NEW YORK UNIVERSITY TANDON SCHOOL OF ENGINEERING
ROBOTIC DESIGN TEAM

PLAN FOR PROJECT SYSTEMS ENGINEERING

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

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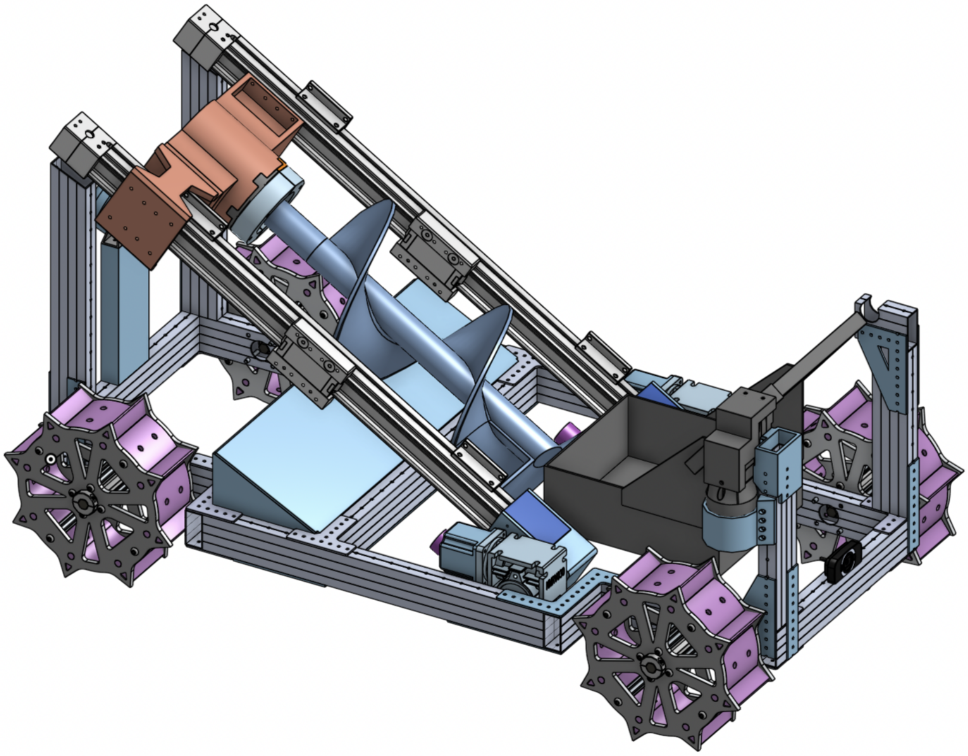
Abstract

Through the Artemis Program, NASA will send the first woman and first person of color on the Moon. The goal is to research native resources such as ice and hydrated minerals below the surface of the planet. The NASA Robotic Mining Competition challenges collegiate teams to create a mining rover which can collect and store icy regolith to simulate a lunar exploration mission. This challenge may be used as data to bring NASA closer to returning humanity to the Moon. The rovers will traverse an artificial lunar terrain, excavate icy regolith simulant, and deposit it into a collection bin.

The New York University (NYU) Tandon School of Engineering Robotic Design Team (RDT), is one such participant in the NASA RMC. Its robotic mining system, ASTRO, is an autonomously operated, mining system capable of excavating icy regolith simulant within the parameters set up by the competition. The 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 system is composed of four subsystems: locomotion, digging, storage and deposition. Each subsystem was designed according to the Systems Engineering Process and thoroughly reviewed to minimize and mitigate possible points of failure and risks. This paper describes the Systems Engineering Process as used by the NYU RDT to develop ASTRO. A computer rendering of the ASTRO system is shown below



PURPOSE STATEMENT

The NASA Systems Engineering Process was implemented by the NYU Robotic Design Team for the 2022 NASA Robotic Mining Competition. Beyond its requirement 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 with the occurrence and management of late-stage changes to the project. Therefore, the team benefited greatly from the thoroughness of the design and, later, validation processes of the NASA Systems Engineering Process. Furthermore, the NASA Systems Engineering Process provided a means to balance the multiple technical disciplines and project management roles on a large and diverse team.

The purpose of this document is to explain the execution of the NASA Systems Engineering Process by the New York University Robotic Design Team (NYU RDT, the "team") for the 2022 NASA Robotic Mining Competition (2022 NASA RMC: Lunabotics).

INTRODUCTION

I. Scope

The NASA RMC is an annual competition hosted by the National Aeronautics and Space Administration (NASA) which challenges university teams to develop an autonomous mining rover to collect and transport simulated extraterrestrial icy regolith (gravel). Teams are evaluated by the mass of gravel collected from beneath a layer of dusty regolith simulant (BP-1).

The NASA Systems Engineering Process (the 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 2020 NASA RMC as well as their description and deadlines.

TABLE 1
PROJECT DELIVERABLES [3]

Deliverable	Description	Deadline
Project Management Plan	A preliminary document stating the early project definition (including the initial project schedule, budget and design philosophy)	October 6, 2021
Outreach Report	A written report describing the team's efforts in engaging their community in STEM education initiatives	April 13, 2022
Systems Engineering Report	A paper discussing the team's use of the SE Process during the design and implementation of their systems (this document)	April 11, 2022
Robot Proof of Life and Data	A video demonstrating the operation of the final system and supporting documentation (i.e. Bill Of Materials)	April 20, 2022

PRE-PHASE A: CONCEPT STUDIES

I. Identifying Stakeholder Expectations

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

NASA's primary expectation requires teams to excavate icy regolith (gravel simulant) located at a given depth beneath the BP-1 simulant. 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 Table 2. These expectations and constraints were confirmed with the release of the 2022 NASA RMC Rules.

Another key project stakeholder 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 e mission. 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.

TABLE 2
MISSION CONSTRAINTS

Constraint	Source [3]
C1: The maximum mass of the system is 80kg	8.1 1.2
C2: The maximum starting dimension of the system is 0.50m width, 1.0m length, 0.50m height	8.1 1.1
C3: The maximum operational height of the robot is 1.5m	8.1 1.5
C4: The system will communicate with the Ground Station using commercial 802.11ac wireless communications (WiFi)	7.4 1
C5: The system will have a means of being disabled (full disconnection from power) using a button with a minimum diameter of 40mm	8.1 2
C6: The system will have 1 test run of 10 minutes	
C7: The system will be delivered to NASA KSC by May 23, 2022	Part I
C8: The system cannot navigate using the walls of the Arena	8.4 1
C9: The system will be self-powered and monitor its power consumption using a COTS power consumption meter	8.1 3

II. Development of Preliminary Mission Parameters

A. Defining Needs, Goals, and Objectives

The mission needs traceable needs, goals, and objectives (NGOs) that align with stakeholders' expectations. Refer to Table 3 for the NGOs developed for this mission by the team.

TABLE 3
Needs, Goals, and Objectives

Mission Parameter	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
Goal (**G2**)	The system should be able to extract gravel icy regolith from the arena
Goal (**G3**)	The system should minimize the amount of unscored BP-1 regolith collected
Goal (**G4**)	The system should be able to deposit the collected regolith into the collection bin
Goal (**G5**)	The system should use minimal resources (mass, bandwidth, electrical power)
Goal (**G6**)	The system should operate autonomously
Goal (**G7**)	The system should be completed on time and within budget
Objective (**Ob1**)	The system should have a maximum mass of 80 kg
Objective (**Ob2**)	The robot should operate fully autonomous
Objective (**Ob3**)	The robot should complete 2 dig and deposit cycles in a maximum of 3 minutes per cycle
Objective (**Ob4**)	The system should use a maximum of 10 kbps (bandwidth)
Objective (**Ob5**)	The system should cost a maximum of $15,000
Objective (**Ob6**)	The system should be completed by May 15, 2022
Objective (**Ob7**)	The system should collect 1 kg of gravel icy regolith
Objective **(Ob8)**	The system should achieve the minimum mining score (1 kg)
Objective **(Ob9)**	The system should be resilient to error or recoverable from it

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 A1 in **Appendix A**.

III. Designing a Concept of Operations

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

IV. Determining Mission Feasibility

Ideally, 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 RMC to review past system performance and possible risks.

A. 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.

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.

PHASE A: CONCEPT DEVELOPMENT

Development of a baselined mission concept was founded upon 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 19, 2021, with the conclusion of Pre-Phase A and ended on October 10, 2021, with the completion of the Systems Requirement 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 finalized in Phase A (see **Appendix B**) dependent on specified parameters for the mission, detailed in the complete NASA RMC Rules and Rubrics document.

II. Initial Trade Study: Addressing Past Concerns and Testing New Ideas for the Rover

During the initial two weeks into Phase A, initial technical risks for each subsystem were determined and evaluated. Team leads created several proposals for a general idea of the rover and after a discussion, worthwhile ideas were created into tasks as follows:

A. April tag localization:

Autonomy was a large focus on the development of ASTRO (RMC 2022). In order to achieve higher points for autonomy, this task was decided to be implemented at the beginning of the year.

B. Excavation Subsystem:

To transition away from the central digging wheel that has been utilized in past system designs, technical leads went on to determine the feasibility of alternate digging mechanisms, that being an auger or articulating conveyor belt arms. A trade study was conducted to determine the most viable solution to optimize weight, power consumption, dust management and cost.

C. Locomotion Subsystem:

In order to maximize the usable space and account for robot dimension changes from the 2022 RMC, many new initiatives were explored. These included optimizing and utilizing gear chain pulleys, tracks, lifting arms, and wheels. Other initiatives included compact methods of digging, floor clearance and lateral movement.

The results of the studies were then presented to a panel of team leads, alumni and advisors and rated in terms of their fulfillment of given requirements.

III. Technical Requirements Definition

A. System Requirements Definition

The technical requirements of the system fall under the following six categories: functional (F), performance (P), interface (I), environmental (E), design (D) and safety (S) [1]. Table 4 lists the system's technical requirements along with the operational goal(s) from which each requirement is derived. The unique requirement identification and its category are indicated in parentheses preceding each requirement in the format: (ID, Category).

Key Driving Requirements are indicated with an asterisk (*). A preliminary system-level technical budget was compiled based upon these requirements and maintained throughout the project lifecycle (Table C1, **Appendix C**).

B. Technical Requirements Verification Plans

The technical requirements verification plans consist of the methodologies used to test compliance of the final system with technical requirements. The plans are outlined in Table D1, **Appendix D**, the requirements verification matrix.

C. Measures of Performance and Technical Performance Measures

Table A2, **Appendix A** describes the Measures of Performance (MOPs), which were formulated in order to ensure design solutions were compliant with system MOEs.

IV. System Requirements Review

On September 19 2021, NYU RDT conducted its Systems Requirements Review (SRR). The team invited three field researchers in robotics who had prior experience in extraterrestrial mobility and actuation. Two of the three researchers had background information in NASA RMC and were able to provide informed analysis on the quality of the technical requirements and verification plans. The deliverables required for this review were:

- Baselined Mission ConOps
- System Requirements and proposed verification plans

The SRR alumni panel assessed the provided documentation based on the following technical criteria from NASA Procedural Requirements 7123.1C, Table G-5 [5]:

- Traceability to the stakeholder expectations
- Essentiality for the development of a completed product
- Accountability for all potential design aspects
- Feasibility based on the studies performed during Pre-Phase A and project resources
- Lack of redundancy between requirements
- Specificity in their wording
- Verifiability

With one minor alteration, that is accounting for a greater margin of error in respect to fabrication, previously ±5% to now ±10%, the SRR panel found that the requirements were in fact sufficient to satisfy the mission. As a direct result, the output of the SRR was a set of successfully baselined requirements and verification.

V. System Decomposition

A. Functional Decomposition

The requirements for the system to accomplish the concept of operations were assessed and allocated to their corresponding subsystem. After this, functional interfaces were designed for their designated subsystem interfaces.

TABLE 4

SYSTEM TECHNICAL REQUIREMENT

Requirement	Traced from	Rationale
(SR1, D+P)*: The system shall have a mass of 80kg	Ob1, C1	While less mass means fewer deductions, more mass allows for more functionality. The latter was deemed more critical.
(SR2, D)*: The system shall have a maximum dimension of 1.0m x 0.50m x 0.50m and not extend above 2.5m during operation	C2, C3	A requirement of the competition
(SR3, D+E+S)*: The system shall have dustproofing measures implemented on all sensitive components	G1, Ob9	The system needs to be able to operate in its environment safely
(SR4, F, P): The system shall be able to receive commands from a human operator at the Ground Control Station wirelessly via 802.11ac and exceed 15 Mbps of bandwidth usage.	Ob8, Ob9, C6, C4	As a backup in case of autonomous failure/error.
(SR5, F+S): The system shall be	C5	Both a requirement

able to fully power off (disconnect from the battery) in case of the operational rule of safety violation		and a safety assurance
(SR6, P)*: The system shall complete at least level 3 partial autonomy (as defined in the NASA RMC Rules and Rubrics)	G6, Ob2, C8	Autonomy is a difficult achievement yet a worthwhile goal for its point allotment
(SR7, F+E): The system shall not employ any components or technologies not suitable for Mars	C9	Requirements for the competition
(SR8, P)*: The system shall be able to deposit at least 2 kg of icy gravel in 10 minutes of operation	Ob8, C6	Obtaining any points is better than obtaining no points.
(SR9, F+S): The system shall have software feedback for all moving mechanisms	Ob9, Ob2	Feedback can help prevent system error and ensure accurate operation
(SR10, P)*: The system shall consume at most 40 Wh of electrical power and monitor said consumption using a COTS device	G5, C10	Minimal power consumption means fewer point deductions
(SR11, I)*: The system shall be able to perform multiple functions simultaneously	Ob3, C6	An efficient system can perform multiple functions at once and save operational time
(SR12, F+S): The system shall be recoverable by error	Ob9	In case of error, recovery prevent total system error

Several models which assigned system functions to different subsystems were developed. Approaches considered included assigning all functions relating to the same requirement to a single subsystem (i.e. autonomy subsystem, dust tolerance subsystem, etc.). Another approach grouped subsystems by discipline (i.e. mechanical subsystem, software subsystem, etc.). Ultimately, the subsystems were created by grouping functions involved in similar steps of the ConOps (i.e. excavation, locomotion and integration) 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 system's high level functional decomposition. Additionally, Figure 2 shows the allocation of functions to the subsystem interfaces. The differentiation of icy and BP-1 regolith was embedded within storage and deposition, in order to fulfill requirement SR11.

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, which is included in Table C1, **Appendix C**. Table 5 shows the allocated requirements for the various subsystems.

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 icy 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 [1]. The MDR was conducted by the team's student leads on September 26, 2021. The success criteria used to evaluate the SRR were taken from NASA Procedural Requirements 7123.1B, Table G-5 [5]. No major changes to the project baseline were made during this review.

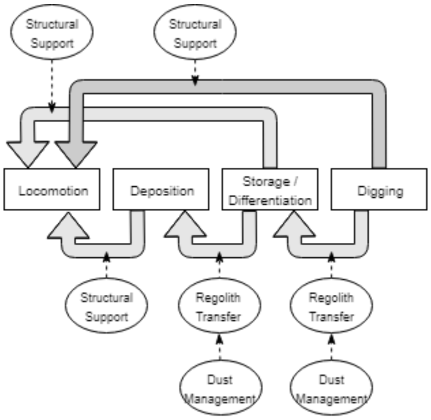


FIGURE 1: System Architecture
System Interface and Functional Allocation (Rectangles are subsystems, grey arrows are interfaces between subsystems, and ellipses are allocated functions)

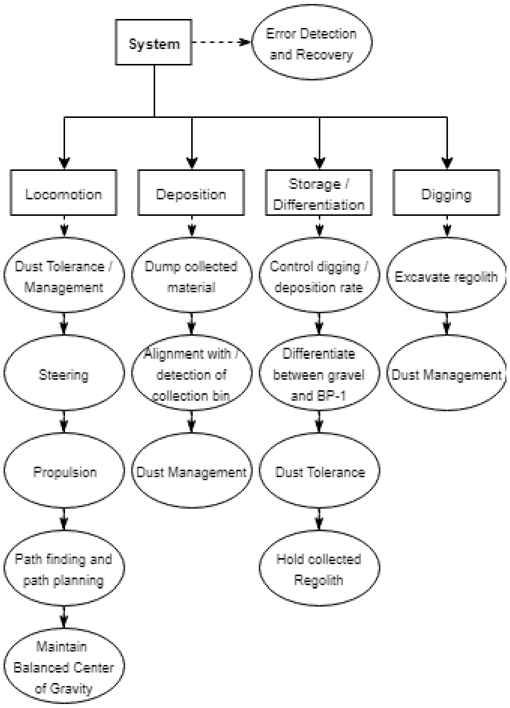


FIGURE 2
System Hierarchy and Functional Decomposition (Rectangles are levels of the hierarchy and ellipses are allocated functions)

TABLE 5
Subsystem Technical Requirements

Requirement	Alloc from
(DiR1, D+P)*: The digging subsystem shall be less than 20kg.	SR1
(DiR2, F): The digging subsystem shall be able to excavate icy regolith autonomously.	SR6
(DiR3, F): The digging subsystem shall excavate 2 kg of gravel.	SR8
(DiR4, D+E+S): The digging subsystem shall minimize the amount of dust disturbed by its operation.	SR3
(DiR5, P): The digging subsystem shall consume no more than 7 Wh of power.	SR10
(DiR6, I): The digging subsystem shall be able to operate in parallel to other subsystems.	SR11
(LR1, D+P)*: The locomotion subsystem shall have a mass no greater than 14 kg.	SR1
(LR2, F): The locomotion subsystem shall be able to navigate and traverse the field autonomously.	SR6
(LR3, D): The locomotion subsystem shall be designed within 0.50m x 0.50m x 1.0m in dimension.	SR2
(LR4, P): The locomotion subsystem shall be able to traverse from the starting position to the digging area in less than 45 sec.	SR8
(LR5, F+D+S): The locomotion subsystem shall be designed with a factor of safety of 2.	SR12
(LR6, P): The locomotion subsystem shall consume less than 7 Wh of power.	SR10
(LR7, I): The locomotion subsystem shall be able to operate in parallel to other subsystems.	SR11
(LR8, I): The locomotion subsystem shall allow for a switch between autonomous and manual control of its operation.	SR6, SR12
(DeR1, D+P)*: The deposition subsystem shall have a mass no greater than 10 kg.	SR1
(DeR2, F): The deposition subsystem shall be able to align with and deposit into the bin fully autonomously.	SR6
(DeR3, F): The deposition subsystem shall not extend above 2.5m during operation.	SR2
(DeR4, P): The deposition subsystem shall deposit its entire payload in less than 30 seconds.	SR8
(DeR5, F+D+S): The deposition subsystem shall be designed with a factor of safety of 2.	SR12
(DeR6, P): The deposition subsystem shall consume less than 7Wh of power.	SR10
(DeR7, I): The deposition subsystem shall be able to operate in parallel to other subsystems.	SR11
(DeR8, D+E+S)*: The deposition subsystem shall reduce the amount of dust disturbed by its operation.	SR3
(StR1, P)*: The storage subsystem shall have a mass less than 6 kg.	SR1
(StR2, F): The storage subsystem shall be able to separate	SR8

icy and BP-1 regolith.	
(StR3, P): The storage subsystem shall consume no more than 1Wh when separating icy and BP-1 regolith.	SR10
(StR4, F+P): The storage subsystem shall store 3kg of gravel.	SR8
(StR5, I): The storage subsystem shall be able to transfer 95% of the stored gravel into the deposition bin within 30 seconds.	SR8
(StR6, F+D+S): The storage subsystem shall be designed with a factor of safety of at least 2.	SR12
(StR7, D+E+S): The storage subsystem shall contain stored regolith and prevent leakage into other parts of the rover.	SR3

Phase B: Preliminary Design

This phase of the Systems Engineering lifecycle focused on the development of a general design for the system and further refined 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 10, 2021, with the completion of the MDR and ended on November 10, 2021, with the completion of the Preliminary Design Review (PDR).

I. Subsystem Design Solutions

Design concepts for individual subsystems were created through trade studies at the commencement of this phase. 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, see *Decision Analysis* in the **Project Management** section.

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. Excavation Subsystem

The key technology required by the digging subsystem to be designed and prototyped is the excavation method. After several stages of evaluation, three design concepts (conveyor belt, digging wheel, and a redesigned auger) were chosen to be prototyped for their efficacy as measured by the previously defined MOEs.

The conveyor belt digging wheel is commonly used on the Bagger 288 excavator and simply combines a conveyor belt with a digging wheel. This method of combining a digging wheel with a conveyor belt allows for deep excavation and for fast and efficient digging due to the size of the digging wheel. However, this method also has a higher complexity.

A digging wheel is a solid mechanism which 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 RMC. Although similar to the conveyor belt digging wheel, the digging wheel is more power efficient as a conveyor belt does not need to be powered and there is a simplification in design.

An auger is a rotating, helical screw blade which acts as a vertical conveyor belt to remove excavated material. Although an auger has a cylindrical shell that prevents the material from falling over the sides, the new design that is being proposed this year does not have this feature. This is because this year's proposal is focused on obtaining a concentrated sample of regolith. At the bottom of the auger, a compartment has been designed, so that when the system is turning clockwise, it acts as a ramp that pushes the material up to the surface, but when the required depth has been reached, the system turns counterclockwise and the regolith is captured by this bucket. In that way, the helical screw only has the purpose of removing the material between the surface and the regolith, while the compartment at the bottom has the purpose of collecting the sample.

This design proved to be able to obtain much cleaner samples than the conveyor belt and diggin wheel, without much contamination of sand particles.

TABLE 6
Subsystem Measures of Effectiveness

Subsystem	Measure of Effectiveness	Traced from
Digging	**DiMOE1**: Be designed to use minimal mass.	DiR1
Digging	**DiMOE2:** Be able to excavate icy regolith, located 30cm beneath a surface layer of BP-1 regolith (depth, m)	DiR3
Digging	**DiMOE3**: Utilize minimal electrical power (Wh).	DiR5
Digging	**DiMOE4**: Mines at the maximum possible rate (kg / s).	SR8, C6
Digging	**DiMOE5**: Design maintains simplicity to prevent mechanical error and completion within project budget and schedule (# of actuators).	Ob6, DiR3
Digging	**DiMOE6**: Operation with minimal disturbance of dust into surrounding air (1-3, qualitative).	DiR4
Locomotion	**LMOE1**: Designed with minimal mass (kg).	LR1
Locomotion	**LMOE2**: Minimize the time to traverse to digging site (s).	LR2, LR4
Locomotion	**LMOE3:** Ability to recover from the error (collisions, etc.) (relatively scored).	Ob9, LR2, LR5
Locomotion	**LMOE4:** Utilize minimal electrical power (Wh)	LR6
Deposition	**DeMOE1**: Be able to deposit regolith into the collection bin (estimated failure rate, %).	DeR2, DeR4
Deposition	**DeMOE2** Utilize minimal electrical power (Wh).	DeR6
Deposition	**DeMOE3:** Deposit payload in minimal time (s).	DeR4
Deposition	**DeMOE4:** Be designed with minimal mass (kg).	DeR1
Deposition	**DeMOE5:** Maximize dust management (% containment)	DeR8
Storage	**StMOE1:** Filtration mechanism utilizes minimal power (Wh).	StR3
Storage	**StMOE2:** Filtration mechanism allows for maximum inflow rate into storage from digging subsystem (kg/s).	StR5, DiR6
Storage	**StMOE3:** Filtration mechanism has the ability to separate gravel from BP-1 (% mass of BP-1 stored)	StR2

Figure 3 shows images of the design concept prototypes. Table 7 lists the scaled scores of each concept based upon the established subsystem MOEs in Table 6. The final design concept chosen for the digging subsystem was the redesigned auger; this was decided mainly upon its ability to collect clean regolith samples.

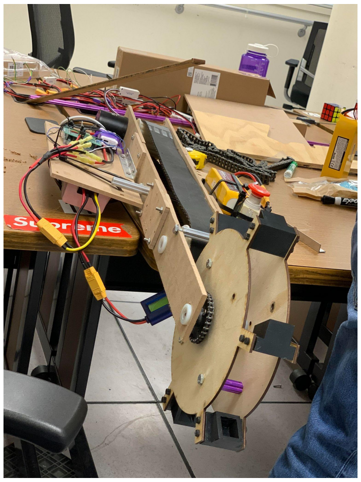


FIGURE 3a
Digging Subsystem Design Concept. Conveyor Belt

FIGURE 3b
Digging Subsystem Design Concept. Redesigned Auger

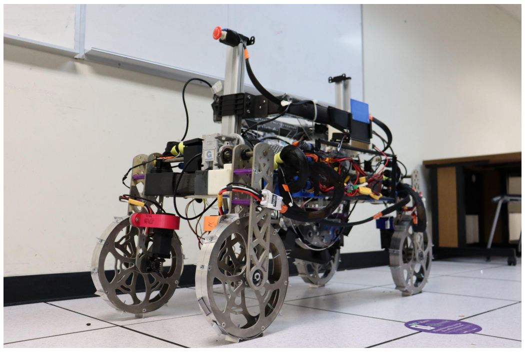


FIGURE 3c
Digging Subsystem Design Concept: Digging Wheel

TABLE 7

Digging Design Concept Trade Study Result

Measure of Effectiveness	Decision Weight	Design Concepts Auger	 Conveyor Belt	 Digging Wheel
DiMOE1	3	20 kg	5.2 kg*	18 kg
DiMOE2	2	0.6m	0.6m	0.6m
DiMOE3	4	40 Wh	5.75 Wh	2.7 Wh*
DiMOE4	5	0.33 kg/s	0.25 kg/s	0.65 kg/s*
DiMOE5	2	2*	2*	4
DiMOE6	3	3*	1	2

* Indicates the best performing metric

i) Storage / Differentiation

The storage system was to be developed specifically as a support to the excavation system by maximizing the collection sample per run via differentiation of icy and BP-1 regolith. Two approaches investigated by the trade study were the use of a vibrating sieve (like the means by which NASA filters the gravel and BP-1 in the collection bin) and a meshed pivot bucket . Both breadboards were evaluated based upon the MOEs defined in Table 8.

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 bucket strives to remove as much BP-1 regolith from the storage as possible by oscillating in small frequencies. With this design being less complex, drawing in minimal electrical power and efficient at differentiation, this concept was chosen. Table 8 shows the results of the trade study and Figure 6 shows the breadboard for the tiered incline plane concept.

TABLE 8

Storage Design Concept Trade Study Result

Measure of Effectiveness	Decision Weight	Design Concepts Vibrating Sieve	 Meshed Bucket
StMOE1	2	< 2 Wh	~0 Wh *
StMOE2	4	0.5 kg / sec	2 kg / sec *
StMOE3	5	> 90% *	~ 85%

* indicates best performing metric

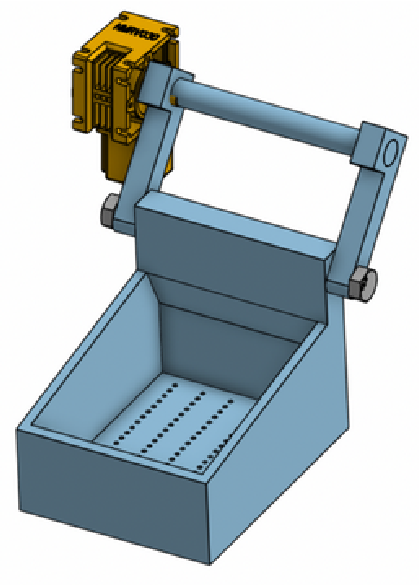


FIGURE 5

Storage / Differentiation Subsystem Design Concept, Meshed Pivot Bucket

ii) Deposition

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 during the trade study: expanding bin, tipping, and chute. Each breadboard was created using different materials and were tested according to the MOEs defined in Table 6.

Expanding bin is an approach which involves a container mounted to an extendable arm, which is positioned over the collection bin where the container is emptied. Expanding tube uses a statically mounted container with a flexible tube which can be articulated over the collection bin. The regolith would flow from the storage container into the collection bin. Both concepts have the advantage of accurate deposition (as a result of their ability to be independently actuated), but require a greater power consumption, mass, and complexity.

Tipping is the simplest approach and involves the use of a "dump truck" assembly which tips a container such that gravity deposits the regolith into the collection bin. Therefore, tipping has the greatest transfer success (i.e. regolith retained during transfer), but requires the locomotion subsystem for alignment.

Chute, like an expanding tube, involves a statically mounted bin with a protruding channel which extends over the collection bin. Regolith is allowed to flow down the channel and into the collection bin. Similar to tipping, it has fewer actuators and therefore requires a lower power consumption. The chute is more dust tolerant than tipping as the regolith is contained by the chute's channel, but does require exact alignment by the locomotion subsystem for success.

The final design concept chosen was tipping the meshed bucket for its efficiency of operation and simplicity of its implementation. The ability for the meshed tipping bucket to be able to combine storage, differentiation, and deposition also influenced the decision to select this design. Table 9 shows the scaled results of the trade study for each design concept and Figure 7 shows images of design concept breadboards with Table 6 .

TABLE 9

Deposition Design Concept Trade Study Results

Measure of Effectiveness	Decision Weight	Design Concepts		
		Expanded Bin	Tipping	Chute
DeMOE1	5	< 10%	< 5%*	< 5%*
DeMOE2	3	10 Wh	4 Wh*	8 Wh
DeMOE3	5	5 sec	2.5 sec	2 sec*
DeMOE4	2	8kg	2kg*	2kg*
DeMOE5	2	> 97%	> 80%	> 95%*

* indicates best performing metric

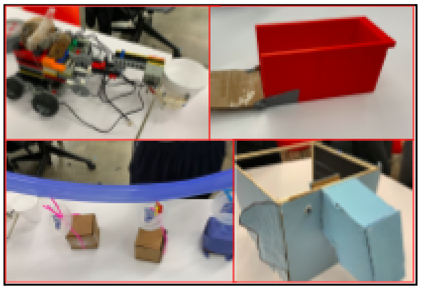


FIGURE 6

Deposition Subsystem Design Concept. From left to right: (top row) expanding bin, tipping, (bottom row) expanded tube, chute

B. Locomotion Subsystem

Several design decisions regarding the locomotion method were examined. A static chassis was continued on from previous years as it led to simpler design and fabrication, but the method of movement in three different design concepts (tread tank, screw tank, and solid wheels). The prototypes were evaluated on the MOEs defined in Table 6.

The tread tank tested two ideas simultaneously, both pertaining to using treads. One side tested a method of construction using a timing belt while the other side tested a method using a duplex chain. The timing belt test determined tensioning would be significantly difficult to work with and the duplex chain was simply too heavy and performed worse as dust and sand got in the treads.

The screw tank tested a locomotion idea that could move axially as well as laterally. This method revolved around using giant screws similar to archimedes screws to push material backwards or forwards to slide the robot axially. However, when both screws were rotated in the same direction, lateral movement could be achieved. This design proved to be difficult to manufacture and difficult to balance both the axial and lateral movement.

Finally the solid wheels had been used in past systems and proved to be capable of moving on the terrain and offered a simple construction method. The largest downside found was that there was poor maneuverability when turning the robot. However this downside was the easiest to minimize and was least likely to cause failure to our robot versus the other design.

To allow for the greatest maneuverability we wanted to maximize traction to allow the robot to turn efficiently. This was one of the biggest considerations when designing the wheel itself.

TABLE 10
Locomotion Design Concept Trade Study Result

Measure of Effectiveness	Decision Weight	Design Concepts	
		Rocker Bogie	Static Chassis
LMOE1	4	14 kg	8 kg*
LMOE2	5	15 - 20 sec*	20 - 40 sec
LMOE3	4	2*	1
LMOE4	3	8 Wh*	8 Wh*

* indicates best performing metric

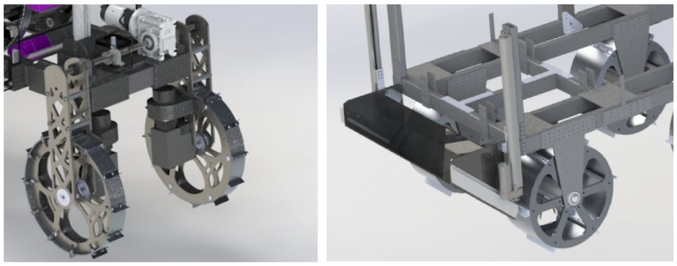


FIGURE 7
Locomotion Subsystem Design Concepts. From Left to Right: Rocker Bogie (PIPER, RMC 2021) and Static Chassis (ORBIT II, RMC 2020)

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. System Design Alternatives

Three system concept alternatives were developed around the possibility of using a different number of individual rovers to accomplish the mission objective:

- 1 rover concept: a single rover containing the separate subsystem components would accomplish the mission task
- 1.5 rover concept: a compromise between the two previous concepts. The system would include a single mobile rover that would transport an immobile digging rover to the digging site and transport the collected regolith to the collection bin.
- 2 rover concept: the system would involve the use of two separate, independent rovers. One rover would mine the regolith while the other would ferry the regolith between the digging rover and collection bin. This concept was discarded due to the complexity already faced in a 1.5 rover faced in RMC 2019.

B. Evaluating System Design Solutions

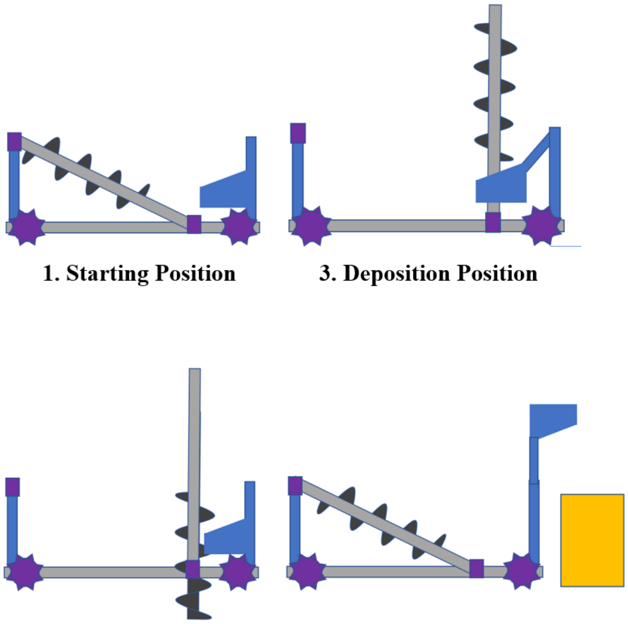
Since the use of additional rovers adds complexity to the system (increasing risks of failure during operation), it was deemed best to utilize a singular rover despite sacrificing increased efficiency via operational parallelism.

Table 11 is a decision matrix made for the three system concepts based upon the system-level MOEs in Table A1. The final system concept chosen was the 1 rover system as it becomes increasingly difficult to accommodate more rovers given the reduced size parameters for the mission. Despite the 1.5 robot system design being successful in past missions, new size constraints make it less feasible. Figure 8 is a generalized flow chart showing the 1 rover system concepts.

B. Evaluating System Design Solutions

The more rovers being used directly correlates to system efficiency (i.e. it ensures operational parallelism). However, using multiple rovers would result in increased complexity and increased probability of failure.

Table 11 is a decision matrix made for the three system concepts based upon the system-level MOEs in Table A1. The final system concept chosen was the 1.5 rover system as it demonstrated a compromise between the advantages and disadvantages of the 1 and 2 rover systems. Figure 9 is a generalized flow chart showing the 1.5 rover system concept.



1. Starting Position 3. Deposition Position

2. Digging 4. Dumping

FIGURE 8
CHOSEN SYSTEM DESIGN CONCEPT (1 ROBOT). STEPS IN OPERATION CONCEPT NUMBERS IN CHRONOLOGICAL ORDER

TABLE 8
SYSTEM DESIGN CONCEPT TRADE STUDY RESULT

Measure of Effectiveness	Decision Weight	Design Concepts 1 Rover	 1.5 Rover
MOE1	3	3*	1
MOE2	5	1	2
MOE3	4	3*	2
MOE4	3	3*	2
MOE5	3	1	1
MOE6	3	2	1
MOE7	3	1	1
MOE8	3	1	1
MOE9	5	1	1

*The MOEs are evaluated relatively, such that higher rating means a better evaluation of the system MOEs.

TABLE 11
SYSTEM DESIGN CONCEPT TRADE STUDY RESULT

Measure of Effectiveness	Decision Weight	Design Concepts 1 Rover	 2 Rover	 1.5 Rover
MOE1	3	1	1	1
MOE2	5	1	3*	2
MOE3	4	3*	1	2
MOE4	3	3*	1	2
MOE5	3	1	1	1
MOE6	3	1	1	1
MOE7	5	1	1	1

*The MOEs are evaluated relatively, such that higher rating means a better evaluation of the system MOEs.

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 presented by the 1 rover system (**Appendix B**).

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 C1, **Appendix C**) was updated with the interfaces.

V. Preliminary Design Review

The Preliminary Design Review occurred on November 18, 2018, 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

The success criteria used to evaluate the SRR was taken from NASA Procedural Requirements 7123.1B, Table G-6 [5]. The system concept was discussed and evaluated against the previously baselined system concept such that the project was now in a state ready to begin the final design and fabrication. The result of the PDR was the approved system design.

Phase C: Final Design 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 14, 2021, with the end of the PDR and ended on March 6, 2022, with the completion of the fabrication process.

I. Design Process and Philosophy

The design process and philosophy fell heavily on creating separate sets of deliverables for the final design within each discipline.

The mechanical team iterated through computer-aided design (CAD) models, fabrication drawings, and computer-aided machining (CAM) files on OnShape to land on their final design. SOLIDWORKS computer-aided design and engineering software, was also utilized for conducting design testing such as mechanical stress simulations and various weight estimations. By analyzing the results of these tests, iterations of the solution were created to enforce areas of weakness and determine the best fabrication methods for each component and arrive to the final mechanical design.

The electrical team presented their deliverables of the final design through both high and low level electrical schematics, circuit board CAD drawings for printed circuit boards (PCBs), and theoretical power calculations. The schematics and CAD designs were completed using EagleCAD, a software produced by Autodesk. With the combination of these, an effective and efficient electrical solution was developed for the system and its final design.

The software team provided state diagrams and algorithms through pseudocode and architectures through their design process. With this, they created a procedure for autonomy in direct relation to the Concept of Operations. Each component has a set of system design goals, listed in Table 12, and their correlated tracabilities to the system requirements and measures of effectiveness. These led to the final and robust design solution for the system.

TABLE 12
System Design Goals

Design Goal	Trace
DG1: Minimize the number of moving parts / actuators of the system (i.e. reuse one actuator for multiple functions)	SR10, SR12, MOE1
DG2: Provide at least one feedback measure per subsystem function	SR6, SR9, SR12, MOE3
DG3: Ensure that all external components have an IP6X rating, all internal components have an IP5X rating	SR6, SR7, MOE7
DG4: Minimize mass, system mass and volume	SR1, SR2
DG5: Utilize a margin of error of at least 1.5 for all designs.	SR12
DG6: Ensure system simplicity by reducing inter-subsystem dependency.	SR11, SR12

A. Excavation Subsystem

The final design of the digging subsystem was a refinement of the concept developed during the previous phase. The final CAD render of the subsystem is included in Figure 10. The primary challenges faced during the development of a final design was making the digging subsystem work as effectively as PIPER (RMC 2020), given the minimized size and weight constraints; a concept which this year has a large dimensional and mass requirement.

The excavation subsystem design is made up of a helical screw with a compartment at the bottom, a mounting mechanism, two linear actuators and two worm gearboxes. It is designed so that when it is rotating in a clockwise direction, the compartment at the bottom acts like a ramp that pushes the material out of the way. Once the required depth is reached, the redesigned auger is turned in a counterclockwise direction. This then allows for the compartment to act like a bucket, where it can store a clean sample of regolith.

The auger is connected to a mounting system that was designed in order to provide stability; each edge of the mounting mechanism is attached to one linear actuator. Consequently the dual-linear actuators are connected to two worm gearboxes that provide a pivot mechanism. This allows for the entire system to rotate, so that it can be stored and extended whenever needed.

This pivot mechanism allows the excavation system to be able to be stored inside the robot. This is because if the excavation system was left in a vertical position, the total length required to reach the regolith would be greater than the size limitations for this year's robot.

The changes made to the subsystem from previous year's systems are primarily aimed to comply with the reduced mass and volume requirements allocated for the subsystem. With the aim of collecting the purest sample of regolith, the team changed the mechanism from a digging wheel to a redesigned auger. The only component that stayed from last year were the linear actuators, given that these have proved to be the most efficient way to move the excavating system to different heights.

The excavation system is composed of various sensors to aid in the autonomy of the system. With load cells in the deposition system, the team is able to measure the force of the material in the bucket and get insight into how full the bucket is and when it should be emptied. Twelve hall effect sensors and magnets are strategically placed around the mechanism to provide feedback on where everything is. For example, four hall effect sensors are placed around the belt of the linear actuators and a magnet is placed on the moving part of the system. With this setup, the sensor can detect when the magnet is in close proximity and tell the user where the linear actuator is. This allows the team to reach the positions for storage, digging, and deposition. The other hall effect sensors are used to know how much the auger has rotated, how much to extend the bucket, and finally how much to pivot.

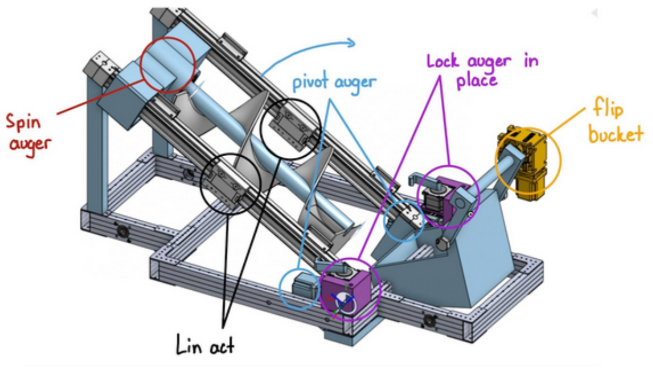


FIGURE 9
Final Computer rendering of the digging subsystem

i) Deposition Subsystem

The deposition subsystem refers to the mechanism responsible for dumping filtered and stored gravel into the deposition bin. Due to smaller dimensional constraints and the nature of the auger excavator, the final design had to accommodate the specified Design Goals.

Several designs were considered for the deposition subsystem, however the ability to swing on a pivot was found to be crucial in both simplicity of construction and operation. This design pivots around the deposition gearbox axle allowing for the storage bin to swing below the auger and out. Figure 11 shows the general configuration for the system, but an additional note should be made that the storage bin is meshed elaborated on in the following section.

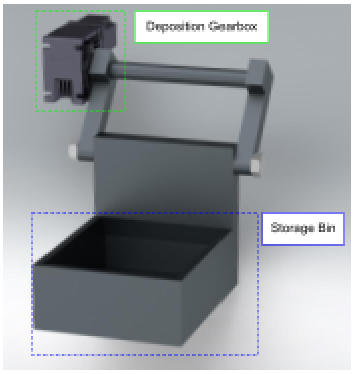


FIGURE 10
Final Computer rendering of the Deposition subsystem

ii) Storage / Differentiation Subsystem

The storage/differentiation is part of the same subsystem as seen in Figure 15, but the method of storage and differentiation are emphasized. The challenge to the final design of this system was dependent on the size of the auger so that the subsystem was within the constraints of the overall robot and how the subsystem would be able to collect the material that was collected from the auger.

The storage system works by waiting for the auger to reach the tallest position, then the storage bin would rotate underneath the auger, after that the auger would spin to release its material, which is the combined BP-1 regolith and ice, and that would fall into the storage system.

The differentiation system works by using the same motor to rotate the storage bin in an oscillating back and forth motion to clear out the BP-1 regolith through the holes in the storage bin. These holes can be seen in Figure 12. And these 6 mm diameter holes were selected to be large enough for regolith to flow through, but small enough to not let ice go through.

Upon testing the design, its efficiency was calculated to be approximately 70%. Testing yields that the storage container would have a maximum capacity of 1.5 kg (this weight depends on the density of the gravel).

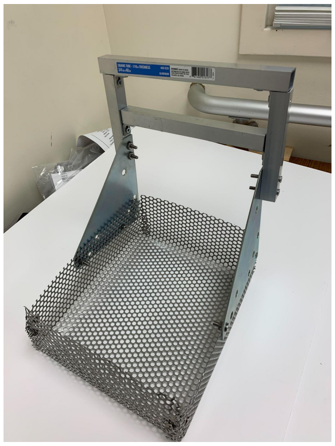


FIGURE 11
Physical Storage and Differentiation System

The storage mechanism uses a single linear actuator to open the deposition chute in order to release filtered gravel into the deposition bin. Load cells are used to obtain the mass of gravel collected and used to evaluate the capacity of the storage container.

B. Locomotion Subsystem

The locomotion subsystem decided on a 4-wheel system that was simple and effective. Our main focus for innovation was the wheel design. The focus for the wheel design was to optimize traction while also providing a solid, sturdy wheel.

This was done by custom designing all parts to fit together and designing the treads/cleat right into the wheel plate. In previous years it was seen that a difficult point for other competing teams at RMC is the low coefficient of friction of BP-1. As observed on ORBIT II, adding cleats to the wheels increases the wheel's traction. We also saw room for improvement over the cleats from last year's robot PIPER as they were small and because the manufacturing process going through quarrent changes to simplify ended up making it flimsy.

Since many of these parts were 3D printed that add quite a bit of weight to the locomotion system. So another consideration was to decrease the weight of the wheel plate. Many simulations were done in SOLIDWORKS to decrease weight while optimizing stiffness.

The locomotion subsystem team chose to implement a direct drive system (one motor for each wheel) to provide differential drive to overcome differences in the terrain of the arena.

The final challenge for the locomotion subsystem is providing feedback for the position of the rover while not utilizing the walls of the arena or magnetic based orientation tracking (C8, C9). Locomotion feedback is accomplished through three main components; the first is a camera placed on the robot and uses computer vision to accurately determine the position and angle of the robot upon detecting eight different AprilTags placed on the outskirts of the arena. The second component is an IMU which would be used as a backup for providing information on the angle of the robot. In the event that the camera cannot detect any AprilTags (which may occur if the robot is angled perpendicular to the tags), data from the IMU can be used to reorient the robot and restore AprilTag detection. The last component is a 360 degree LIDAR sensor placed at the front of the robot used for obstacle detection. The LIDAR can detect any obstacles (crates or boulders) 10 cm from the front wheels of the robot. Upon detection of an obstacle, the microcontroller connected to the LIDAR would immediately stop the wheels of the robot from turning. A 360 LIDAR has not yet been utilized in previous years' designs and will serve to protect the mechanical integrity of the robot.

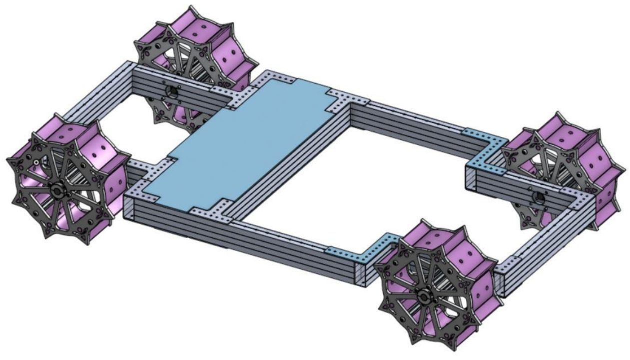


FIGURE 12

Final Computer rendering of the Locomotion Subsystem

E. Subsystem Interfaces

The system contains several central interfaces: the interface between the digging subsystems, locomotion subsystems, the storage/differentiation and deposition subsystems, and the communications interface which coordinates robot actions under both manual and autonomous control.

The interface between the digging and frame subsystems consists of a simple plate mounting where the auger could sit on top of. The plate for the digging mechanism allows for easy removal during maintenance and ease of construction. Additional supports were added to ensure durability.

Meanwhile, the motor gearboxes for the wheels are directly screwed into holes within the frame. The holes cut within the beams were as small as possible to minimize strength lost in the frame. This simple method allowed for ease of manufacturing while taking advantage of the small amount of volume available.

Seeing as the storage, differentiation, and deposition subsystems were all integrated into a single piece, this meant that all objectives could be completed with a single operation. This operation was the simple rotation of the storage bin such that it could be flipped around and above the deposition bin allowing for the material to fall out over the deposition bin.

Finally, coordinated control of the entire system is possible through our communications interface. The communications interface supports both manual and autonomy control, including the option to alternate between the two control modes. The following components comprise of our communications interface:

- **Ground Control Station (GCS)**: a machine intended to be used in isolation from the competition arena. The GCS allows team members to exercise manual control of the robot
- **Server**: a machine located at the deposition bin along with the computer vision assembly inside the competition arena. The server provides processing power for autonomous control of the robot
- **Robot**: a machine located inside the competition arena which travels the arena, excavates and deposits regolith-simulant material

The communications interface must not exceed the bandwidth requirement (SR4). Therefore, data transmitted over the arena border must be minimized. Furthermore, fluidity between manual and autonomy operations encourages autonomy prioritization when possible.

The solution implemented in this system employs the server as the center of communication and computational resources. The server runs the primary control architecture of the system, thereby issuing commands to the robot. The bandwidth requirement does not encompass the data transmitted between the robot and the server within the arena, thus allowing for such data to be transmitted without restriction. The GCS is a contribution endpoint in the network. It delivers manual control commands to the server, which are then relayed to the robot.

The strategy implemented for our communications interface employs the server as the center of communication and computation. The server is an intermediary between the GCS and Robot in the line of communications to preserve simplicity for the data necessary from the GCS. As a result, the server would be the machine to directly command the Robot. Data sent between the server and the robot does not fall under the bandwidth requirement and can thus be transmitted freely.

To ensure parallelism of data between the server and the robot, two microcontrollers (MCUs) exist on the robot as part of our communications interface. One MCU, labeled the controller MCU, serves to command the robot and the other, labeled the data MCU, serves to communicate sensor data. Each MCU is independent of the other. The controller MCU will communicate with the server to receive robot commands and send success/failure messages. The data MCU will communicate with the server to send current data readings from the LiDAR and IMU sensors.

The connection between the GCS and the server operates under a low-bandwidth protocol. During autonomous mode operation, communication between the GCS and server is limited to the start and stop commands, as well as basic reporting of state changes and errors. Manual control is designed as a last recourse in the case of critical system error under autonomous control. When operating under manual mode, approximately one byte of data is communicated from the GCS to the server reflecting which key(s) have been pressed. Whilst autonomy is the priority for its comparatively lower bandwidth, manual control has nonetheless been optimized to minimize its own bandwidth. Figure 13 shows the diagram of the system interface and Figure 14 shows its autonomous processing infrastructure.

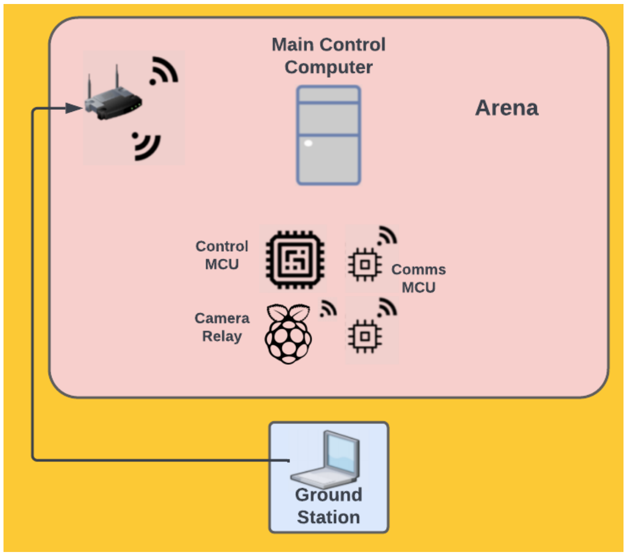


FIGURE 13
Control System Interface Diagram

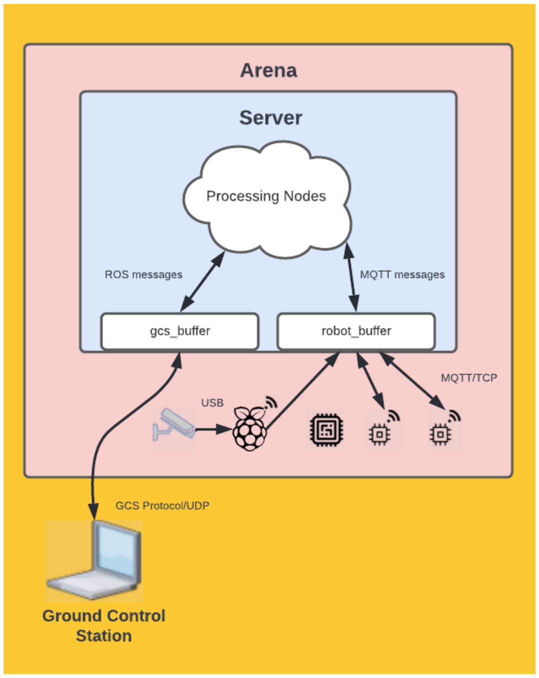


FIGURE 14
Autonomous Program Interface / Control Flow Diagram

II. Design Verification

In order to verify the final design (specifically a review of the proposed fabrication process and the feasibility of the design concepts), a brassboard of the final design was created prior to the Critical Design Review. It was constructed from wood and verified:

- Manufacturability and form

- Sizing
- Interface placement
- System flexibility/rigidity

III. Critical Design Review

Due to scheduling conflicts and geographically distributed origins of the team members, less progress was made during the January break period than previously expected. Hence, the Critical Design Review (CDR), which was originally scheduled for January 23, was conducted on January 30, 2022. The reviewing panel consisted of three faculty members at NYU Tandon specializing in robotics and fabrication/manufacturing, and the project advisor (acting as the capacity of stakeholder). The review panel commented on the feasibility and merit of the final design. Furthermore, they compared the deliverables to the success criteria taken from NASA Procedural Requirements 7123.1C, Table G-7 [5]. The deliverables reviewed by the panel were:

- The final design (CAD, schematics, and state diagrams)
- The brassboard prototypes of the design concepts and testing results
- Fabrication procedure plans (timeline ensuring completion of tasks by desired dates)
- The Final Design Specification (presentation given to the review panel)

The final product of the CDR is the baselined final design and the fabrication plans for each subsystem component.

IV. Fabrication

Following the completion of the Critical Design Review, the fabrication process began. Each student lead and functional group has different responsibilities during the fabrication process. The **Project Management** section describes these functional groups in further detail.

The mechanical engineering functional group produced the physical structure of the robot. Activities conducted by the mechanical functional group include: determining fabricated components' materials, finding COTS components and vendors that fit systems requirements, machining raw materials into subsystem components, and assembling subsystems.

The electrical engineering team was responsible for producing the electronic components and 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 functional group also was responsible for the distribution of signals and fabricated a custom microcontroller breakout board. 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 protection PCB.

Finally, the software team was responsible for producing the high-level code and processes running on the main server and GCS. This included deriving the communication protocol, both between the GCS and main server (UDP heartbeat protocol) and the main server and rovers (TCP MQTT). Moreover, the software team was responsible for the autonomous operation protocol and code.

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 20, 2022. Phase D ends on April 19th, 2022, 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 is to take all the separate subsystems and integrate them into one system. The rover system was split into three subsystems: auger (digging) assembly, frame assembly, and wheel assembly , This was done by following an integration plan which began at the end of Phase C. Figure 15 shows the integration plan (a component hierarchy) utilized for all the subsystems which dictated the order of assembly and which components need to be assembled.

As of March 21, 2021, the digging subsystem was 90% integrated and the storage subsystem 80% integrated (according to their integration plans). Integration of the entire system should occur by April 4, 2021.

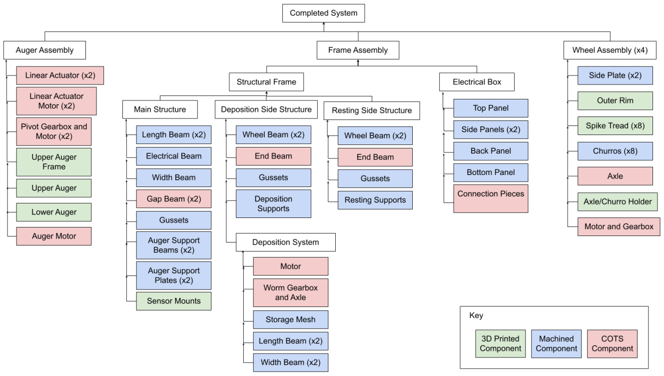


FIGURE 15

Simplified Subsystem Component Hierarchy and Integration Plan

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 (Table D1, **Appendix D**).

Figure 16 shows the partially integrated digging subsystem.

FIGURE 16

Partially Integrated Digging Subsystem (March 28, 2021)

Before integration, each subsystem was verified individually with the set requirements specific to that subsystem. Figure 17 shows one verification test performed on the storage subsystem testing compliance with requirement StR2 and measure of performance MOP1. As demonstrated, these verification processes are controlled tests of specific functions of each subsystem.

Based upon the performance of each subsystem during verification, relaxing 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 17

Verification being performed on the Storage Subsystem

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 as regolith and, prior to testing, the team buries gravel at the required depth beneath the sand. This testing process usually occurs several times in late April (the week of April 22). Figure 18 shows the validation process for ASTRO.

IV. System Delivery

The completed system will be delivered (shown in a proof-of-life video) to NASA on April 16, 2021. Due to changes in the Robotic Mining Competition, this delivery takes the form of a video documenting the rover completing various functions and demonstrating a fulfillment of NASA's expectations for said system.

The video 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 in late April.

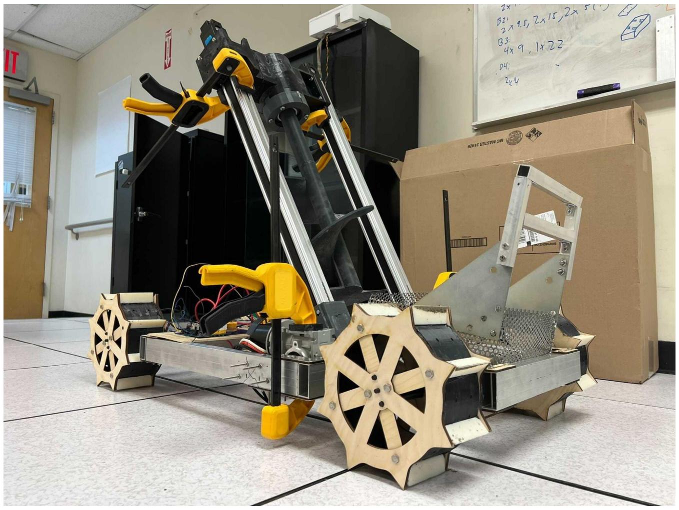


FIGURE 18

Validation of ASTRO

[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. 2021). *NASA RMC Registration, Rules, and Rubrics*.

APPENDIX A: TECHNICAL MEASURES

TABLE A1
SYSTEM MEASURES OF EFFECTIVENESS

Measure of Effectiveness	Traced from
MOE1: Capability to differentiate gravel icy regolith from BP-1 regolith	Ob7
MOE2: Able to collect at least 2 kg of gravel in 10 minutes	C6
MOE3: System has a mass less than 80kg	Ob1, C1
MOE4: System uses less than 40 Wh of electrical power	Ob8
MOE5: System uses less than 15 Mbps bandwidth for communication	Ob4
MOE6: System is capable of operating in the target environment	Ob3

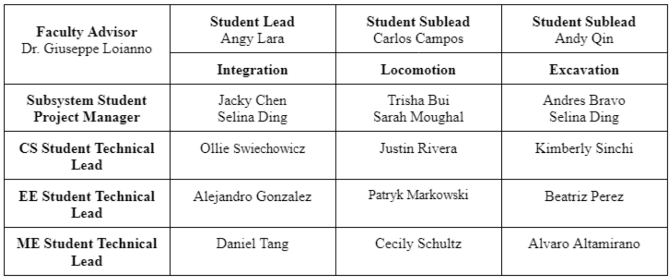
TABLE A2
SYSTEM MEASURES OF PERFORMANCE

Measure of Performance	Traced from
MOP1: Remove 66% of BP-1 from regolith and BP-1 during differentiation	MOE1
MOP2: The system will make two runs, the first to deliver the minimal mining requirement (1kg) and the second to deliver the remaining 1 kg.	MOE2
MOP3: System mass is less than 80 kg	MOE3
MOP4: System provides the capability to protect critical components against dust intrusion.	MOE6

PROJECT MANAGEMENT

The New York University Robotic Design Team is a group of 55 undergraduate 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 lead is Angy Lara. The systems engineers and team subleads are Carlos Campos and Andy Qin.

Given the scope of the project and amount of engineering disciplines involved the team is organized into project and technical teams. The team is organized into project teams based on robot systems (locomotion, excavation, integration). Each project team has a project lead and three technical teams led by technical leads specializing in a discipline (mechanical, electrical, or computer engineering). See Figure 19 for a diagram of the team structure.



Faculty Advisor Dr. Giuseppe Loianno	**Student Lead** Angy Lara	**Student Sublead** Carlos Campos	**Student Sublead** Andy Qin
	Integration	**Locomotion**	**Excavation**
Subsystem Student Project Manager	Jacky Chen Selina Ding	Trisha Bui Sarah Moughal	Andres Bravo Selina Ding
CS Student Technical Lead	Ollie Swiechowicz	Justin Rivera	Kimberly Sinchi
EE Student Technical Lead	Alejandro Gonzalez	Patryk Markowski	Beatriz Perez
ME Student Technical Lead	Daniel Tang	Cecily Schultz	Alvaro Altamirano

FIGURE 19
TEAM ORGANIZATIONAL STRUCTURE

I. Technical Requirements Management

Technical requirement management was divided by a layered method. The project leads were responsible for the oversight of the requirement management of a project team as a whole and the sub technical leads managed technical requirements in a specific area. Such technical requirements including continuous testing on the design to ensure requirements were 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

Interface management was generally managed by the technical leads and systems engineers. Interface management was performed at design, fabrication, and integration stages. Specifically, the leads responsible for interface management were responsible for identifying interfaces and their requirements in the system.

III. Configuration Management

Configuration Management systems include the codebase kept on GitHub, mechanical CAD files and electrical and embedded systems' diagrams. All of this documentation is required for the completion of the project (Assessing sources of error, technical reviews, etc.) and for future year's project development. Configuration management workflow is depicted in Figure 20.

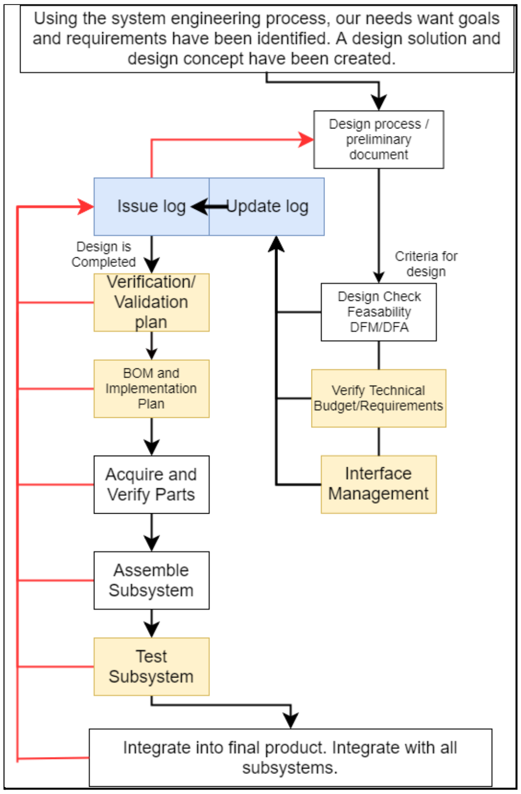


FIGURE 20

CONFIGURATION MANAGEMENT WORKFLOW EMPLOYED BY THE TEAM

CAD files were made and stored using the Onshape platform allowing for the simultaneous viewing and sharing of CAD files over a cloud as well as version control and online viewing through a browser. The software helped maximize time spent working on files and minimize the time spent sharing, updating and organizing files. The mechanical and electrical technical leads were responsible for reviewing all CAD documents and assessing dependencies and finding 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 code was organized into Ground Control Station, Server and Robot Code repositories for better organization. The Ground Control Station and Server repositories hosted communication and autonomy code and the Robot Code repository hosted embedded systems code. The software engineering technical leads were responsible for identifying defects and dependency conflicts within the codebase. The electrical engineering leads 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

Project and technical leadership was responsible for performing risk management in two to three week cycles. Risks were classified as operational (risks associated with project communication) or functional (risks associated with the performance of the rover). Risks are recorded in the risk matrix included in Table E1, **Appendix E**. Every cycle risks were assessed based on severity and likelihood. New risks were identified as the production continued.

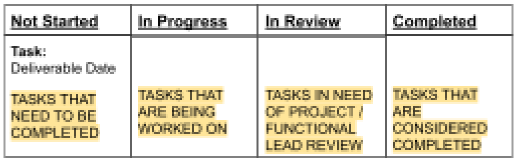
V. Technical Data Management

Technical documentation consists of the supporting documentation produced during the project (i.e. System Requirement Specification, Preliminary Design Specification and Presentation, Final Design Specification, fabrication plans and COTS component datasheets). Most documentation was stored on the team Google Drive with accounts provided by the university and owned by each member. Technical documents were uploaded to the platform or collected via Google Forms and stored in a spreadsheet. Prior year's documentation is stored in a compressed archive within a shared folder.

VI. Technical Planning

Technical planning consists of the management and tracking of project progress. Student leads and systems engineers conducted regular technical and project planning. The majority of the project planning was recorded in the project schedule baselined during the Concept Development Phase (prior to the submission of the Plan for Systems Engineering deliverable). The schedule was routinely revised. Figure F1, **Appendix F** includes the proposed project schedule (Gantt Chart) for the project and the actual progression of the project lifecycle.

Project progress was tracked using a master Kanban board, Figure 21 is an example, on Trello (similar to the SCRUM project methodology) that was constantly updated by the team. The board was used to track progress of tasks, making schedule slips easy to identify and mitigate.



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

Decision Analysis was primarily conducted using trade studies during the preliminary and final design phases. 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 decision analysis was implemented to ensure complete assessment of each potential option as well as distilling which ideas were used and brought through the prototyping phase to minimize capital and time spent.

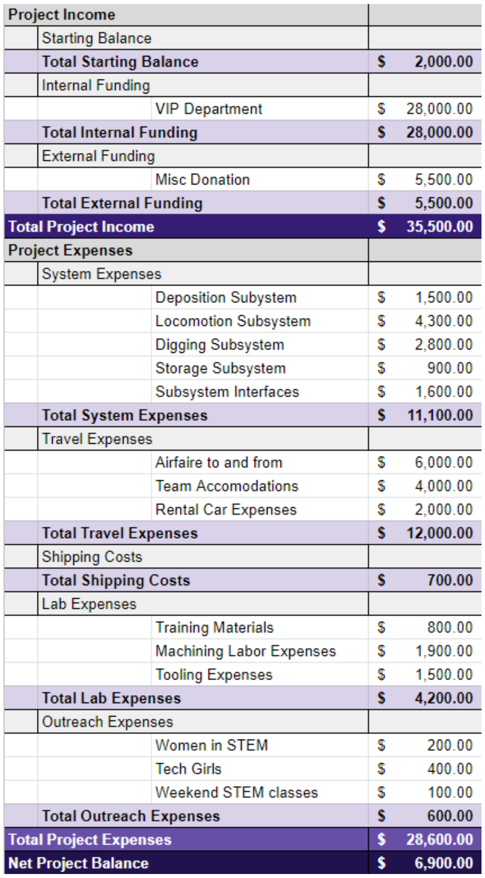
Trade studies were conducted for the subsystem concept development, system concept development, and final design development and implementation. Each trade study concluded in the construction of some form of prototype. During the preliminary design phase, the trade study product was a subsystem breadboard (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

Budget management was a major priority of project leads. The main source of capital was the Departments of Electrical and Computer Engineering, and Vertically Integrated Projects at New York University's Tandon School of Engineering. Open fundraising was held over the summer of 2021 and the team raised approximately $5,700.

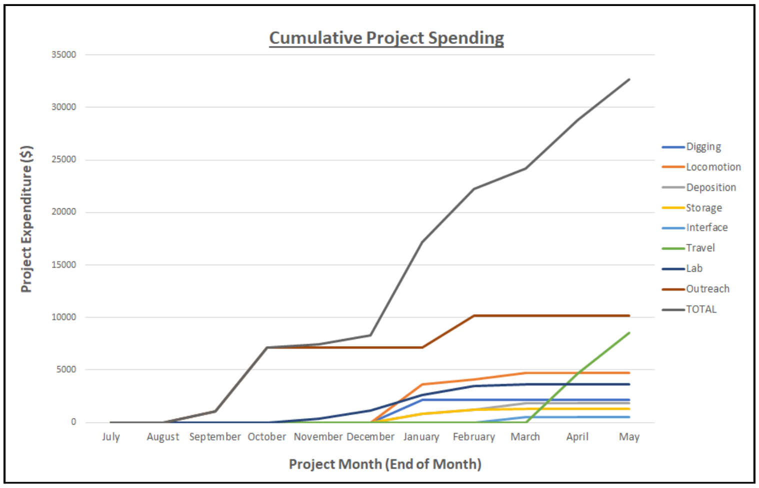
The overall budget of the project is shown in Table 13. Furthermore, Figure 22 shows project spending over the duration of the project. One note, travel expenses to and from a make-up competition in Orlando, Florida are included in the budget.

TABLE 13:
FINAL PROJECT BUDGET

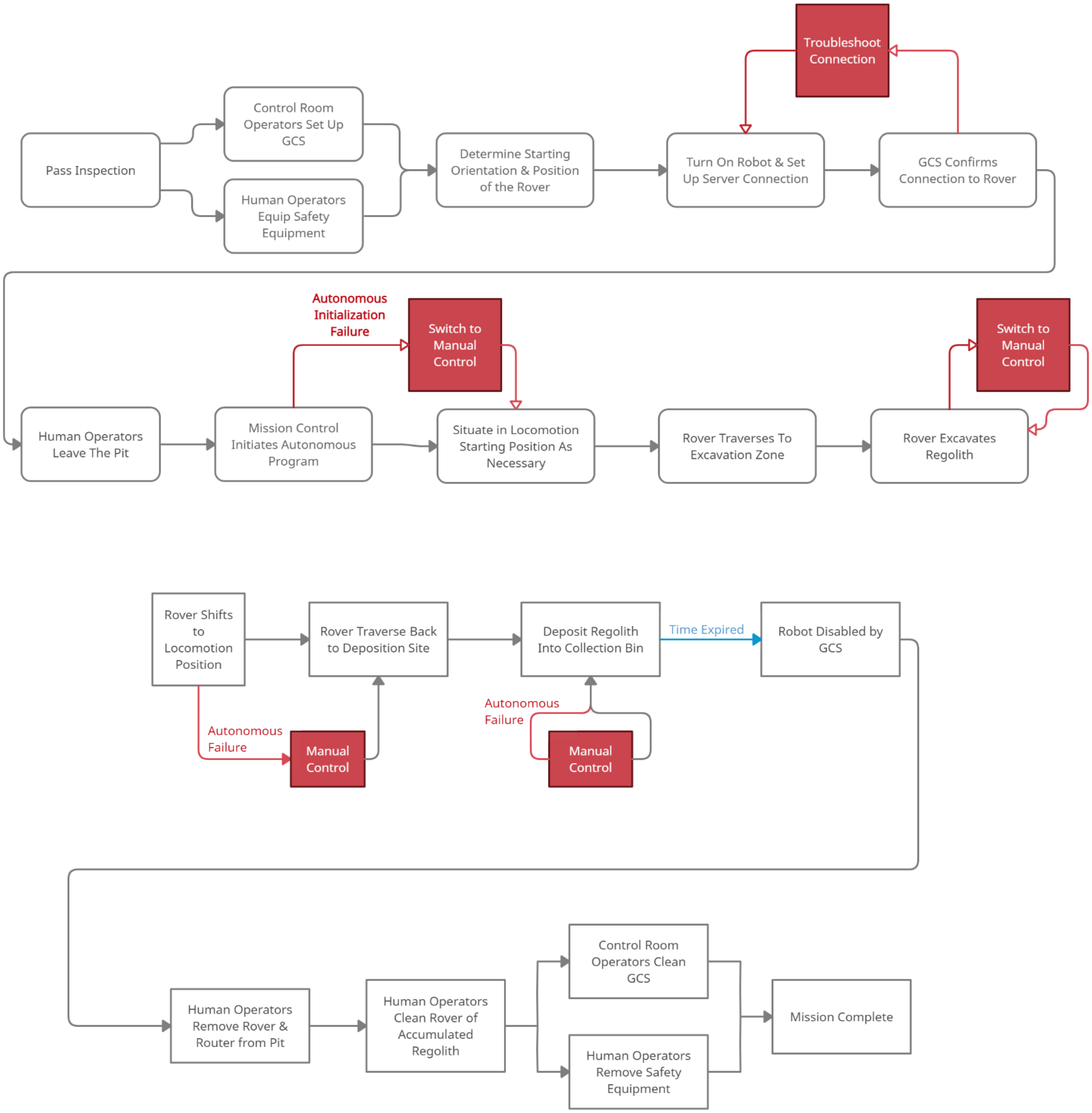


Project Income			
	Starting Balance		
	Total Starting Balance		**$ 2,000.00**
	Internal Funding		
		VIP Department	$ 28,000.00
	Total Internal Funding		**$ 28,000.00**
	External Funding		
		Misc Donation	$ 5,500.00
	Total External Funding		**$ 5,500.00**
Total Project Income			**$ 35,500.00**
Project Expenses			
	System Expenses		
		Deposition Subystem	$ 1,500.00
		Locomotion Subsystem	$ 4,300.00
		Digging Subsystem	$ 2,800.00
		Storage Subsystem	$ 900.00
		Subsystem Interfaces	$ 1,600.00
	Total System Expenses		**$ 11,100.00**
	Travel Expenses		
		Airfaire to and from	$ 6,000.00
		Team Accomodations	$ 4,000.00
		Rental Car Expenses	$ 2,000.00
	Total Travel Expenses		**$ 12,000.00**
	Shipping Costs		
	Total Shipping Costs		**$ 700.00**
	Lab Expenses		
		Training Materials	$ 800.00
		Machining Labor Expenses	$ 1,900.00
		Tooling Expenses	$ 1,500.00
	Total Lab Expenses		**$ 4,200.00**
	Outreach Expenses		
		Women in STEM	$ 200.00
		Tech Girls	$ 400.00
		Weekend STEM classes	$ 100.00
	Total Outreach Expenses		**$ 600.00**
Total Project Expenses			**$ 28,600.00**
Net Project Balance			**$ 6,900.00**

FIGURE 22
Cumulative Project Spending.



APPENDIX B: MISSION CONCEPT OF OPERATION



Appendix C: Technical Budget

TABLE C1

Initial Technical Budget (October 20, 2021)

Budget Criteria	Weight (kg)	Bandwidth (kbps)	Power Consumption (Wh)	Capital Cost ($)	Operation Duration (s)	Regolith Manipulation	Volume (m3)
Total System Target	75	15	45	10000	600	5 kilograms scored	0.72
Locomotion Subsystem Allocation	10	8	20	2300	270	*N/A*	0.20
Excavation Subsystem Allocation	10	2	5	1900	90	0.8333 kg/s offload rate	0.19
Storage / Differentiation Subsystem Allocation	5	0[1]	5	850	150[2]	40 kg payload capacity	0.08
Auger 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 C2

Actual Technical Budget (March 7, 2022)

Budget Criteria	Weight (kg)	Bandwidth (kbps)	Power Consumption (Wh)	Capital Cost ($)	Operation Duration (s)	Regolith Manipulation	Volume (m3)
Total System Target	69	0[5]	42.4	9922	600	5 kilograms scored	0.84
Locomotion Subsystem Allocation	32	0[5]	20.8	4692	480	*N/A*	0.81
Integration 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]	40 kg payload capacity	0.09
Excavation Subsystem Allocation	15	0[5]	12.3	2142	300	0.35 m mining depth 0.16 kg/s digging rate	0.28
Excavation - 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 D: Requirement Verification

TABLE D1
Requirement Verification Matrix

Requirement No.	Shall Statement	Verification Success Criteria	Verification Method	Phase	Results
SR1	The system shall have a mass of 80kg	The system mass is less than or equal to 80kg.	Individual components are measured for compliance with the sum / final system is weighed	C and D	Estimates place the mass at 70 kg.
SR2	The system shall have a maximum dimension of 1.0m x 0.5m x 0.5m	The system dimension is less than the max	The final system is measured and compared to the volume	D	Brassboarded concepts fit within this dimension, final system integration has not yet occurred.
SR3	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.
SR4	The system shall be able to receive commands from a human operator at the Ground Control Station wirelessly via 802.11ac and use less than 10 kbps of bandwidth	Control over the system can be recovered by the manual operator and the full operation of the rover can be done with less than 10 kbps	During design, a hypothetical command scenario will be conducted to ensure bandwidth utilization, during verification, autonomy will be aborted and an entire run manually operated with < 10 kbps	C and D	Individual subsystems have been controlled manually from the GCS. Final system manual control has measured an average 2 kpbs
SR5	The system shall be able to fully power off (disconnect from the battery) in case of the operational rule of safety violation	The system disconnects fully on emergency power-off with no ability to recover	During verification, the system will be fully powered off (repeatedly) to ensure reliability	D	The circuit is made to do so, the components were tested, the final system must still be verified during operation.
SR6	The system shall complete at least level 3 partial autonomy (as defined in the NASA RMC Rules and Rubrics)	The system meets all requirements of level 3 autonomy during verification	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.
SR7	The system shall not employ any components or technologies not suitable for Mars	The system does not use unaccepted technology.	During design, no prohibited technologies will be employed	B and C	No prohibited technologies were used.
SR8	The system shall be able to deposit at least 2 kg of icy gravel in 10 minutes of operation	The system collected and deposited 2 kg of gravel under simulated competition conditions	Individual components will be tested for individual performance towards the requirement. During verification, the completed system will be run and its performance measured	C and D	Final system operation still untested (as of April 11, 2022)
SR9	The system shall have software feedback for all moving mechanisms	The autonomous program functions as intended	During design, measures will be identified and the correct sensors acquired. During verification, the autonomous program will be tested	B, C and D	All software feedback mechanisms function and can accurate determine the state of the system.
SR10	The system shall consume at most 40 Wh of electrical power and monitor said consumption using a COTS device	The power consumption will be less than the maximum	Individual component power consumption will be calculated. During verification, system power will be calculated	C and D	Estimates places consumption at 42.8 Wh; however, this is a liberal estimate, therefore actual consumption will be lower.
SR11	The system shall be able to perform multiple functions	The system is able to operate in parallel	Develop system concepts that provide parallelism. Verification	B, C and D	Final system operation still untested (as of April 11,

	simultaneously		will ensure parallelism		2022)
SR12	The system shall be recoverable from error	Simulated errors do not result in mission failure	The error will be simulated during verification and recovery tested	D	Final system operation still untested (as of April 11, 2022)

Appendix E: Project Risk Management Matrix

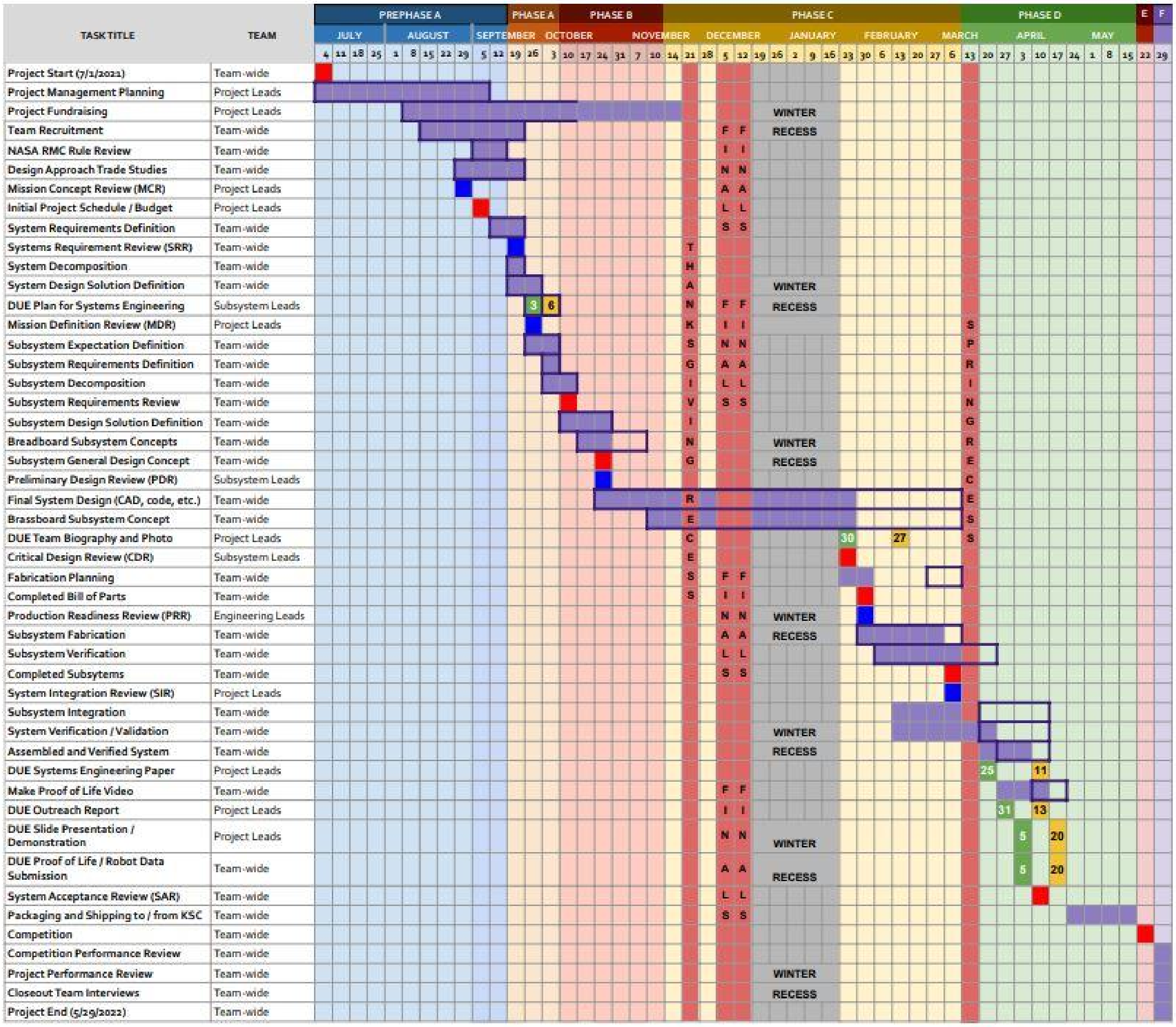
TABLE E1

Risk Management Matrix

Risk No.	Risk	Discovered	Category	Impact	Probability	Mitigation Strategy	Status*
Ri1	Nuc fails to localize machine	Phase A	Operational	LOW	HIGH	Rotate the robot until an AprilTag is detected. Wait 30 seconds until switching to manual controls	**Completed**
Ri2a	Robot fails to move (Drive vectors sent, received but no movement)	Phase A	Operational	HIGH	LOW	Find reverse of drive vector and input (backtrack)***1** Switch to manual control	**Retired**
Ri2b	Robot encounters obstacle ***2**	Phase A	Operational	HIGH	HIGH	Move around the obstacle by sensing obstacle (lidar) Switch to manual control	**Completed**
Ri2c	April Tags cannot be detected (difficult to determine if robot is moving)	Phase B	Operational	LOW	HIGH	Based off IMU reading, the robot will rotate as appropriate Switch to manual control	**Completed**
Ri3a	Bucket fails to pivot to position for robot movement	Phase B	Operational	LOW	LOW	Maintain Auger in digging position, lower speed of robot whilst moving	**Retired**
Ri3b	Falling into the hole that was dug	Phase A	Operational	HIGH	LOW	Save (x, y) position of previously dug hole into a data structure and compare with current robot position. Evade previously dug hole by 0.5 meters	**Completed**
Ri4a	Auger screw does not move upwards	Phase B	Operational	HIGH	LOW	Switch to manual control	**Completed**
Ri5a-c	Risks for state 10 are identical to state 5						
Ri6a	Robot does not properly align with deposition bin	Phase A	Operational	HIGH	LOW	Slightly traverse away from the bin to ensure AprilTag detection. Retry alignment procedure Switch to manual control	**Completed**
Ri6b	Deposition unit cannot reach deposition bin	Phase A	Operational	HIGH	LOW	There will be considerable effort to ensure the coordination of the bucket will reach deposition height	**Retired**
Ri6c	Crash with Depo Bin/Wall	Phase A	Operational	HIGH	HIGH	Localize robot, move until parallel to the AprilTags (through traversal or rotation)	**Completed**

APPENDIX F: PROJECT SCHEDULE

PROJECT TITLE	2022 Robotic Mining Competition	COMPANY NAME	NYU Robotic Design Team
PROJECT MANAGER	**Student Lead:** Angy Lara **Faculty Advisor:** Giuseppe Loianno	PROJECT DATES	July 7, 2021 - May 22, 2022



TASK TITLE	TEAM
Project Start (7/1/2021)	Team-wide
Project Management Planning	Project Leads
Project Fundraising	Project Leads
Team Recruitment	Team-wide
NASA RMC Rule Review	Team-wide
Design Approach Trade Studies	Team-wide
Mission Concept Review (MCR)	Project Leads
Initial Project Schedule / Budget	Project Leads
System Requirements Definition	Team-wide
Systems Requirement Review (SRR)	Team-wide
System Decomposition	Team-wide
System Design Solution Definition	Team-wide
DUE Plan for Systems Engineering	Subsystem Leads
Mission Definition Review (MDR)	Project Leads
Subsystem Expectation Definition	Team-wide
Subsystem Requirements Definition	Team-wide
Subsystem Decomposition	Team-wide
Subsystem Requirements Review	Team-wide
Subsystem Design Solution Definition	Team-wide
Breadboard Subsystem Concepts	Team-wide
Subsystem General Design Concept	Team-wide
Preliminary Design Review (PDR)	Subsystem Leads
Final System Design (CAD, code, etc.)	Team-wide
Brassboard Subsystem Concept	Team-wide
DUE Team Biography and Photo	Project Leads
Critical Design Review (CDR)	Subsystem Leads
Fabrication Planning	Team-wide
Completed Bill of Parts	Team-wide
Production Readiness Review (PRR)	Engineering Leads
Subsystem Fabrication	Team-wide
Subsystem Verification	Team-wide
Completed Subsytems	Team-wide
System Integration Review (SIR)	Project Leads
Subsystem Integration	Team-wide
System Verification / Validation	Team-wide
Assembled and Verified System	Team-wide
DUE Systems Engineering Paper	Project Leads
Make Proof of Life Video	Team-wide
DUE Outreach Report	Project Leads
DUE Slide Presentation / Demonstration	Project Leads
DUE Proof of Life / Robot Data Submission	Team-wide
System Acceptance Review (SAR)	Team-wide
Packaging and Shipping to / from KSC	Team-wide
Competition	Team-wide
Competition Performance Review	Team-wide
Project Performance Review	Team-wide
Closeout Team Interviews	Team-wide
Project End (5/29/2022)	Team-wide

LEGEND:

🟪 Allocated duration of task	☐ Cu Current Date	1 Target Submission Day, RMC Products	🟥 Project Milestone	☐ Project Milestone
🟥 Holidays (Non-working)	▨ Reduced Work Periods	30 NASA RMC Deadline Day	🟦 Systems Engineering Review	☐ Systems Engineering Review
☐ Actual task duration	■ Cancelled task	☐ Actual Submission Da of RMC Deadlines		