Systems Engineering Paper

Lunar Regolith Excavator

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Abstract

Each May, NASA holds a competition in Kennedy Space Center at Cape Canaveral, FL: the Lunabotics Mining Competition. JBU has participated in this competition for three years running and will compete again in May of 2013. For this competition, the JBU Lunabotics team designed a fully autonomous robot with a digging mechanism never seen at the competition. One of the requirements of the competition is to develop a solution to the design problem using a Systems Engineering approach. The JBU design team divided the robot design into sub-systems which were integrated together to work seamlessly towards the goal of mining completely autonomously. The different subsystems were as follows: Excavation, Storage and Ejection, Mobility, Frame, Power, Communication, and Control/Autonomy. The team developed subsystem requirements and interfaces, analyzed and tested these subsystems before integration, and finally tested the complete system. As a result of this requirements breakdown and subsystem testing, the robot worked the first time upon full system integration.

In order to gain a leading edge on the other teams and increase the probability of winning the competition, JBU established several goals. These goals were as follows: keep the mass of the Lunabot under 50kg, have the robot operate fully autonomously, that is, without user control, maximize dust tolerance by encasing all electronic equipment and using dust tolerant design methods for mechanical systems (i.e. belt drives instead of chain drives, dust shields encasing much of the robot, etc.), and integrate mechanical and electrical systems to minimize complexity and reduce the overall mass of the robot.

The end result of this project was a fully autonomous, functioning Lunabot that performs the task of mining 30kg of lunar regolith simulant within the ten minute time constraint as set forth by the NASA competition judges. It should also be noted that the team met their overall mass budget of 60.0kg, weighing in, before the competition, at 52 kg.

1) Introduction

1.1 General Information

In May 2013, the National Aeronautics and Space Administration (NASA) will host the fourth annual Lunabotics Mining Competition (LMC) at Kennedy Space Center in Orlando, Florida. The competition is mainly to "engage and retain students in science, technology, engineering and mathematics."[1] Its primary objective is to develop and apply lunar excavation concepts to the design, construction, and testing of a robot.

For future projects in space, NASA desires to optimize its missions by using lunar resources. One of those resources is lunar soil (regolith) which can be processed to obtain vital substances such as water and oxygen. In order to obtain regolith, mining and transport machinery are needed. Thus, the Lunabotics Mining Competition is organized with the purpose of collecting valuable data to develop such a prototype. It is a worldwide event that invites universities from across the globe to design, build, and test a robot that is able to excavate and transport lunar regolith samples. Whether these prototypes succeed or not, the main goal is to collect valuable data on the weaknesses and strengths of the different designs.

The competition is also intended to promote workforce development in science, technology, engineering, and mathematics (STEM) by engaging college students in an exciting, challenging project that will provide them with realistic engineering experience [2].

John Brown University (JBU) is returning for its fourth year in the competition. Last year's JBU team had a successful participation in the competition, obtaining fifth place on the Onsite Mining, second place on the Systems Engineer paper and third place on the Outreach report.

Based on this success, this year's team designed the mobility subsystem based on the previous prototype (2012). However, since the main goal of this year's team is to achieve an autonomous robot, the rest of the subsystems were redesigned in order to fit and facilitate the new criteria.

The JBU team (Golden Eagles) utilized a systems engineering approach to design the prototype. The team derived the main requirements for their design from the LMC Rules and Rubrics. The team divided these requirements into subsystems to manage the project's complexity. Requirements, interfaces, and testing were defined at the subsystem level to ensure that the design as a whole will effectively complete its essential functions.

The JBU team tested at the component, subsystem, and interface levels before performing system level testing in order to ease integration and ensure overall success of the robot. At the time of this paper's submission, the team has constructed a working Lunabot. Due to the efficient and hard work of testing each subsystem individually, the integration of the prototype was functional in the first attempt, though some fine adjustments had to be made. Through testing, the Lunabot has demonstrated its ability to accomplish the mission requirements and achieve the team's goal of obtaining 1120 points to win the LMC. Figure 1 shows JBU's 2012-2013 Lunabot prototype.

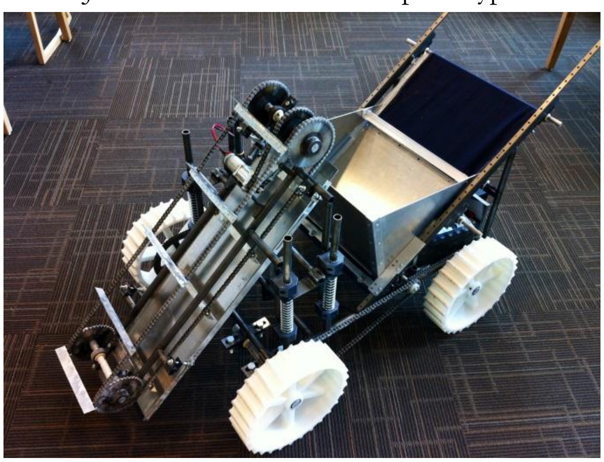

Figure 1: JBU Lunabot Prototype

The JBU team is comprised of five senior-level engineering students. The students each took responsibility for the different subsystems, and utilize a collaborative approach to the design and systems integrations. In this way the systems engineering approach was included on every level. The team met weekly with their faculty advisor to review the design progress and receive suggestions on the project. Alongside the business oriented meetings, the team organized different activities, such as cooking and dinner activities, to increase the team spirit in the group. In general, the team attributes the successful operation of the Lunabot to the cooperation and interaction of all team members toward the goal and the thorough testing at a subsystem level.

This paper demonstrates the Golden Eagles application of systems engineering principles to the design of the 2013 Lunabot prototype. The team defined the mission objective and system level requirements, created a concept of operations, and held different design reviews to contribute to the wholeness of the project.

1.2 Problem Statement

JBU team's goal is to build a lunar regolith-excavating robot which operates primarily autonomously but has the ability to be controlled wirelessly as well. To achieve the team's goals, the robot must weigh less than sixty kilograms and excavate a minimum of thirty kilograms during a ten minutes competition attempt. The robot shall report the total energy consumed after each competition attempt and a small bandwidth usage. The robot shall also operate in a way that avoids any kind of dust projection. Finally, the robot's overall design shall be equipped to work under damaging dusty conditions.

1.3 Objectives and Goals

The 2013 JBU's team's main objective is to design, build, and test a completely autonomous prototype to meet all the requirements given by NASA LMC.

In case the autonomous system fails, the robot shall also contain a backup user operated control system. This system utilizes an Xbox controller and a frequency module to communicate wirelessly between the user and the robot, accomplishing all the operations previously mentioned via user input rather than autonomy.

Since the primary goal of the competition is to collect valuable data for future missions in space, this JBU team designed a new digging mechanism that should work under lunar conditions.

Given the previous specific goals the team designed a "point's budget." The JBU team's goals for the robot based on the score rubrics are summarized in Table 1.

Table 1: Points Budget

Mining Category Elements	Specific Points	Actual	Units	Points
Pass Inspections				1000

Regolith over 10kg	3/kg	30	Kg	60
Average Bandwidth	-1/50kb/sec	500	Kb/sec	-10
Lunabot Mass	-8/kg	60	Kg	-480
Report Energy Consumed	0	1	1 or 0	20
Dust Tolerant and dust free	0 to 100	80	Judges' criteria	80
Full Autonomy	500	1	1 or 0	500
TOTAL				1120

2) Concept of Operation

The concept of operation of this year's design is based on autonomy. Therefore, all the subsystems were designed to facilitate this task. In addition, each subsystem accomplishes the given criteria described by NASA rules. These operations include:

- The user should be able to activation/ deactivation the autonomous mode for the robot.
- Autonomously traverse the Lunarena to reach the mining area using a way-point system along with a mapping technique. This includes:
    - Running over small obstacles
    - Avoiding big obstacles.
- Autonomously excavate at least 30kg of simulant without producing clouds of dust or affecting the performance of the prototype.
- Autonomously return to the target collecting area using a beacon system.
- Autonomously deposit the collected regolith in the collection bin without leaving any sample behind.
- Have a backup control system to enable user control in case of autonomous malfunction. This system will be activated/ deactivated by the user.

In addition, the Lunabot system is to measure and report its own power during the competition. The robot is designed to protect all its components are protected from dust, as well as to minimize dust projection during the competition.

3) Systems Engineering

Due to the complexity of the Lunabot design, the systems engineering approach is crucial. Since the team is formed by senior students, the project was expected to be finished during one academic year at JBU. Table 2 shows the major tasks the team completed for each of the phases described in the systems engineering process outlined by Dr. David Beale [3].

Table 2: Team Phases and Tasks

Phase	Task	Execution
Pre-Phase A	Study and define mission objectives, test 2012 robot	09/08/2012-10/6/2012
Phase A	Brainstorming, trade studies, conceptual design review	10/7/2012-11/7/2012
Phase B	Concept selection, subsystem assignment, subsystem design, subsystem integration	11/10/2012-11/15/2012
Phase C(1)	Verify interfaces, finalize design, final design review	11/16/2012-12/10/2012
Phase C(2)	Order parts, parts modification, software coding	12/11/2012-1/20/2013
Phase D(1)	Component testing, software testing and application, functionality verification	1/20/2012-3/20/2013
Phase D(2)	Subsystem fabrication, "flat robot," subsystem testing, initial build review	2/20/2013-3/15/2013
Phase D(3)	Subsystem integration, system testing, design modifications	3/26/2013-5/1/2013
Phase D(4)	Outreach demonstration, compete at NASA LMC*	4/26/2013-6/1/2013

*Future Task

At this time, the team has completed the Lunabot prototype and performed both subsystem and system level testing. The team's prediction for the competition is to earn a total of 1120 points.

3.1 Systems Design and Management

When creating the conceptual design, the team divided the overall system into three subsystems: mechanical, software development, and electrical. This was then further divided into functional subsystems. Since it is a five member team, in addition to the technical work, the students needed to develop tasks such as fundraising, outreach presentations, and general paperwork. The team used the subsystem division and management system shown in Figure 2 to divide work and establish communication. Each subsystem was assigned to a team member. All the members of the team discussed and approved the fundamental decisions of the project, acting as a board of directors. The design process for each of these subsystems is described in detail in the Interfaces section.

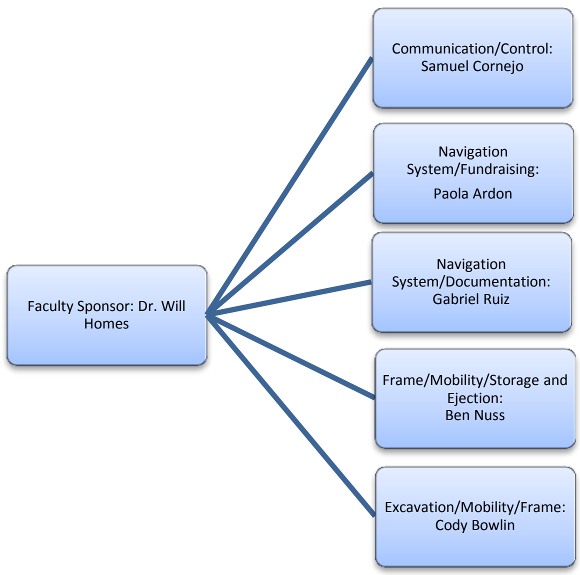

Figure 2: Project Management Hierarchy

3.1.1 Technical Constraints

To successfully complete this year's robot, the JBU team operated within many constrains. Some of these were based on the rubrics given by NASA, others included some of the specific goals for the team pointed towards autonomy. These constraints are:

- Mass less than 60 kg. This includes the robot's power and navigation system that will help to achieve autonomy (beacon system located at the bin).
- The robot must fit in a size box of 0.75m wide x 1.5 m long x 0.75m high at the beginning of the competition.
- Timing: The robot must reach the excavation area, excavate, and return to the collecting bin in a time frame of ten minutes.
- Bandwidth: the average wireless bandwidth used may not exceed 500 Kbps.
- Wireless Range (robot to access point) at least 50ft.
- Wireless Range (access point to control center): at least 200 ft.
- Mechanical systems to support and facilitate autonomy while simultaneously meeting other constrains.

3.1.2 Budget

To complete the project, the JBU team received funds from donations and grants. The team received one scholarship from Arkansas Space Grant Consortium. Additionally, the team was sponsored by JBU, Nance Machine, and MACROlite Composites. Table 3 shows the team's budget of $15,164 and the corresponding breakdown based on subsystems. The table shows the predicted budget as well as the team's current spending.

Table 3: Project Budget

Source	Original Funding	Additional Funding
JBU Grant	$2,500	
ARSGC Grant		$6,500
Other donations		$500
TOTAL:	**$9,500**	
System	**Predicted**	**Spending as of 4/23/2013**
Frame	$516.02	$0
Mobility	$1072.04	$0
Excavation	$1655.09	$90
Storage/Ejection	$247.39	$120
Autonomy	$877.80	$1130
Power	$2115.20	$0
Testing	$700.00	$100
Travel	$7675.00	$600
Team Spirit	$540.00	$335
TOTAL:	**$15,164.54**	**$2375**

3.1.3 Schedule

The systems life cycle was applied to the system as a whole, but also to each subsystem. To enable efficient management of the systems life cycle, JBU's team developed a schedule. Table 4 shows the schedule for the design process. This schedule facilitated the implementation of systems engineering throughout the design process.

Table 4: Project Schedule

Task	Duration	Deadline
Brainstorming	12 days	9/22/2012
Conceptual Design Review	1 day	10/9/2012
Concept Selection and Subsystem Assignment	1 day	10/11/2012
Subsystem Design	25 days	10/17/2012
Full Design	7 days	11/18/2012
Order Parts	50 days	12/3/2012
Final Design Review	1 day	1/28/2013
Subsystem Assembly	17 days	2/28/2013
Subsystem Testing	7 days	3/23/2013
Initial Build Review (Electrical)	1 day	3/29/2013
Initial Build Review (Mechanical)	1 day	3/30/2013
Full System Testing	28 days	4/23/2013
NASA Documentation	28 days	4/22/2013
Video of Lunabot Operation	5 day	4/30/2013
Competition	4 days	5/20/2013

3.1.3.1 Design Reviews

Throughout the design process, the team participated in several design reviews to solicit feedback and to ensure the quality of the project. JBU's faculty members and staff, local industry professionals, and local machine experts participated in these reviews to give the team a better perspective and advice on the project. In addition, the different design reviews kept the team keep accountable to the schedule implemented at the beginning of the design process. Table 5 shows the different design reviews throughout the process.

Table 5: Design Reviews Schedule

Review	Purpose	Date
First Design Review	Ensure that the team has properly understood the requirements of the project	October 23rd, 2013
Final Design Review	Present real solutions and final designs to the different subsystems to achieve autonomy and other operations.	February 13th, 2013
Initial Build Review	Ensure that the design is complete. Present first prototype of subsystems including flat robot.**	March 12th, 2013
System Integration Review (EAB)*	Present the prototype to the advisory board. Ensure all the subsystems work properly together. Check for testing, completeness and functionality.	April 12th, 2013

*Engineering Advisory Board
**Flat robot: all the circuitry done, however not necessarily in the circuitry housing.

3.1.3.2 Risks

Following the stated schedule was crucial for the team to finish the project. However, throughout the process, the team had to overcome some delays that threatened the prototypes completion. One major delay was figuring out autonomy. Starting this year, the goal was not only to get a fully functional robot, but also an autonomous one. The team spent more time doing research and designing autonomy than expected. As a consequence, the actual building and testing of the prototype was also delayed, which represented a major risk to the project. Nevertheless, since every subsystem was thoroughly designed and tested individually, the integration of the whole system was successfully completed in 24 hours.

The second major challenge for this year's team was financial resources. At the beginning of the project the team was lacking financial support, which contributed to the delay of the building and testing process. Fortunately, after 6 months the team was able to raise the sufficient funds that were needed to finish the prototype.

3.1.4 Project Life

The systems life cycle for the 2013 JBU Lunabot began at the 2012 LMC when two junior students accompanied the 2012 senior JBU team to the competition. These students used the competition week to talk to other teams, evaluate conditions in the LunArena, brainstorm design approaches, and gain experience for the subsequent competition.

The team will continue the testing and maintenance phases until the 2013 LMC, at which point the Lunabot shall perform its intended purpose. The team will again bring two junior students to the LMC to provide future development of the Lunabotics tradition at JBU. Following the LMC, the 2013 Lunabot shall continue to function as an outreach tool for the 2014 Lunabot team, allowing them to perform demonstrations and hands on activities with outreach audiences.

3.2 System Requirements

The system requirements in Table 6 incorporate both the team's goals of autonomy and qualification requirements implemented by NASA for the competition. These requirements drive each subsystem requirement and are listed with a reference number in Table 6.

Table 6: System Requirements

System Requirements	
Functional	Excavate, carry, and eject 30kg of lunar simulant (F.1)
	Fit within 1.5m x 0.75m x 0.75m in initial position (F.2)
	Weigh less than 50kg (F.3)
	Use no more than 500kb/sec of average bandwidth (F.4)
	Eject simulant into bin 0.5m above the surface
	Autonomous operation (F.5)
	Maneuverable through a simulated Lunar environment with obstacles and craters (F.6)
Performance	Excavate 30kg in 3.5 minutes (P.1)
	Operate in a dust free, dust tolerant fashion (P.2)
	Autonomously adjust digging depth (P.3)
	Yield power consumption readings (P.4)
Interface	Operable with NASA's provided network (I.1)
	Self-contained and non-interfering with other teams (I.2)
	Provide real time (within 5 seconds) health and diagnostic information (I.3)
	Inform decision on continued autonomous operation (I.4)
Verification	Fully functional in test LunArena (V.1)
	Functional with test network (V.2)
	Capable of continual operation for 20 minutes (V.3)
Other	Monitor position in LunArena, proximity to obstacles, payload, excavation rate, battery health, and bandwidth usage (O.1)

3.3 System Hierarchy

The project can be simplified by logically breaking the system into a hierarchy. The complete system resides on the top level of the hierarchy, followed by the two primary subsystems in which the project was divided. Figure 3 shows the hierarchy followed to reach to complete JBU's Lunabot.

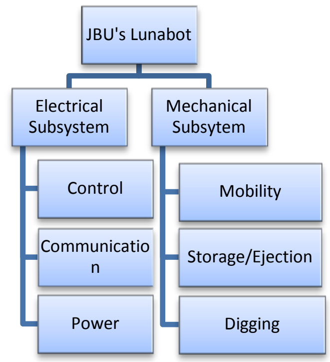

Figure 3: Technical Hierarchy

3.4 Systems Analysis and Control

Throughout the design process, the JBU team considered many possible design solutions. In order to choose the best alternative, the team used decision matrices. Since the design of some of the subsystems, mobility and power, were kept from last year's robot, there was no need to create a decision matrix for those. However, because this year's team's main goal is to reach autonomy, other subsystems were redesigned to facilitate the task.

3.4.1 Trade-off Assessments

Digging Mechanism

The team considered two options for the excavation system as shown in Figure 4. Option 'a' utilized an excavation system integrated with the wheels (Wheel digger). However this design proved challenging to implement with autonomy. The main idea was for the robot to dig while making zero point rotation, but caused complications in autonomous control of system orientation. Option 'b' was a scrape lifter, which was chosen due to an easier implementation for autonomy based on the decision matrix in Table 7. The design of this system is furhter explained in the Digging subsystem portion of the Interfaces section.

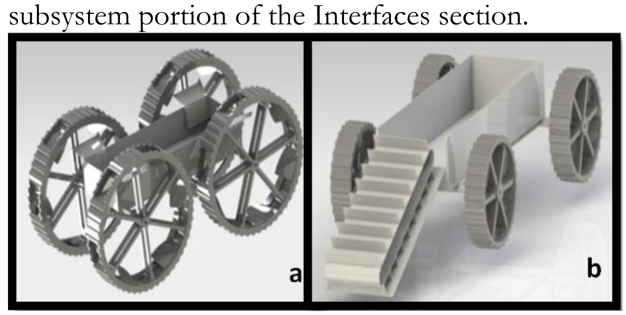

Figure 4: Concept Renderings of Digging Mechanisms

Table 7: Decision Matrix for Digging Mechanism

		Wheel Digger (Figure 4-a)			Scrape-Lifter (Figure 4-b)		
MUST		Comments		Y/N	Comments		Y/N
Collect Dirt				Y			Y
Deposit Dirt in Collection Bin				Y			Y
Does not need to be adjusted while digging		Will need initial adjustment		Y	Will need initial adjustment		Y
Meet 10kg qualification goal				Y			Y
WANTS	Wgt	Comments	SC	WtSc	Comments	SC	WtSc
Limited Dust Creation	10		10	100		10	100
System Integration	15		10	150		0	0
Lightweight	17.5		4	70		10	175
High rate of Mass Collection	17.5		8	140		10	175
A Centering Effect on Center of Gravity	10		10	100		9	90
Easy to implement Autonomy	20	Extra rotation throws off navigation	6	120		10	200
Easy to manufacture	10		6	60		10	100
TOTALS	100			640			740

Storage/ Ejection Mechanism

The storage/ejection system uses fabric due to the light weight.

The first option considered was an entire collection bin constructed of fabric material. However, the initial calculations showed that the size of the motor needed to lift the regolith would be very large.

Second, the team considered a conveyor belt combined with a rigid container to hold the regolith. This container will be pulled up with the fabric in order to dump. This design was selected based on the decision matrix shown in Table 8. For further explanation of the design see the Ejection subsystems in the Interfaces section.

Table 8: Decision Matrix for the Ejection Mechanism

		Cloth-arm			Hybrid		
MUST		Comments		Y/N	Comments		Y/N
Store 30 kg				Y			Y
Eject collected regolith				Y			Y
Fit inside size envelope				Y			Y
Wants	Wt	Comments	SC	WtScr	Comment	SC	WtScr
Minimum Weight	25	The motor needed weighs too much	3	75		10	250
Torque	15	Requires much more torque	4	60		10	150
Minimal Cloth Stress/Strain	10		4	40		10	100
Small Size	20		10	200		7	140
Dust Tolerance	15		10	150		6	90
Ease of Fabrication	15		10	150		6	90
Totals	100	Totals		675	Totals		820

Control System

Since the primary goal is to reach autonomy, the team needed to select the best way to control the whole system.

- The team began by analyzing a microprocessor as the "brain" of the system due to the efficiency of the processor of a microcontroller. However, the implementation of a microcontroller was more complicated than expected.
- As a second option, the team considered using multiple microcontrollers. The team defined these as "task oriented" microcontrollers to manage each operation of the prototype. Two options were considered: MSP430 and Arduino board. The team chose Arduino based on previous experience. Table 9 shows the decision matrix for the control system.

Table 9: Decision Matrix for Control System

		TI MSP430			Arduino MEGA		
MUST		Comments		Y/N	Comments		Y/N
Process Sensors in real time		Not all type of sensors		Y			Y
Enough Inputs (5 roughly)		7		Y	50		Y
Enough Outputs (5 roughly)		7		Y	50		Y
Upload code as soon as it is powered up				Y			Y
Enough Memory (RAM)				N			Y
WANTS	Wgt	Comments	SC	WtSc	Comments	SC	WtSc
Easy to program	50		5	250		7	350
Affordable	15		10	150		8	120
Available Faculty Sources	30		10	300		10	300
Power Consumption	5		9	45		8	40
TOTALS	100			745			810

3.4.1 General Algorithm

For JBU's team, a general algorithm to represent the different stages of the robot's performance was crucial, mainly because of the possibility to operate on either autonomy or manual mode. Figure 5 shows the robot's state machine, which simulated both the electrical and mechanical performance of the robot during the competition.

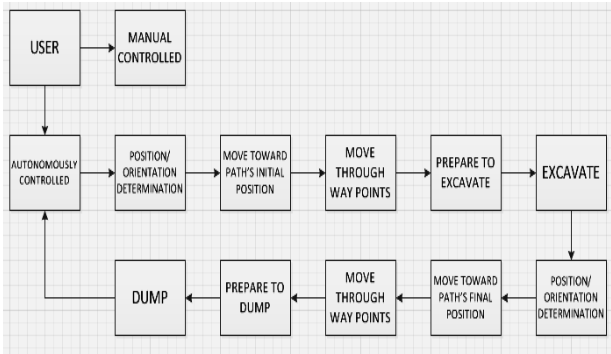

Figure 5: State Machine for the System's performance

3.4.2 Possible failure

JBU's team recognized the potential for the system to fail in many aspects. Three of those aspects are considered high risk to the performance of the robot during the competition run.

3.4.2.1 Getting Stuck in the LunArena/Robot Tipping Over

It is possible for the robot to stop operating properly if it falls into any of the obstacles in the LunArena. Also, it might tip over if it runs over an obstacle. The risk increases if the robot is working in autonomous mode because it is unlikely that the autonomy code can identify or respond to these occurrences. This risk is mitigated by adding a way-point system to allow the robot to go around the big obstacles and to go over only small ones. This high risk item is also mitigated by operator take over. At any point in the robot operation, the operator can take manual control of the robot.

3.4.2.2 Power Failure

If power fails to be delivered to each of the electrical components, the robot's mission will be compromised. This risk is mitigated by extensive testing prior to the competition in order to ensure the batteries can supply power to the robot for more than ten minutes. Also, this risk can be reduced by fully charging the batteries and checking each of the power connections before each competition run.

3.4.2.3 Motor Failure

If any of the motors fail, the robot will be disqualified because it will be unable to complete the tasks that the competition requires. This risk is mitigated by making sure that none of the motors receive more power than what they are rated for and by connecting fuses to each motor in case of excessive current draw.

In addition to the aforementioned risks, the team also considered autonomy code, actuator, excavation system, and communication failure. These types of risks can be mitigated by having spare parts during the competition. To tabulate the risks, a risk analysis chart was used, as shown in Figure 6. The possible failure was assigned a severity and likelihood on the scale of 1 to 5, 5 being the highest.

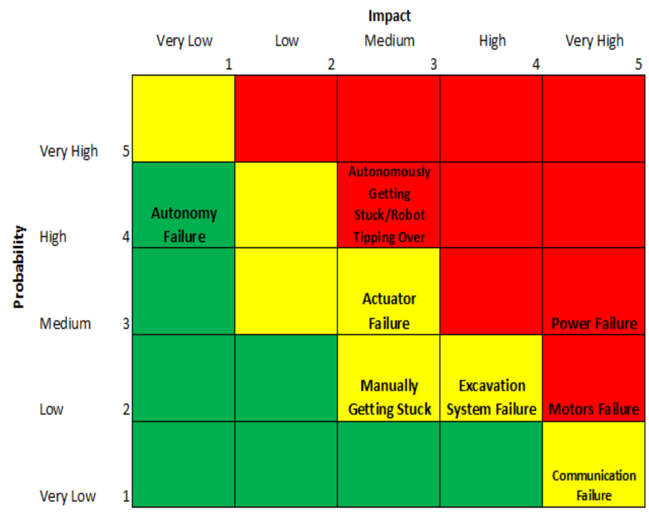

Figure 6: Risk Analysis Chart

3.5 Configuration Management

Most of the JBU team's design work and test results were created and documented online, so the team organized the design information in a folder accessible by all members. This folder also provided access to 2012 JBU team's documentation including documentation, design files, presentation, pictures, budget, and expense spreadsheets.

The team used this online folder to monitor the progress of the design and to support its management.

The team completed routine back-ups occurred for this online folder to ensure that all essential data was available in case of undesirable data lost.

3.6 Deliverables

JBU's team must deliver the following:

- A mobile robot capable of performing the tasks required by the competition.
- A working wireless control system. This includes: a computer, wireless access point, handheld controller.

- The navigation system. This includes the beacon system and batteries.
- A manual explaining the functionality of the robot, including diagrams.
- A video showing at least one full cycle of the robot's operations, between 0.5 and 5 minutes long.

The documentation is due on April 22nd, 2013, while the video is due on April 30th, 2013. The rest of the derivable are due on May 20th at the competition time.

4) Interfaces

During the initial design the team defined the interfaces between and operations of each subsystem. The following sections describe this progression and resulting interfaces.

One of the goals of JBU's team was to keep the whole design under the design mass budget. Table 10 shows the mass budget for physical subsystem of the prototype.

Table 10: Mass Budget

Subsystem	Mass Budget(kg)	Actual
Excavation	14	13.3
Storage/Ejection	6	4.1
Frame	7	6.5
Mobility	18	18
Power	5	4
Control	10	9.7
Total:	**60**	**55.6**

4.1 Mechanical Subsystems

4.1.1 Excavation

4.1.1.1 Requirements

Table 11 shows the requirements for the excavation system.

Table 11: Excavation Subsystem Requirements

Requirements	Basis
Collect 30 kg of BP-1 in 3.5 minutes.	P.1, TB
Be able to operate without adjustment during mining phase.	P.3
Fit under the 0.75m height restrictions	F.2
Be able to dig irregularly sized particles that may be found in the BP-1, both rocks and soil.	F.1, V.1
Maintain the clearance requirements while not digging.	SR
Operate on a 12V power supply.	PB
Operate with the interference of dust and in a way that allows for dust shielding.	P.2
Contribute to a center of gravity that is centered between the wheels.	SR
Weigh less than 14 kg	MB

4.1.1.2 Subsystem Hierarchy

Figure 7 shows the system hierarchy for the excavation subsystem.

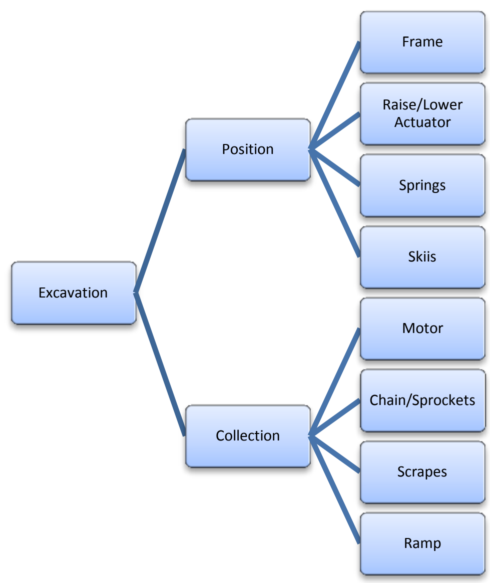

Figure 7: Excavation Subsystem Hierarchy

4.1.1.3 Basis of Design

The design of the excavation system is the product of the team's brainstorming session and is governed by the requirements listed above. Combining a reverse chain-and-paddle system with a ramp, the team designed a system that would scrape the top layer of regolith into the hopper. The resulting concept is a system that would work on the moon while retaining the familiar chain-and-paddle design. A model of this system is shown in Figure 8.

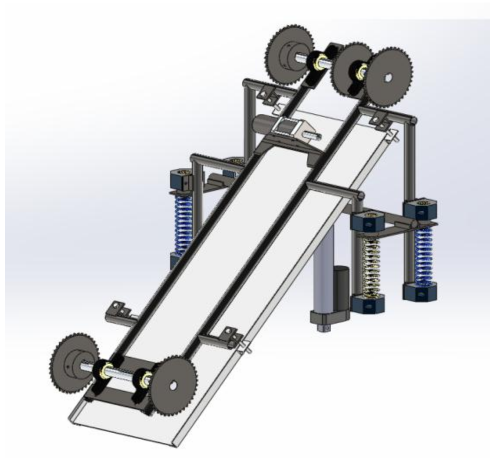

Figure 8: Excavation Subsystem 3-D Model

4.1.1.4 Interfaces

The excavation system interfaces with the power, frame, control, and storage/ejection subsystems. The excavation frame mounts to the main frame via eight linear sleeve bearings on four vertical posts. For the collected regolith to be stored correctly, the excavation system must align with the hopper, and the storage/ejection system must have adequate volume and proper clearance.

The interface between the frame and the excavation systems allows the excavation frame to be raised and lowered. This results in two positions for this interface. These positions are shown in Figure 9.

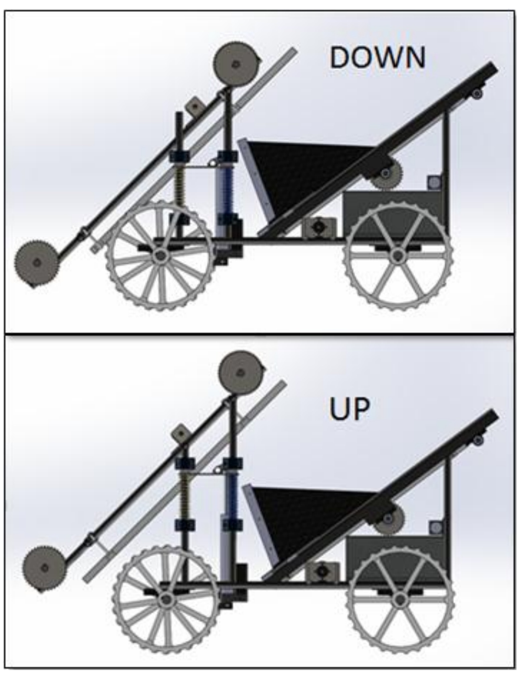

Figure 9: Excavation and Storage Interfaces

The Power and Control subsystem sections describe the excavation subsystem's interfaces with the electrical system.

4.1.1.5 Design Margins

Factoring in regolith loss and partially empty scrapes, the excavation system can deposit 30 kg in 2 minutes. The time budget along with inefficiencies in the scrapes and ramp were factored together to ensure that enough regolith would be collected in the time limit.

4.1.1.6 Risk Assessment

To minimize areas of risk, a risk assessment was completed for the Lunabot. The resulting areas of risk and corresponding methods for risk mitigation are shown in Table 12.

Table 12: Excavation System Risks

Risk	Mitigation Strategy
Scrape bending causing efficiency loss	Addition of end caps, thorough testing
Failure due to incorrect positioning	Careful testing and measurement of each position
Binding between excavation and main frames	Addition of linear bearings, sand all surfaces, system testing
Failure due to ramp bending/breaking by scraping too deep	Addition of skis to control depth, extensive testing

4.1.1.7 Testing

Before starting any permanent construction of the excavation system, the team constructed a wooden model to gauge the performance of the proposed system design. The team performed extensive experimentation with different scrape sizes and multiple ramp configurations. These tests, performed in a model LunArena using a mixture of sand and flour, confirmed that the reverse chain-and-paddle design would effectively collect the lunar simulant. Due to subsystem testing at the prototype phase, the final subsystem functioned as desired during the first testing run. The simulant was collected and deposited into the hopper as desired.

The excavation system was tested in each position to ensure that it would not bind and that the robot would remain under the size limit.

4.1.1.8 Reliability

The excavation system has withstood every test performed to this point. The excavation motor does not stall until the front digging sprocket is almost completely buried, which is impossible due to the excavation depth control system. The scrapes perform as desired at full speed and power, and even after a complete stall, the scrapes experience only marginal deformation.

4.1.2 Storage/ Ejection

4.1.2.1 Requirements

Table 13 shows the requirements for the storage/ejection system.

Table 13: Storage/Ejection Subsystem Requirements

Requirements	Basis
Hold up to 30kg of BP-1. (P.1)	P.1
Be capable of depositing the BP-1 into the LunaBin at the given dimensions of 0.5m above the regolith's surface. (F.1, F.5)	F.1, F.5
Be capable of dumping the regolith in 60 seconds (TB)	TB
Operate in a way that allows for dust shielding (P.2)	P.2
Operate on a 12V power supply, drawing a maximum of 6A of current. (Power Budget)	PB
Contribute to a center of gravity that is centered between the wheels. (System Requirement)	SR
Weigh less than 6 kg	MB

4.1.2.2 Subsystem Hierarchy

Figure 10 shows the system hierarchy for the storage/ejection subsystem.

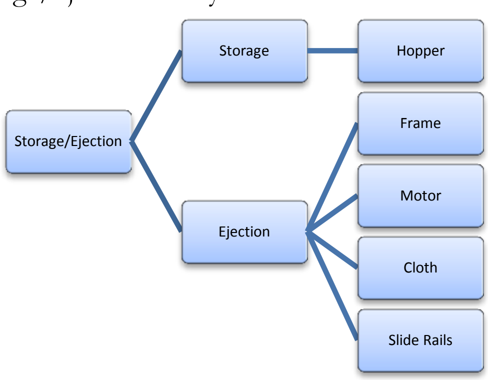

Figure 10: Storage/Ejection Subsystem Hierarchy

4.1.2.3 Basis of Design

The design of the storage/ejection system is the result of the team's efforts to fully integrate the storage and ejection processes. The cloth, which forms part of the hopper's fourth side, is also the means by which the regolith is ejected. This allows the whole process to be powered by a single motor, resulting in a lightweight, innovative ejection process. The storage and ejection process is illustrated in Figure 11.

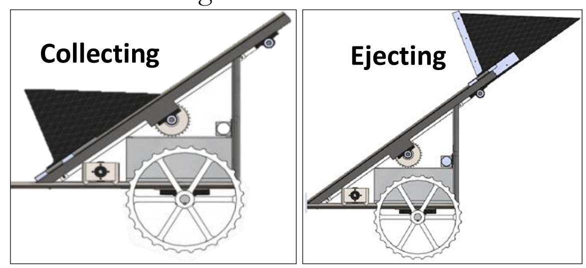

Figure 11: Storage/Ejection Subsystem 3-D Model

4.1.2.4 Interfaces

The storage/ejection system interfaces with power, control, frame and excavation systems. The rails on which the hopper slides are mounted directly on to the frame. The motor and the bearings for the axles that hold the cloth also mount directly to the frame. The storage bin slides down under the top end of the excavation system to catch the collected regolith, ending up underneath the end of the digging ramp, with a clearance of 8 cm.

The Power and Control subsystem sections describe the storage/ejection subsystem's interfaces with the electrical system.

4.1.2.5 Design Margins

To successfully meet the team's goal of 30 kg of regolith, the storage/ejection system shall hold and dump that amount. The heaviest parts of the storage/ejection system are the motor and axles that hold the cloth. The infinite life fatigue safety factor for these axles was calculated to be 1.4. The team decided that this was a large enough factor, because the robot will have only a limited life.

4.1.2.6 Risk Assessment

Table 14 shows the key areas of risk and their corresponding mitigation strategies.

Table 14: Storage/Ejection System Risks

Risk	Mitigation Strategy
Binding in linear guide rails	Slotting mounting brackets to allow lateral travel of bearing mounts.
Loss of regolith from the edges of the cloth	Addition of angle brackets along the path of the bin and on the inside to keep regolith from falling out the sides.
System failure due to ripping cloth	Thorough system testing, sanding down all sharp or rough surfaces to avoid snags

Since the lunar simulant has a higher angle of repose than the flour-sand mixture in the JBU test arena, the team plans to test the storage/ejection process during their practice run at the LMC. The team will then be able to determine if the sides of the bin must be adjusted.

4.1.2.7 Testing

Before construction of the robot began, the team built a wooden prototype of the storage/ejection system. Using this prototype, the team verified the cloth bin concept. The motor was capable of pulling up a full hopper, and the cloth proved strong enough for the load requirements.

During this testing phase the team determined that the cloth would bow too much with the added weight of the collected simulant which will result in loss of regolith. Therefore the team decided to add a partial fourth side to the bin. This maintained the dumping concept, except that the regolith would be deposited only from the bottom of the bin. The team also observed the cloth ripping after getting caught on a sharp edge of metal while under a full load. This precipitated a change in the support bracket under the cloth at the sides of the hopper.

4.1.2.8 Reliability

Through the testing process, the storage/ejection system has proven it can successfully retain and deposit loads of at least 30 kg. As long as there are no sharp edges that could cause the cloth to rip, the cloth will withstand these loads.

4.1.3 Mobility

4.1.3.1 Requirements

Table 15 shows the requirements for the mobility system.

Table 15: Mobility Subsystem Requirements

Requirement	Basis
Able to drive constantly for the entire competition run	P.1
Operate at variable speeds, both forward and backward on the uneven terrain	F.7
Operate without sinking into the regolith	F.7
Able to perform a zero-radius turn	F.7
Tough enough to withstand small obstacles presented in the LunArena, such as rocks and craters	F.7
Able to operate under varying loads (50 – 120kg [adding in a safety factor of 1.5])	V.1
Provide a clearance of at least 15cm	F.7
Able to operate in a very dusty environment	P.2
Operate on a 24V power supply	V.1
Contributes to a center of gravity that is centered between the wheels	F.7
Weigh less than 18 kg	MB

4.1.3.2 Subsystem Hierarchy

Figure 12 shows the system hierarchy for the mobility system.

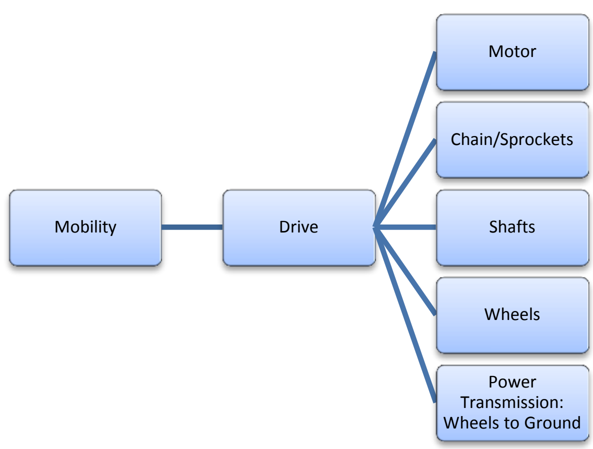

Figure 12: Mobility Subsystem Hierarchy

4.1.3.3 Basis of Design

The design of the mobility system was taken from the 2012 JBU team's system due to it exemplary performance at the competition [4]. Since there were only two mechanical team members, and because the system functioned reliably, the team decided to modify the previous year's design to fit on a new robot.

4.1.3.4 Interfaces

The Frame, Control, and Power subsystems interface with the Mobility subsystem. The wheel assemblies and drive motors attach directly to the frame. The Power and Control subsystem sections describe the mobility subsystem's interfaces with the electrical system.

4.1.3.5 Design Margins

Because the Mobility system was taken almost entirely from the previous year's design, many of the same design margins were maintained. A gear ratio of 1:4 was used to drive the wheels. Therefore, the wheels have torque and low rotation speeds. If all the weight of the robot was carried by one wheel, the axle would still have a safety factor of 1.9.

4.1.3.6 Risk Assessment

Table 16 shows the key areas of risk and their corresponding mitigation strategies for the mobility subsystem.

Table 16: Mobility System Risks

Risk	Mitigation Strategy
Shaft bending causing failure	Shaft design with safety factor
Unable to maneuver	Tread design on wheels, 15cm clearance, thorough testing
Motor malfunction causing failure	Careful motor selection, purchase of back-up motor
Wheel breaking	Redesign of wheels, careful driving

4.1.3.7 Testing

Because the mobility system was employed on last year's robot, the team did no initial system testing before system integration. As expected, no problems were encountered in this integration process. The mobility system was the first subsystem integrated with the frame. Therefore, it has been involved in all later tests. It successfully traverses the sand-flour mixture in the model LunArena under loads from 60 kg to 90 kg.

4.1.3.8 Reliability

The mobility system has functioned correctly throughout the testing process. Also, since the same system was employed by last year's JBU team, the system has already proved itself in the actual LunArena.

4.1.4 Frame

4.1.4.1 Requirements

Table 17 shows the requirements for the Frame system.

Table 17: Frame Subsystem Requirement

Requirements	Basis
Support all the other systems in a way that allows them to fit within the overall size constraints	F.2
Hold and sustain static loads of 50 – 120kg [adding in a safety factor of 1.5]	F.1, V.1
Must hold and protect the electrical systems	SR
Able to withstand the dynamic forces and vibrations from driving on uneven surfaces and from moving components	F.1, V.1
Contributes to a center of gravity that is inside the square formed by the wheels	SR

4.1.4.2 Subsystem Hierarchy

Figure 13 shows the system hierarchy for the frame subsystem.

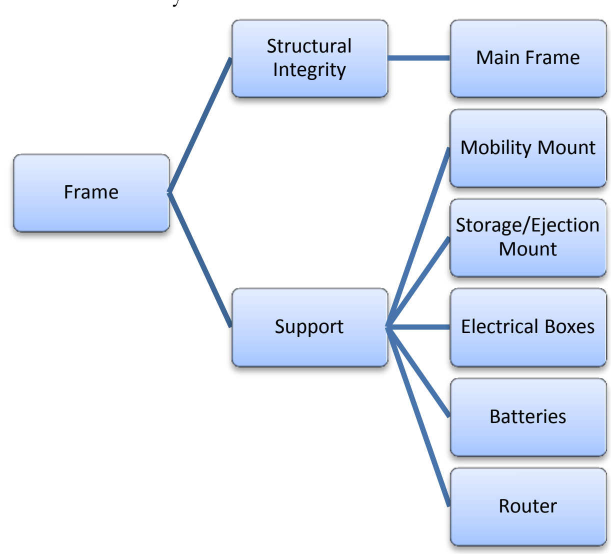

Figure 13: Storage/Ejection Subsystem Hierarchy

4.1.4.3 Basis of Design

The frame was designed to support the excavation, storage/ejection, and electrical systems while meeting the requirements listed above. The size, strength, mass, and ease of fabrication of the material also impacted the design.

4.1.4.4 Interfaces

The frame interfaces with each of the other subsystems. The definition of these interfaces was a key area of the design process. All other subsystem components are connected in some way directly to the frame.

4.1.4.5 Design Margins

The frame was designed to carry loads of up to 120 kg. This is 1.5 times greater than the combined masses of the robot and a full hopper of collected regolith. Even with this entire load applied to a single member, the safety factor is 2.13.

4.1.4.6 Risk Assessment

Table 18 shows the key areas of risk and their corresponding mitigation strategies.

Table 18: Storage/Ejection System Risks

Risk	Mitigation Strategy
Frame failure due to bending	Designed with safety factor
Insufficient support of subsystems	Careful mount design, interface testing
Weld failure	Reinforced welds, strength testing

4.1.4.7 Testing

Throughout the entire fabrication process, the dimensions of the different parts of the frame were monitored to ensure that joints were not warped by the heat. The team applied loads to different parts of the frame to test weld strength and monitor deflection. Then, the team added the individual components and completed tests with full system integration. The frame withstood each of our tests even with the varying loads produced by the various moving parts.

4.1.4.8 Reliability

Through the testing process, the frame has proved it can successfully support each of the other subsystems without any noticeable bending or deflection.

4.2 Electrical Subsystems

4.2.1 Autonomy

4.2.1.1 Requirements

Table 19 shows the requirements for the autonomy subsystem. Because autonomy depends on many other subsystems, the following table shows the requirements for each.

Table 19: Autonomy Subsystem Requirements

Requirements	Basis
Infrared Sensors:	
1cm to 10cm for the sensor used to position the robot in the dumping bin. It is considered that the minimum range of this sensor needs to be very small for dumping purposes	V.1, F.6, O.1
10cm to 1m for the sensors located on the sides of the robot. Even though the minimum range is still critical, the robot will be able to sense the walls as close as 10cm which will give it time to relocate itself away from the target	V.1, F.6
Photo Transmitter:	
To have a minimum of 20 lumens	V.1, F.6
Have a power Consumption less than 10W	O.1, F.6
Weight a maximum of 0.08 Kg	F.3, F.6
Be able to set a frequency	V.1, F.6
Photo Detector:	
Weight less than 9 kg	F.3, F.6
Be able to be programmable with different frequencies	F.6
Weight Sensor:	
To be able to sense up to 50Kg	F.1, F.6
To be programmable using C code	F.6
Have a mass budget less than 0.2454kg	MB

4.2.1.2 Subsystem Hierarchy

Figure 14 shows the system hierarchy for the autonomy subsystem.

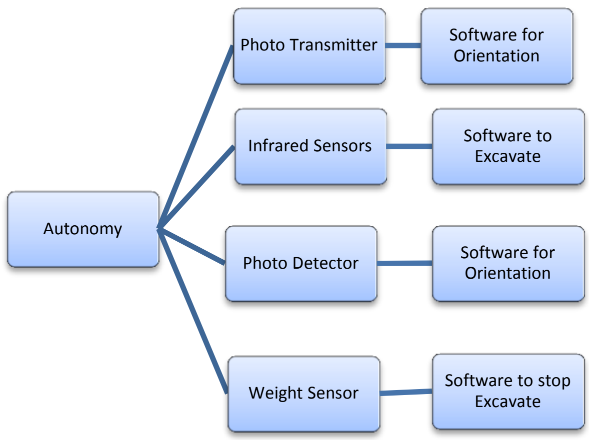

Figure 14: Autonomy Subsystem Hierarchy

4.2.1.3 Basis of Design

The autonomy subsystems was thoroughly designed, considering all the possible navigation routines that the robot will need to follow in the competition in order to accomplish all the operations. This is the first time that JBU's team is designing autonomy. Based on the navigation requirements, the team chose the sensors that will better suit the necessities of the robot.

4.2.1.4 Interfaces

Autonomy was designed to efficiently integrate with mechanical operations of robot. The sensors used for this subsystem were placed so that reliable data was available at the corresponding stage of the mission. Different microcontrollers were dedicated to specific sensory tasks to lower timing issues that could decrease the dependability of the position knowledge. All the information gathered from the robot's environment is then processed by the central processing unit microcontroller to make the most suitable decision.

4.2.1.5 Design Margins

All the design decisions for the sensory system were based on the navigation routine that the robot needs to follow during the ten minutes lapse of the competition. In addition, the weight of the sensors used was also considered so that the overall system would not be affected. Further, the software for autonomy was designed and programmed as efficiently as possible to avoid timing issues, and other bugs that might arise in the competition.

4.2.1.6 Risk Assessment

The most critical risks and mitigation strategies for the power system are shown in Table 20.

Table 20: Power System Risks

Risks	Mitigation Strategy
Failure of IR sensors	Design a backup in the software program to avoid walls and obstacles
Failure in Photo detector/Phototransistor	Design a backup program for the robot to navigate following the straightest path.
Failure in the autonomy software	Have a backup system to control wireless

4.2.1.7 Testing

In order to test autonomy, the team performed many tests at the sensory level to ensure the accuracy and precision of the collected data. Once these tests were completed, the team proceeded to the writing and testing of the autonomy software as a whole. It is imminent that hard testing will reveal timing issues and bugs in the programmed code. This testing process will continue until the competition day.

4.2.1.8 Reliability

The results of the testing reveal that some minimal errors can occur in the navigation system. At the beginning of the design process, the team analyzed the error margin at which the system could perform without affecting the success of the operation in the competition. Due to the thorough design and analysis of data, those error margins are within the expected rate.

4.2.2 Control

4.2.2.1 Requirements

Table 21 shows the requirements for the control system.

Table 21: Control System Requirements

Requirement	Basis
Process Sensors in real time	F.6, F.8, P.3
Enough Inputs (5 roughly)	F.6, F.8, P.3
Enough Outputs (8 roughly)	F.6, F.8, P.3
Upload code as soon as it is powered up	F.6, F.8, P.3
Enough memory	F.6, F.8, P.3
Mass in kg less than 10 kg	MB

4.2.2.2 Subsystem Hierarchy

Figure 15 shows the hierarchy for the control system.

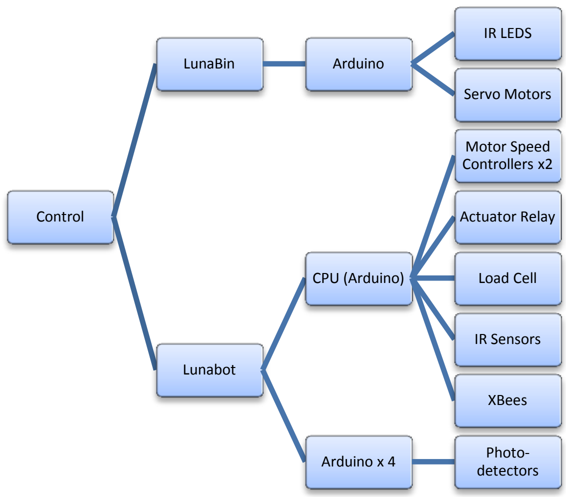

Figure 15: Storage/Ejection Subsystem Hierarchy

4.2.2.3 Basis of Design

The control system design was derived from the subsystem requirements, the electromechanical components included in each mechanical subsystem, and the 2012 JBU Lunabot control system design. Based on the previous decision matrix, an Arduino Mega microcontroller with an attached XBee shield was selected to control the Lunabot. The team used the Arduino manual code from 2012 Lunabot as a basis for the 2013 control system and made modifications and additions as necessary. Figure 16 shows the control diagram for the system.

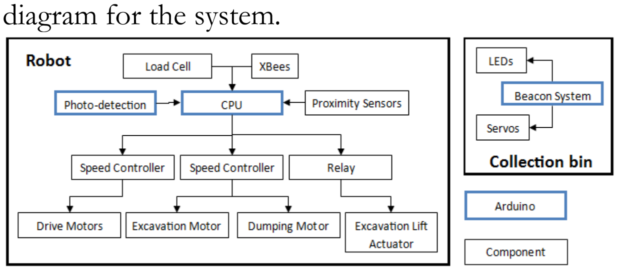

Figure 16: Control Flow Diagram

4.2.2.4 Interfaces

The control system interfaces directly with all other subsystems. The system is contained in the electronics box which mounts directly to the frame. The control system utilizes five Arduinos. The central processing unit is the Arduino in charge of receiving and sending data to the user during manual control. On the autonomous mode, the control system will receive and react according the sensory data as previously explained in the Autonomous subsystem section. The buttons of an Xbox controller determine the actions that the Lunabot will perform. On the manual mode, the Xbox programmed code creates a data packet containing the commands for each electromechanical component in the robot. The central processing unit also has direct control over the four motors, the actuator, the load cell, and the IR sensors. This Arduino contains the code for the manual control of the Lunabot and the autonomy code. The other four Arduinos are in charge of gathering the data obtained from each photo-detector. One of those four Arduinos is in charge of processing the obtained data and sending it to the central processing unit to be used by the autonomy code.

4.2.2.5 Design Margins

The Arduino manual code from last year's robot was closely examined before starting to write this year's code. This allowed the team to save time by getting familiarized with the programming language and learning how the devices can be controlled with a microprocessor. Because of this, the 2013 team was able to optimize last year's code, implementing necessary modification and additions.

4.2.2.6 Risk Assessment

The most critical risks and mitigation strategies for the control system are shown in Table 22.

Table 22: Control System Risks

Risk	Mitigation Strategy
Lose signal from control room	Test to ensure consistent connection with no interruptions
Arduinos behavior is not the expected one	Check that every Arduino is been supplied with enough power, check all the connections between Arduinos
Manual code does not respond	Make sure the Arduino had a setup time of no less than 10 seconds

4.2.2.7 Testing

The Arduinos, drive motors, dumping and excavation motors, and excavation actuator were all tested on a component level, and the primary testing of the control system occurred in the construction of a "flat robot." To accomplish this, all electromechanical components and interfaces were tested to verify full functionality. The components were simultaneously connected to the control system and the team verified their control of the whole robot before anything was connected to the frame, as Figure 17 shows.

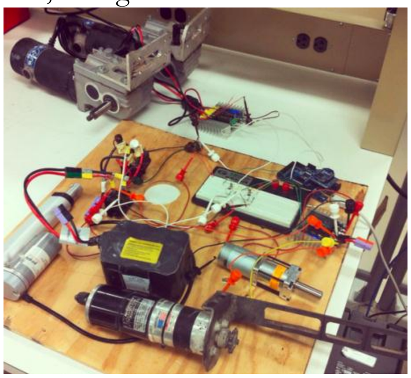

Figure 17: Golden Eagles-"Flat Robot"

The microcontroller was interfaced with the user interface and XBee system as well, and that interface was tested to ensure that the microcontroller received commands and properly converted them to signals for the electromechanical components. The integrated test with the mechanical components verified that the control system met both its subsystem and system requirements during autonomy and manual mode.

4.2.2.8 Reliability

The control system was verified on a component, system, and integration level before it was connected to the robot frame, and the system functioned reliably in tests. The control system was then consolidated into an electronics box to mount on the frame, as shown in Figure 18.

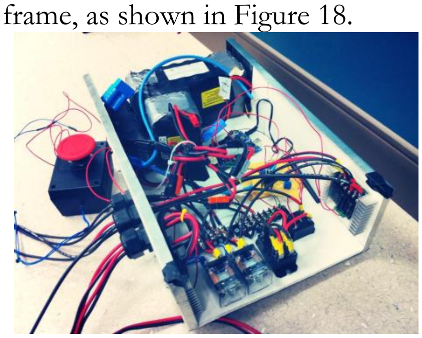

Figure 18: Electronics Housing

4.2.3 Power

4.2.3.1 Requirements

Table 23 shows the requirements for the power system.

Table 23: Power System Requirements

Requirement	Basis
On-board batteries must provide power to all components for a minimum of 10 minutes.	V.3
Batteries must be rechargeable and easy to remove	O.1
Must utilize a large red push button that will deactivate all onboard power, thus immobilizing the Lunabot	O.1
Must be light enough to fit within Lunabot weight constraints	F.3
Must be self-protecting in case of excessive current draw	O.1
All connections should be tolerant of vibration, dust, and other unforeseen interference	P.2
Must protect communication equipment from dangerous voltage fluctuations	O.1
Having a Mass less than 5 kg	MB

4.2.3.2 Subsystem Hierarchy

Figure 19 shows the hierarchy for the power system.

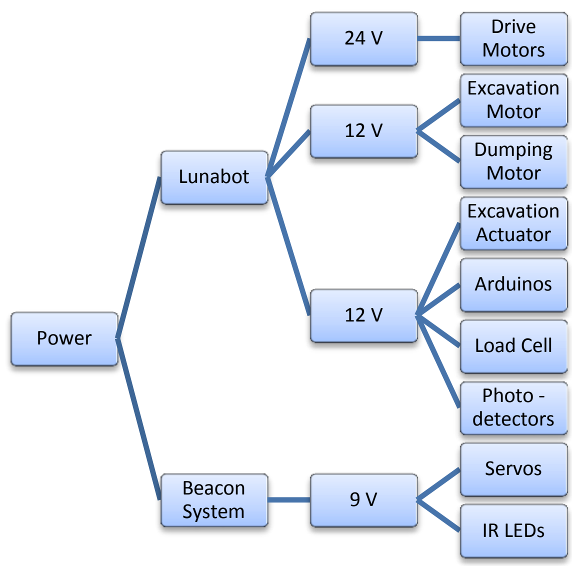

Figure 19: Power System Hierarchy

4.2.3.3 Basis of Design

The design of the power system is based on the subsystem requirements, testing of the 2012 JBU Lunabot, and the electromechanical parts required by the mechanical subsystems. The team completed power consumption calculations based on the rated current draw for each component and the intended voltage. The power system was based on these calculations and an energy-per-unit-mass ratio. A three lithium-ion battery network was chosen, similar to that of the 2012 robot, in order to minimize the need for voltage regulation and to isolate control components from electromechanical components. In order for the navigation system to properly work a fourth battery is used outside of the robot to power the beacon system.

4.2.3.4 Interfaces

The power system is divided into two sections: the Lunabot's power system and the Beacons' power system. The battery network is mounted inside of the electronics box in order to have the all the wiring protected from dust. The emergency stop switch controls the flow of power from the battery network through the use of Double Pole Double Throw (DPDT) Relays. A 12 V battery powers the control system and the excavation actuator, another 12 V battery supplies power to the excavation and dumping system, and a 24 V battery powers the mobility system. A 9 V battery powers the beacon system which is outside of the robot. Each battery was connected to fuses in order to protect the system in case of extremely high current draw.

4.2.3.4 Design Margins

All energy calculations were completed based on a 20-minute competition run rather than the actual 10 minutes. This provided a safety factor of 2 for the system. Further, since no battery would fit the design criteria exactly, batteries with slightly more power than the required amount were selected.

4.2.3.5 Risk Assessment

The most critical risks and mitigation strategies for the power system are shown in Table 24.

Table 24: Power System Risks

Risks	Mitigation Strategy
Connection coming loose	Securely attach connectors, install strain relief, monitor during testing
Battery drain due to unexpected conditions	Design margins included in battery selection, thorough testing, fully charge batteries prior to competition
Blowing fuses due to motor or actuator stall	Intentional fuse selection, careful Lunabot operation

4.2.3.6 Testing

To test the power system, the team recorded the time to discharge the batteries at a controlled rate and monitored the current flow using a multimeter. From this data, they verified the capacity of each battery.

The emergency stop button was also tested and verified that immediately after the button was pressed no power passed through the switch. Subsystem tests for the power system were impractical since such tests would only re-confirm battery capacity. Thus tests were performed solely on a system level during competition style testing.

Throughout system testing, the team monitored the endurance of power connections, and discovered that the permanent connections and strain relief adequately maintained power flow.

4.2.3.7 Reliability

The results of both component and system level testing revealed that the power subsystem is capable of powering all Lunabot operations for 46 minutes, with a loss of efficiency after 40 minutes. Based on the verification process, the team does not expect failure from the power system.

4.2.4 Communication

4.2.4.1 Requirements

Table 25 shows the requirements for the communication system.

Table 25: Communications System Requirements

Requirements	Basis
Maximum bandwidth of 500 kbps	F.4
Design must provide a way to wirelessly activate the autonomous mode of the Lunabot	I.1, F.6, V.1, V.2
Design must allow the user to operate the robot from an isolated location if needed	I.1, F.8, V.1, V.2
Time delays between data transfer from user to robot and vice versa must be less than 0.1 seconds	I.1, F.4, V.1, V.1
Design must allow the user to monitor all the actions that the Lunabot is performing while in autonomous mode	F.4, P.4, O.1, V.1, V.2
Mass less than 10kg and a consumption power less than 1.010 W	MB

4.2.4.2 Subsystem Hierarchy

Figure 20 shows the hierarchy for the power system.

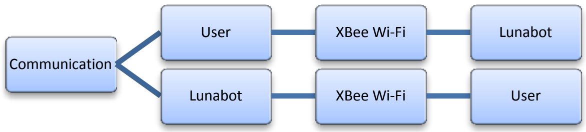

Figure 20: Communication System Hierarchy

4.2.4.3 Basis of Design

The communication system design was derived from the subsystem requirements, but the electrical component used in the system is different from past years. The past three years, JBU's Lunabot teams have used a router to achieve wireless communication between the user and the robot. This year, the communication system uses XBee Wi-Fi Modules to wirelessly communicate. The team selected the XBee instead of routers because of its low power consumption, 0.5W, compared to the 6W the router consumes.

4.2.4.4 Interfaces

Two XBees are used for the communication system. The first XBee was programmed to listen to the IP address where the manual control code is been executed. This XBee is in charge of listening to the commands coming from the user's computer. The second XBee was been programmed to write to the same IP address as the first XBee but with a different port number. Different port numbers prevent data collision. The second XBee sends monitoring data to the user. Both XBees are connected to the computer through an access point router.

4.2.4.5 Design Margins

To check if the XBee could perform wireless communication with the same reliability as the router does, JBU's 2012 Lunabot's code was changed during the design phase of JBU's 2013 Lunabot in order to work with the XBee. Through testing, the team verified that the XBees work efficiently.

4.2.4.6 Risk Assessment

The most critical risks and mitigation strategies for the power system are shown in Table 26.

Table 26: Communication System Risks

Risks	Mitigation Strategy
Communication loss	Check communication LED on XBee shield, making sure to leave a setup time before running the Xbox controller code
XBee stops working	Check it with the XBee Development Board, replace it with spare one

4.2.5.7 Testing

To test the communication system, the team ran the Lunabot for 20 minutes, and constantly sent commands to the robot from the Xbox controller. One team member pushed the buttons on the controllers and verified that the Lunabot received the correct signal and sent back the correct data to the user based on the signal it received. To test bandwidth, the team logged into the router after the run to obtain the data necessary to calculate average bandwidth. This test was performed at a subsystem level as well as a system level. The average bandwidth was 50kbps, which is well below the 500kbps limit, as desired.

4.2.5.8 Reliability

The result of the testing showed that the XBee allows successful wireless data communication, consuming less power and weighing much less than a router. Also, the time delay between data transfer is insignificant, thus, the Lunabot responds immediately after the command was sent from the computer.

5) Systems Integration

As previously stated, the team performed exhaustive testing from the component level up to the system level. This effective method allowed the team to successfully achieve a fully functional prototype on the first integration attempt. At the system level, the team created a competition style environment to test the Lunabot and practice operation. A mixture of flour and sand was placed in a test sand box simulating the LunArena to test the excavation, ejection, and mobility subsystems.

5.1 Requirement Flow-Down to Validation Check Out

The requirements for each subsystem are derived directly from the overall system requirements. Functionality was added to the

Lunabot one system at a time to minimize the quantity of errors and interface issues. The team began by interfacing the control subsystem with all electromechanical components. Through testing the functionality of the manual wireless control and autonomy were validated. Simultaneously, the mobility and frame were integrated. These two assemblies were then independently tested and, once verified, were integrated together. As previously mentioned, thanks to the thorough design process and individual component testing, the fully working prototype was achieved on the first integration attempt.

5.2 Technology Readiness Level

Technology Readiness Level (TRL) is a measure used to assess the maturity of evolving technologies, mainly during their development [5]. Table 25 shows the TRL chart that describes the maturity of JBU's Lunabot project.

Table 25: Technology Readiness Level

Subsystem	TRL (August 2012)	TRL (April 2013)
Excavation	1	6
Storage and Ejection	1	7
Mobility	9	9
Frame	3	9
Autonomy	1	4
Control	3	6
Power	9	9
Communication	3	6

6) Conclusions and Reflection

At the time of submission, the JBU Golden Eagles are implementing full testing of all systems under competition loading. This includes testing to make sure that all points goals are still within the scope of the project. So far, testing has indicated that the time budget should be met for excavation and ejection. Autonomous testing has been successful insofar as it has worked inside the lab. The team expects for all systems to function properly at the competition and to attain to the 1120 Lunapoints goal. This is all possible because of a successfully implemented systems engineering approach. The team has been very dedicated and all members have worked closely with one another to make sure that all goals are met for the competition. This is also thanks, in no small part, to the technical and spiritual guidance of their faculty mentors, Dr. Tim Gilmour and Dr. Will Holmes. The team is confident in the overall design and functionality of the robot and looks forward to doing well in the 2013 Lunabotics Mining Competition.

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