NEW YORK UNIVERSITY TANDON SCHOOL OF ENGINEERING
ROBOTIC DESIGN TEAM

2022-2023 SYSTEMS ENGINEERING REPORT

Affiliated University:
New York University Tandon School of Engineering

Team Members:

Aaron Bliss	Carlos Campos	Guarien Barone	Megan Chang	Robert Xi
Akram Khairi	Cinerita Andrandes	Ifedayo Olusanya	Meghana Ramesh	Sally Gao
Alberto Melgar	Daniel Plaza	James Xie	Michael McCloskey	Sarah Moughal
Alexander Hsu	Darrien Gopaul	Jason Liu	Nabira Ahmad	Seeger Zou
Alvaro Altamirano	Davi Zheng	Joanna Ibrahim	Nayan Sarode	Semi Hong
Andy Qin	David Feng	Justin Rivera	Neha Das	Seyed Ali Madani
Anik Barua	Devansh Agarwal	Kevin Shaw	Nishat Shamiha	Shihang Wei
Ben Bayor	Elizabeth Mendoza	Kimberly Sinchi	Patryk Markowski	Yanka Sikder
Bonnie Wu	Elodie Choi	Leo Shin	Peter Han	Yeseon Kim
Bryant Luna Ramos	Florjon Haxhija	Leo Wang	Pranav Nedunghat	Yun Hao Dong
Cameron Bedard	Giancarlos Cabrera	Mashfee Alam	Rajat Kirloskar	
Carina Yan	Guanru Chen	Maya Martinez	Ricky Zhang	

Faculty Advisor:
Dr. Giuseppe Loianno

This document has been reviewed by the team's faculty advisor prior to submission to NASA.

Dr. Giuseppe Loianno, Faculty Advisor

ABSTRACT

While NASA may be on the brink of sending humans to the Moon and other planetary bodies, sustaining life will become impossible without establishing Earth independence. Through In-Situ Resource Utilization (ISRU) technologies, NASA aims to harvest the native planetary resources required for a sustainable human presence.

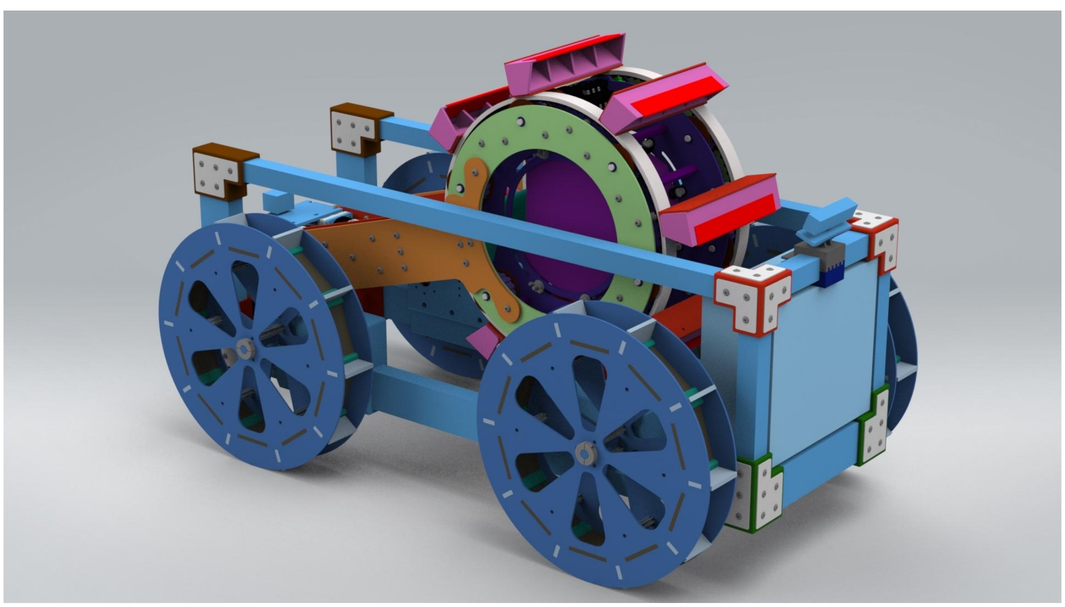
The annual NASA Lunabotics Competition challenges university student teams to develop robotic mining systems from commercially available technologies that can lead to revolutionary systemic outcomes. Teams must create rovers to traverse an artificial lunar terrain, excavate icy regolith simulant, and deposit into a collection bin.

The New York University (NYU) Tandon School of Engineering Robotic Design Team (RDT), is one such participant in NASA Lunabotics. Its robotic mining system, AMIGO, is an autonomously operated, mining system capable of excavating icy regolith simulant within the parameters set up by the competition and RDT.

NYU RDT utilized the NASA Systems Engineering process when designing, building and testing its system to ensure that its solution effectively addresses the competition requirements.

The 2022-2023 RDT is divided into technical and non-technical competencies. The technical atmosphere is constructed of our Mechanical, Electrical, and Software competencies. Within each, there is a Systems Engineer. The non-technical is constructed of our Project Managers, Marketing & Public Relations and Outreach committees. Each competency was designed with inter-relational aspects according to the Systems Engineering Process and thoroughly reviewed to minimize and mitigate possible points of failure and risks.

Throughout the project life cycle, RDT follows the Systems Engineering V-model, an iterative system development life cycle. This paper describes the Systems Engineering Process as used by the NYU RDT to develop AMIGO. A computer rendering of AMIGO is shown below.



Final System CAD Rendering

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Purpose Statement

The NASA Systems Engineering Process was implemented by the NYU Robotic Design Team for the 2023 NASA Lunabotics Competition. Beyond requirements by the competition, the NASA Systems Engineering Process was chosen because of its extensive documentation (the NASA Systems Engineering Handbook) and thorough verification processes. The team has previously struggled in two major aspects; the occurrence and management of late-stage changes to the project and undervaluing sub-milestones in key phases of the project. Therefore, the team benefited greatly from the recursive, iterative, and thoroughness of the design and, later, the validation processes of the NASA Systems Engineering Process.

The purpose of this document is to explain the execution of the NASA Systems Engineering Process by NYU RDT for the 2023 NASA Lunabotics Competition.

Introduction

I. Scope

NASA Lunabotics Competition inspired by the Artemis program and hosted by the National Aeronautics and Space Administration (NASA) challenges university teams around the country to design and build an autonomous robotic Lunar excavator capable of collecting, transporting and depositing simulated extraterrestrial icy regolith simulants (gravel). Teams are evaluated by the mass of gravel collected from beneath a layer of dusty regolith simulant (BP-1).

As of September 2022, the in-person mining component of the NASA Lunabotics Competition was canceled. However, competing teams are still evaluated on the other project deliverables (remotely) as outlined in *II. Project Deliverables*.

The NASA Systems Engineering Process is a project management and design methodology developed by NASA for its spaceflight and exploration missions. The process is explained in NASA's Systems Engineering Handbook (Revision 2) [1]. Further reference is provided in the Expanded Guidance for NASA Systems Engineering (Volumes 1 and 2) [2].

This document is divided into sections by the major phases of the NASA Systems Engineering Lifecycle: Pre-Phase A *Concept Studies*, Phase A *Concept Development*, Phase B *Preliminary Design*, Phase C *Final Design and Fabrication*, and Phase D *System Integration, Verification, and Validation*. Phase E *Operations* and Phase F *Closeout* are not included in the scope of this document. This document also includes a description of the management processes of the project and an appendix containing supplementary tables and figures.

II. Project Deliverables

Table 1 lists the deliverables for the 2023 NASA Lunabotics Competition as well as their description and deadlines.

TABLE 1
PROJECT DELIVERABLES

Deliverable	Description	Deadline
Project Management Plan	A preliminary document stating the early project definition (including the initial project schedule, budget and design philosophy)	October 19, 2022
Outreach Report	A written report describing the team's efforts in engaging their community in STEM education initiatives	February 15, 2023
Systems Engineering Report	A paper discussing the team's use of the SE Process during the design and implementation of their systems *[Current Document]*	March 29, 2023
Technical Presentation	A presentation to a panel of judges about the spirit and technical outcome of the project	March 29, 2023
Robot Proof of Life and Data	A video demonstrating the operation of the final system and supporting documentation (i.e. Bill Of Materials)	March 29, 2023

Pre-Phase A: Concept Studies

The purpose of the Concept Studies Phase of the Systems Engineering Lifecycle is to analyze the feasibility of the proposed mission based upon the success criteria presented by the project stakeholders. A thorough analysis of the mission is necessary to reduce future risks from poor project planning or unforeseen operational situations. [1]

The planning and development of the mission and system concept required by Pre-Phase A were started prior to the release of the official 2023 NASA Lunabotics Challenge Guidebook on August 28, 2022. Therefore, the initial assumptions made about the mission concept and possible operational conditions were based upon the team's experience from previous years' of the Lunabotics and Robotic Mining (in-person) Competition. Upon the release of the Guidebook, these assumptions were compared to the official expectations for the mission.

I. Identifying Stakeholder Expectations

The primary stakeholder and the final customer of the completed system is the NASA Lunabotics Judging Panel. Their expectations for the system are explicitly outlined in the NASA Lunabotics Challenge Guidebook, which describes the competition's operational conditions, constraints on the design of the rovers, and scoring procedures [3].

NASA's primary expectation for the produced system was to maximize the mass of icy regolith (gravel simulant) located at a given depth beneath simulated extraterrestrial regolith (BP-1 simulant) collected from the testing arena and deposited into a collection receptacle within an allotted period of time. Other expectations for the system is that it has minimal mass, power consumption, and communication bandwidth usage*, utilize an innovative design, operate autonomously, and minimize the amount of BP-1 simulant disturbed by its operation* (referred to as the system's dust management and tolerance). Additionally, NASA has imposed a set of constraints on the final system, which are outlined in Appendix A. These expectations and constraints were partially confirmed with the release of the 2023 NASA Lunabotics Challenge Guidebook.

Another key project stakeholder, aside from NASA, is New York University, which holds financial responsibility for the project as its primary sponsor. Conditions for securing the funds for the mission include providing a challenging engineering project for the members of the team, performing well at the competition, and utilizing the university's resources to design and fabricate the robot.

The final stakeholder is the student team itself, whose expectations include that the team does well in the competition, the project be challenging and interesting, and the project be achievable given their knowledge and abilities. Therefore, when evaluating the mission concept feasibility, the requirements of the system must be achievable given the available human resources.

II. Development of Preliminary Mission Parameters

A. Defining Needs, Goals, and Objectives

Given the set of expectations from the mission's stakeholders, developing a traceable set of needs, goals, and objectives (NGOs) represents the first step in defining a scope for the mission [1]. See Table 2 for the NGOs developed for this mission by the team.

B. Defining Measures of Effectiveness

Measures of Effectiveness (MOEs) are the first form of Technical Measures developed by the mission and are the "operational" measures of success that directly contribute to evaluating the system's achievement of the mission in the intended environment. MOEs are eventually used as the basis for the development of a concept of operations and system requirements and are used to evaluate alternative system concepts during the design stage [2]. The MOEs are listed in Table B1 in Appendix B.

III. Designing a Concept of Operations

A preliminary Concept of Operations is required to fully define the mission and assess its feasibility. See **Appendix C** for the Concept of Operations as maintained across the project lifecycle by the team.

IV. Determining Mission Feasibility

A thorough effort is made to ensure that a mission and potential system concept are feasible in Pre-Phase A. Given the limited availability of project capital prior to the acquisition of funding, conducting a physical concept study would have been difficult. Instead, the concept study was conducted using experience from participation in previous years of the

NASA Lunabotics Competition to evaluate potential operational scenarios and review past system performance and possible risks.

TABLE 2

Mi□□ion□ Need□, Goal□ and Objective□

Parameter	ID	Definition
Need	N1	The system needs to accumulate the maximum amount of points possible in a single mining run.
Goal	G1	The system should be able to traverse and operate in the arena
	G2	The system should be able to extract gravel icy regolith from the arena
	G3	The system should minimize the amount of unscored BP-1 regolith collected
	G4	The system should be able to deposit the collected regolith into the collection bin
	G5	The system should use minimal resources (mass, bandwidth*, electrical power)
	G6	The system should operate autonomously
	G7	The system should be completed on time and within budget
Objective	Ob1	The system should have a maximum mass of 60 kg
	Ob2	The robot should operate fully autonomous (as defined by NASA Lunabotics Guideline)
	Ob3	The robot should complete two dig/deposit cycles in a maximum of 5 minutes per cycle
	Ob4	The system should use a maximum of 30Mbps (bandwidth)
	Ob5	The system should cost a maximum of $12,500
	Ob6	The system should be completed by March 29, 2023
	Ob7	The system should collect 10 kg of gravel icy regolith (5 kg/cycle)
	Ob8	The system should achieve the minimum mining score (1kg)
	Ob9	The system should be resilient to error or recoverable from it
	Ob10	The system should be simplistic to further reduce possible points of failure

** Set utilizing previous NASA Lunabotics Competition In-Person Guidelines and Utilized as a Basis Pre-Release of this year's Guidebook*

A. Evaluating Mission Operational Scenarios

Operational scenarios are subject to change every year, both as a result of changes made to NASA's expectations and uncontrollable environmental variables. In discussing the feasibility of the mission, the various past operational scenarios were analyzed.

In previous years, system operation and mission execution were affected primarily by the changes in NASA's expectations. Prior to 2017, rovers were expected to collect BP-1 regolith simulant. Starting in 2017, rovers were given the option to collect more valuable gravel icy regolith simulant. In 2018, collected BP-1 was given no point value. These changes did increase the mission difficulty. In 2017, 46.7% of participating teams attained the minimum mining requirement while only 13.6% of teams reached this goal in 2018 [4]. Nevertheless, a portion of teams still successfully completed the minimum mission requirements. Hence, it can be concluded that changes in operational expectations would not result in a change in overall mission feasibility.

In 2018, the mission's operational scenario was greatly affected by the weather; practice runs were canceled as a result of rain, the time allotted for setup was truncated, and the regolith became more compact as a result of the increased humidity. These factors did contribute to the rover's suboptimal performance and would, therefore, affect mission feasibility.

Upon the release of the 2019 NASA RMC Rules, these conclusions were validated. One change made in 2019 was the relocation of the testing arena indoors, which eliminates the possibility of operational variation as a result of environmental factors. The area of the testing arena is also reduced for the 2019 RMC, which is deemed to be beneficial to possible mission success as less time would need to be taken to traverse the field.

B. Past System Performance

Atlas 7 (RMC 2017) (Atlas 3, 4, 5, and 6 were suboptimal prototypes) focused on achieving a minimal mass, power consumption, and bandwidth. In order to minimize redundant systems and achieve minimal mass, the Atlas 7's wheels were made to not only move the rover but also dig. While Atlas 7 did meet that expectation, it was not able to excavate BP-1 regolith simulant due to both inadequate motor torque and mechanical failure.

ORBIT I (RMC 2018) was intended to find a middle ground between Atlas II and 7, while also incorporating design changes to meet the new expectation of solely excavating icy regolith simulant. It featured a central digging drum capable of being lowered 0.65 meters below the surface to reach the gravel. Using the same design and manufacturing methods as Atlas 7, ORBIT I was able to achieve a minimal power consumption (but over-engineered redundancy resulted in a high mass). As a result of the change to the operational scenario due to poor weather conditions and mechanical failure in the deposition subsystem, ORBIT I ultimately failed to achieve competition expectations.

ORBIT II was a two rover system adding cleats to the locomotion system's wheels to provide added traction when traversing through regolith. They were effective in traversing forwards and backwards but had difficulty traveling. Among past rovers made by the team however it was the b

PIPER was influenced by the systems of ORBIT II utilizing similar spoked wheels proven to be effective in locomoting on regolith but with a raised chassis as opposed to ORBIT I's static chassis. The two rover design of ORBIT II was backed away from to simplify the design in favor of prioritizing autonomy.

ASTRO was intended to be similar to previous robots coming out of a team break due to COVID. The primary goal was to build a functioning robot coming from little technical knowledge since the previous robot was built years prior and members had much less experience with robotics and systems engineering. The systems engineering process was developed but the robot was ultimately minimally functional because of time constraints.

Past systems demonstrated both mission feasibility as well as the potential for mission failure as a result of unmitigated risks and inadequate system verification. The current system should be built with redundancy, but in trading off with mass, redundancy should not be so heavily weighted. More robust fabrication and further validation in potential operating conditions would also help mitigate possible mission failure as a result of a mechanical problem, specifically a redesigned deposition mechanism as well as more efficient subsystem interfaces. As these risks are preventable, the conclusion is that overall mission feasibility is supported by experience with previous systems.

PHA□E A: CONCEPT DEVELOPMENT - DONE

The primary purpose of Phase A is to develop a baselined mission concept from the expectations of the mission stakeholders defined in Pre-Phase A. Baselined products include a formal Concept of Operations, a set of technical requirements, and a preliminary verification and validation plan. Furthermore, this baseline is used to develop a proposed system architecture where system functions are allocated to specific components and mechanisms [1]. Phase A of the mission began on September 18, 2022, with the conclusion of Pre-Phase A on September 17, 2022, with the completion of the Mission Definition Review.

I. Formalizing the Concept of Operations

A preliminary Concept of Operations was developed in Pre-Phase A based upon the expected parameters of the mission. This ConOps was re-evaluated and baselined in Phase A (see Appendix C) based upon the actual mission parameters as defined in the 2023 NASA Lunabotics Guidebook.

II. Technical Requirements

A. System Requirements Definition

The system's technical requirements are divided into six categories: functional (F), performance (P), interface (I), environmental (E), design (D) and safety (S) [1]. Table D1, **Appendix D** lists the technical requirements for the system and the constraints and operational expectations from which each requirement is derived. The unique requirement ID and its category are indicated in parenthesis preceding each requirement in the format: (ID, Category). Key Driving Requirements are indicated with an asterisk (*). An initial system level technical budget was also drafted based upon these requirements and maintained throughout the project lifecycle (Table E1, **Appendix E**).

B. Subsystem Requirements Definition

The subsystem requirements are derived from system requirements tailored to the needs of different subsystems. These requirements are summarized in Table G2, **Appendix G**, a requirements verification matrix.

III. Preliminary Verification and Validation Plan

A. Measures of Performance and Technical Performance Measures

Technical requirements and MOES were further defined with Measures of Performance (MOPs). They are listed in Table B2, Appendix B.

B. Verification Plans

The technical requirements verification plans are methodologies created to test the final system for compliance with the technical requirements. These plans are summarized in **Appendix F**

IV. System Decomposition

A. Functional Decomposition

The various functions the system needed to perform to accomplish the concept of operations and system requirements were outlined and allocated to various subsystems. Functional interfaces were also designed and allocated to subsystem interfaces from these allocations.

Several models which assigned system functions to different subsystems were developed. Approaches considered included one approach which assigned all functions relating to the same requirement to a single subsystem (i.e. an autonomy subsystem, a dust tolerance subsystem, etc.). Another approach grouped subsystems by discipline (i.e. mechanical subsystem, software subsystem, etc.). In the end, the subsystems were created by grouping functions involved in similar steps of the ConOps (i.e. digging, depositing, locomotion and storage) into subsystems. By taking this approach, subsystems and their interfaces can be made to operate concurrently during mission execution, as per requirement SR11.

B. System Architecture

Figure 1 shows the high-level system's functional decomposition. The allocation of functions to the subsystem interface is described in Figure 1. The differentiation of icy and BP-1 regolith was grouped with storage so that differentiation could happen simultaneously to digging in order to fulfill requirements.

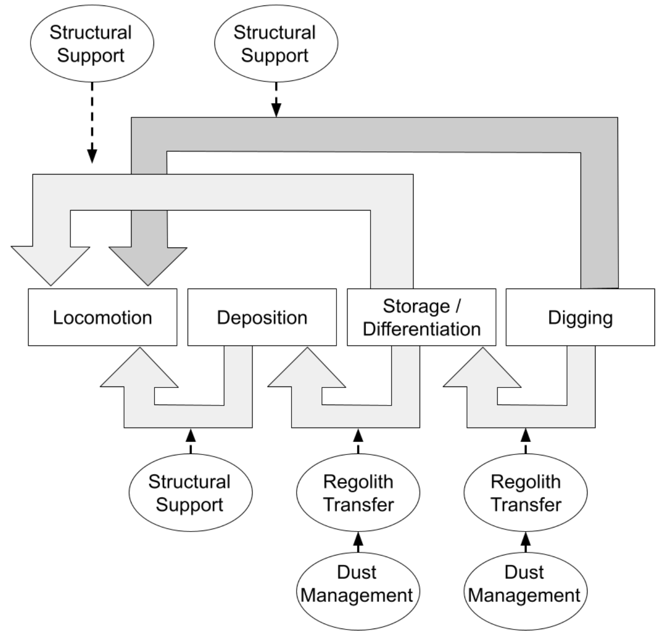


FIGURE 1: SYSTEM ARCHITECTURE
SYSTEM INTERFACES AND FUNCTIONAL ALLOCATIONS (RECTANGLES ARE SUBSYSTEMS, GREY ARROWS ARE INTERFACES BETWEEN SUBSYSTEMS, AND ELLIPSES ARE ALLOCATED FUNCTIONS)

C. Allocation of Subsystem Requirements

Following the creation of system architecture, the technical requirements were similarly decomposed and allocated to the individual subsystems. These allocated requirements were then used to further define the technical budget for the system.

D. Identifying Required Technologies

The identification of system functions and their allocation to individual subsystems provides a good idea of the technologies required for the system:

- A means of separating icy and BP-1 regolith
- A means of efficiently excavating BP-1 regolith
- A means to navigate the testing pit autonomously without the use of the walls
- A means of transferring excavated regolith to the collection bin

V. Mission Definition Review

The Mission Definition Review (MDR) is conducted to review whether the proposed system architecture is responsive to the functional and performance requirements previously defined. No major changes to the project baseline were made during this review.

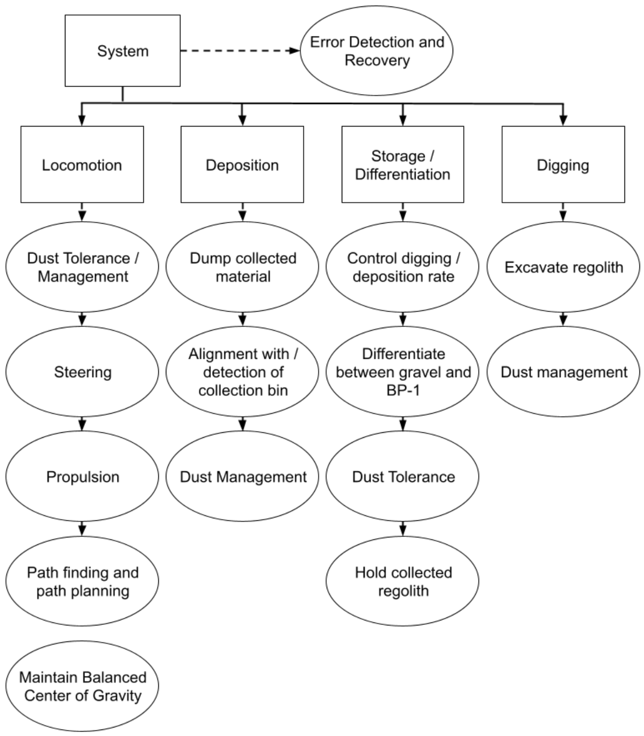


FIGURE 2
System Hierarchy and Functional Decomposition (Rectangles are levels of the hierarchy and ellipses are allocated functions)

Phase B: Preliminary Design

The primary purpose of the Preliminary Design Phase of the Systems Engineering lifecycle is to develop a general design for the system as well as further refine the mission baseline developed in Phase A. Moreover, it is during Phase B that all technology development, prototyping, and risk mitigation are completed [1]. Phase B of the project started on October 9th, 2022, with the completion of the MDR and ended on September 25th, 2022 with the completion of the Preliminary Design Review (PDR).

I. Subsystem Design Solutions

Design concepts for individual subsystems are created through trade studies conducted at the start of Phase B. The concepts in the trade study were evaluated using a list of MOEs for each subsystem that were created based upon the subsystem requirements. For a description of the trade study process utilized by the project.

The following sections outline the designs which made it to the last stage of the trade study. Table 6 outlines the MOEs defined for each subsystem and used to evaluate the potential design concepts.

A. Digging Subsystem

The key technology required by the digging subsystem is the excavation method. After several stages of evaluation, three design concepts: conveyor belt digger, auger, and digging wheel, were chosen to be prototyped for their efficacy as measured by the previously defined MOEs in Appendix B.

The conveyor belt digger is popular amongst NASA Lunabotics teams and has previously demonstrated its overall effectiveness. While the conveyor belt design allows for deep excavation, in order to minimize power consumption, the belt must be kept narrow, sacrificing the overall digging rate.

An auger is a rotating, helical screw blade which acts as a vertical conveyor belt to remove excavated material. Additionally, creating a cylindrical shell around the auger would result in effective dust management. However, testing determined that the power requirement for an auger mechanism would be significantly greater than the other mechanisms due to the sheer properties of regolith.

A digging wheel rotates on a fixed axis and utilizes shovels to excavate regolith. This design has been utilized in past systems implemented by the team for the NASA Lunabotics. Although similar to the conveyor belt, the digging wheel is more power efficient as its circular geometry requires less torque than the elliptical geometry of a conveyor belt. It also allows for continuous digging with the only limitations being the size of the container where the regolith is being stored and the radius of the digging drum, as it has an extruding central axis. To mitigate that restriction, a new digging wheel implementation with embedded motors was designed and tested.

TABLE 3
Digging Design Concept Trade Study Results

Measure of Efficiency (Appendix D)	Decision Weight	Design Concepts		
		Auger	Conveyor Belt	Digging Wheel
SR4	3	20.95 kg	5.2 kg*	18 kg
SR31	2	0.6m	0.6m	0.6m
SR3	4	32 Wh	5.75 Wh	2.7 Wh*
E5	5	0.033 kg/s	0.248 kg/s	0.65 kg/s*
OB10	2	2	1*	4

* Indicates the best performing metric

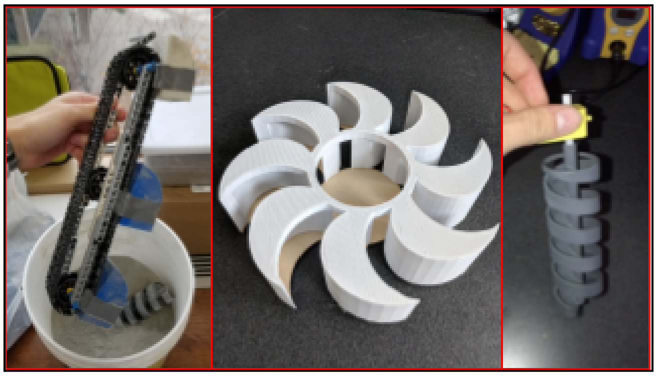


FIGURE 3

Based on the design metrics, the digging wheel was chosen. This was mainly due to its efficiency and capability of continuously excavating large amounts of regolith.

B. Locomotion Subsystem

Several design decisions regarding the structure of the locomotion chassis were examined during the trade study, specifically the use of a static chassis without a suspension mechanism, and spring chassis with an articulated wheel.

The static chassis is simpler, therefore lighter and has a lower likelihood for mechanical error. However, as it has no suspension mechanism, it is not able to handle potential collisions, possibly resulting in longer field traversal time.

The suspension mechanism chassis system is able to traverse obstacles easier, but are more complex to fabricate.

The static chassis was chosen for its lower mass and complexity. In order to mitigate the risk of failure as a result of inability to traverse large mounts, the design requires larger wheels, with big cleats in order to increase the traction of the system, and a more robust autonomous strategy. Table 4 lists the scaled scores of each concept based upon the established subsystem MOEs in Table B1 and Figure 4 shows the breadboarded concepts.

TABLE 4
Locomotion De□ign Concept Trade Study Re□ult□

Measure of Efficiency (Appendix D)	Decision Weight	Design Concepts	
		Suspension Chassis	Static Chassis

SR4	3	10 kg	8 kg*
SR41	1	1*	2
SR28/29	5	2	1*

* indicates best performing metric

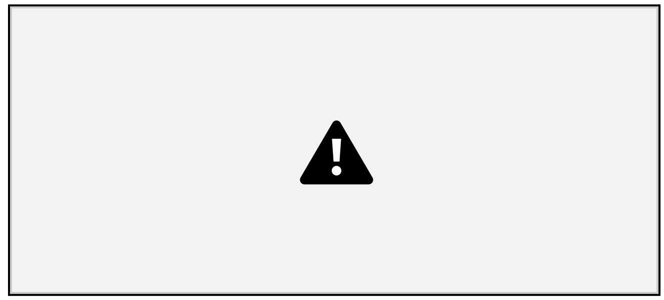


FIGURE 4
Locomotion Sub□y□tem De□ign Concept□. From Le□t to Right: rocker bogie, □tatic □rame

The static chassis was chosen due to its simplicity and stability, also to compensate for the lack of suspension, larger wheels were chosen that provided more traction and greater capability for turning.

C. Storage / Differentiation Subsystem

The primary technology developed for the storage and differentiation subsystem was the means by which the icy and BP-1 regolith would be separated. The two systems proposed are the following. One system would use a vibrating motor and aluminum mesh to sieve the sand out of the deposition bin. The second system proposed would be a passive aluminum mesh that would not require motors to sieve the material; it would count on the mesh material and inertia from the gravel/icy regolith, as it falls from the shovel to the deposition bin. Both storage bins have the same size and are located at the center of the digging drum.

The vibrating sieve is simple and effective; however, being an active mechanism, it does require significant electrical power. Furthermore, its low filtration rate would bottleneck the operation of the rest of the subsystems.

The meshed deposition bin that uses the pivot motors to sieve through the material would remove the necessity of extra motors, therefore reducing the possible failure points in the system. It would also reduce the overall weight of the system.

TABLE 5
Storage De□ign Concept Trade Study Re□ult□

Measure of Efficiency (Appendix D)	Decision Weight	Design Concepts: Vibrating mesh with dedicated motor	Passive mesh
SR3	2	< 2 Wh	0*
SR41	4	0.5 kg / sec*	0.5 kg / sec*
D5	5	> 90%*	70 - 80%

* indicates best performing metric

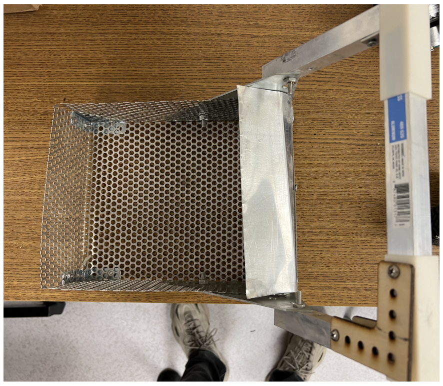


FIGURE 5
STORAGE / DI□□ERENTIATION SUB□Y□TEM DE□IGN CONCEPT, TIERED INCLINED PLANE

The passive meshed bin was chosen due to its ease of manufacture, and the reduction of a failure point by removing a motor from the system operation.

D. Deposition Subsystem

The primary technology involved in the deposition subsystem is the means of transferring the collected regolith from the storage subsystem to the collection bin. Three concepts were examined: conveyor belt, side deposition, and tipping "dump truck" bin. For each design a prototype was created and tested according to the MOEs defined in Table B1.

A conveyor belt deposition is an approach which involves buckets attached to a conveyor belt. The belt would be raised over the collection bin and under the storage container. The regolith would be moved from the storage container into the collection bin.

The side deposition approach involved having a deposition bin at the center of the digging drum, once sufficient material was collected, the locomotion system would align parallel to the deposition bin. The digging wheel would be raised to the required height, and a side door on the deposition bin would open and allow gravity to pull the material down into the collection bin. The disadvantage is that the locomotion system would need to be very precise to achieve the correct orientation, and have a large power consumption due to the reorientation.

The tipping is the simplest approach and involves the use of a "dump truck" functionality which tips a container such that gravity deposits the regolith into the collection bin. The tipping mechanism uses the same motors that are used for excavation, therefore decreasing the complexity of the system. It also does not require any positive control, which decreases the complexity of the system.

TABLE 6
DEPO□ITION DE□IGN CONCEPT TRADE STUDY RE□ULT□

Measure of Efficiency (Appendix D)	Decision Weight	Design Concepts: Conveyor Belt	Side Deposition	Tipping
SR42	5	1	1	1
SR3	3	7.5 Wh	10 Wh	4 Wh*
SR4	2	5kg	8kg	2kg*
SR40	2	> 98%*	> 97%	> 80%

* indicates best performing metric

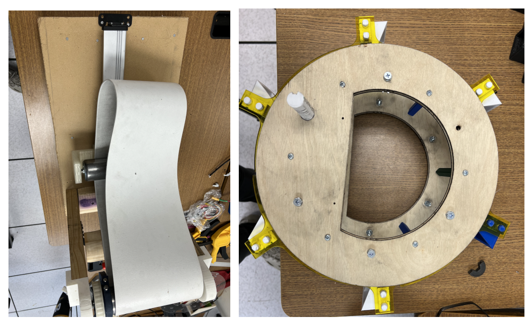


FIGURE 6
DEPO□ITION SUB□Y□TEM DE□IGN CONCEPT. FROM LE□T TO RIGHT: (TOP ROW) EXPANDING BIN, TIPPING, (BOTTOM ROW) EXPANDED TUBE, CHUTE

The tipping subsystem was chosen for its simplicity of operation and efficiency of weight and power consumption. Table 6 shows the scaled results of the trade study for each design concept and Figure 6 shows images of design concept breadboards.

E. Manual Control

Manual control is the control system that allows the rover's systems to be operated from the ground control station via a laptop (SR21 & 24). This acts as a failsafe in case autonomous control fails partially or is only finished partially. Manual control is designed to send minimal and reliable data wirelessly or via ethernet. Manual control signals sent to the rover planned to be limited to one byte each to limit the bandwidth use. Controls were to be simplified as much as possible. The option of using a Logitech controller to make the controls for the rover more intuitive was looked into.

F. Hardware Communication

To communicate between the GCS and the rover a raspberry pi and Arduino teensy were to be placed on the rover and connected over I2C. A pi was chosen since it has more computing power for processing information like camera data. A teensy was also chosen because it has 32 hardware PWM Pins and many hardware interrupt pins compared to the pi's 2 PWM pins and no interrupt pins. These pins are needed for all of the considered sensors.

Manual control was intended to send a maximum of 1 byte per command wirelessly from the GCS to the pi connected to the teensy over i2c sending signals to control motors and receiver sensor data.

G. Autonomous Control

I. General Autonomy

Autonomous control was split into three control systems, excavation, deposition and locomotion. Each autonomous system was to be outlined with a state diagram (Figure 1, **Appendix H**) and implemented with a state machine. Each autonomy would then be a part of a more general full autonomy state machine also outlined in a state diagram (Figure 2-4, **Appendix H**).

II. Excavation Autonomy

Excavation autonomy (Figure 2, **Appendix H**) is the system that automates from after entering the excavation zone to excavating and retracting any excavation mechanisms into their original position. This autonomy was assessed to be the most achievable in the given time constraint and prioritized (SR23).

The plan for excavation was to use some sensor to measure the material in the rover to signify when to stop excavating. The use of a load cell to measure the mass of the material or either an IR break beam or distance sensor to check if material piled up to the top of the bin.

III. Deposition Autonomy

Deposition autonomy (Figure 3, **Appendix H**) is the system that automates from before entering the deposition zone to aligning with the bin and depositing regolith. This system requires some way for the rover to localize with the bin to approach precisely and deposit.

The system involved using a camera to identify the deposition bin and localize with it allowing the rover to approach and deposit. Either a board with color blocks and OpenCV or AprilTags were planned to be used to identify the bin and localize it. Both involve the use of a visual aid attached to the bin and a camera on the rover. Hall effect sensors were planned to be used to detect the orientation of the shovels on the digging drum to signal if they were blocking the opening over the internal storage bin.

IV. Locomotion Autonomy

Locomotion autonomy (Figure 4, **Appendix H**) is the system that automates traversing the obstacle zone. Locomotion autonomy entails detecting obstacles and some localization technique that doesn't involve detecting the walls of the competition area. Obstacles like craters, mounds and boulders need to be detected to be avoided and localization ensures the rover is progressing towards the intended destination zone (either the excavation or deposition zone).

The system involved using either an IMU (without gps) or some depth camera to estimate the rovers distance traveled. Point Cloud data from the depth camera or LiDAR was planned to be used to record the path traveled by the robot and identify obstacles.

II. System Design Solutions

Following the development of the subsystem design concepts, they were combined into potential system concepts. These concepts were then compared to the system level MOEs and a trade study was conducted to evaluate the system concept alternatives.

A. Software Alternatives

For locomotion autonomy two obstacle detection techniques were proposed. Either a 360 degree single beam LiDAR attached to the front of the rover or a

RealSense camera were to be used to detect obstacles for the autonomous locomotion system. The use of an XBox 360 Kinect camera and Mynt eye stereo depth camera were also considered but deemed ineffective.

Two autonomous locomotion traversal strategies were also proposed. With one the rover would localize itself with one camera in the back detecting a calibration aid on the deposition bin and detect obstacles in the front with a depth camera. The rover would then not switch orientation so that the back camera was still facing the deposition bin and could localize as the rover traverses towards the deposition zone. The other was to have the rover traverse the obstacle zone without localizing throughout and then turn around towards the deposition bin using a camera on the front side and only localize as it traverses towards the deposition zone.

B. Flow Chart of System Concept

Figure 7 shows the rover in its assigned position on each of the three different phases of the competition. Locomotion, Excavation and Deposition.

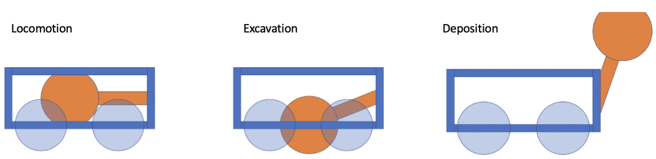


FIGURE 7
CHOSEN SYSTEM DESIGN CONCEPT

III. Refining System ConOps

Following the development of the system and subsystem design concept, the concept of operations was refined to include the new operational scenarios (**Appendix C**). In addition subsystem requirements in Appendix D, were developed for each specific subsystem design.

IV. Interface Design Solutions

Given the set of the developed subsystem and system design solutions, the interface design can achieve a greater level of resolution. Based on the developed individual subsystem concepts, the initial technical budget (Table E1, **Appendix E**) was updated with the interfaces.

V. Preliminary Design Review

The Preliminary Design Review occurred on October 23, 2022, and was attended by a team alumnus, the team's faculty advisor, and a postdoctoral student studying systems engineering. The purpose of the PDR is to review the preliminary design developed during Phase B for its adherence to the system and allocated requirements. Deliverables reviewed during the PDR were:

- The baselined mission concept (requirements, architecture, ConOps)
- The allocated subsystem requirements
- Validated subsystem design concepts with trade study results
- Validated system design concept with decision analysis
- The Preliminary Design Specification

A. Evaluating Software Design Solutions

Using a 360 degree single beam LiDAR would allow the rover to detect obstacles but not transmit video data or as clear environment depth data as a RealSense camera. The RealSense camera has more functionality and is compatible with chosen electrical systems so it was prioritized and use of a similar LiDAR was researched as a fail safe measure.

B. Control Board

After much further deliberation the necessity of the in-rush-current protection was found to be unnecessary. The 32 HW PWMs made it very simple to design the control board and enable as many sensors as we wanted. Motors were controlled via the PWM communication which is the most consistent with the existing embedded systems code and analog circuitry. In the design, the addition of hall-effect sensors was used as a scheme to enable better locomotion and excavation orientation. The scheme consists of placing the hall effects at particular places and understanding where they were with respect to the magnets on the different components of the machine. There was also an issue with the linear actuators moving in different polarities so the use of an H-bridge was designed to solve that technical issue however, it wasn't pursued due to a Mechanical change of plans.

The use of the motors was to fulfill mechanical excavation, locomotion, and deposition purposes.

Pha□e C: Final De□ign and Fabrication

The purpose of the Final Design and Fabrication phase of the Systems Engineering lifecycle is to further refine the preliminary design developed during the previous stage and then fabricate the final system [1]. Phase C began on November 14th, 2022, with the end of the PDR and ended on October 23th, 2022, with the completion of the fabrication process.

I. Design Process and Philosophy

The deliverables for the final design vary between the functional groups. The mechanical group delivered the final design in the form of computer-aided design (CAD) models, fabrication drawings, and computer-aided machining (CAM) files. The electrical group delivered electrical schematics and circuit board CAD drawings. The software group delivered completed state diagrams and algorithms written as pseudocode.

The mechanical component of the design process focused on producing the physical forms of the functional mechanisms of the system as well as to perform element analysis to determine the best fabrication method for each component. The electrical and software components of the design process involved the identification of feedback measures, the creation of an autonomy procedure based on the system Concept of Operations. Table D1 lists the system design goals and their traceability to the system requirements and measures of effectiveness.

Mechanical engineering designs were completed using Onshape, a solid modeling and computer-aided design and engineering (CAD / CAE) software provided by the company to the team under an educational license. Onshape was also utilized for design testing (mechanical stress simulations and weight estimations). Electrical engineering designs were completed using EasyEDA, a software utilized for electrical schematics and printed circuit board design, under an educational license. Software utilized several open source software packages including ROS2 or the Robotics Operating System 2 for use on Linux Ubuntu to establish wireless communication with the rover.

A. Digging Subsystem

The final design of the digging subsystem was a refinement of the concept developed during the previous phase as well as the design by RDT's previous digging system on, ORBIT 1 (2018). The final CAD render of the subsystem is included in Figure 8.

The digging subsystem consists of a central digging wheel which is attached to two side arms. The digging wheel rotates using two fixed off center motors and a timing belt that is attached to free rotating aluminum rings, the rings in turn utilize shovels to excavate regolith. The digging wheel consists of eight shovels mounted on two ring gears. Each aluminum ring is actuated using a 2nm NEO motor with 100:1 gearbox and seven idler gears, creating a planetary mechanism. The two side arms are attached to a shaft, placed at the back of the rover, that is powered by two 2nm NEO motors and 80:1 worm gearbox respectively.

The primary challenge faced during the development of a final design was calculating the correct pivot point location in order to transverse the digging drum to its required excavation depth while also reaching the required height for the deposition system, while not going over the size limitations.

The main improvements made to the digging system from the previously used digging system in ORBIT 1 were the following. The primary improvement was in the deployment of the excavation subsystem. ORBIT 1 utilized linear vertical actuators to transverse the excavation subsystem, nonetheless this was changed to a pivoting system as discussed above. This allows for a wider range of mobility in both excavation and deposition. The second major change was in how the digging drum was powered, it went from being a single central axis to two independent motors with timing belt and idler gears. The third major improvement was aimed at mass and volume reduction of the subsystem. Steel ball bearings were replaced with plastic bushing. The width of the drum (i.e. distance from the faces of the cylinder) was reduced from 39 cm to 22 cm to fit within the chassis of the rover. And minor details were also improved in order to have a smoother operation of the ring gears. For example, the thickness of aluminum sun rings was increased in order to allow for countersinking screws from the excavation shovels, removing the screw head from the timing belt, allowing for a better contact of the gear and the timing belt.

The digging subsystem provides feedback of the angular velocity of the digging wheel and the angular velocity of the entire drum as it pivots, this is used by rotary encoders attached to the pivot point shaft and the two idle gear shafts on the digging drum.

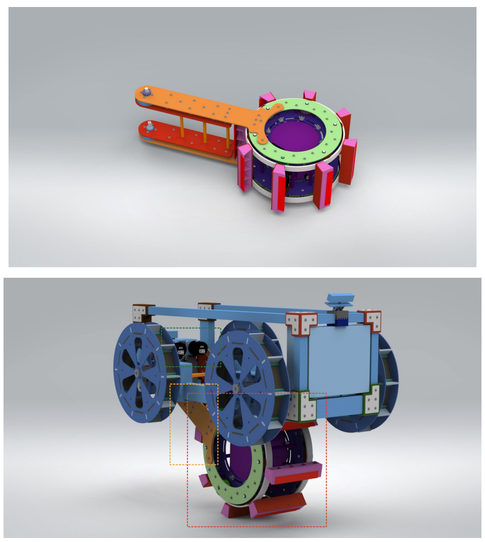


FIGURE 8

CAD Render for Digging Subsystem

Figure 8 shows the deployed excavation subsystem. The red selection displays the digging drum, the orange selection displays the side arms that hold the digging drum, the green selection displays the shaft that powers the translation system.

B. Locomotion Subsystem

The locomotion subsystem faced dimensional constraints imposed by the competition but also by the digging subsystem. The locomotion subsystem requires a high structural stability chassis, given the weight and vibrating properties of the excavating subsystem. Therefore, the entire locomotion system was redesigned. Another key consideration for the design of the subsystem was building the chassis such that the lack of a suspension mechanism would not inhibit its ability to traverse the obstacle field. Figure 9 shows the final locomotion subsystem.

The chassis was designed with hollow aluminum rods, connected with 3-way 3D printed interference fit connections. The wheel design utilized in the subsystem is a derivation of the wheels used in NASA's VIPER Mars rover. The wheels consist of wheel cleats that are covered on either side by the wheels side plates, therefore creating a watermill like structure. This provides considerable contact surface area from the wheel to the sand, while not allowing lateral displacement of it. Therefore allowing for a high reaction force that increased the traction and therefore maneuverability of the rover. The wheel width was determined by the excavation dimensional requirements and the system constraints. The wheel diameter was increased to 0.5m. The wheels' motor mounts had to be completely redesigned to serve the wheel's dimensions and the structure of the chassis. A case for the gearbox was designed in order to be dustproof and allow a smooth force transfer from the gearbox to the chassis, by enabling a wide range of connections to distribute the load. It was designed to sit on top of the lower chassis beam in order to provide structural strength to the connection. The locomotion subsystem team chose to implement a 4 wheel direct drive system (one motor for each wheel) to provide a differential drive to overcome differences in the terrain of the arena.

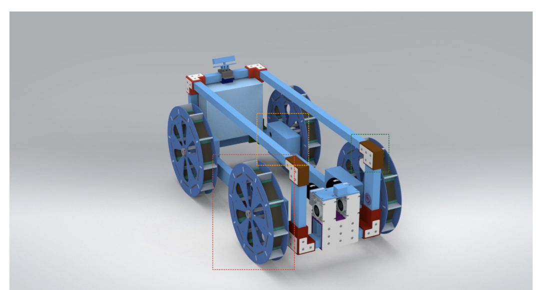


FIGURE 9

CAD Render for Locomotion Subsystem

Figure 9 shows the locomotion system. The red selection displays the wheel, the orange selection displays the wheel gearbox case that allows for force transmission from wheel to chassis, the green selection displays the 3D printed connections for the aluminum beams that conform the chassis.

C. Deposition Subsystem

The deposition subsystem design concept was modified significantly from the previous ORBIT 1 rover based on extensive testing data and manufacturing feedback. The pivot point sub-assembly was designed to combine the digging subsystem with deposition. The digging drum is rotated around 150° from its digging position down in the ground to its deposition position 0.5m above ground. This allows for sufficient clearance in order to deliver the material into the specified location. This technique allowed for the same two motors to carry out two tasks, therefore reducing the complexity of the entire rover. In order to achieve that, the location of the pivot point was carefully calculated, as described above, in order to reach the required digging depth, storage and transportation position and deposition orientation. The deposition bin inside the digging drum was designed and positioned as such, so that at excavation position the open face was parallel to the surface, and at deposition position it archives a large enough angle for the gravel to flow down due to gravity.

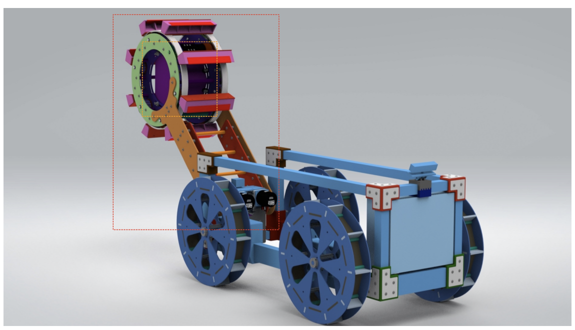


FIGURE 10

CAD Render for Deposition Subsystem

Figure 10 shows the excavation subsystem in deposition position. The red selection displays the excavation subsystem, the orange selection displays the meshed aluminum deposition bin.

D. Storage / Differentiation Subsystem

The storage subsystem design concept employed a heptagon meshed aluminum box inside the digging wheel. Utilizing a precise orientation, the digging subsystem was able to passively collect material at digging depth, store it at transportation orientation and deposit at the correct position in order to deliver the collected regolith. The pivot point was utilized to create vibration on the digging wheel and therefore on the storage subsystem, this allowed for active filtration to remove the remaining dust that wasn't passively removed by the aluminum mesh.

The deposition system included force sensors that would give important feedback of the state of capacity of the bin. In addition a potentiometer was used to measure the exact angle for the excavation system, that could also be used to know the specific location the system had to reach in order to deposit the material.

The deposition bin was made out of meshed aluminum and 3D printed connections.

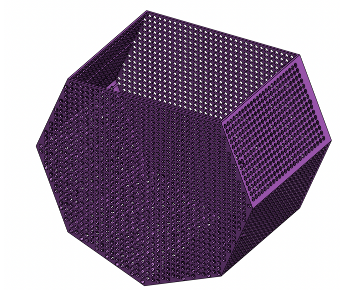


FIGURE 11

CAD Render for Storage Subsystem

Figure 11 Shows the deposition bin with the perforated aluminum plates. This allows for passive filtering, in addition the geometry allows for passive collection and deposition.

E. Manual Control

The final design for manual control involved dividing the rover's functions into actions and assigning each action a key or key combination on the GCS keyboard (Figure 5, **Appendix H**) (SR 21 & 24). Each action was assigned a value sent in hex with a maximum size of one byte (Table 1, **Appendix H**). Limiting the size of transmitted data was to limit the rover's bandwidth usage. Commands were converted to their assigned 1 byte hex value and sent wirelessly using a ROS2 (roverics Operating System) publisher and subscriber. The publisher ran on the GCS and sent the simplified command on a topic to the subscriber listening on the same topic running on the pi.

F. Hardware Communication

The final line of hardware communication was from the GCS (laptop) to a raspberry pi wirelessly, to an Arduino teensy over I2C and to motors and sensors over hardware PWM pins (Figure 6, **Appendix H**).

Embedded Arduino code was used to control the motors and process sensor data from rotary encoders. Two motors were used to rotate parallel sun rings in the digging drum synchronized using PID control.

G. Autonomous Control

I. General Autonomy

General autonomy was finalized as a state machine without error states to transition between types of autonomous control (excavation, deposition, and locomotion) but was not used since only excavation autonomy was finalized.

II. Excavation Autonomy

Excavation autonomy (Figure 2, **Appendix E**) was prioritized due to time constraints and the difficulty of creating functional autonomous control from no existing autonomy in prior rovers (SR23). The autonomy was defined in a final state diagram using technical understanding of the rover's excavation mechanism, PID control of two synchronized drum motors and data from a rotary encoder on the pivoting arm motor to determine which position the arm was in.

H. Control Board

The control board has a lot of nuances to it. The 3.3V pins of the raspberry pi and the teeny needed to be independent of each other. There needs to be a master and slave communication protocol between the sensors and the teensy. The Raspberry Pi acted as a master to the teensy in the context of i2C communication protocol. The teensy essentially worked as a sensor and PWM broker following the instructions decided by the raspberry pi. The raspberry will send a manual control Hex encoding (encoded by the software subsystem) and then was tasked to execute those functions with its several GPIO PWM pins.

I. Power Distribution Board

The use of the motor's capacitive load raised concerns and issues over whether or not the spark fun max had in-rush current protection or not. The desire to create an in-rush current protection circuit was conceived. The completion of the schematic for the in-rush current (Figure 6 , **Appendix G**) was to prevent the jerking of the motors issue previously observed . The first sprint's experimentation of whether this issue persists made that circuit useless since the circuit where the problem occurred had a wire gauge where the wire wasn't large enough to conduct that much power. The first sprint assignments were to research ideal motors for the tentative design of the robot with respect to the mechanical team's tentative design and their specifications with respect to that design. The lack of awareness of the rotary encoders' data collection capabilities began an investigation into the Controller Area Network Communication protocol. The protocol was tested and the data collection wasn't successful via that protocol. Therefore the transition back to the rotary encoder data collection was done. The potential motors were then recorded. The addition of the motors with a majority vote by the electrical team to the BOM followed shortly after the vote. The rise of concern about the battery being protected happened after being aware of the limited budget given. The design of the Power Distribution Schematic and Board was done with both Battery Protection Circuits and the In-rush-protection circuit was then executed. The preference for a smaller form factor was also desired for preference of less time in assembly for the final robot.

II. Design Verification

In order to verify the final design (specifically a review of the proposed fabrication and feasibility of the design concepts) prototypes were manufactured out of the intended materials in order to be tested individually, or test individual subassemblies.

III. Critical Design Review

The critical Design Review took place on January 11, 2023. The review took place with every member of the team present and NASA engineer to serve as the professional guide. During the CRR the following deliverables were presented:

- CAD models, stress and strain simulations and physical prototypes
- Revised PCBs and dust proof connectors
- Research on computer vision and autonomous strategy

- Fabrication procedure plans
- The Final Design Specifications

IV. Fabrication

Following the completion of the Critical Design Review, the fabrication process began. The responsibilities were separated into two teams: Excavation/Deposition/Storage subsystems and Locomotion subsystem, which also included camera mounts and EE box. Each team lead assigned specific manufacturing responsibilities to a team member, while also supervising the progress and integration of all the subsystem parts. Each member conducted the following activities: determining fabricated components' materials, finding COTS components and vendors that fit systems requirements and machining raw materials into subsystem components. Once they were manufactured the team lead would assemble the parts together with the members.

The electrical engineering team was responsible for deciding the necessary electronic components and designing and laying out the circuitry for the system as well as the design of the embedded system code and structure. At a high level, the electrical team developed the simple operating system (single thread, single process) run on the microcontrollers directly managing each subsystem.The electrical engineers did so with the use of asynchronous interrupt calls as well as they were aware that certain circumstances aren't predictable. The electrical functional group also was responsible for the distribution of signals and fabricated a custom control board with LED indication of power that manages and integrated softwares commands with the rest of the electrical components on the robot. Similarly, they chose the electronic COTS components that met the subsystem requirements and integrated them into the electrical assembly. Finally, the electrical engineering team managed the power distribution to the subsystems and the safety of the subsystem in case of electrical failure through the creation of a custom power distribution and circuit protected PCB.The electrical engineering team tested out the feasibility of their layout by doing rigorous Design Review Checks for both circuit and layout together as well as testing it out with the use of CircuitPro and an LPKF milling machine.

The final design included figures 2 and 6 for practicality purposes of meeting the particular deadline and handing in the deliverables of what was included in the design but the entirety of all of the figures in figures 2-6 was executed except for 5 because we found it to be an unnecessary and redundant addition. There were 4 separate orders of the board. Because of the misunderstanding of Gerber files and the miscommunication of the Gerber file prior. The first 3 orders of the PCBs occurred with a manufacturer known as JLPCB. The following figure 7 is the inclusivity of figure 6 in the Appendix D.

The following figure 2 circuit highlighted in figure 7 is shown below. There is a 3.3V plane around that is a common plane for every pin that shares that net's plane. The 5V plane is a very thick trace to conduct enough current. The following is the original PDB that was designed to just include figure 2. However, the design didn't have wire management in mind and it didn't have as many planes as they could have been. The Power Distribution Board with protective ICs (Figures 2-4, **Appendix G**) here.

Therefore, the addition of the GND plane on both the top and bottom was executed. The Power Distribution Board (Figures 2-4, **Appendix G**) layout of the protections and switching regulator. The purpose of the protections were to enable the battery not to discharge so quickly. Moreover, the switching regulator was just to use as an alternative to the much larger form factor off the shelf switching regulator.

In the end, there was a lot of improvement in between figures through 4 but, had fewer ICs just in case the circuits didn't work. The trace widths of the traces are also wider in between the pins of the fuses and motor Xt-90 pins. There is a larger tolerance of isolation between the power and ground planes. There is also much more organization to enable cleaner wire management.

Phase D: System Integration, Verification, and Validation

Phase D of the Systems Engineering Lifecycle involves the integration, verification, and validation of the individual subsystems and final system. It is in this phase that testing is performed to ensure the manufactured system fulfills all of the technical requirements derived and allocated in previous phases [1]. Phase D began during the fabrication process as various subsystems completed their fabrication process prior to March 10 2023. Phase D ends on March 29, 2023, when the final system must be delivered to NASA for operation (in the form of the proof of life video deliverable). Three main activities that are performed during Phase D are integration, verification, and validation.

It is important to note that the integration, verification and validation processes occurred recursively throughout the project at lower levels of the system hierarchy and maturity of the project. For example, each subsystem was prototyped at both the preliminary and final design phase in order to verify that the concepts developed functioned and met subsystem and system requirements. Phase D represents the application of these processes on the final fabricated components of the final system.

I. System Integration

System integration involves the assembly of the various fabricated enabling products into a higher level component in the system. Integration followed an integration plan that was baselined in the final design portion of Phase C and updated following fabrication. (Figure 15, **Appendix G)** shows the integration plan (a component hierarchy) utilized for the digging subsystem which dictated the order of assembly and which components needed to be assembled.

II. System Verification

System verification is the process of checking whether the system meets its technical requirements using controlled tests as described by the requirement verification plans baselined during Phase A and updated in Phases B and C (**Appendix F**).

A. Manual Control

The bandwidth of manual control was tested frequently to make sure that it was as minimal (Table 8). All manual controls were tested to ensure full functionality and successful wireless communication (SR 21 & 23).

TABLE 8
Manual Control Bandwidth Table

Manual Control Bandwidth			
Key Press*/ Sec	0.5	1	2
Bandwidth (bytes/ sec)	1	2	4

*a keypress sends a command on press and release

B. Hardware Communication

Communication from the GCS to the pi to the teensy to the motors and rotary encoders on the rover were continuously tested as parts were swapped out and the embedded code was modified. Some wires or broken motor controllers sometimes broke communication so frequent testing identified hardware problems early due to constant awareness of which parts in the rover were functional. A control board (Figures 7 and 14 **Appendix G**) was fabricated and used to extend signal wires from the teensy through the board to more secure screw terminals.

The following shows the wire management (Figure 15 , **Appendix G**) layout that describes how we will assemble everything in the robot's EE box.The Wire Management layout can be found in Appendix D Wire Management. The wire management involved the use of several dust proof connectors that are linked within the draw.io diagram that can be found here. The motivation for this unorthodox method of wire management that doesn't follow any standard conventions are due to the mechanical subsystem limitations of the space that the robot can occupy. With the size restriction in mind the layout found in the link and to the left was the clearest we could manage as of Mar 27, 2023. The necessity of the dustproof connectors is high due to the terrain the robot would be traversing.

C. Autonomous Control

I. Excavation Autonomy

Excavation autonomy (Figure 2, **Appendix H**) was prioritized due to time constraints and the difficulty of creating functional autonomy after having no functional autonomy in the prior year's Lunabotics rover (SR23, **Appendix D**).

II. Deposition Autonomy

Deposition autonomy (Figure 3, **Appendix H**) was not completed due to time constraints but progressed towards. The rover was successfully able to identify the visual aid planned to be used to localize the rover (Figure 12).

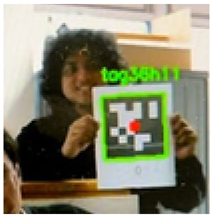


FIGURE 12
AprilTag Identification by rover camera

III. Locomotion Autonomy

Locomotion autonomy (Figure 4, **Appendix H**) was not completed due to time constraints but was progressed towards. Data from the 360 single beam LiDAR and Intel RealSense camera were both simulated in RViz, ROS2 simulation software, since testing with the physical rover was limited. RViz, data collection simulation software, in conjunction with Gazebo, environment simulation software, allowed obstacle detection to be worked on virtually (Figure 13). The rover was able to successfully detect boulders in a Gazebo simulated environment.

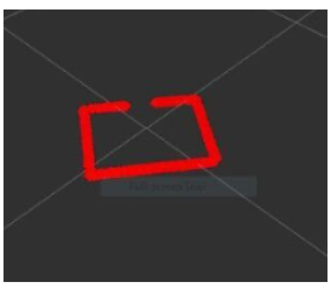


FIGURE 13
Simulated LiDAR data on RViz

Initially, each subsystem was verified individually for compliance with their subsystem's allocated requirements. Figure 14 shows one verification test where locomotion, excavation and deposition were revised for simple functionality. As demonstrated, these verification processes are controlled tests of specific functions of each subsystem.

Based upon the performance of each subsystem during verification, relaxing certain requirements to the performance of each subsystem is weighed, with possible changes to the subsystems, accounting for remaining time and budget for the project.

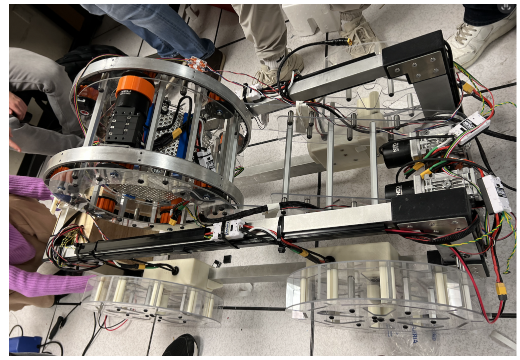


FIGURE 14
Veri□ication being per□ormed on the Subsystem □ub□y□tem

D. Power Distribution Board without ICs validation

The power distribution board was evaluated to produce enough current to power up to 5 motors at one time. The motor's power connections were connected to the Power Distribution board and then evaluated with 5 motors at once. They were evaluated by connecting them to the teensy PWM commands and tested at varied duty cycles.The power distribution board was also tested by whether or not the motor controllers and the Control Board's LED were valid. Within the testesting of the regular power distribution board the need to ensure unstable battery discharge rose. The need for the power distribution board with the ICs rose.What replaced the 12V to 5V switching regulator was an off the shelf switching regular that we purchased. The following are the assembled boards whose designs are shown in the previous phase.The below are the boards that were used to integrate with software's code and the mechanical ee box (Figures 13 and 14 **Appendix G**). Figures 15 show the power consumption being way below our maximum of 50 Whrs due to us choosing a more power efficient solution by using the buck converter rather than a switching/linear regulator.The entire robot worked at 11.3 Whrs (Figure 16 **Appendix G**).

E. Control Board Testing

The control board (Figures 7 and 14, **Appendix G**) was tested by evaluating whether or not it can retain sensory data and give PWM commands when connected to the board and we evaluated it to be able to perform as expected. The addition of particular rotary encoders made the hall-effect sensors unnecessary.

III. System Validation

System validation involves testing the completed system in the actual or simulated environment in which the final product will operate, and checking whether the system fulfills all of its technical requirements. Lacking proper facilities to replicate the exact testing environment of the RMC, the final system is tested on a public beach. Sand has similar properties to regolith and, prior to testing, gravel is buried at the required depth beneath the sand. This testing process usually occurs several times in late April. Figure 18 shows the validation process for AMIGO the rover utilized for the 2023 RMC.

IV. System Delivery

The completed system was demonstrated to NASA on March 29, 2023. Due to previous changes in the Robotic Mining Competition, this delivery is in the form of a video documenting the rover completing various functions and fulfilling NASA's expectations for said system. The system is also delivered to New York University, another important stakeholder in the project, as a demonstration of the robot at NYU's annual research exposition.

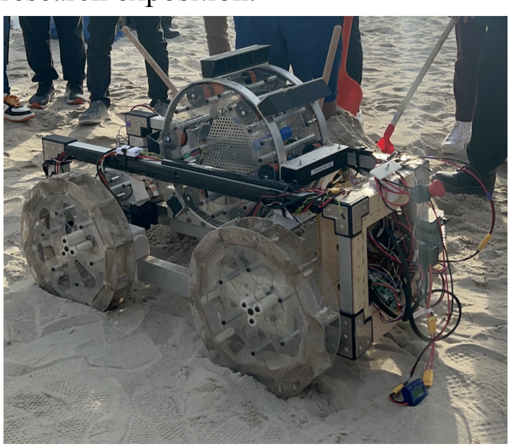


FIGURE 15
Validation of AMIGO

Project Management

The New York University Robotic Design Team is a group of 60 undergraduate and graduate students currently enrolled in New York University. The students represent a diverse set of engineering disciplines. The team is advised by Dr. Giuseppe Loianno. The team's student leads and lead systems engineers are Carlos Campos and Andy Qin.

Given the scope of the project and organization of the system, the team is organized into a matrix divided into functional and project teams. Each subteam is led by a student leader. Functional teams are composed of all individuals working on a similar engineering aspect of the robot (software, electrical and mechanical engineering), while the project teams are composed of individuals from the three functional groups, working collaboratively on a single subsystem. This approach is meant to encourage interdisciplinary collaboration.

I. Technical Requirements Management

Technical requirement management was handled as a tiered approach. The functional leads were responsible for the requirements management of the system as a whole, while the system project leads were responsible for managing the technical requirements at the subsystem level. This includes performing continuous testing on the design and fabricated components to ensure that the requirements are being met. Changes to the requirements that were discussed outside the relevant reviews were discussed with the systems engineer and team advisor (acting as the stakeholder) for its effect on the success of the mission. No major changes to the requirements baseline were made during the project.

II. Interface Management

While each project group leader was responsible for managing their individual subsystems, their requirements, and their verification processes, the interface management was generally managed by the functional leads and systems engineer. Interface management was performed at the design, fabrication, and integration phases. Specifically, the leads responsible for interface management were responsible for identifying interfaces and their requirements in the system.

III. Configuration Management

The project's configuration items include: the code for the software developed for the system (autonomy, communications, and the embedded systems), the mechanical system's CAD files, and the electrical and embedded systems' schematics and CAD files. All of this data is required for the completion of the project (technical reviews, determining sources of errors, etc.) as well as for guidance for future year's project development.

The CAD documents were managed using the OnShape platform which allows for the collaborative sharing of files through a cloud software as well as version control and model preview functions, which is used to help visualize system designs at technical assessments. Additionally OnShape is free to use. The mechanical engineering functional group lead was responsible for reviewing all submitted CAD documents for dependency conflicts and defects.

All of the project's code was maintained on a private git repository on the GitHub web service. GitHub provides this service free for students and allows for both cloud sharing and version control. The software engineering functional lead was responsible for identifying defects and dependency conflicts in the autonomy and communications code. The electrical engineering functional lead did the same for the embedded system's code. Past year's documents are maintained as public repositories on the NYU RDT organization on GitHub as well.

IV. Technical Risk Management

Risk management was performed throughout the project lifecycle. Risks were classified as either operational risks (i.e. risks associated with the project) or a functional risk (i.e. risks associated with the function of the rover). Risks were tracked in a risk matrix which identified the risk classification, severity, discovery date, mitigation plan, and mitigation result. This risk matrix is included in Table I1, **Appendix I**. At each of the major reviews, the subsystem leads and the systems engineer reviewed the risk classifications from previous stages of the project. Furthermore, new risks were identified given the progress and development of the system.

V. Technical Data Management

Technical documents include the supporting documentation generated during the project such as the System Requirement Specification written, the Preliminary Design Specification and Presentation, Final Design Specification, fabrication plans and COTS component datasheets. The majority of the documents were kept on Google Drive, provided by the university, and shared with each member of the team. Technical documents were either uploaded to the platform or completed as technical forms (using the related Google Forms product) and then stored in a spreadsheet. Previous year's documents are maintained as a compressed archive within a shared folder.

VI. Technical Planning

The technical planning process involves the management and tracking of the progress made by the project and its team. The project's technical planning was conducted by the student leads and systems engineer. The primary product of the technical planning process was the project schedule, which was baselined during the Concept Development Phase (prior to the submission of the Plan for Systems Engineering deliverable). It was then regularly revisited and revised. Figure J1, **Appendix J** includes the proposed project schedule (Gantt Chart) for the project and the actual progression of the project lifecycle.

Additionally, project progress was also tracked using a master project Kanban board (i.e. similar to the SCRUM project methodology) that was updated weekly by the project leads. The board kept track of the progression of specific tasks, making schedule slips easy to identify and mitigate. Figure 21 is an example of the Kanban board kept during the project.

Overall, the project stayed organized. The only major slip occurred as a result of delays during January break, in which less work was accomplished than previously planned (as a result of fewer team members being in New York during the break than previously anticipated). This led to a 10-day reduction in the final system validation process.

Not Started	In Progress	In Review	Completed
Task: Deliverable Date TASKS THAT NEED TO BE COMPLETED	TASKS THAT ARE BEING WORKED ON	TASKS IN NEED OF PROJECT / FUNCTIONAL LEAD REVIEW	TASKS THAT ARE CONSIDERED COMPLETED

FIGURE 21
KANBAN BOARD UTILIZED BY THE TEAM IN MANAGING THE TECHNICAL PLANNING PROCE□□.

VII. Technical Assessment and Decision Analysis

The majority of decision analysis was conducted using trade studies occurring in the preliminary design phase and the final design phase. Trade studies were conducted in four stages. In the first stage, ideation, the focus was placed on the quantity of ideas rather than quality. In the second stage, these ideas were reviewed and eliminated on the basis of logic (i.e. logically, how would the concept perform when measured according to the technical measures). In the following stage, the concepts were re-evaluated based upon research done into either past implementations of the concept by teams at NASA RMC or upon similar implementations in industrial or scientific settings. Poorly evaluated ideas were either dropped or combined to improve their scoring against the technical measures. All ideas were clarified into fully defined concepts. In the final stage, the remaining concepts were prototyped and their scaled performance as measured by the predefined metrics (i.e. MOE / MOP) were compared to determine the best concept.

This tiered decision analysis was implemented as a means of ensuring a thorough analysis of each possible option as well as limiting the number of concepts that were taken to the prototyping/ implementation phase to preserve project resources (human and funds).

Trade studies were conducted for the subsystem concept development, system concept development, and final design development and implementation. Each trade study concluded in the construction of some form of prototype. During the preliminary design phase, the trade study product was a subsystem breadboard (a functional demonstration). During the final design phase, this product was a brassboard (a functional and loose design demonstration). Prototypes were evaluated according to the same technical measures and using the same verification procedures defined prior to the trade study. Being scaled representations of the final system (and often being of different materials from each other) the prototypes' performance were normalized by standard score and compared accordingly.

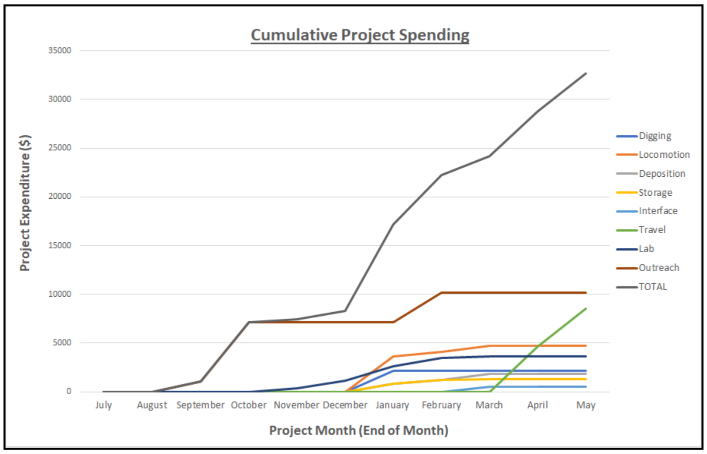
VIII. Budget Management

The management of project funds is an important component of the management of the project. The main source of capital for the project is from the Departments of Computer Science and Engineering, Electrical and Computer Engineering, and Undergraduate Academics at New York University's Tandon School of Engineering. Fundraising occurs at the start of the academic year.

The overall budget of the project is shown in Table 13. Furthermore, Figure 22 shows project spending over the duration of the project. One note, travel expenses to and from a make-up competition in Tuscaloosa Alabama are included in the budget.

TABLE 13:
FINAL PROJECT BUDGET

Project Income	Budgetted	Actual	Difference
Initial Balance			
Initial Balance	**$ 4,862.32**	**$ 4,862.32**	**$ -**
Internal Funding			
CSE Department	$ 5,000.00	$ 5,000.00	$ -
ECE Department	$ 4,000.00	$ 4,000.00	$ -
MAE Department	$ 3,000.00	$ -	$ (3,000.00)
Honors Program	$ 1,000.00	$ 2,000.00	$ 1,000.00
Undergraduate Academics	$ 5,000.00	$ 5,000.00	$ -
Office of Undergrad Recruitment	$ 1,000.00	$ 1,000.00	$ -
Total Internal Funding	**$ 19,000.00**	**$ 17,000.00**	**$ (2,000.00)**
External Funding			
Crowdfunding Campaign	$ 3,620.00	$ 5,820.00	$ 2,200.00
HVR Registration	$ 4,300.00	$ 4,000.00	$ (300.00)
Corporate Sponsorships	$ 5,500.00	$ 500.00	$ (5,000.00)
Total External Funding	**$ 13,420.00**	**$ 10,320.00**	**$ (5,100.00)**
Total Project Income	**$ 37,282.32**	**$ 32,182.32**	**$ (7,100.00)**
Project Expenses			
System Material Expenses			
Deposition Subystem	$ 1,700.00	$ 1,494.68	$ (205.32)
Locomotion Subsystem	$ 2,100.00	$ 4,435.05	$ 2,335.05
Digging Subsystem	$ 3,800.00	$ 2,142.00	$ (1,658.00)
Storage Subsystem	$ 750.00	$ 1,272.13	$ 522.13
Total System Expenses	**$ 8,350.00**	**$ 9,343.86**	**$ 993.86**
Travel Expenses			
Airfaire to and from Competition	$ 4,000.00	$ 3,750.00	$ (250.00)
Team Accomodations	$ 2,500.00	$ 2,500.00	$ -
Rental Car Expenses	$ 1,200.00		$ (1,200.00)
Total Travel Expenses	**$ 7,700.00**	**$ 6,250.00**	**$ (1,450.00)**
Shipping Costs			
Total Shipping Costs	**$ 3,000.00**	**$ 2,000.00**	**$ (1,000.00)**
Lab Expenses			
Training Materials	$ 300.00	$ 300.00	$ -
Tooling Expenses	$ 1,200.00	$ 1,100.00	$ (100.00)
Total Lab Expenses	**$ 1,500.00**	**$ 1,400.00**	**$ (100.00)**
Outreach Expenses			
HVR Robotics Competition	$ 11,000.00	$ 13,200.00	$ 2,200.00
Total Outreach Expenses	**$ 11,000.00**	**$ 13,200.00**	**$ 2,200.00**
Total Project Expenses	**$ 31,550.00**	**$ 32,193.86**	**$ 643.86**
Net Project Balance	**$ 5,732.32**	**$ (11.54)**	**$ (7,743.86)**


Cumulative Project Spending
Project Expenditure ($)
35000
30000
25000
20000
15000
10000
5000
0
July
August
September
October
November
December
January
February
March
April
May
Project Month (End of Month)
Digging
Locomotion
Deposition
Storage
Interface
Travel
Lab
Outreach
TOTAL

RE□ERENCE□

[1] Hirshorn, S. R., Voss, L. D., & Bromley, L. K. (2017). *NASA Systems Engineering Handbook Revision 2*.

[2] National Aeronautic and Space Administration (2016). *Expanded Guidance for NASA Systems Engineering (Vol. 1 and 2).*

[3] National Aeronautic and Space Administration (Sept. 14, 2022). *2023 NASA Lunabotics Challenge Guidebook*.

[4] National Aeronautic and Space Administration (Dec. 2022). *RMC Archive 2020*. Retrieved from **https://www.nasa.gov/content/rmc-archive-2020**

[5] National Aeronautic and Space Administration (Apr. 2013). NASA Procedural Requirements 7123.1B. Retrieved from **https://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal_ID=N_PR_7123_001B_&page_name=main**

Appendix A: Mission Constraints

ID	Constraint	Source [3]	Competency Impact		
			Mechanical	Electrical	Software
C1	The maximum mass of the system is 80kg	5.1.1	High	Intermediate	Low
C2	Maximum volumetric space of the system is 1.1m in length, 0.6m in width, and 0.6m in height	5.1.1	High	Intermediate	Low
C3	The maximum operational height of the robot is 1.5m	5.1.1	High	Intermediate	Low
C4	The system has four (4) lifting points, clearly marked (ISO 7000-1368) for students and NASA staff.	5.1.2	Intermediate	Low	Low
C5	The system cannot incorporate touch sensors.	5.1.9	Low	Intermediate	Intermediate
C6	The system will have a means of being disabled (full disconnection from power) using a COTS red button with a minimum diameter of 40m.	5.1.10	Intermediate	High	Low
C7	The system will be self-powered and monitor its power consumption using a COTS power consumption meter	5.1.11	Low	High	Intermediate
C8	The system cannot utilize fundamental physical processes, gasses, fluids or consumables that would not work in an off-world environment.	5.1.12	High	Low	Low
C9*	The system cannot be anchored to the sand prior to the beginning of the proof of life demonstration	6.3.3	High	Low	Low
C10*	The system must move on the sand surface	6.3.10	High	Intermediate	Intermediate
C11*	The system being weighed will be recorded for the Proof of Life video	6.3.14	-	-	-
C12*	The dimensions of the system will be recorded by the faculty member to certify its validity within the competition.	6.3.14	-	-	-
C13**	The system will communicate with the Ground Station using commercial 802.11ac wireless communications (WiFi)	*Pre-Existing NASA RMC Guideline (In-Person)*	Low	Intermediate	High

**Mission Constraint Catered Towards Remote Competition*

***Mission Constraint Towards Previous NASA Lunabotics Competition and Utilized as a Basis Pre-Release of the Guidebook*

Appendix B: Technical Measures

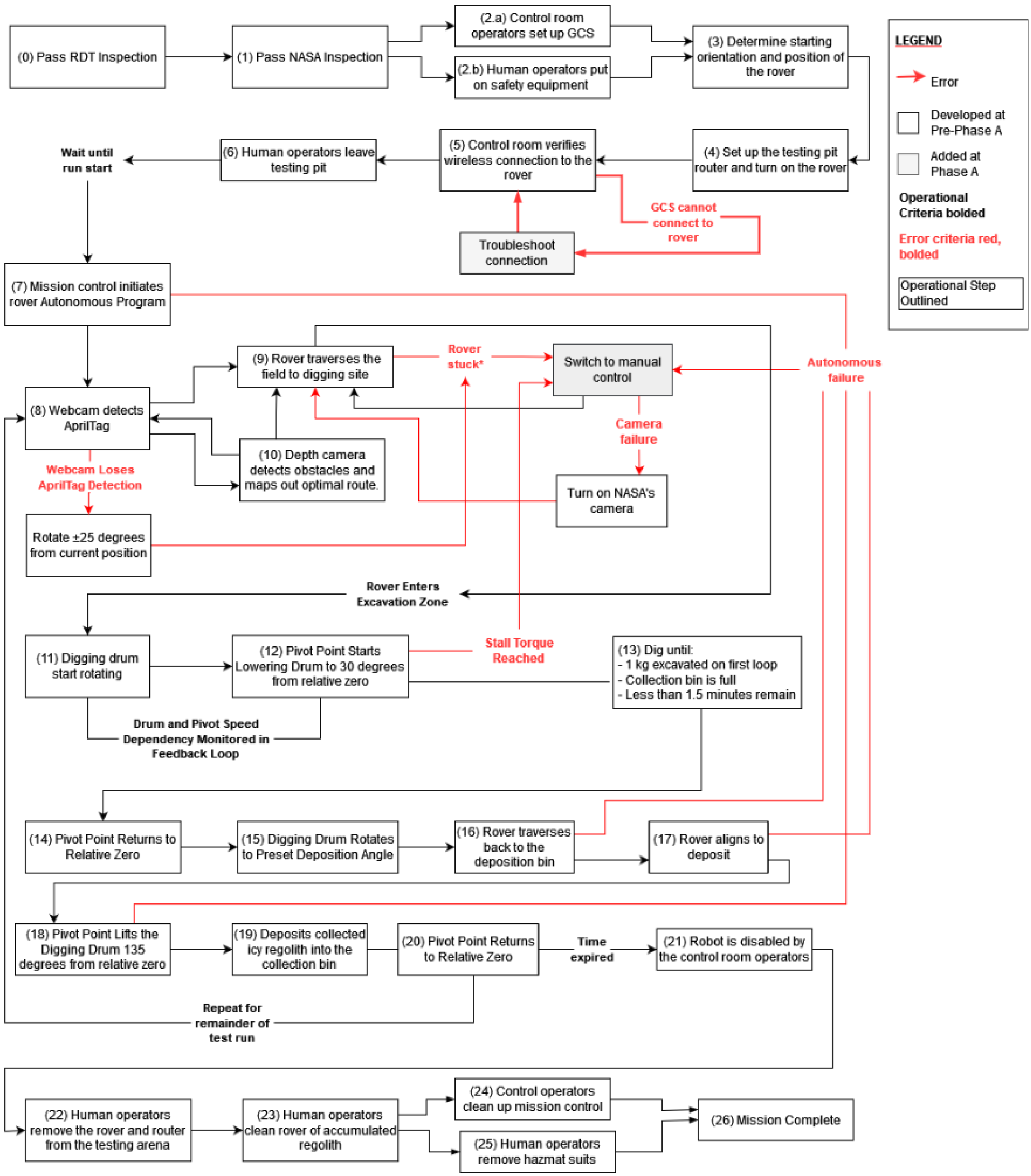
TABLE B1
System Measures of Effectiveness

ID	Definement	Traced From
MOE1	Capability to differentiate gravel icy regolith from BP-1 regolith	G2
MOE2	Able to collect at least 10 kg of gravel in 15 minutes	Ob3, Ob7
MOE3	Capable of operating fully autonomously consistently (as defined by NASA Lunabotics Guidelines)	G6, Ob2
MOE4	System has a mass less than 80kg	C1, G5, Ob1
MOE5	System uses less than 40 Wh of electrical power	G5
MOE6	System is capable of operating in the target environment	C8, C9, C10, G1
MOE7	System uses less than 15 Mbps bandwidth for communication*	Ob4

TABLE B2
System Measures of Performance

ID	Definement	Traced From
MOP1	Remove 75% of BP-1 from regolith and BP-1 during differentiation	MOE1
MOP2	The system will make two runs, prioritizing the first run to focus on collecting and depositing the necessary minimum 1kg of icy regolith.	MOE2
MOP3	System mass is less than 65 kg	MOE4
MOP4	Provide capability for the system to perform without GCS input	MOE6
MOP5	System provides the capability to protect critical components against dust intrusion.	MOE7

Appendix C: Mission Concept of Operations



Appendix D: Technical Requirements

TABLE D1

System Technical Requirements

ConOp Stage	ID	Requirement	Category	Affected Competency	Rationale	Traced From
(0)	SR1	Robot communication with control room shall be checked every 30-60 sec	F+S	Electrical, Software	The system needs to assure communication to the GCS to effectively collect and assess information	*Actions deemed necessary from prior NASA Lunabotics and NASA RMC participation*
	SR2	Robot shall be able to collect data about its environment	F+P+I	Software	The system needs to assess its environment to determine location and future actions.	
	SR3	Robot shall use a maximum of 40 Whrs of power	F+P	Mechanical, Electrical, Software	Minimal power consumption means fewer point deductions	
(1)	SR4	The system shall have a mass less than 70kg	P+D	Mechanical, Electrical, Software	While less mass means fewer deductions, more mass allows for more functionality. A prioritization of functionality over minimizing mass was concluded.	C1, Ob1
	SR5	The system shall have a maximum dimension of 1.1m x 0.60m x 0.60m	D	Mechanical	Mission requirement	C2
	SR6	The system shall not extend above 1.5m during operation	F+P+D	Mechanical	Mission requirement	C3
	SR7	The system shall have a minimum of four (4) lifting points clearly marked (ISO 7000-1368), safe for human hands and for students and NASA staff to use in a safe manner	D+S	Mechanical	Mission requirement	C4
	SR8	The robot shall have a kill switch with a minimum diameter of 40 mm.	D+S	Mechanical, Electrical	Requirement and safety assurance	C6
	SR9	The robot shall have a kill switch located on the surface of the system and require no additional steps to access it.	D+S	Mechanical, Electrical	Requirement and safety assurance	C6
	SR10	The system shall be able to fully power off (disconnect from the battery) in case of the operational rule of safety violation.	D+S	Electrical	Requirement and safety assurance	C6
	SR11	The system shall not employ any components or technologies not suitable for Mars.	F+E+D	Mechanical	Mission requirement	C8
	SR12	The system shall have dustproofing measures implemented on all sensitive components.	E+D+S	Mechanical, Electrical, Software	The system needs to be able to operate in its environment safely	

	SR13	Router ID shall be changed to "Team_##".	P	Software	* Pre-Existing NASA Lunabotics Competition (In-Person)	C13***
	SR14	Router shall be set to communicate over channel 1 or 11.	P	Software	* Pre-Existing NASA Lunabotics Competition (In-Person)	C13***
(2.a)	SR15	The GCS shall connect wirelessly over the router to the robot using USA IEEE 802. 11b, 802 11g, or 802 11n standard wireless communication.	F+I	Electrical, Software	* Mission requirement	-
	SR16	The GCS shall be able to connect to a router via ethernet.	F	Software	* Mission requirement	G1
	SR17	The robot shall have manual control.	F+P	Electrical, Software	The system needs to be able to operate in case of autonomy failure	G1
	SR18	The GCS shall be able to initiate full autonomous control.	F+P	Electrical, Software	The system needs to operate fully autonomous to gain the maximum number of points in its respective category	G6, Ob2
	SR19	The GCS shall be able to initiate partial autonomous control for locomotion, excavation and deposition.	F+P	Electrical, Software	The system needs to operate partially autonomous to gain the maximum number of points in its respective category	G2, G6
	SR20	The GCS shall be able to operate manual control.	F+P	Electrical, Software	The system needs to be able to communicate with the GCS to operate in case of autonomy failure	G1
(3)	SR21	The team shall be able to declare the robot's orientation by placing an arrow on a reference point that marks the forward direction of the robot.	P+I+D	Mechanical, Electrical, Software	* Mission requirement	-
(4)	SR22	The robot shall have an On-switch to turn on the robot.	F+P	Electrical	Mission requirement	C6
(5)	SR23	Robot shall receive a ping to verify connection.	F+P	Electrical, Software	The system needs to ensure there is an established communication with the GCS.	Ob2
(7)	SR24	The robot shall determine its starting position.	F+P+E	Software	For autonomy to commence, the system needs to know where in the field it is located.	Ob2
	SR25	The robot shall perform all actions autonomously.	P+E+D	Mechanical, Electrical, Software	The system needs to operate fully autonomous to gain the maximum number of points in its respective category	G6

(8)	SR26	The system shall be able to detect AprilTags.	F+I+E	Software	AprilTag detection by the system is needed as Locomotion Autonomy and Localization relies on reading the AprilTags	G6
(9)	SR27	The robot shall traverse the field to the digging site while obstacles (hills, divots) are presented.	P+E+D+S	Mechanical, Electrical, Software	Although the system is aimed to climb over and crawl out of these obstacles, for the sake of time per run, avoiding obstacles will provide the system more time to excavate and deposit.	G1
	SR28	The robot shall be able to climb over boulders that are 20 cm high and 40 cm in diameter.	P+E+D	Mechanical, Electrical, Software	The system needs to recover and return to the ideal path if encountered any of these scenarios to continue the run.	G1, Ob9
	SR29	Rover shall be able to crawl out of craters that are 40 cm deep and 40 cm in diameter.	P+E+D	Mechanical, Electrical, Software		
	SR30	Robot shall move at least 14 m.	P+D	Mechanical, Electrical, Software	The system needs to run at least once to the excavation zone and return back to the deposition bin to secure the required minimum of 1kg.	G1
(13)	SR31	Robot shall excavate to at least 30 cm depth and at most 45 cm.	F+E+D	Mechanical, Electrical, Software	The system needs to reach the icy regolith simulant to collect the minimum 1kg sample.	G2
	SR32	Robot shall be able to collect at least 1kg of excavated regolith.	P	Mechanical, Electrical	Mission Requirement	G2
	SR33	Robot shall be able to filter out material less than 2 cm in diameter.	P+D	Mechanical	No points are accumulated when depositing BP-1 regolith simulant.	G2, G3
(16)	SR34	The robot shall locate itself within the mining zone.	F+E+D	Electrical, Software	The system needs to identify its own location as an input to achieve autonomy	G1
	SR35	The robot shall traverse back to the deposition bin.	P+E	Mechanical, Electrical, Software	The system needs to deposit the icy regolith but due to the configuration of the system, the back of the robot has to face the deposition bin.	G1
	SR36	Robot shall turn back towards the deposition bin.	P+E	Mechanical, Electrical, Software		
	SR37	Robot shall be able to measure its distance from the deposition bin.	F+E	Electrical, Software	Due to design, the system needs proper alignment to ensure proper deposit.	G1
	SR38	Robot shall align with deposition bin.	P+E	Mechanical, Electrical, Software	The system needs to minimize the amount of lost regolith during deposition.	G1

(19)	SR39	Robot shall move to 10 cm away from the deposition bin	F+P	Mechanical, Electrical, Software	Due to design, the system needs proper distance to ensure proper deposit.	G1
	SR40	The robot shall deposit collected icy regolith into the collection bin	F+I+D	Mechanical, Electrical, Software	Mission requirement	G3, G4
	SR41	The system shall be able to deposit at least 1 kg of icy gravel in 15 minutes of operation	F+P	Mechanical, Electrical, Software	Mission requirement	G3, G4, Ob8
	SR42	Robot shall deposit material at least 0.5 m above the ground	F+P+E	Mechanical, Electrical, Software	Mission requirement	G4

TABLE D2
Subsystem Technical Requirements

Subsystem	ID	Requirement	Category	Traced From
Locomotion	L1	The robot shall be able to move forward, backward	F+P+E+D	SR27
	L2	The robot shall be able to move left (clockwise) and right (counterclockwise) no more than ± 25 DEGREES	F+P	
	L3	The robot shall have (4) wheels	D	
	L4	The robot shall have a clearance of 15 cm	D+S	
	L5	The robot shall be able to climb over mounds that are MAX 10 cm high	D+S	
	L6	The robot shall be able to carry the Excavation and Deposition subsystem (arbitrary 40kg)	I+D	
	L7	The robot shall have a dedicated volume for the EE box	I+D	
	L8	The robot shall dustproof the EE box with a rating of IP6X	D+S	
	L9	The robot shall have a dedicated placement for the camera	I+D	
	L10	The system shall record its power consumption using a COTS product	P+I+D	
	L11	The system shall record the torque provided on each motor	P+I+D	
	L12	The system shall use a maximum of 20 Whrs of power	P+D	
	L13	The robot shall distribute the battery power to all other components	F+I+D	
	L14	The robot shall detect obstacles 3m away so that it doesn't have to turn more than ± 25 degrees	F+P+E	
	L15	The robot shall retain a map to remember optimal path and obstacles	P+E+S	
	L16	The robot shall always be able to detect the AprilTags	P+E	
	L17	The robot / camera mount shall be able to shake/vibrate minimally	P+I+D	
	L18	The webcam shall be elevated high enough such that it maintains AprilTag in sight	P+I+D	
	L19	The depth camera shall be elevated enough such that it maintains vision of the arena	P+I+D	

	L20	The robot shall be able to determine its position and orientation	P
	L21	The robot shall carry the EE box	I+D
	L22	The EE box shall have a maximum volume of (28cm x 19cm x 18cm)	D
	L23	The robot shall have connectors that can survive the environment (testing, shipping and handling, troubleshooting...etc)	E+S
	L24	The robot shall have flush connections	F+D
Excavation	E1	The robot shall have a digging drum that is able to rotate	P+D
	E2	The robot shall have a pivot system that is able to rotate/lift the drum 60 degrees (40cm below the ground)	F+P+I+D
	E3	The robot shall be able to carry a minimum of 1kg of excavated regolith	P+D
	E4	The robot shall have sensors to detect hard stop (maximum digging depth)	F+E+S
	E5	The robot shall be able to excavate 0.1kg/min	F+P
	E6	The system shall know when its rotation cycle reaches relative 0	F+P+I
	E7	The system shall allocate space for wire management / cable running	I+D+S
	E8	The system shall not interfere with camera detection	I+D
	E9	The system shall record its power consumption using a COTS product	P+I+D
	E10	The system shall record the torque provided on each motor	P+I+D
	E11	The robot shall dustproof each motor with a rating of IP6X	D+S
	E12	The system shall have a maximum mass of 35 kg	D
Deposition	D1	The deposition system shall be able to carry a load of 1kg of excavated regolith	F+P
	D2	The deposition system shall be able to deposit the excavated regolith	F
	D3	The deposition system shall not extend past 1.5 m off the ground	D
	D4	The deposition system shall deposit excavated regolith 0.5 m off the ground	P+I+E+D
	D5	The deposition system shall be able to filter icy regolith simulant	F+D
	D6	The camera shall be able to detect the deposition bin	F+I
	D7	The robot shall be able to localize with the bin	P+I
	D8	The robot shall align with the bin	P+I
	D9	The robot shall approach to 80 cm away from the bin	F+P+I
	D10	The system shall not interfere with camera detection	I+D
	D11	The system shall record its power consumption using a COTS product	P+I+D
	D12	The system shall record the torque provided on each motor	P+I+D
	D13	The robot shall dustproof each motor with a rating of IP6X	D+S
	D14	The system shall use a maximum of 10 Whrs of power	D

Appendix E: Technical Budgets

TABLE E1

Initial Technical Budget (October 20, 2022)

Budget Criteria	Weight (kg)	Bandwidth (kbps)	Power Consumption (Wh)	Capital Cost ($)	Operation Duration (s)	Regolith Manipulation	Volume (m3)
Total System Target	75	15	45	15000	600	5 kilograms scored	0.72
Locomotion Subsystem Allocation	10	8	20	2300	270	*N/A*	0.20
Deposition Subsystem Allocation	10	2	5	1900	90	0.5444 kg/s offload rate	0.19
Storage / Differentiation Subsystem Allocation	5	0[1]	5	850	150[2]	45 kg payload capacity	0.08
Digging Subsystem Allocation	30	5	10	4000	240	0.35 m mining depth 0.16 kg/s digging rate	0.25
Locomotion - Digging Interface (Structural)	6	*N/A*	*N/A*	150	*N/A*	*N/A*	*N/A*[3]
Locomotion - Storage Interface (Structural)	5	*N/A*	*N/A*	150	*N/A*	*N/A*	*N/A*[3]
Locomotion - Deposition Interface (Structural)	5	*N/A*	*N/A*	150	*N/A*	*N/A*	*N/A*[3]
Digging - Storage Interface	2	0[1]	2.5	250	240[4]	Will allow for 0.16kg/s	*N/A*[3]
Storage - Deposition Interface	2	0[1]	2.5	250	90[4]	Will allow for 0.833 kg/s	*N/A*[3]

TABLE E2

Actual Technical Budget (February 7, 2023)

Budget Criteria	Weight (kg)	Bandwidth (kbps)	Power Consumption (Wh)	Capital Cost ($)	Operation Duration (s)	Regolith Manipulation	Volume (m3)
Total System Target	65	0[5]	38.7	1253	600	10 kilograms scored	0.84
Locomotion Subsystem Allocation	25	0[5]	17.1	4692	480	*N/A*	0.81
Deposition Subsystem Allocation	10	0[5]	4.3	1816	120	0.8333 kg/s offload rate	0.03
Storage / Differentiation Subsystem Allocation	8	0[5]	0	1272	10[1]	30 kg payload capacity	0.09
Digging Subsystem Allocation	18	0[5]	12.3	2142	300	0.42 m mining depth 0.13 kg/s digging rate	0.28
Locomotion - Digging Interface (Structural)	1	*N/A*	*N/A*	79	*N/A*	*N/A*	*N/A*[4]
Locomotion - Storage Interface (Structural)			***-----INTERFACE WAS REMOVED IN FINAL DESIGN----***				
Locomotion - Deposition Interface (Structural)	1	*N/A*	*N/A*	64	*N/A*	*N/A*	*N/A*[4]
Collection Bin Mounted Controller	2	15	5	496	600[1]	*N/A*	0.04
Digging - Storage Interface	N/A	0[3]	0	0	240[2]	Will allow for 0.16kg/s	*N/A*[4]
Storage - Deposition Interface	N/A	0[3]	0	0	90[2]	Will allow for 0.833 kg/s	*N/A*[4]

[1] Automatic process that requires no communication with GCS
[2] Subsystem operates simultaneous to other subsystems (passive)
[3] Volumes for interfaces are contained within subsystem volume allocation
[4] Interface operates during interfaced subsystem's allocated operation
[5] Individual subsystems no longer communicate directly with the GCS.

Appendix F: Requirements Verification

ConOps Stage	ID	Requirement	Verification Success Criteria	Verification Method	Phase	Results
(0)	SR1	Robot communication with control room shall be checked every 30-60 sec	The system will send a response statement back to the GCS to verify connection with the system	Response from the system will be monitored during the allotted time checks.	A	The system is properly connected and communication is secured at each time check.
	SR2	Robot shall be able to collect data about its environment	Obstacles are highlighted in the point cloud	Higher Altitudes will be colored blue, lower altitude colored yellow	C and D	Information deciphered for locomotion autonomy
	SR3	Robot shall use a maximum of 40 Whrs of power	The power consumption will be less than the maximum and will be monitored using a COTS device	Individual component power consumption will be calculated. During verification, system power will be calculated	C and D	Estimates place consumption at 38.7 Wh; however, this is a liberal estimate, therefore actual consumption will be lower.
(1)	SR4	The system shall have a mass less than 70 kg	The system mass is less than or equal to 70kg.	Individual components are measured for compliance with the sum / final system is weighed	C and D	Estimates place the mass at 64.5 kg.
	SR5	The system shall have a maximum dimension of 1.1m x 0.60m x 0.60m	The system dimension is less than the max	The final system is measured and compared to the volume	D	The entirety of the system (pre-extension) fits within 95% of the required volume.
	SR6	The system shall not extend above 1.5m during operation	The system dimension is less than the max	The final system during any necessary extension, translation or rotation will be measured from its greatest extension	D	The system has a maximum height of 1.2m
	SR7	The system shall have a minimum of four (4) lifting points clearly marked (ISO 7000-1368), safe for human hands and for students and NASA staff to use in a safe manner	The system will have (4), marked and visually available to any personnel.	Accessibility and clear visuals denoting lifting points of the robot.	C	The system has (4) clearly distinguished locations to safely be lifted by the personnel.
	SR8	The robot shall have a kill switch with a minimum diameter of 40 mm.	The system disconnects fully on emergency power-off with no	During verification, the system will be fully powered off	D	The circuit is made to do so, the components were

	SR9	The robot shall have a kill switch located on the surface of the system and require no additional steps to access it.	ability to recover	(repeatedly) to ensure reliability		tested, the final system must still be verified during multiple operational scenarios.
	SR10	The system shall be able to fully power off (disconnect from the battery) in case of the operational rule of safety violation				
	SR11	The system shall not employ any components or technologies not suitable for Mars	The system does not use unacceptable technology.	During design, no prohibited technologies will be employed	B and C	No prohibited technologies were used.
	SR12	The system shall have dustproofing measures implemented on all sensitive components	During operation in the target environment, the system functions as intended	During fabrication individual components will be tested for dust tolerance, during verification, the entire system will be tested for full functionality exposed to dust	C and D	The electrical enclosures were buried in BP-1 and found to not have allowed any regolith inside.
	SR13	Router ID shall be changed to “Team_##”	Router ID is presented as the intended title.	Team will visually note the Router ID preset to the intended title.	B	The router ID properly displays the intended title.
	SR14	Router shall be set to communicate over channel 1 or 11	Data and operational steps are successfully communicated to the rover over respective channels.	During testing, information will be sent to the robot solely over channels 1 or 11.	B	The router properly communicates to the robot over channel 1 or 11.
	SR15	The GCS shall connect wirelessly over the router to the robot using USA IEEE 802. 11b, 802 11g, or 802 11n standard wireless communication	Send data from one device and display on another	Visual check	B	Successfully transmit and view data between devices
(2.a)	SR16	The GCS shall be able to connect to a router via ethernet	Verify stable network	Visually check to see if network is secured	A	Successfully connected to the network
	SR17	The robot shall have manual control	The robot will be able to decipher key actions from the GCS and translate that to electromechanical actions	During the design stage, key inputs are delivered to the robot to perform preliminary actions.	B	The robot was able to perform given a set of inputs from the GCS

	SR18	The GCS shall be able to initiate full autonomous control	The system is able to receive a call action for various levels of autonomy (None, Partial, Full) during verification	During verification, an autonomous run will be initiated repeatedly to ensure reliability.	C	The robot is able to receive the "Go-Ahead" condition to initiate any level of autonomy
	SR19	The GCS shall be able to initiate partial autonomous control for locomotion, excavation and deposition.				
	SR20	The GCS shall be able to operate manual control				
(3)	SR21	The team shall be able to declare the robot's orientation by placing an arrow on a reference point that marks the forward direction of the robot.	The robot will be clearly marked with a visual sign that distinguishes front and back of the robot.	Visual check	A	Successful demonstration of the forward arrow.
(4)	SR22	The robot shall have an On-switch to turn on the robot	An on-switch will be easily accessible via the EE box to power on the robot	Once the on-switch is activated, a visual check will be conducted to see if power is distributed to all motores	B and C	Successful on-switch was incorporated and power was distributed to all components.
(5)	SR23	Robot shall receive a ping to verify connection	The system will accept a response statement from the GCS to verify connection	Response from the system will be monitored	B and C	The system detects and accepts the ping request.
(7)	SR24	The robot shall determine its starting position	The webcam is able to read and decipher AprilTag to determine its location within the arena	Returns the X,Y position of the robot relative to the corner of the arena	C and D	The robot can locate where it is located at the beginning of the mining run.
	SR25	The robot shall perform all actions autonomously	The system meets all requirements of full autonomy as stated by the NASA Lunabotics Guideline	During verification, an autonomous run will be completed repeatedly to ensure reliability.	D	While autonomy has been simulated via computer models, final testing has yet to take place.
(8)	SR26	The system shall be able to detect AprilTags	A box is drawn around a still captured image of the AprilTag	Visual Confirmation	B and C	The system is able to draw boxes around each AprilTag presented
(9)	SR27	The robot shall traverse the field to the digging site while obstacles (hills, divots) are presented	The robot and/or driver is able to detect and redirect itself from the obstacles ahead.	The environment will be simulated and the robot will traverse the mock arena primarily avoiding any obstacles.	B and C	The robot and/or driver has sufficient maneuverability to redirect themselves from the presented obstacles

	SR28	Robot shall be able to climb over boulders that are 20 cm high and 40 cm in diameter	Simulated errors do not result in mission failure	The error will be simulated during verification and recovery tested	D	Final system operation tested as of March 19, 2023
	SR29	Rover shall be able to crawl out of craters that are 40 cm deep and 40 cm in diameter				
	SR30	Robot shall move at least 14 m	The translation of the robot after 5 minutes will be measured	A 14m distance will be marked on a simulated environment and a timer will be set once the robot begins to move to note efficiency.	B and C	The robot at its highest speed setting is able to traverse the designated distance within 1 minute time.
	SR31	Robot shall excavate to at least 30 cm depth and at most 45 cm	The maximum extension of our excavating system will be measured to see if it reaches within set boundaries.	The centerpoint of our excavation system will be marked and traced how much lateral displacement was conducted.	C and D	At its maximum, the excavation system successfully reached 42 cm in depth from ground level.
(13)	SR32	Robot shall be able to collect at least 1kg of excavated regolith	Post excavation, the storage system will be weighed to note the weight of regolith collected.			
	SR33	Robot shall be able to filter out material less than 2 cm in diameter				
	SR34	The robot shall locate itself within the mining zone	The webcam is able to read and decipher AprilTag to determine its location within the arena	Returns the X,Y position of the robot relative to the corner of the arena	C and D	The robot can locate where it is located at the beginning of the mining run.
	SR35	The robot shall traverse back to the deposition bin				
	SR36	Robot shall turn back towards the deposition bin				
(16)	SR37	Robot shall be able to measure its distance from the deposition bin				
	SR38	Robot shall align with deposition bin	Utilizing AprilTag X,Y coordinates, the appropriate yaw must be reached	The environment will be simulated and the robot will turn to a specific yaw if and when commanded to	D	While alignment has been simulated via computer models, final testing has yet to take place.

(19)	SR39	Robot shall move to 15 cm away from the deposition bin	The webcam is able to read and decipher AprilTag to determine its location within the arena	Returns the X,Y position of the robot relative to the corner of the arena	C and D	The robot can determine where it is located at the deposition phase.

APPENDIX G: Electrical Systems Management

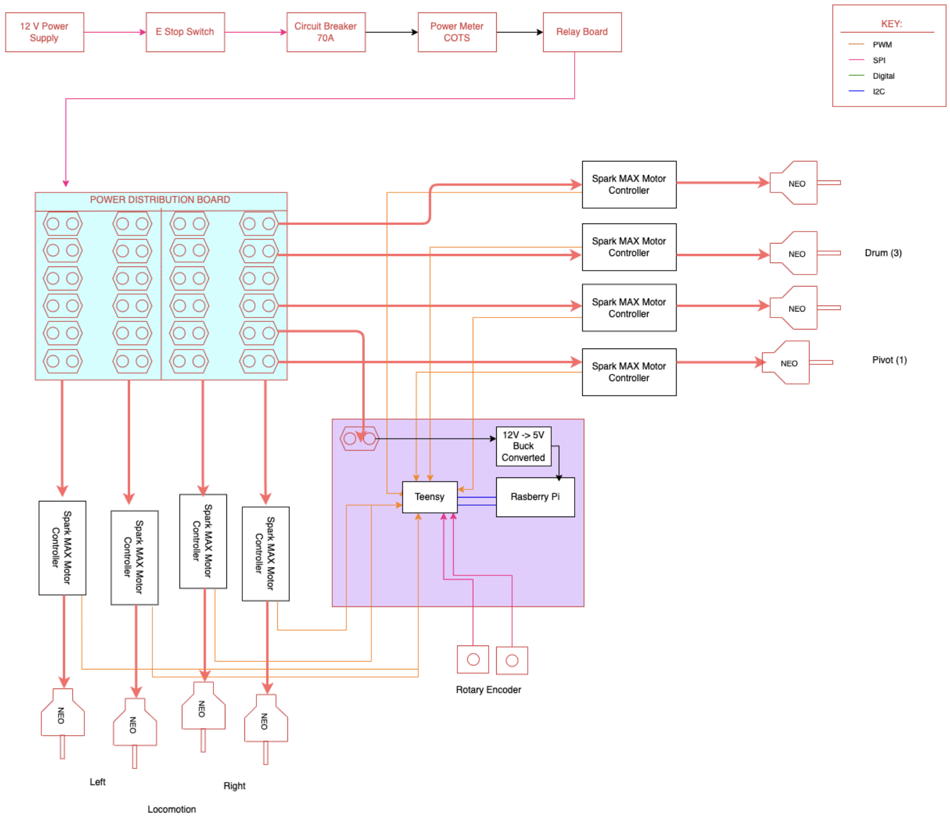


Figure G1: The Input and Output Diagram

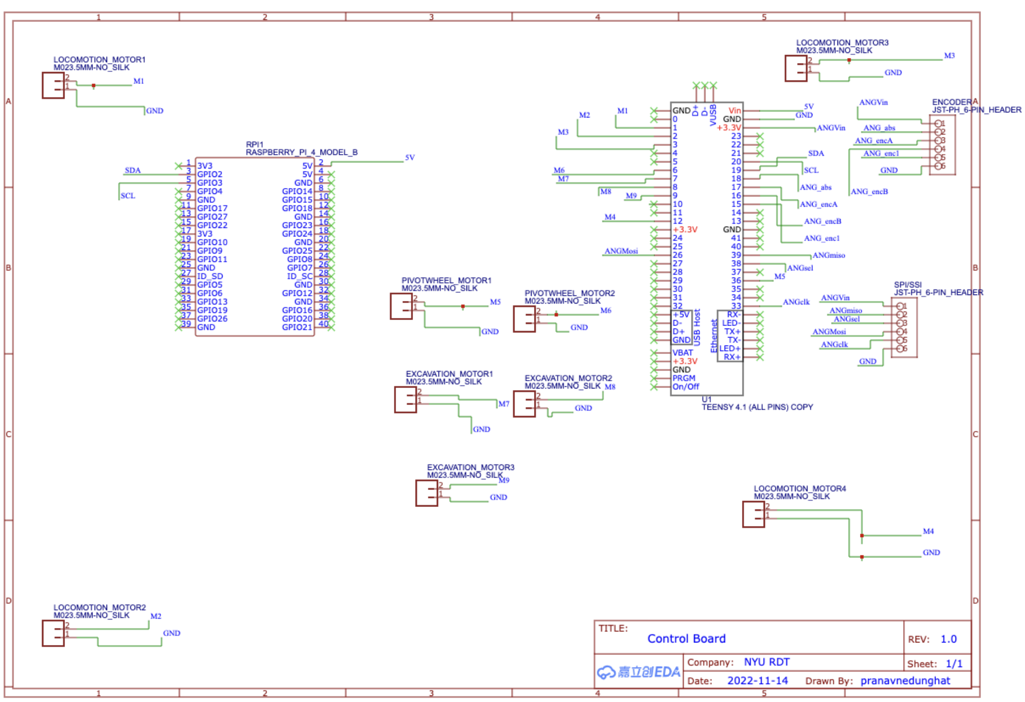


Figure G2: The control Board schematic

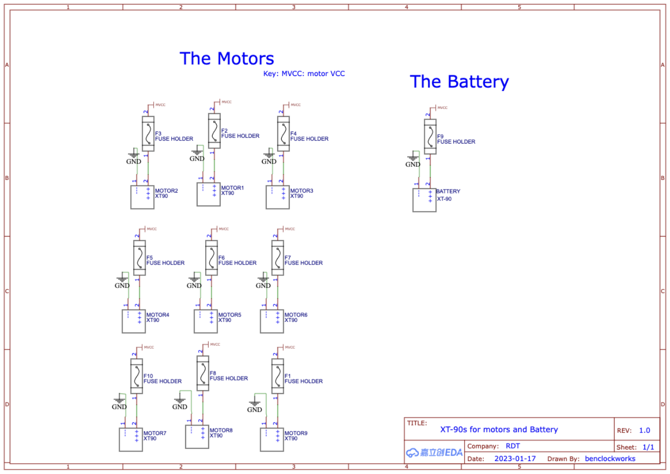


Figure G3: The Motors and Battery circuit

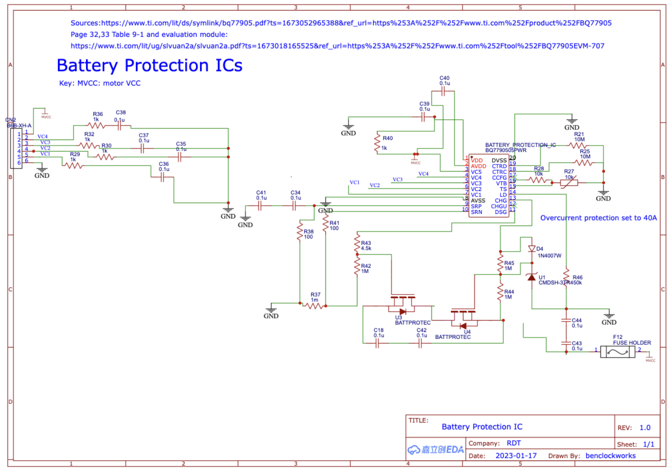


Figure G4: The Battery Protection Circuits

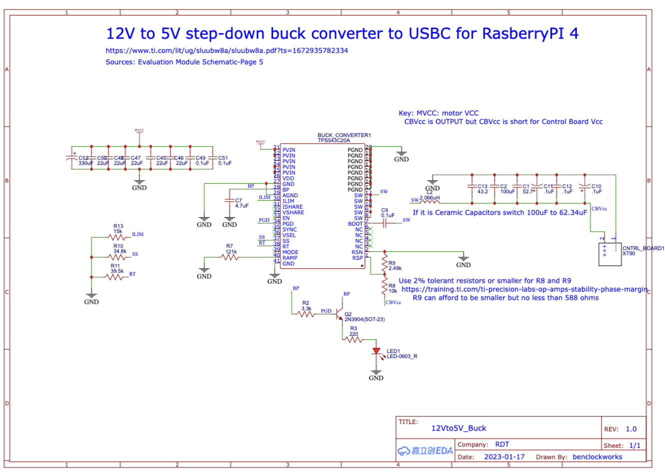


Figure G5: 12 to 5V Step-down Buck Converter

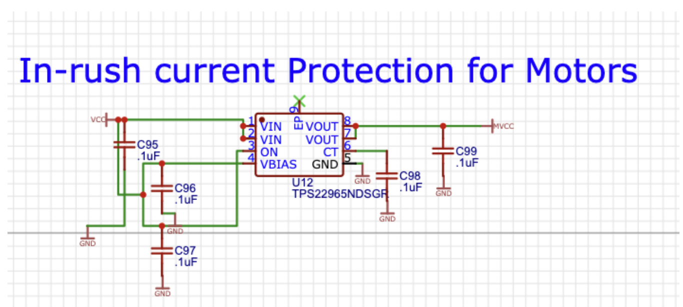


Figure G6: In-rush Current Protection circuit (Abandoned due to lack of necessity)

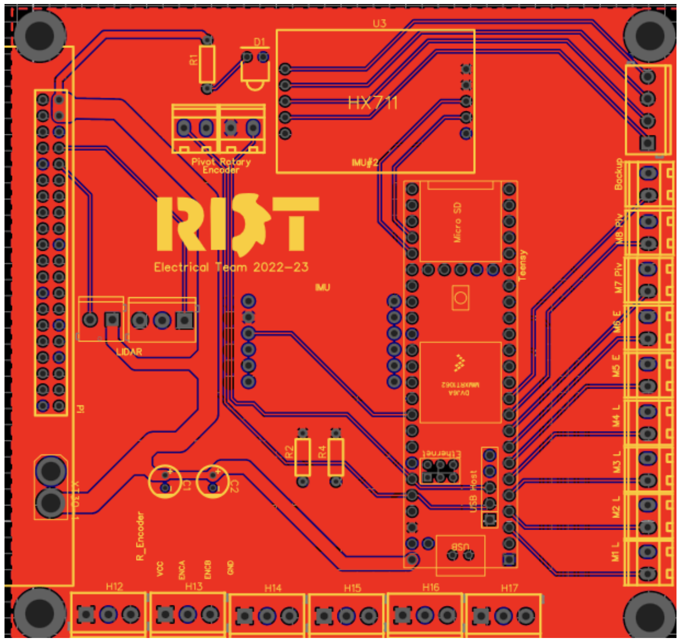


Figure G7: The RDT Control Board

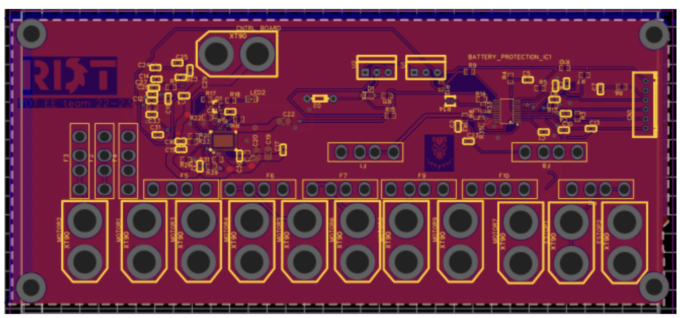
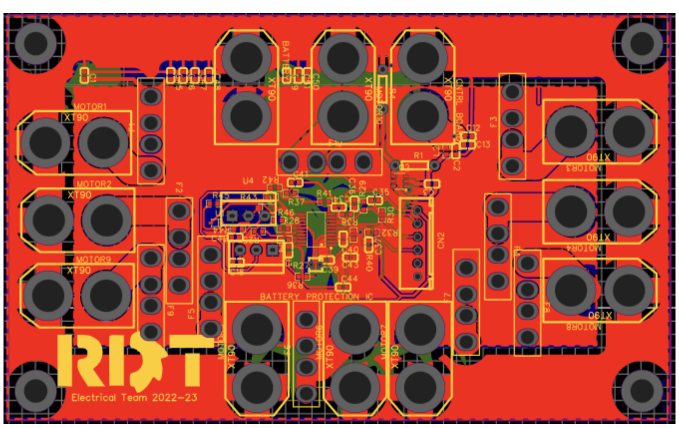


Figure G8: The older PDB



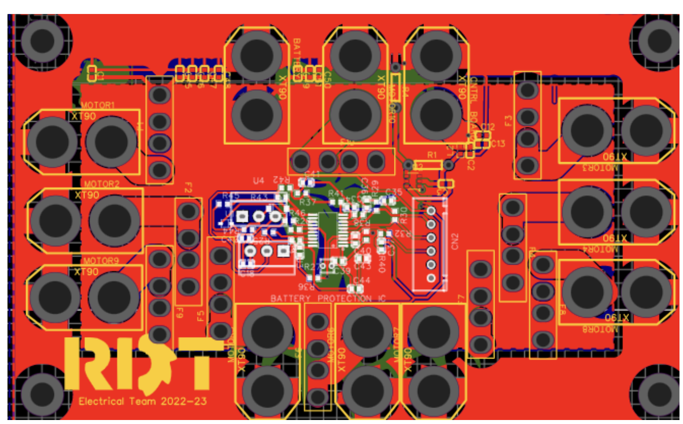
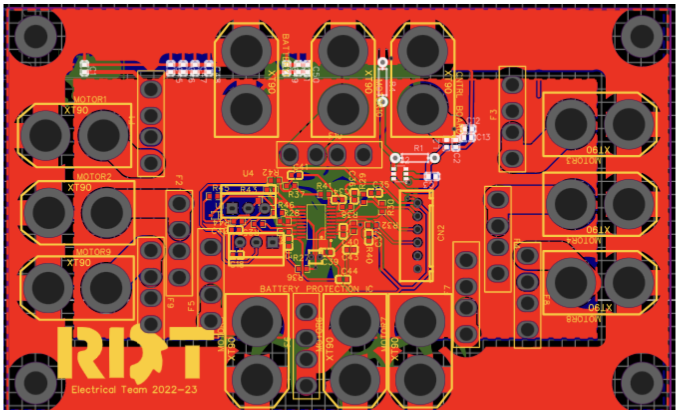


Figure G9: The Power Distribution board with the ICs Figure G10: The Battery Protection IC within Figure G9



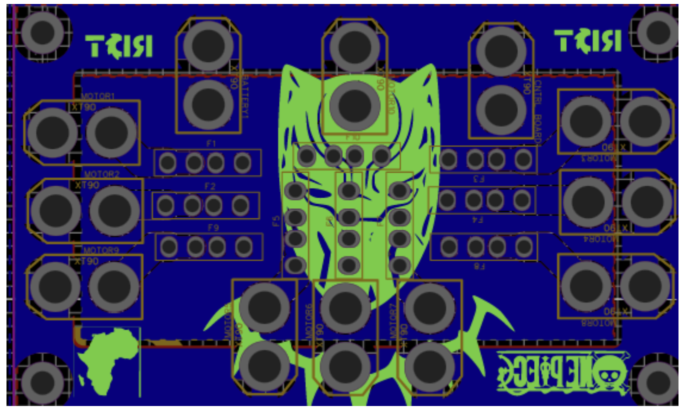


Figure G11: The 12 to 5V Buck converter within figure 9 Figure G12: The Regular Power Distribution Board's bottom side

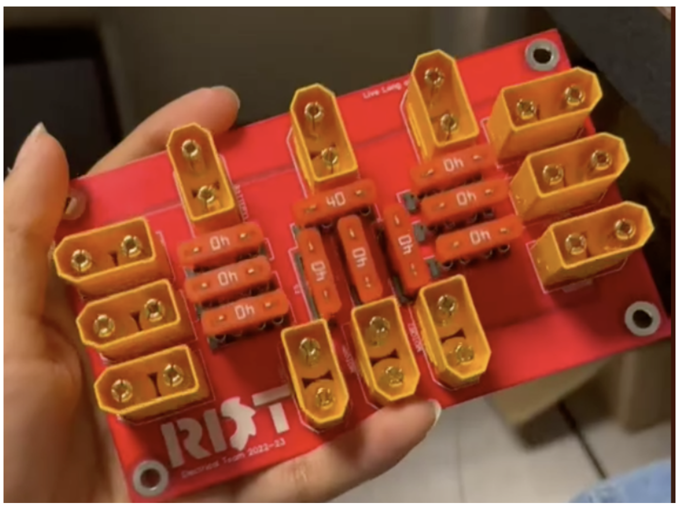


Figure G13. The Regular Distribution reworked and assembled

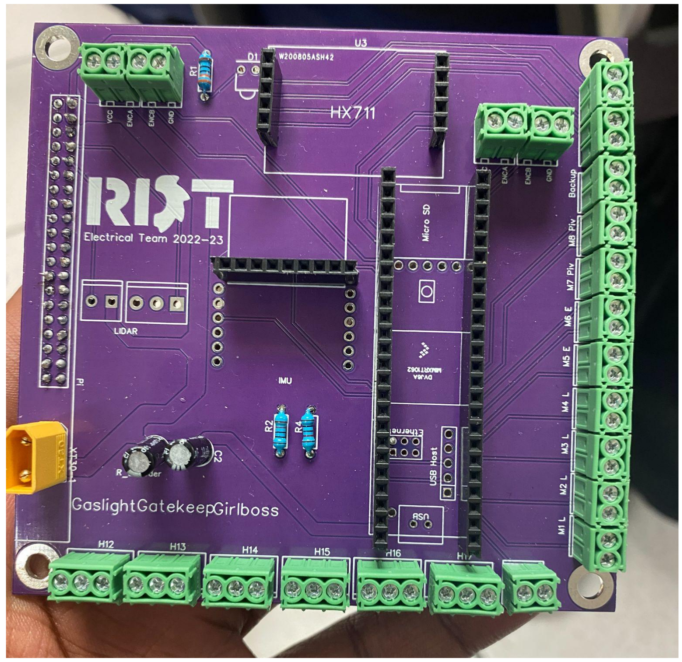


Figure G14. The final reworked control board

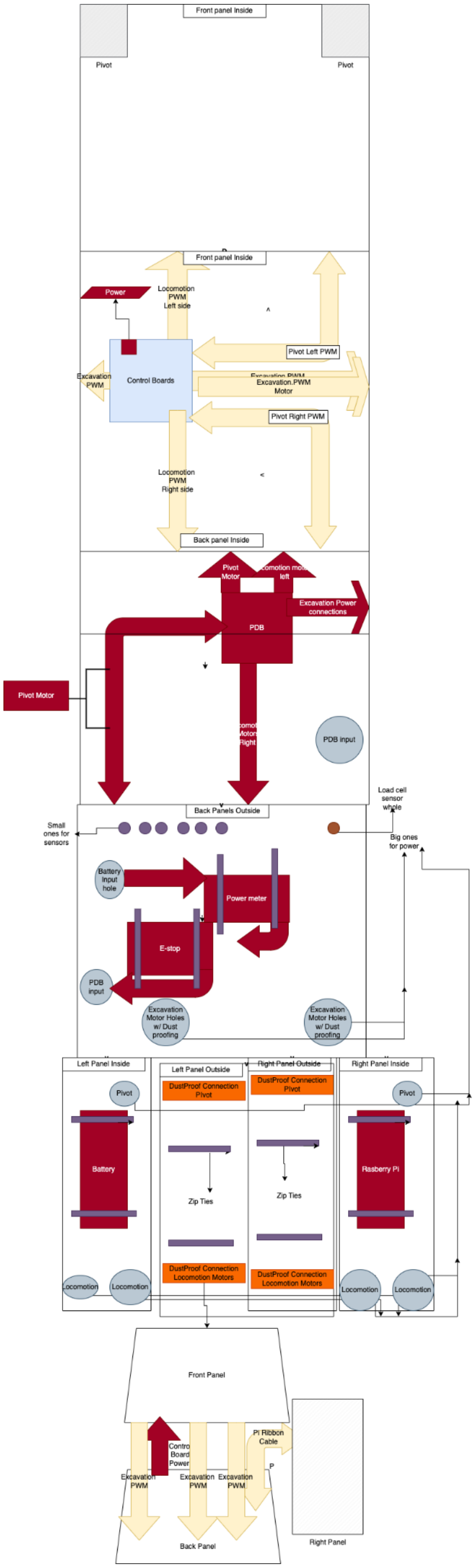


Figure G15: The Wire Management layout

Figure G16: The Power Consumption of the entire Robot

Appendix H: Software Systems

FIGURE H1

General Autonomy State Diagram

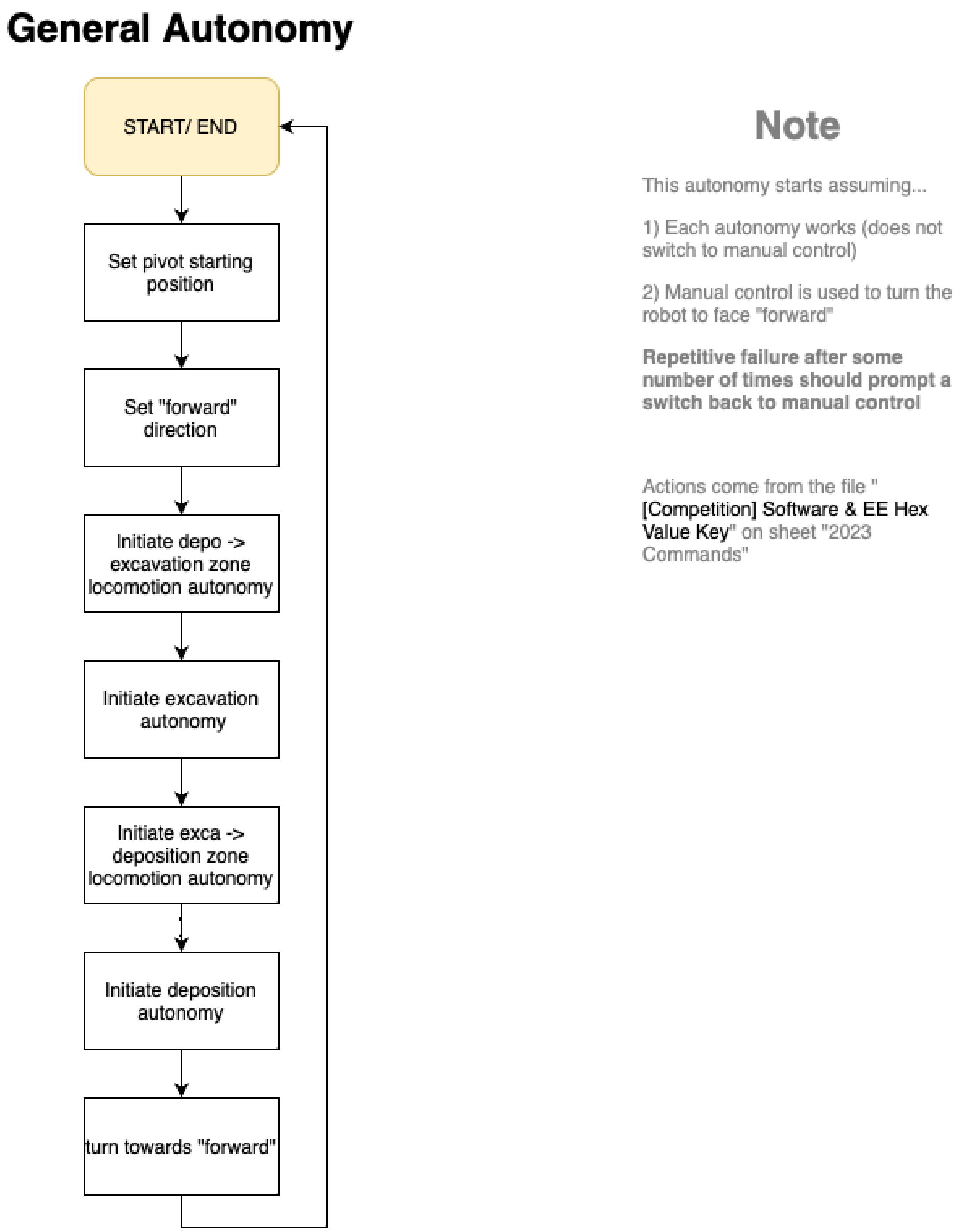


FIGURE H2

Excavation Autonomy State Diagram

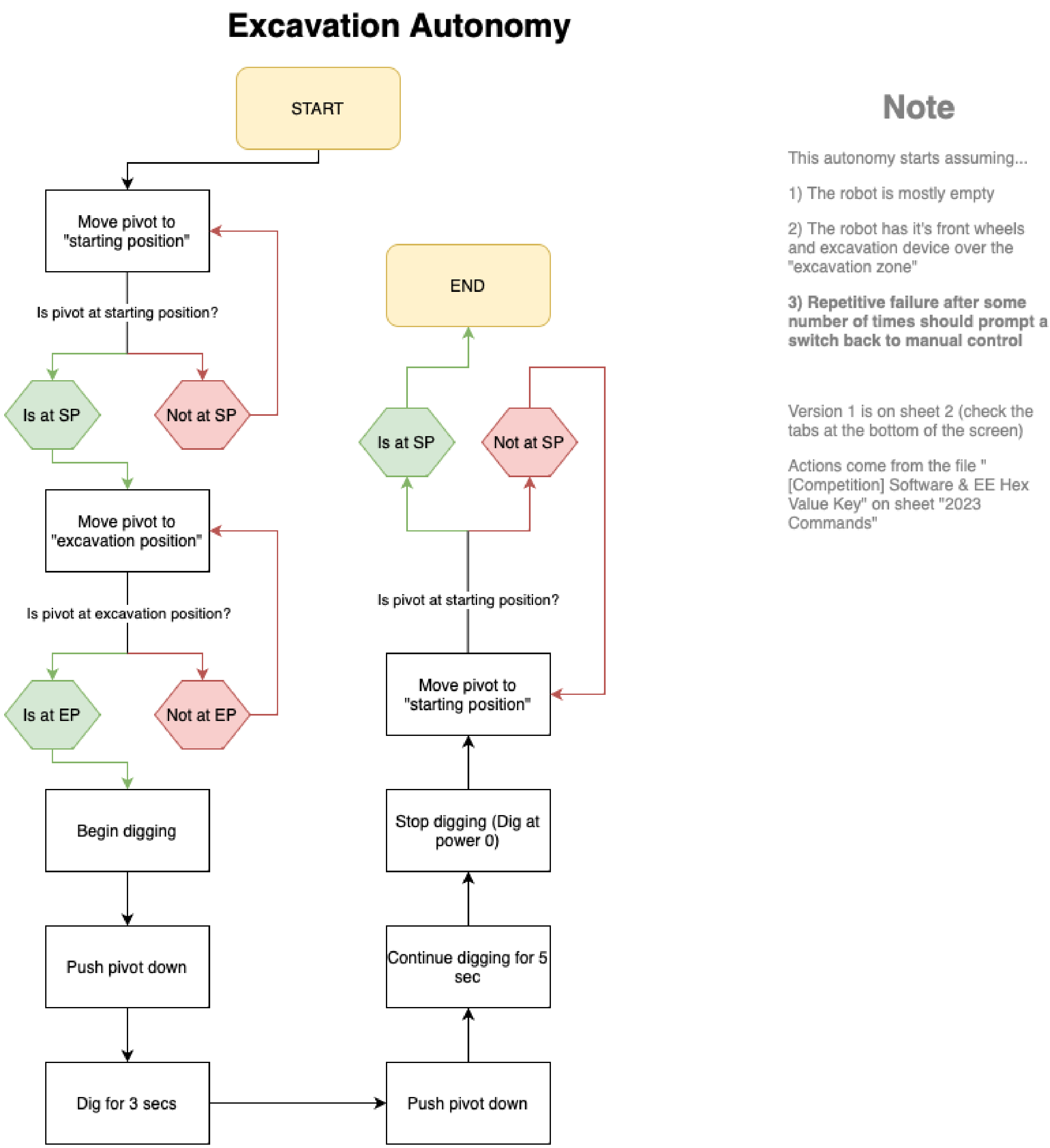


FIGURE H3

Deposition Autonomy State Diagram

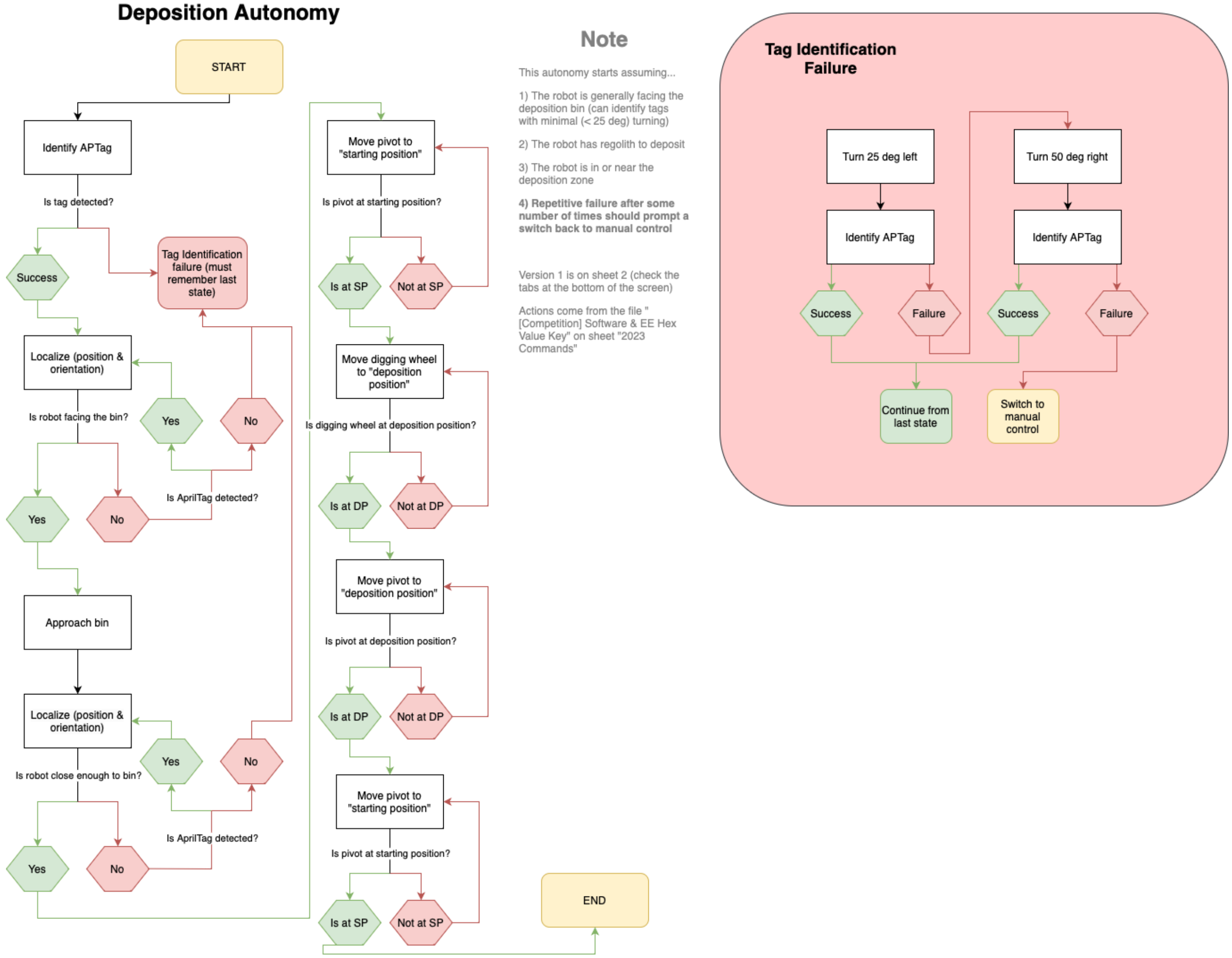


FIGURE H4

Locomotion Autonomy State Diagram

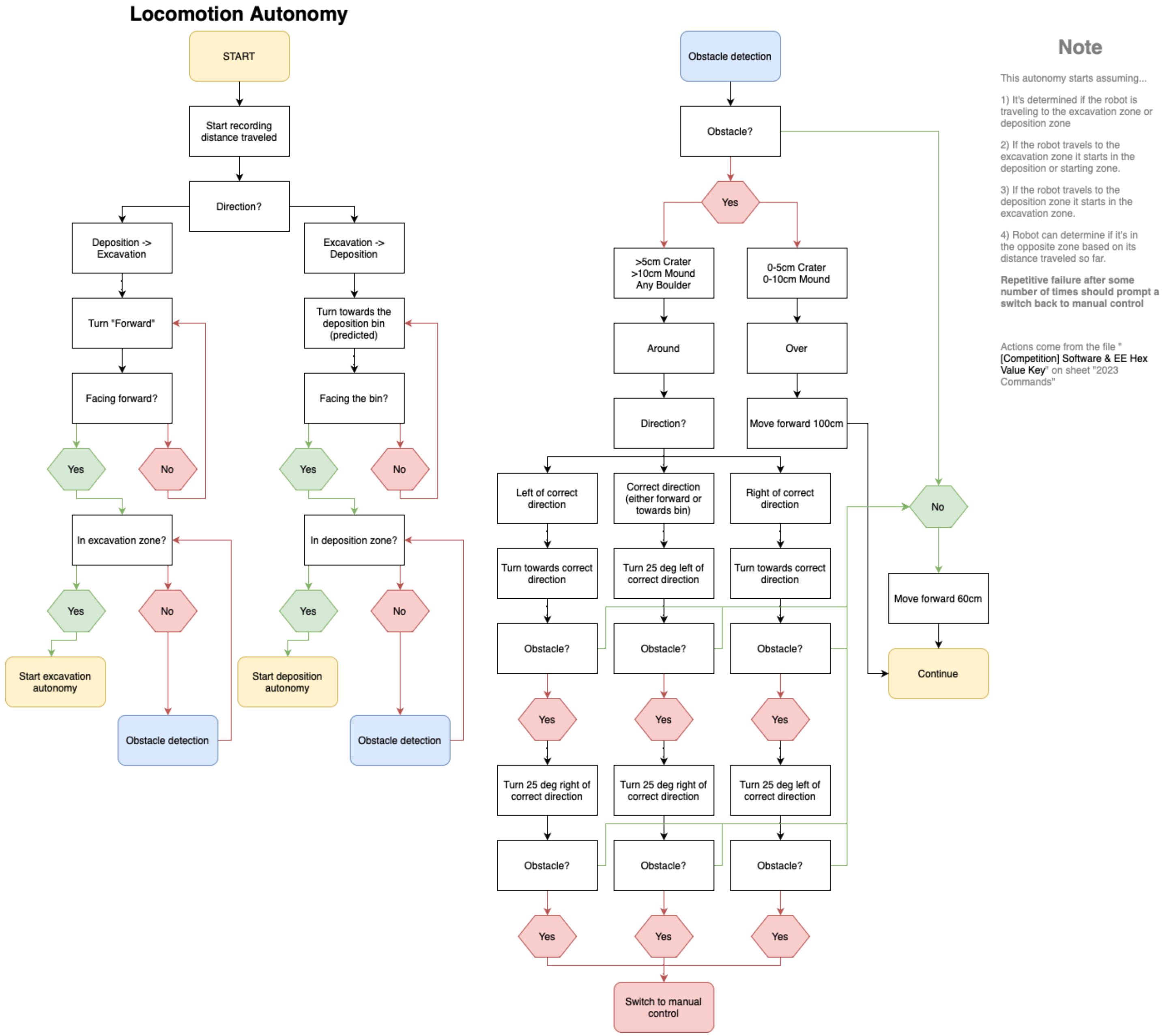


FIGURE H5
Manual Control Scheme (Keyboard)

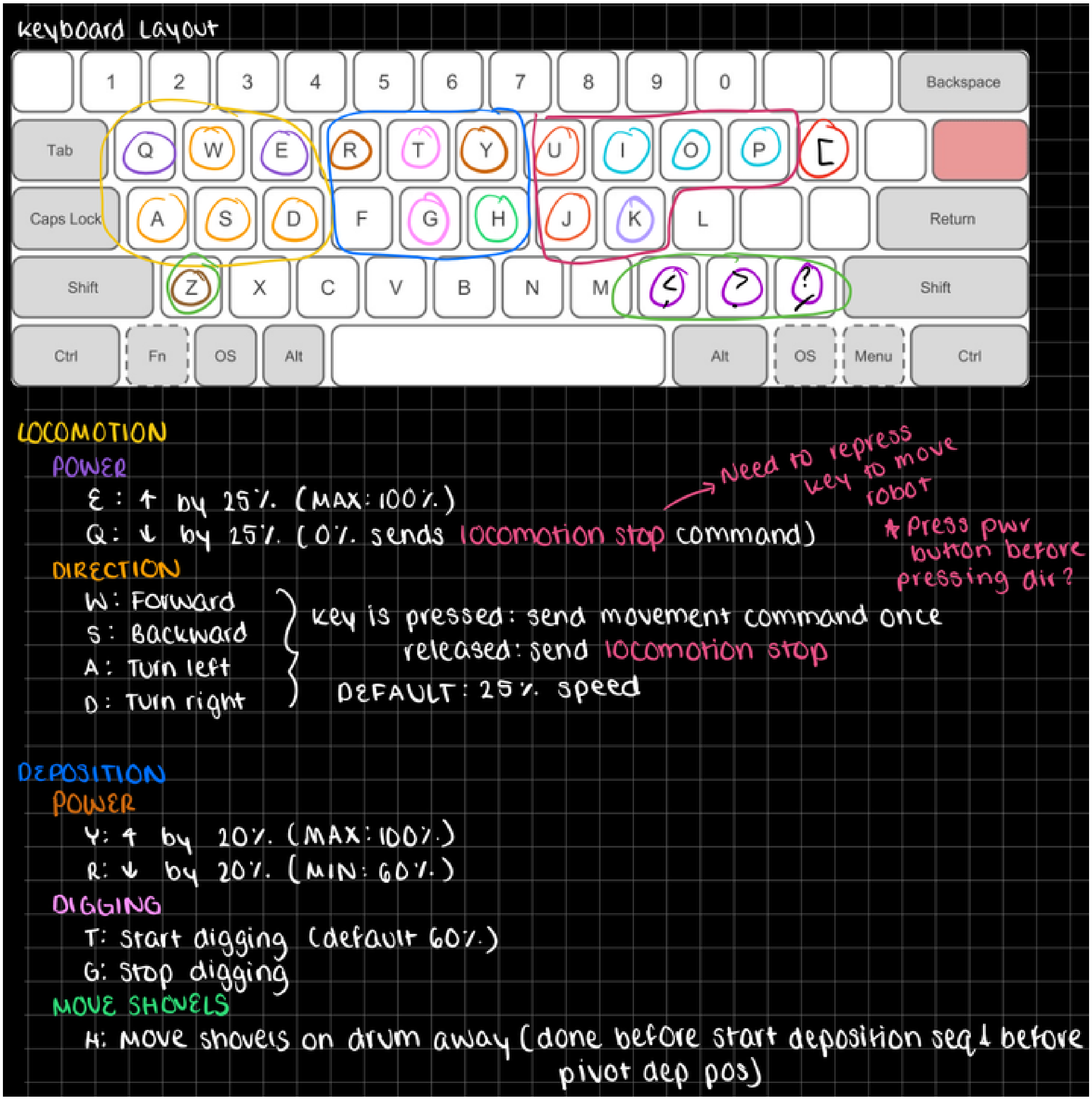


TABLE H1

Manual Control Command Key Table

	1st Nibble		2nd Nibble		Together
Category	**Command**	**Hex**	**Value**	**Hex**	**Hex**
Safety	EMERGENCY STOP	0	EMERGENCY STOP	0	0 0
Locomotion	Locomotion Stop	1	Locomotion Stop	0	1 0
	Forward	2	25%	0	2 0
		2	50%	1	2 1
		2	75%	2	2 2
		2	100%	3	2 3
	Backward	3	25%	0	3 0
		3	50%	1	3 1
		3	75%	2	3 2
		3	100%	3	3 3
	Left	4	25%	0	4 0
		4	50%	1	4 1
		4	75%	2	4 2
		4	100%	3	4 3
	Right	5	25%	0	5 0
		5	50%	1	5 1
		5	75%	2	5 2
		5	100%	3	5 3
Excavation/ Deposition	Pivot Actions	6	Zero Pivot	0	6 0
		6	Pivot to Locomotion Position	1	6 1
		6	Pivot to Deposition Position	2	6 2
		6	Pivot to Excavation Position	3	6 3
		6	Stop Pivot	4	6 4
		6	Push Pivot Up	5	6 5
		6	Push Pivot Down	6	6 6
	Drum Actions	7	Move Shovels on Drum Away	0	7 0
		7	Stop Digging	1	7 1
		7	Dig 10%	2	7 2
		7	Dig 20%	3	7 3
		7	Dig 30%	4	7 4
Other	Request Data	8	Request data	0	8 0
	Switch to Autonomous Control	8	Switch to Autonomous Control	1	8 1

TABLE H2

Locomotion, Excavation and Deposition Autonomous Command Key Table

	1st Byte		2nd Byte			Together
Category	**Command**	**Hex**	**Description**	**Value**	**Hex**	**Hex**
Safety	EMERGENCY STOP	0	ESTOP	0	0	0 0
Locomotion	Locomotion Stop	1	Locomotion Stop	0	0	1 0
	Front Left Wheel Move	2	FLW Stop	0	0	2 0
		2	Forward % Power	[1-100]	[1-64]	2 [1-64]
		2	Backward % Power	[(-1)-(-100)]	[FF-9C]	2 [FF-9C]
	Front Right Wheel Move	3	FRW Stop	0	0	3 0
		3	Forward % Power	[1-100]	[1-64]	3 [1-64]
		3	Backward % Power	[(-1)-(-100)]	[FF-9C]	3 [FF-9C]
	Back Left Wheel Move	4	BLW Stop	0	0	4 0
		4	Forward % Power	[1-100]	[1-64]	4 [1-64]
		4	Backward % Power	[(-1)-(-100)]	[FF-9C]	4 [FF-9C]
	Back Right Wheel Move	5	BRW Stop	0	0	5 0
		5	Forward % Power	[1-100]	[1-64]	5 [1-64]
		5	Backward % Power	[(-1)-(-100)]	[FF-9C]	5 [FF-9C]
Excavation/Deposition	Set Pivot Locomotion Position & Forward Direction	6	Zero Piv and set For	0	0	6 0
	Move Pivot to Locomotion Position	7	Piv Loco Pos	0	0	7 0
	Move Pivot to Deposition Position	8	Piv Depo Pos	1	1	8 1
	Move Pivot to Excavation Position	9	Piv Exca Pos	2	2	9 2
	Move Drum to Deposition Position	A	Drum Depo Pos	0	0	A 0
	Spin Drum	B	Stop Drum	0	0	B 0
		B	Forward % Power	[1-100]	[1-64]	B [1-64]
		B	Backward % Power	[(-1)-(-100)]	[FF-9C]	B [FF-9C]
	Move Pivot	C	Stop Pivot	0	0	C 0
		C	Upward % Power	[1-100]	[1-64]	C [1-64]
		C	Downward % Power	[(-1)-(-100)]	[FF-9C]	C [FF-9C]

TABLE H3

Data and Other Autonomous Command Key Table

Data	Get Pivot Angle	D	Get Piv Angle	0	0	D 0
	Check Pivot Position	E	Piv at Loco Pos?	0	0	E 0
		E	Piv at Depo Pos?	1	1	E 1
		E	Piv at Exca Pos?	2	2	E 2
	Is Drum at Deposition Position	F	Drum at Depo Pos?	0	0	F 0
	IMU Get yaw acceleration	10	Yaw Acceleration	0	0	10 0
	IMU Get pitch acceleration	11	Pitch Acceleration	1	1	11 1
	IMU Get forwards acceleration	12	Forward/ Backward Acceleration	2	2	12 2
	IMU Get left/right acceleration	13	Left/ Right Acceleration	3	3	13 3
Other	Switch to Manual Control	FF	Switch to MC	0	0	FF 0

Appendix I: Project Risk Management Matrix

TABLE I1

Risk Management Matrix

Risk No.	Risk	Discovered	Category	Impact	Probability	Mitigation Strategy	Status*
Ri1	The rover fails to move in the test arena	Pre-phase A	Operational	HIGH	LOW	Ensure that the rover is designed to increase friction with surface and has sufficient torque to move its mass	Retired (Phase C)
Ri2	The project goes over budget and late as a result of slips	Pre-phase A	Organizational	MEDIUM	HIGH	The team will work with a large budget margin for the system materials and operate with a time safety margin.	In progress (Phase D)
Ri3	Communication failure between GCS and rover	Phase A	Operational	LOW	LOW	The communication protocol will be recoverable. In case of disconnect, the system will enter E-stop mode.	Retired (Phase B)
Ri4	Autonomy failure (i.e. collision, vision system error)	Phase A	Operational	LOW	HIGH	The operator will restore the rover to manual control and recover from error.	Retired (Phase B)
Ri5	Regolith obstructing operation of components	Phase A	Environmental	HIGH	LOW	The system will be designed with IP6X rated components. Electronics will be sealed in IP6X rated enclosure	Retired (Phase C)
Ri6	Rovers do not disengage upon reaching mining area	Phase B	Operational	HIGH	MEDIUM	The system will be designed with a reliable disengagement mechanism. Stress testing will be performed to reduce probability of this risk to LOW	In review (Phase D)
Ri7	Deposition rover does not align properly with digging rover	Phase B	Operational	HIGH	LOW	In autonomy, excess sensor data will allow for small positional changes to ensure alignment. Manual controller will practice for alignment.	In review (Phase D)
Ri8	Joined rover gets stuck in a hole or on an obstacle during traversal	Phase B	Operational	MEDIUM	MEDIUM	Large wheels are designed to easily overcome obstacles. The digging rover can be lowered to elevate the robot rear.	Retired (Phase C)
Ri9	Project loses momentum after in-person mining canceled	Phase C	Organizational	HIGH	HIGH	Participation in the University of Alabama competition instead should provide a worthwhile goal	Retired (Phase C)
Ri10	Deposition subsystem may be overloaded and fails to offload all regolith.	Phase C	Operational	HIGH	LOW	Regolith transfer will occur slowly to ensure a good capacity is reached in the deposition rover.	Identified (Phase D)
Ri11	Last minute failures during verification leads to last minute changes to the project	Phase C	Organizational	HIGH	HIGH	Incremental verification during fabrication and integration reduces probability of major system faults	In progress (Phase D)

* Statuses are as of March 29, 2023 and can possibly be: identified (risk has been identified and mitigation strategy developed, however, mitigation has not been implemented), in progress (risk mitigation strategy being implemented), in review (mitigation strategy being verified for effectiveness), and retired (risk successfully mitigated)

Appendix J: Project Schedule

Project Schedule

PROJECT TITLE	Lunabotics 2023	COMPANY NAME	NYU Robotic Design Team
PROJECT MANAGER	Student Lead: Andy Q. & Carlos C. Faculty Advisor: Giuseppe Loianno	PROJECT DATES	July 3, 2022 - May 28, 2023