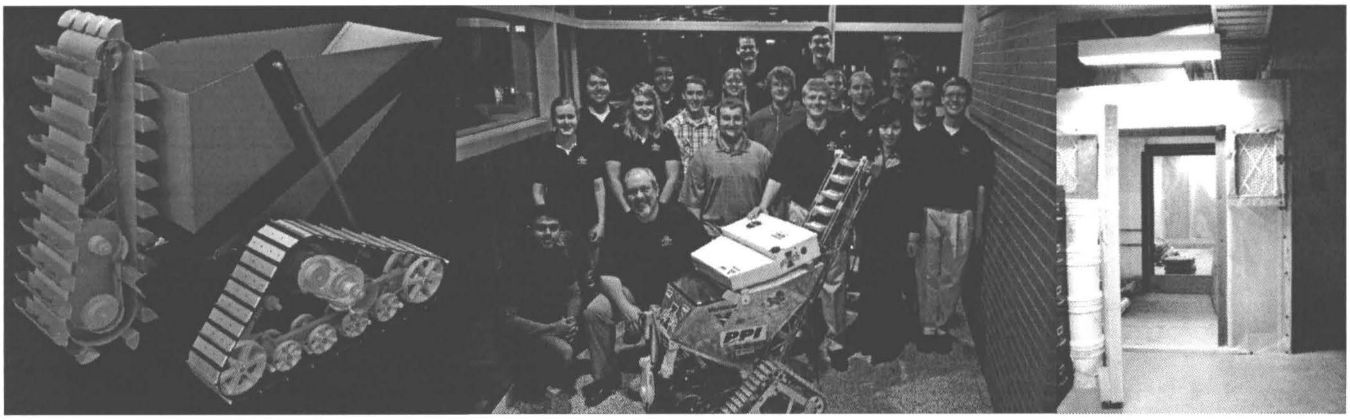
System Engineering Paper

4/24/2012

Iowa State University
Team LunaCY

Faculty Advisor: James Heise
Team members: Bauer, Jonathan
Beougher, Nathan G.
Boe, Caleb
Canahui, Ricardo
Charles, John P
Cooper, Zachary Davis Job
DeShaw, Mark A.
Fontanella, Luan Gasparetto
Friel, Mark
Goebel, Katie
Grant, Alex Martinsdacosta
Graves, Matt
Harms, Ryan Andrew
Hill, Aren
Isely, Kevin Lee
Jose, Sonia
Klein, Andrew
Kolstad, Lauren Wickham
Lamp, Daniel A.
Lindquist, Mariangela Martin
Lopes, Daniel da Paula
Lourens, Rob
Matthews, Christopher
McCleish, Ryan
McNeill, Benjamin Hinshaw
Miller, Christopher
Niedergeses, Joseph
Oakland, Matthew E.
Obren, Daniel
Parker, Regan Michael
Peiffer, David James
Pitkin, Ashley Laura
Poetting, Matthew Joseph
Quetsch, Timothy
Reding, Bobby
Reinert, Joseph
Reuter, Benjamin Jordan
Schieber, Garrett Luke
Sullivan, Bryan Zachary
Thiesfeld, Riley
VanWeelden, Shaun
Walck, Christopher
White, Kyle
Williams, Marcus L



Abstract

The Iowa State University team, Team LunaCY, is composed of the following sub-teams: the main student organization, the Lunabotics Club; a senior mechanical engineering design course, ME 415; a senior multidisciplinary design course, ENGR 466; and a senior design course from Wartburg College in Waverly, Iowa. Team LunaCY designed and fabricated ART-E III, Astro Robotic Tractor – Excavator the Third, for the team's third appearance in the NASA Lunabotic Mining competition.

While designing ART-E III, the team had four main goals for this year's competition: to reduce the total weight of the robot, to increase the amount of regolith simulant mined, to reduce dust, and to make ART-E III autonomous. After many designs and research, a final robot design was chosen that obtained all four goals of Team LunaCY.

A few changes Team LunaCY made this year was to go to the electrical, computer, and software engineering club fest at Iowa State University to recruit engineering students to accomplish the task of making ART-E III autonomous. Team LunaCY chose to use LabView to program the robot and various sensors were installed to measure the distance between the robot and the surroundings to allow ART-E III to maneuver autonomously. Team LunaCY also built a testing arena to test prototypes and ART-E III in. To best replicate the competition arena at the Kennedy Space Center, a regolith simulant was made from sand, QuickCrete, and fly ash to cover the floor of the arena. Team LunaCY also installed fans to allow ventilation in the arena and used proper safety attire when working in the arena.

With the additional practice in the testing arena and innovative robot design, Team LunaCY expects to make a strong appearance at the 2012 NASA Lunabotic Mining Competition.

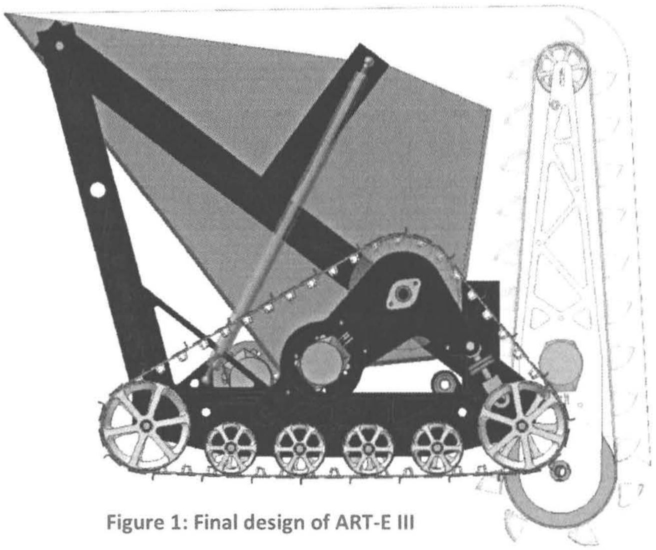


Figure 1: Final design of ART-E III

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1 Introduction

1.1 Purpose

This paper is intended to give an understanding of the functionality of Team LunaCY's robot, ART-E, or the Astro Robotic Tractor-Excavator. The paper is intended to explain the background and design process leading up to the final design solution to accomplish the required objectives. The goal is to guide the reader through each system of the robot, explaining the process used to design, build, and test it.

1.2 Background

Team LunaCY is a student lunabotics organization from Iowa State University that is competing in the third annual NASA Lunabotics Mining Competition. Team LunaCY has been hard at work designing, manufacturing, and testing a robot, the ART-E III, to contend in the 2012 Lunabotics Mining Competition. ART-E III is the third model of Team LunaCY's line of lunabots, the ART-E series.

The NASA Lunabotics Mining Competition is an international competition designed to promote interest in space activities, specifically related to the fields of science, technology, engineering, and mathematics. The competition is centered on excavating lunar regolith, which is identified as a necessary first step towards collecting resources and building bases on the moon. There are a variety of challenges related to technical design for a lunar environment, the most prominent of which are the reduced gravity and vacuum environment. The distinctive physical properties of lunar regolith add even more complexity to the design task. According to NASA, advances in lunar regolith mining have the potential to notably influence the nation's space program and exploration operations.

1.2 Basis for design

The lunar robot prototype will mine lunar material using a digging conveyor. This digging conveyor will be a vertical mount that will actuate up and down for various digging depths using a winch system that will also be used for the disposal. Once the robot has filled its hopper it will use a tread system designed with enough traction for transporting material. The robot will traverse to the disposal area and dump material, similar to a dump truck, into a bin by using a set of 2 shocks to lift the hopper. The hopper will be reset to the original position by the winch described earlier. As the robot moves around obstacles, it will use a variety of sensors to navigate. These sensors will be used to locate obstacles or to calculate the position of robot in the arena.

1.3 Major design reviews

A specific list of requirements that every competing lunabot must meet was provided by NASA. This list of technical rules and the team requirements by team LunaCY were set for each system. During the systems requirements review (SRR) at the beginning of the project, the robot specifications (section 1.4) and system requirements (section 2) were defined. The preliminary design review (PDR) was used to confirm the basics of each system, confirming that it accomplishes all the requirements and is ready to continue. Proof of concepts was used to demonstrate functionality of designs. The critical design review (CDR) confirmed that all the final system designs were able to fulfill all design requirements. The designs were finalized and confirmed to be within constraints. The risks were minimized and testing and research established the systems were ready for fabrication. The robot will be tested and will undergo an operational readiness review (ORR) before heading to the NASA Lunabotics mining competition. This will confirm that the robot is fully functional to system requirements.

1.4 Requirements flow down

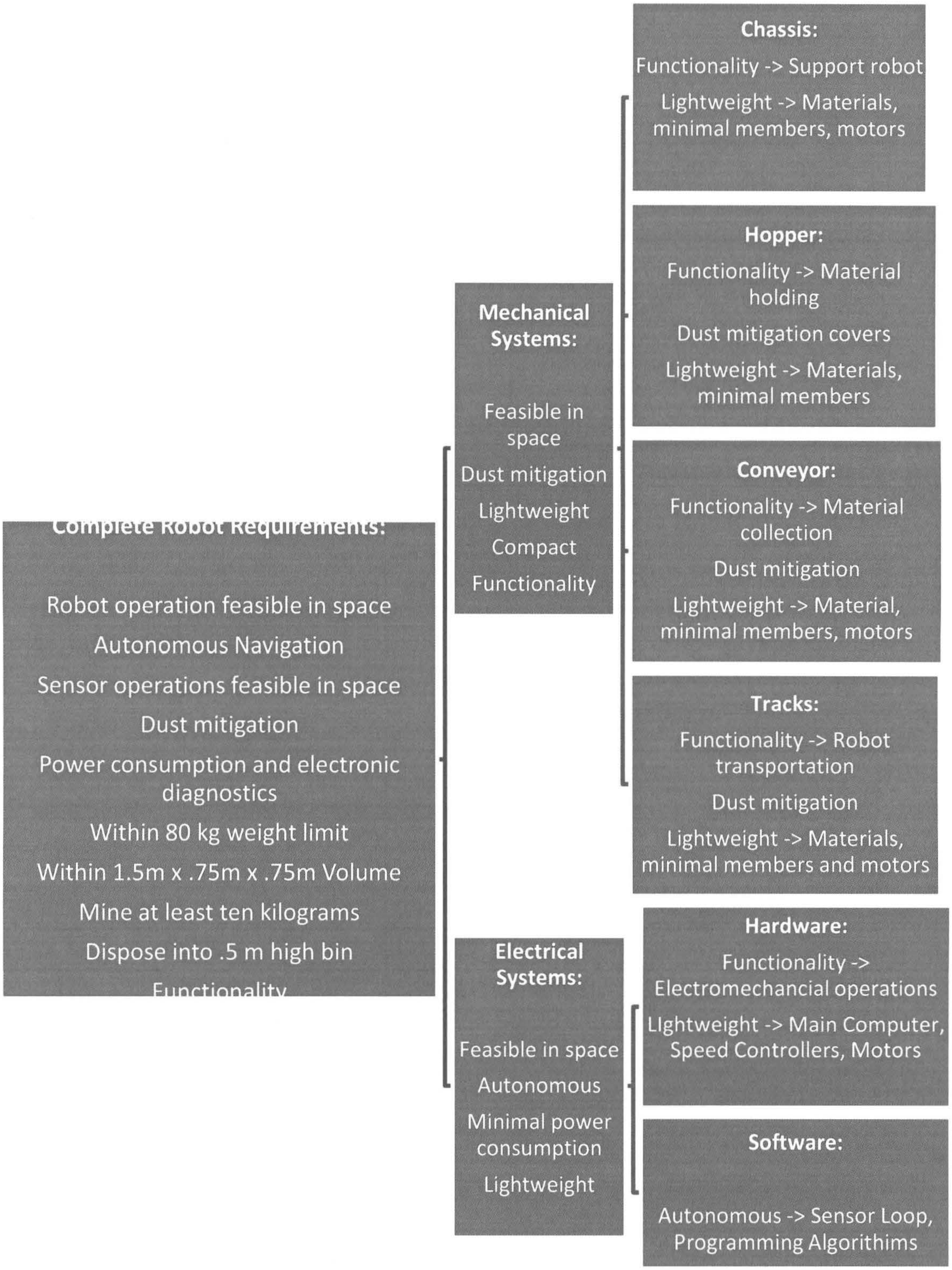

Figure 2: The requirements flow down shows the major requirements of the robot and its systems.

1.5 Requirements and Deliverables

The basic requirements of the robot are listed below as defined by the NASA Lunabotics rules and robot requirements by Team LunaCY.

- Mine at least ten kilograms
- Dispose into .5 m high bin
- Within 80 kg weight limit
- Within 1.5m x .75m x .75m Volume
- Robot and sensor operation feasible in space
- Autonomous Navigation
- Power consumption and electronic diagnostics
- Dust mitigation in mining

1.6 Budget

Iowa State University (ISU) Lunabotics has gained many sponsors throughout the year. Some of our sponsors are Vermeer, Caterpillar, Precision Pulley and Idler (PPI), ISU College of Engineering, ISU Mechanical Engineering Department, Grainger, National Instruments, and Banker's Trust. The team received a total of about $19,000 in sponsorship. This will cover the cost of the robot and the travel expenses. Table 1 gives an approximate cost breakdown for each system. Dust mitigation consists of thermoformed plastic covers. The disposal subsystem consists of aluminum sheeting, gas shocks, the winch assembly, and fasteners. The frame of the robot is made up of aluminum anodized tubes. The conveyor is a more complex mechanical system, consisting of a basic structure, belting, and buckets. The tracks are the most intricate mechanical system on the robot, having a wide variety of parts including a tensioner, belting, drive, and fasteners. Electronics consist of all parts of the robot that use or transfer electricity. This includes motors, wires, an onboard computer, speed controllers, sensors, and microcontrollers.

Table 1: ART-E III budget breakdown

System	Cost ($)
Dust Mitigation	120
Disposal	400
Frame	500
Conveyor	1000
Tracks	1500
Electronics	7500

2 Robot Design

The third generation of the ART-E robot is significantly different from its predecessors. The previous versions of ART-E have used an auger to collect the regolith material and used a conveyor to transport the material from the hopper to the collection bin. However, the rules of the competition have changed this year, and new constraints have been added. This prompted Team LunaCY to significantly alter the design of the robot to make sure that the design would remain competitive. Table 2 shows the start and finish times for the robot.

Table 2: System schedule for ART-E III

Task Name	Start	Finish
Tracks	**Mon 8/22/11**	**Fri 5/11/12**
Design and Research	Mon 8/22/11	Fri 2/24/12
Manufacturing	Mon 2/27/12	Fri 4/27/12
Testing and verification	Mon 4/30/12	Fri 5/11/12
Excavation System	**Mon 8/22/11**	**Fri 5/18/12**
Design and Research	Mon 8/22/11	Fri 1/27/12
Manufacturing	Mon 1/30/12	Fri 4/27/12

Testing and verification	Fri 2/17/12	Fri 5/18/12
Electronics	**Mon 8/22/11**	**Fri 5/18/12**
Design and Research	Mon 8/22/11	Fri 3/30/12
Prototyping	Fri 10/28/11	Fri 5/4/12
Testing	Mon 12/5/11	Fri 5/18/12
Hopper	**Mon 1/16/12**	**Fri 5/11/12**
Design and Research	Mon 1/16/12	Fri 2/17/12
Manufacturing	Mon 2/20/12	Fri 3/30/12
Testing and verification	Mon 4/23/12	Fri 5/11/12
Frame	**Mon 1/16/12**	**Fri 5/4/12**
Design and Research	Mon 1/16/12	Fri 3/2/12
Manufacturing	Mon 3/5/12	Mon 4/16/12
Testing and verification	Mon 4/2/12	Fri 5/4/12

2.1 Concept of Operations

2.1.1 Mechanical Operations

The primary objective of the third generation of Iowa State University's Astro Robotic Tractor – Excavator is to collect the BP-1 lunar soil simulant and transport it to a collection bin. The robot will accomplish this task by utilizing systems which must function synchronously to create an efficient mining process. The necessary mechanical systems were determined to be an excavation system, a material storage system, a material removal system, and a transportation system. The selected design to gather the lunar soil simulant is a digging conveyor. The buckets on the conveyor have been carefully constructed to withstand the forces generated by the digging motion. The conveyor is attached directly to the hopper, the chosen system for temporarily storing material. The hopper has been designed to store the regolith simulant during the digging and transportation processes. The material must then be removed from the hopper when the robot reaches the collection bin. This will be accomplished by a pair of gas springs that will rotate the hopper about a pivot point at the back of the robot. These gas springs apply a constant force in one direction, however, and must be acted against to lower the hopper and to keep it down. This counteractive force will be applied by a winch system. The winch will be attached to the frame of the robot and will extend and retract to determine the position of the hopper. Because the conveyor is hard-mounted to the hopper, the winch will also control the robot's digging depth by adjusting the length of belt extended. When the hopper is full, the robot will carry the soil simulant to the collection bin. To traverse the simulated lunar landscape, the robot will use a track system designed to navigate a sand-like environment effectively.

2.1.2 Digital and Electrical Operations

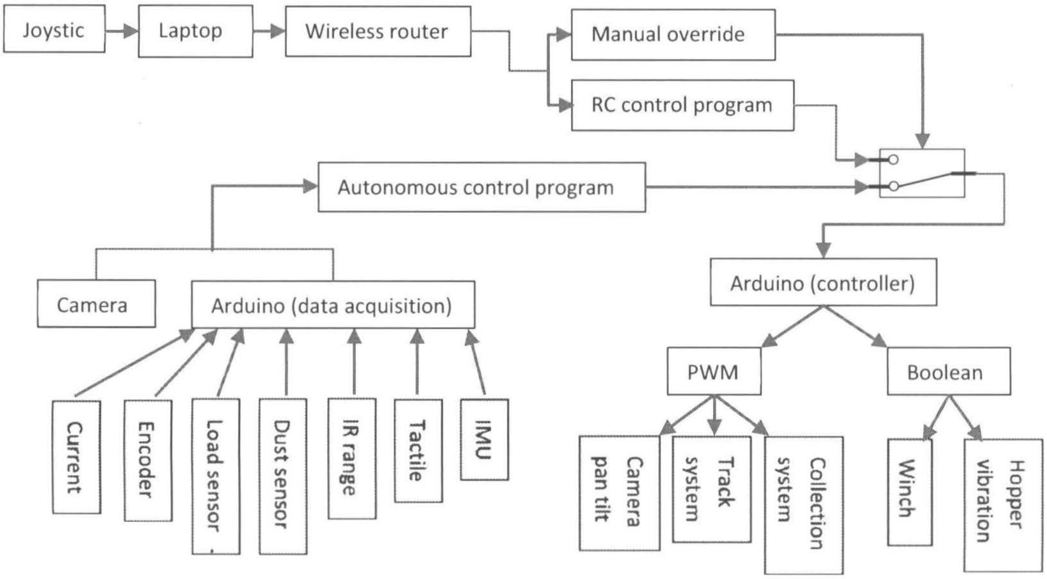

Figure 3 Flow diagram of the non-autonomous and autonomous control program

The program in figure 3 is run by a combination of electric hardware. Batteries supply power to the onboard computer, Arduino boards, speed controllers and motors. PWM signals sent from the Arduino are received by speed controller which then runs the motors. Each subsystem motor will be run this way. The sensors run off the Arduino boards and send information through them, which is then sent to the onboard computer. From the onboard computer the programming takes information from each sensor and acts appropriately. More detailed description is later in the programming and electric hardware sections.

2.2 Systems Hierarchy

ART-E's systems were broken down into a hierarchy to demonstrate how the main components make up the systems.

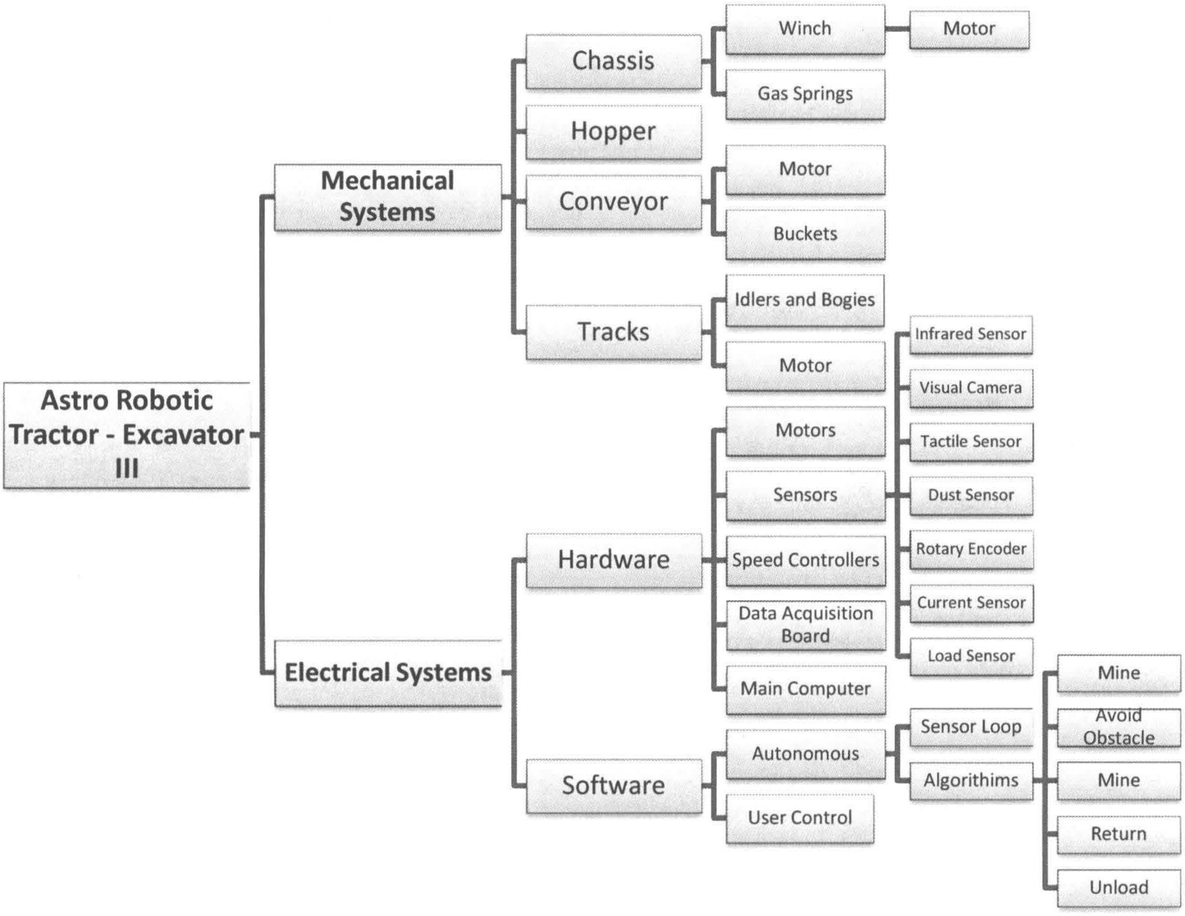

Figure 4 System Hierarchy

2.3 Chassis

The drastic redesign in the newest version of ART-E required a completely different frame than the previous versions have had. Based on the constraints, the frame needed to allow ART-E to stay within the allotted volume and to dispose of material at the correct height. It also needed to be operational in a lunar environment and as lightweight as possible. The new chassis still had to provide a simple way to integrate all of the robot's systems while also providing adequate support for all of the loads the robot would be generating. The chassis would ideally remain low in weight to keep the overall mass of the robot down.

Several unique design elements were incorporated during the creation of the chassis to reduce its weight without compromising the structural reliability. The frame was designed to have minimal members and is constructed using 6061 T6 Aluminum. The main component pieces are hollow, and several pockets were milled out of the sides to cut excess weight.

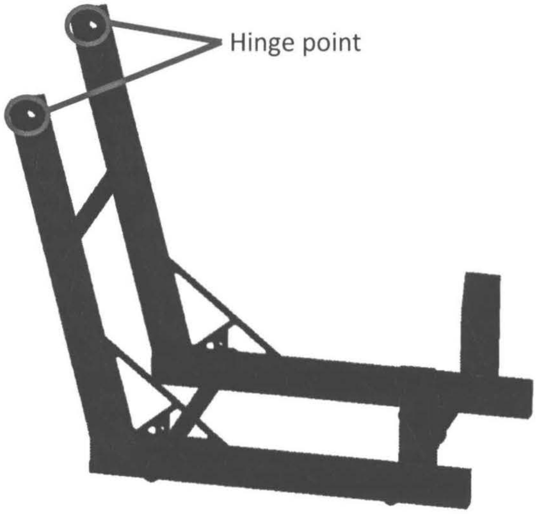

Figure 5 Frame of robot

The frame is comprised of square tubing, cross pieces, and gussets to provide adequate support for the regolith simulant that will be loaded into the hopper. Additionally, the cross sectional strength of the square tubing provides extra rigidity for the hinge point. This hinge point connecting the hopper to the chassis is arguably the most important point on the frame. It is the point that the hopper will rotate about when in motion to dump or return to a digging position. Loads from the BP-1 in the hopper will be supported mainly by this connection while the regolith simulant is dumped into the collection bin. A failure at this connection would be catastrophic to the robot's functionality. Because of this, the team paid careful attention to the material that would be used for the hinge to ensure that a failure would not occur.

2.4 Disposal System

The process of storing and evacuating the regolith from the robot consists of two main systems; the hopper and the winch assemblies. Each of these individual systems must be designed to withstand the concerns present in a lunar environment.

2.4.1 Hopper

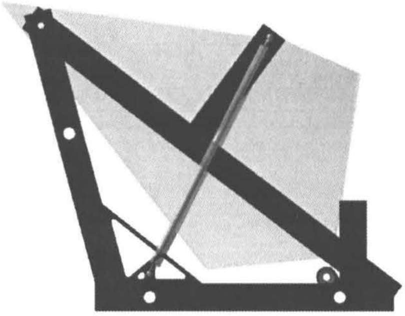

Figure 6 Hopper and Frame

The hopper will store the regolith simulant gathered by the conveyor during the digging process and contain it during transit from the mining area to the collection bin. The hopper has been designed to rotate about a single pivot point attached to the main frame and simply dump the lunar soil simulant into the collection bin. This significantly simplifies the overall design of the robot by reducing the number of required systems. The hopper is a key component that defines a large portion of ART-E III's design. The hopper's shape was designed based on the distribution of material when conveyor and bucket testing were completed. The single pivot point allows the hopper to rotate, with the gas springs providing the motive force enabling the rotation. The hopper is made from 1/16" 6061 sheet aluminum bent at the joints and riveted to give it its shape. A composite hopper was originally planned early in the design process to allow for much lighter construction, however due to the size required we were unable to find the necessary equipment to construct the hopper with this process. The preliminary hopper design was able to hold 110 kg of regolith simulant, but due to changes in the frame design, this value was reduced to 90 kg.

The dumping action of the hopper will be accomplished by the lifting motion of the gas shocks and the speed of the dumping will be controlled by the winch system. The failure of the structural integrity and alignment of the hopper and its supports will result in the loss of primary function of the removal of the regolith from the hopper.

2.4.2 Winch and Gas Springs

The winch is responsible for pulling the hopper and digging conveyor down into the regolith as seen in figure 7. Linear actuators were considered for this purpose, but they were not as feasible as a winch due to their limited range of motion. The winch was positioned underneath of the hopper due to the geometric constraints of both units. The winch is set back toward the middle of the robot in order to clear the bottom of the hopper, and the belt it moves runs under a pulley attached to the front horizontal round aluminum tube. This pulley is used to reroute the belt's path, providing a bend to allow any regolith material to fall off before the belt is wound up by the winch. After the pulley, the belt continues up and attaches to a cross member of the hopper frame. The materials used for the winch and belt were chosen based on their ability to support the intense tension loads that will be generated by the robot. The belting material was also selected due to its thermal properties being acceptable for lunar operation. The connection points to the frame are also important, since a failure in this system would eliminate the robot's ability to collect the regolith simulant. To ensure the stability of the winch and belt, materials were selected to have a factor of safety of 2 or greater. The motor chosen to run the winch is a brushless Milwaukee drill motor, again ensuring the robot's ability to operate in a lunar environment and also to standardize the motor selection used throughout the robot for interchangability.

The gas springs used to lift the hopper into dumping position are attached to the rectangular tubing that runs the length of the robot by a connection gusset plate. This connection is placed toward the back of the robot to clear the track motors. Gas springs were chosen since they are sealed from the environment. The gas springs were selected to provide 400 pounds of force, approximately 1.6 times the force needed to rotate the hopper. This factor of safety verifies that the hopper will be able to dump even if the density of the BP-1 is higher than the estimated value due to environmental conditions like humidity at competition.

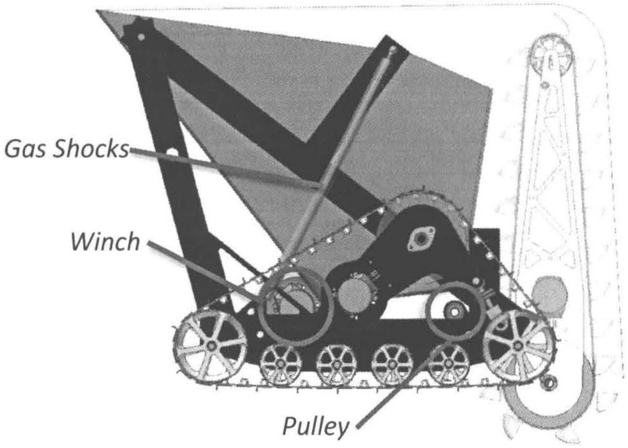

Figure 7 Overall Design of ART-E III.

2.5 Conveyor

After comparing several designs, a conveyor system was found to be the most optimal design for ART-E III's material gathering system. The digging conveyor is an excavation system that collects BP-1 by lowering a rotating belt into the material and using buckets attached to the belt. The belt is wrapped around two pulleys as seen in figure 8. The digging conveyor is attached to the front of the hopper to give the winch control of the dig depth. The position of the hopper, and therefore the digging conveyor, will be determined by the use of a potentiometer on the hinge point of the hopper. The conveyor was designed to use the same bogie and drive sprocket designs as the track assembly to simplify the manufacturing process. The motor driving the digging conveyor is the same model that is driving the tracks and the winch since they have similar requirements for operation. The belting on the conveyor is made from a cut resistant PVC material to prevent damage due to the abrasive nature of the lunar soil simulant. Steel belting was considered to increase the belt's thermal tolerances for lunar operation, but due to the weight difference the PVC reinforced belting was selected.

The digging system is designed to be simple and effective, minimizing moving parts to increase reliability. The system was designed to keep the regolith simulant from clogging up the belt or any of the conveyor parts. The conveyor frame was designed to allow material to pass through it, preventing any components from binding. In addition, the motor mount and the connected gear will be covered, preventing dust from getting into the chain drive. The bogies were also designed to evacuate any dust that finds its way into the system.

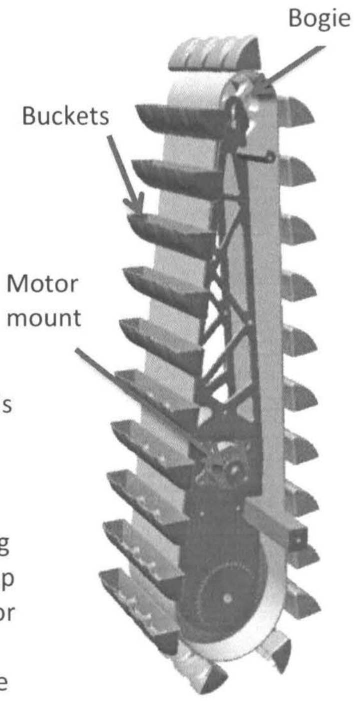

Figure 8: Final concept design of the digging conveyor.

2.6 Tracks

To transport ART-E III, a tracked system is utilized consisting of the typical frame, bogies and idlers, and conveyor belt. The tracks should be capable of transporting the robot across lunar terrain and in addition be reliable, robust, and lightweight. The track system used on ART-E III is a modified version of the past track design. The new track design uses a central structural support as opposed to an outer bracket type frame that held the previous track system together. In order to reduce weight, pockets were milled into the bottom support, and plate aluminum was used for the drive system supports. The bottom support connects to the chassis and provides mounting points for all of the bogies and idlers.

Each track is driven by a Milwaukee brushless drill motor. A variety of calculations was completed to compare the existing 24 volt direct current motor with the Milwaukee to conclude that the drill motor would provide more power than the previous motor while also weighing less.

2.6.1 Track Improvements

The basic design of the previous tracks included a brushed DC motor with a right angle gearbox between the drive "squirrel cage" and the lower idlers and bogies. All parts were contained between two water jet cut plates and the belting was tensioned by advancing the front bogie. Issues observed with the previous tracks during operation were largely in the idlers and bogies. The plates on the outside had a tendency to trap in the idlers and bogies. To improve this, one central plate was designed with idlers and bogies on the outside to allow regolith to escape. Additionally, lightening pockets will be milled and drafted to the outside in the idlers and bogies to facilitate ejection of regolith.

Assembly of the previous tracks was time consuming and it made repair and replacement of parts difficult. This stems from the fact that the tracks had no sub-assemblies. To change out a motor, the plates must be separated, involving the removal of idlers, bogies, and all drive elements. As an improvement, the tracks were divided into two sub-assemblies: one bottom frame for the idlers and bogies and one section to contain the drive motor and drive wheel. The two interface at a hinge on side and a tensioner on the other. This allows quick removal of belting and easy separation of sub-assemblies. To further aid the robot assembly, the tracks will be attached to the frame via two easily accessible points – in contrast to the previously hard to reach points. The fasteners will be tightened by Nylock nuts, which will be resistant to vibration and easy to take on and off. Vibration resistant fasteners will keep the tracks from losing connections during the mining process. The time needed to swap out a spare track is estimated at less than 90 seconds with two operators, needing only two nuts and one wire harness to be swapped.

To further simplify the tracks, both sides of the robot are fitted with identical tracks. This means that the robot will not be exactly symmetrical, but the manufacturing and replacement of the system will be much easier. This decision enabled the team to build a single extra track that could be used on either side of the robot if a track needed to be replaced. To provide access to the interior of the track, Team LunaCY decided that a tensioning system would be imperative. This system allows the tension in the tracks to be adjusted for different terrains as well as be removed for track maintenance with ease. Retaining the design from last year was initially considered, but after analysis, it was concluded that by changing the overall geometry of the track and the placement of the tensioning device would result in the optimization of the system.

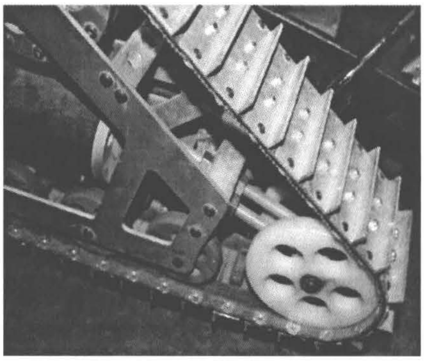

Figure 9 Tensioner

As demonstrated by figure 9, the tensioning system on the design from the previous robot was well hidden, resulting in difficulties while adjusting and fixing the track. It also consisted of a dual threaded rod/nut design which provided the appropriate tension, but was difficult to adjust. To minimize access problems the team came up with a second iteration of the tensioner shown in figure 10. This system not only replaced the dual rod design with a single threaded rod, but it also reduced the number of tensioning nuts from four to two. In addition, it reduced the traveling distance from 1.5 inches to just half an inch to release the belt. Once the track geometry was finalized, the design of the tensioning system was finalized. The upper part of the track system pivots about a point on the front half of the idler plate. When the two circular nuts are turned about the threaded rod shaft, the tension is increased or decreased. When the two nuts are fastened such that they are at the top end of the threaded rod, the track belting is in maximum tension. Figure 10 shows how the tensioning system fits on the entire track assembly.

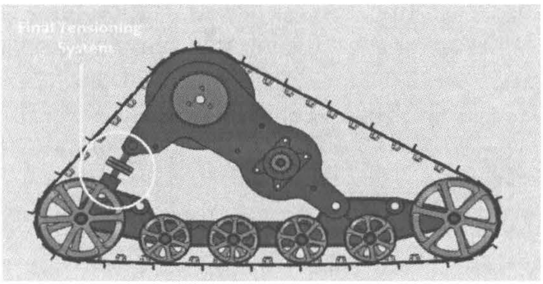

Figure 10 New Tensioner with Tracks

2.7 Hardware and Sensors

2.7.1 Hardware

The hardware selection for ART-E III was designed with performance, efficiency, and weight in mind. The main power system consists of a LiPo battery system, four PWM motor controllers, and four brushless motors. The brushless motors control the track system, excavation system, and unloading system. Recent research has led our design toward lighter, more energy-dense brushless motors. In order to accommodate the replacement of larger DC motors from the old system with a brushless configuration, the power system was designed to accommodate multiple motor types. The motor controllers can operate either brushed DC, or brushless motors, and the system is designed with a voltage configuration that can accommodate both. The LiPo batteries were chosen because they are some of the lightest commercially available batteries, and can easily satisfy the robot's power needs in a small, lightweight package. Other components were also designed with weight in mind. The motor controller, brushless motors, and computer were some of the lightest commercially available. Therefore, the power system will make up a very small portion of the overall weight of the robot, with no compromise to performance.

2.7.2 Sensors

There will be three main infrared sensors for distance measurements from the robot. Two will be mounted on the front of the robot and "sweep" across a 180-degree angle to determine if objects are in front of the robot. The third will be mounted underneath the robot on the front, facing downward, to act as a cliff sensor (detecting craters before the robot falls into them). A camera will take advantage of optical flow to determine objects in front of the camera by comparing two frames of reference and calculating distance. An accelerometer/gyroscope-based movement sensor will give accurate information about current acceleration and angular velocity of the robot, which will aid the rotary encoder and give an extra level of redundancy to determine how far the robot moves and turns. There will be dust sensors mounted on the top of the robot in order to determine the amount of dust in the air. If there is a large amount of dust, measures will be taken to mitigate the dust.

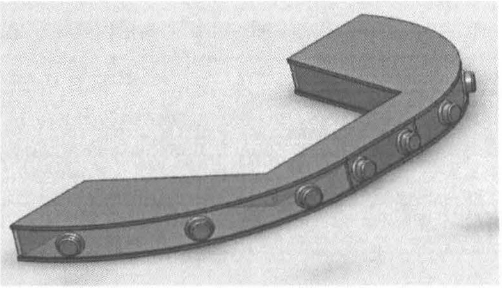

Figure 11 Bumper

Three current sensors will be used, with two on the track batteries and one on the conveyor battery in order to measure power used. Multiple load sensors are used on the bottom of the hopper in order to determine how much BP-1 is in the hopper. Sensor tradeoffs were bumper vs. infrared (dust, distance) and rotary encoder vs gyroscope/accelerometer (distance measurement). The bumper will work whether or not there is dust in the arena while the infrared sensors become useless. If dust is floating in the area of view of IR then the sensors will detect this as an obstacle when none is present. For these sensors the failures that could occur will be from calibration error or sensors breaking during operation. This is taken care of by the calibration of the sensors before each run and inspection of sensor operation

The static bumper is a completely solid design. Currently the bumper will be built out of 3/16" aluminum plate and Lexan. The outputs of the bumper's push button sensors will affect the decisions of the overall movement of the robot. The system needs to be able to identify between and obstacle on the right side or the left side of the body of the robot as well as be able to withstand the impact of a rock at full speeds (with a full load of BP-1). The weight of the front and back bumpers should be no more than 5 lbs and must allow enough clearance for the digging conveyor to lift up as the hopper is dumped. As the design is simple (no moving parts) there are not many failure modes. The main two are the breaking of sensors and the breaking of the frame of the bumper. Both pose a threat to the robot, however if sensors were to break, this would be detrimental to the robot's performance. Not only would the robot be unable to detect objects, points would be lost in the category of obstacle avoidance. If the frame of the bumper were to break this could also pose a problem to the robot. The most detrimental would be a complete breakage of the bumper attachment, ultimately sacrificing obstacle avoidance and protection to the frame; however the likelihood of this event is very low. For this system, the life cycle is about 1 year, or until either a new robot is designed and/or the current bumper design is thrown out. Figure 12 is a sketch of how the sensors on the system will be laid out (**Camera, Potentiometer, Current Sensor, Rotary Encoder, Bumper, Load**).

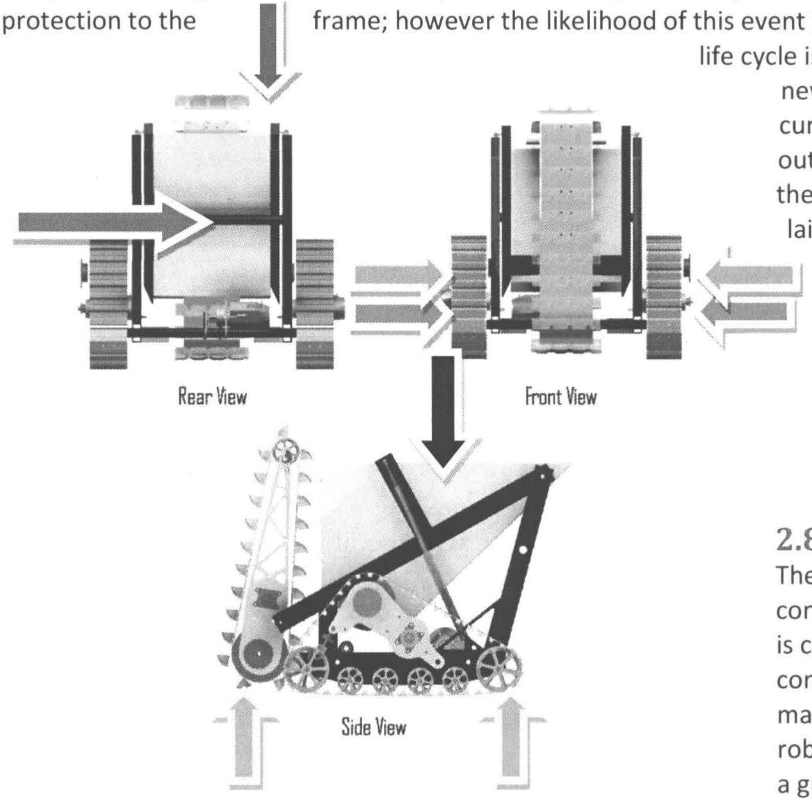

Figure 12: Sensor Placement

2.8 Programming

The control system consists of two control programs. The first program is compiled on a laptop in the control room. This program is the main user interface between the robot and the operator. It includes a graphic user interface, joystick interface, and a wireless communication system which passes information between users and the robot. The second program is loaded onto a single board computer onboard the robot. The onboard control program uses data acquisition hardware to control the robots power system. The onboard control program will consist of three levels of control computation, which include a set of low level data acquisition tools, a set of dynamic control tools, and an autonomous control program.

Both control programs are developed in a LabVIEW environment, which will be broken down into an application upon completion. The lowest level of data acquisition uses the "LabVIEW interface for Arduino," a third party software toolkit for LabVIEW, that turns an Arduino microprocessor into a DAQ board. All mechanical control commands and sensor data will communicate over this interface. Along with the Arduino interface, the control program will make use of low level vision acquisition, as well as a wireless network interface to communicate with the control room user interface. The dynamic level of control is where the basic robotic control functionality and sensor fusion will exist. An attitude sensor was created using the fusion of 3-axis accelerometer data and 3-axis gyroscope data. They are combined using a complimentary filter, which combines two estimates of orientation – one from the gyroscopes, and one from the accelerometers. The complimentary filter then combines both sets of data in a way that is accurate and fast computation of orientation is found. This sensory system can then be used for passive obstacle avoidance, providing a quick indication when the robot is driving over a rock or into a crater. It will also assist the tracking of a visual aid used in the navigation system. A camera is used to track a retro-reflective tape rectangle mounted on the collection bin. The size of the rectangle image allows for the prediction of distance away from the rectangle, while the amount of distortion allows for angle prediction. A closed loop controller uses rotary encoder feedback to move a desired distance. Any time a distance is commanded, the robot will move this distance with a margin within 1cm/m. A similar closed loop controller uses gyroscope feedback to turn a desired angle with a margin within .0011cm/degree. Closed loop controllers will also use current and velocity feedback to control the functionality of autonomous mining routines, and dumping routines.

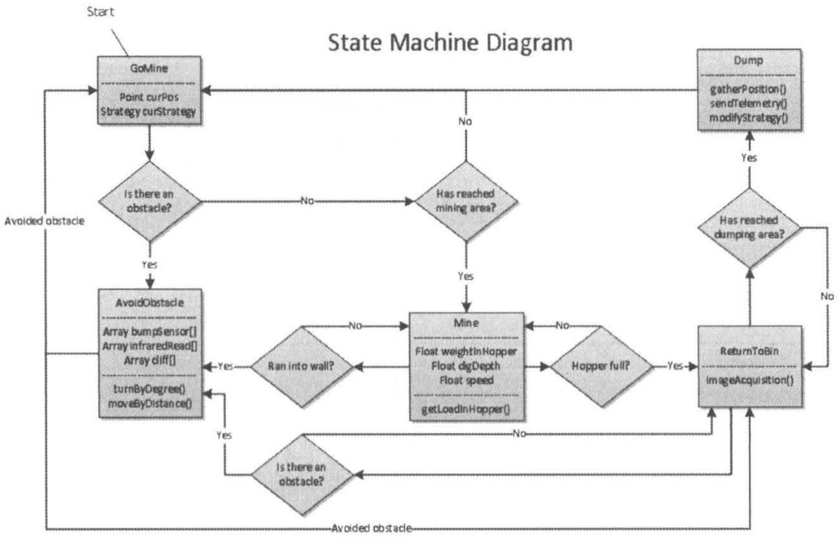

Figure 13: State machine diagram for autonomous operations

The autonomous program will be implemented via a State Machine pictured above. Basically, the robot will start by going to the mining area. If it runs into an obstacle in the obstacle area, it will avoid it using a strategy. If we run into it, we could employ this strategy: Go backward, turn by 90 degrees in the opposite direction the obstacle, move a small distance, turn by 90 degrees again, and then continue like normal. Otherwise, if the IR senses the obstacle, we can avoid it before we actually touch the object. Then, when we reach the mining area, we tell the robot to mine. Finally, when the robot's hopper is filled, we return to the bin area (through the obstacle area, avoiding obstacles again), and then dump the material into the bin. An algorithm know as A* is used during autonomous operation. Using the known grid spaces, A* will find the optimal route for the robot to take while considering the grid spaces that are not useable due to objects in the way. The algorithm updates with every change in the grid.

ART-E III uses a visual rectangle detection-based system for determining its position within the arena. The basic idea is that if it can identify a rectangle with known position and size within the arena, it can use the apparent size and shape to determine its distance from, and angle with respect to, the rectangle. These two parameters will give a position of the robot within the arena in polar coordinates. In order to develop and test the mechanical and autonomous systems explained above, we developed a test platform to implement all of our control and sensory prototypes. We used the chassis and track system of our first competing robot, ART-E I, and reconfigured it to have similar control characteristics as our anticipated new robot design. Through testing of the programming, it has been found that any failure of the program would come from the failures of the sensors associated with the program.

The tests the team has run are:

i. Moving by increments of 0.5m (the grid length) and turning by increments of 45 degrees (the granularity of angles with our grid).
ii. Sending and receiving data over the STM interface.
iii. Updating grid from moving / turning (if the robot is in the correct orientation in the grid after a move / turn).
iv. Complete system test (if the robot can go from its start position, through the obstacle area, to mining area and back)

3 Testing and Verification

3.1 Systems

The systems of the robot were tested prior to the competition. Extensive testing will be done once the robot is fully assembled to test the integration of the systems. Testing will include full runs of the competition autonomy to ensure that any places where the robot gets caught up in the autonomy can be fixed with redundancies. Each system will also be stressed beyond the predicted loads should the robot hit any anomalies in the BP-1. This testing will ensure that mechanical, electrical and software all follow the predicted models. An example of this is when the digging conveyor hits a large rock while digging. The load and rotation sensors carefully monitor the system during the digging process and the program adjusts the digging conditions to compensate to ensure that there will be no mechanical damage.

3.2 Arena

The first step towards developing an adequate testing environment was to have the BP-1 regolith simulant used in competition analyzed. A comparable simulant was then synthesized. It was crucial that as similar of a simulant as possible was created so that collection, deposition, and dust mitigation goals were met. Once the formula of the simulant was synthesized, it was mass produced and an enclosure was developed for which testing could be conducted. The optimization of all of the robotic systems and the need to test the robot as an integrated system vindicated the construction of a more specialized, spacious, and functional testing arena, which was built with the intent of existing as an environment in which full scale mining routines by ART-E III could be performed.

This arena was conceptualized in SolidWorks and designed by a team of five engineers. It was largely constructed of wood 2 x 4s and plywood. The 8’3” wide x 24’ long structure was partitioned into two sections: one section filled with the regolith simulant for testing and one section for cleaning and storing of test models robot components, and safety equipment. The testing space requires 57 cubic feet of simulant to have a 6” depth. In order to have the potentially harmful stimulant contained, the entire testing arena was shrouded in at least one layer of 6 mil thickness plastic sheeting. Since the simulant is composed of such fine particulate and has a reasonably long settling time, it was proposed that an air circulatory system would be implemented in the testing arena. Within this system there would be a fan in sequence with ductwork that draws the outside air into the testing section and another assembly of ductwork with air filters that would allow the air within the testing section to be discharged outside of the arena. This would ensure that there would not be a large pressure accumulation within the testing section by keeping it in constant relation with the outside ambient air. In the cleaning and storage section, there are two windows made of air filters for the purpose of maintaining a pressure balance between this section and the outside ambient air.

3.3 Conveyor

The disposal system for the first two iterations of ART-E has been a conveyor system, so a great deal of testing has been performed on this system. Because of this it was considered advantageous to have the design optimized further and modified to withstand digging loads. Rigorous testing was conducted and calculations were made to finalize the digging conveyor as the regolith collection system of ART-E III. While the drive sprocket rotated at 30 rpm, belt speed of 46 fps, a collection rate of 110 kilograms per minute was calculated.

3.3.1 Conveyor Buckets

The most apparent influence the bucket design has on the functionality of the robot is determining the material collection rate. The capacity of the bucket is an evident design variable, but a more subtle yet undeniably crucial factor is the trajectory that the regolith simulant would have as it is discharged from the buckets into the hopper. If the simulant accumulates unevenly, the full capacity of the hopper would not be reached, which would effectively lower the efficiency of each mining routine. To create the optimal bucket, four different bucket forms were designed and tested. The designs varied in length, width, depth and profile edge/sweep to see which type would dispel the simulant the most efficiently.

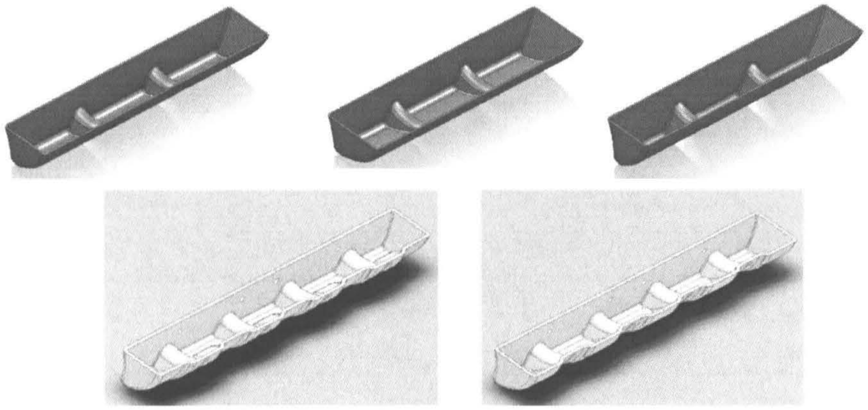

Figure 14: The top three buckets are possible designs; however the bottom two buckets were chosen for the final design. The two buckets alternate on the conveyor belt.

Each bucket was secured to a prototype conveyor and hopper, and a video was taken of its operation. After examining the BP-1 simulant's arc of motion, the team determined that shallow, wide, and long bucket geometry would be most effective. This shape allowed the regolith simulant to not only be discharged the greatest distance, but also the most evenly. Due to these results, the final bucket design was chosen to be shallow and to have an alternating tooth profile to improve the material gathering rate over a simple flat edge design.

Two different materials were considered for the manufacturing of the buckets: Lexan and ABS plastic. Both materials are very durable and would undoubtedly be robust enough to withstand the experimental and theoretical digging forces. Lexan was ultimately selected for its impact resistance to cyclic loading and the longevity of its life cycle. To fabricate the buckets, a thermoforming machine was used to mold sheets over CNC milled aluminum profiles.

3.4 Tracks

3.4.1 Track Frame Design Analysis

Since a failure of the track system at the competition last year rendered ARTE II immobile, a substantial amount of research and development was devoted to optimizing the track design this year. The idler plate of the track system was subjected to finite element stress analysis to ensure operational reliability. Since the part was milled from aluminum 6061-T6, the stress analysis was conducted in SolidWorks using corresponding material properties. Static loading was also assumed.

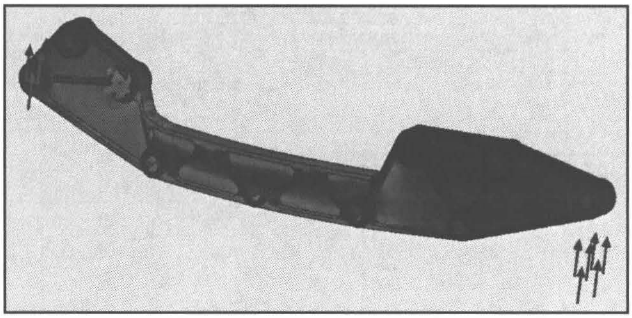
Figure 15 Track Frame

In the first of two virtual stress tests, an evenly distributed load was applied along the idler plate. The test was designed to simulate the robot resting on level ground. A total force of 1368 N was calculated from an estimated maximum mass of 140 kg, which included both the mass of the lunar rover and a full load of regolith simulant. Loads of 114 N were applied to the six locations where wheel axles contact the frame. The two connection points on each side of the rover where the track system attaches to the frame of the robot were selected as fixed for the stress analysis. After conducting the finite element analysis, the maximum displacement experienced by the idler plate was found to be 0.015 mm, and the maximum stress was found to be 8.56 MPa. As expected, the largest stress was located at the chosen fixed contact points on the frame. Sharp corners also developed high stress concentrations. Considering the yield strength for Aluminum 6061-T6, this static load test has a factor of safety of 32.

The second loading analysis assumed a fully loaded hopper, static loading conditions, and maximizum bending stresses in the frame due to the force distribution. Again, the weight of the fully-loaded robot was assumed to be 1368 N. Using the relative CG locations and reaction forces, the force distribution was determined. An upward force of 576 N was expected to occur in the rear axle slot of each frame, and an upward force of 108 N was expected to occur in the front axle slot. The finite element analysis predicted a maximum deflection of 1.2 millimeters and a maximum stress of 39 MPa. The predicted deflection is not expected to inhibit robotic performance. The predicted stress corresponds to a factor of safety of 7. Although the analysis did not account for dynamic motion, the frame is still projected to endure the stresses of operation and will be robust enough to traverse the simulated lunar environment.

3.4.2 Bogies and Idlers

To determine the optimal bogie system, the team researched many designs and found that a rocker bogie placement design was both the simplest and the most cost-effective system. In this particular design, the bogies are positioned on a slight curve rather than in a linear fashion. This design enhances maneuverability when navigating hostile terrain. The track is tensioned so that all bogies and idlers are in contact with the track belt. This ensures uniform distribution of the weight of the Lunabot.

Since the previous bogie design was acceptable last year, the team considered retaining it. However, after running stress and deformation analyses, changing the inner geometry of the holes from circular to triangular increased the load capacity of the system and effectively reduced its weight (see fig. 16).

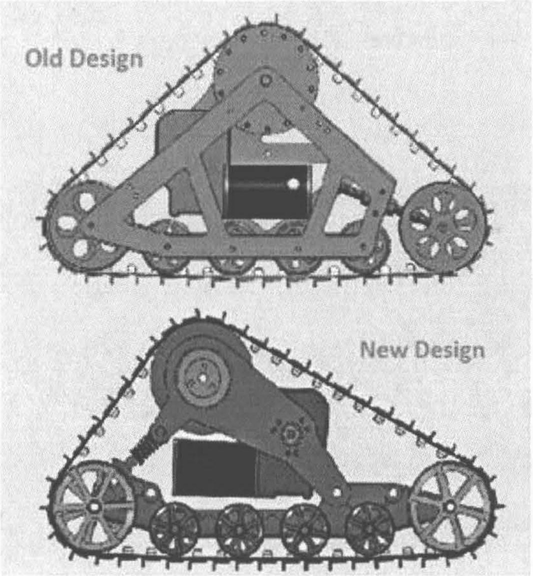

Figure 16: Comparison of Bogie and Idler Designs

Table 3: Bogie and idler analysis

Part	Mass(lbs)	FOS
Bogie 5 Spoke	0.1003	11.3
Bogie 6 Spoke	0.0885	11.0
Bogie 7 Spoke	0.0767	10.6
Idler 5 Spike	0.3341	15.8
Idler 6 Spoke	0.2838	16.2
Idler 7 Spike	0.2334	14.9

Three designs with five, six, and seven spokes were considered. According to the stress analysis, all the designs would perform reliably with high factors of safety. Nevertheless, the seven-spoke bogie and idler designs were chosen to minimize the weight (refer above to table 1). Also refer to figure 17 for stress and deformation analyses.

Both the bogies and idlers have tapered edges to allow material to flow through them without getting congested. This will help prevent the regolith simulant from binding the track system. The bogies and idlers were manufactured from Delrin plastic since it is inexpensive, strong, and easy to machine.

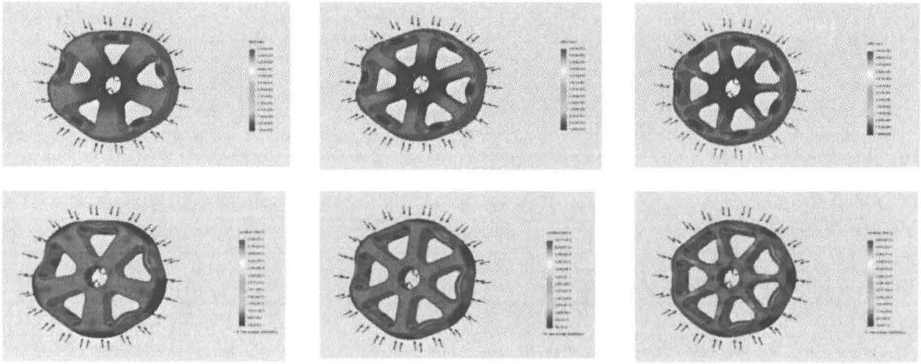

Figure 17 Bogie Analysis

4 Conclusions

4.1 Deliverables

Each system and team working on ART-E III had a separate set of deliverables that needed to be accomplished in order to make the project a success. The tracks had a simple, yet difficult goal: to transport the robot and material wherever necessary. It was designed to be robust, light weight, and effective. The excavation system had the goal to collect material quickly, while keeping dust mitigated and remaining light weight. Finally, the disposal system had the goal to quickly and reliably dump the material that was collected. The combined final robot systems described throughout the paper is the design solution produced by Team LunaCY to accomplish these goals.

4.2 Final Remarks

Team LunaCY devoted many hours designing, fabricating, and testing the new robot, ART-E III. The new challenges put forth by the 3rd annual NASA Lunabotics mining competition encouraged the development of many new systems and algorithms to accomplish the new goals. ART-E III is team LunaCY's simple, unique, and robust solution to the competition, using a new dumping system, bucket collection system, and improved tracks the new robot is lighter weight and more efficient.

5 Sources

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