Systems Engineering Report

Buckeye Lunabotics Team

The Ohio State University - Columbus, OH

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Abstract

This report documents the Buckeye Lunabotics Team's robot created for the 2024 NASA Lunabotics Competition, with a focus on the team's project management and use of systems engineering principles. The team was made up of undergraduate and graduate students from The Ohio State University. The robot is designed to semi-autonomously travel across, excavate, and deposit lunar regolith to simulate berm building robots for future NASA Artemis missions.

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1 Introduction

The NASA Lunabotics challenge tasks undergraduate and graduate students with building a robot that can semi-autonomously travel, excavate, and deposit lunar regolith. The Buckeye Lunabotics team was officially founded in 2023 with the goal of competing in the 2023-2024 NASA Lunabotics challenge. The team's robot, shown in Figure 1, was created entirely from scratch during the 2023-2024 academic year. By using systems engineering principles, the team was able to follow the project schedule, adhere to the project milestones, and submit the required deliverables in a timely manner. The effective utilization of systems engineering significantly mitigated conflicts, facilitated streamlined communication, and minimized the need for extensive re-engineering toward the project's conclusion. This report comprehensively details these endeavors, offering insights into the team's achievements, setbacks, and valuable lessons acquired throughout the process.

This report is split into two primary sections. The first major section will focus on the team's project engineering efforts. It includes a discussion of the project's technical objectives, the team's background, the major review meetings, the project schedule, and the team's budget. The second major section focuses on the systems engineering principles used by the team. It includes a discussion of the system hierarchies, requirements, interfaces, and engineering specialties. It then summarizes the robot's concept of operations, outlines the technical performance measurements, reviews different trade studies, and documents the team's efforts at system verification.

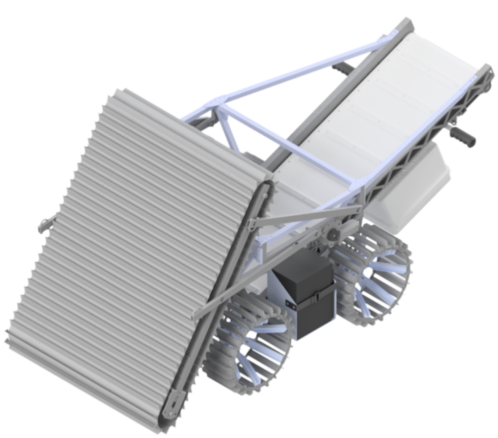

Figure 1: Rendering of the team's robot with the intake system fully deployed.

2 Project Engineering Merit

2.1 Project Technical Objectives

The team's primary technical objective was to maximize the robot's regolith volume throughput because that was the primary scoring points criterion. This parameter was prioritized above all others, shaping the majority of design decisions made by the team. The team's secondary technical objective was to minimize the mass, targeting a goal of approximately 40 kg. The team chose this as a second technical objective because mass has a relatively high penalty, with 8 points lost per kg of mass [2].

The team's third technical objective was to achieve dust protection, fulfilling criteria for a dust-tolerant design. This objective was prioritized due to the relatively low time investment required, and irrespective of point bonuses, incorporating elements of a dust-tolerant design would enhance the robot's reliability.

Energy usage and data bandwidth were not chosen as primary technical objectives because the team's point analysis showed that effort spent towards minimizing those parameters would be better spent trying to maximize the robot's excavation volume. For automation, the team chose to achieve the excavation autonomy level with the goal of completing both excavation and dump autonomy. This decision stemmed from the team's first appearance in the competition, having a small programming team, and anticipated access limitations to test facilities.

2.2 Team Background

In its inaugural year, participating in the NASA challenge, the Buckeye Lunabotics team began a completely new design journey. Consequently, the team prioritized mechanical design, opting for a straightforward electrical and software stack approach. This decision was made because the knowledge required for the electrical and software components depended on the completion of the mechanical design, which would not be available until after the preliminary design stage was complete. Introducing a complex software and electrical system would have left insufficient time for thorough testing. As part of a broader Ohio State student organization known as *FIRST* Alumni and Robotics at Ohio State (FROS) [1], the team had access to motors and electrical components owned by the organization.

The team is currently made up of 4 freshman, 3 sophomores, 3 juniors, 2 seniors, and 1 masters student. The team represents a variety of departments with five members studying mechanical engineering, five members studying electrical and computer engineering, two members studying computer science and engineering, and one members studying agricultural engineering.

2.3 Major Reviews

Three major reviews were held throughout the year so that the project leadership, mechanical subteam, and electrical subteam could verify critical decisions made during a specific phase of the project. The different subteams typically met during different days of the week, based on the schedule of each team's members, so between reviews, many team members were not actively involved in all aspects of the project. To streamline communication, each subteam meeting would began with the subteam leader giving an overview on the other subteam's progress. Then, at the major reviews, the entire team would come together and verify that everyone approved of the decisions made regarding the system architecture before the next phase of the project began.

The first review was the System Requirements Review (SRR), which took place only a few weeks into the project. At this review, the team agreed on requirements and technical performance measurements. Since this review was completed around the time the Project Management Proposal (PMP) was drafted, the schedule and budgets remained the same. This review was a control gate on all items related to robot design. Once the review was complete, the mechanical subteam began to narrow down mechanisms for intake, drive, and dump and the electrical subteam began to investigate different electrical architectures.

The second review was the Preliminary Design Review (PDR), which took place once the team created a high level design of the robot. At this point, many changes in the project occurred as the team realized how mechanically complex the robot design was. This led to an increase in the mechanical budget, decrease in the electrical budget, and an extension of the manufacturing schedule. Additionally, requirements related to drive sensor feedback were removed due to the decreased electrical budget. This review was a control gate for the mechanical and electrical design. Once this stage was complete, the team began to consider detailed design, choose electronic components, and develop prototypes to test the high level concepts.

Finally, the third review was the Critical Design Review (CDR) that was held once the CAD model was finished, prototypes were finished being tested, and subsystem integration was complete. At this review, the team once again extended the manufacturing schedule to account for the amount of CNC time required to manufacture certain parts. Additionally, the robot mass TPM was increased due to the amount of structural framing that was added to support the team's primary technical objective of maximizing the regolith throughout of the robot.

2.4 Schedule of Work

The team built an initial schedule for the PMP, which is included in Figure 11 (located in Appendix 1). To create this schedule, the team plotted the competition deliverables, then scheduled the SRR, PDR, and CDR, and finally filled in specific milestones. The team's original goal was to work primarily on requirements and design during the fall semester, then switch to manufacturing, testing, and verification during the Spring semester. The team's schedule shifted over the course of the project. The schedule at the time of writing is included in Figure 12 (located in Appendix 1). The schedule changes are summarized in Table 1 on page 3.

At the Preliminary Design Review (PDR) the team suspected a shift in schedule would be required. After testing the prototypes, the team officially shifted the schedule to allow for more detailed unit level design. Additionally, the team shifted the CDR to after winter break, which allowed the team to dedicate more time to finishing up the CAD, performing FEA, and performing other integration analyses.

At the CDR, the team expanded the manufacturing time primarily, particularly for the drive and intake systems. Delays in the drive system arose due to the necessity for CNC machines to produce cycloidal gearboxes. However, access to CNC machines was constrained as they were concurrently utilized by students involved in other projects, such as senior design capstone. To counterbalance this scheduling conflict, the team augmented the mechanical budget and opted to outsource certain parts requiring labor-intensive manufacturing techniques to SendCutSend. In total, the team made two SendCutSend orders totaling $592. Although expensive, this saved the team approximately two weeks of fabrication.

Although manufacturing delays were anticipated at the CDR, the team's manufacturing schedule fell further behind than expected during January and February because of student availability, difficulty reserving machine shop time, and shipping delays. In order to speed up manufacturing, the team raised the system's mass requirements and skipped time-intensive weight saving measures. Even with the technical requirement reductions, the manufacturing delays pushed the subsystem integration, full system assembly, and testing into March. The team performed the first full system test on 3-14-2024. Changes were identified and made the following week, with the proof of life test occurring on 3-24-2024.

2.5 Cost and Budget

The team set an initial budget for the PMP based on the team's experience and research of other team's budgets. The budget was adapted multiple times throughout the year to reflect the team's needs and priorities. The team's budget revisions and expenditures are summarized in Table 2. Itemized revisions of the electrical,

Table 1: Major Milestone Dates for Different Schedule Revisions

Schedule Revisions				
Milestone	Initial (PMP)	Rev. 1 (PDR)	Rev. 2 (CDR)	Actual
SRR	9/18/2023	9/18/2023	9/18/2023	9/18/2023
PDR	10/30/2023	10/30/2023	10/30/2023	10/30/2023
CDR	12/18/2023	1/6/2024	1/6/2024	1/6/2024
SPA	2/12/2024	2/20/2024	3/1/2024	3/14/2024
Proof of Life	3/18/2024	3/18/2024	3/18/2024	3/24/2024

Table 2: Team Budget Revisions and current Expenses

Team Expenses				
Category	Budgets			Spent
	PMP	PDR	Latest	
Mechanical	$1,900.00	$2,500	$2,514	$2,186
Electrical	$2,550.00	$1,200	$1,085	$856
Administrative	$550.00	$250.00	$275.00	$0
Travel	$1,575.00	$1,500.00	$4,528	$2,818
Total	$6,575.00	$5,450	$8,402	$5860

administrative, mechanical, and travel expenditures are included in Appendix B (Tables 15, 16, 17, 18 respectively).

The team was only funded with sources related to Ohio State because the team is new and has not focused on getting dedicated sponsors. The team's primary fundraising was a $3,500 grant from Ohio State's Transportation Research Endowment Program (TREP), which is an endowment fund sponsored by Honda for research and student organizations related to transportation. The second funding source was $2,000 from the Ohio State Engineer's council, which is a program where Ohio State engineering student organizations can earn funds for volunteering at engineering events. The remaining cash needed for the project was pledged by FROS, the student organization that manages the Buckeye Lunabotics Team. The team expects that sponsorships should be able to sustain the team in future years. A comparison of the team's revenue and expenditures are included in Table 3.

Table 3: Team Revenue and Expenses

Team Finances	
Category	Amount
TREP Grant	+$3,500
Misc. Funding	+$2,000
Robot Parts	-$3,600
Admin & Travel	-$4,803
Total	-$2,903

The first major change to the budget occurred after the PDR, where the team recommended increased mechanical funding to buy parts needed to accomplish the regolith throughput objective. To support this change without increasing overall cost burdens, the team searched for cost reductions in the electrical budget. The team identified that by reducing the stretch goals for the electrical system, the team could primarily use electronics already owned by the team while still meeting the key system requirements.

The second major change was an increase in the travel budget, which occurred after the team received the $3,500 TREP grant from Ohio State for covering competition travel expenses. The team originally planned and budgeted only for only attending the Lunabotics Qualification Challenge at UCF. With the new funding, the team planned on attending both the Lunabotics Qualification Challenge at UCF and the Lunabotics OnSite Challenge at KSC. Attending both significantly increased the travel budget because the team had to extend the trip and pay for the team's advisor to attend (the team has a student as a representative for the UCF Qualification challenge). In addition to these cost increases, the team also underestimated the cost of robot transportation which ended up costing around $800 for the vehicle rental.

The mechanical budget was increased $600 at the PDR to accommodate the team's aggressive regolith throughput objective. The budget increases were focused on outsourced fabrication using SendCutSend and purchasing additional stock material to support the regolith storage requirement targeted by the team. The SendCutSend purchases were justified by the manufacturing time saved, which was estimated at around 2 weeks. The additional stock material was needed due to an underestimate by the team in the budget proposed in the PMP.

The electrical budget was significantly cut from $2,550 to $1,200 after the PDR to offset the team's increased mechanical and travel budget. This was possible due to cuts made over the entire electrical budget. The first set of cost savings came from using inexpensive electrical components. For example, the team was able to find a COTS energy logger that cost $22.99 which was much less than the $200 budgeted during initial research. Another choice the team made was to use 12V for most of the electrical system which lowered the cost of components (such as the voltage regulator) but decreased our energy efficiency due to I^2R losses, which resulted in a higher watt-hour requirement. The team decided this was an acceptable tradeoff considering the relatively low penalty for energy usage.

The electrical budget was also reduced by using parts already owned by the student organization managing the team, and from other robotics teams in the area. As a result, the team did not have to buy any motors or motor controllers. Although great for the budget, the motors and motor controllers received had two downsides. The first was that they were relatively inefficient, which further increased the team's energy usage. This was considered an acceptable loss given the cost of buying more efficient components would have been significant and the relatively low penalty for energy usage. The second tradeoff was that the motors allocated for drive and the four-bar linkage lacked encoders or other sensor data which would make it difficult to perform autonomy. To counteract this, the mechanical team integrated a separate encoder for the four bar linkage mechanism, but the team decided to remove the requirements related to sensor feedback for the drive system. This was an acceptable tradeoff due to the team's low autonomy requirements.

The team still has future spending which is represented by the $2700 difference between the actual spending and the current total spending listed in Table 2. The majority of the remaining purchases are for competition travel related items such as food and advisor travel costs. The team still expects to spend around $275 for administrative purchases such as merchandise and other promotional material needed for competition. Finally, the team expects to spend around $600 dollars on mechanical and electrical purchases. This will include new parts for fixing issues discovered during testing, buying new tools for competition, and buying spares of critical components such as motors and electronics.

3 Systems Engineering Merit

3.1 System Hierarchies

The team initially decided to break down the lunar excavation system into two main components: the robot itself, and the arena. The team recognized that the primary subsystems for the arena are the regolith, obstacles, and zones. The robot was split into five subsystems, the software, electronics, dump, intake, and chassis. While defining the system requirements, the team had already decided that the chassis would include the frame, wheels, and storage. The electronics would consist of the battery, motors, kill switch, and energy logger. The software included autonomy, robot control, and the driver station. The full system hierarchy for the SRR is included in Figure 2.

For the PDR stage, the team defined which assemblies were part of the arena subsystems. The team decided on a design for both intake and dump subsystems, with the intake consisting of a belt and bucket design that would require a deployment system, and the dump consisting of a conveyor belt design. The software, electronics, and chassis subsystems were further refined based on the team's high level design concept. The PDR system hierarchy is located in Figure 3.

For the CDR system hierarchy, the electronics subsystem had more assemblies added to it, so the team decided to split it into 3 different subsystems: controls, power, and motors. This focused the electronics subsystem into categories that include the specific electrical components of the robot. Notably, the team had decided to use a Raspberry Pi 4B and a RP2040 CAN Development Board for processors. For motor controllers, the team decided to use SparkMAXs and VictorSPXs. for controlling the robot's motors. The CDR system hierarchy can be found in Figure 4.

3.2 Requirements

When creating the list of requirements, the team used a numbering scheme with three different categories: system requirements, mechanical requirements, and controls requirements. System requirements relate to the entire robot system and are prefixed with SYS. Mechanical requirements relate to mechanical design, and are prefixed with MECH. Finally, control requirements relate to the electrical and software subsystems and are prefixed with CTRL. The team began by creating a list of requirements from the NASA Lunabotics Guidebook [2]. Those requirements are located in Table 4.

The team established their own system requirements based on their technical objectives which further constrained the design. The team's system requirements are listed in Table 5. After completing trade studies on the relevant tasks the team derived a list of lower level requirements for the drive, intake, and dump subsystems.

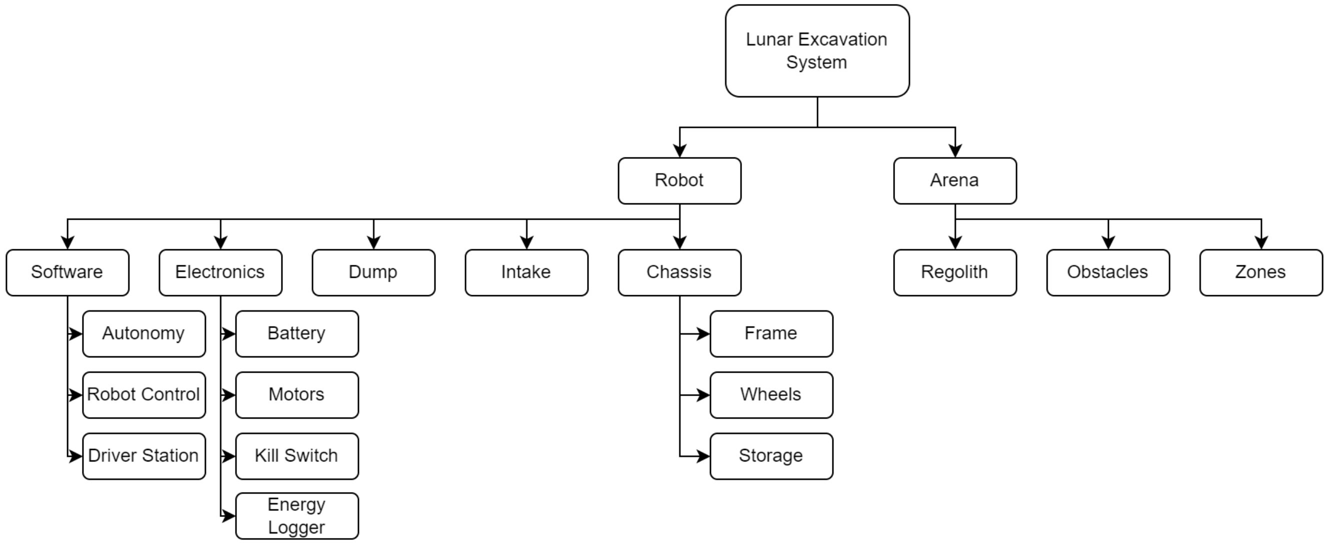

Figure 2: System Hierarchy from the SRR.

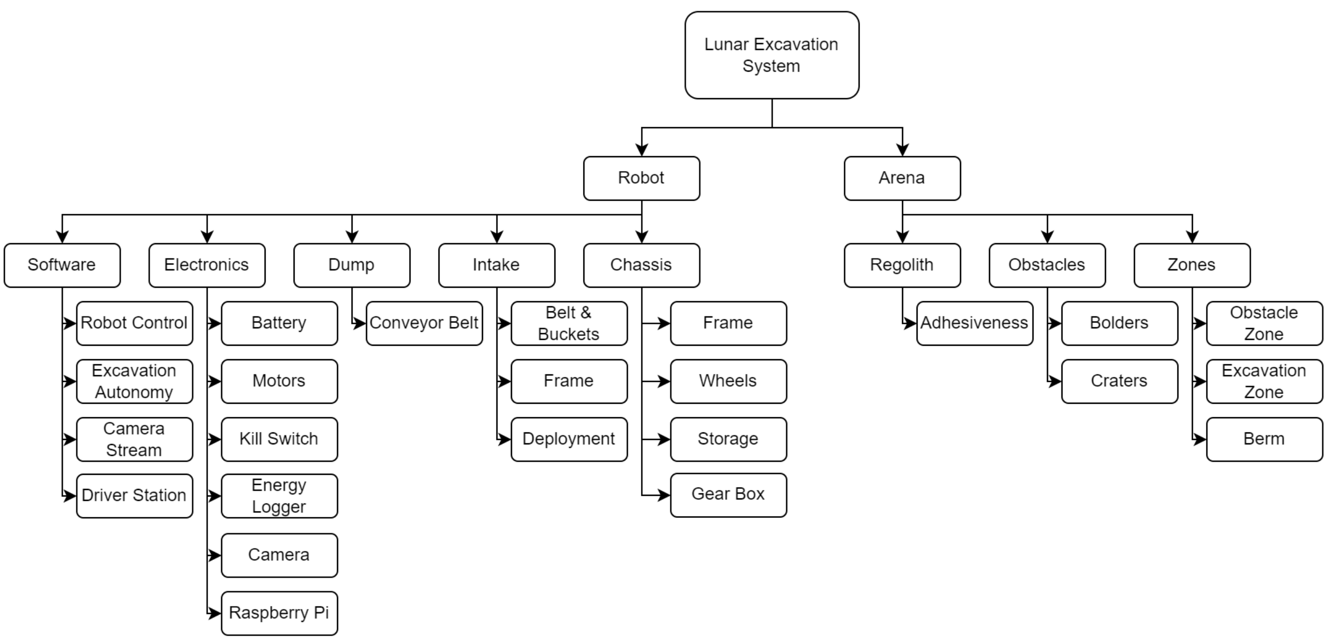

Figure 3: System Hierarchy from the PDR.

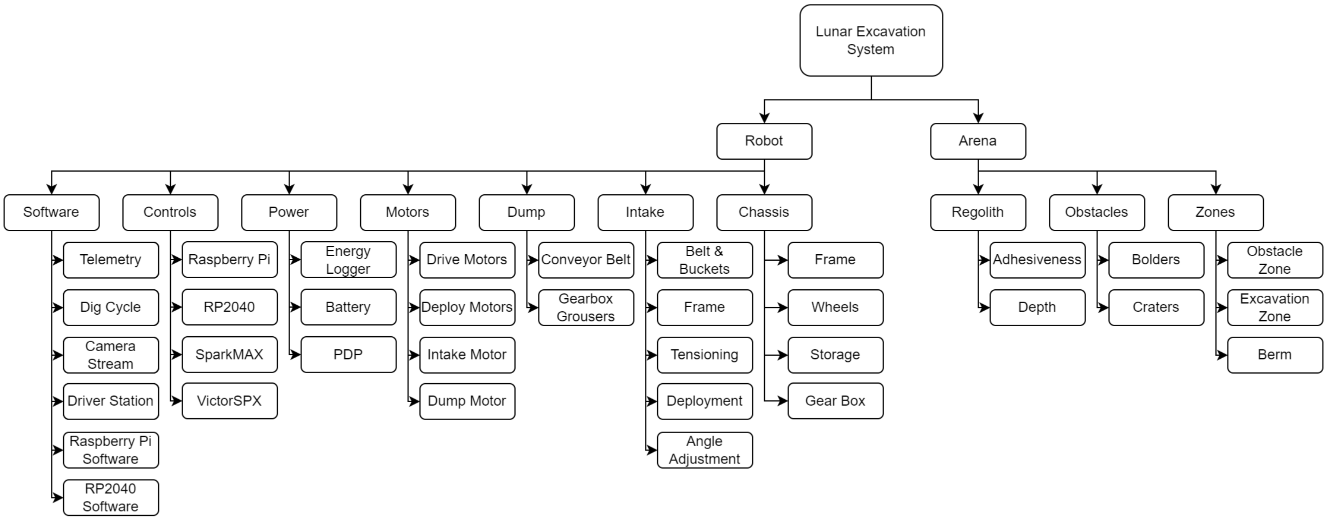

Figure 4: System Hierarchy from the CDR.

Table 4: System Requirements from Competiton Guidebook

Competition System Requirements	
Number	Requirement
SYS-1	Shall be able to be teloperated via 802.11b/g/n standard.
SYS-2	Shall operate for 30 minutes on a full charge.
SYS-3	Shall have a kill switch.
SYS-4	Shall record energy usage in a manner that can be retrieved when the robot is powered off.
SYS-5	Shall only use physical processes, fluids, and consumables that are space capable.
SYS-6	Shall fit within 1.5m*0.75m*0.75m.
SYS-7	Shall weigh less than 80 kg.
SYS-8	Shall not exceed 2.5m in height fully extended.
SYS-9	Shall be able to avoid craters 0.5m wide.
SYS-10	Shall be able to avoid rocks 0.4m wide.
SYS-11	Shall have four lifting points clearly marked (ISO 7000-1368).
SYS-12	Shall have a central hoist point or sling system based around the robot's center of gravity.

Table 5: System Requirements from Team

Team System Requirements	
Number	Requirement
SYS-13	Shall have active dust control per NASA guidebook section 3.9.
SYS-14	Shall be able to autonomously intake regolith from the excavation zone.
SYS-15	Shall stop after 1 second of no signal while teleoperated.
SYS-16	Shall support a maximum load of 100A.
SYS-17	Shall be capable of streaming a camera feed.
SYS-18	Shall have a breaker for each motor
SYS-19	Shall be able to supply up to 40A per motor.

Table 6: Derived Requirements for Drive Subsystem

Drive Requirements	
Number	Requirement
MECH-1	Shall be able to turn in place.
MECH-2	Shall be able to move.
MECH-3	Shall be able to support 65 kg per wheel.

Table 7: Derived Requirements for Intake Subsystem

Intake Requirements	
Number	Requirement
MECH-4	Shall be able to collect lunar regolith.
CTRL-1	Shall have stall detection.
CTRL-2	Shall be able to control the intake elevation.

Table 8: Derived Requirements for Dump Subsystem

Dump Requirements	
Number	Requirement
MECH-5	Shall store lunar regolith.
MECH-6	Shall be able to dump lunear regolith.
CTRL-3	Shall have stall detection.
CTRL-4	Shall have a method of determining the amount of regolith currently stored.

The drive subsystem requirements are located in Table 6, the intake subsystem requirements are located in Table 7, and the dump subsystem requirements are located in Table 8.

3.3 Interfaces

The three main systems were the electrical, mechanical, and driver station as shown in the high level N^2 chart in Figure 5. External to the robot system was any human input and interaction with the course arena. Interactions with the regolith in the course were with the mechanical system for intake and dumping. There are many connections between each system and internal to the systems. Analyzing these interfaces was critical to project success because it enabled smooth system integration. A detailed N^2 chart for each system is presented in Appendix C: Figure 13 for the electrical system, Figure 14 for the mechanical system, and Figure 15 for the driver station.

While all interfaces are critical, there are several notable interfaces that will be highlighted beginning with interfaces between systems. First, an I^2C encoder interfaces between a mechanical and electrical system to provide feedback on intake positioning. This interface enables accurate height adjustment and reliable deployment for requirement CTRL-2. Next, the electrical system communicates with the driver station over WiFi, with the interactions between the router and Raspberry Pi being critical functions since the robot was designed to not be fully autonomous. The Raspberry Pi and driver station laptop are continuously sending heartbeat messages over the network to enable requirement SYS-15. Lastly, the motor interfaces linking the mechanical and electrical systems enables the robot to interact with its environment by actuating the drive wheels, digging buckets, or dump belt.

There were several interfaces internal to the electrical system worth mentioning. To fulfill requirement CTRL-1/CTRL-3, the RP2040 microcontroller interfaces with the SparkMax brushless motor controllers over CAN bus, which provides sensor feedback from the motor. The microcontroller reads telemetry from the SparkMAX motor controllers to monitor the motor speed so that it can respond appropriately if it detects the motor stalled. To fulfill requirement SYS-3, all power from the batteries to the motors pass through an E-stop button to allow a human to deactivate the robot at any moment. Importantly, the battery connects to the energy logger before the E-stop, allowing the display interface to be read even while power to the robot has been cut off to satisfy SYS-4.

The mechanical system had many internal interfaces. The regolith storage was integrated into the frame that connected to other mechanical subsystems such as the wheels or four bar linkage. The team made the interface of the four bar linkage to the intake and frame as compact as possible to fulfill SYS-6 size requirement while leaving as much width as possible for intake buckets. Timing belts for the intake and dump sub-systems interfaced with a belt tensioning system attached to each frame for easy adjustment. Next, the dump belt interfaces with the frame with dynamic sealing flaps to prevent the mined regolith from leaking out of the storage container.

The interfaces within the driver station enable software control. All commands and information goes through the laptop, where USB and ethernet data streams connect to the network and controller. The laptop software interfaces with its display using a custom GUI to display camera frames to fulfill SYS-17 and to provide buttons for autonomous functionality. Moving one-time use buttons, such as the autonomous functions, to the GUI enables more controller buttons to be used for human driver assistance features.

3.4 Engineering Specialities

3.4.1 Reliability

Reliability of the robot system is critical to robot success. Based on initial testing, the team is 90% confident the systems would function properly during a 30 minute competition run. The team anticipates the robot could be in hot Florida weather, so to prevent 3D printed components from softening, all parts were printed in temperature resilient PETG filament. Additionally, from initial system testing, the team was able to identify failure modes in the desire and implemented solutions to mitigate the same failure mode in the future. On the initial system testing on March 14th, the key linking the intake motor to its gearbox sheared due to the low key engagement. A machined component was made to connect to the gearbox input to extend key contact to reduce the risk of this failure mode in the future. In the month prior to competition, the team will continue to conduct extensive testing in sand pits to find system limits to ensure the robot will operate in acceptable performance capabilities for competition.

3.4.2 Logistics

Logistics and part availability were considered to ensure that if a system fails, there would be a 75% chance the team could acquire the necessary parts to repair the faulty system in 6 hours. Components of the robot structure are primarily made from readily available aluminum sheet metal and box tubing. Since the design used commonly available stock metal dimensions, any raw material will be purchased from a local hardware store at competition if needed. Additionally, most components were made with the use of hand-tools and will be brought to competition to aid in on-site repairs. These tools include:

- Cordless drill with drill set

1 Electrical	Motor Outputs	Telemetry, Camera Frames, Heartbeat	
Encoder Feedback	2 Mechanical		Dumps Regolith
Controller Commands Heartbeat		3 Driver Station	
Human Presses E-Stop	Mines Regolith, Lifting Locations	Situational Cameras, Human Control	External

Figure 5: N^2 Chart of System Interfaces.

- Riveting tools
- Hack saw
- Vice
- Hammer
- 3D printer with filament

Additive FDM manufacturing will be used to fabricate PETG plastic components if any printed parts fail or for complicated repairs. To improve the printing speed, a 0.6 mm nozzle will be installed on the printer to ensure parts can be ready in a timely manner. For the components that are logistically difficult to quickly obtain replacements of, the team will be bringing backups. For example, spare motors and a LiFePO4 battery will be packed.

3.4.3 Transportability

One of the considerations with the robot design is transportability, and a 90% chance the robot would not get damaged during transportation was selected. To ship the robot to Florida, the robot will be loaded completely assembled in a mini-van. A wagon style cart was purchased to transport the robot indoors and along paths. Next, there are four handles per requirement SYS-11 to lift the robot between the vehicle and the cart and up and down stairs. The width of the robot is around 0.7m, which allows it to pass through the average 0.813m wide interior US door. Lastly, four eye bolts are placed on top of the rover frame to allow for lifting from an overhead crane with a cable sling per requirement SYS-12.

3.4.4 Safety

Safety is the most important aspect of robot design; while the team took extensive measures to ensure the safety of those that interact with the robot, there is never a 0% chance of injury. Therefore, the team selected a 0.1% acceptable level for minor injury for the competition. Safety has been considered in all aspects of the electrical, mechanical, and software design. For the electrical system, the primary area of focus is battery safety. A built-in battery management system in the robot's LiFePO4 batteries ensures cell voltages remain balanced and provides protection from overcharge, over-discharge, high temperature, short-circuit, and discharge overcurrent. When charging the batteries, one team member will always be present in case there are any issues. The electrical system is 12V, which is generally not high enough to pose significant harm to people. Additionally, safety drove requirement CTRL-1/CTRL-3, so a motor would quickly stop if it gets jammed. An E-stop switch is present on the side of the robot per requirement SYS-3, which allows the robot to easily be shutdown if behaving unexpectedly or to work on the robot. Importantly, the E-stop was positioned to be out of the path of moving intake components and at a height that can be pressed with a kick.

For the software, the team implemented a two way heartbeat system for SYS-15 so that the robot can automatically power off motors and enter a safe state if it ever loses connection to the driver station. Additionally, the software uses the encoder to block certain human-controller commands if the intake is an unsafe position. This prevents the intake from spinning before it is deployed and the intake from going below ground level unless it is spinning. Mechanically, sharp edges of the robot were deburred to reduce the chance of small cuts while handling the system. The drive gearboxes are non-backdrivable due to the high gear reduction so the robot can't roll away when placed on a slanted surface. Additionally, ergonomic handles were placed on the robot to indicate safe points for carrying the robot. Lastly, pinch points from chain transmissions were enclosed or positioned out of reach. These considerations across each system help the team meet its desired safety level for the robot.

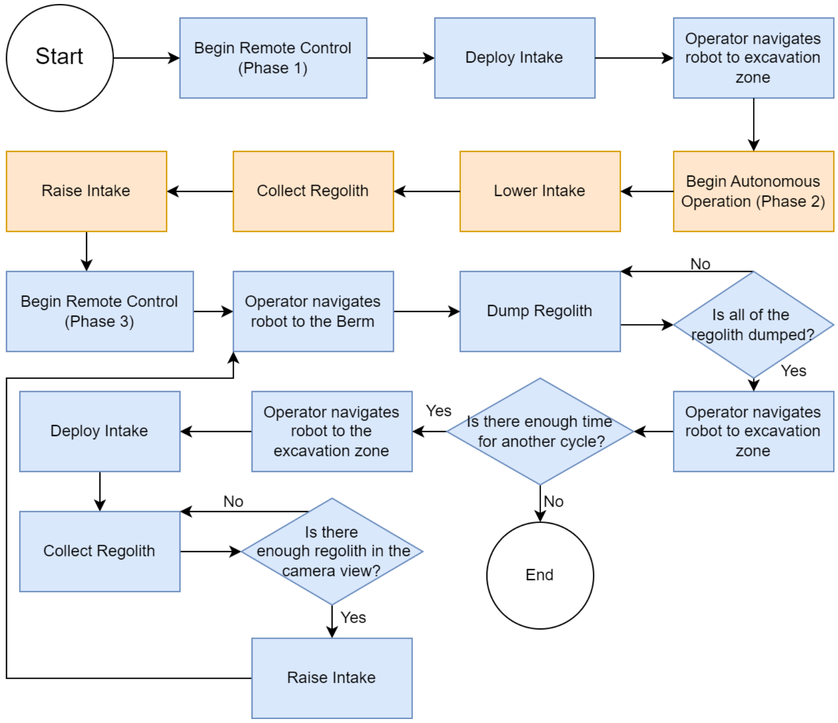

Figure 6: The Robot's Operational Flowchart.

3.5 Concept of Operations

For the Concept of Operations, the team created a flowchart, shown in Figure 6, which represents what steps the team and robot would perform during competition. In Phase 1, the robot will start off in initial state, which is shown in Figure 7. Via remote control, the operator will first deploy the intake to stabilize the robot. With the intake deployed, the operator will orient the robot, and navigate the robot through the obstacle zone, avoiding any obstacles in the way with a camera view.

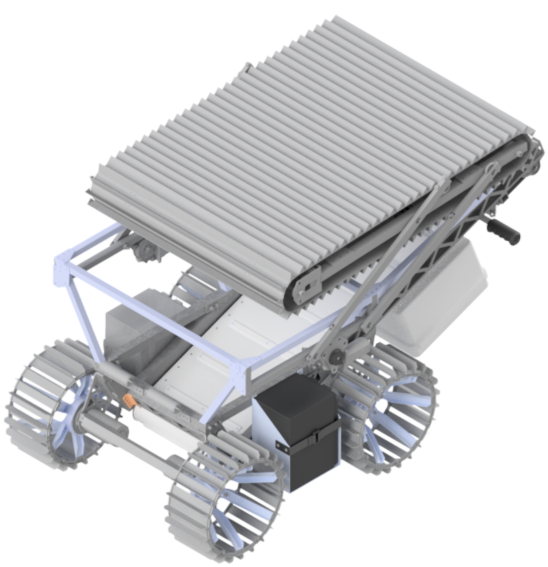

Figure 7: Rendering of the robot's initial state.

Once the robot is in the excavation zone, the robot will enter phase 2 which is fully autonomous. The robot will lower the intake to ground level, and will start collecting regolith while slowly moving forward. The intake operation is pre-programmed on the robot, with set conditions deciding how long the intake is conducted. Once the intake is completed, the robot will stop collecting regolith and will raise the intake off of the ground.

The robot will then enter phase 3 and returns back to remote control. The operator will navigate the robot to the berm, with the rear of the robot facing towards the dumping target area. Once the robot is next to the berm, the operator will start the dump system and let the robot dump out all of the regolith in the storage. Once the operator verifies that all of the regolith is dumped through a camera, they will stop the dump and check if there is enough time to complete another cycle of excavation and construction. If the team decides that there is enough time, then the operator will navigate the robot back to the excavation zone. The operator will complete the intake cycle through remote control instead of through autonomy. The operator stops the intake once they verify that there is enough regolith in the storage. Then the operator repeats phase 3 from the beginning.

3.6 Technical Performance Measurement

For the SRR, the team created initial technical performance measurement (TPMs) displayed below in Table 9.

Many of these initial TPMs were selected based on modeling scored point scenarios in an Excel document. The TPM evolved over the project lifecycle, but the team recognized excavation volume and cycle time the most difficult to achieve and the most risky for the project success.

To gain an understanding of the feasibility of these TPM the team conducted theoretical modeling to verify the feasibility of the desired intake excavation. The team used the regolith properties for BP-1 and LHS-2E shown in Table 19 (located in Appendix D) to model the soil scooping with MATLAB code. The program found the geometry of a bucket scooping path using parametric equations of Trochoid curves shown below in Eq. 1 and Eq. 2.

$$x = vt - rsin(\omega t) \tag{1}$$

$$y = -rsin(\omega t) \tag{2}$$

Where v is the robot's horizontal speed, r is radius of bucket tip, and w is angular velocity of intake. Using the current and previous bucket path along some digging height below ground level, the full geometry of the one scoop could be found. Next, each path was split up into small slices for numerical integration. At each slice, the energy, mass, and torque were separately calculated. The torque was found using the force needed to shear the soil at its shear plane using the Mohr-Coulomb theory to find the failure shear stress shown in Eq. 3.

$$\tau = c + \sigma tan(\phi) \tag{3}$$

Where τ is failure shear stress, c is cohesion, σ is normal stress, and ϕ is the internal friction angle. In this scenario, the normal stress was found from the weight of the soil above the shear plane. The energy was calculated using work from shearing the soil, energy required to bring the mass element to the top of the intake and to add enough kinetic energy to match the speed of the bucket. Lastly, the mass throughput was found purely from the geometry of the soil slice. These calculations resulted in the graphs presented in Figure 8, where the green lines in the upper left show the shear planes at different positions along the scoop path.

From these results, the team used MATLAB's optimization library to optimize the intake parameters, such as horizontal speed, radius, rpm, and digging depth; however, the optimized output improvement was not substantial even after modifying the loss function many times. The only trend from parameter optimization was that the intake width should be as wide as possible. Because of this, the scooping parameters were selected primarily from a mechanical packaging perspective. The result of this was that this simulation showed that the TPM for the excavation volume, cycle time, and energy were feasible. The design could theoretically fill the storage container in 83 seconds, using 2750 joules of energy. The program also provided a force for the bucket that was utilized to perform a FEA simulation of the bucket shown in Figure 9.

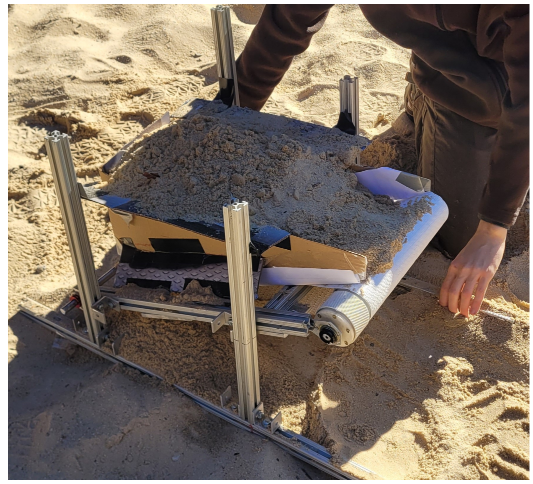

Figure 10: Testing the dumping system prototype.

The other risky aspect of the TPM was the regolith dumping. The team opted to prototype this aspect of the design to evaluate the feasibility of different designs. A prototype dump belt system can be seen in Figure 10. This rough prototype was able to dump roughly 0.013 m3 in 7 seconds, which would be roughly 65 seconds extrapolated to the robot's storage container volume. The team thought of various ways of improving the dump speed by adding grousers to the belt, reducing the elevation angle, and increasing the dump belt width.

As the project evolved, the TPMs became more refined and more were added. Notably, the target mass increased as the team began progressing with the CAD design. Additionally, weight saving measures like pocketing were skipped to save time. The team did not initially set associated systems with the TPM, so this was added. The final TPM table is shown in Table 10.

3.7 Trade Studies

Trade studies were used to identify an optimal drivetrain and dump system given the team's capabilities and the high level performance objectives. These trade studies produced more specific requirements for the dump and drivetrain subsystems that could be tested experimentally to determine where the high level objectives were being met.

Starting in 2022, the team began researching trends in drivetrain design for Lunabotics robots. This consisted primarily of watching robot matches from previous years, and qualitatively assessing the performance of different drivetrain types. Online documentation in the form of technical posters and papers were also consulted when assessing previously identified trends. Given the

Table 9: The team's initial technical performance measurements

Initial TPMs				
TPM	Unit	Target	Worse Case	Relative Importance
Excavation Volume	m^3	0.8	-0.1	0.3
Dust Mitigation	Points	20	-10	0.05
Cycle Time	s	250	-30	0.2
Energy Used	Wh	500	50	0.1
Autonomy Level	-	Excavation AND Dump Automation	Excavation OR Dump Automation	0.1

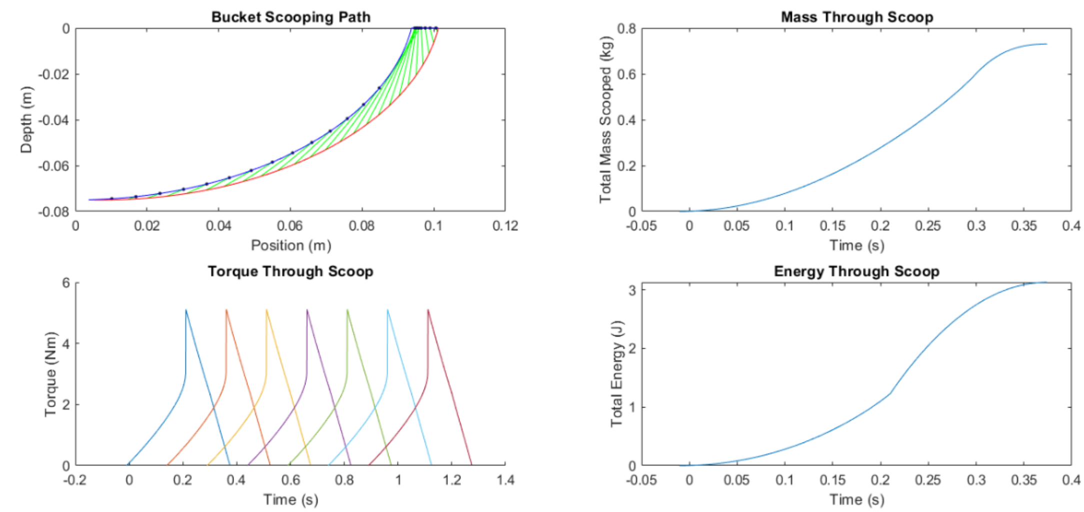

Figure 8: MATLAB Scooping Simulation.

sparse amount of reliable quantitative data available on the performance of different Lunabotics drivetrains, the analytical hierarchy process was used for comparing different designs and characteristics. A decision matrix of different designs are shown in Table 11.

Once the team determined which drivetrain type would be the best fit for the team's goals, the team again used trade analysis to choose the drivetrain motors. Inputs for this analysis included efficiency, cost, power, and mechanical characteristics. The decision matrix for motor selection can be found in Table 12.

After going through initial concept generation, the team identified several promising designs for the dump system. To determine which method the team would proceed with, various characteristics of the designs were compared. A decision matrix comparing the different methods discovered during the trade study is located in Table 13.

3.8 Verification of System

The team has created a test plan for completing the robot system verification. The test plan is summarized in Table 14. For each key driving requirement, a test was devised that should isolate the requirement's specific functionality. Certain tests were performed at the team's build site, but others required a sand pit for true verification. The team has attempted some of the tests at the Ohio State volleyball pits, but cold weather has caused many of the tests to be invalidated because of the different properties of frozen sand.

In addition to testing the system key driving requirements, the team developed tests for the key interfaces. For mechanical interfaces, the team put above expected loads on critical interfaces to verify all functionality should work during competition. On the software front, many of the interfaces were tested with simulated versions of the different software components. For example, to verify the robot code, the team developed a simulated version of the RP2040 software that recorded commands sent from the RaspberryPi.

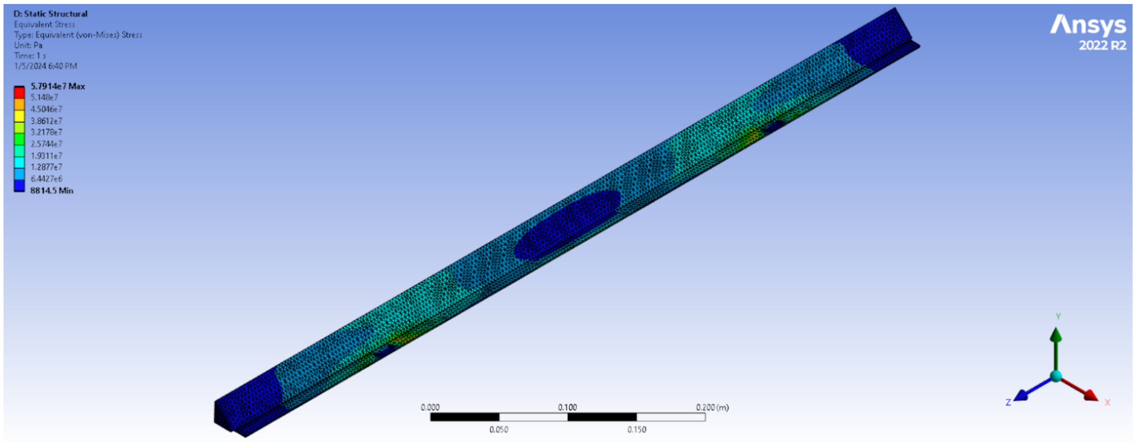

Figure 9: FEA simulation of the bucket using Ansys.

Table 10: The team's final technical performance measurements

Final TPMs						
TPM	Unit	Target	Worse Case	Priority	System	Requirement
Excavation	m^3	0.8	0.4	10	Dump, Intake, Chassis	MECH-4
Mass	kg	65	80	6	Robot	SYS-7
Size	m	0.74 x 1.3 x 0.74	0.75 x 1.5 x 0.75	1	Robot	SYS-6
Dust Mitigation	Points	20	10	2	Dump, Intake	SYS-13
Cycle Time	s	250	400	9	Robot	MECH-2
Energy Used	Wh	300	600	5	Electrical	SYS-2
Autonomy Level	-	Complete Excavation Automation	Automated Intake Elevation Control	7	Software	CTRL-2
Drive Speed	m/s	0.1	0.05	4	Chassis	MECH-2
Storage Volume	m^3	0.12	0.1	8	Chassis	MECH-5
Data Rate	kbps/s	2000	3000	3	Software	SYS-17

Table 11: Decision matrix for drivetrain design.

Decision Matrix of Drivetrain Designs							
			Skid Steer		Indepedent Steer		Ackerman Steer
Criteria	Importance	Treads	4 Wheels	6 Wheels	6 wheels	4 Wheels	4 Wheels
Size	4	1	5	3	1	2	4
Weight	4	1	5	4	1	2	3
Actuators	3	5	5	5	3	3	4
Turning Ability	5	3	3	2	5	5	4
Complexity	1	3	5	4	1	2	3
Cost	2	2	5	3	1	2	4
Durability	3	3	5	4	1	2	3
Payload Capacity	2	5	2	2	4	3	4
	Total:	64	104	79	56	68	88

Table 12: Decision matrix for drivetrain motors.

Decision Matrix of Drivetrain Motors						
Criteria	Importance	BAG	CIM	Mini CIM	NEO 550	NEO
Size	1	4	1	2	5	3
Weight	3	4	1	2	5	3
Integration	4	5	5	5	4	4
Failure Modes	2	5	5	5	3	4
Torque	5	1	4	3	2	5
Efficiency	2	2	3	3	5	4
Required Gearing	4	2	4	3	1	5
Durability	2	4	5	5	3	4
Cost	6	5	5	5	2	2
	Total:	101	116	111	84	109

Table 13: Decision matrix for dump system designs.

Decision Matrix of Dump System Designs					
Criteria	Importance	Auger	4-Bar Bucket	Rotational Bucket	Conveyor Belt
Size	5	3	1	2	4
Weight	4	2	1	2	3
Ease of Integration	2	3	1	2	4
Efficiency	1	1	2	3	4
Complexity	3	4	1	3	3
Durability	4	4	2	3	2
Cost	2	1	2	3	4
Dust Protection	2	2	4	3	1
Dust Generation	3	2	3	3	2
	Total:	70	45	67	77

Table 14: Verification tests for the key driving requirements.

Verification of Requirements	
Requirement	Verification Test
Shall operate for 30 minutes on a full charge	Drive robot on sand, run intake and dump at full speed for 30 minutes.
Shall have a kill switch	Place robot on blocks, hit kill switch, verify all power is removed and controls do not work.
Shall record energy usage	Use a load tester to place a constant load on the electronics and verify load tester and energy logger agree on energy used.
Shall fit within 1.5m*0.75m*0.75m.	Measure robot dimenssions.
Shall weigh less than 80 kg.	Weigh robot using calibrated scale.
Shall not exceed 2.5m in height fully extended	Raise intake to max height and measure robot height above ground.
Shall stop after 1 second of no signal while teleoperated	Run controls, remove power from router, verify robot stops within 1 second.
Shall be able to turn in place.	Load dump with sand 0.12 m^3 of sand, then attempt to do a 360°turn.

4 Conclusion

The team was successfully able to design, manufacture, and test a system for the NASA Lunabotics 2024 Competition. The team combined project management and systems engineering principles to navigate the season in a smooth and effective manner. Although setbacks occurred throughout the project, these strong project foundations successfully kept the team in a position to successfully produce all needed deliverables before the deadline. The skills learned by the team will be invaluable for future success as members transition into the professional world of engineering.

5 Acknowledgements

The team would like to thank many people for their help and assistance over the last year. First, we would like to thank our faculty advisor, Dr. Saeedeh Ziaeefard, for her continuous guidance on engineering, business, and project management. We would like to thank Dr. Andy Bruening and the PAST Foundation for letting us use their space to build our robot. In addition, we would like to extend our gratitude to the Bonini Family for providing robot transportation to and from tests. Finally, we want to thank the Columbus School For Girls and Metro High School robotics teams for letting us borrow their tools and supplies.

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Appendix A Project Schedules

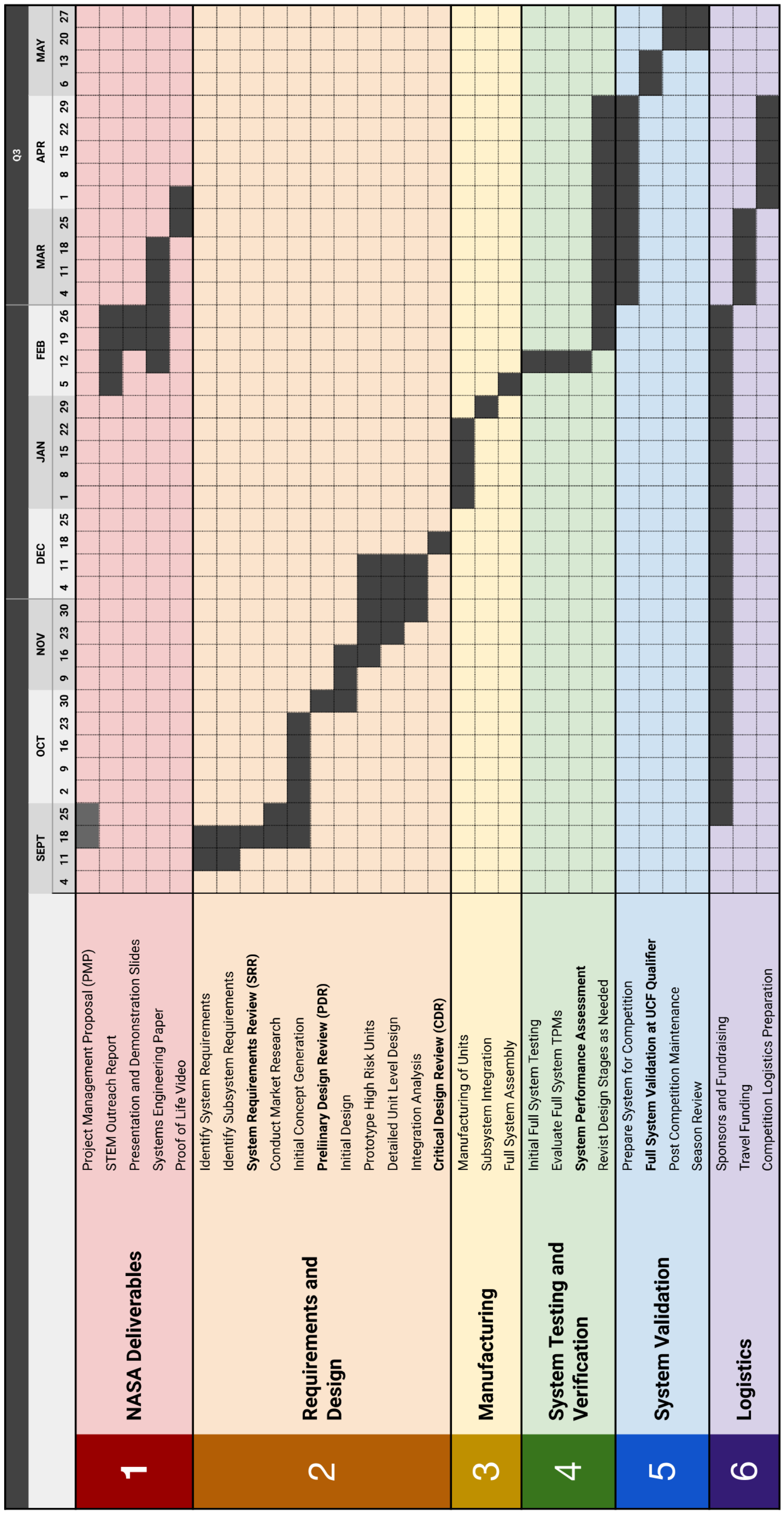

Figure 11: The team's planned schedule.

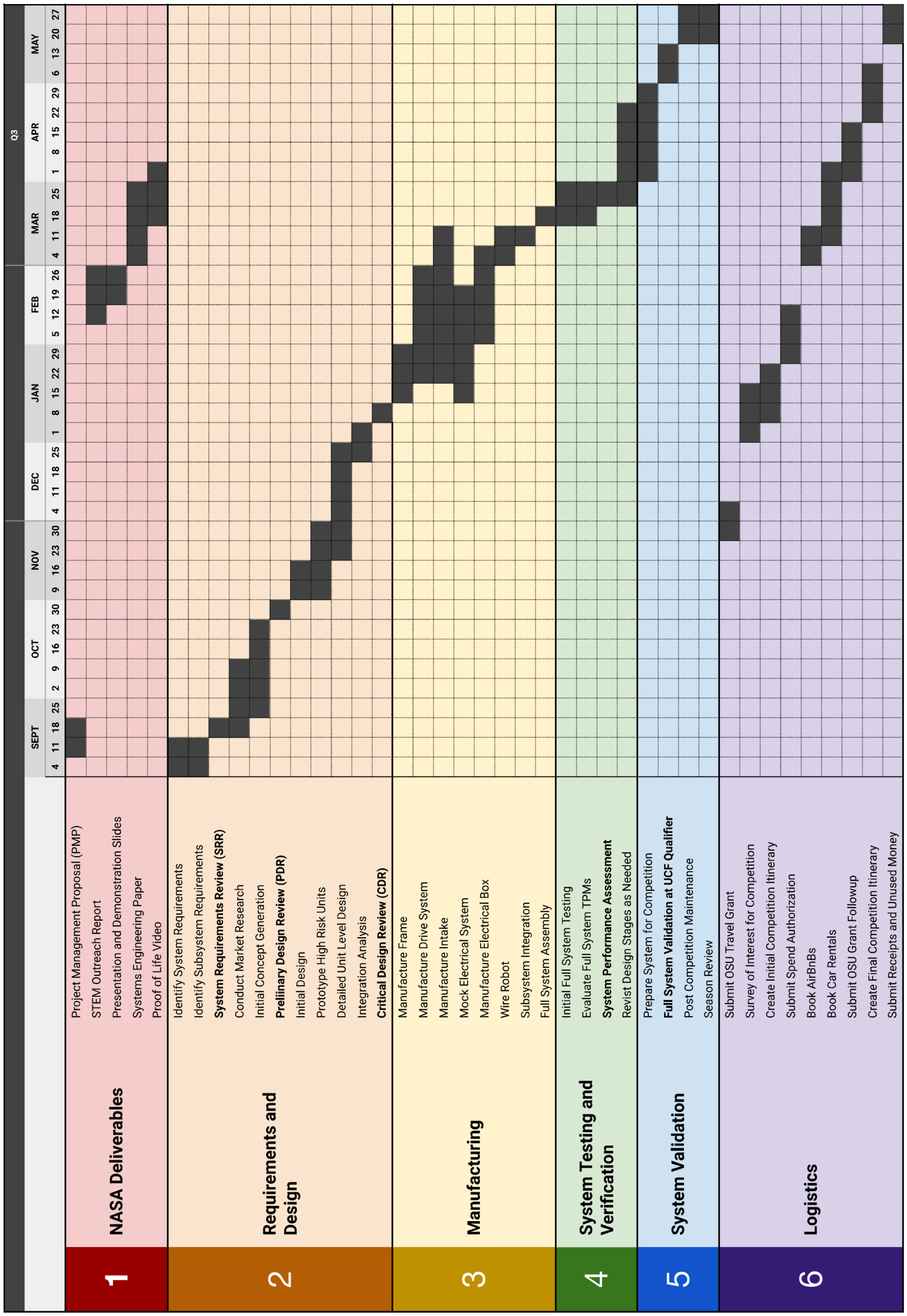

Figure 12: The team's actual schedule.

Appendix B Project Budgets

Table 15: Team's Electrical Budget

Electrical Budget				
Category	**Parts**	**Budgeted**	**Spent**	**Expected**
Motor Control	Drive Motor Controllers	$200.00	$0.00	$0.00
Motor Control	Mechanism Motor Controllers	$150.00	$0.00	$90.00
Processing	Microcontrollers	$100.00	$42.00	$42.00
Processing	Main processor	$300.00	$62.00	$62.00
Communication	Wireless Access Point	$200.00	$31.49	$31.49
Wiring	Electrical Connectors	$100.00	$165.20	$118.20
Wiring	Wire / cables	$100.00	$78.00	$78.00
Power Distribution	Batteries	$350.00	$279.98	$418.00
Power Distribution	Voltage Regulator	$50.00	$9.95	$9.95
Power Distribution	Kill Switch	$0.00	$52.68	$52.68
Sensing	Cameras	$200.00	$0.00	$0.00
Sensing	Energy Data Logger	$300.00	$22.99	$22.99
Sensing	Encoders	$100.00	$20.00	$20.00
Actuators	Motors	$200.00	$0.00	$48.00
Actuators	Linear Actuators	$200.00	$0.00	$0.00
Enclosure	Electrical Enclosure	$0.00	$69.49	$69.49
Tools	Soldering Iron	$0.00	$23.00	$23.00
	Total:	$2,550.00	$856.78	$1,085.80

Table 16: Team's Administrative Budget

Administrative Budget				
Category	**Parts**	**Budgeted**	**Spent**	**Expected**
Merchandise	Team Shirts	$175.00	$0.00	$175.00
Promotion	Buttons	$75.00	$0.00	$0.00
Organization	Tool Bins	$100.00	$0.00	$100.00
Organization	Parts Organizer	$100.00	$0.00	$0.00
Documentation	Office Supplies	$100.00	$0.00	$0.00
	Total:	$550.00	$0.00	$275.00

Table 17: Team's Mechanical Budget

Mechanical Budget				
Category	**Parts**	**Budgeted**	**Spent**	**Expected**
Stock Material	Metal & Plastic Sheets	$150.00	$200.14	$250.00
Stock Material	Extruded Profiles	$150.00	$523.49	$580.00
Stock Material	FDM Filament	$100.00	$37.98	$50.00
Stock Material	Other (textiles, cables, etc.)	$75.00	$105.80	$105.80
Hardware	Threaded Fasteners / Rivets	$125.00	$129.71	$150.00
Hardware	Other Fasteners	$100.00	$17.07	$50.00
Hardware	Adhesives / Coatings	$100.00	$18.80	$40.00
Power Transmission	Bearings, Gears, Belts	$500.00	$395.22	$450.00
Tools	Tools & Machine Tooling	$200.00	$219.49	$300.00
Manufacturing	SendCutSend	$250.00	$538.92	$538.92
Manufacturing	Other Out Sourcing	$150.00	$0.00	$0.00
	Total:	$1,900.00	$2,186.62	$2,514.72

Table 18: Team's Travel Budget

Travel Budget				
Category	**Parts**	**Budgeted**	**Spent**	**Expected**
Vehicles	Rental	$0.00	$1,106.00	$1,106.14
Vehicles	Fuel	$675.00	$0.00	$400.00
Lodging	Orlando (4 Nights)	$900.00	$1,018.42	$1,018.42
Lodging	KSC (3 Nights)	$0.00	$693.65	$693.65
Lodging	Hotel (Car Travellers)	$0.00	$0.00	$200.00
Lodging	Hotel (Advisor @ KSC)	$0.00	$0.00	$300.00
Flight	Advisor Plane Ticket	$0.00	$0.00	$250.00
Food	Team Dinners	$0.00	$0.00	$560.00
	Total:	$1,575.00	$2,818.07	$4,528.21

Appendix C Interface Charts

1.1 Batteries	Anderson SB50, Ring Terminals	Ring Terminals						Battery Mounts		
	1.2 E-Stop		Ring Terminals							
		1.3 Energy Logger								Display Screen
Drains Batteries		Ring Terminals	1.4 PDP Board	12V-5V Converter			40A Breakers			
				1.5 Raspberry Pi	USB, 5V				UDP, Camera Frames	
				USB	1.6 RP2040		CAN, PWM	I		
				USB		1.7 Cameras		Mounting Brackets		
					CAN		1.9 Motor Controllers	Motor Outputs		
					I^2C Encoder			2 Mechanical		Dumps Regolith
				TCP/IP /Heartbeat, Controller Commands					3 Driver Station	
	Human Presses Button							Mines Regolith, Lifting Locations	Situational Cameras, Human Control	External

Figure 13: N^2 Chart of Electronic Interfaces.

1 Electrical	Electronics Box, Battery Mounts, Camera Mounts		Neo Motor with Gearbox	Window Motor	Camera Mounts	Neo Motor with Gearbox	SIM Motor with Gearbox		
	2.1 Storage Frame	Rivets & Screws	Idler Rollers, Belt Tensioning	Bushing Pivots			Wheel Mounting Brackets		
		2.2 Handles & Lifting Hooks							
	Gap Seals		2.3 Dump Belt						Deposits Regolith
I^2C Encoder				2.4 Four Bar Linkage	Bushing Pivots				
					2.5 Intake Frame	Belt Tensioning, Dust Brushing			
	Regolith Depositing					2.6 Intake Belt & Buckets	Mined Regolith Puts Load on Wheels		
							2.7 Wheels		Drives on Regolith
								3 Driver Station	
Human Presses E-Stop		Humans & Crane Lifting				Excavates Regolith		Situational Cameras, Human Control	External

Figure 14: N^2 Chart for the Mechanical Interfaces.

1 Electrical	Motor Outputs	Wifi (802.11n)		Heartbeat, Telemetry			
Encoder Feedback	2 Mechanical						Dumps Regolith
Wifi (802.11n)		3.1 Router	Ethernet				
		Ethernet	3.2 Datalogger	Ethernet			
Heartbeat, Commands, Controller State			Ethernet	3.3 Laptop	Camera Display		
				Autonomous Commands	3.4 GUI		
				USB, Controller Commands		3.5 Controller	
Human Presses E-Stop	Mines Regolith, Lifting Locations			Situational Cameras		Human Control Input	External

Figure 15: N^2 Chart for the Driver Station Interfaces.

Appendix D Regolith Properties

Table 19: Properties of Different Lunar Regolith Simulants

Regolith Properties				
Lunar Simulant	**Density ($\frac{kg}{m^3}$)**	**Cohesion (kPa)**	**Internal Friction Angle (°)**	**Source**
BP-1	1500-1800	0.0-2.0	39-51	[2]
LHS-2E	1400	0.356	30.5	[3]