8th NEW YORK UNIVERSITY TANDON SCHOOL OF ENGINEERING
ROBOTIC DESIGN TEAM

SYSTEMS ENGINEERING PAPER

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NEW YORK UNIVERSITY TANDON SCHOOL OF ENGINEERING

Abstract

New York University's student-led Robotic Design Team designed a lunar excavation rover to compete in NASA's 2024 Lunabotics Competition. The project mission was to be awarded the most points by prioritizing certain success metrics defined in NASA's 2024 Lunabotics Guidebook [3]. The project was made following the systems engineering process defined in NASA's Systems Engineering Handbook [1].

Systems engineering defines a process to design complex systems and organize project stakeholder, cost budget, and schedule information. A central point of the process is defining and refining requirements that ensure the design meets the stakeholder's needs, wants, and goals. The project utilizes systems engineering to ensure the rover meets the goals set by the primary stakeholder, NASA, to maximize BP-1 regolith deposited into a berm and autonomous operation, and minimize bandwidth usage, power consumption, system mass, system volume, and dustproof internal systems, while meeting cost and scheduling limitations, and meeting mission constraints. The process allows proper management of project goals, including the budget and requirements, and encourages a more structured and cohesive team. It also improved the documentation of the engineering of NYU's 2023-2024 rover compared to without the systems engineering process.

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Pre-Phase A: Conceptual Study

The purpose of Pre-phase A was to understand the mission and outline high level system and project management details. NASA's 2024 Lunabotics Guidebook was the reference used to outline initial Technical Performance Measurements (TPM), System Hierarchy, and Project Technical Objectives (PTO) [3]. TPMs were allocated to the system hierarchy in an Initial Technical Budget (Table 2). NASA deliverables and major system reviews, including the System Requirement Review (SRR), Preliminary Design Review (PDR) and Critical Design Review (CDR), were outlined in the Initial Project Schedule (Appendix D, Figure D1).

Project Technical Objectives (PTOs)

Project Technical Objectives (PTOs) represent the primary goals and performance criteria for the mission. PTOs serve as a foundation for project planning during the design phase by establishing priorities and ensuring that design choices made are congruent with the mission's goals. They are pivotal in testing by serving as standards to assess the system's performance.

The PTOs developed by the team are centered around maximizing points during the competition, as outlined in NASA's 2024 Lunabotics Guidebook competition scoring procedure [3]. These objectives include maximizing the material volume in the constructed berm and autonomous operation while concurrently minimizing the system's mass, power consumption, and bandwidth. Other objectives originating from stakeholders other than NASA were to minimize cost, system complexity, and to optimize the resource allocation throughout the project lifecycle.

Phase A: Preliminary Analysis

The purpose of Phase A was to outline initial System Requirements, Concept of Operations (ConOps) and further defining the systems of the rover in an updated System Hierarchy. A System Requirement Review (SRR) was held to assist in those developments.

System Requirement Review (SRR)

The System Requirement Review (SRR) consisted of two meetings: a meeting of the systems engineers, all of whom were required to read the Guidebook thoroughly and in its entirety, and a general body meeting, to provide more diverse perspectives [3]. The requirements at this phase consisted mostly of operational requirements and constraints, based directly on the required operations for the competition. This review ensured that the requirements were aligned with the guidebook, and that there were sufficient constraints to prevent the rover from breaking any guidelines. A significant change from the previous year, at the suggestion of a team advisor, was the addition of rationale for all of the requirements, to provide future reviews with context for the purpose of each requirement. The Technical Performance Measurements (TPMs) were initially based on the performance of the previous year's rover where possible and approximations otherwise (Table 2). No changes were made to the TPMs during this review, as it was deemed too early to determine the feasibility of these measurements to a higher degree of certainty. The initial schedule was created to include key deadlines included in the guidebook, as well as the design reviews (Appendix D, Figure D1). The cost budget was initially allocated to each system based on estimates for tools, materials, and other expenses (Appendix D, Table D1). The project was on schedule and within budget at the time of the review, so no modifications were made.

System Hierarchy

The rover is broken down into five systems: travel, excavation, construction, power, and communication systems; outlined in the systems hierarchy diagram (Figure 1).

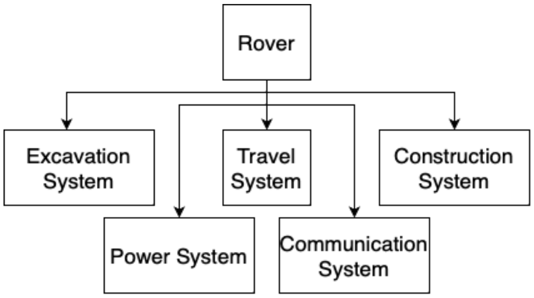


Figure 1: System Hierarchy

The travel system involves the chassis, wheels and components involved in operating travel autonomy, manual locomotion, and obstacle avoidance.

The excavation system consists of components involved in excavating and storing regolith such as the conveyor belt and the deposition bin, and excavation autonomy.

The construction system consists of components involved moving stored regolith on the rover to deposit it into a berm.

The power system consists of all components involved in distributing power, and any electronic components aside from the onboard computer and cameras. This includes two batteries, one distributing power to the onboard computer and the other to all other components.

The communication system contains all systems relating to sending data wirelessly to the rover and communication between the ground control station, onboard computer, and microcontroller to manipulate motors based on sensor data.

Mission Constraints

Mission Constraints were outlined based on the Guidebook, budget, and safety considerations to ensure the rover followed the required specifications (Table 1) [3].

Table 1: Constraints Table

Constraints
CT1: The rover shall have replacement parts for all operational mechanisms deemed "prone to failure"
CT2: The rover shall be tested under double the maximum expected load under sustained forces.
CT3: All electronics shall be protected from BP-1 Regolith
CT4: The rover shall not exceed 1.5m length x 0.75m width x 0.75m height at safety inspection and at the start of each competition attempt
CT5: The rover shall not exceed 1.75m in additional height (2.5m above regolith surface) at any point in the competition
CT6: The rover shall not exceed 80 kg of mass
CT7: All subsystem Material and tooling cost shall be under $25,000
CT8: The rover shall perform all operation autonomously
CT9: The single "Kill Switch" shall be a COTS red push-motion button with a minimum diameter of 40mm
CT10: The rover shall use a COTS electronic data logger
CT11: The rover shall not have any components requiring more than 24V
CT12: The rover shall use less than 200Kb/s

Technical Performance Measures (TPMs)

The initial technical performance measures were estimated based on a high level design of all the subsystems and documented in the Initial Technical Budget (Table 2). For the travel, excavation, and construction systems approximations were made based on similar systems from previous years designs. Following review milestones, changes to the initial are reflected in the Final Technical Budget (Table 3).

Table 2: Initial Technical Budget

System	Technical Performance Measurements				
	Mass	Band width	Power Consumption	Capital Cost	Operation Time
Travel	15 kg	-	7 Wh	$1,899	160 s
Excavation	15 kg	-	17 Wh	$4,300	320 s
Construction	5 kg	-	6 Wh	$4,177	120 s
Power	5 kg	-	-	$2,233	-
Communication	5 kg	-	-	$2,889	-

Table 3: Final Technical Budget

System	Technical Performance Measurements				
	Mass	Band width	Power Consumption	Capital Cost	Operation Time
Travel	11 kg	8 kbps	68.3 Wh	$3,324	630 s
Excavation	7.28 kg	4 kbps	31.8 Wh	$4,260	590 s
Construction	40 kg	3 kbps	31.9 Wh	$2,748	580 s
Power	9.3 kg	-	-	$2,673	-
Communication	Mass	-	-	$2,140	-

Mass allocations were increased to reflect an increase in size and heavier materials. Initially bandwidth allocations were negligible as they were too minimal to be measured in previous years. New bandwidth and time allocations were based on each autonomous operation plan. Power consumption was increased to operate heavier and more complex components.

Capital cost allocations were increased due to the increase in funding through grants, donations, and sponsorships. This increase in funding allowed freedom while designing the rover, allowing additional components to be added to the design to make it more efficient and robust.

The placement of the conveyor belt (mentioned later in Preliminary Design & Trade Studies) allows for both the excavation and deposition of the regolith facilitating operations of the excavation and construction systems but in Technical Budget allocations it is considered part of the excavation system to make each allocations exclusive.

Requirements & Engineering Specialties

Requirements were outlined and categorized based on the Guidebook, mission constraints, schedule limitations and budget limitations. initial/ high level requirements were outlined and categorized by system (Table 4) [3]. More specific requirements were derived from the initial level requirements, categorized, and used to guide the design of the rover. Requirements were categorized as Operational (**O**), Performance (**P**), Interface (**I**), Reliability (**R**), Transportability (**T**), and/or Safety (**S**) as indicated in bold before the requirement. Additionally, requirements were labeled if they were Derived (**D**) from a trade study (Tables 5-10).

Table 4: Initial Level Requirements

Travel System
The rover shall be able to traverse throughout the competition field
The rover shall have a reference point arrow
The rover shall be able to be lifted
Excavation System
The rover shall be able to collect regolith material
Construction System
The rover shall be able to construct a berm
Power System
The rover shall turn off with a "Kill Switch"
The rover shall measure and display its power consumption
The rover shall power itself
The battery on board the rover shall be protected
Communication System
The rover shall be able to communicate with the GCS

The computer onboard the rover shall be able to communicate with the sensors and actuators on the rover

Table 5: General/ All System Requirements

General/ All Systems
G1: The rover's components shall be enclosed from dust.
G2: The project shall stay on budget and schedule.
G3: The rover's construction shall provide a valuable learning experience.

Table 6: Travel System Requirements

Travel System
T1: (OP) The rover shall be able to turn 20° in place
T2: (PR) The rover shall be able to turn in place without digging into the ground
T3: (OI) The rover shall be able to climb out of 0.5 cm deep craters
T4: (O) The rover shall be able to go forward and backwards
T5: (O) The rover shall be able to traverse to the berm building zone, excavation zone and construction zone
T6: (OR) The rover shall be capable of navigational planning based on location and obstacles accurate to 5 cm
T7: (PRD) The rover shall be able to localize a maximum distance of 8.5 meters from targets accurate to 5 cm
T8: (P) The rover shall identify obstacles at least 8.5 meters away
T9: (P) The rover shall have a minimum turn radius of 20 cm
T10: (OIR) The rover shall be able to find its location and angle in the competition field (aka localization) in 5 seconds
T11: (P) The rover shall be able to detect all rocks greater than or equal to 10 cm in its path
T12: (P) The rover shall be able to detect all craters greater than or equal to 40 cm in its path
T13: (IT) The rover shall have a central hoist point or sling system based around the rovers center of gravity
T14: (ITs) The rover shall have a minimum of 4 hand lifting points and be lifted by 1 person per 20 kg of mass.
T15: (S) The rover lifting points shall be safe for human hands
T16: (ID) The dust build up inside the rover shall not exceed 200g.

Table 7: Excavation System Requirements

Excavation System
E1: (OP) The rover shall be able to excavate 0.013 m3 of BP1 material
E2: (OPI) The rover shall be able to store 0.021 m3 of excavated BP1 material
E3: (PR) The rover shall measure the amount of material collected. The load shall measure at least 20kg it shall be accurate to at least +/-1kg
E4: (D) The excavation system shall not exceed 18 kg in mass

Table 8: Construction System Requirements

Construction System
CS1: (OP) The rover shall be able to deposit 0.021 m3 of material in the berm zone in 2 minutes
CS2: (O) The rover shall be able to detect the berm status (height, location in berm building zone)
CS3: (O) The rover shall determine if the deposition bin is empty
CS4: (D) The deposition bin shall not exceed 5 kg in weight

Table 9: Power System Requirements

Power System
P1: (OIPSR) The "Kill Switch" shall shut down power to all rover components except the onboard computer and data logger and stop the rover's motion instantaneously and each time when pressed
P2: (OIS) The rover shall measure and display its power usage clearly to the judge
P3: (P) The rover shall not draw more than 70A continuously at a time
P4: (P) The onboard computers, lidar, and cameras shall not draw more than 23.76Wh in 35 mins
P5: (OP) The rest of the rover shall not draw more than 133.2 Wh in 35 mins
P6: (SR) The batteries on the rover shall have reverse polarity protection and fuses to prevent too much power being drawn

Table 10: Communication System Requirements

Communication System
CM1: (OPIR) The rover shall receive a ping in 10-30 ms and be able to move to verify communication by publishing a command through manual control
CM2: (OI) The jetson shall connect to the same router as the GCS and communicate with the teensy
CM3: (O) The rover's wireless communication system shall support ethernet connectivity

<u>CM4</u>: (P) The router shall communicate with the rover at a distance of 12m apart
<u>CM5</u>: (ID) The jetson shall be able to communicate with the sensors and actuators on the rover over I2C
<u>CM6</u>: (D) All parts of the rover shall be under the teams control at all times with commands for every robotic operation including an emergency stop

Concept of Operations (ConOps)

The ConOps were majorly driven by the requirements of the competition and outline the manual and autonomous operation of the rover including states of failure (see **Appendix A**). A manual control system was designed as a safeguard to allow for continuous operation in the event of autonomous operation failure. The ConOps was designed to allow for multiple runs during the competition to maximize the amount of regolith collected.

After passing the RDT and NASA inspection the rover shall test communications and begin competition by initiating autonomous operations. The autonomous control program consists of identifying the starting position, identifying the excavation zone, and moving to the excavation zone while avoiding any detected obstacles. In the excavation zone, the regolith shall be excavated and collected until the rover's storage is full, or if excavating time runs out. Once done, the rover shall switch into the locomotion mode and shall identify and traverse to the construction zone while overcoming any obstacles. Once the berm building zone is identified, the height and distribution of the berm, shall be identified (berm Status). If there is remaining run time, the rover shall return to the digging zone. If the run ends, the rover shall be emptied and set into a transportable position.

Risk Management

Starting in Phase A, risks were identified, assessed, and documented in risk matrices to ensure successful operations were probable (see **Appendix B**). Project risks were scored from 1 to 4 in likelihood and severity and sections of the matrix were colored for low (green), medium (yellow), and high (red) risks.

<u>Phase B:</u> Preliminary Design & Technology Comparison

The purpose of Phase B was to assess the systems' feasibility at completing the mission. System requirements were developed through assessing system interfaces and making an integration plan. A Preliminary Design Review was conducted to assist in those developments.

Preliminary Design Review (PDR)

PDR consisted of a general body meeting and a meeting of technical and systems engineering project leads. The purpose of conducting a PDR is to review the preliminary design and make changes in accordance with the findings. During the PDR, derived requirements were added as highlighted by review and trade studies, research was conducted for each of the subsystems, and allocations for mass, bandwidth, and power consumption were increased due to the increased size of the rover. Based on these changes made, some system prototypes were chosen to be researched further. The schedule was slightly pushed back due to additional time needed for prototyping. Apart from these changes, the budget remained the same. Various systems and ideas were tested, and systems not meeting the requirements were subsequently discontinued.

New Design or Design Update

The system hierarchy takes inspiration from the 2017-2018 rover ORBIT and 2022-2023 rover AMIGO but replaces the excavation/ deposition system with a separate excavation and construction system (Figures 1-2). This was to bring attention to the different requirements of each system and emphasize their interface.

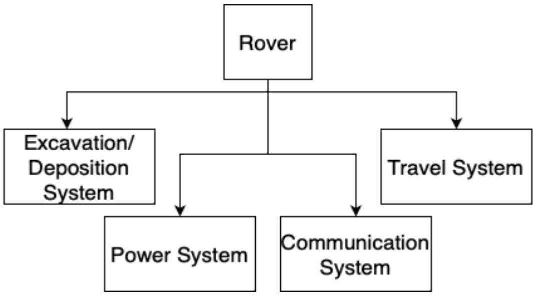


Figure 2: ORBIT (2017-2018) and AMIGO (2022-2023) System Hierarchy

The travel system's wheels are an updated design from the cleated wheels on AMIGO but with shorter cleats and open faces to prevent them from filling with regolith (Figures 3-4).

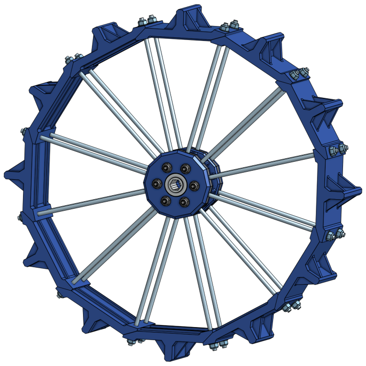


Figure 3: TITAN (2023-2024) wheel.

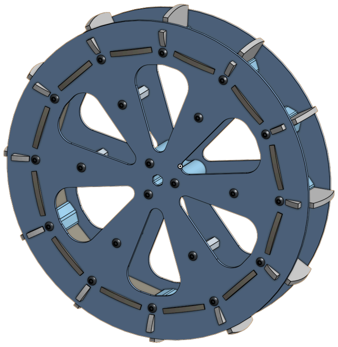


Figure 4: AMIGO (2022-2023) wheel.

The excavation system's conveyor belt shovels take inspiration from ORBIT's shovel lined conveyor belt but with a longer belt due to the larger size constraint (Figure 5). The conveyor belt on ORBIT was primarily used for deposition, had smaller rollers, no shovels, and was not designed to sustain expected forces while excavating. Internal supports were added to increase structural integrity to allow for the design to sustain larger forces and shovels were added to facilitate the collection of regolith.

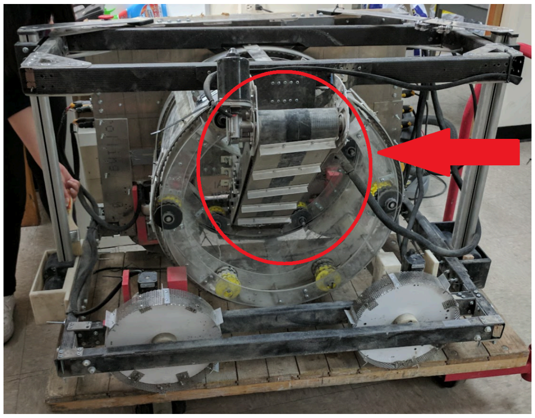


Figure 5: ORBIT (2017-2018) rover.

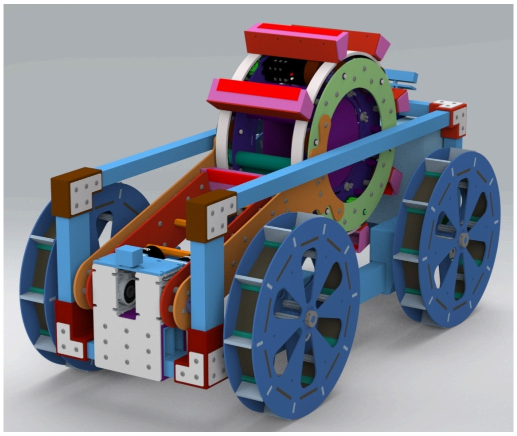


Figure 6: AMIGO (2022-2023) rover.

The excavation system's shovels on the conveyor belt are an updated design of the shovels on the digging drum on AMIGO (Figure 6). Functionally, both designs help to excavate and collect the desired amount of regolith. The major changes include making the shovels double sided to support deposition as well as excavation.

The construction, power, and communication systems all utilize new designs.

Preliminary Design & PDR Trade Studies

I. Travel System

The travel system design includes the chassis and wheels. The chassis is an aluminum frame designed to maximize the internal volume for regolith collection while leaving some external volume for the wheels and cameras within the volume constraint. The wheels were designed to ensure the rover can turn in place without digging into the ground (Table 6: **T1**, **T2**) and be able to climb out of small craters (**T3**).

Table 11: Wheel Design Trade Study

Criteria	**AMIGO**	**TITAN**
Dust Build-up (0.8)	4 - Prone to dust build up in the interior of the wheel	8 - Less dust build up due to having no side plates
Complexity (0.5)	4 - Complex due to tolerances and greater number of parts	8 - Less complex to assemble due to simpler geometry
Structural Integrity (0.9)	6 - Made with polycarb, brittle and prone to breaking	7 - More structurally sound due to the addition of spokes
Cost (0.5)	5 - $442.83	6 - $285.53
Weight	13.1	19.7

To facilitate this, a preliminary spoked wheel designed to help gain traction was proposed and compared to the wheel design from AMIGO in a trade study (Table 11). The weighted metrics used were dust build up, complexity, structural integrity, and cost. The new TITAN wheel was superior in all categories, with less regolith build up due to the elimination of side panels, a lower complexity due to less components and simpler geometry, increased structural stability due to internal spokes, and a lower cost due to the majority of the components being 3D printed. This trade study highlighted the importance of minimizing regolith buildup in the wheels (**T16**).

II. Excavation System

The excavation system design includes the mechanism used for excavating regolith. The chosen conveyor belt design primarily focuses on the ability to excavate and store regolith while minimizing the mass of the system (Table 7: **E1**, **E2**, **E4**). A conveyor belt system was chosen over the digging drum system that was used for the previous year's AMIGO rover as it would more easily distribute the mass, decreasing the resulting moment and placing less stress on the pivot deployment system.

Table 12: Conveyor Belt Trade Study

Criteria	**Polycarbonate Arm**	**Aluminum Box Arm**
Complexity (0.5)	7 - Simpler manual tensioning system	5 - Complex jack-screw system
Cost (0.1)	8 - $348	4 - $815
Mass (1)	8 - 10.5kg	4 - 15kg
Tensioning System Reliability (0.2)	3 - Probable to be tensioned insufficiently	6 - Likely to be tensioned sufficiently
Weight	**12.9**	**8.1**

A trade study compared a conveyor belt with side panels manufactured with polycarbonate and a conveyor belt with side panels manufactured with aluminum box tubes (Table 12). The weighted metrics used were the complexity to manufacture and to assemble, the cost of purchasing the components and manufacturing the conveyor belts, the mass of the conveyor belts, and tensioning reliability. The aluminum conveyor belt had a more reliable tensioning system due to the incorporation of a jack-screw tensioning mechanism. However, the polycarbonate conveyor belt was much lighter than the aluminum conveyor belt, cost far less, and was also less complex due to a simpler tensioning system, which was deemed more critical to operational success (**E1**, **E2**). This trade study highlighted the importance of minimizing mass (**E4**).

III. Construction System

The construction system design includes the deposition bin and the mechanism used to lift it. The bin and scissor lift used to lift it was designed to maximize regolith storage for deposition (Tables 7-8: **E2**, **CS1**).

The placement of the excavation system's conveyor belt allows it to be used for deposition of material. The conveyor belt serves to transport the regolith from the bin to the construction zone by reversing the direction of the belt. The scissor lift allows for the bin to extend to an angle at which the regolith is able to fall onto the conveyor belt, and it was chosen as compared to other options it allows for the maximum angle during construction while minimizing the angle during excavation and locomotion.

IV. Power System

The power system design includes two batteries, one distributing power to the onboard computer and the other to all other powered components, excluding the onboard computer and cameras. The power system also includes a kill switch and power consumption monitor (Table 9: **P1**, **P2**).

A trade study was conducted to decide which communication protocol between the microcontroller and onboard computer. The weighted metrics used to compare protocols I2C and SPI were the number of pins used on the microcontroller, the speed of the communication between the computer and microcontroller, and the complexity of the implementation. Even though SPI with interrupt is faster, the time allotted in the schedule did not permit testing and implementation of a new communication protocol, SPI with interrupt. There was also the uncertainty of potentially installing additional sensors, which limited availability of remaining pins. These factors determined I2C was the better design choice and it became a required part of the system (Table 10: **CM5**).

Table 13: Embedded Communication Protocol Trade Study

Criteria	**SPI with interrupt**	**I2C - one master**
Pin Count (0.9)	2 - At least 5	9 - Always 2
Speed - Computer to Microcontroller (0.5)	6 - Up to 60 Mbps	2 - Up to 400 kbit/s (must get control of the bus first)
Speed - Microcontroller to Computer (0.5)	6 - Extremely small delay to prompt communication, then up to 60 Mbps	2 - Up to 400 kbit/s (must get control of the bus first)
Complexity (0.3)	7 - Simple because alerts from microcontroller are on separate pin	4 - Complex due to need to get control of bus everytime communication is needed
Weight	**9.9**	**11.3**

V. Communication System

The communication system design consists of the Ground Control Station (GCS) laptop, onboard computer, cameras and communication between them (Table 10: **CM1-6**). Communications are outlined in the Communication Architecture Diagram (Figure 8). The system prioritized bandwidth efficiency, reliability, and high-speed communication. In previous rover iterations, such as AMIGO, the Raspberry Pi was utilized as the onboard computer for the rover. However, to prioritize faster data transmission, the Jetson was considered as an alternative onboard computer to the Pi. A Logitech controller was considered as an option for manual control, to improve upon the method of using a keyboard, which involved managing numerous commands.

A trade study was conducted between the potential onboard computers, the Nvidia Jetson and the Pi (Table 14). The primary objective was to assess whether using the Jetson would be more advantageous than using the Pi, which has been used in the past. The trade study aimed to evaluate various factors including cost, computing power, memory bandwidth, and CPU between the two single board computers. The trade studies found that the Jetson possesses higher computing power and therefore is faster than the Pi and would prove more efficient for processing data from the cameras.

Table 14: Single-Board Computer Trade Study

Criteria	**Raspberry Pi 4**	**Jetson Orin Nano**
Cost (0.3)	9- $60	1- $495
Computing Power (0.9)	5- Moderate	8- High
Memory Bandwidth (0.6)	4- Moderate	6- High
CPU (0.5)	3- 64-bit quad-core ARM Cortex-A72	7- 6-core Arm Cortex-A78AE
Weight	**11.1**	**14.6**

Another trade study was conducted between the potential travel autonomy depth cameras, the RealSense D415 and the RealSense D455 (Table 15). The trade study centered on assessing the distinct features of the cameras, analyzing factors such as cost, depth range, complexity, and depth accuracy. In evaluating complexity, it was noted that the D455 camera stands out due to its integrated gyroscope sensor. This feature significantly reduces complexity, particularly in handling transformations for localization. Due to this, the D455 was chosen over the D415.

Table 15: Camera Trade Study

Criteria	**RealSense D455**	**RealSense D415**
Cost (0.2)	3- $419	6- $267
Complexity (0.9)	8- Less complex for calculations due to gyroscope sensor	4- More complex for transformation calculations
Depth Range (0.7)	5- .6 m to 6 m	3- .5 m to 3 m
Depth Accuracy (0.6)	5- <2% at 4 m	3- <2% at 2 m
Weight	**14.3**	**8.7**

Interfaces

The System Interface Diagram describes the interactions between the various systems of the rover with respect to the mechanical, electrical & signal, data, crane mount, and manual control interfaces (Figure 7).

The travel system connects with the excavation, construction, and power systems via mechanical interfaces on the chassis. It interfaces with the excavation system via the pivot point, the construction system via the scissor lift and the power system via the EE/ electrical box. The system also interfaces with the crane via the crane mount on the chassis, allowing for transportation of the rover (Table 6: **T13, T14**).

The power system interacts with the travel, excavation, construction, and communication systems via electrical & signal interfaces. It provides each of those systems with electrical power and signal to control the operation of motors and sensors. This interface can also cut power via a mechanical “Kill Switch” and display power usage (Table 9: **P1, P2**). The EE box is a mechanical interface used to power each system.

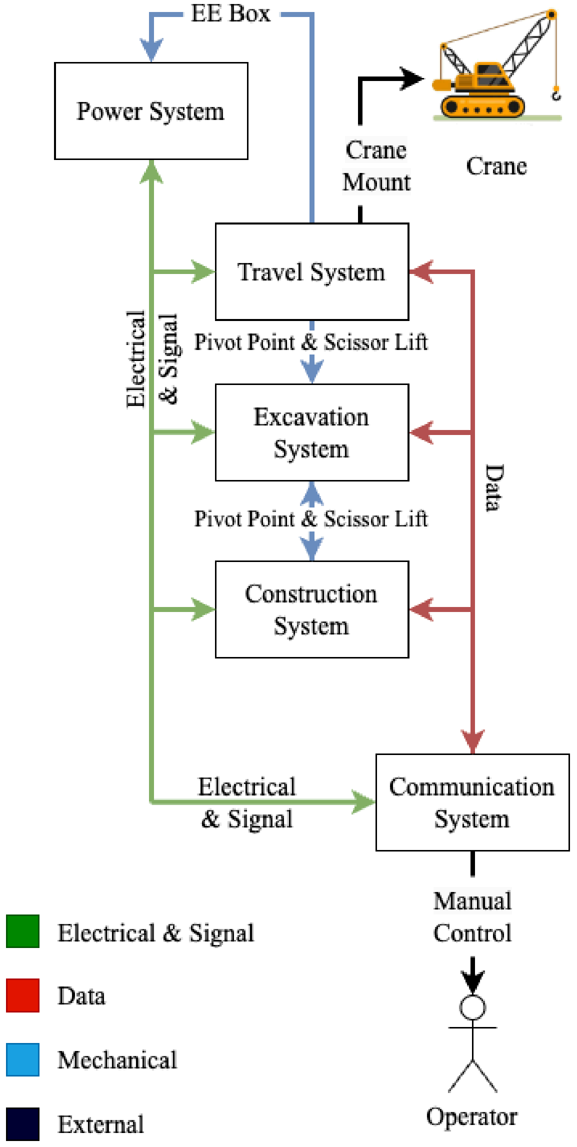


Figure 7: System Interface Diagram

The communication system interacts with the travel, excavation, construction, and power systems via data interfaces. The Ground Control Station transmits commands to the router via ethernet and wirelessly to the microcontroller on the rover, dictating motor and sensor actions (Figure 8, Table 10: **CM2, CM6**). The communication system also interfaces with the rover operator via manual control, granting an external operator control of the rover.

Interfaces influenced the design by being considered in the requirements which are considered during each design review. Interface design changes are expanded on in the Changes to Finalize System Design section.

Autonomous Control Strategy

The autonomous control of the rover was subdivided into three distinct strategies to achieve full autonomy: travel, excavation, and construction. Each strategy was thoroughly outlined with a state diagram (See **Appendix E**) and implemented as a state machine.

Travel autonomy is responsible for traversing the arena. The strategy is a multifaceted operation, involving localization, obstacle detection, and navigational path planning. Localization focuses on accurately determining the rover's location within the arena, without detecting the walls of the competition area (Table 6: **T7**, **T10**). Obstacle detection is centered around identifying and avoiding obstacles, such as craters and boulders (**T8**, **T11**, **T12**). Navigational path planning involves creating a path based on the acquired localization and obstacle data (**T6**).

Two localization strategies were proposed. The initial strategy involved utilizing the RealSense depth camera for both identifying AprilTags and detecting craters. The alternative strategy proposed using two Logitech webcam cameras, one on the front of the rover and one on the back, ensuring continuous localization at all times. For obstacle detection, a trade study was conducted to choose the RealSense D455 depth camera (Table 15). SLAM algorithms and Nav2 (ROS2 Navigation Stack) were considered for path planning.

Excavation autonomy is responsible for digging and collecting regolith in the excavation zone (Table 7: **E1**, **E2**). A load cell and infrared sensor were considered to measure the amount of the material collected in the deposition bin, which would prove helpful for both excavation and construction autonomy (**E3**).

Construction autonomy is responsible for moving collected regolith on the rover to deposit it into a berm (Table 8: **CS1**). To measure the height of the berm the RealSense D455 depth camera was considered (**CS2**). To sense if the bin was empty, and measure the angle of the bin, a hall effect and a rotary encoder sensor (respective) were considered (**CS3**).

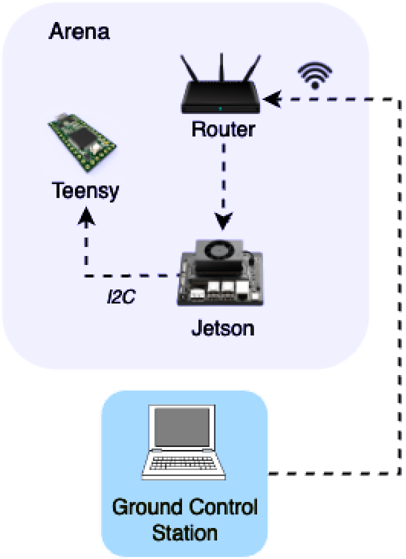


Figure 8: Communication Architecture Diagram

<u>Phase C:</u> Final Design & Fabrication

The purpose of Phase C was to fabricate the rover and develop necessary code to meet the mission requirements (Tables 4-10). A Critical Design Review was conducted to preliminarily verify the final design met the mission requirements through ongoing trade studies involving part and system specification comparisons and the construction of prototypes. Some elements of the previous phases were revisited as systems needed to be changed to fit the requirements.

Critical Design Review (CDR)

The critical design review consisted of a general body meeting and then a meeting with the technical leads and the systems engineers of the team. The purpose of the CDR was to review the design against the system requirements and to verify that the design satisfied the requirements. During the CDR the system requirements were refined to better reflect the goals to be achieved and design changes were made accordingly. Additionally, a few more requirements were added as needed to fully define the goal of the design. Changes in the requirements and verification of the design resulted in a few design modifications. The schedule was modified to allow for more time to complete these design changes. More funding was acquired so the allocations in the cost budget were increased. TPMs were modified as follows: an increase in mass, refined time allocations, and a more reasonable power consumption allocation. Due to additional funding received during this period, these changes were accommodated without having to make major changes to the budget.

Changes to Finalize System Design

The final design explained here utilizes feedback from all three design reviews but is in a state prior to most verification and validation testing. It builds upon the design primarily explained in the Preliminary Design & Trade Studies and the Autonomous Control Strategy sections.

I. Travel System

The final travel system design consists of 4 wheels attached to an aluminum chassis. The wheel design consists of a 3D printed outer ring, steel spokes, and a 3D printed hub, assembled together using aluminum plates to hold the spokes in place. The CDR highlighted that this system is required to be able to support the mass of the rover which influences slight changes in its geometry and the 3D printing plastic chosen (Table 6: **T17**).

For the final localization autonomy, the method of relying solely on the RealSense camera compromised rover localization, so the second strategy of utilizing two Logitech webcams was chosen. Four rotary encoders will also be on each wheel to provide motion feedback. Fiducial markers will be used as the primary method for the robot to localize itself, with three markers strategically placed on each side of the berm box within the construction zone, and an additional marker positioned in the starting zone.

The RealSense D455 camera and the LiDAR will be positioned on the front of the rover. The RealSense will be angled downward to detect smaller boulders and craters, while the LiDAR's 360 degree single beam will detect boulders.

Gazebo and RViz are to be integrated with Nav2, a collection of software packages integrated with ROS2 to create a path based on obstacle and localization data.

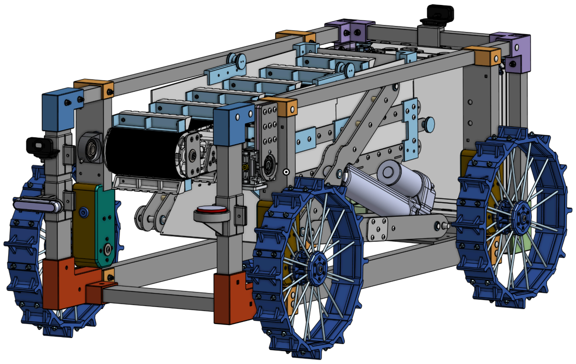


Figure 9: Locomotion/ Travel Position

II. Excavation System

The excavation system's conveyor belt was modified to satisfy the requirements after the CDR review identifying its mass as an issue (Table 7: **E4**).

The changes made to the conveyor belt focused on decreasing the mass by changing the material of the arms from aluminum to polycarbonate, reducing the mass by 30%. Furthermore, by adding cutouts to the conveyor pulleys and reducing the infill, the mass further reduced by 10% to meet the mass requirement (**E4**).

The final excavation strategy remained the same but operations were adjusted slightly for changes in the physical design.

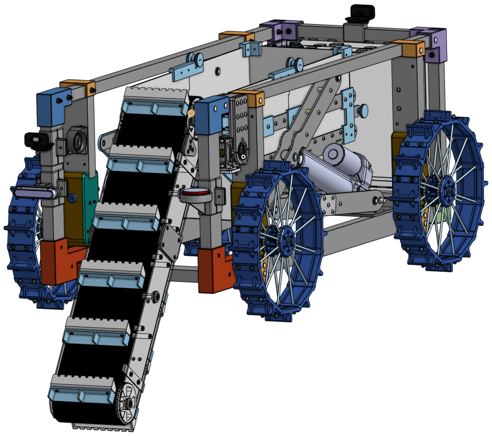


Figure 10: Excavation Position

III. Construction System

Design changes were made to the construction system's implementation of the deposition bin and scissor lift to satisfy the requirements.

The changes made to the deposition bin focused on fully containing the conveyor belt during transportation to adhere to NASA's dimensional constraints (Table 1: **CT4**, **CT5**). The geometry of the bin was changed from a wedge shape to a rectangular box, allowing for storage of the belt and an increase in the amount of regolith stored from 0.021 m^3 to 0.048 m^3 to better satisfy the deposition requirement (Table 8: **CS1**). A trade study was conducted post CDR to help determine the optimal geometry and material composition for the bin (Table 15). The volume, mass and the manufacturing complexity and structural integrity were the parameters compared. Apart from the geometries the major difference between the two designs were the materials used to manufacture - the triangular design used aluminum while the rectangular one used polycarbonate. Using polycarbonate directly influenced the overall weight and functionality of the bin. These factors were deemed more vital to mission operations, and the trade study highlighted the importance of minimizing the mass of the deposition bin (Table 8: **CS4**).

Table 15: Deposition Bin Geometry Trade Study

Criteria	**Triangular Aluminum Deposition Bin**	**Rectangular Polycarbonate Deposition Bin**
Volume (1)	4 - 0.0198 m3	8 - 0.0485 m3
Mass (0.7)	3 - 8.895 kg	7 - 4.139 kg
Complexity (0.2)	3 - Triangular geometry more difficult to assemble	5 - Rectangular geometry has readily available complementary components
Structural Integrity (0.5)	6 - more structurally stable due to aluminum composition	4 - less stable due to polycarbonate composition
Weight	**9.7**	**15.9**

The changes made to the scissor lift system from previous iterations focused on maximizing the height which the bin can extend to maximize material deposition (Table 8: **CS1**). Previously, the scissor lift consisted of a linear actuator on a scissor lift which was attached to the bottom of the bin. To allow for the use of larger linear actuators, which increased the height and the mass it can carry, the number of linear actuators was increased to two, and the scissor lifts were attached to the sides of the bin.

In the final construction autonomy strategy remained the same but operations were adjusted slightly for changes in the physical design.

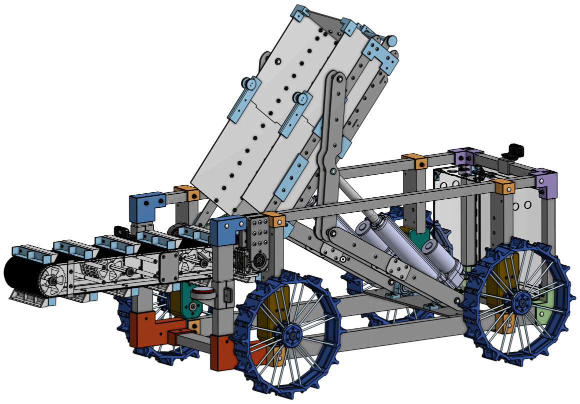


Figure 11: Deposition/ Construction Position

IV. Power System

The major changes to the power system were a result of additional attention to safety and dust proofing after the CDR.

Many safety precautions were implemented on the relay board to provide a visual indication whenever any of the batteries have low voltage or are connected in reverse polarity (Table 9: **P6**). This feature promises reliability of battery sources while the rover is operating.

The components inside the box are kept safe from regolith interference through dustproof connectors, which still allows signal and data transmission to each component outside the box (Table 5: **G1**).

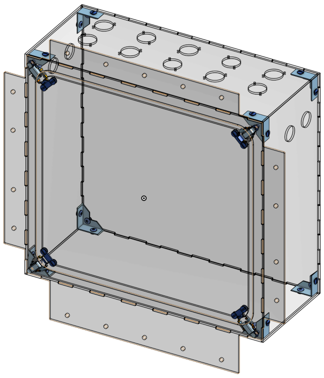


Figure 12: Electrical Box/ EE Box

V. Communication System

The communication system continues as the design changes to optimize operations. After the CDR several "actions" were added to the control scheme to allow for more control of the rover.

The details of the communication system developed after the CDR since the changes to the other systems' design have slowed. Wireless communication with the rover was achieved on Linux Ubuntu by employing a variety of open-source software packages, including ROS2 (Robot Operating System 2). To optimize bandwidth efficiency, manual control commands are to be restricted to a single byte (Table 1: **CT12**). An Xbox controller is to be used for manual control to make driving controls more intuitive (Table 10: **CM6**). While a Logitech controller was initially considered, testing and research found that the Xbox controller's compatible libraries were easier to use. With the Xbox controller, two distinct profiles are to be configured to accommodate all commands, allowing for seamless switching.

Phase D: System Assembly, Integration, Test, and Launch (SAITL)

The purpose of the ongoing Phase D is to tune the final rover assembly through testing to verify and validate the system requirements.

Verification of System Meeting Requirements

System verification was performed to ensure the rover met the requirements and was documented in verification tables simplified for **Appendix C**. Many system verification tests were performed in a sand replication of some competition scenario at a local beach.

To verify software operations Data from both the depth camera and the LiDAR were simulated in RViz, a ROS visualization software as well as with Gazebo, an environment simulation software. The rover and competition arena were also constructed in Gazebo to facilitate realistic competition testing (Figure 13).

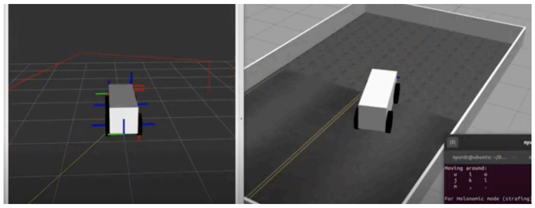


Figure 13: Simulated Locomotion on RViz and Gazebo

Validation of System Meeting Requirements

System validation will be conducted to ensure that meeting the verified requirements translates to successful performance at the Lunabotics Competition. Systems are to be validated by reconstructing the competition arena to scale, and testing a continuous 15 or 30 minute round of operations.

Project Management

Project managers worked diligently to manage the team effectively. The triple constraints—scope, time, and cost—were carefully evaluated in creating the project schedule. The adoption of scrum methodology helped the team practice an agile mindset and pivot whenever necessary. In Pre-Phase

A, the project schedule was designed to have 10 sprints, each lasting 2-4 weeks, with a sprint review and retrospective planned at the end of each sprint.

In terms of cost, the budget was initially set at $36k with a breakdown of $35k provided to us from university departments with an additional $1000 from the previous year of our Rising Violets Fundraising Project. Every expense was categorized by the competency which made the expense, the impact to the competency's budget, detail of the necessary equipment/supplies, and the justification for each purchase.

To facilitate success of the project, each planned milestone included opportunities to accommodate any encountered issues.

Schedule of Work

Our goal in regards to schedule planning was to implement a detailed project schedule to mitigate potential risks of regressions in our project cycle due to technology, design, or fabrication shortfalls. The initial schedule was projected during the Systems Requirement Review (SSR). Since the Team in previous seasons experienced project setbacks, it was important to include buffer time in the schedule. Our initial schedule, shown in Appendix D Figure D1, for example, allocated November for prototyping and planned to begin manufacturing in December. However, due to challenges such as machine accessibility, design flaws identified during preliminary and critical design reviews, and the need for a major revision to our software strategy, the project schedule had to be revised. These adjustments, shown in Figure D2, reflect our current schedule to meet our high-level objectives.

Our project schedule established a framework for reaching key milestones, including a System Requirement Review (SRR), Preliminary Design Review (PDR), Critical Design Review (CDR), and All Team Meetings. These milestones and meetings were crucial for discussing each competency area's responsibilities and for making any necessary adjustments to keep the project on track. This approach allowed the project to either progress to the next milestone or pause to reassess and realign as needed.

In these All Team Meetings, the scrum methodology emphasized transparency from each competency group about their current project phase, accomplishments at the end of the sprint, and upcoming plans. This strategy ensured that all team members were informed about the progress and future plans, facilitating the organization of project tasks and prioritization of essential work. For instance, the electrical team was tasked early in the season with revitalizing last season's rover. They made notable progress in the first two sprints, but encountered a wiring issue in the third sprint. The following sprint saw inventory challenges that caused minor delays and unexpected expenses due to the need for replacement parts. Similarly, the mechanical team implemented a major design change in the rover's locomotion system, switching to steel rods and affecting the project's budget.

This initial schedule served not only as a roadmap for achieving the project's objectives but also as a flexible plan that could adapt to unforeseen challenges. Changes to the schedule were informed by our iterative reviews and the scrum methodology. This allowed us to manage the project effectively, addressing issues such as the electrical team's wiring problems and the mechanical team's design pivot, which necessitated budget adjustments.

Our project schedule has changed over the season as a result of project challenges. In October, upon

review of the UCF's Lunabotics Guidebook, the team's software strategy had to be revised to account for the differences between the UCF and KSC arenas [5]. In December, around the CDR, the team was one month behind schedule on manufacturing as a result of limited accessibility to NYU's 3D printing machines. This set back helped determine the high priority of acquiring 3D printers of good quality which also impacted our cost budget.
Furthermore, in accordance with the Project Management Plan (PMP), prototyping was initially scheduled from October to November, with manufacturing set from December to March. However, the project unfolded differently. First, during the Preliminary Design Review on October 22nd, there were design issues that necessitated pushing back the start of prototyping by one month. Then, the Critical Design Review on December 10th brought significant design changes that additionally prevented us from starting manufacturing. These revisions were compounded by the realization that the scope of necessary 3D printing couldn't be met solely with NYU's machines, prompting us to acquire two team-owned 3D printers. This sequence of adjustments, made in response to new information about our location sites and insights from the reviews, allowed us to identify and address these challenges, leading to a revised schedule for prototyping and manufacturing.

Cost Budget

The tracking and maintaining of cost budget allowed the competencies to make informed decisions and to prioritize cost-effective purchases. The initial cost budget was estimated during the Systems Requirement Review (SRR). Afterwhich cost budget was regularly reviewed during the All Team Meetings.
In each sprint, every purchase made by our team was tracked via a Bill of Materials formatted on Google Sheets, organized by competency. The document allowed each competency to track their spending according to their allocated budget (derived from the operational budget).

At the start of our competitive season, the team received $30,000 in funding from NYU's Vertically Integrated Program and projected an additional $5,000 grant from the Electrical and Computer Engineering department amounting to a total of $35,000. In addition, with the team's previous fundraising campaign, Rising Violets, the team had an additional $1,000. Thus, with a total initial project cost budget totaling to $36,000, the initial cost budget, created at the time of the SRR, divided into $22,500 for an operational budget, $8,000 for a competition travel budget, and $3,500 into a non-operational/emergency budget in September. The operational budget was then allocated to each competency based on the competency's previous season's spending history and the expected needs of each competency as seen in Table 16.

Table 16: Initial Operational Cost Budget

Operational Expenses	Initial Budget
Mechanical	$12,500.00
Electrical	$3,702.52
Software	$2,793.61
Marketing & Finance	$1,239.78
Outreach	$1,000.00
Travel for Testing	$840.00
Emergency Operational	$424.09
Total Operational Expenses	**$22,500**

The current operational cost budget can be seen in Table 17.

Table 17: Current Operational Cost Budget

Operational Expenses	Initial Budget
Mechanical	$9,794.45
Electrical	$2,440.36
Software	$2,034.38
Marketing & Finance	$640.96
Outreach	-
Travel for Testing	-
Emergency Operational	-
Total Operational Expenses	**$15,144.81**

Our initial cost budget estimation, predicted most months' spending to be between $1,000 to $3,000 as detailed in the initial cost budget in Appendix D Table D1. This would be when the rover was predicted to be fully constructed.

Unexpectedly, the team did not begin spending until the 3rd sprint as seen in Appendix D Table D2 so there was no change in the budget at the time of the PDR. This allowed us to be more flexible on our two 3D printer purchases in December, after the CDR, to help save on manufacturing costs and time via decreased manufacturing time and increased production quality. Not having to rely on shared 3D printers increased reliability and allowed the team to achieve technical requirements, essentially staying under the mass constraints without compromising the strength (Table 1: **CT6**). This also reduced prototyping time, helping the team review and test system requirements more efficiently.

As for the travel cost budget, given the number of members in the team, and the competition overlapping with the university's commencement and finals, the original allocated budget of $8,000 was not sufficient to cover all expenses for UCF and KSC Lunabotics competition rounds. This led us to apply and successfully acquire a $5,000 department grant for additional funds for travel. Following a major review with the financial advisor of the Vertically Integrated Department, information for funding was fully broken down to us. The team had additional unused funds from 2023, which included a $5,000 grant. Our travel budget increased from $8,000 to $18,000 as a result of the grants, the breakdown of which can be seen in Table 18. The new total budget for the project increased to $40,500.

Table 18: Travel and Shipping Costs

Travel Expenses	
UFC Travel	$3,500.00
UFC Housing	$2,200.00
KSC Travel	$3,500.00
KSC Housing	$2,200.00
Shipping	$3,400.00
Rental Cars and Gas	$2,500.00
Total Travel Expenses	**$17,300.00**

Part of competition expenses included rover shipping and materials to build a shipping crate. Both were initially projected expenses for the mechanical competency's operational budget; however, with the additional travel funds, these operational expenses could now be covered by the new travel budget allowing the mechanical competency to freely use the projected $3000 expense for other needs. This, in turn, reduced manufacturing delays due to the new financial flexibility of acquiring more resources. An additional $300 was reallocated to the mechanical competency from the outreach competency based on the needs of the competencies as the schedule progressed. Having additional funds also led to a change in technical performance measures (TPMs), since more funds were added to each subsystem. The evolved budget hence made it possible to prototype additional designs while allowing the mechanical competency to consider materials of better quality for each subsystem.

Conclusion

Following the systems engineering process as defined in NASA’s Systems Engineering Handbook, NYU’s Robotic Design Team designed a successful berm building lunar rover to compete in NASA’s Lunabotics competition [1]. Phase E Operations and Sustainment will take place during the two rounds of competition at the UCF and KSC as defined in the corresponding guidebooks [5][3].

Appendix A: ConOps

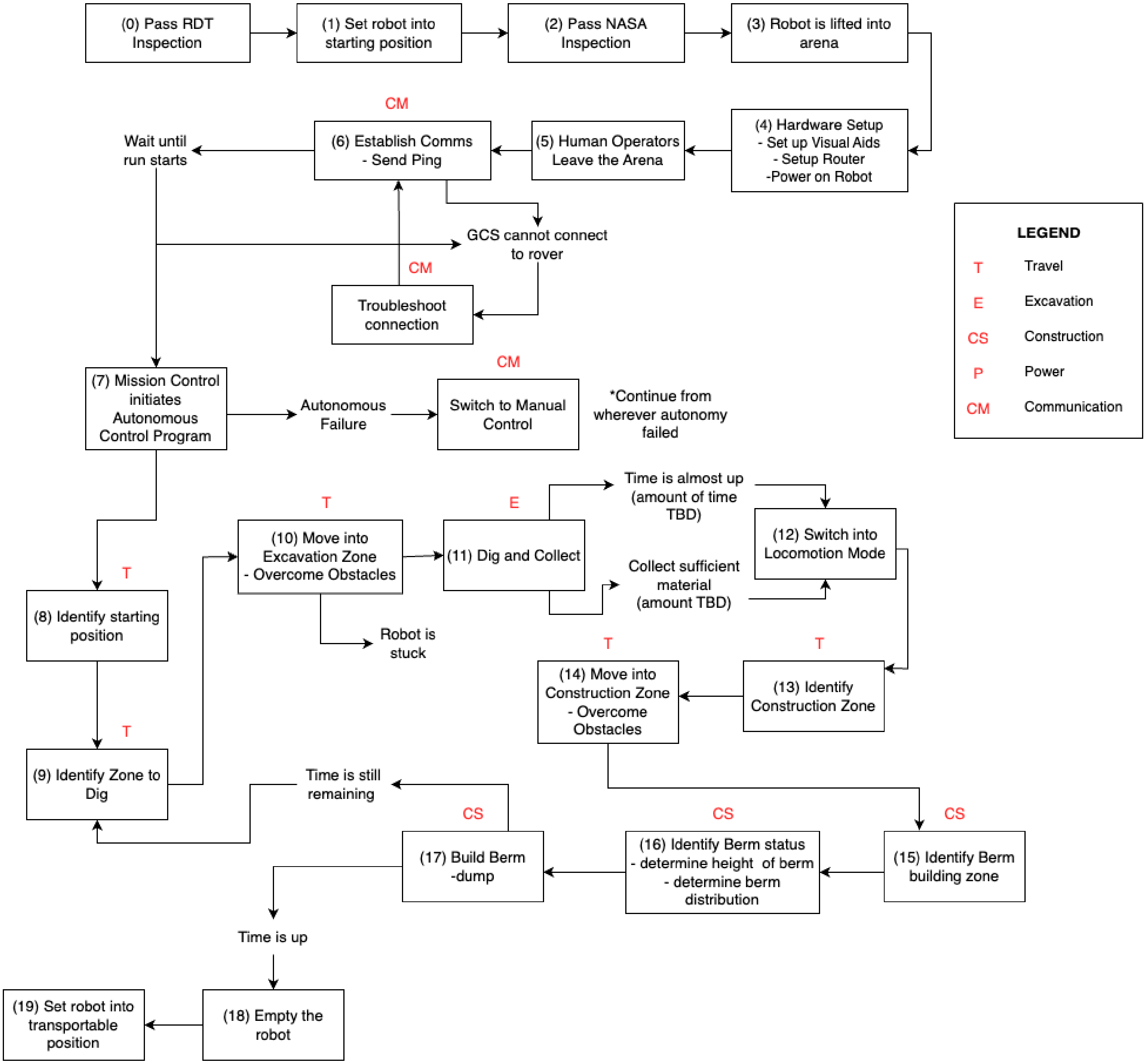
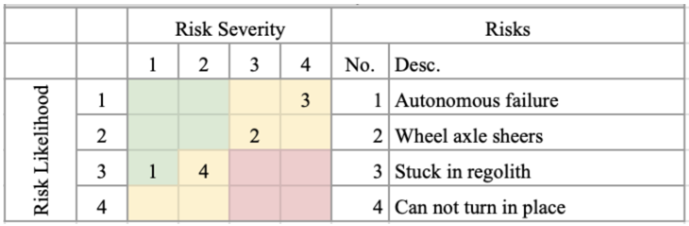


Figure A1: ConOps

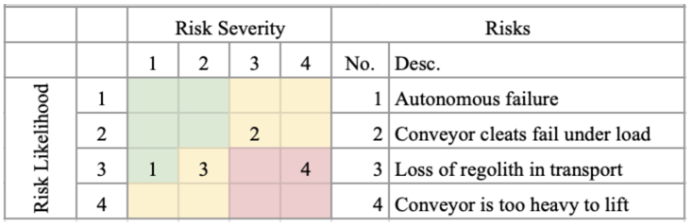
Appendix B: Risk Tables

Table B1: Travel System Risks



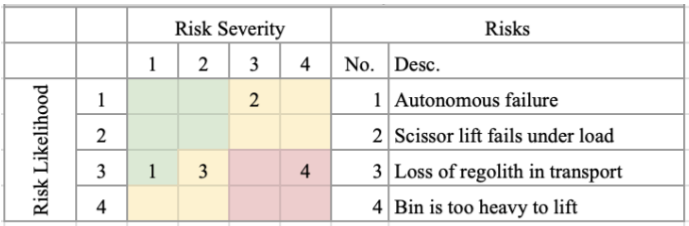
		Risk Severity				Risks	
		1	2	3	4	No.	Desc.
Risk Likelihood	1				3	1	Autonomous failure
	2			2		2	Wheel axle sheers
	3	1	4			3	Stuck in regolith
	4					4	Can not turn in place

Table B2: Excavation System Risks



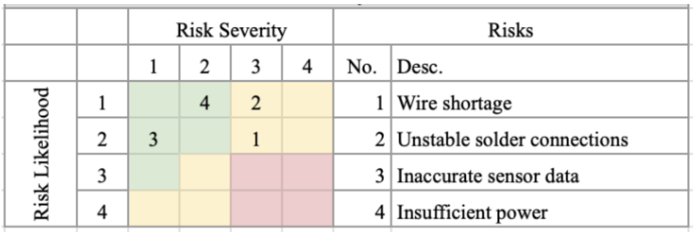
		Risk Severity				Risks	
		1	2	3	4	No.	Desc.
Risk Likelihood	1					1	Autonomous failure
	2			2		2	Conveyor cleats fail under load
	3	1	3		4	3	Loss of regolith in transport
	4					4	Conveyor is too heavy to lift

Table B3: Construction System Risks



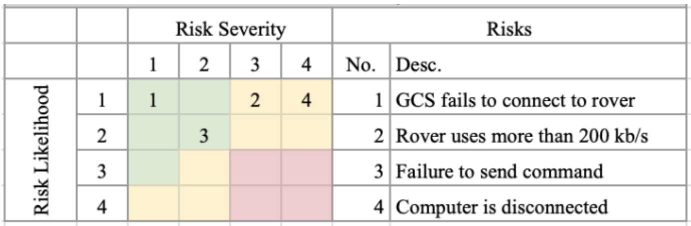
		Risk Severity				Risks	
		1	2	3	4	No.	Desc.
Risk Likelihood	1			2		1	Autonomous failure
	2					2	Scissor lift fails under load
	3	1	3		4	3	Loss of regolith in transport
	4					4	Bin is too heavy to lift

Table B4: Power System Risks



		Risk Severity				Risks	
		1	2	3	4	No.	Desc.
Risk Likelihood	1		4	2		1	Wire shortage
	2	3		1		2	Unstable solder connections
	3					3	Inaccurate sensor data
	4					4	Insufficient power

Table B5: Communication System Risks



		Risk Severity				Risks	
		1	2	3	4	No.	Desc.
Risk Likelihood	1	1		2	4	1	GCS fails to connect to rover
	2		3			2	Rover uses more than 200 kb/s
	3					3	Failure to send command
	4					4	Computer is disconnected

Appendix C: Verification Tables

Table C1: Travel System Verification

Requirement	Verification Success Criteria	Verification Method	Results
T5: (O) The rover shall be able to traverse to the berm building zone, excavation zone and construction zone	The rover is able to move from one point, over an uneven sandy terrain	Test in sand arena	Success as defined
T3: (OI) The rover shall be able to climb out of 0.5 cm deep craters*	The wheels are able to get the rover out of the 0.5cm deep craters	Test in sand arena	Success as defined
T16: (ID) The dust build up inside the rover shall not exceed 200g**	The dust build up in the wheels is less than or equal to 200 g	Test in sand arena	Success as defined to be reevaluated as design develops

*Verifies strength of mechanical interfaces (pivot, EE box, and scissor lift)

**Verifies dust proofing of mechanical interfaces (pivot, EE box, and scissor lift)

Table C2: Excavation System Verification

Requirement	Verification Success Criteria	Verification Method	Results
E1: (OP) The rover shall be able to excavate 0.013 m3 of BP1 material	The rover is able to excavate 0.013 m3 or more of BP1 material	Testing in sand arena	Unverified
E2: (OPI) The rover shall be able to store 0.021 m3 of excavated BP1 material*	The rover shall be able to store 0.021 m3 of excavated BP1 material	Testing in sand arena	Unverified
E4: (D) The excavation system shall not exceed 18 kg in mass	The excavation system shall weigh 18 kg or less.	Measuring the mass of the conveyor belt system after manufactured	Unverified

*Verifies regolith transfer over the pivot (between excavation and construction systems)

Table C3: Construction System Verification

Requirement	Verification Success Criteria	Verification Method	Results
CS1: (OP) The rover shall be able to deposit 0.021 m3 of material in the berm zone in 2 minutes	The deposition bin can lift a minimum of 0.021m3 of material and deposit it.	Load deposition bin with sand and deposit in sand arena	Unverified
CS2: (O) The rover shall be able to detect the berm status (height, location in berm building zone)	The rover shall differentiate between low, medium, and high elevation berms.	The depth camera shall point at a mound and data from the onboard computer will be monitored.	Unverified
CS3: (O) The rover shall determine if the deposition bin is empty	The rover shall differentiate between an empty and full bin.	Empty and at least 2 kg of material filled bin will be tested.	Unverified

Table C4: Power System Verification

Requirement	Verification Success Criteria	Verification Method	Results
P1: (OIPSR) The kill switch shall turn off all components on the rover*	The multimeter indicates 0 voltage and moving components stop immediately.	Press the kill switch and check the voltage.	Success as defined to be reevaluated as design develops
P2: (OIS) & P5: (OP) The rover shall measure and display power consumption and shall not exceed 133.2Wh in 35 min*	The power consumption data from the power meter for the whole run should be below 133.2Wh	Measure the total power usage of the whole rover while in operation with power meter.	Unverified
P6: (SR) The batteries on the rover shall have reverse polarity protection	The relay board will continue to relay power	Connect a battery in reverse polarity.	Success as defined
P6: (SR) The rover shall have fuses to prevent too much power being drawn	The fuses will melt when the threshold overcurrent is attained.	Supply a current higher than 20A.	Success as defined

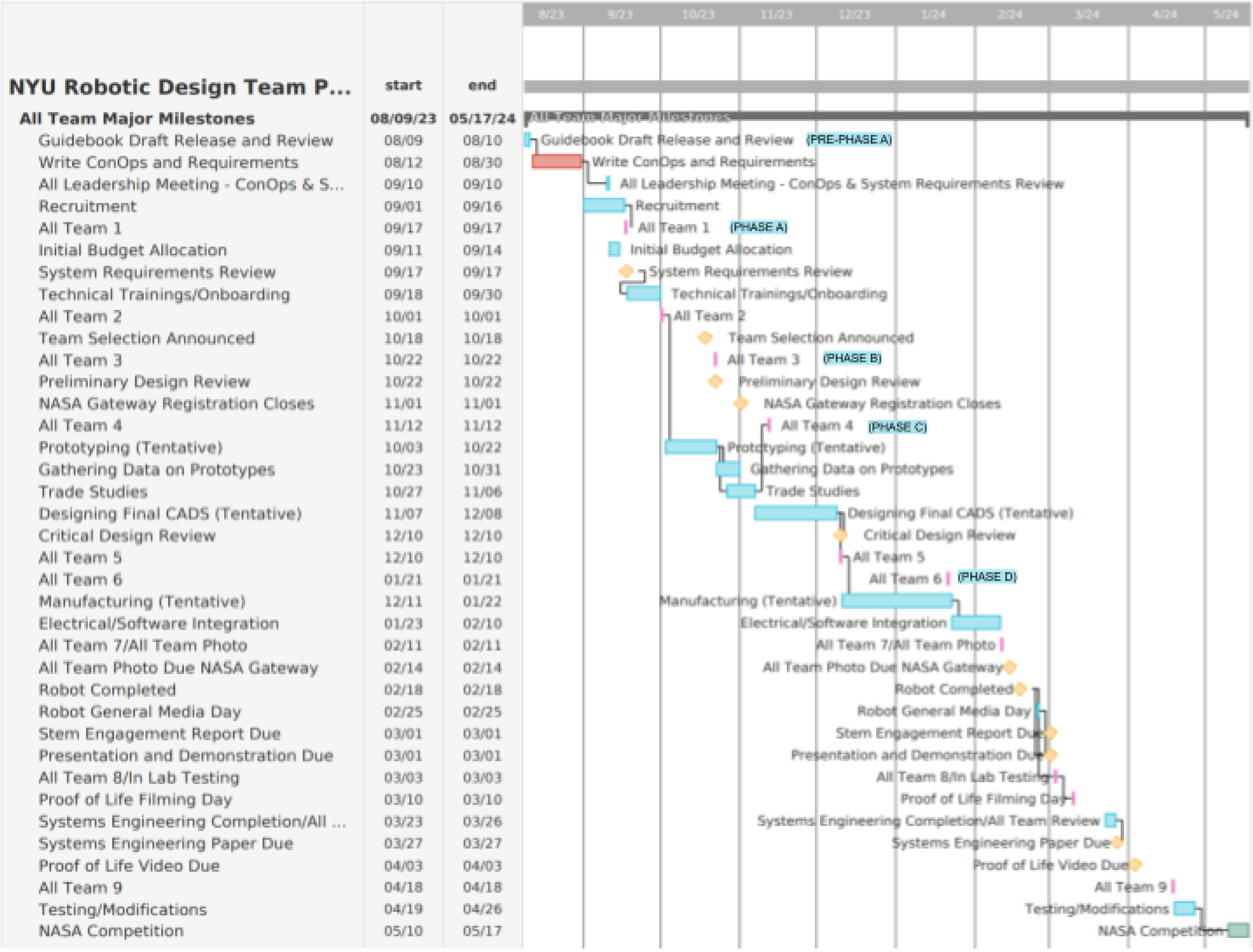
*Verifies power transfer and safe power cut off over the electrical interface between the power system and all other systems

Table C5: Communication System Verification

Requirement	Verification Success Criteria	Verification Method	Results
CM1: (OPIR) The rover shall verify communication by publishing a command*	The GCS transmits commands to the rover, which interprets and executes an action	Test manual control	Success as defined to be reevaluated as design develops
CM4: (P) The router shall communicate with the rover at a distance of 12m apart	The GCS can successfully send and receive data at a minimum of 12m distance apart from the rover	Testing manual control across various distances	Success as defined
CT12: The rover shall use less than 200Kb/s	Manual control shall remain under 12kbps	Test bandwidth of manual control	Averaged 10.4kbps for a basic one-to-one communication exchange
CM3: (O) The rover's wireless communication system shall support ethernet connectivity	The GCS shall be able to communicate to the rover through ethernet	Check to see if the network is connected and reliable	Success as defined

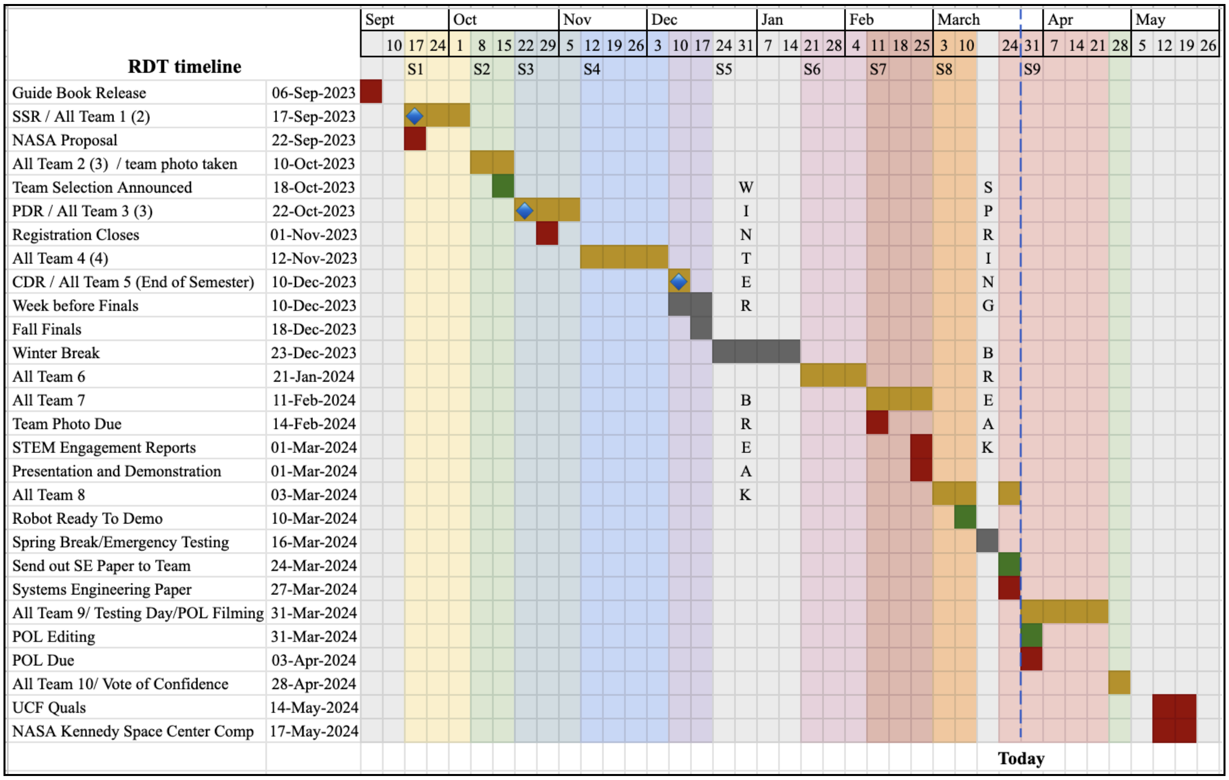
*Verifies data transfer over the data interface between communication system and all other systems

Appendix D: Project Management



NYU Robotic Design Team P...	start	end
All Team Major Milestones	**08/09/23**	**05/17/24**
Guidebook Draft Release and Review	08/09	08/10
Write ConOps and Requirements	08/12	08/30
All Leadership Meeting - ConOps & S...	09/10	09/10
Recruitment	09/01	09/16
All Team 1	09/17	09/17
Initial Budget Allocation	09/11	09/14
System Requirements Review	09/17	09/17
Technical Trainings/Onboarding	09/18	09/30
All Team 2	10/01	10/01
Team Selection Announced	10/18	10/18
All Team 3	10/22	10/22
Preliminary Design Review	10/22	10/22
NASA Gateway Registration Closes	11/01	11/01
All Team 4	11/12	11/12
Prototyping (Tentative)	10/03	10/22
Gathering Data on Prototypes	10/23	10/31
Trade Studies	10/27	11/06
Designing Final CADS (Tentative)	11/07	12/08
Critical Design Review	12/10	12/10
All Team 5	12/10	12/10
All Team 6	01/21	01/21
Manufacturing (Tentative)	12/11	01/22
Electrical/Software Integration	01/23	02/10
All Team 7/All Team Photo	02/11	02/11
All Team Photo Due NASA Gateway	02/14	02/14
Robot Completed	02/18	02/18
Robot General Media Day	02/25	02/25
Stem Engagement Report Due	03/01	03/01
Presentation and Demonstration Due	03/01	03/01
All Team 8/In Lab Testing	03/03	03/03
Proof of Life Filming Day	03/10	03/10
Systems Engineering Completion/All ...	03/23	03/26
Systems Engineering Paper Due	03/27	03/27
Proof of Life Video Due	04/03	04/03
All Team 9	04/18	04/18
Testing/Modifications	04/19	04/26
NASA Competition	05/10	05/17

Figure D1: Initial Project Schedule



RDT timeline	
Guide Book Release	06-Sep-2023
SSR / All Team 1 (2)	17-Sep-2023
NASA Proposal	22-Sep-2023
All Team 2 (3) / team photo taken	10-Oct-2023
Team Selection Announced	18-Oct-2023
PDR / All Team 3 (3)	22-Oct-2023
Registration Closes	01-Nov-2023
All Team 4 (4)	12-Nov-2023
CDR / All Team 5 (End of Semester)	10-Dec-2023
Week before Finals	10-Dec-2023
Fall Finals	18-Dec-2023
Winter Break	23-Dec-2023
All Team 6	21-Jan-2024
All Team 7	11-Feb-2024
Team Photo Due	14-Feb-2024
STEM Engagement Reports	01-Mar-2024
Presentation and Demonstration	01-Mar-2024
All Team 8	03-Mar-2024
Robot Ready To Demo	10-Mar-2024
Spring Break/Emergency Testing	16-Mar-2024
Send out SE Paper to Team	24-Mar-2024
Systems Engineering Paper	27-Mar-2024
All Team 9/ Testing Day/POL Filming	31-Mar-2024
POL Editing	31-Mar-2024
POL Due	03-Apr-2024
All Team 10/ Vote of Confidence	28-Apr-2024
UCF Quals	14-May-2024
NASA Kennedy Space Center Comp	17-May-2024

🔷	Systems Engineering Review
🟨	Sprint Duration
🟥	Deadlines and Deliverables
🟩	Team Deadlines
⬛	Voluntary Sprints

Figure D2: Current Project Schedule

Table D1: Initial Projected Operational Cost Budget

		Prototyping		Manufacturing				
	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER	JANUARY	FEBRUARY	MARCH	
System Heirarchy Expenses								
Excavation	$ -	$ -	$ 400.00	$ 2,400.00	$ 1,500.00	$ -	$ -	
Power	$ -	$ 1,080.00	$ 47.98	$ 392.50	$ 588.36	$ 101.97	$ 21.78	
Travel	$ 498.99	$ 400.00	$ -	$ -	$ 600.00	$ 400.00	$ -	
Communication	$ 2,200.63	$ -	$ 371.56	$ 316.94	$ -	$ -	$ -	
Construction	$ 1,714.45	$ 62.96	$ 1,300.00	$ 600.00	$ 500.00	$ -	$ -	
Total	$ 4,414.07	$ 1,542.96	$ 2,119.54	$ 3,709.44	$ 3,188.36	$ 501.97	$ 21.78	**$ 15,498.12**

Table D2: Current Operational Cost Budget

		Prototyping				Manufacturing			
	Sprint 1	Sprint 2	Sprint 3	Sprint 4	Sprint 5	Sprint 6	Sprint 7	Sprint 8	Total
System Heirarchy Expenses									
Excavation	$ -	$ -	$ -	$ 1,100.12	$ 1,950.65	$ -	$ 1,209.00	$ -	$ 4,259.77
Power	$ -	$ -	$ -	$ 1,203.44	$ 402.90	$ 1,066.70	$ -	$ -	$ 2,673.04
Travel	$ -	$ -	$ -	$ 2,141.12	$ 1,077.00	$ -	$ 105.50	$ -	$ 3,323.62
Communication	$ -	$ -	$ 1,163.53	$ 862.40	$ 8.45	$ -	$ 105.97	$ -	$ 2,140.35
Construction	$ -	$ -	$ -	$ 589.02	$ 1,403.67	$ 485.63	$ 269.71	$ -	$ 2,748.03
Total	$ -	$ -	$ 1,163.53	$ 5,307.08	$ 3,439.00	$ 1,066.70	$ 1,420.47	$ -	**$ 15,144.81**

Appendix E: Autonomy

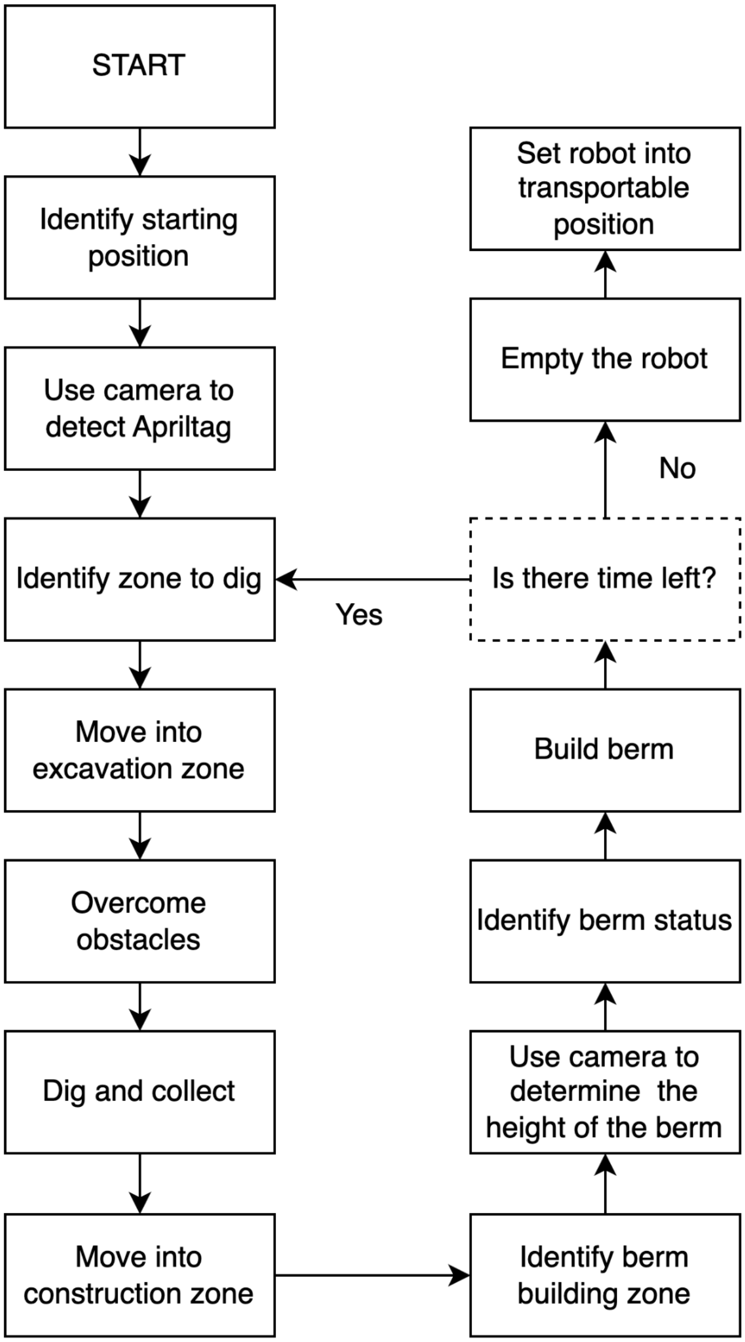


Figure E1: General Autonomy Diagram

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[3] National Aeronautic and Space Administration (Sept. 12, 2023). *2024 NASA Lunabotics Challenge Guidebook.*

[4] National Aeronautic and Space Administration (Sept. 1, 2023). *Lunabotics 2024 Frequently Asked Questions (FAQ)*. Retrieved from **https://www.nasa.gov/wp-content/uploads/2023/09/faqs-01.pdf?emrc=892cd6?emrc=892cd6**

[5] UCF's Lunabotics 2024 (Jan. 5, 2024). *Project Development Challenge Guidebook.* Retrieved from **https://cdn.shopify.com/s/files/1/0398/9268/0862/files/UCF_Lunabotics_Guidebook_2024_30ad44dc-91a1-4576-8cd5-c04016447965.pdf?v=1704479411**