when the six-bar linkage was assembled but, with changes to the design, they too had to be changed and the mounting positions of them were moved multiple times. All of these factors added weight and length the system and it became unclear as to whether the motors ordered would be able to handle the new parameters.

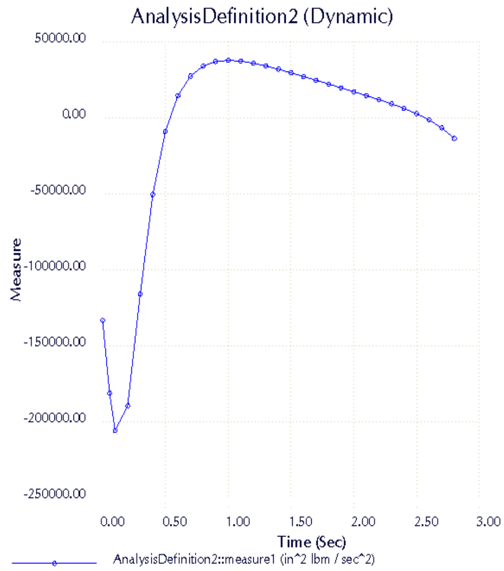


Figure 34: Analysis of the amount of Torque ($in^2 lbm$) to rotate the full drum.

After taking into account all of these factors, it was decided that a redesign of the excavation system was necessary to alleviate all of the problems that would be more work and effort to fix than they were worth. A more simplistic four bar linkage design was made which would both excavate and dump from the same side of the robot. This included the use of a linear actuator which was ordered as soon as the design was completed. Upon manufacturing of the new parts, assembly and mounting of the new system was relatively simple and testing was allowed to continue. The linear actuator was tested first to ensure that the linkage could move through its entire range of motion. This was followed by testing of the excavating drum's motor to ensure that the drum could rotate 360 degrees. It was seen that the drum was having trouble clearing the forked arms that it was mounted to, but a simple grinding of the aluminum edges where the drum had been welded corrected that issue.

Once both systems were working both correctly and in unison, the wooden mock up that the excavation system had been installed on was taken out the sand volleyball courts located outside the FAMU-FSU College of Engineering. Initial sand tests proved that the excavating drum could be rotated both fully into the sand and then above the required height of 0.5m that the Lunabin, which is the required height at the NASA Lunabotics competition. Also, the drum did rotate and excavated some sand. An issue that ensued was that the motor seemed to stall when met with any significant amount of sand to excavate. This was not a serious issue however because it was discovered that the battery being used to excavate was not drawing enough current for the motor to rotate under loaded conditions. The batteries that will be used on the Hexcavator platform will draw more than enough current to alleviate this problem.

VI. Environment, Health and Safety

The environment that the Hexcavator will be competing in is the Lunar Arena that was described earlier in this report. It will have craters and obstacles scattered throughout which will serve to test the robotic platform's ability to maneuver over them. The material itself will be mock lunar regolith which is a byproduct of volcanic activity, called BP-1, which serves to recreate the lunar surface[3].

Health is something that is of great importance to NASA and every team during the competition. This is due to the fact that the lunar regolith material is toxic in nature and should not be handled without breathing apparatus and chemical suits. Both of these will be provided by NASA for the testing days as well as the competition days.

Safety is also a major factor in the Lunabotics competition and is one of the design parameters that each robotic platform must be equipped with. A red emergency stop button must be installed on all robots so that they may be quickly and safely shut down in the event of malfunction or loss of control. Only NASA officials are allowed to be present in the Lunar Arena during testing and competition of any robot. Teams must be located in a control room which is equipped with optical devices to see their robot and control it accordingly. Specifically for the Hexcavator, safety measured have been employed throughout the design, manufacturing, assembly, and testing phases to ensure that all team members are safe at all times. Specifically with the use of electronics, before any testing or change to the system is done, all wires are checked and each team member makes sure that they are clear of any electrical charge before anything is powered up. Also, two different methods of safety switches have been installed for the testing of electronics to further reduce any risk of harm to any team member. In addition, all moving apparatus are fully checked and all team members stand clear before any testing is done and no one approaches the platform tested until everyone is sure that it has been powered down correctly and is in a safe position.

VII. Conclusions

The Lunabotics Competition Senior Design Team will be competing with the robot, Hexcavator, in the Third annual NASA Lunabotics Competition on May 23rd 2012 at the Kennedy Space Center. NASA set many design parameters which were all followed in the design of the robot. The maximum dimensions allowed for any competing robot were 1.5m length, 0.75m width, and 0.75m height. The maximum weight could not exceed 80kg. The robot designed was 1.41m tall, 0.74m wide, 0.66m tall, and had a final weight of 54.75kg. Other parameters included having a wireless communication system and an emergency stop button which were both accounted for and installed in the design. Finally, the robot had to be able to operate in a lunar environment, encountering obstacles and craters, and had to excavate a minimum of 10kg of lunar regolith. The Hexcavator platform was designed with all components regolith resistant and can easy overcome any obstacle set in its path due to its carbon fiber "C" shaped legs. The excavation drum installed will be able to excavate over 10kg of lunar regolith in one excavation pass during competition.

The locomotion scheme used was that of a hexapedal RHex family of robots. This configuration calls for an alternating tripod gate in which three of the six legs will be planted firmly on the lunar soil at all times. This is accomplished using a Buehler clock in which the carbon fiber legs spend five times as much time on the ground as they do rotating through the air.

The wireless communication system was designed in conjunction with the requirements specified by NASA. Therefore, it was outfitted with WiFi, uses minimum bandwidth, and a simulated delay. This wireless connection was established by using the WiFly GSX. Its task then was to the communicate data serially to a microcontroller. The microcontroller chosen to receive this data was the Arduino Mega 2650, which is easy to interface with, has four serial connections, uses low bandwidth, and is inexpensive. The processed data is then sent to another microcontroller, the Baby Orangutan, which controls speed and leg position. This control is achieved via motor driver, encoder, and decoder. The motor driver drives the Maxon 65 leg motors and the encoder and decoder relay real time data back to the Baby Orangutan to make the proper control adjustments.

Power is supplied to the entire robotic system by three batteries, two at 37V and the other at 12V. The two 37V batteries will run the locomotion scheme and the 12V will run both the microcontrollers and the excavation system. The microcontrollers will be regulated via voltage regulator, a NTE1934. In addition, fuses and a safety switch were installed to ensure that the Hexcavator is safe at all times. The fuses are in place to reduce a surge and save all electronic components. The safety switch, required by NASA, is a large red button that can be used at any time to completely shut down the robot’s power in the event of a failure or loss of control.

A wireless camera was implemented into the final overall design to increase robotic visibility during the Lunabotics competition. This was done at the teams discretion but was deemed necessary due to the lacking vantage point that NASA supplies. It will especially be useful when the lunar regolith is disturbed and disperses into the air, limiting visibility that NASA provides.

The excavation system was designed to be within the robot’s center of gravity range in any position or situation. It is a four bar linkage design that employs a linear actuator to rotate a large rotating drum into the lunar regolith. The linkage and linear actuator are both mounted to cross members outfitted on the Hexcavator’s frame. In the excavating position, the drum will be directly in front of the robot and will rotate into the lunar surface. The linear actuator will be fully extended at this point. When regolith is excavated, the linear actuator will retract and the four bar linkage will rotate to a position above the robot. It is from this position that the robot will traverse the course and deposit the regolith in the NASA LunaBin.

A budget of $10,000 was allotted to the Lunabotics Competition Senior Design Team. This amount was given by the FAMU-FSU College of Engineering, National Space Grant, and Northrop Grumman. A total amount of just under $6,500 was spent on necessary material, hardware, electronics, and travel accommodations.

VII. Acknowledgements

We would like to thank FAMU-FSU College of Engineering, Dr. Jonathan Clark, National Space Grant, Northrop Grumman and Kennedy Space Center for all of their individual contributions.

The FAMU-FSU College of Engineering for providing us with the valuable opportunity to work on this senior design project because it was an enlightening learning experience for engineering application, team dynamics, professionalism and a myriad of other things.

Dr. Jonathan Clark, our project sponsor, was also invaluable in the success of this project. He motivated us to stay on task throughout the semester and helped point out potential failures in our design.

We would also like to thank the National Space Grant and Northrop Grumman for funding our project and making it possible to purchase all of the components necessary to our project.

Finally, we would like to thank NASA's Kennedy Space Center for hosting the competition which was the backbone of our entire senior design project.

VIV. References

[1] *Advantech - Industrial Computer , Embedded Computer, Industrial Automation, Industrial Motherboard, Network Security Appliance, Digital Video Surveillance, Panel PC, Industrial IO*. Tech. Web. 27 Nov. 2011. <http://www.advantech.com/products/PCM-3644/mod_7424349A-016A-495D-9154-44FE8A0FA56D.aspx>.

[2] *Advantech - Industrial Computer , Embedded Computer, Industrial Automation, Industrial Motherboard, Network Security Appliance, Digital Video Surveillance, Panel PC, Industrial IO*. Tech. Web. 27 Nov. 2011. <http://www.advantech.com/products/PCM-3355/mod_07D970F1-0B9D-4069-BCEE-A8B46A143D42.aspx>.

[3]National Aeronautics and Space Administration. Lunabotics Mining Competition. 2011. 29 September 2011 <http://www.nasa.gov/offices/education/centers/kennedy/technology/lunabotics.html>.

[5] Maxon Motors. *RE-65-353294_11_EN_084*. PDF.

[6] Spark Fun Electronics <http://www.sparkfun.com/products/10050>

X. Biographical Sketch

Seth Murphy is a senior at Florida State University and is studying computer engineering. He was born in Sarasota, FL and has lived in Florida his whole life. Upon graduating, he plans on pursuing a Master's degree in computer engineering, with a concentration in embedded systems. He was interested in the NASA Lunabotics competition because he wanted to use his programming background to create a mechanically and electronically complex system capable of solving a problem. When he has free time, he enjoys working out and watching football.

Shannon Berger is a senior Mechanical Engineering Student at Florida State University. She was born and raised in Clearwater, Fl and always wanted to be an engineer. Upon graduation she will be working as a summer intern for the United States Nuclear Regulatory Commission and will then pursue a master's degree in Mechanical Engineering at the FAMU/FSU College of Engineering.

James Fadool is a senior mechanical engineering student at Florida State University. He currently works at the STRIDe lab as a researcher interested in manufacturing and design. He is also a teaching assistant for the Mechatronics I class for the College of Engineering. Outside of school James enjoys riding and fixing motorcycles.

Rob Sistare is a senior Electrical Engineering student at Florida State University and is due to graduate in Spring 2012. He currently works at the Center for Advanced Power systems (CAPS) as an administrative aid. He plans on attending graduate school to pursue a masters in Electrical Engineering. His hobbies include SCUBA diving maintaining and riding motorcycles and generally tinkering with electronics.

Devin Walden is a senior electrical engineering major at Florida A&M University, originally from Tampa, FL. He intends to become the first PH.D electrical engineer in my family. He aspires to become a great professor/researcher creating programs for engineering students that is based on building the social and interpersonal ability of these particular students. Engineers are not known for their savvy in dealing with people and communicating well with others so it is his vision to introduce a program as a future Engineering Professor teaching future engineering professionals not only how to apply scientific and mathematical principles but learn the art of winning friends and influencing people.

McKenzie Reed is a Mechanical Engineering student at the FAMU/FSU College of Engineering. He was born and raised in West Palm Beach, Florida. Going up in an automotive family, McKenzie became interested in pursuing Engineering during his teenage years. Upon graduation, he would like to continue onto graduate school to focus in Thermal Fluids and Propulsion. In his free time, McKenzie enjoys going to Florida State football games and drawing.

VIII. Appendix

<u>Engineering Drawings</u>

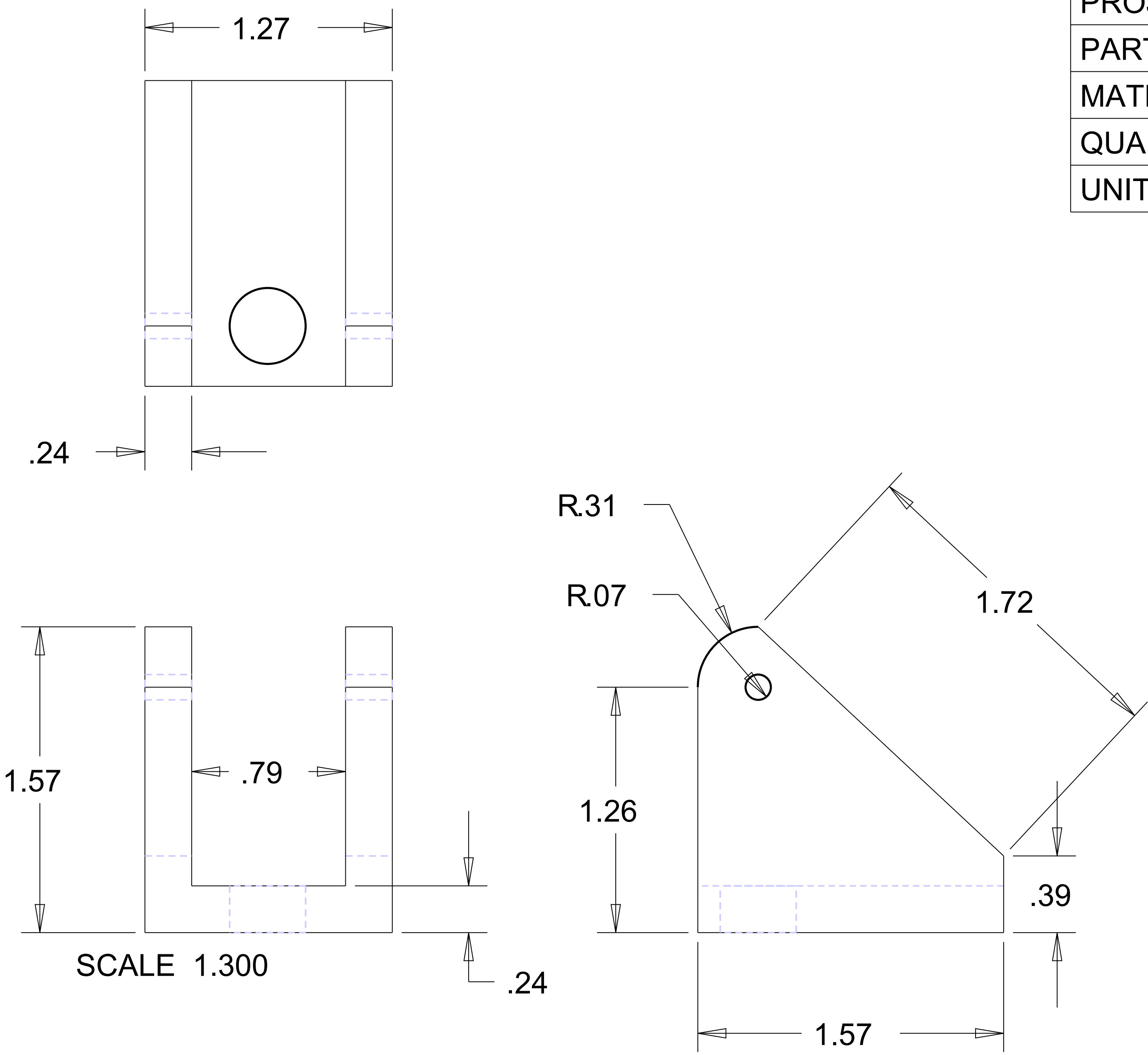
- Actuator Mount
- Braces for L Bracket
- Cross Member
- Drum
- Frame
- L Bracket
- Leg
- Leg Clamp
- Link 3
- Link 3 Reverse

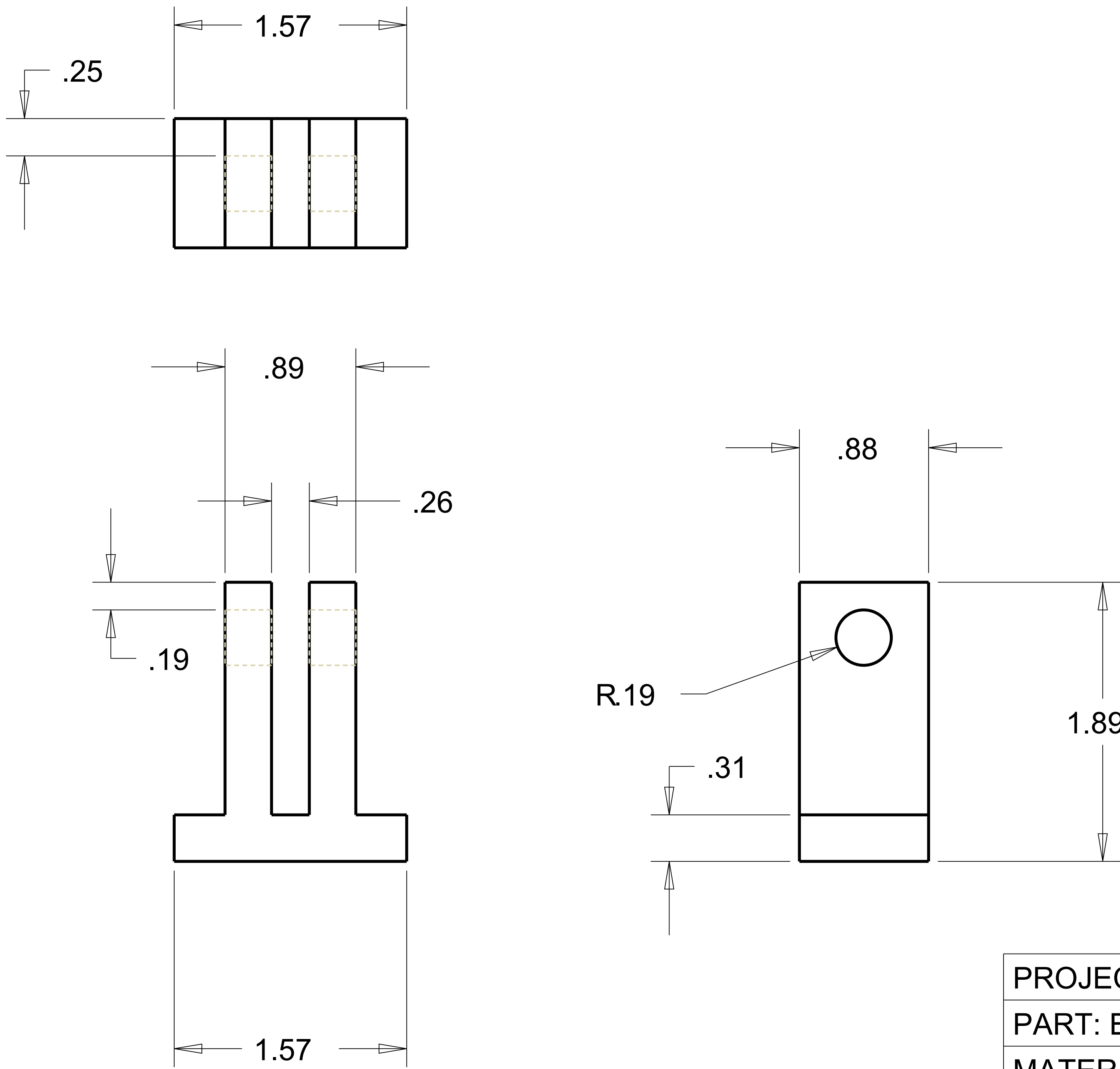
<u>Motor Specifications</u>

- Excavation Drum
- Excavation Linkage
- Locomotion Motors

<u>Extraneous Specifications</u>

PROJECT: HEXCAVATOR
PART: ACTUATOR MOUNT
MATERIAL: STEEL
QUANTITY: 2
UNITS: INCH





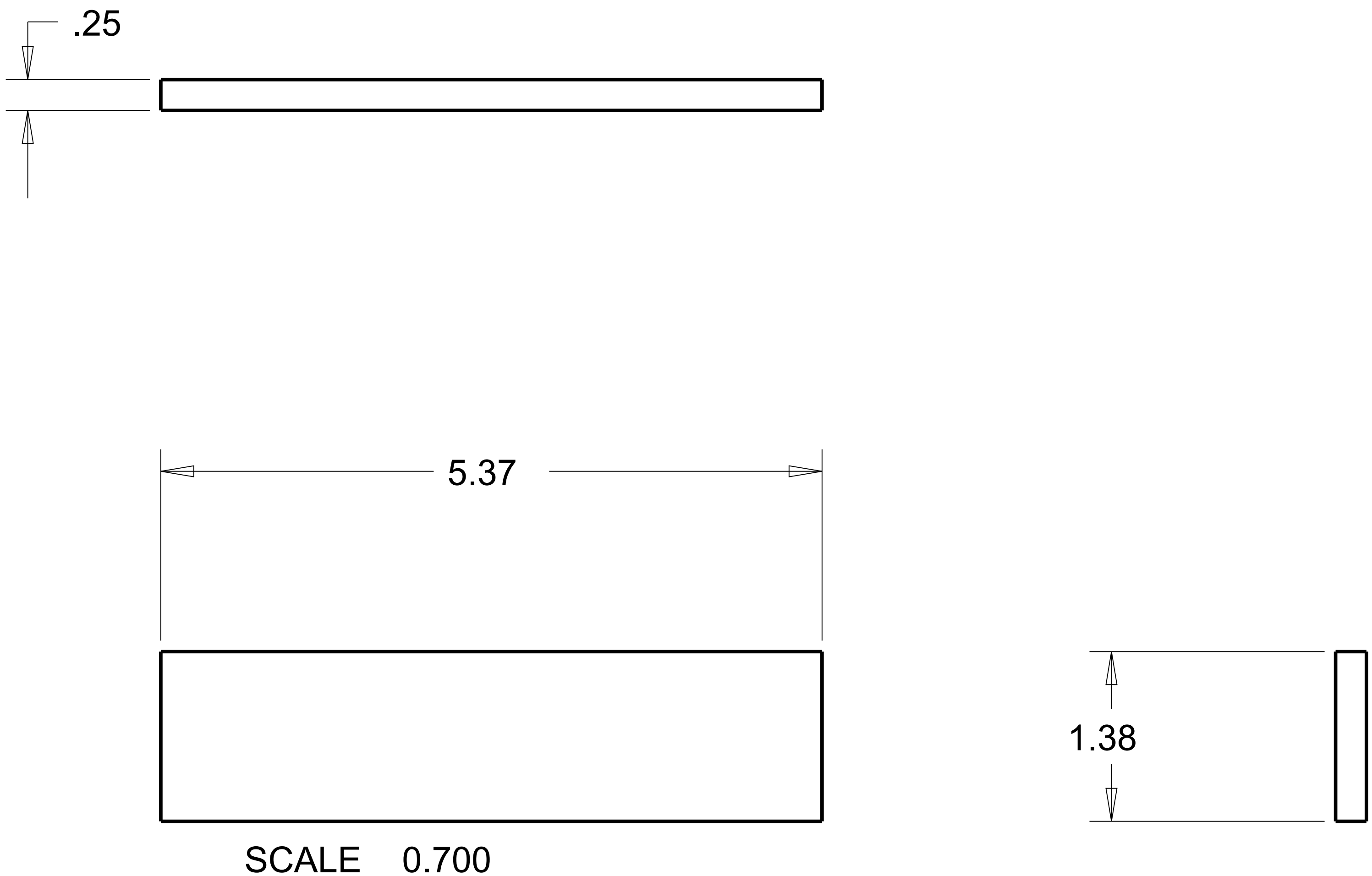
PROJECT: HEXCAVATOR

PART: BRACKETS FOR L BAR

MATERIAL: ALUMINUM 6061

QUANTITY: 2

UNITS: INCH



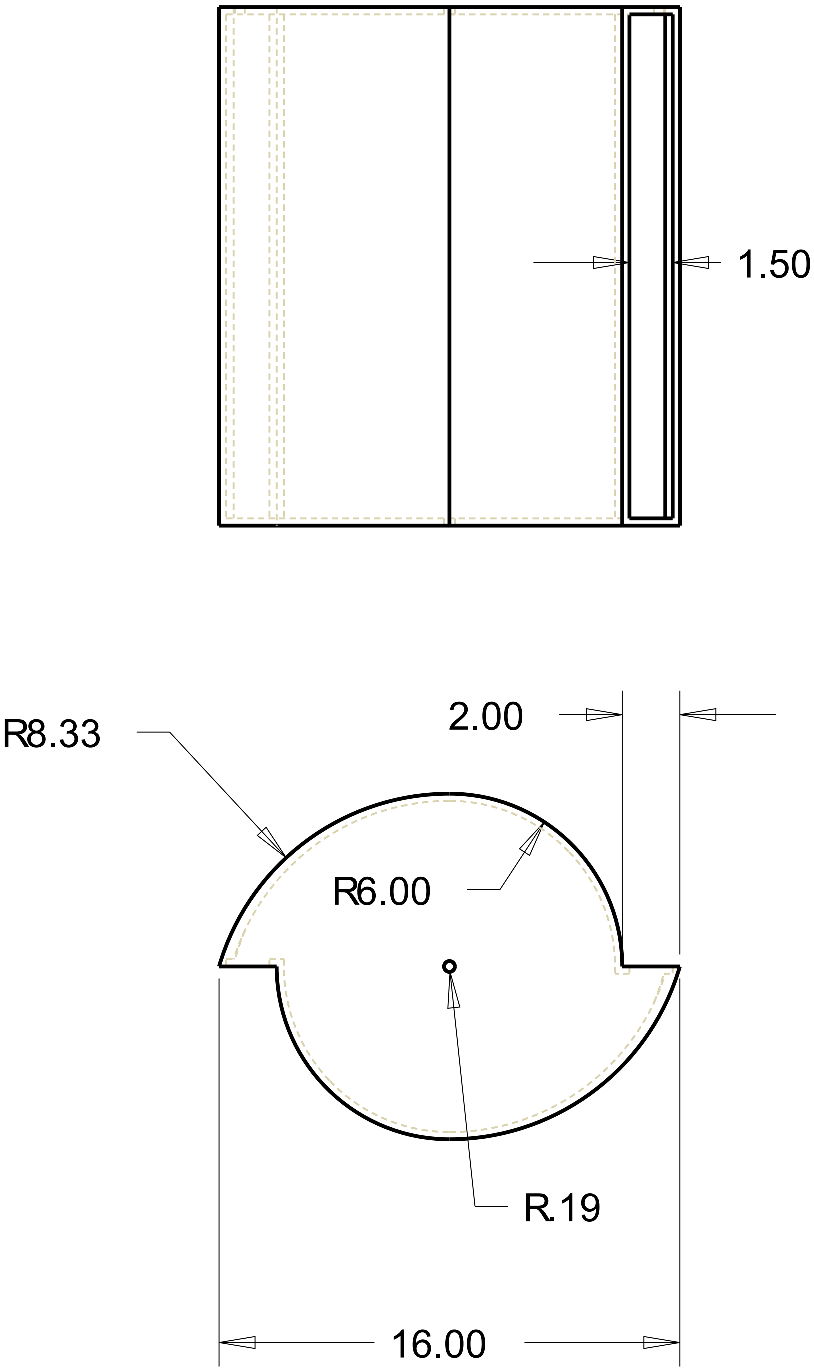
PROJECT: HEXCAVATOR

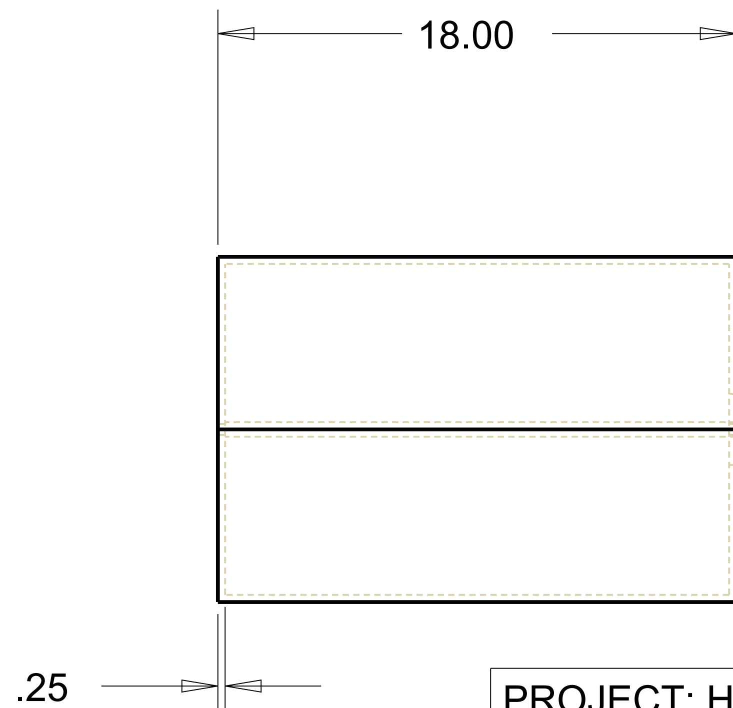
PART: L BRACKET CROSSMEM

MATERIAL: ALUMINUM 6061

QUANTITY: 8

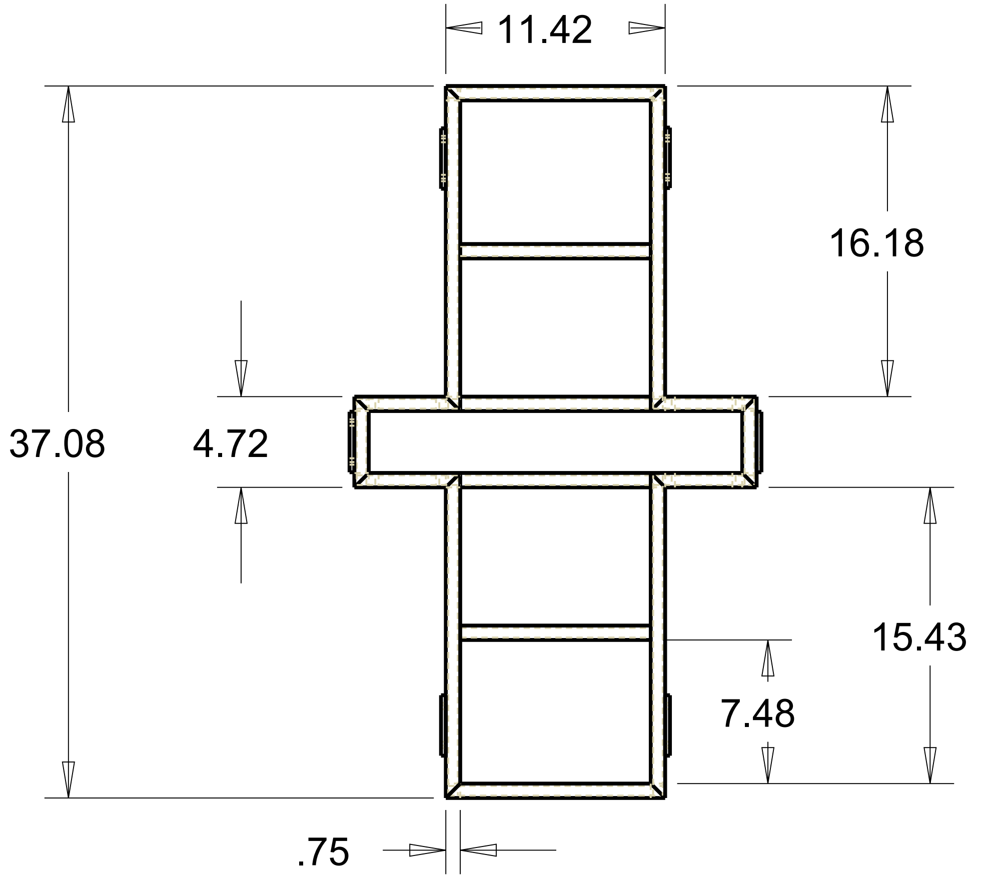
UNITS: INCH

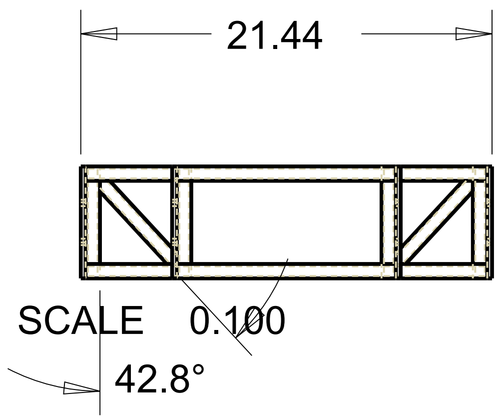




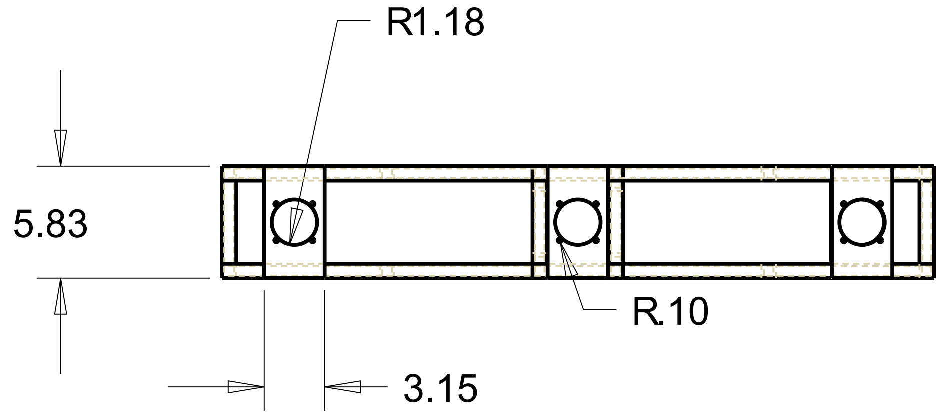
PROJECT: HEXCAVATOR
PART: DRUM
MATERIAL: ALUMINUM 6061
QUANTITY: 1
UNITS: INCH
NOTE: DRUM OPENING:1.5"

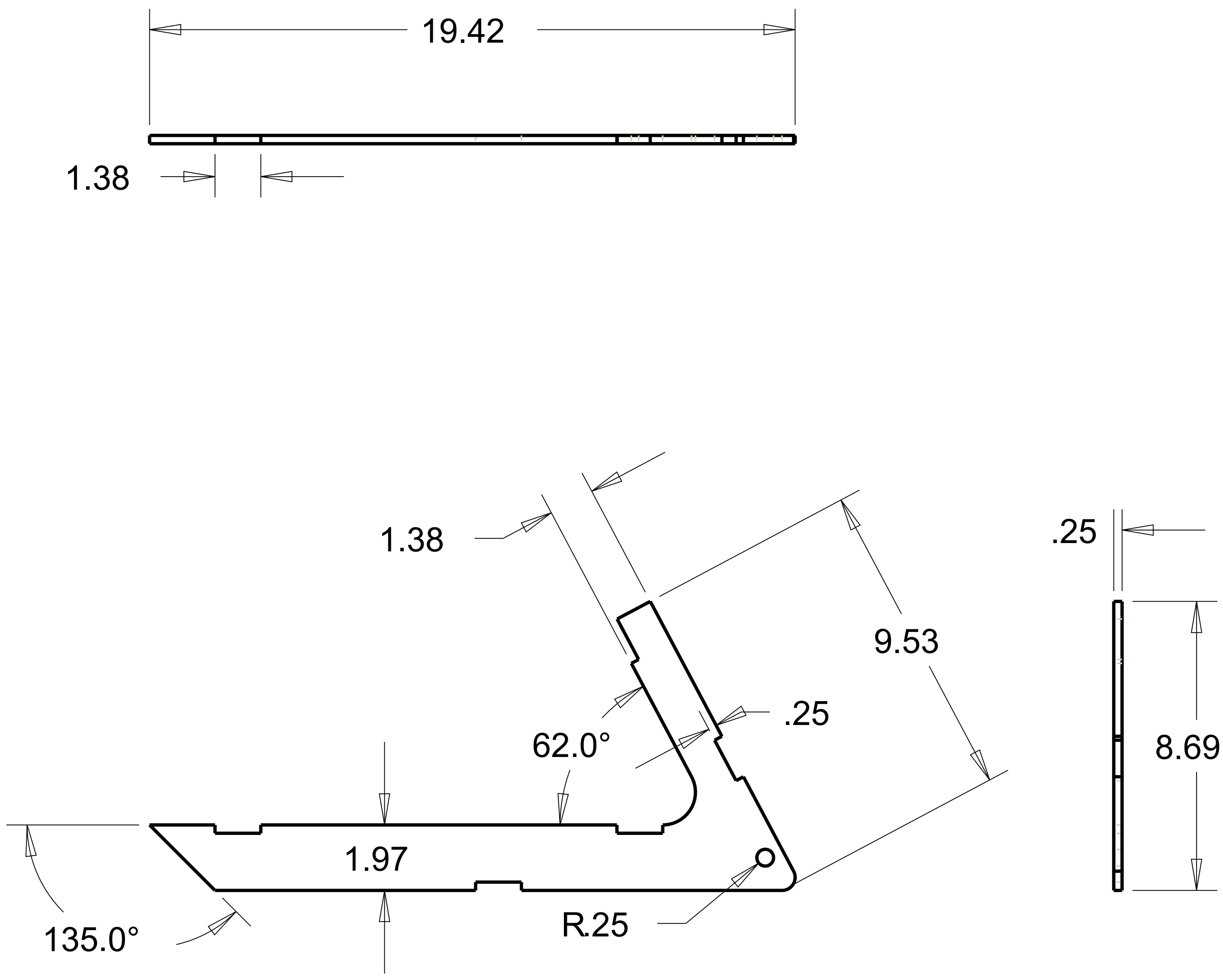
PROJECT: HEXCAVATOR	
PART: FRAME	
MATERIAL: ALUMINUM 6061	
QUANTITY: 1	
UNITS: INCH	
NOTE: FRAME IS 0.75" TUBE	



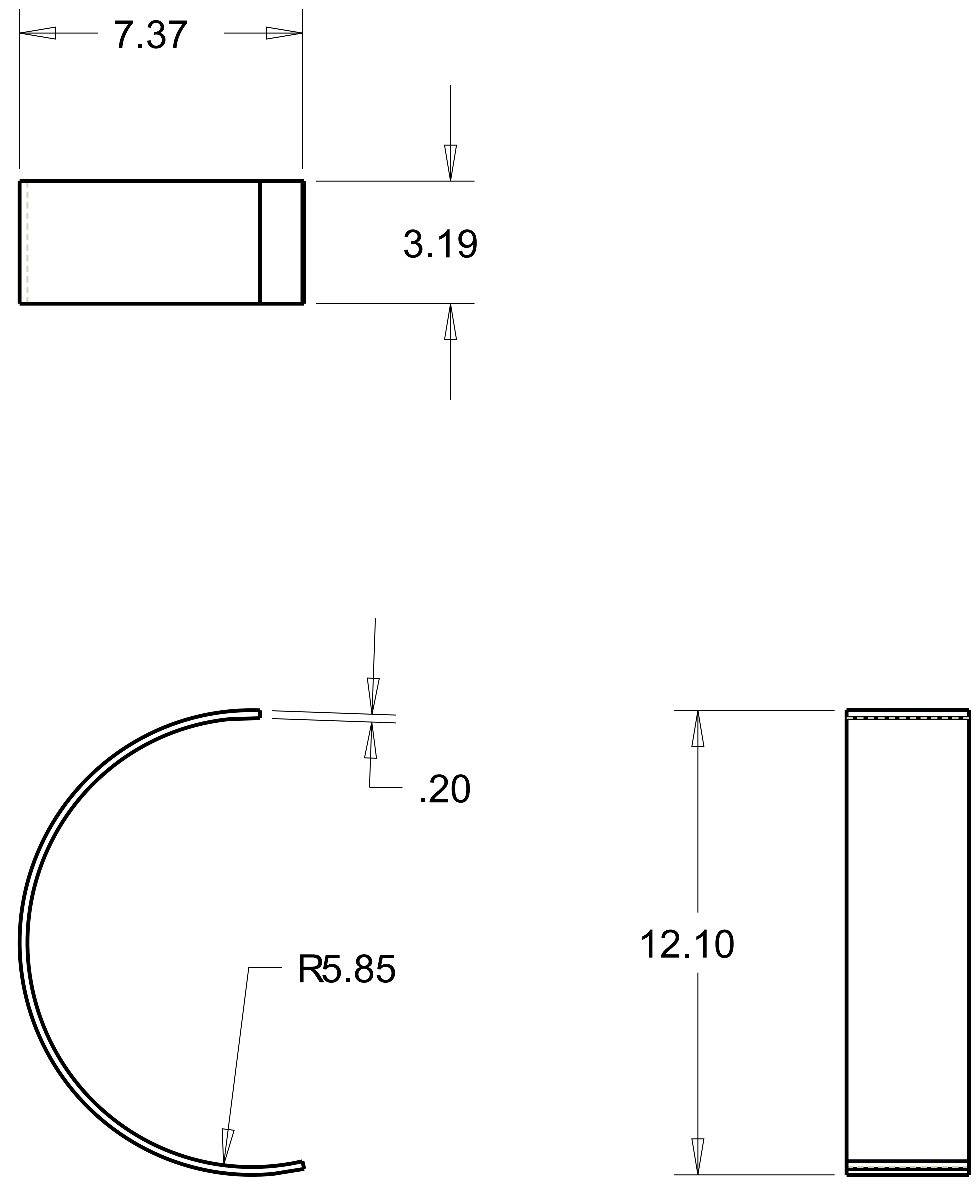


SCALE 0.100

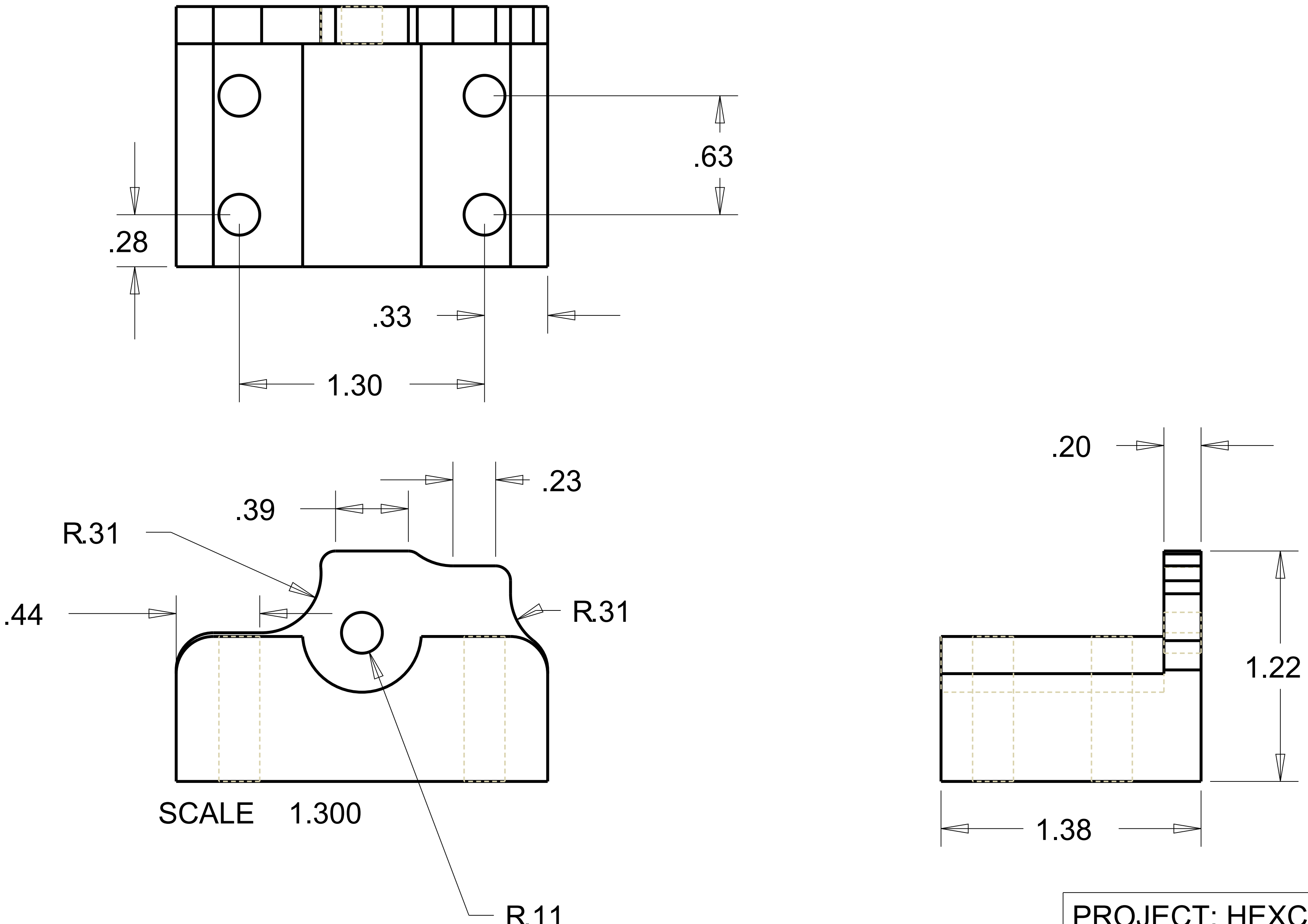




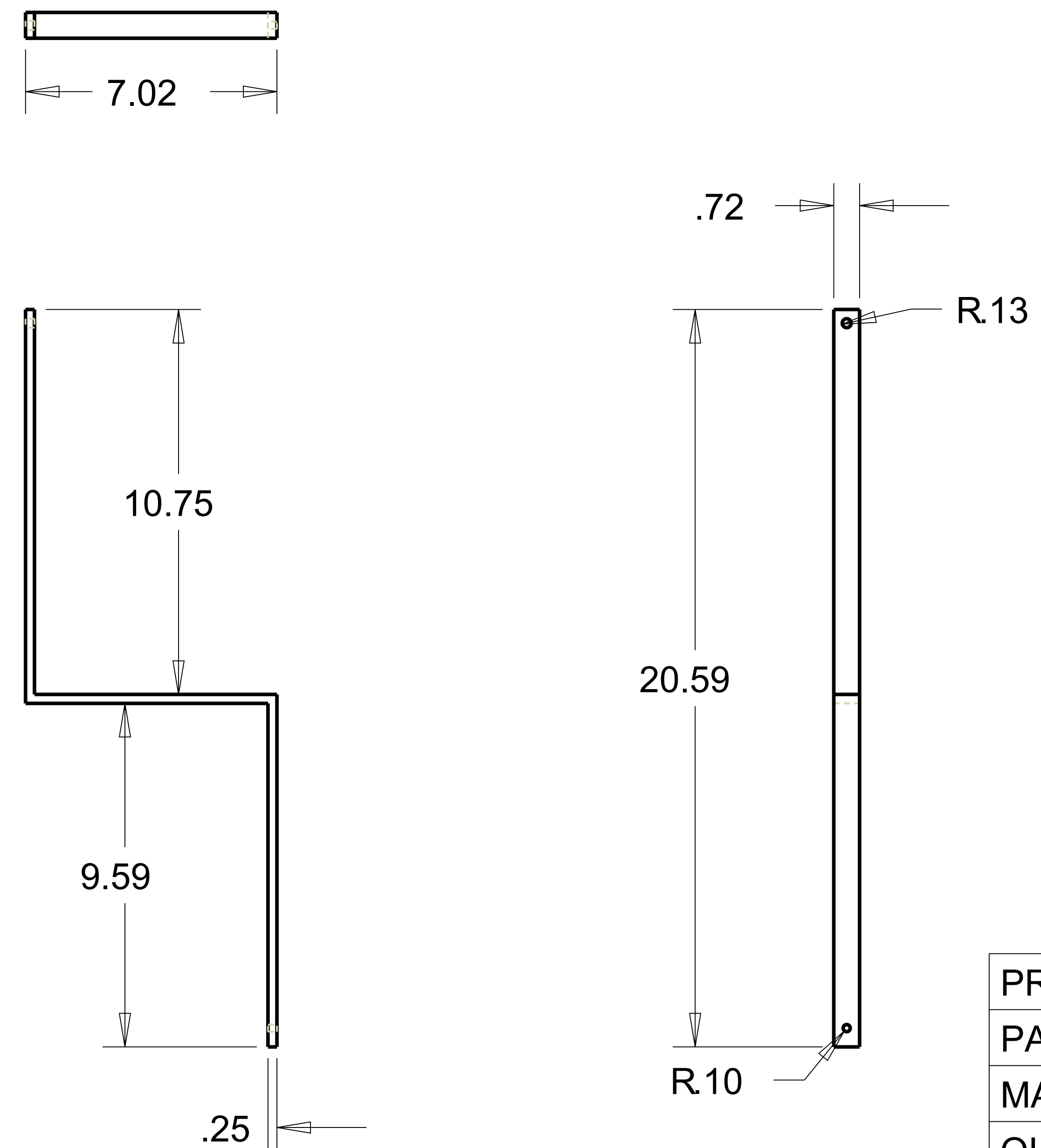
PROJECT: HEXCAVATOR
PART: L BRACKET
MATERIAL: ALUMINUM 6061
QUANTITY: 2
UNITS: INCH



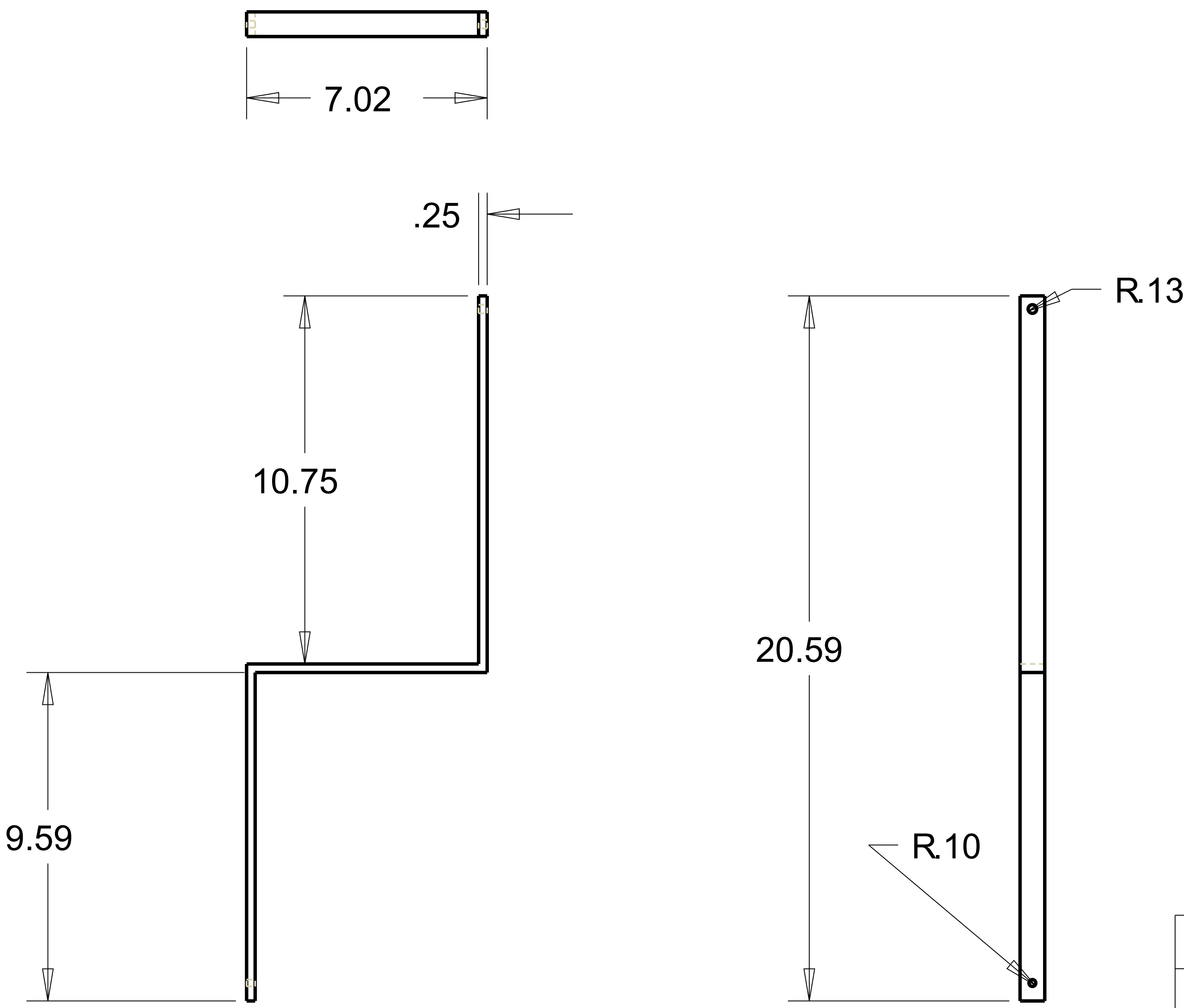
PROJECT: HEXCAVATOR
PART: LEG
MATERIAL: CARBON FIBER
QUANTITY: 6
UNITS: INCH



PROJECT: HEXCAVATOR	
PART: LEG CLAMP	
MATERIAL: ALUMINUM 6061	
QUANTITY: 6	
UNITS: INCH	



PROJECT: HEXCAVATOR
PART: LINK 3
MATERIAL: ALUMINUM 6061
QUANTITY: 1
UNITS: INCH



PROJECT: HEXCAVATOR
PART: LINK 3 REVERSE
MATERIAL: ALUMINUM 6061
QUANTITY: 1
UNITS: INCH

NASA's Third Annual Lunabotics Mining Competition

Rules & Rubrics, Revision 2

Kennedy Space Center Visitor Complex

Kennedy Space Center, Florida

Introduction

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

The competition will be conducted by NASA at the Kennedy Space Center Visitor Complex. The teams that can use telerobotic or autonomous operation to excavate lunar regolith simulant, called Black Point-1 or BP-1, and score the most points wins the Joe Kosmo Award for Excellence. The team will receive the Joe Kosmo Award for Excellence trophy, KSC launch invitations, team certificates for each member, a $5,000 team scholarship, and up to $1,000 travel expenses for each team member and one faculty advisor to participate at one of NASA's remote research and technology tests. Awards for other categories include monetary team scholarships, a school trophy or plaque, team and individual certificates, and KSC launch invitations.

Undergraduate and graduate student teams enrolled in a U.S. or international college or university are eligible to enter NASA's Lunabotics Mining Competition. Design teams must include: at least one faculty with a college or university and at least two undergraduate or graduate students. NASA has not set an upper limit on team members. A team should have a sufficient number of members to successfully operate their Lunabot. Teams will compete in up to five major competition categories including: on-site mining, systems engineering paper, outreach project, slide presentation (optional), and team spirit (optional). Additionally, teams can earn bonus points for mined and deposited BP-1 in the competition attempts, having multidisciplinary teams, and collaborating between a majority institution and a U.S. minority serving institution. All documents must be submitted in English.

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

For more information, visit NASA's Lunabotics Mining Competition on the Web at www.nasa.gov/Lunabotics; on Facebook at www.facebook.com/Lunabotics; on YouTube at http://www.youtube.com/user/Lunabotics; and follow Lunabotics on Twitter at http://twitter.com/#!/Lunabotics.

Lunabotics On-Site Mining Category

This year the scoring for the Mining Category will not be based primarily on the amount of material excavated in the allowed time but instead will require teams to consider a number of design and operation factors such as dust tolerance and projection, communications, vehicle mass, energy/power required, and level of autonomy. Each team must compete on-site at the Kennedy Space Center Visitor Complex, Florida in the United States of America on May 21-26, 2012. A minimum amount of 10 kg of BP-1 must be mined and deposited during each of two competition attempts according to the rules to qualify to win in this category. In the case of a tie, the teams will compete in a tie-breaking competition attempt. The judges' decisions are final in all disputes. The teams with the first, second, and third most LunaPoints averaged from both attempts will receive team plaques, individual team certificates, KSC launch invitations, $3,000, $2,000, and $1,000 scholarships and 30, 25, and 20 points toward the Joe Kosmo Award for Excellence, respectively. Teams not winning first, second, or third place in the mining category can earn one bonus point for each kilogram of BP-1 mined and deposited up to a maximum average of ten points toward the Joe Kosmo Award for Excellence. The most innovative and lunar like design will receive the Judges' Innovation Award at the discretion of the mining judges.

1) Teams must arrive at the Lunabotics Mining Competition Check-In Tent in Parking Lot 4 of the Kennedy Space Center Visitor Complex no later than 12:00 p.m. (noon) on Tuesday, May 22, 2012.

Game Play Rules

2) Teams will be required to perform two official competition attempts using BP-1 in the LunArena provided by NASA. NASA will fill the LunArena with compacted BP-1 that matches as closely as possible to lunar regolith. NASA will randomly place three obstacles and create two craters on each side of the LunArena. Each competition attempt will occur with two teams competing at the same time, one on each side of the LunArena. After each competition attempt, the obstacles will be removed, the BP-1 will be returned to a compacted state, if necessary, and the obstacles and craters will be returned to the LunArena. The order of teams for the competition attempts will be chosen at NASA's discretion. See Diagrams 1 and 2.

3) In each of the two official competition attempts, the teams will score cumulative LunaPoints. See Table 1 for the Mining Category Scoring Example. The teams' ranking LunaPoints will be the average of their two competition attempts.

   A) Each team will be awarded 1000 LunaPoints after passing the safety inspection and communications check.

   B) During each competition attempt, the team will earn 2 LunaPoints for each kilogram in excess of 10 kg of BP-1 deposited in the LunaBin. (For example, 110 kg of BP-1 mined will earn 200 points.)

   C) During each competition attempt, the team will lose 1 LunaPoint for each 50 kilobits/second (kb/sec) of average data used throughout each competition attempt. A minimum of 10 kg of BP-1 must be mined and deposited in the LunaBin during each competition attempt or the team will lose 100 LunaPoints, which is the maximum number of LunaPoints for this rule. (For example, 5000 kb/sec will lose 100 points.)

   D) During each competition attempt, the team will lose 10 LunaPoints for each kilogram of total Lunabot mass. (For example, a Lunabot that weighs 80 kg will lose 800 LunaPoints.)

   E) During each competition attempt, the team will earn 100 LunaPoints if the amount of energy consumed by the Lunabot during the competition attempt is reported to the judges after each attempt. The amount of energy consumed will not be used for scoring; a team must only provide a legitimate method of measuring the energy consumed and be able to explain the method to the judges.

   F) During each competition attempt, the judges will award the team 0 to 200 LunaPoints for regolith dust tolerant design features on the Lunabot and regolith dust free operation. If the Lunabot has exposed mechanisms where dust could accumulate during a lunar mission and degrade the performance or lifetime of the mechanisms, then fewer points will be awarded in this category. If the Lunabot raises a substantial amount of airborne dust or projects it due to its operations, then fewer points will be awarded. Ideally, the Lunabot will operate in a clean manner without dust projection, and all mechanisms and moving parts will be protected from dust intrusion. The Lunabot will not be penalized for airborne dust while dumping into the LunaBin. All decisions by the judges regarding dust tolerance and dust projection are final.

G) During each competition attempt, the team will earn 250 LunaPoints if the Lunabot is able to drive autonomously (no teleoperation), through the obstacle area only. The Lunabot may be teleoperated in the mining area and LunaBin/starting area. A minimum of 10 kg of BP-1 must be mined and deposited in the LunaBin during each competition attempt to receive these LunaPoints. The points for autonomy through the obstacle area and full autonomy are mutually exclusive.

H) During each competition attempt, the team will earn 500 LunaPoints if full autonomy is achieved and a minimum of 10 kg of BP-1 is mined and deposited in the LunaBin. No teleoperation is allowed to achieve full autonomy status. The points for autonomy through the obstacle area and full autonomy are mutually exclusive.

Mining Category Elements	**Specific Points**	**Actual**	**Units**	**LunaPoints**
Pass Inspections				1000
Regolith over 10 kg	+2/kg	110	kg	+200
Average Bandwidth	-1/50kb/sec	5000	kb/sec	-100
Lunabot Mass	-10/kg	80	kg	-800
Report Energy Consumed	+100	1	1= Achieved 0= Not Achieved	+100
Dust Tolerant Design & Dust Free Operation	0 to +200	150	Judges' Decision	+150
Autonomy through Obstacles	+250	0	1= Achieved 0= Not Achieved	0
Full Autonomy	+500	500	1= Achieved 0= Not Achieved	+500
Total				1050

Table 1: Mining Category Scoring Example

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

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

6) A team's Lunabot will only excavate BP-1 located in that team's respective mining area at the opposite end of the LunArena from the team's starting area. The team's starting direction will be randomly selected immediately before the competition attempt.

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

8) Each team is responsible for placement and removal of their Lunabot onto the BP-1 surface. There must be one person per 23 kg of mass of the Lunabot, requiring four people to carry the maximum allowed mass. Assistance will be provided if needed.

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

10) The Lunabot operates during the 10-minute time limit of each competition attempt. The competition attempts for both teams in the LunArena will begin and end at the same time.

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

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

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

Field Rules

14) At the start of each competition attempt, the Lunabot may not occupy any location outside the defined starting position.

15) The LunaBin top edge will be placed so that it is adjacent to the side walls of the LunArena without a gap and the height will be approximately 0.5 meter from the top of the BP-1 surface directly below it. The LunaBin top opening will be 1.65 meters long and .48 meters wide. See Diagrams 1 – 3. A target may be attached to the LunaBin for navigation purposes only. This navigational aid must be attached during the setup time and removed afterwards during the removal time period. The mass of the navigational aid is included in the maximum Lunabot mass limit of 80.0 kg and must be self-powered.

16) There will be three obstacles placed on top of the compressed BP-1 surface within the obstacle area before each competition attempt is made. The placement of the obstacles will be randomly selected before the start of the competition. Each obstacle will have a diameter of approximately 20 to 30 cm and an approximate mass of 7 to 10 kg. There will be two craters of varying depth and width, being no wider or deeper than 30 cm. No obstacles will be intentionally buried in the BP-1 by NASA, however, BP-1 includes naturally occurring rocks.

17) The Lunabot must operate within the LunArena: it is not permitted to pass beyond the confines of the outside wall of the LunArena and the LunaBin during each competition attempt. The BP-1 must be mined in the mining area and deposited in the LunaBin. A team that excavates any BP-1 from the starting or obstacle areas will be disqualified. The BP-1 must be carried from the mining area to the LunaBin by any means and be deposited in the LunaBin in its raw state. A secondary container like a bag or box may not be deposited inside the LunaBin. Depositing a container in the LunaBin will result in disqualification of the team. The Lunabot can separate intentionally, if desired, but all parts of the Lunabot must be under the team's control at all times. Any ramming of the wall may result in a safety disqualification at the discretion of the judges. Touching or having a switch sensor springwire that may brush on a wall as a collision avoidance sensor is allowed.

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

Technical Rules

19) During each competition attempt, the Lunabot is limited to autonomous and telerobotic operations only. No physical access to the Lunabot will be allowed during each competition attempt. In addition, telerobotic operators are only allowed to use data and video originating from the Lunabot and the NASA video monitors. Visual and auditory isolation of the telerobotic operators from the Lunabot in the Mission Control Center is required during each competition attempt. Telerobotic operators will be able to observe the LunArena through overhead cameras in the LunArena through monitors that will be provided by NASA in the Mission Control Center. These color monitors should be used for situational awareness only. No other outside communication via cell phones, radios, other team members, etc. is allowed in the Mission Control Center once each competition attempt begins.

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

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

22) The Lunabot must be equipped with an easily accessible red emergency stop button (kill switch) of minimum diameter five cm on the surface of the Lunabot requiring no steps to access. The emergency stop button must stop the Lunabot's motion and disable all power to the Lunabot with one push motion on the button. It must be

highly reliable and instantaneous. For these reasons an unmodified “Commercial Off-The-Shelf” (COTS) red button is required. A closed control signal to a mechanical relay is allowed as long as it stays open to disable the Lunabot. The reason for this rule is to completely safe the Lunabot in the event of a fire or other mishap. The button should disconnect the batteries from all controllers (high current, forklift type button) and it should isolate the batteries from the rest of the active sub-systems as well.

23) The communications rules used for telerobotic operations follow:

A. LUNABOT WIRELESS LINK

1. Each team will provide the wireless link (access point, bridge, or wireless device) to their Lunabot, which means that each team will bring the Wi-Fi equipment/router and set their own IP addresses.
    a. NASA will provide an elevated network drop (Female RJ-45 Ethernet jack) in the LunArena that extends to the Mission Control Center, where NASA will provide a network switch for the teams to plug in their laptops.
        i. The network drop in the LunArena will be elevated high enough above the edge of the regolith bed wall to provide adequate radiofrequency visibility of the LunArena.
        ii. A shelf will be setup next to the network drop and located 4 to 6 feet off the ground and will be no more than 50 feet from the Lunabot. This shelf is where teams will place their Wireless Access Point (WAP) to communicate with their Lunabot. The distance from the LunArena to the Mission Control Center will be around 150 – 200 feet.
        iii. The WAP shelves for side A and side B of the LunArena will be no closer than 25' from each other to prevent electromagnetic interference (EMI) between the units.
    b. NASA will provide a standard 110VAC outlet by the network drop. Both will be no more than 2 feet from the shelf.
    c. During setup time before the match starts the teams will be responsible for setting up their access point.
2. The teams must use the USA IEEE 802.11 b/g standard for their wireless connection (WAP and rover client). Teams cannot use multiple channels for data transmission. Encryption is not required but it is highly encouraged to prevent unexpected problems with team links.
    a. During a match, one team will operate on channel 1 and the other team will operate on channel 11.
    b. The channel assignments will be made upon team check-in with the LunaPit crew chief.
3. Each team will be assigned an SSID that they must use for their wireless equipment.
    a. SSID will be “Team_##”
    b. Teams will broadcast their SSID
4. Bandwidth constraints:
    a. Teams will be awarded the Efficient Use of Communications Power Award for using the least amount of average bandwidth during the timed and NASA monitored portion of the competition. Teams must collect the minimum 10 kg of BP-1 to qualify for this award.
    b. The communications link is required to have an <u>average</u> bandwidth of no more than 5 megabits per second. There will not be a <u>peak</u> bandwidth limit.

B. RF & COMMUNICATIONS APPROVAL

1. Each team must demonstrate to the communication judges that their Lunabot and access point is operating only on their assigned channel. Each team will have approximately 15 minutes at the communication judge’s station.
2. To successfully pass the communications judge's station a team must be able to command their Lunabot (by driving a short distance) from their Lunabot driving/control laptop through their wireless access point. The judges will verify this and use the appropriate monitoring tools to verify that the teams are operating only on their assigned channel.
3. If a team cannot demonstrate the above tasks in the allotted time, the team will be disqualified from the competition.
4. Each team will receive an assigned time from the LunaPit crew chief, on a first come, first serve basis, on Monday, May 21, 2012 or Tuesday, May 22, 2012 to show the communication judges their compliance with the rules.
5. The NASA communications technical experts will be available to help teams make sure that they are ready for the communication judge’s station on Monday, May 21, 2012 or Tuesday, May 22, 2012.

6. Once the team arrives at the communication judge's station, the team can no longer receive assistance from the NASA communications technical experts.
7. If a team is on the wrong channel during their competition attempts, the team will be required to power down and be disqualified.

C. WIRELESS DEVICE OPERATION IN THE PITS

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

24) The Lunabot must be contained within 1.5 m length x 0.75 m width x 0.75 m height. The Lunabot may deploy or expand beyond the 1.5 m x 0.75 m footprint after the start of each competition attempt, but may not exceed a 1.5 meter height. The Lunabot may not pass beyond the confines of the outside wall of the LunArena and the LunaBin during each competition attempt to avoid potential interference with the surrounding tent. The team must declare the orientation of length and width to the inspection judge. Because of actual lunar hardware requirements, no ramps of any kind will be provided or allowed. An arrow on the reference point must mark the forward direction of the Lunabot in the starting position configuration. The judges will use this reference point and arrow to orient the Lunabot in the randomly selected direction and position. A multiple robot system is allowed but the total mass and starting dimensions of the whole system must comply with the volumetric dimensions given in this rule.

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

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

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

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

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

30) No team can intentionally harm another team's Lunabot. This includes radio jamming, denial of service to network, BP-1 manipulation, ramming, flipping, pinning, conveyance of current, or other forms of damage as decided upon by the judges. Immediate disqualification will result if judges deem any maneuvers by a team as being offensive in nature. Erratic behavior or loss of control of the Lunabot as determined by the judges will be cause for immediate disqualification. A judge may disable the Lunabot by pushing the red emergency stop button at any time.

31) Teams must electronically submit documentation containing a description of their Lunabot, its operation, potential safety hazards, a diagram, and basic parts list by April 30, 2012 at 12:00 p.m. (noon) eastern time in the United States.

32) Teams must electronically submit video documentation containing no less than 30 seconds but no more than 5 minutes of their Lunabot in operation for at least one full cycle of operation by April 30, 2012 at 12:00 p.m. (noon) eastern time in the United States. One full cycle of operations includes excavation and depositing material. This video documentation is solely for technical evaluation of the Lunabot.

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

Shipping

33) Teams may ship their Lunabots to arrive no earlier than May 14, 2012. The Lunabots will be held in a safe, unairconditioned area and be placed in the team's LunaPit by Monday, May 21, 2012. The shipping address is:

Kennedy Space Center Visitor Complex
Lunabotics Mining Competition
Mail Code: DNPS
Kennedy Space Center, FL 32899

34) Return shipping arrangements must be made prior to the competition. All Lunabots must be picked up from the Kennedy Space Center Visitor Complex no later than 5:00 p.m. on Tuesday, May 29, 2012. Any abandoned Lunabots will be discarded after this date.

LunArena Diagrams

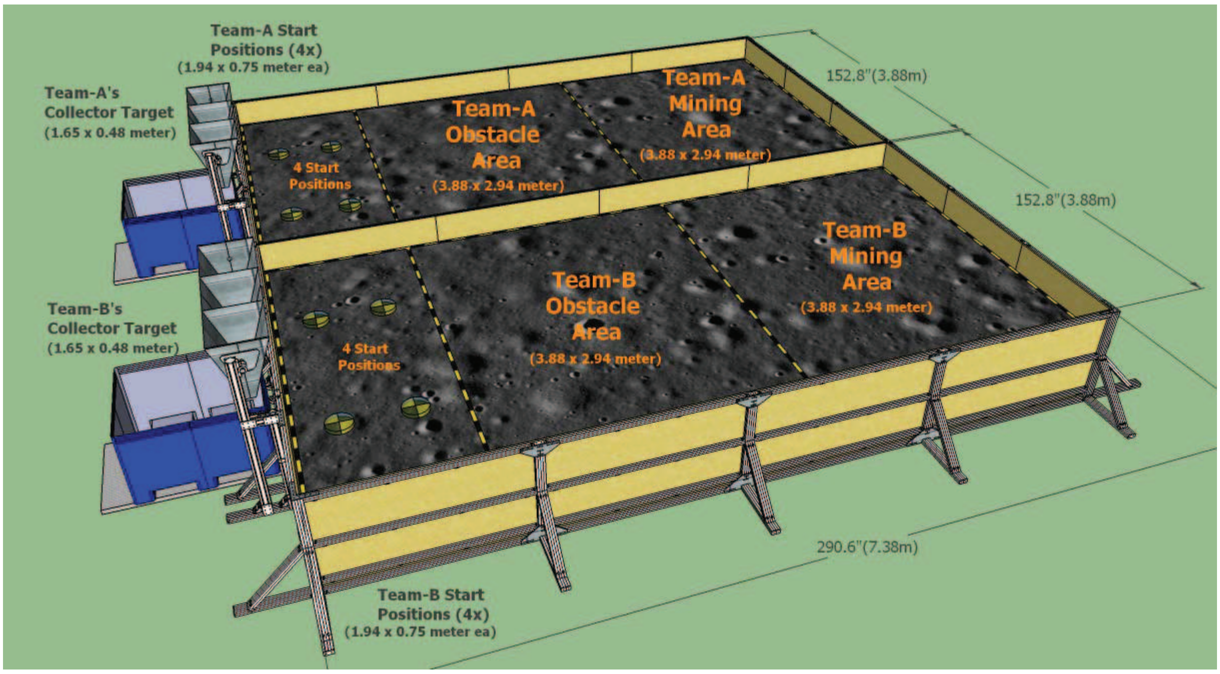


Diagram 1: LunArena (isometric view)

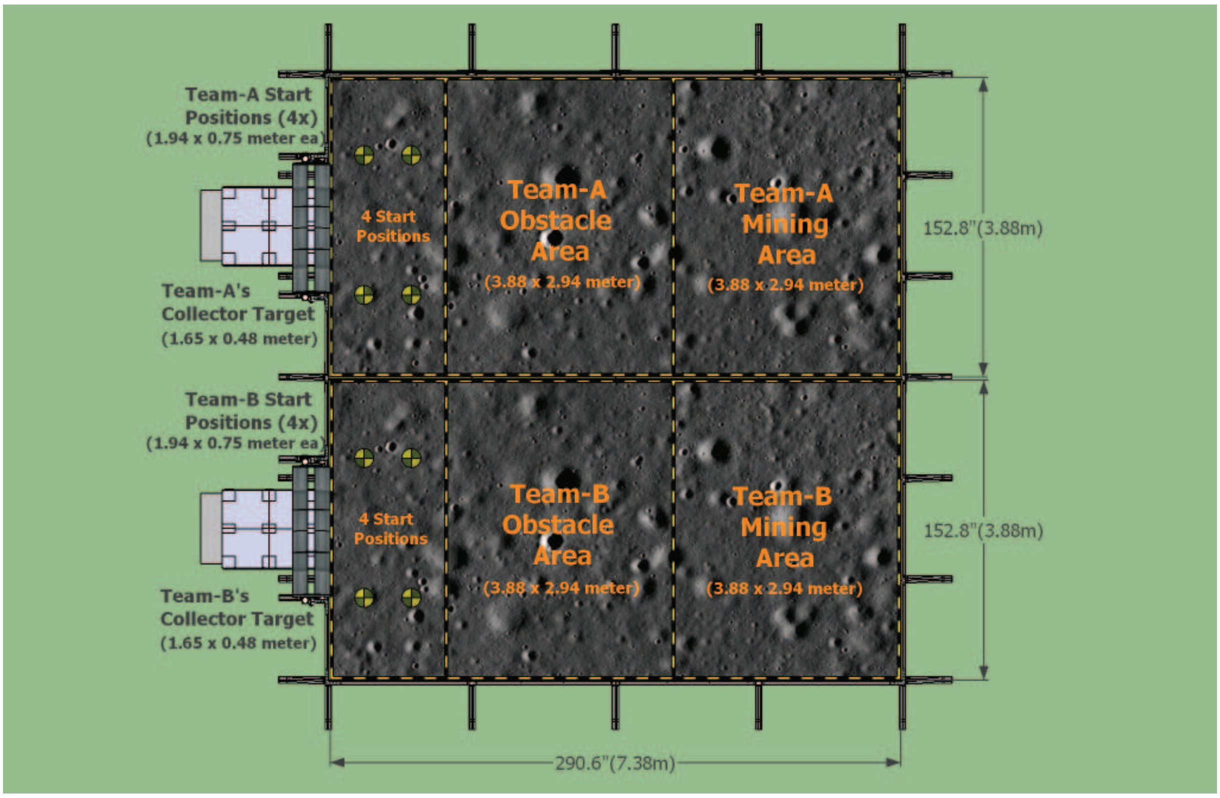


Diagram 2: LunArena (top view)

LunaBin Diagram

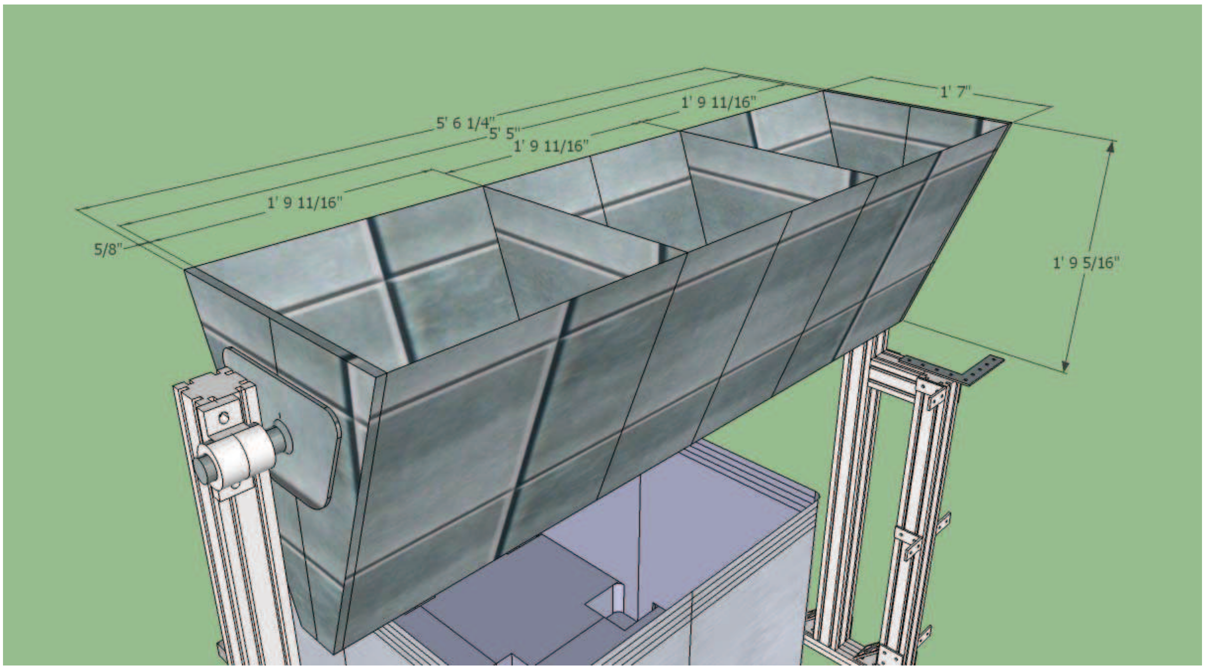


Diagram 3: LunaBin

Lunabotics Systems Engineering Paper

Each team must submit a Systems Engineering Paper electronically in PDF by April 23, 2012 at 12:00 p.m. (noon) eastern time in the United States. Cover page must include: team name, title of paper, full names of all team members, university name and faculty advisor's full name. **Appendices are not allowed.** All pertinent information required in the rubric must be in the body of the paper. A minimum score of 15 out of 20 possible points must be achieved to qualify to win in this category. In the case of a tie, the judges will choose the winning Systems Engineering Paper. The judges' decision is final. The team with the winning Systems Engineering Paper will receive a team plaque, individual certificates, and a $500 team scholarship. Second and third place winners will receive individual team certificates.

For reference, the NASA Systems Engineering Handbook is available at: http://education.ksc.nasa.gov/esmdspacegrant/LunarRegolithExcavatorCourse/Site%20Documents/NASA%20SP-2007-6105.pdf.

Lunabotics Systems Engineering Paper Scoring Rubric					
Elements	**4**	**3**	**2**	**1**	**0**
Content: • Formatted professionally, clearly organized, correct grammar and spelling, maximum of 20 pages not counting the cover and source pages only; 12 font size; single spaced. No appendices allowed. • Cover page • Introduction • Purpose • Sources	All five elements are exceptionally demonstrated	Five elements are clearly demonstrated	Four elements are clearly demonstrated	Three or less elements are clearly demonstrated	Zero elements are clearly demonstrated
Intrinsic Merit: • Deliverables identified • Budget • Schedule • Major reviews: system requirements, preliminary design and critical design • Illustrations support the technical content	All five elements are exceptionally demonstrated	Five elements are clearly demonstrated	Four elements are clearly demonstrated	Three or less elements are clearly demonstrated	Zero elements are clearly demonstrated
Technical Merit: • Concept of operations • System Hierarchy • Basis of design • Interfaces defined • Requirements definition • Design margins • Trade-off assessment • Risk assessment • Reliability • Verification • Requirement flow-down to validation and checkout • Use of system life cycle	One point for each element exceptionally demonstrated up to twelve points.				

Lunabotics Outreach Project Report

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

Each team must submit a report of the Lunabotics Outreach Project electronically in PDF by April 23, 2012 at 12:00 p.m. (noon) eastern time in the United States. Cover page must include: team name, title of paper, full names of all team members, university name and faculty advisor's full name. A minimum score of 15 out of 20 possible points must be achieved to qualify to win in this category. In the case of a tie, the judges will choose the winning outreach project. The judges' decision is final. The team with the winning outreach project will receive a team plaque, individual certificates, and a $500 team scholarship. Second and third place winners will receive individual team certificates.

Lunabotics Outreach Project Scoring Rubric

Elements	4	3	2	1	0
Content: • Introduction • Outreach recipient group identified • Purpose • Cover page	All four elements are exceptionally demonstrated	Four elements are clearly demonstrated	Three elements are clearly demonstrated	Two elements are clearly demonstrated	Zero elements are clearly demonstrated
Educational Outreach: • Inspires others to learn about robotics, engineering or lunar activities • Quality of the outreach • Utilizes hands-on activities	All three elements are exceptionally demonstrated	Three elements are clearly demonstrated	Two elements are clearly demonstrated	One element is clearly demonstrated	Zero elements are clearly demonstrated
Creativity: • Inspirational • Engages others in robotics, engineering or lunar activities • Material corresponds to audience's level of understanding	All three elements are exceptionally demonstrated	Three elements are clearly demonstrated	Two elements are clearly demonstrated	One element is clearly demonstrated	Zero elements are clearly demonstrated
Illustrations and Media: • Appropriate • Demonstrates the outreach project • Pictures	All three elements are exceptionally demonstrated	Three elements are clearly demonstrated	Two elements are clearly demonstrated	One element is clearly demonstrated	Zero elements are clearly demonstrated
Formatting and Appearance: • Correct grammar and spelling • Five-page limit (cover page and appendices excluded in page count) • Clearly organized	All three elements are exceptionally demonstrated	Three elements are clearly demonstrated	Two elements are clearly demonstrated	One element is clearly demonstrated	Zero elements are clearly demonstrated

Lunabotics Slide Presentation and Demonstration

The Lunabotics Slide Presentation is an optional category in the overall competition. The presentation and demonstration must be no more than 20 minutes with an additional 5 minutes for questions and answers. It will be judged at the competition in front of an audience including NASA and private industry judges. The presentations must be submitted electronically in PDF by April 23, 2012 at 12:00 p.m. (noon) eastern time in the United States. A cover slide must contain the team name, title of presentation, full names of all team members, university name, and faculty advisor's full name. A minimum score of 18 out of 24 possible points must be achieved to qualify to win in this category. In the case of a tie, the judges will choose the winning presentation. The judges' decision is final. The team with the winning presentation will receive a team plaque, individual team certificates, and a $500 team scholarship. Second and third place winners will receive individual team certificates.

Lunabotics Slide Presentation Scoring Rubric					
Elements	**4**	**3**	**2**	**1**	**0**
Content: • Cover slide • Introduction • Purpose • Sources referenced	All four elements are exceptionally demonstrated	Four elements are clearly demonstrated	Three elements are clearly demonstrated	Two or less elements are clearly demonstrated	Zero elements are clearly demonstrated
Technical Merit: • Final Lunabot design • Design process • Design decisions • Lunabot functionality • Safety features • Special features	All six elements are exceptionally demonstrated	Six elements are clearly demonstrated	Five elements are clearly demonstrated	Four or less elements are clearly demonstrated	Zero elements are clearly demonstrated
Creativity: • Innovative • Inspirational • Engaging • Highlights what makes the Lunabot design unique • infuses personality	All five elements are exceptionally demonstrated	Five elements are clearly demonstrated	Four elements are clearly demonstrated	Three or less elements are clearly demonstrated	Zero elements are clearly demonstrated
Illustrations and Media: • Appropriate • Supports the technical content • Shows progression of project • Clearly presents design of Lunabot	All four elements are exceptionally demonstrated	Four elements are clearly demonstrated	Three elements are clearly demonstrated	Two or less elements are clearly demonstrated	Zero elements are clearly demonstrated
Formatting and Appearance: • Proper grammar • Correct spelling • Readable • Aesthetically pleasing	All four elements are exceptionally demonstrated	Four elements are clearly demonstrated	Three elements are clearly demonstrated	Two or less elements are clearly demonstrated	Zero elements are clearly demonstrated
Presentation: • Makes presentation at competition • Demonstrates Lunabot under hardwire and pendent control during presentation • Engages audience • Answers questions	All four elements are exceptionally demonstrated	Four elements are clearly demonstrated	Three elements are clearly demonstrated	Two or less elements are clearly demonstrated	Zero elements are clearly demonstrated

Lunabotics Team Spirit

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

Lunabotics Team Spirit Competition Scoring Rubric				
Elements	**3**	**2**	**1**	**0**
Teamwork: • Exhibits teamwork in and out of the LunArena • Exhibits a strong sense of collaboration within the team • Supports other teams with a healthy sense of competition	All three elements are exceptionally demonstrated	Three elements are clearly demonstrated	Two or less elements are clearly demonstrated	Zero elements are clearly demonstrated
Attitude: • Exudes a positive attitude in all interactions, not limited to competition attempt • Demonstrates an infectious energy • Motivates and encourages team • Keeps pit clean and tidy at all times	All four elements are exceptionally demonstrated	Four elements are clearly demonstrated	Three or less elements are clearly demonstrated	Zero elements are clearly demonstrated
Creativity: • Demonstrates creativity • Wears distinctive team shirts or hats • Decorates team's LunaPit to reflect school/team spirit	All three elements are exceptionally demonstrated	Three elements are clearly demonstrated	Two or less elements are clearly demonstrated	Zero elements are clearly demonstrated
Engage: • Engages audience in team spirit activities • Engages other teams in team spirit activities • Makes acquaintances with members of other teams	All three elements are exceptionally demonstrated	Three elements are clearly demonstrated	Two or less elements are clearly demonstrated	Zero elements are clearly demonstrated
Originality: • Demonstrates originality in team activities • Displays originality in the team name • Displays originality in the team logo	All three elements are exceptionally demonstrated	Three elements are clearly demonstrated	Two or less elements are clearly demonstrated	Zero elements are clearly demonstrated

Categories for Bonus Points

Collaboration between a majority school with a designated United States Minority Serving Institution
Collaboration between a majority school and a designated U.S. minority serving institution (MSI) must be identified by November 30, 2011. MSI student team members must submit their student participant forms and transcripts and be indicated on the team roster by January 31, 2012 at 12:00 p.m. (noon) eastern time in the United States to receive the 10 bonus points. A list of U.S. minority serving institutions may be found at: http://www2.ed.gov/about/offices/list/ocr/edlite-minorityinst.html.

Multidisciplinary Engineering Teams
Team members from each different science, technology, engineering or mathematics (STEM) discipline* will count for one bonus point up to a maximum of ten. Disciplines will be indicated on the student participant form by January 31, 2012 at 12:00 p.m. (noon) eastern time in the United States. No bonus points will be given in this category if a team has only one discipline represented. If a member of the team is in a STEM discipline that is not on this list, the team lead or faculty advisor may e-mail Susan.G.Sawyer@nasa.gov` to request approval of that discipline for the competition.

Aeronautical Engineering
Aerospace Engineering
Astrobiology
Astronautical Engineering
Astronomy
Astrophysics
Atmospheric Sciences
Bacteriology
Biochemistry
Biology
Biophysics
Chemical Engineering
Chemistry
Civil Engineering
Computer Engineering
Computer Science
Electrical Engineering
Engineering Management
Environmental Engineering
Geography
Geological Engineering
Geosciences
Health Engineering
Industrial/Manufacturing Engineering
Information Technology
Materials/Metallurgical Engineering
Mathematics
Mechanical Engineering
Microbiology
Mining Engineering
Natural Resource Management
Nuclear Engineering
Oceanography
Optics
Physics
Software Engineering
Systems Engineering

*Team members may be from other disciplines, but only STEM disciplines are awarded bonus points.

Mined and Deposited BP-1
Teams not winning first, second, or third place in the mining category can earn one bonus point toward the Joe Kosmo Award for Excellence for each kilogram of BP-1 mined and deposited up to a maximum of ten points during their competition attempts.

Categories & Awards

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

Category	Required/ Optional	Due Dates	Award	Maximum Points toward Joe Kosmo Award for Excellence
On-site Mining in the LunArena	Required	May 23-26, 2012	First place $3,000 team scholarship and Kennedy launch invitations	30
			Second place $2,000 team scholarship and Kennedy launch invitations	25
			Third place $1,000 team scholarship and Kennedy launch invitations	20
			Teams not placing 1st, 2nd, or 3rd will receive one point per kilogram mined and deposited up to 10 points	Up to 10
Systems Engineering Paper	Required	April 23, 2012	$500 team scholarship	Up to 20
Outreach Project Report	Required	April 23, 2012	$500 team scholarship	Up to 20
Slide Presentation and Demonstration	Optional	April 23, 2012 and On-Site on May 23-26, 2012	$500 team scholarship	Up to 24
Team Spirit Competition	Optional	All Year	$500 team scholarship	Up to 15
Collaboration With a Minority Serving Institution	Optional	Nov. 30, 2011		10 bonus points
Multidisciplinary Team	Optional	Jan. 31, 2012		Up to 10 bonus points
Joe Kosmo Award for Excellence	Grand Prize for Most Points	All Year	A school trophy, $5,000 team scholarship, KSC launch invitations, and up to $1,000 travel expenses for each team member and one faculty advisor to attend one of NASA's remote research and technology tests	Total of above points, maximum of 129 points possible
Judges' Innovation Award	Optional	May 23-26, 2012	A school trophy	
Efficient Use of Communications Power Award	Optional	May 23-26, 2012	A school trophy	

Lunabotics Checklist

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

☐ Registration Application*	November 30, 2011
☐ Systems Engineering Paper	April 23, 2012
☐ Outreach Project Report	April 23, 2012
☐ On-site Mining	May 21-26, 2012
o Team Check-in, Unload/Uncrate Lunabot	May 21 & 22, 2012 by noon
o Practice Days	May 21-23, 2012
o Competition Days	May 23-26, 2012
o Awards Ceremony	May 26, 2012 (evening)

Optional Competition Elements

☐ Presentation File	April 23, 2012
☐ Team Spirit	All year

Required Documentation

☐ Registration Application	November 30, 2011
☐ Letter of Support from lead university's Dean of Engineering	November 30, 2011
☐ Letter of Support from lead university's Faculty Advisor	November 30, 2011
☐ MSI Collaboration Notification	November 30, 2011
☐ Team Roster with MSI students indicated	January 31, 2012
☐ Student Participant Form	January 31, 2012
☐ Faculty Form	January 31, 2012
☐ Transcripts (unofficial copy is acceptable)**	January 31, 2012
☐ Signed Media Release Form	January 31, 2012
☐ Request for Team Invitation Letter for International Teams***	February 24, 2012
☐ Team Photo including faculty (high resolution .jpg format preferred)	March 30, 2012
☐ Team Biography (200 words maximum)	March 30, 2012
☐ Head Count Form	March 30, 2012
☐ Revised Team Roster (no changes accepted after this date)	March 30, 2012
☐ Rule 31 documentation	April 30, 2012
☐ Rule 32 video	April 30, 2012

Optional Documentation

☐ Student Resume (optional)	January 31, 2012

*Registration is limited to the first 60 approved teams. Registration is limited to one team per university campus. Internationally, registration is limited to 10 teams per country. Registration will end when NASA approves 60 applications or on November 30, 2011, whichever occurs first.

**Each student's Transcript or Statement of Marks must be from the university and show:

- name of university
- name of student
- major course of study
- current student status within the 2011-2012 academic year
- coursework taken and grades

***International team's invitation letters for visa request purposes will be mailed during the week of February 27, 2012 with only the names of faculty advisors and student team members on the team roster who have completed their participant forms and submitted their transcripts or statement of marks. NASA will not provide individual letters.

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

Definitions

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

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

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

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

Functional task – The excavation of BP-1 from the LunArena by the Lunabot and deposit of BP-1 from the Lunabot into the LunaBin.

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

Practice time – Teams will be allowed to practice with their Lunabots in the LunArena. NASA technical experts will offer feedback on real-time networking performance during practice attempt. Only one practice attempt is required and guaranteed.

Reference point – A fixed location signified by an arrow showing the forward direction on the Lunabot that will serve to verify the starting orientation of the Lunabot within the LunArena.

LunaBin – A collector bin in NASA's Lunabotics Mining Competition provided by NASA for each competition attempt into which each team will deposit excavated BP-1. The LunaBin will be large enough to accommodate each team's excavated BP-1. The LunaBin will be stationary and located adjacent to the LunArena. See Diagram 3.

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

LunaPoints – Points earned from the two competition attempts in NASA's Lunabotics Mining Competition will be averaged to determine ranking in the on-site mining category.

LunArena – An open-topped container (i.e., a box with a bottom and 4 side walls only), containing BP-1, within which the Lunabot will perform each competition attempt. The inside dimensions of the each side of the LunArena will be 7.38 meters long and 3.88 meters wide, and 1 meter in depth. The BP-1 aggregate will be less than one meter in depth. A dividing wall will be in the center of the LunArena. The LunArena for the practice days and official competition will be provided by NASA. The LunArena will be outside in an enclosed tent. The LunArena lighting will consist of artificial lamps inside a tent structure. Assume daylight conditions. The atmosphere will be an air-conditioned tent without significant air currents and cooled to approximately 77 degrees Fahrenheit. See Diagrams 1 – 3.

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

Time Limit – 10 minutes to set up the Lunabot in the LunArena, 10 minutes for the Lunabot to perform the functional task, and 5 minutes to remove the Lunabot.

maxon DC motor and maxon EC motor
Key information

See also: Technology – short and to the point, explanation of the motor

The motor as an energy converter

The electrical motor converts electrical power P_{el} (current I and voltage U) into mechanical power P_{mech} (speed n and torque M). The losses that arise are divided into frictional losses, attributable to P_{mech} and in Joule power losses P_J of the winding (resistance R). Iron losses do not occur in the coreless maxon DC motors. In maxon EC motors, they are treated formally like an additional friction torque. The power balance can therefore be formulated as:

$$P_{el} = P_{mech} + P_J$$

The detailed result is as follows

$$U \cdot I = \frac{\pi}{30\,000} n \cdot M + R \cdot I^2$$

Electromechanical motor constants
The geometric arrangement of the magnetic circuit and winding defines in detail how the motor converts the electrical input power (current, voltage) into mechanical output power (speed, torque). Two important characteristic values of this energy conversion are the speed constant k_n and the torque constant k_M. The speed constant combines the speed n with the voltage induced in the winding U_{ind} (=EMF). U_{ind} is proportional to the speed; the following applies:

$$n = k_n \cdot U_{ind}$$

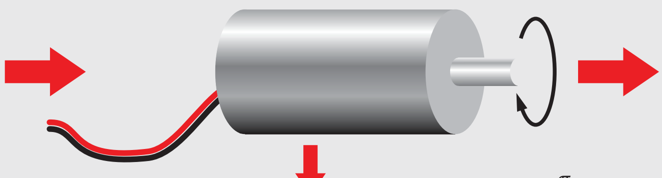
Similarly, the torque constant links the mechanical torque M with the electrical current I.

$$M = k_M \cdot I$$

The main point of this proportionality is that torque and current are equivalent for the maxon motor.
The current axis in the motor diagrams is therefore shown as parallel to the torque axis as well.

Units
In all formulas, the variables are to be used in the units according to the catalog (cf. physical variables and their units on page 42).

The following applies in particular:
– All torques in mNm
– All currents in A (even no-load currents)
– Speeds (rpm) instead of angular velocity (rad/s)



$P_{el} = U \cdot I$ $\quad P_J = R \cdot I^2$ $\quad P_{mech} = \frac{\pi}{30\,000} M \cdot n$

Motor constants
Speed constant k_n and torque constant k_M are not independent of one another. The following applies:

$$k_n \cdot k_M = \frac{30\,000}{\pi}$$

The speed constant is also called specific speed. Specific voltage, generator or voltage constants are mainly the reciprocal value of the speed constant and describe the voltage induced in the motor per speed. The torque constant is also called specific torque. The reciprocal value is called specific current or current constant.

Motor diagrams

A diagram can be drawn for every maxon DC and EC motor, from which key motor data can be taken. Although tolerances and temperature influences are not taken into consideration, the values are sufficient for a first estimation in most applications. In the diagram, speed n, current I, power output P_2 and efficiency η are applied as a function of torque M at constant voltage U.

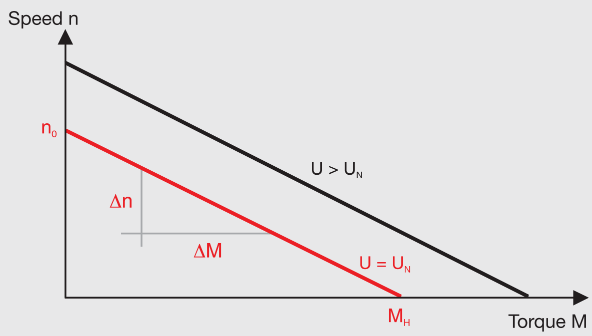
Speed-torque line
This curve describes the mechanical behavior of the motor at a constant voltage U:
– Speed decreases linearly with increasing torque.
– The faster the motor turns, the less torque it can provide.
The curve can be described with the help of the two end points, no-load speed n_0 and stall torque M_H (cf. lines 2 and 7 in the motor data).
DC motors can be operated at any voltage. No-load speed and stall torque change proportionally to the applied voltage. This is equivalent to a parallel shift of the speed-torque line in the diagram. Between the no-load speed and voltage, the following proportionality applies in good approximation

$$n_0 \approx k_n \cdot U$$

where k_n is the speed constant (line 13 of the motor data).

Independent of the voltage, the speed-torque line is described most practically by the slope or gradient of the curve (line 14 of the motor data).

$$\frac{\Delta n}{\Delta M} = \frac{n_0}{M_H}$$



Derivation of the speed-torque line
The following occurs if one replaces current I with torque M using the torque constant in the detailed power balance:

$$U \cdot \frac{M}{k_M} = \frac{\pi}{30\,000} n \cdot M + R \cdot \left(\frac{M}{k_M}\right)^2$$

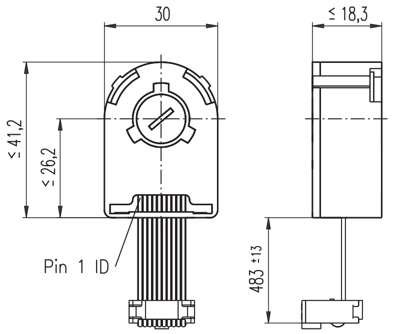
Transformed and taking account of the close relationship of k_M and k_n, an equation is produced of a straight line between speed n and torque M.

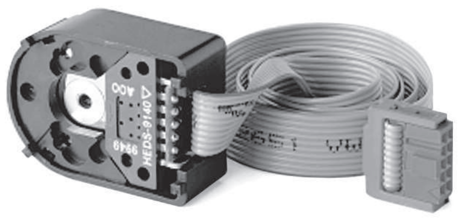
$$n = k_n \cdot U - \frac{30\,000}{\pi} \cdot \frac{R}{k_M^2} \cdot M$$

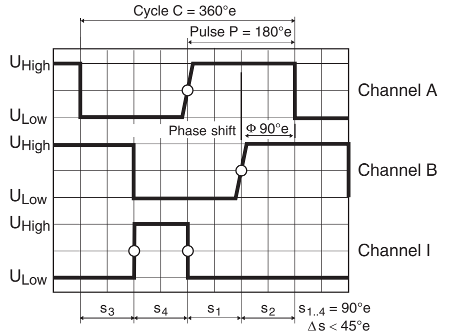
or with the gradient and the no-load speed n_0

$$n = n_0 - \frac{\Delta n}{\Delta M} \cdot M$$

Encoder HEDL 5540 500 CPT, 3 Channels, with Line Driver RS 422







Direction of rotation cw (definition cw p. 48)

- Stock program (red)
- Standard program (white)
- Special program (on request) (grey)

Order Number	110512	110514	110516
Type			
Counts per turn	500	500	500
Number of channels	3	3	3
Max. operating frequency (kHz)	100	100	100
Max. speed (rpm)	12000	12000	12000
Shaft diameter (mm)	3	4	6

maxon Modular System

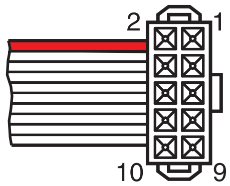
+ Motor	Page	+ Gearhead	Page	+ Brake	Page	Overall length [mm] / ● see Gearhead (110512)	(110514)	(110516)
RE 25	77/79					75.3		
RE 25	77/79	GP 26 / GP 32	227/229			●		
RE 25	77/79	KD 32, 1.0 - 4.5 Nm	235			●		
RE 25	77/79	GP 32, 0.75 - 6.0 Nm	230/232			●		
RE 25	77/79	GP 32 S	249-251			●		
RE 25, 20 W	79			AB 28	318	105.7		
RE 25, 20 W	79	GP 26 / GP 32	227/229	AB 28	318	●		
RE 25, 20 W	79	KD 32, 1.0 - 4.5 Nm	235	AB 28	318	●		
RE 25, 20 W	79	GP 32, 0.75 - 6.0 Nm	230/232	AB 28	318	●		
RE 25, 20 W	79	GP 32 S	249-251	AB 28	318	●		
RE 35, 90 W	81						91.7	
RE 35, 90 W	81	GP 32, 0.75 - 4.5 Nm	229				●	
RE 35, 90 W	81	GP 32, 0.75 - 6.0 Nm	231/232				●	
RE 35, 90 W	81	GP 32, 4.0 - 8.0 Nm	234				●	
RE 35, 90 W	81	GP 42, 3.0 - 15 Nm	237				●	
RE 35, 90 W	81	GP 32 S	249-251				●	
RE 35, 90 W	81			AB 28	318	124.2		
RE 35, 90 W	81	GP 32, 0.75 - 4.5 Nm	229	AB 28	318	●		
RE 35, 90 W	81	GP 32, 0.75 - 6.0 Nm	231/232	AB 28	318	●		
RE 35, 90 W	81	GP 42, 3.0 - 15 Nm	237	AB 28	318	●		
RE 35, 90 W	81	GP 32 S	249-251	AB 28	318	●		
RE 35, 90 W	81	GP 32, 4.0 - 8.0 Nm	234	AB 28	318	●		
RE 40, 150 W	82						91.7	
RE 40, 150 W	82	GP 42, 3.0 - 15 Nm	237				●	
RE 40, 150 W	82	GP 52, 4.0 - 30 Nm	240				●	
RE 40, 150 W	82			AB 28	318	124.2		
RE 40, 150 W	82	GP 42, 3.0 - 15 Nm	237	AB 28	318	●		
RE 40, 150 W	82	GP 52, 4.0 - 30 Nm	240	AB 28	318	●		
A-max 26	102-108					63.5		
A-max 26	102-108	GP 26, GS 30	227/228			●		
A-max 26	102-108	GP 32, 0.4 - 2.0 Nm	231			●		
A-max 26	102-108	GP 32, 0.75 - 6.0 Nm	230/233			●		
A-max 26	102-108	GS 38, 0.1 - 0.6 Nm	236			●		
A-max 26	102-108	GP 32 S	249-251			●		
A-max 32	110/112						82.3	
A-max 32	110/112	GP 32, 0.75 - 6.0 Nm	231/233				●	
A-max 32	110/112	GS 38, 0.1 - 0.6 Nm	236				●	
A-max 32	110/112	GP 32 S	249-251				●	

Technical Data

Supply voltage V_{CC}	5 V ± 10%
Output signal	EIA Standard RS 422
driver used:	DS26LS31
Phase shift Φ	90°e ± 45°e
Signal rise time (typically, at C_L = 25 pF, R_L = 2.7 kΩ, 25°C)	180 ns
Signal fall time (typically, at C_L = 25 pF, R_L = 2.7 kΩ, 25°C)	40 ns
Index pulse width	90°e
Operating temperature range	-40 … +100°C
Moment of inertia of code wheel	≤ 0.6 gcm²
Max. angular acceleration	250 000 rad s^{-2}
Output current per channel	min. -20 mA, max. 20 mA
Option	1000 Counts per turn, 2 Channels

The index signal I is synchronised with channel A or B.

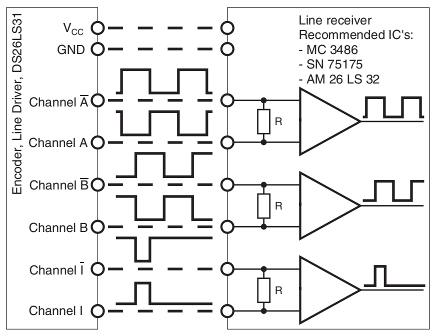
Pin Allocation



1 N.C.
2 V_{CC}
3 GND
4 N.C.
5 Channel $\overline{A}$
6 Channel A
7 Channel $\overline{B}$
8 Channel B
9 Channel $\overline{I}$ (Index)
10 Channel I (Index)

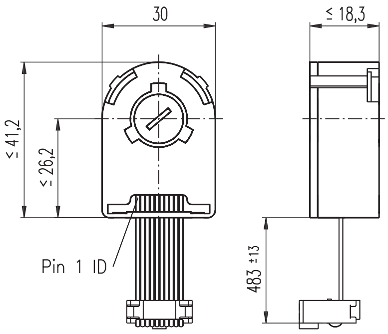
Pin type Berg 246770
flat band cable AWG 28

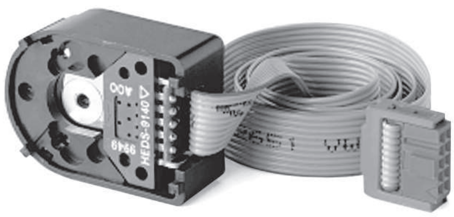
Connection example

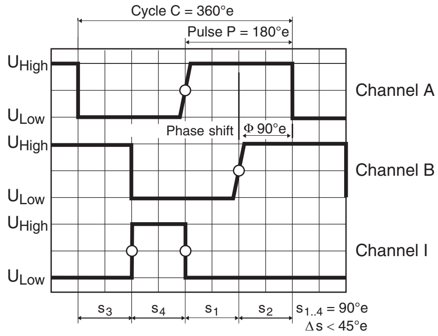


Terminal resistance R = typical 120 Ω

Encoder HEDL 5540 500 CPT, 3 Channels, with Line Driver RS 422





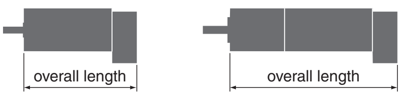


Direction of rotation cw (definition cw p. 48)

- Stock program
- Standard program
- Special program (on request)

Order Number

Type	110512	110514	110516	110518
Counts per turn	500	500	500	500
Number of channels	3	3	3	3
Max. operating frequency (kHz)	100	100	100	100
Max. speed (rpm)	12000	12000	12000	12000
Shaft diameter (mm)	3	4	6	8



maxon Modular System

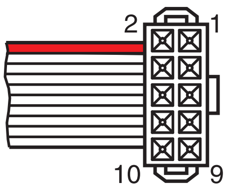
+ Motor	Page	+ Gearhead	Page	+ Brake	Page	Overall length [mm] / ● see Gearhead			
RE 50, 200 W	83								128.7
RE 50, 200 W	83	GP 52, 4 - 30 Nm	241						●
RE 50, 200 W	83	GP 62, 8 - 50 Nm	242						●
RE 65, 250 W	84								157.3
RE 65, 250 W	84	GP 81, 20 - 120 Nm	243						●
EC 32, 80 W	154						78.4		
EC 32, 80 W	154	GP 32, 0.75 - 4.5 Nm	229				●		
EC 32, 80 W	154	GP 32, 0.75 - 6.0 Nm	231/233				●		
EC 32, 80 W	154	GP 32 S	249-251				●		
EC 40, 170 W	155							103.3	
EC 40, 170 W	155	GP 42, 3.0 - 15 Nm	237					●	
EC 40, 170 W	155	GP 52, 4.0 - 30 Nm	240					●	
EC-max 30, 40 W	166						62.6		
EC-max 30, 40 W	166	GP 32, 1 - 6 Nm	233				●		
EC-max 30, 40 W	166			AB 20	316		101.7		
EC-max 30, 40 W	166	GP 32, 1 - 6 Nm	233	AB 20	316		●		
EC-max 30, 40 W	166	GP 32 S					●		
EC-max 30, 40 W	166	GP 32, 4.0 - 8.0 Nm	234						
EC-max 30, 60 W	167						84.6		
EC-max 30, 60 W	167	GP 32, 4.0 - 8.0 Nm	234						
EC-max 30, 60 W	167	GP 42, 3 - 15 Nm	238				●		
EC-max 30, 60 W	167			AB 20	316		120.4		
EC-max 30, 60 W	167	GP 42, 3 - 15 Nm	238	AB 20	316		●		
EC-max 40, 70 W	168							81.4	
EC-max 40, 70 W	168	GP 42, 3 - 15 Nm	238					●	
EC-max 40, 70 W	168			AB 28	317			121.4	
EC-max 40, 70 W	168	GP 42, 3 - 15 Nm	238	AB 28	317			●	
EC-max 40, 120 W	169							111.4	
EC-max 40, 120 W	169	GP 52, 4 - 30 Nm	241					●	
EC-max 40, 120 W	169			AB 28	317			140.8	
EC-max 40, 120 W	169	GP 52, 4 - 30 Nm	241	AB 28	317			●	

Technical Data

Supply voltage V_{CC}	5 V ± 10%
Output signal	EIA Standard RS 422
driver used:	DS26LS31
Phase shift Φ	90°e ± 45°e
Signal rise time	
(typically, at C_L = 25 pF, R_L = 2.7 kΩ, 25°C)	180 ns
Signal fall time	
(typically, at C_L = 25 pF, R_L = 2.7 kΩ, 25°C)	40 ns
Index pulse width	90°e
Operating temperature range	-40 ... +100°C
Moment of inertia of code wheel	≤ 0.6 gcm²
Max. angular acceleration	250 000 rad s⁻²
Output current per channel	min. -20 mA, max. 20 mA
Option	1000 Counts per turn, 2 Channels

The index signal I is synchronised with channel A or B.

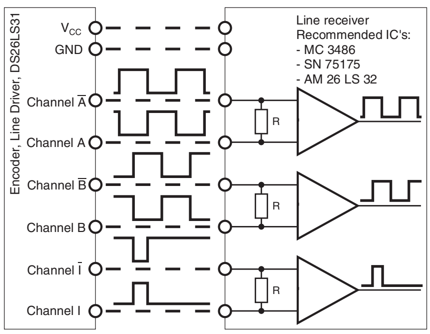
Pin Allocation



1 N.C.
2 V_{CC}
3 GND
4 N.C.
5 Channel $\bar{A}$
6 Channel A
7 Channel $\bar{B}$
8 Channel B
9 Channel $\bar{I}$ (Index)
10 Channel I (Index)

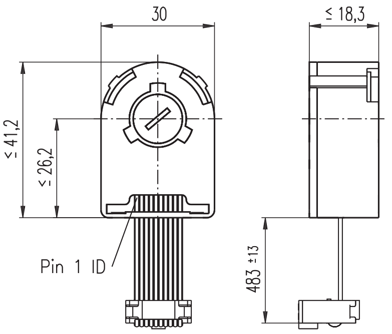
Pin type Berg 246770
flat band cable AWG 28

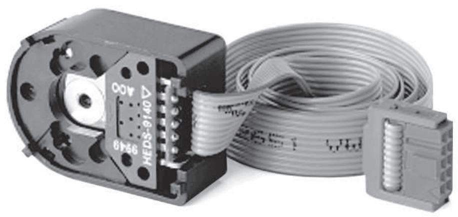
Connection example

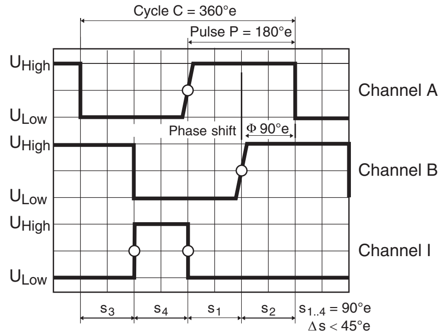


Terminal resistance R = typical 120 Ω

Encoder HEDL 5540 500 CPT, 3 Channels, with Line Driver RS 422







Direction of rotation cw (definition cw p. 48)

- Stock program
- Standard program
- Special program (on request)

Order Number

Type	110512	110514	110516
Counts per turn	500	500	500
Number of channels	3	3	3
Max. operating frequency (kHz)	100	100	100
Max. speed (rpm)	12000	12000	12000
Shaft diameter (mm)	3	4	6

maxon Modular System

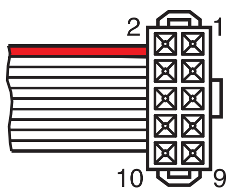
+ Motor	Page	+ Gearhead	Page	+ Brake	Page	Overall length [mm] / ● see Gearhead		
RE 25	78					63.8		
RE 25	78	GP 26 / GP 32	227/229			●		
RE 25	78	KD 32, 1.0 - 4.5 Nm	235			●		
RE 25	78	GP 32, 0.75 - 6.0 Nm	230/232			●		
RE 25	78	GP 32 S	249-251			●		
RE 25, 20 W	78			AB 28	318	94.3		
RE 25, 20 W	78	GP 26 / GP 32	227/229	AB 28	318	●		
RE 25, 20 W	78	KD 32, 1.0 - 4.5 Nm	235	AB 28	318	●		
RE 25, 20 W	78	GP 32, 0.75 - 6.0 Nm	230/232	AB 28	318	●		
RE 25, 20 W	78	GP 32 S	249-251	AB 28	318	●		
EC-4pole 22	173					70.1		
EC-4pole 22	173	GP 22 / GP 32	224/233			●		
EC-4pole 22	173	GP 32 S	249-251			●		
EC-4pole 22	174					87.5		
EC-4pole 22	174	GP 22 / GP 32	224/233			●		
EC-4pole 22	174	GP 32 S	249-251			●		
EC-4pole 30	175						67.6	
EC-4pole 30	175	GP 32, 4.0 - 8.0 Nm	234				●	
EC-4pole 30	175	GP 42, 3 - 15 Nm	238				●	
EC-4pole 30	175			AB 20	316		79.1	
EC-4pole 30	175	GP 32, 4.0 - 8.0 Nm	234	AB 20	316		●	
EC-4pole 30	175	GP 42, 3 - 15 Nm	238	AB 20	316		●	
EC-4pole 30	176						84.6	
EC-4pole 30	176	GP 32, 4.0 - 8.0 Nm	234				●	
EC-4pole 30	176	GP 42, 3 - 15 Nm	238				●	
EC-4pole 30	176			AB 20	316		96.1	
EC-4pole 30	176	GP 32, 4.0 - 8.0 Nm	234	AB 20	316		●	
EC-4pole 30	176	GP 42, 3 - 15 Nm	238	AB 20	316		●	
EC-i 40, 50 W	190							49.0
EC-i 40, 50 W	190	GP 32, 1 - 6 Nm	233					●
EC-i 40, 50 W	190	GP 32 S	249-251					●
EC-i 40, 70 W	191							59.0
EC-i 40, 70 W	191	GP 32, 1 - 6 Nm	233					●
EC-i 40, 70 W	191	GP 32 S	249-251					●

Technical Data

Supply voltage V_{CC}	5 V ± 10%
Output signal	EIA Standard RS 422
driver used:	DS26LS31
Phase shift Φ	90°e ± 45°e
Signal rise time	
(typically, at C_L = 25 pF, R_L = 2.7 kΩ, 25°C)	180 ns
Signal fall time	
(typically, at C_L = 25 pF, R_L = 2.7 kΩ, 25°C)	40 ns
Index pulse width	90°e
Operating temperature range	-40 ... +100°C
Moment of inertia of code wheel	≤ 0.6 gcm²
Max. angular acceleration	250000 rad s^{-2}
Output current per channel	min. -20 mA, max. 20 mA
Option	1000 Counts per turn, 2 Channels

The index signal I is synchronised with channel A or B.

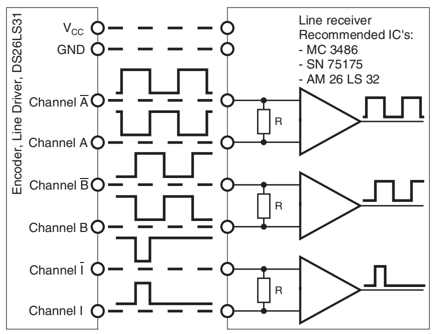
Pin Allocation



1 N.C.
2 V_{CC}
3 GND
4 N.C.
5 Channel $\bar{A}$
6 Channel A
7 Channel $\bar{B}$
8 Channel B
9 Channel $\bar{I}$ (Index)
10 Channel I (Index)

Pin type Berg 246770
flat band cable AWG 28

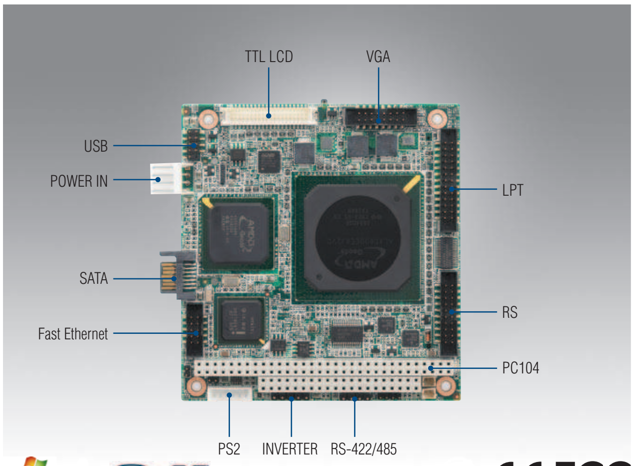
Connection example



Terminal resistance R = typical 120 Ω

PCM-3355

AMD LX800/LX600 PC/104 SBC, CRT, TTL, Ethernet, USB, COM, CFC



Features

- AMD low power LX800/500 MHz and LX600/366 MHz Processor
- 24-bit TFT LCD interface
- Supports compact size 96 x 90 mm PC/104 standard dimension
- Supports two RS-232, one RS-422/485, and two USB 2.0 ports
- Supports Embedded Software API and Utility

Software APIs: Watchdog, SMBus, Brightness, H/W Monitor, Backlight On/Off

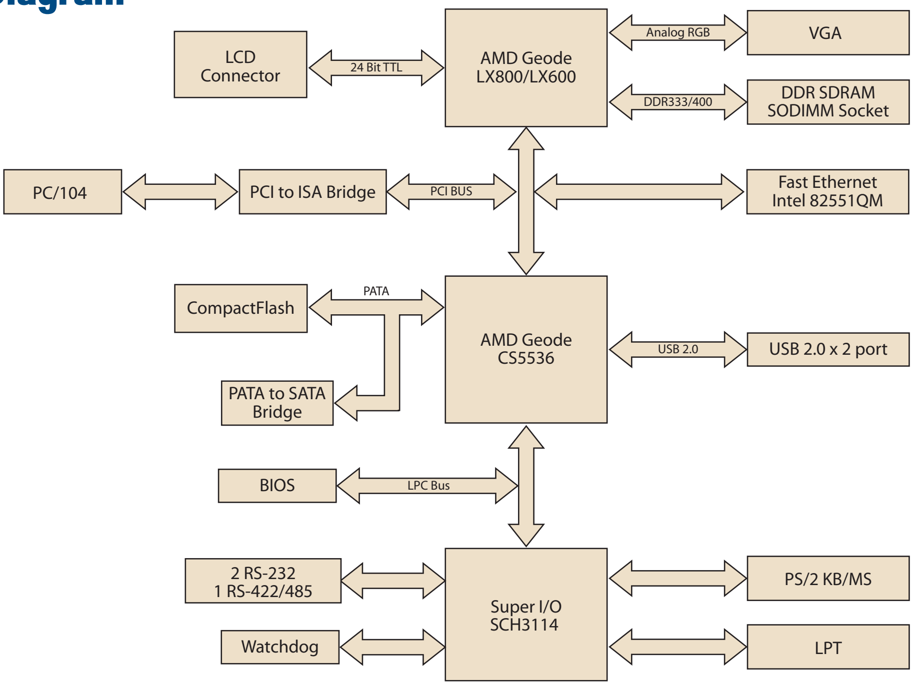
Utilities: BIOS flash, Monitoring

Specifications

Processor System	CPU	AMD Geode™ LX800, 500 MHz/AMD Geode™ LX600, 366 MHz
	Frequency	500 MHz/ 366 MHz
	L2 Cache	128 KB
	System Chipset	AMD CS5536
	BIOS	Award 4-Mbit
Memory	Technology	DDR 333/400 MHz
	Max. Capacity	1 GB
	Socket	1 x 200-pin SODIMM
Display	Chipset	AMD Geode LX800/LX600
	VRAM	Optimized Shared Memory Architecture up to 64 MB system memory
	CRT	Supports up to 1920 x 1440 x 32 bpp at 85 Hz Supports up to 1600 x 1200 x 32 bpp at 100 Hz
	TTL LCD	Supports up to 1600 x 1200 x 32 bpp at 60 Hz for 24-bit single channel TFT
	Dual Display	CRT+TTL
Ethernet	Speed	10/100 Mbps
	Controller	Intel 82551QM
	Connector	Box Header
Watchdog Timer		Output System Reset Programmable counter from 1 ~ 255 minutes/ seconds
Storage	CompactFlash	Compact Flash socket (Type I)
	SATA	1 SATA, up to 1.5 Gb/s (150 MB/s) (Transfer from PATA)
	Floppy	1 82077AA compatible
Internal I/O	USB	2 x USB 2.0
	Serial	2 RS-232 from COM1/2, 1 RS-422/485 from COM3 (ESD protection for RS-232: Air gap ±15kV, Contact ±8kV)
	Parallel (LPT)	1, IEEE 1284, EPP, and ECP compatible
	SMBus	1
	Keyboard/Mouse	1
Expansion	PC/104 slot	1
Power	Power Type	AT
	Power Supply Voltage	± 5% only to boot up (12 V is optional for LCD inverter and add on card)
	Power Consumption (Typical)	LX800: 1.45 A @ +5 V, 2 mA @ +12 V
	Power Consumption (Max, test in HCT)	LX800: 1.74 A @ +5 V, 0.1 A @ +12 V
	Power Management	ACPI/ APM1.2
	Battery	Lithium 3 V/210 mAH
Environment	Operational	0 ~ 60° C (32 ~ 140° F) (Operational humidity: 40° C @ 85% RH non-condensing)
	Non-Operational	-40° C ~ 85° C and 60° C @ 95% RH non-condensing
Physical Characteristics	Dimensions (L x W)	96 x 90 mm (3.8" x 3.5")
	Weight	0.097 kg (0.214 lb)
	Height	Top Side: 8.7 mm; Bottom Side: 10.6 mm

Last updated : 9-May-2011

Board Diagram



Ordering Information

Part No.	CPU	Memory	TTL	SATA	Fast Ethernet	USB2.0	RS-232	RS-422/485	LPT/KB/MS	Expansion	Thermal Solution	Operating Temp.
PCM-3355F-L0A1E	AMD LX800	SODIMM	24-bit	Yes	1	2	2	1	Yes/Yes	PC/104	Passive	0 ~ 60° C
PCM-3355L-J0A1E	AMD LX600	SODIMM	24-bit	No	1	2	2	1	Yes/Yes	PC/104	Passive	0 ~ 60° C
PCM-3355Z-512LA1E	AMD LX800	512 MB bundle	24-bit	Yes	1	2	2	1	Yes/Yes	PC/104	Passive	-20 ~ 80° C
PCM-3355Z2-512LA1E	AMD LX800	512 MB bundle	24-bit	Yes	1	2	2	1	Yes/Yes	PC/104	Passive	-40 ~ 85° C

Note: Wide temp version has bundled with extended temperature grade memory module

Packing List

Part No.	Description	Quantity
	PCM-3355 SBC	
	Startup Manual	
	Utility CD	
1700060202	Cable 6P-6P-6P PS/2 KB & Mouse 20 cm	1
1700260250	LPT Port cable 25P to 26P 2.0 mm 25 cm	1
1703040157	RS-422/485 W/D-SUB COM 4P 15 cm	1
1703060053	PS2 Cable 6P (MINI-DIN)-6P (Wafer 2.0 mm) 6 cm	1
1703100121	USB 2-Port cable 10P 12 cm IDC 2.0 mm	1
1700008894	SATA data cable 7P 30 cm	1
1703150102	SATA power cable B4P-5.08/SATA 15P 10 cm	1
1701200220	RS-232 x 2 ports 2.0 mm 22 cm	1
1701160150	VGA Cable 15P to 16P 2.0 mm D-SUB 15 cm	1
1700005158	LAN cable RJ45 10P-2.0 mm 12 cm	1
9660104000	PC/104 screw and copper post package	1
1960016313T000	Heatsink for PCM-3355 (LX800/ LX600, 47.1 x 47.1 x 7.5 mm)	1
1960016315T000	Heatsink for PCM-3355 (CS5536, 22.7 x 22.8 x 6.3 mm)	1

Optional Accessories

Part No.	Description
165313222B	PC/104 connector 64-pin (Long pin)
165312022B	PC/104 connector 40-pin (Long pin)

Embedded OS/API

Embedded OS/API	Part No.	Description
WinCE	2070007869	Image CE 6.0 Pro PCM-3355 V1.2 ENG
Win XPE	2070007790	XPE WES2009 PCM-3355 Image GX3 V4.0 ENG
	2070007910	XPE WES2009 GX3 LX800 V4.0 MUI24
QNX		V6.3.2/ 6.4.1
Linux		Ubuntu 9.10
Software API	205E000019	SUSI 3.0 SW API for ESBC B: 20091116 XP

Value-Added Software Services

Software API: An interface that defines the ways by which an application program may request services from libraries and/or operating systems. Provides not only the underlying drivers required but also a rich set of user-friendly, intelligent and integrated interfaces, which speeds development, enhances security and offers add-on value for Advantech platforms. It plays the role of catalyst between developer and solution, and makes Advantech embedded platforms easier and simpler to adopt and operate with customer applications.

Software APIs

Control

GPIO

General Purpose Input/Output is a flexible parallel interface that allows a variety of custom connections. It allows users to monitor the level of signal input or set the output status to switch on/off a device. Our API also provides Programmable GPIO, which allows developers to dynamically set the GPIO input or output status.

SMBus

SMBus is the System Management Bus defined by Intel® Corporation in 1995. It is used in personal computers and servers for low-speed system management communications. The SMBus API allows a developer to interface a embedded system environment and transfer serial messages using the SMBus protocols, allowing multiple simultaneous device control.

I²C

I²C is a bi-directional two wire bus that was developed by Philips for use in their televisions in the 1980s. The I²C API allows a developer to interface with an embedded system environment and transfer serial messages using the I²C protocols, allowing multiple simultaneous device control.

Monitor

Watchdog

A watchdog timer (WDT) is a device that performs a specific operation after a certain period of time if something goes wrong and the system does not recover on its own.
A watchdog timer can be programmed to perform a warm boot (restarting the system) after a certain number of seconds.

Hardware Monitor

The Hardware Monitor (HWM) API is a system health supervision API that inspects certain condition indexes, such as fan speed, temperature and voltage.

Hardware Control

The Hardware Control API allows developers to set the PWM (Pulse Width Modulation) value to adjust fan speed or other devices; it can also be used to adjust the LCD brightness.

Display

Brightness Control

The Brightness Control API allows a developer to interface with an embedded device to easily control brightness.

Backlight

The Backlight API allows a developer to control the backlight (screen) on/off in an embedded device.

Power Saving

CPU Speed

Make use of Intel SpeedStep technology to reduce power power consumption. The system will automatically adjust the CPU Speed depending on system loading.

System Throttling

Refers to a series of methods for reducing power consumption in computers by lowering the clock frequency. These APIs allow the user to lower the clock from 87.5% to 12.5%.

Software Utilities

BIOS Flash

The BIOS Flash utility allows customers to update the flash ROM BIOS version, or use it to back up current BIOS by copying it from the flash chip to a file on customers' disk. The BIOS Flash utility also provides a command line version and API for fast implementation into customized applications.

Embedded Security ID

The embedded application is the most important property of a system integrator. It contains valuable intellectual property, design knowledge and innovation, but it is easily copied! The Embedded Security ID utility provides reliable security functions for customers to secure their application data within embedded BIOS.

Monitoring

The Monitoring utility allows the customer to monitor system health, including voltage, CPU and system temperature and fan speed. These items are important to a device; if critical errors happen and are not solved immediately, permanent damage may be caused.

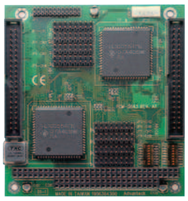
eSOS

The eSOS is a small OS stored in BIOS ROM. It will boot up in case of a main OS crash. It will diagnose the hardware status, and then send an e-mail to a designated administrator. The eSOS also provides remote connection: Telnet server and FTP server, allowing the administrator to rescue the system.

Flash Lock

Flash Lock is a mechanism that binds the board and CF card (SQFlash) together. The user can "Lock" SQFlash via the Flash Lock function and "Unlock" it via BIOS while booting. A locked SQFlash cannot be read by any card reader or boot from other platforms without a BIOS with the "Unlock" feature.

PC/104 Datacom Modules



PCM-3643

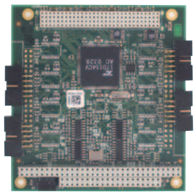
4/8 RS-232 COM Port Module

Specifications

General	
Bus Interface	PC/104 (ISA)
Chipset	Standard 16550, 16650, or 16750 compatible chipsets for serial ports
Channel	4/8 port RS-232 support
Baud Rate	50 ~ 115, 200 bps
Data Bits	5, 6, 7 or 8-bits
Stop Bit	1, 1.5, or 2
Parity	Even, odd, or none
Interrupt Level	IRQ 3, 4, 5, 6, 7, 9, 10, 11, 12 or 15
I/O Connector	40-pin header
Mechanical and Environmental	
Dimensions (L x W)	96 x 90 mm (3.8" x 3.5")
Weight	0.084 kg (0.185 lb)
Temperature	Operating: 0 ~ 60° C (32 ~ 140° F); Storage: -40 ~ 85° C (-10 ~ 185° F)
Operating Humidity	0% ~ 90% relative humidity, non-condensing
Power	
Power Supply Voltage	+5 V, ± 5 % tolerance on power supply
Power Consumption	+5 V @ 400 mA (typical)

Ordering Information

P/N	Description
PCM-3643-08A1E	8 x COM RS-232 Port Module
PCM-3643-04A1E	4 x COM RS-232 Port Module



PCM-3644

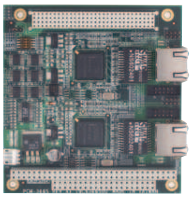
RS-232/422/485 COM Port Module

Specifications

General	
Bus Interface	PC/104-Plus (PCI interface only)
I/O Address	0 x 000 ~ 0 x 3F8
UART	4 x 16C550 (PCM-3614), 8 x 16C550 (PCM-3618)
IRQ	3, 4, 5, 6, 7, 9, 10, 11, 12, 15
Data Bits	5, 6, 7, 8
Stop Bits	1, 1.5, 2
Parity	none, even, odd
Speed (bps)	50 ~ 921.6 K
Connectors	4/8 DB-9 male
Signal Support	TxD+, TxD-, RxD-. CTS+, CTS-, RTS+ and RTS-
Surge Protection	1000 V_{DC}
Mechanical and Environmental	
Dimensions (L x W)	96 x 90 mm (3.8" x 3.5")
Weight	0.084 kg (0.185 lb)
Temperature	Operating: 0 ~ 60° C (32 ~ 140° F); Storage: -40 ~ 85° C (-10 ~ 185° F)
Operating Humidity	0% ~ 90% relative humidity, non-condensing
Power	
Power Supply Voltage	+5 V, ± 5 % tolerance on power supply
Power Consumption	+5 V @ 400 mA (typical)

Ordering Information

P/N	Description
PCM-3644-08A1E	8 x COM RS-232 Port Module
PCM-3644-04A1E	4 x COM RS-232 Port Module
PCM-3644H-04A1E	4 x COM RS-422 Port Module



PCM-3665

Dual GbE Module

Specifications

General	
Bus Interface	PC/104-Plus (PCI interface only)
Chipset	Intel® 82541PI (PCI 10/100/1000 Mbps)
Port	Single/Twin Ethernet port
Speed	10/100/1000 Mbps
Compatibility	PCI version 2.2, 33 MHz PCI
Mechanical and Environmental	
Dimensions (L x W)	96 x 90 mm (3.8" x 3.5")
Weight	0.09 kg (0.198 lb)
Temperature	Operating: 0 ~ 60° C (32 ~ 140° F) Storage: -40 ~ 85° C (-10 ~ 185° F)
Operating Humidity	0% ~ 90% relative humidity, non-condensing
Power	
Power Consumption	Dual LAN: +5 V @ 1.2 A (typical) Single LAN: +5 V @ 0.6 A (typical)
Power Supply Voltage	+5 V, ±5 % tolerance on power supply

Ordering Information

P/N	Description
PCM-3665-00A1E	Dual GbE with RJ45 connector Module
PCM-3665P-00A1E	Dual GbE w/o RJ45 connector Module
PCM-3665-01A1E	Single GbE w/o RJ45 connector Module