Telerobotic Excavator Designed to Compete in NASA's Lunabotics Mining Competition

Team Lunar Solutions

March 11, 2011

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Executive Summary

The second annual NASA Lunabotics Mining competition is to be held in May 23-28, 2011. The goal of the competition is for teams of university level students to design, build, test and compete with a fully integrated lunar excavator on a simulated lunar surface. Our team, named Lunar Solutions I, will be representing Temple University's College of Engineering in the competition. The team's main goal was to build a robot which is able to compete with other teams, and ultimately win the competition. The main challenge of the competition was to build a wireless robot that can excavate and collect a minimum of 10 kilograms of the regolith material within 15 minutes. The robot must also be designed to operate in conditions similar to those found on the lunar surface.

The design of the lunar excavator is constrained by a set of requirements determined by NASA and detailed in the competition's rulebook. The excavator must have the ability to communicate with the "main base" wirelessly, and over a Wi-Fi network. Human operators are located at a remote site approximately 60 meters away from the simulated lunar surface upon which the robot must excavate the lunar regolith surface. During the competition, the robot will operate in a separate area from the control room in an area referred to as the "Lunarena." From the control room, the operators will have to control the robot using visual feedback from cameras placed both within the arena and on the robot. Using this visual feedback the human operators control the robots movement using both keyboard and joystick commands. In order to place in the competition, a minimum of 10 kg of regolith material has to be excavated, collected, and dumped into a specific location. For that reason, the robot must be provided with an effective and powerful excavation system.

Our excavator uses tracks for the drive system. After performing extensive research and trade studies, we concluded that tracks would be the most effective method for transporting the excavator. When designing the excavation system, we analyzed several design options from the previous year's competition. We decided to use a front loader to collect the material, rather than a conveyer belt system or auger. Many of the designs from last year's competition used a conveyer belt mechanism to mine regolith and dump it into a temporary storage bin place on the robot. Using the front end loader approach allowed us to combine the scooping system and storage unit, which meant that the excavation system required less space.

In order to accept and process commands from the wireless link to the excavator, we used an Arduino microprocessor board with an Ethernet shield attached to it. The Arduino is used to control the excavator as well as to provide TCP/IP communication ability to the unit. The Ethernet board is connected to a Wi-Fi Linksys bridge to provide access to the Wi-Fi network. An IP wireless camera with pan and tilt options, was added to the system to aid in the excavator's operation by providing increased visibility. As required by NASA, our excavator does not employ any fundamental process which could not be used in a lunar environment. We have used only materials and technologies that can operate in the vacuum of space, and also handle the physical constraints found on the lunar surface.

Space exploration could provide solutions for many of our energy and resource issues. Because exploring space can be very risky and dangerous, it is necessary to develop robotic systems that can be sent to space and perform tasks in place of humans. The Lunabotics Mining Competition gives students an opportunity to come up with new and innovative methods to explore and mine the lunar surface.

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1. INTRODUCTION

In May 2011, NASA will host the second annual Lunabotics Mining Competition at Kennedy Space Center, Florida. Our team (Lunar Solutions I) will be representing Temple University in this year's competition. The competition is open to teams of graduate and undergraduate students. Teams are challenged to design, build, and remotely operate a robot which shall be referred to as a "lunabot". A lunabot is electro-mechanical system, designed to excavate, transport, and deposit material (lunar regolith simulant) in a simulated lunar environment. The goal of the competition is for teams to design, build, and operate the lunabot that can excavate the most simulant within the 15 minute time limit.

Our team, Lunar Solutions I, will be representing Temple University in this year's competition. The team is comprised of four undergraduate engineering students and two faculty advisors. This paper discusses the process of designing and realizing the excavator we intend to use in the Lunabotics Mining Competition.

1.1. Document Overview

The purpose of this document is to provide a detailed description of our project's mission objectives, and the methodology used to achieve those objectives. The organization of the document is based on the various steps of the system life cycle as outlined by NASA in the NASA Systems Engineering Handbook. The problem statement is outlined in section 1.2. This section discusses the purpose of our project, and lists our mission objectives. Section 2 contains the requirements and specifications of our system. Deliverables, schedules, budget, and constraints can be found in this section. The design and integration of the lunabot's subsystems are located in section 3. This section also provides analysis of our conceptual and preliminary designs.

1.2. Purpose and Mission Objectives

The purpose of this project was to design and build a lunar excavator, capable meeting the requirements necessary to win the Lunabotics Mining Competition. During the competition attempt, the excavator has 15 minutes to mine, transport, and deposit lunar simulant (i.e., simulated lunar surface). In order to win the competition, the excavator must deposit more simulant in the collection bin than the competitor's excavators. A minimum of 10Kg of simulant must be deposited in the collection bin at the end of the competition attempt in order for a team to qualify. A well designed and constructed excavator has the potential, not only to win the competition, but also to provide new and innovative ideas which can be used in future space exploration applications.

Our mission objective for this project is to design and build a lunar excavator capable of mining at least 15Kg of simulant, transporting it across the competition's playing field, and depositing it into the collection box. During our allotted time in the Lunarana we plan to make several trips to excavate the stimulant and return to the collection box. The drive system has been design to make at least 5 trips to we plan to deposit approximately 75Kg of simulant.

The purpose of this project was to design and build a lunar excavator, capable of excavating as much lunar material as possible within a limited amount of time. The excavator must be operated remotely over a wireless communication link. A well designed and constructed excavator has the potential, not only to win the competition, but also to provide new and innovative ideas which can be used in lunar exploration applications. NASA specifies several design constraints which had to be taken into consideration when designing our system.

Our mission objective:

> Design and build a lunar excavator that can excavate a maximum amount of stimulant in a given amount of time and satisfy all the design constraints set forth by NASA in the 2011 Lunabots Mining Competition Rules.

2. SYSTEMS ENGINEERING PROCESS

The excavator is a relatively large system, which is dependent on the proper execution and interfacing of several subsystems. We used the system life-cycle to break the design process into manageable steps. In this section we breakdown the system engineering design process. First the initial concept of operation is discussed followed by excavator architecture. Then the schedule with major reviews is discussed, the project deliverables, engineering specifications, conceptual design and finally the preliminary design.

2.1. Preplanning and Concept Studies

This section describes the preplanning phase of the system life-cycle. During this phase we established the basic concept of operations and architecture of our system based on our mission objective.

2.1.1. Initial Concept of Operations

The initial concept of operations was conceived after researching similar excavation and lunar systems. We analyzed our mission objectives to determine what functions the system would have to perform for mission success.

According to the Lunabotics Mining Competition rulebook, at the start of the competition attempt "[t]the excavator hardware shall be placed in randomly designated starting zones"(2010). Once the competition attempt has begun, the operator (located in a control room) will remotely drive the excavator across the playing field to the designated mining area. Once the excavator reaches the mining area it will excavate as much lunar simulant as possible. When the excavator is done the mining process, the operator will remotely drive the excavator to the collector box, where it will deposit the collected stimulant and if time allows the process is repeated to excavate more stimulant.

2.1.2. Initial Excavator Architecture

The preliminary design of the system architecture includes all subsystems deemed necessary to perform the tasks needed for operation as labeled in Figure 1. The operator control is performed using visual feedback from cameras both within the lunar arena and on the robot via the communication system. Both keyboard and joystick commands are sent over the wireless link to the excavator's onboard control system which in turn drives all of the actuators for both driving on and excavating the lunar regolith.

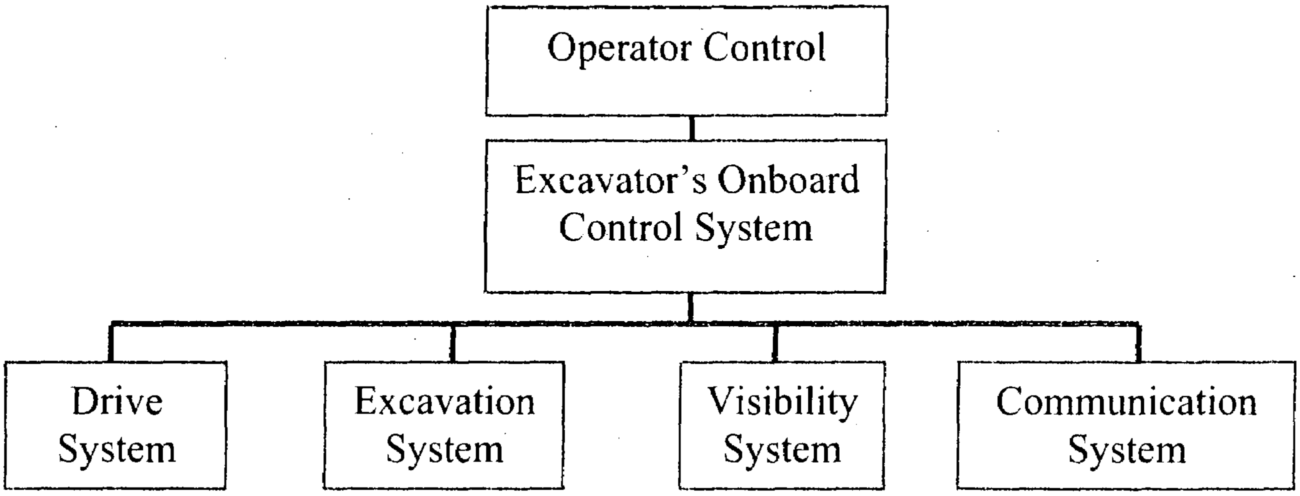


Figure 1: Conceptual System Architecture

2.2. Schedule and Major Reviews

The system life-cycle, as defined in the NASA Systems Engineering Handbook, was used as the basis for dividing the project into scheduled tasks. Work on the excavator's design began in September 2010 and scheduled for completion by May 2011.

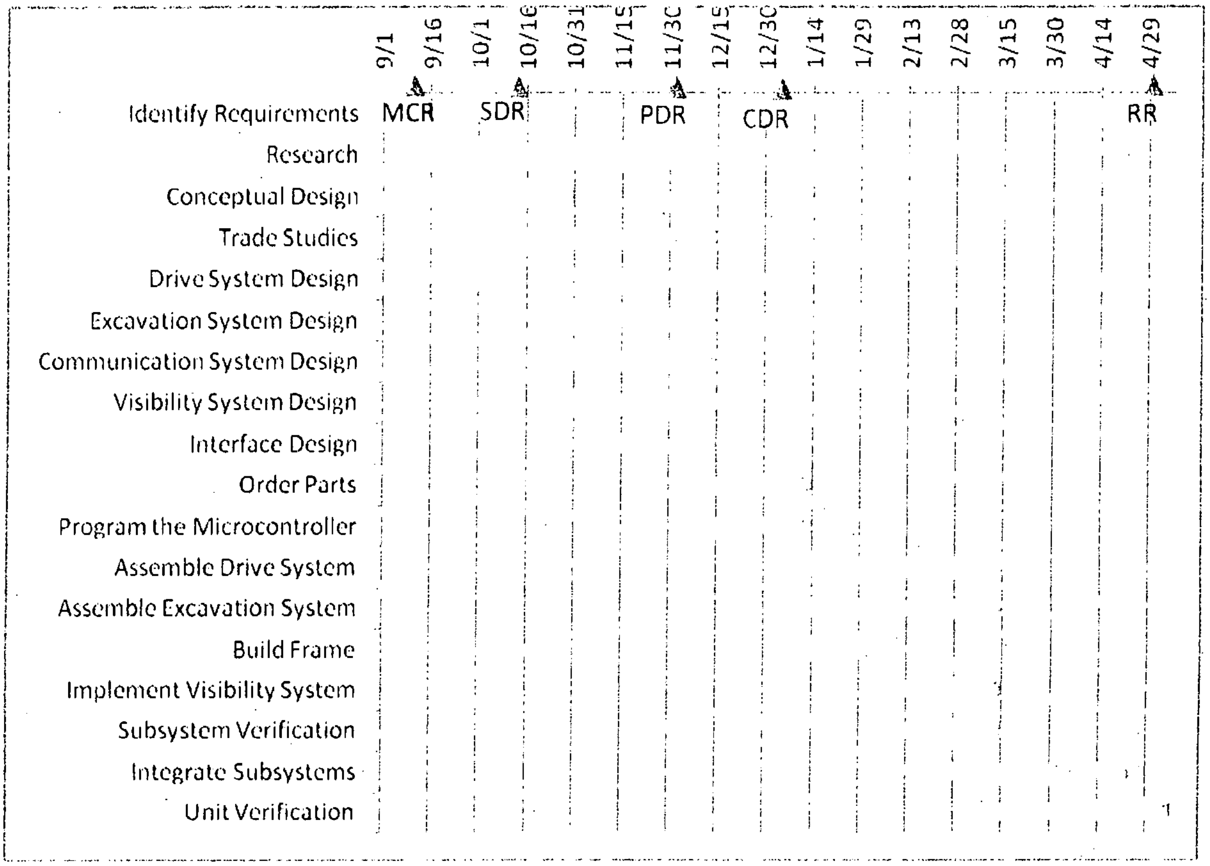


Figure 2 Project Schedule

The five major project reviews are marked as red triangles on the schedule in Figure 2. These reviews were conducted by our two faculty advisors for approval to begin the next stage of development. The Mission Concept Review (MCR) and System Definition Review (SDR) were reviewed by our advisors prior to establishing a preliminary design. The Preliminary Design Review (PDR) and Critical Design Review (CDR) presented a detailed description of the excavator's architecture and concept of operations. The system was not completely integrated at the time of this paper's writing, but the Readiness Review (RR) is scheduled to take place before the competition.

2.3. Deliverables

The process of designing and building the lunar excavator produces several deliverables which can be used to track the design's progress from planning to realization. Deliverables can be divided into three main categories: documentation, hardware, and software.

Documentation Deliverables:
1. Mission Concept Review
2. System Definition Review
3. Preliminary Design Review
4. Critical Design Review
5. Readiness Review

Hardware Deliverables:

1. Drive System
2. Excavation System
3. Communication System
4. Visibility System
5. Control System
6. Completed Excavator

Software Deliverables:

1. User Input Mapping Software
2. Microprocessor Software

2.4. Engineering specifications

This section is divided into two subsections. The first section outlines the requirements necessary to accomplish our mission objectives, and the second describes the design margins considered to ensure all requirements were met.

2.4.1. Requirements Definition

This section addresses both the technical and non-technical requirements of our lunar excavator. The excavator's system requirements are flowdown requirements, derived from the mission objective. Table 1 summarizes the performance requirements and Table 2 the non-technical requirements.

Technical requirements help ensure that the lunabot will be able to perform its functions at an acceptable level for mission success. Technical requirements include: functional requirements, performance requirements, and interfacing requirements.

Non-technical requirements are also critical to mission success, but they do not relate directly to the functionality of the excavator. Some of these requirements were explicitly stated by NASA in the competition's rules, while others were determined based on financial and time constraints. Factors such as safety and transportability were also considered for non-technical requirements.

System level requirements dictate the requirements of the subsystems, which then flowdown to the subsystem's components. The list below provides a list of the system level requirements and the corresponding subsystem level requirements.

Requirement Type	Excavator Requirements	Corresponding Subsystem Requirements
Performance Requirements	The operator and excavation unit must be able to communicate wirelessly over a distance of at least 70 feet.	• The Wi-Fi router must be able to transmit at least 70 feet. (Communication System)
	The excavator shall provide the operator with 270 degrees of visibility.	• The excavator's visibility system must provide the operator with at least 270 degrees of visibility. (Visibility System) • Any onboard visual information must be wirelessly sent to the operator. (Communication System)
	The excavator must be travel at a minimum speed of .12 m/sec	• The drive system shall move the excavator at a minimum speed of .12 m/sec. (Drive System)
	The excavator shall collect at least 1.5 Kg per minute.	• The excavation system shall be able to collect and store regolith at a rate of 1.5Kg per minute. (Excavation System)
	The excavator shall have enough battery power to run at full power for 20 minutes.	• The battery must provide enough amp hours to run all systems at full power for at least 20 minutes. (Electrical Power System)
	The wireless communication between the excavator and operator must not exceed an average of 5Kbits per second.	• The combined bandwidth of the control signals, and video information cannot exceed an average of 5Kbits per second. (Communication and Visual Systems)

Table 1: Performance Requirements

Requirement Type	Excavator Requirements	Corresponding Subsystem Requirements
Interfacing Requirements	The operator control, excavation system, drive system, and visibility system must all be interfaced.	• The operator control shall send wireless control signals to the onboard control system. • The visibility system will wireless send visual feedback to the operator. • The excavation and drive system will be controlled by the excavator's onboard control system.
Physical Requirements	The weight of the lunabot cannot exceed 80Kg.	• The combined weight of each subsystem (excluding operator control) cannot exceed 80Kg.
	The dimensions of the excavator shall not exceed 1 meter high, 1.64 meters long, and . 48 meters wide it its starting position.	• No subsystem on the excavator can exceed the given dimensions.
Environmental Requirement	The excavator shall not employ any fundamental process that cannot be used in a lunar environment.	• The subsystems cannot use: pneumatics, hydraulics, combustion engines, or any component that could not be used in a vacuum or withstand extreme temperatures.
Safety Requirement	The excavator shall be equipped with a red emergency stop button at least 5cm in diameter.	• The electrical power system must be equipped with an emergency stop button.
Transportability and Durability Requirement	The excavator shall be durable enough to be sent from Pennsylvania to Florida in working condition.	• Each subsystem and interfaces between subsystems must be manufactured in such a way that they can withstand shipping.
Cost Requirement	The combined cost of parts and manufacturing cannot exceed $4,000.	• The combined cost of all subsystem and interface components cannot exceed $4000.

Table 2 Non-technical Requirements

2.4.2. Reliability and Design Margins

The requirements listed above provide the minimum requirements for mission success. Design margins were added to increase the probability of achieving our design requirements.

When determining the system budgets, a 30% margin was added to weight estimates, and a 10%

margin was added to power and bandwidth estimates. These margins provide suitable compromise between performance reliability and cost.

2.5. Conceptual Design

2.5.1. Trade Studies and Tradeoff Analysis

We used trade studies to compare several design possibilities for each of the excavator's subsystems. By assigning a weight to various criteria (cost, weight, etc.) based on importance, we were able to establish a grading system for comparing different methods. Table 3 summarizes the transportation trade study.

Trade Study for Transportation Method					
		Wheels		**Tracks**	
Criteria	**Weight**	**Grade**	**Score**	**Grade**	**Score**
Design Complexity	15%	4	.6	1	.15
Mobility	30%	2	.6	5	1.5
Weight	15%	4	.6	2	.3
Durability	25%	2	.5	4	1
Speed	15%	5	.75	2	.3
Totals			**2.6**		**3.25**

Table 3: Transportation Trade Studies

The excavator will have to be travel over a playing field of lunar simulant, with properties similar to lunar soil. The powdery simulant poses a high risk for wheel slippage (Ishigami, Nagatani, & Yoshida, 2007). The playing field also contains several obstacles which the excavator must be avoided. Due to these factors, mobility was determined to be the most important criteria in selecting a transportation method. Tracked vehicles provide greater mobility because their larger footprint exerts a larger tractive ability (Hornback, 1998). Another high priority factor for selecting a transportation method was durability. When a vehicle is used primarily off-road, tracked vehicles are more reliable (Hornback, 1998) and hence from Table 3 we see the advantage of the tracks versus the wheels for this specific lunar-type surface.

Tracked vehicles are inherently heavier, and more complex than wheeled vehicles, but these factors were not considered high priority because cost and weight could be reduced in other subsystems to compensate.

We investigated three excavation systems: specifically 1) front-end loader, 2) an auger, and 3) a conveyer belt system and the results are summarized in Table 4. The conveyor belt system is very simple with typically one motor running a belt with "digging elements" connected to the rotating belt. The cost and weigh of the conveyor are high due to both the length and type of belt employed. Augers can also be used but due to its operation in a "screw-type" configuration to dig, this to us posed a problem that one would have to dig deep into the surface to excavate a decent amount of stimulant. As one digs beeper with the auger this loading on the auger's motor could become prohibitive. The front-end loader is a slightly more complex system due to one (or two) arms are used with linear actuators versus rotary motors of the auger and conveyor systems. However, when using a large bucket at the end of the arm(s) a large amount of stimulant can be excavated in one simple motion. Of the three proposed excavation systems, the front-end loader provided the highest excavation speeds and our final choice.

Trade Study for Excavation System							
		Front-end Loader		**Auger**		**Conveyer Belt System**	
Criteria	**Weight**	**Grade**	**Score**	**Grade**	**Score**	**Grade**	**Score**
System Complexity	20%	2	.4	3	.6	4	.8
Durability	25%	4	1	4	.5	2	.5
Cost	10%	3	.3	3	.3	4	.4
Weight	15%	1	.15	2	.3	4	.6
Excavation Speed	30%	4	1.2	3	.9	2	.6
Totals			**3.05**		**2.6**		**2.9**

Table 4 Excavation Method Trade Study

2.6. Preliminary Design

After reviewing several design options during the conceptual phase, and completing the System Definition Review, the decision was made to design an excavator with a front-end loader and a two track drive system.

2.6.1. Concept of Operations

The operator will control the excavator from the control room using a joystick connected to a laptop via USB. The laptop will use a wireless access point (WAP) to transmit control signals to the excavator's onboard router. The microcontroller uses these signals to control the excavator's drive and excavation systems.

The excavator will be placed in a randomly selected location and orientation, prior to the beginning of its competition run. The wireless IP camera mounted on the excavator will stream video to the operator throughout the duration of the competition using the excavator's onboard router. The operator will utilize the provided visual information to drive the excavator to the designated mining zone.

Once the excavator reaches its destination, it will begin the mining process. The excavator uses linear actuators to control an arm which is attached to a bucket. The bucket will scoop and hold the lunar simulant. After the mining process is complete, the excavator will traverse the playing field to the collector box. One of the actuators will lift the bucket so that its base is aligned with the top of the collector box (1 meter high). The second actuator will then tilt the bucket to deposit its load into the collection box.

2.6.2. System Architecture

A Product Breakdown Structure (PBS) of the lunabot's architecture can be seen below in Table 5. On the left hand side is operator control system in the remote control room which is comprised of laptop computer which allows the operator to have vision directly on the robot using the on-board cameras. These cameras can be both panned and tilted using mapped keyboard commands to give full visual access around the robot. The joystick is used for controlling (i) both tracks of the robot, and (ii) both linear actuators on the robot arm. Finally the wireless router is used to send all of these commands over the WiFi network to excavator. On the excavator side there are four main subsystems, namely: (i) electrical power subsystem; (ii) drive system subsystem; (iii) excavation subsystem; and (iv) the visibility subsystem; and (v) the control and data handling subsystems. Commands transmitted over the WiFi network are picked up on the excavator's wireless router. These commands are then sent to the Arduino microcontroller for decoding and processing. The Arduino then processes this data and send the proper commands to the other drive, excavation, and the vision system.

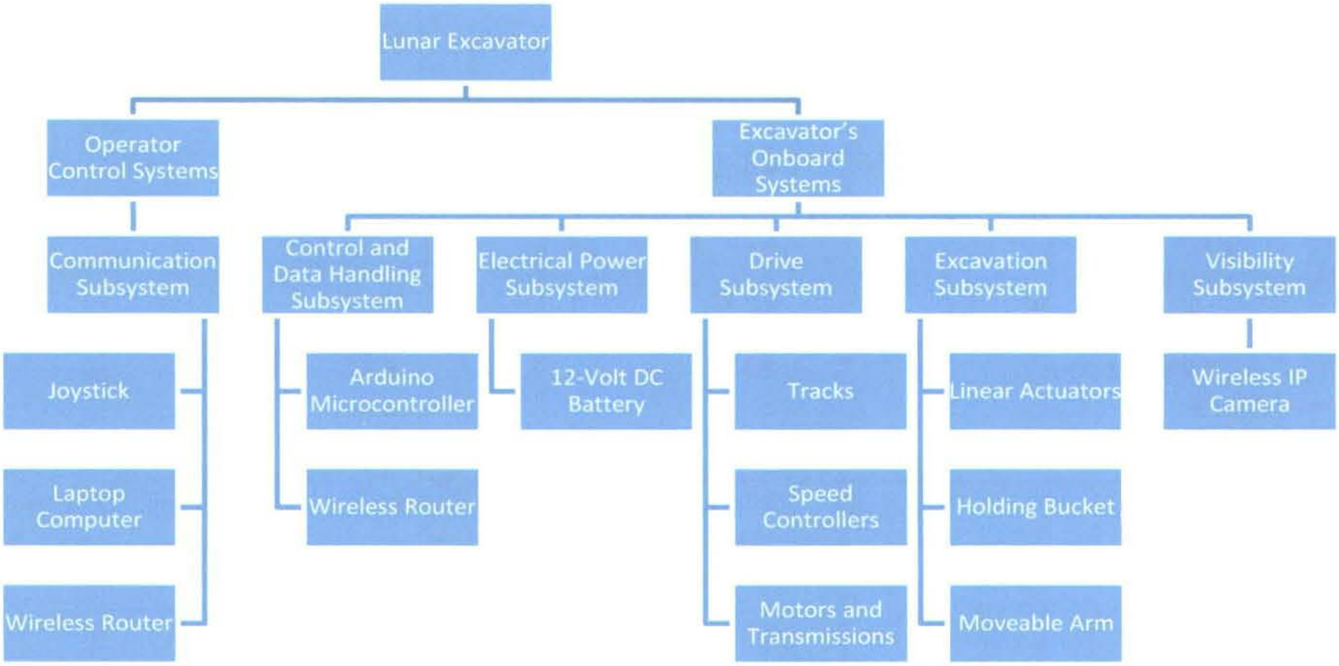


TABLE 5: PBS of System Architecture

2.6.3. Budgeting and Bill of Materials

The entire mass budget for the excavator is summarized in Table 6. It was our intent to use lightweight composite for framing as opposed to steel along with rubber tracks to as to keep the weight to a minimum. The batter is the heaviest component and will be used to not only supply the electrical power to all subsystems but also act as a counterweight when the excavator is lifting simulant to the deposit bins (this is the point of highest tipping moment when the arms are fully extended.)

Mass Budget			
Component	**Mass**	**Quantity**	**Total mass**
Track (band and wheels)	2 Kg	2	4 Kg
Motor	1.304 Kg	4	5.216 Kg
Transmission	2.296 Kg	2	4.592 Kg
Large Actuator	1.8 Kg	1	1.8 Kg
Mini Actuator	.9 Kg	1	.9 Kg
Bucket	4.5 Kg	1	4.5 Kg
Arm	4.1 Kg	1	4.1 Kg
Frame	3.6 Kg	1	3.6 Kg
Battery	6.6 Kg	2	13.2 Kg
Speed Controllers	.1 Kg	2	.2 Kg
Router	.802 Kg	1	.802 Kg
Microcontroller and Ethernet Shield	.134 Kg	1	.134 Kg
Interfacing Hardware (wires, bolts, fuse panel, etc)	4.2 Kg	1	4.2 Kg
Total			47.234 Kg
Total + 30% Contingency			61.4042 Kg

Table 6: Mass Budget

Table 7 summarizes the cost budget which required to be less than $4,000 and we were comfortably under this constraint.

Bill of Materials			
Part	**Number**	**Cost in U.S. Dollars**	**Total**
Joystick	1	50	50
Arduino Microcontroller	1	65	65
Wi-Fi Router	2	22	44
Speed Controller	4	90	360
Battery	2	100	200
Fuse Panel	1	40	40
Emergency Stop	1	60	60
IP Camera	1	125	125
Tracks	2	250	500
Transmissions	2	200	400
Motors	4	120	480
Linear Actuators	2	150	300
Front End Loader	1	150	150
Total			2774

Table 5: Cost Budget

2.6.4. Interfacing

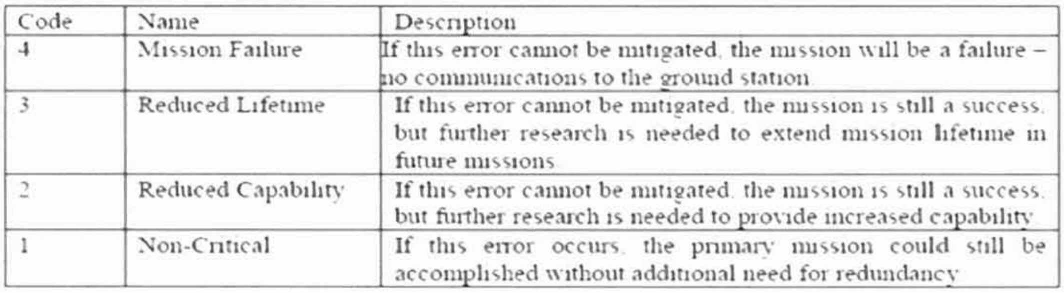
Table 8 summarizes the interfacing connections between the excavator's subsystems. Ground is electrical return for all components and the 12V supply are for the three subsystems of control, drive , and excavation. The 5V supply is completely for the operation of the onboard video camera. Command signals are sent from the operator interfaces in the control room and are communication signals that are then decoded by the Arduino microprocessor for control commands. Right and left motor control are for the drive systems and large control is for the main linear actuator of the arm and mini control is for raising and lowering of the bucket at the end of the arm. Video is an output to the operator's laptop in the control room. Appendix B shows the schematic wiring diagrams for the drive system control, the linear actuator control, and camera control.

Subsystem Interface Signals		
Signal Name	Output System	Receiving System(s)
GND	EPS	All
12V DC	EPS	Control, Drive, Excavation
5V DC	EPS	Visibility
Command Signals	Communication	Control
Camera Control	Communication	Visibility
Speed Control Left	Control	Drive
Speed Control Right	Control	Drive
Large Actuator Control	Control	Excavation
Mini Actuator Control	Control	Excavation
Video	Visibility	Communication

Table 6: Subsystem Interfaces

2.6.5. Risk Management

Single point failures are analyzed in this section using failure mode analysis are summarized in the Tables below. Each Table has a part, failure mode, code number, effect and the mitigation. The codes for failure levels come from NASA's lunabotics website.



Code	Name	Description
4	Mission Failure	If this error cannot be mitigated, the mission will be a failure – no communications to the ground station
3	Reduced Lifetime	If this error cannot be mitigated, the mission is still a success, but further research is needed to extend mission lifetime in future missions
2	Reduced Capability	If this error cannot be mitigated, the mission is still a success, but further research is needed to provide increased capability
1	Non-Critical	If this error occurs, the primary mission could still be accomplished without additional need for redundancy

Table 7: Failure Mode Analysis Code from www.education.ksc.nasa.gov

Electrical Power System Failure Mode Analysis				
Part	Failure	Code	Effect	Mitigation
Battery	Battery not sufficiently charged	4	Excavator will not have enough power to complete its mission.	Include a second redundant battery. Manage power budget so battery does not require a full charge to complete the mission.
Wiring	Wires to power distribution system become disconnected	4	Excavator's systems will not receive power.	Test connections immediately before the start of the competition.
DC to DC converter	Component failure	3	Onboard camera will not receive power. Operator will have to rely solely on overhead cameras for visibility.	Include redundant converters.

Table 10 EPS Failure Mode Analysis

Communication Failure Mode Analysis				
Part	Failure	Code	Effect	Mitigation
Router	Unable to transmit data.	4	Operator will not be able to send command signals to the excavator.	Extensive router testing.
	Unable to receive data.	3	Operator will receive not receive video from the excavator.	Extensive router testing.
Laptop or Joystick	Laptop or joystick malfunction.	4	Operator will not be able to send command signals to the excavator.	Bring redundant laptop and joystick.

Table 11 Comm. Failure Mode Analysis

Control System Failure Mode Analysis				
Part	Failure	Code	Effect	Mitigation
Microcontroller	Output pin failure.	4	Depending on the pin, the excavation or drive system will fail.	Trade studies on the reliability of various microcontrollers.

Table 12 Control Failure Mode Analysis

Drive System Failure Mode Analysis				
Part	Failure	Code	Effect	Mitigation
Speed Controller	The PWM to each speed controller is not equal.	3	May result in difficulty maneuvering the excavator.	Reliability testing of various speed controllers.
Motor	Motors deliver inadequate torque or RPMs.	3	Difficulty in maneuvering the excavator.	Contingency margins added to motor performance.
Tracks	Track becomes misaligned or band becomes lose.	2	Difficulty maneuvering the excavator.	Track reliability testing.

Table 13 Drive Failure Mode Analysis

Excavation System Failure Mode Analysis				
Part	Failure	Code	Effect	Mitigation
Linear Actuator	Either linear actuator fails.	4	Excavator will be unable to mine or deposit regolith.	Include a second redundant battery. Manage power budget so battery does not require a full charge to complete the mission.
	Linear actuator does not perform at required speed.	4	Excavator will not be able to complete its tasks within the time limit.	Contingency margins added to actuator requirements.
Bucket	Bucket warping.	2	Excavator may not be able to carry its maximum amount of simulant.	Stress testing of bucket.

Table 14 Excavation Failure Mode Analysis

2.6.6. Verification Plan

This section outlines the plan to verify that the excavator, and subsystems, meet the design requirements.

Requirement	Verification Plan
The opearator and excavation unit must be able to communicate wirelessly over a distance of at least 50 feet.	Place the operator router 70 feet from the excavator. Demonstrate the ability of the operator to wirelessly control all of the excavator's processes from this distance.
The excavator shall provide the operator with 270 degrees of visibility.	Demonstration of the operator's ability to pan the camera.
The excavator must be travel at a minimum speed of .12 m/sec	Record the length of time it takes the excavator to travel 3.6 meters. It should take a maximum 30 seconds.
The excavator shall collect at least 1.5 Kg per minute.	Use a testing box (filled with a substitute for simulant) to determine how much material is excavated in a minute.
The excavator shall have enough battery power to run at full power for 20 minutes.	Determine the length of time each onboard system is likely to be active and test the battery using these times.
The wireless communication between the excavator and operator must not exceed an average of 5Kbits per second.	Use bandwidth monitoring software to monitor the system's average, and peak bandwidth usage.

Table 15 Verification Planning

Requirement	Corresponding Subsystem Requirements
The operator control, excavation system, drive system, and visibility system must all be interfaced.	Test each interface separately to demonstrate proper functioning.
The weight of the lunabot cannot exceed 80Kg.	Weight each component before assembly, and weight the entire excavator after system integration.
The dimensions of the excavator shall not exceed 1 meter high, 1.64 meters long, and .48 meters wide it its starting position.	Measure the final dimensions of the excavator.
The excavator shall not employ any fundamental process that cannot be used in a lunar environment.	Inspection.
The excavator shall be equipped with a red emergency stop button at least 5cm in diameter.	Inspection and advisor verification.
The excavator shall be durable enough to be sent from Pennsylvania to Florida in working condition.	Perform stress tests on any components that can be replaced without endangering our schedule or cost budget.
The combined cost of parts and manufacturing cannot exceed $4,000.	Bill of materials.

Table 16 Verification Plan

2.7. Final Design

Figure 3 shows an overview of the finalf design and is comprised of essentially 3 main subsystems: (i) the drive system which uses two plastic treads on both sides of the robot; (ii) the excavation subsystem which uses a large arm with a linear actuator (attached with the robot base to the arm) and the excavating bucket (attached to the robot arm a secondary mini linear actuator that is not shown), and (iii) the vision subsystem which is not shown (shown later) but will be attached to the midsection of the robot arm.

2.7. Final Design

Figure 3 shows an overview of the final design and is comprised of essentially 3 main subsystems: (i) the drive system which uses two plastic treads on both sides of the robot; (ii) the excavation subsystem which uses a large arm with a linear actuator (attached with the robot base to the arm) and the excavating bucket (attached to the robot arm a secondary mini linear actuator that is not shown), and (iii) the vision subsystem which is not shown (shown later) but will be attached to the midsection of the robot arm.

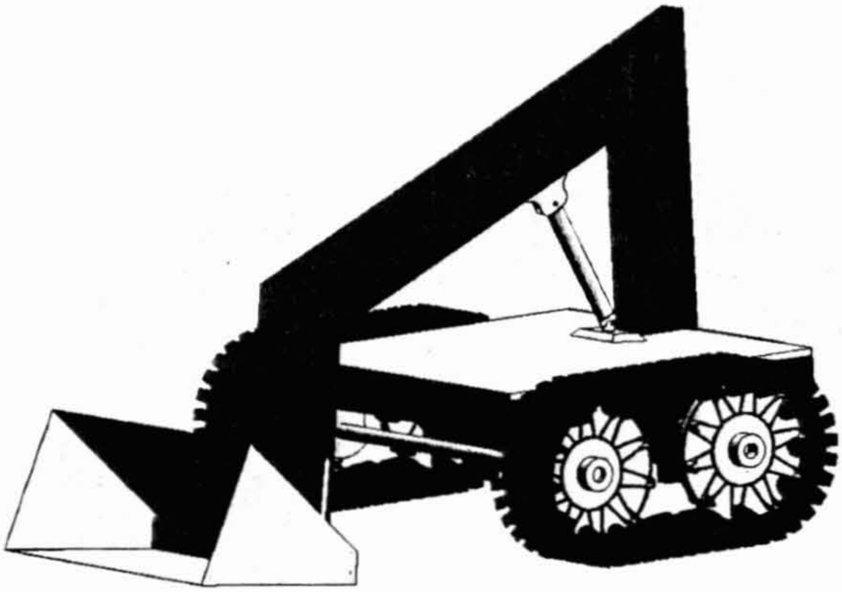


Figure 3: The Lunar Solutions I Excavator

2.7.1. Drive Subsystem

The excavator uses a two track system for transportation. The drive system is capable of moving the excavator forwards or backwards. Turning is achieved by rotating the tracks in opposite directions simultaneously. The drive systems architecture is shown in Figure 4 below and a side view is shown in Figure 5. Each track is driven by a transmission with a preset gear ratio (discussed later) that is in turn driven by two motors.

The drive system is controlled by the Arduino Microcontroller. The microcontroller outputs two pulse width modulated (PWM) signals to the speed controllers. One PWM controls the left track's speed controller, and the other PWM controls the right track's speed controller. The speed controllers are Victor 884s. The Victor 884 interprets a 5V 2ms pulse as full-forward, a 1ms pulse as full-reverse, and a 1.5ms pulse as neutral.

Figure 4: Drive System Architecture

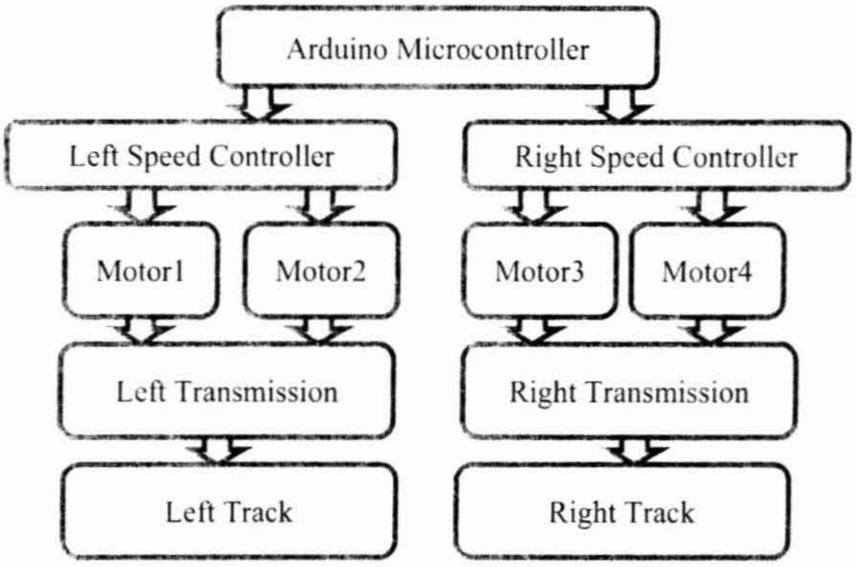


Figure 4: The Lunar Solutions I Excavator

Both Victor 884s drive two FIRST CIM Motors. At maximum efficiency, these motors have a speed of 4,614 RPM and a torque of 45 oz-in. Because these motors provide such low torque and high RPM, we used the Banebots P80 Gearbox with 192:1 ratio to reduce the RPMs and increase the output torque. This gearbox also provides an option of mounting 2 motors for higher torque output. Using Equation 1 belows, we can predict the output of our drive system. With this set up which consists of two FIRST CIM motor, and 192:1 Banebots Gearbox, we will be able to deliver a max 17000 oz-in torque with max speed of 24 RPM on one track.

$$\mathbf{Torque = (2 * Torque_{motor}) * Ratio_{gearbox}}$$

$$\mathbf{Speed = Speed_{motor} / Ratio_{gearbox}}$$

Equation 1: Equations for Torque and Speed

The motors drive the two tracks, molded from a soft 70 durometer nitrile material. Each track is 4" wide, and has a 10" diameter. This large area will allow for the large torque produces through the greaing system to be transferred to a large surface area and hence reducing any slipping (or spinning) between the track and the surface simulant.

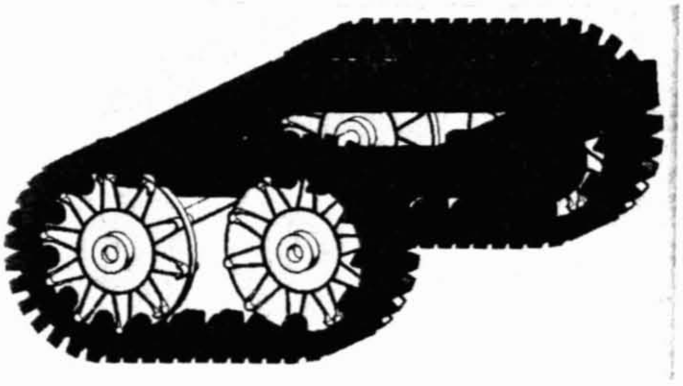


Figure 5 Side View of Drive System

2.7.2. Excavation Subsystem

The excavation system, which utilizes a front-end loader design, serves two main purposes. It is used to perform the mining process, and also to deposit simulant in the collection box. Both of these processes are executing using linear actuators to control an arm and bucket.

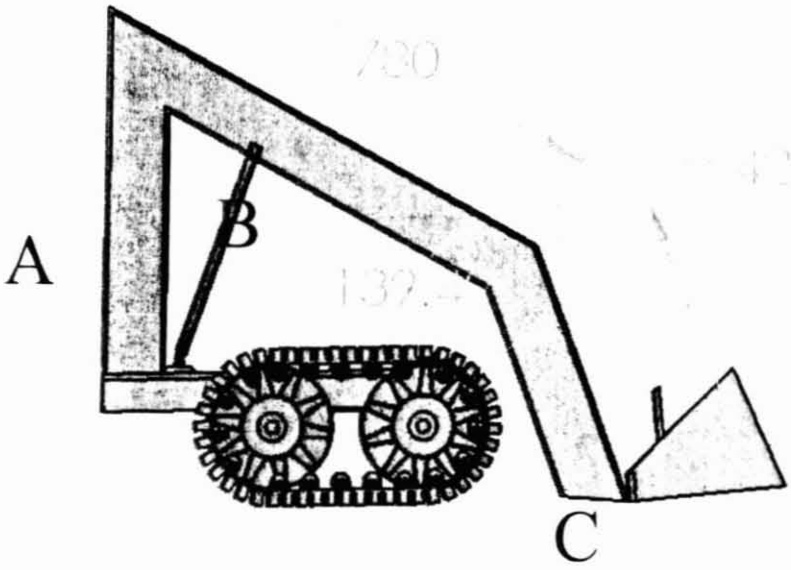


Figure 7 Side View of Excavator

The figure above shows the basic architecture of the excavation system. The arm used to lift the bucket consists of three sections (A,B, and C). It was constructed out of Fiberglass Reinforced Plastic (FRP) I beams. FRP was chosen because it is very strong while also being light weight. Section B of the arm can be raised or lowered using the linear actuator (LA1) shown in Figure 8.

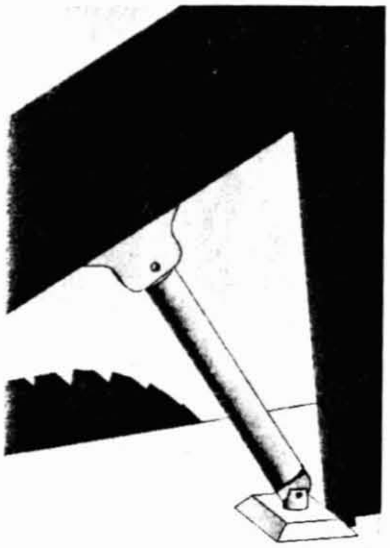


Figure 8 Actuator LA1

There is a second 12 V DC linear actuator (LA2) located between sections B and C, which is used to tilt the bucket when it is depositing the regolith. This is attached to the top edge of the bucket pushing back against a solid support.

When the excavator begins the mining process, the linear actuators will retract so that the arm is in its fully lowered position as shown in Figure 9. When in the fully lowered position the bucket is able to collect simulant. After the mining process is complete, the operator will use LA1 to raise section B during the transportation process.

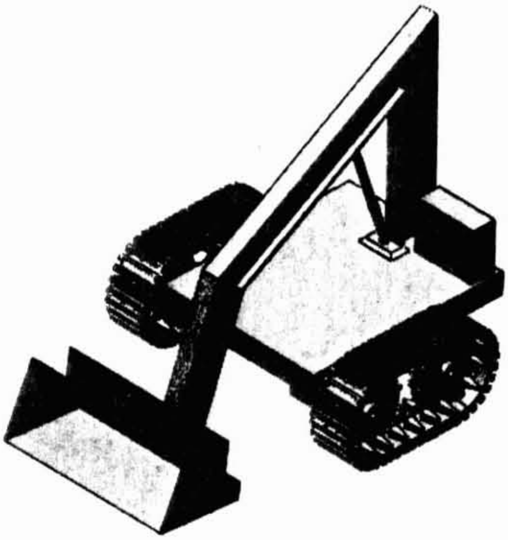


Figure 9 Full Down Position

When the excavator reaches the collection bin, LA1 is used to raise the arm and bucket to the fully raised position as shown in Figure 10 below.

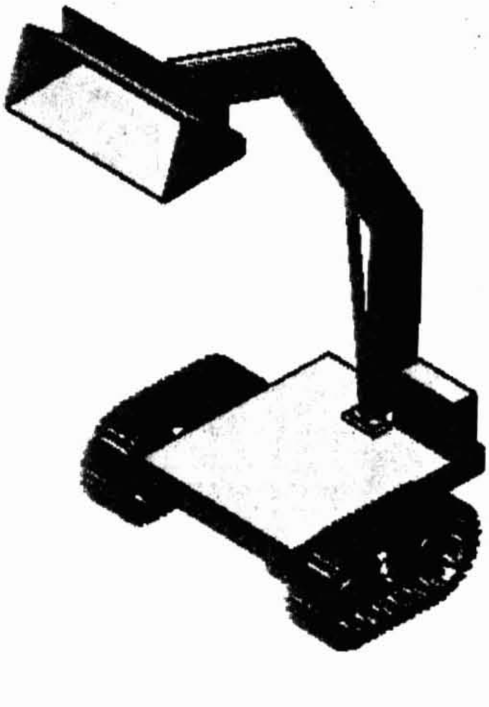


Figure 10 Full Up Position

The linear actuators were chosen based on the force needed to lift the bucket, arm, and simulant load (15+lbs.)

In order to select the appropriate linear actuator for the job, we had to determine the force need to lift the bucket and I beam with a full load of regolith (15 Kg). The calculation for the total force of both linear actuators is shown below in Equation 2. The combined weight of the bucket, arm, and lunar regolith, is between 20 and 30 Kg. To lift the filled bucket a distance of 65 centimeters from the pivot point, we will need a torque of 160 Newton/meter. Provided that the distance from actuator to pivot point is about 20 centimeters, the system will need a force of 800 Newton which is about 170 pounds of force. Therefore, a linear actuator capable of lifting 200 pounds with a speed of approximately 1 inch/second was selected.

$$\sum \mathbf{M_0} = \mathbf{0} = \mathbf{F_{actuator}}\,\mathbf{D_{actuator}} - \mathbf{F_{weight}}\,\mathbf{D_{weight}}$$

Equation 2. The Force Required

We simulated the movement of the arm using SolidWorks, a Computer Aided Drafting (CAD) tool. This helped us determine the necessary size and stroke of the linear actuator. After reviewing the CAD simulations we selected an 8 inch linear actuator with the capacity to lift 200 pounds. Another factor which we took into consideration when choosing a linear actuator was speed. Our linear actuator extends at an average 1 inch/second which will allow us to excavate enough material within the time limit. We used a similar approach to calculate the necessary requirements for the linear actuator used to tilt and empty the bucket. The second actuator will be 8 inches and deliver a force of 150 pounds.

The lunar simulant used for the competition has a density of approximately 2.9 grams/cm^3. The dimensions of the bucket (shown below) are 30×30×50 cm. The buckets total volume is approximately 12×10^3 cm^3. It is able to hold up to 30Kg of regolith, exceeding our design requirement of 15Kg. The entire bucket was made out of carbon steel to avoid distortion during the scooping process. The carbon steel of the bottom plate is 1/8" thick, and all other surfaces are 1/16" thick.

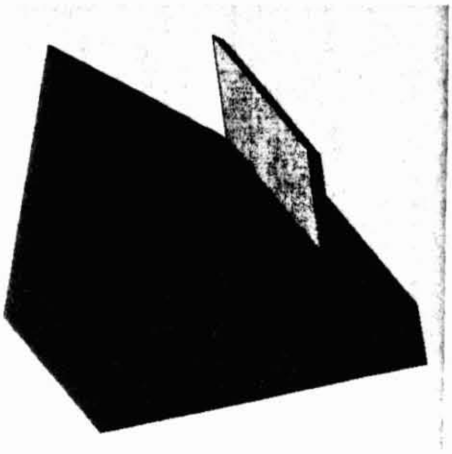


Figure 11 Side View of Bucket

2.7.3. Communication Subsystem

The communication system handles all operator input to the excavator's control system, and provides the user with video from the wireless IP camera. The three main hardware components of the communication system are: an analog joystick, a laptop computer, and a Linksys Wireless-G router. The interfacing of these components can be seen in the diagram below.

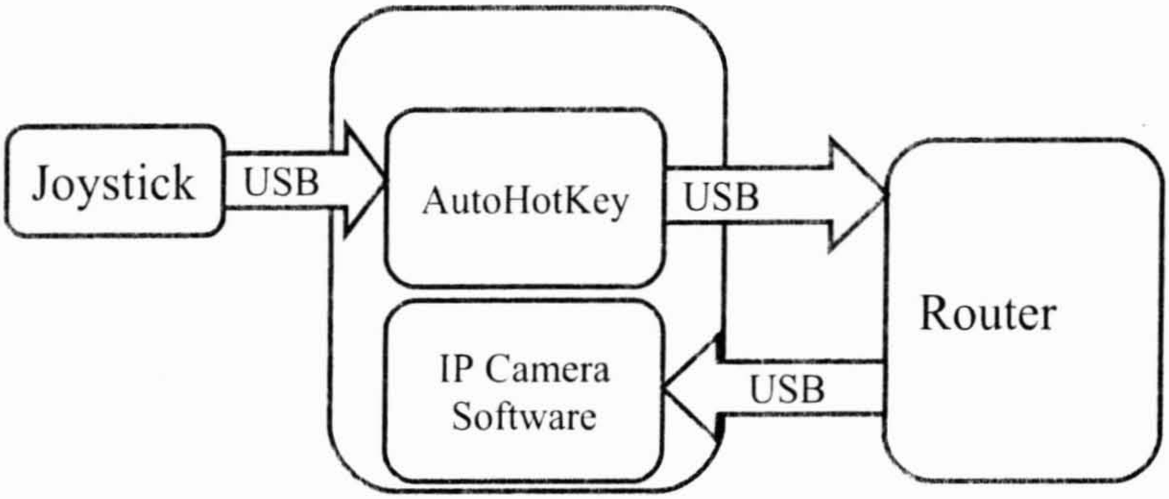


Figure 12 Communication System Architecture

The operator uses the analog joystick to control the drive and excavation systems. The X and Y position of the joystick control the drive system's speed and turning direction, respectively. The excavation system's linear actuators are controlled by four buttons located on the joystick. Two buttons are assigned to each actuator. One button causes extends the actuator while the other retracts it.

The laptop uses an open-source utility, called AutoHotKey, to remap input from the joystick to command signals. The joystick input signals can be seen in the table below.

Joystick Input Signal		
Signal Name	Possible Values	Description
JoyX	0 to 100	Position of joystick on the X axis from far left (0) to far right (1), where 50 marks the neutral (center) position.
JoyY	0 to 100	Position of joystick on the Y axis from completely back (0) to completely forward (1), where 50 marks the neutral (center) position.
Joy1	0 or 1	When button 1 is depressed, Joy1=1. Signals LA1 to

		raise arm.
Joy2	0 or 1	When button 2 is depressed, Joy2=1. Signals LA1 to lower arm.
Joy3	0 or 1	When button 3 is depressed, Joy3=1. Signals LA2 to raise bucket.
Joy4	0 or 1	When button 4 is depressed, Joy4=1. Signals LA2 to lower bucket.

Table 17 Joystick Input

AutoHotKey runs a script, which continuously monitors the joystick input signals and assigns keyboard characters accordingly. The source code of the AutoHotKey script and character assignments can be found in the table below.

Character Assignment Based on Joystick Position			
JoyX value	JoyY value	Character Assignment	Notes
45<JoyX<55	85<JoyY	9	Joystick in full forward position. Excavator will move forward at greatest speed.
	75<JoyY<85	8	
	65<JoyY<75	7	
	55<JoyY<65	6	
	45<JoyY<55	5	Joystick in neutral position. Excavator will remain stationary.
	35<JoyY<45	4	
	25<JoyY<35	3	
	15<JoyY<25	2	
	10<JoyY<15	1	Joystick in full back position. Excavator will move backwards at highest speed.
85<JoyX	45<JoyY<55	a	Joystick is far right. Excavator will

			turn right.
75<JoyX<85		s	
65<JoyX<75		d	
55<JoyX<65		f	
45<JoyX<55		5	Joystick in neutral position. Excavator remains stationary.
35<JoyX<45		h	
25<JoyX<35		j	
15<JoyX<25		k	
10<JoyX<15		l	Joystick is far left. Excavator will turn right.

Table 18 Character Assignments

Once a keyboard character has been assigned, it is sent (via Wi-Fi) to the Arduino where it can be interpreted. The command signal is transmitted using a Linksys Wireless-G router, connected to the laptop, as a wireless access point (WAP). The router also receives video information from the onboard wireless IP camera. This process we be described in greater detail in the visibility section.

2.7.4.

Control Subsystem

Onboard control of the drive and excavation systems is handled by the Arduino Mega microcontroller. The Mega is connected to an Arduino Ethernet Shield, which allows it to connect to the onboard Linksys Wireless-G router.

The Arduino receives command signals from the operator as characters (discussed in the previous section). These signals are interpreted by code stored in the Arduino's internal flash memory.

The code assigns output signals to specified digital I/O pins, based on the input character. Motorpinleft (defined as pin 2) and motorpinright (defined as pin 3), output PWM signals to the speed controllers.

2.7.5.

Visibility Subsystem

Because the operator will never be able to view the excavator directly, an adequate visibility system is crucial for mission success. NASA provides two cameras which provide an overhead view of the playing field, but these cameras do not provide enough detail for the operator to maneuver the excavator around obstacles, or line up with the collection bin.

To provide the operator with a greater level of visual detail, we equipped our excavator with an F-series wireless IP camera. It features panning and tilting options, and adjustable frame rates and resolution. The camera is connected to the onboard router via USB so that it can send video information to the operator's PC.

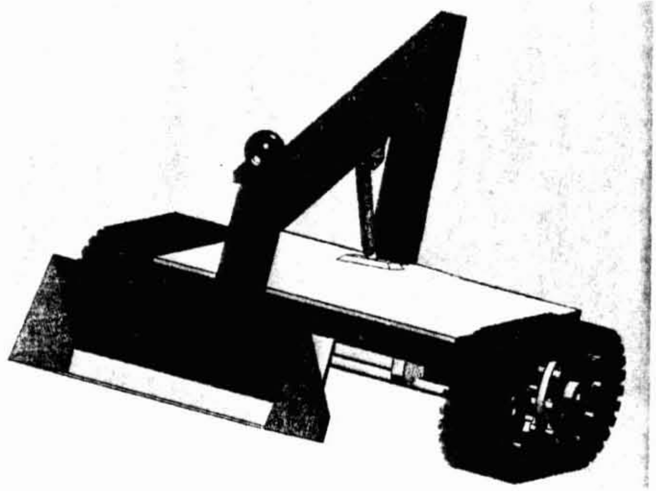


Figure 13: Robot with camera mounted on the robot's arm.

Another benefit of using a wireless IP camera is that it reduces the number of processes handled by the microcontroller. The camera's built-in RISK32 processor compresses images using the standard M-JPEG format. . The IP camera is IEEE 802.11b compatible and it can wirelessly transmit video to the operator's laptop. The IP camera comes with its own software, which we installed on the operator's laptop. The software allows the operator to pan or tilt the camera, providing a greater range of visibility.

NASA requires the average bandwidth of all communication between the operator and excavator be below 5Mbits/s. The command signals to the Arduino require less that 1 Mbit/s. This leaves 4Mbits/sec for the wireless IP cameras. We added a 25% contingency, so the average bandwidth allowed for the visibility system must be less than 3Mbits/s. The bandwidth needed for the camera was calculated using the equation below. The equation uses 10 bits per byte as opposed to 8, to allow for some overhead (Mesnik, 2005).

$$\text{Bandwidth} = \text{Image size in Bytes} * 10\,\frac{10\text{ bits}}{\text{Byte}} * \text{Frame rate in } \frac{\text{frames}}{\text{second}}$$

Equation 3. Bandwidth Consumption using MJPEG Compression

We used a VGA resolution rate of 640× 480 which will yield image size about 30 Kilobytes. At a frame rate of 4fps, the camera will require a bandwidth of about 1.2 Mbits/sec to transmit the video that it captures.

2.7.6. Electrical Power Subsystem

The electrical power system (EPS) provides power all of the excavator's onboard systems. Power is provided by two, 12VDC 20Ah batteries.

The batteries are connected in parallel, and run through a safety relay which can be used to immediately disconnect power to the main fuse panel in an emergency. This emergency disconnect is controlled by a single pole, single throw, normally closed emergency stop switch. The e-stop switch has a 2.13" diameter button which is easily accessible in case of an emergency.

Every component on the excavator that requires power is wired to the fuse panel. The linear actuators each use two 20A fuses. There are two 40A fuses for the Victor 884 speed controllers, and two 40A fuses for the IP camera and Arduino. There are four fused circuits at five amps for the two IP cameras, bin sensor, and the Arduino controller.

2.7.7. Integration

After being built, each subsystem was thoroughly tested to reduce integration problems. Once tested, the electrical, drive, excavation, visibility, and control systems were integrated using the system architecture described in section 2.6.2., and the interfacing described in section 2.6.4..

2.8. System Verification and Analysis

A full testbed has been constructed within our lab to act as a small scale version of the Lunarena that will be setup at Kennedy Space Center. It is comprised of a bed filled that is 12 feet long and 5 feet wide and 8 inches deep filled with lunar stimulant . Figure 14 shows the testbed during construction phase with plastic exterior around wooden framing. The plastic exterior is used so as the lunar stimulant doesn't escape into the external air that we discover can set off fire alarms. This will allow for the testing of all subsystems particularly the drive subsystem and the excavations subsystem in a real but smaller scale competition arena. We have setup a wireless network within the lab using wireless routers which is similar that we will be using at the Kennedy Center. This will allow us to test all communications both to and from the lunar excavator so as to ensure its robustness.

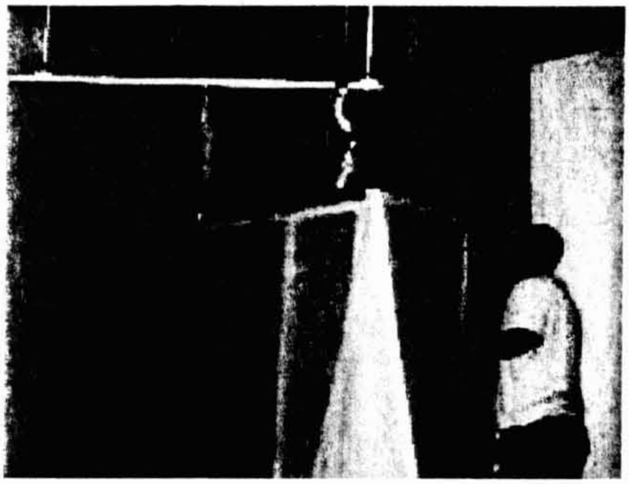


Figure 14: Construction of the testbed arena.

Figure 15 shows the testbed with framing and the platic removed and the Temple University 2010 lunabot's excavator in the pit arena.

Figure 15: Testbed arena with framing removed and 2010 Temple Lunabot

2.8.1. Unit and Subsystem Testing

The drive system has been tested within the constructed testbed system within the lab. This test was performed only with the drive system and a can be seen in Figure 16 below and also a video of this test can be seen at the following link on YouTube:

http://www.youtube.com/watch?v=LJhT6LAFOec&feature=player_embedded

Figure 16: Test of the tread drive system inside the testbed arena.

The excavator arm system has been constructed and is currently being tested. Figure 16 below show a picture from with the arm holding a 5 gallon bucket of water. We did notice high stress points under this test and have done some modification to reinforce certain joints in the arm with aluminum brackets and a critical part was where the robot arm is connected to the robot base.

Figure 16: Test of the arm drive system lifting a 5 gallon bucket of water..

This test was performed only with the drive system and a can be seen in Figure 14 below and also a video of this test can be seen at the following link on YouTube:

http://www.youtube.com/watch?v=lcnyjnqFFZw

2.8.2. Integration Testing

Integration testing will be performed in the weeks that follow the subsystem testing. A matrix of test is being designed under all of the situations we expect to encounter in the Lunarena.

3. CONCLUSION AND FUTURE WORK

A complete design has been performed on a lunar robot excavator for the 2011 Lunabots competition. During this design process all system requirements, constraints, specifications, failure mode analysis have been performed. The current design is modeled after a front-end loader design after consideration of both conveyor belt and auger type excavation designs. The drive system is of a tank-tread like system so as to maximize the contact area between the robot's treads and the lunar surface so as to minimize "slipping" between the tread system and lunar surface as opposed to a wheeled system with smaller contact area.. Currently we are under subsystem testing followed by integration testing. A full small scale testbed of the Lunarena has been constructed and is currently begin used to test all subsystems followed by the full system integration testing.

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5. APPENDICES

APPENDIX A: PRODUCT SPECIFICATION

Lunar Solutions

The Excavation Robot

Overview:

What is the Excavation Robot?

It is a machine which is designed specifically to meet NASA specific requirements and constraints for the Lunabotics competition.

This robot is vacuum friendly!

Features:

- Control:

  The robot is controlled by a microcontroller for ease of programming.

  User can control the robot by any computer connected to the internet.

- Drive system:

  Two tracks directly driven by four motors.

  Speed control.

  Special designed tracks for maximum traction.

- Excavation system:

  Front end loader for excavating and dumping material.

- Communication:

  Communicates over TCP/IP protocol with a bandwidth of 2-45MB/sec.

- Vision:

  IP WIFI cameras integrated on the excavator for environment awareness.

[illegible]

Dimensions:

2 M high, 0.75 M wide and 1.5 M long

Weight:

75 KG (without load)

Maximum load:

15 KG of material.

Battery life

4 Hours of operation

Power requirements:

12 V

Safety:

Emergency switch is attached for immediate shutdown

Communication Bandwidth:

5 MB/sec

APPENDIX B: WIRING SCHEMATICS

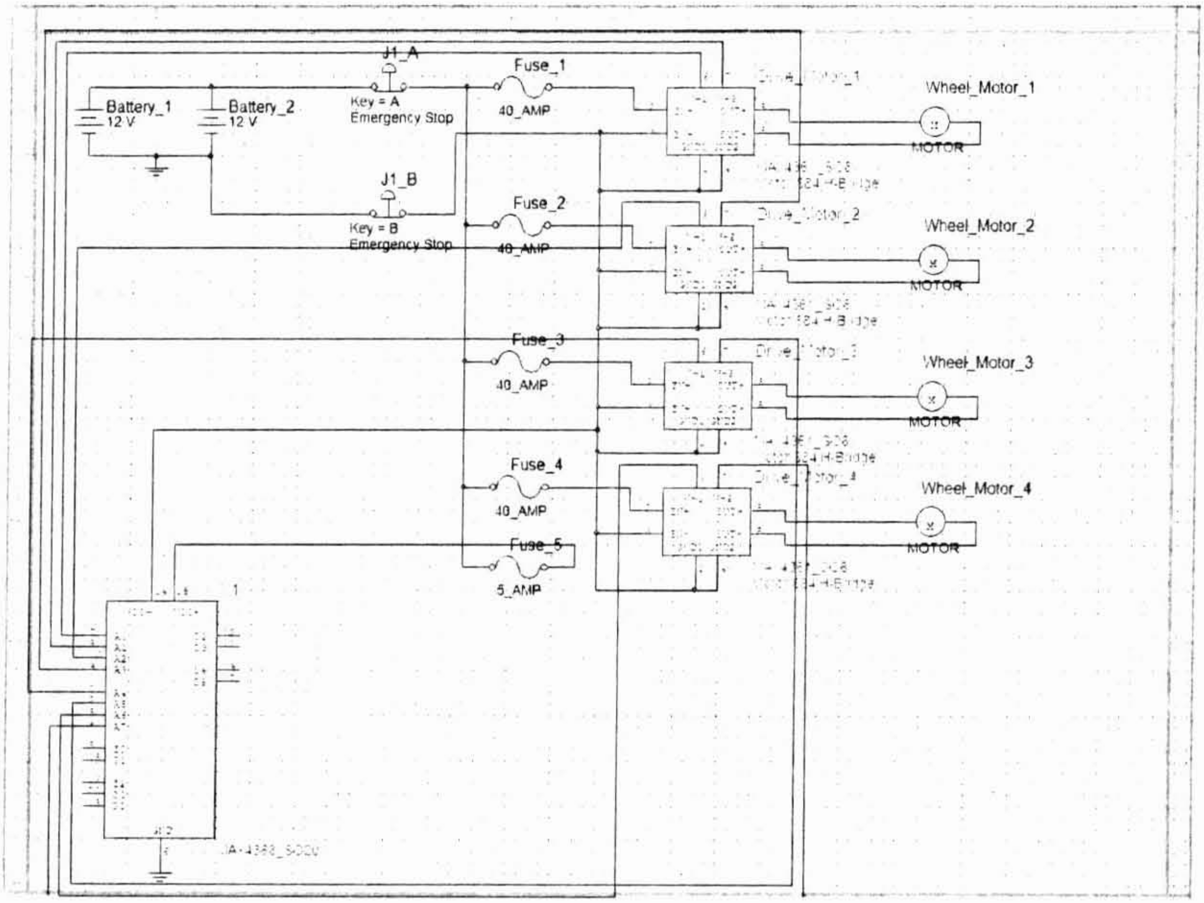

Figure 17.Main Controller & Drive System

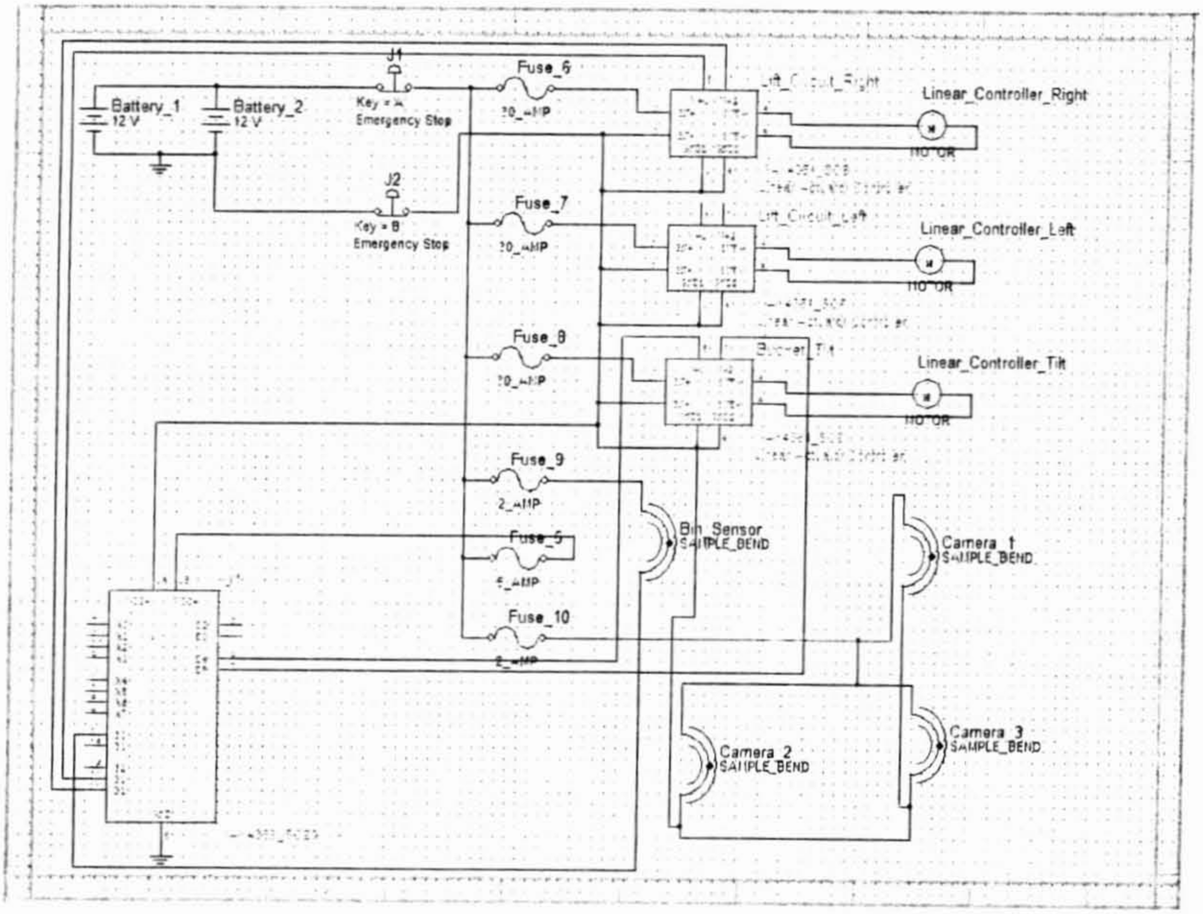

Figure 18.Linear Actuator & Camera Control