NEW YORK UNIVERSITY TANDON SCHOOL OF ENGINEERING

ROBOTIC DESIGN TEAM

2018-2019 SYSTEMS ENGINEERING REPORT

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New York University Tandon School of 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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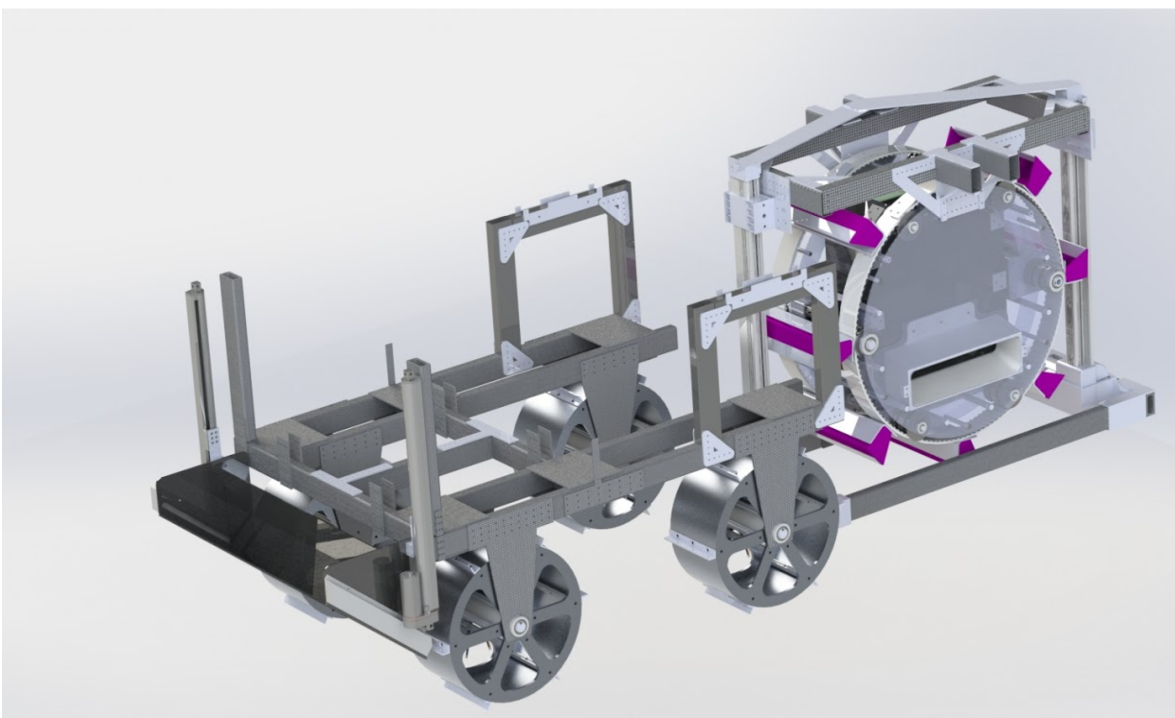
Abstract

NASA is on the brink of sending humans to other planetary bodies (Mars and the Moon), but sustaining life will be impossible without harvesting the native resources such as ice and hydrated minerals below the surface of the planet. The NASA Robotic Mining Competition challenges university student teams to develop robotic mining systems that may be applied to the future of resource harvesting on Mars. Teams must create rovers to traverse an artificial Martian 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, ORBIT 2 (Operational Robot Built in Tandon 2), 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 ORBIT 2. A computer rendering of the ORBIT 2 system is shown below.



Final System CAD Rendering

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PURPOSE STATEMENT

The NASA Systems Engineering Process was implemented by the NYU Robotic Design Team for the 2019 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 2019 NASA Robotic Mining Competition (2019 NASA RMC).

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). As of February 2019, the in-person mining component of the NASA RMC was canceled. However, competing teams are still evaluated on the other project deliverables (remotely) as outlined in *II. Project Deliverables*.

The NASA Systems Engineering Process (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 2019 NASA RMC as well as their description and deadlines.

TABLE 1
PROJECT DELIVERABLES [3]

Deliverable	Description	Deadline
Plan for Systems Engineering	A preliminary document stating the early project definition (including the initial project schedule, budget and design philosophy)	November 14, 2018
Outreach Report	A written report describing the team’s efforts in engaging their community in STEM education initiatives	March 28, 2019
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 2, 2019
Technical Presentation	A presentation to a panel of judges about the spirit and technical outcome of the project	April 20, 2019
Robot Proof of Life and Data	A video demonstrating the operation of the final system and supporting documentation (i.e. Bill Of Materials)	May 1, 2019

PRE-PHASE A: CONCEPT STUDIES

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

The planning and development of the mission and system concept required by Pre-Phase A were started prior to the release of the official 2019 NASA RMC Rules and Rubrics on September 6, 2018. Therefore, the initial assumptions made about the mission concept and possible operational conditions were based upon the team's experience from previous years' of the RMC. Upon the release of the Rules, these assumptions were compared to the official expectations for the mission.

I. Identifying Stakeholder Expectations

The primary stakeholder and the final customer of the completed system is the NASA 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].

In previous years, NASA's primary expectation for the produced system was that it maximize the mass of simulated extraterrestrial regolith (BP-1 simulant) collected from the testing arena and deposited into a collection receptacle within an allotted period of time. In recent years this expectation has changed, requiring teams to only 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 2019 NASA RMC Rules.

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

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

TABLE 2
MISSION CONSTRAINTS

Constraint	Source [3]
C1: The maximum mass of the system is 80kg	Rule 20
C2: The maximum starting dimension of the system is 0.75m width, 1.5m length, 0.75m height	Rule 23
C3: The maximum operational height of the robot is 1.5m	Rule 23
C4: The system will communicate with the Ground Station using commercial 802.11ac wireless communications (WiFi)	Rule 35
C5: The system will have a means of being disabled (full disconnection from power) using a button with a minimum diameter of 40mm	Rule 22
C6: The system will have 2 test runs of 10 minutes each	Rule
C7*: The system will be delivered to NASA KSC by May 6, 2018	Part I
C8: The system cannot navigate using the walls of the Arena	Rule 3
C9: The system cannot utilize compressed fluids (hydraulics/pneumatics), explosives, or similarly unsuitable materials for extraterrestrial environments (i.e. GPS, magnetic compasses)	Rule 26, Rule 15
C10: The system will be self-powered and monitor its power consumption using a COTS power consumption meter	Rule 21

*This constraint, while no longer implemented as a result of changes made to the Rules on February 14, 2019, is still relevant to achieve the Robot Proof of Life deliverable on May 1, 2019

II. Development of Preliminary Mission Parameters

A. Defining Needs, Goals, and Objectives

Given the set of expectations from the mission's stakeholders, developing a traceable set of needs, goals, and objectives (NGOs) represents the first step in defining a scope for the mission [1]. See Table 3 for the NGOs developed for this mission by the team.

B. Defining Measures of Effectiveness

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

TABLE 3
MISSIONS 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 60 kg
Objective (**Ob2**)	The robot should operate fully autonomous (as defined by Rule 3j [3])
Objective (**Ob3**)	The robot should complete two dig/deposit cycles in a maximum of 5 minutes per cycle
Objective (**Ob4**)	The system should use a maximum of 15 Mbps (bandwidth)
Objective (**Ob5**)	The system should cost a maximum of $10,000
Objective (**Ob6**)	The system should be completed by April 20, 2019
Objective (**Ob7**)	The system should collect 20 kg of gravel icy regolith (10 kg/cycle)
Objective **(Ob8)**	The system should achieve the minimum mining score (1kg)
Objective **(Ob9)**	The system should be resilient to error or recoverable from it

A. Evaluating Mission Operational Scenarios

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

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

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

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

B. Past System Performance

The system developed for the 2019 NASA RMC would be the fourth complete system developed for RMC by the NYU team. Previous systems offer insight into the feasibility of the mission and possible risks.

The first successful system developed for the NASA RMC was the Atlas II rover (RMC 2012 - 2016). It featured a large central digging wheel (drum) mounted on an articulating arm. The drum would collect regolith and the arm would tip the contents of the drum into the collection bin. Atlas II performed well; however, Atlas II did not achieve minimal mass and power consumption.

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

The primary purpose of Phase A of the Systems Engineering Process is to develop a baselined mission concept 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 16, 2018, with the conclusion of Pre-Phase A and ended on October 20, 2018, with the completion of the Mission Definition Review.

I. Formalizing the Concept of Operations

A preliminary Concept of Operations was developed in Pre-Phase A based upon the expected parameters of the mission. This ConOps was re-evaluated and baselined in Phase A (see **Appendix B**) based upon the actual mission parameters as defined in the NASA RMC Rules and Rubrics.

II. Technical Requirements Definition

A. System Requirements Definition

The system's technical requirements are divided into six categories: functional (F), performance (P), interface (I), environmental (E), design (D) and safety (S) [1]. Table 4 lists the technical requirements for the system and the constraints and operational expectations from which each requirement is derived. The unique requirement ID and its category are indicated in parenthesis preceding each requirement in the format: (ID, Category). Key Driving Requirements are indicated with an asterisk (*). An initial system level technical budget was also drafted based upon these requirements and maintained throughout the project lifecycle (Table C1, **Appendix C**).

B. Technical Requirements Verification Plans

The technical requirements verification plans are methodologies created to test the final system for compliance with the technical requirements. These plans are summarized in Table D1, **Appendix D**, a requirements verification matrix.

C. Measures of Performance and Technical Performance Measures

Various Measures of Performance (MOPs) were created to further define the technical requirements and MOEs. They are listed in Table A2, **Appendix A**.

III. System Requirements Review

The Systems Requirements Review (SRR) took place on September 7, 2018. The reviewing panel for the SRR consisted of a group of four NYU RDT alumni, as they, having previously competed in the NASA RMC, were familiar with the competition and its expectations. Not being current members of the team, they could provide an objective analysis of the technical requirements and verification plans. The deliverables required for this review are:

- Baselined Mission ConOps
- System Requirements and proposed verification plans

During the review, the team's student leads presented the deliverables. The panel evaluated the requirements based upon the criteria from NASA Procedural Requirements 7123.1B, Table G-4 [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

The panel determined that the requirements did, in fact, satisfy the mission. The only change made as a result of the SRR was the reduction of the mass requirement from 75kg to 70 kg to account for a margin of error as a result of fabrication. For the ORBIT 1 (RMC 2018) system, the system's mass was measured as 73kg at the final design, however, after fabrication was measured to be 78kg. Upon delivery to RMC, it was measured at 74kg. Hence, a margin in excess of 5kg is meant to protect against these fluctuations. The output of the SRR is a set of successfully baselined requirements and verification.

IV. System Decomposition

A. Functional Decomposition

The various functions needed to be performed by the system to accomplish the concept of operations and system requirements were listed and allocated to the various subsystems. From these allocations, functional interfaces were also designed and allocated to subsystem interfaces.

TABLE 4
SYSTEM TECHNICAL REQUIREMENTS

Requirement	Traced from	Rationale
(SR1, D+P)*: The system shall have a mass of 70kg	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 1.5m x 0.75m x 0.75m 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 able to fully power off (disconnect from the battery) in case of the operational rule of safety violation	C5	Both a requirement 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 one approach which assigned all functions relating to the same requirement to a single subsystem (i.e. an autonomy subsystem, a dust tolerance subsystem, etc.). Another approach grouped subsystems by discipline (i.e. mechanical subsystem, software subsystem, etc.). In the end, the subsystems were created by grouping functions involved in similar steps of the ConOps (i.e. digging, depositing, locomotion and storage) into subsystems. By taking this approach, subsystems and their interfaces can be made to operate concurrently during mission execution, as per requirement SR11.

B. System Architecture

Figure 1 shows the high-level system's functional decomposition. Additionally, Figure 2 shows the allocation of functions to the subsystem interfaces. The differentiation of icy and BP-1 regolith was grouped with storage so that differentiation could happen simultaneous to digging, in order to fulfill requirement SR11.

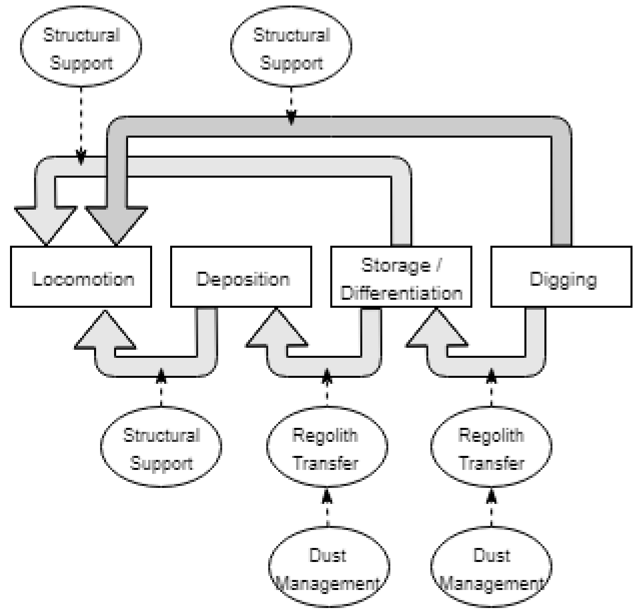


FIGURE 1: System Architecture
System Interfaces and Functional Allocations (Rectangles are Subsystems, grey arrows are interfaces between Subsystems, and ellipses are allocated Functions)

C. Allocation of Subsystem Requirements

Following the creation of system architecture, the technical requirements were similarly decomposed and allocated to the individual subsystems. These allocated requirements were then used to further define the technical budget for the system, 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 in conjunction with two team alumni on October 20, 2018. 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.

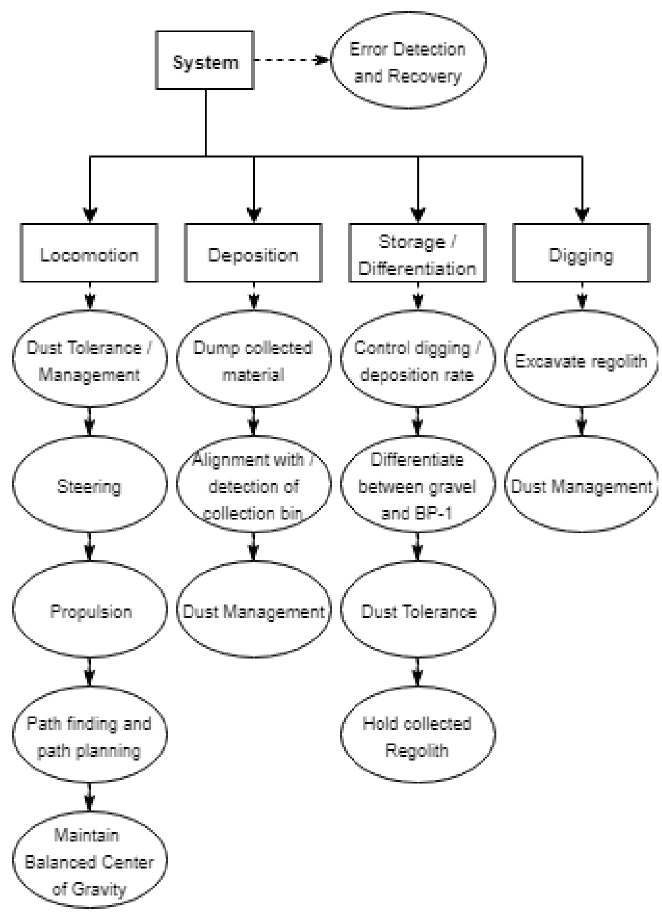


FIGURE 2
System Hierarchy and Functional Decomposition (Rectangles are levels of the hierarchy and ellipses are allocated Functions)

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 0.75m x 0.75m x 1.5m 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 icy and BP-1 regolith.	SR8
(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

The primary purpose of the Preliminary Design Phase of the Systems Engineering lifecycle is to develop a general design for the system as well as further refine the mission baseline developed in Phase A. Moreover, it is during Phase B that all technology development, prototyping, and risk mitigation are completed [1]. Phase B of the project started on October 20, 2018, with the completion of the MDR and ended on November 14, 2018, with the completion of the Preliminary Design Review (PDR).

I. Subsystem Design Solutions

Design concepts for individual subsystems are created through trade studies conducted at the start of Phase B. The concepts in the trade study were evaluated using a list of MOEs for each subsystem that were created based upon the subsystem requirements. For a description of the trade study process utilized by the project, see *Decision Analysis* in the **Project Management** section on page 26.

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

A. Digging Subsystem

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

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

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

A digging wheel 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, the digging wheel is more power efficient as its circular geometry requires less torque than the elliptical geometry of a conveyor belt.

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 digging wheel; this was decided mainly upon the team's experience designing and fabricating said design, as well as its general fulfillment of all of the requirements for the subsystem as per the results of the trade study.

TABLE 7
DIGGING DESIGN CONCEPT TRADE STUDY RESULTS

		Design Concepts		
Measure of Effectiveness	Decision Weight	Auger	Conveyor Belt	Digging Wheel
DiMOE1	3	20.95 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	0.033 kg/s	0.248 kg/s	0.65 kg/s*
DiMOE5	2	2*	2*	4
DiMOE6	3	3*	1	2

* Indicates the best performing metric

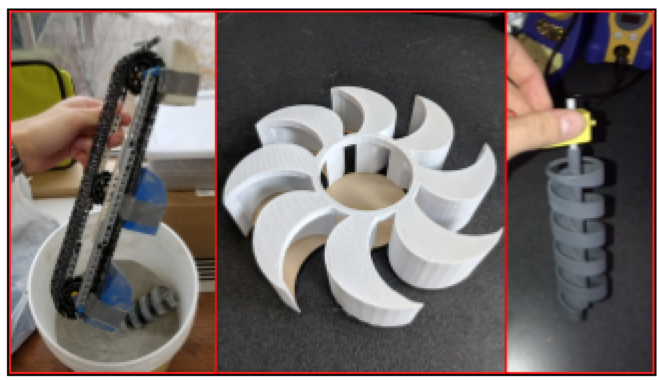


FIGURE 3
DIGGING SUBSYSTEM DESIGN CONCEPTS. FROM LEFT TO RIGHT: CONVEYOR BELT, DIGGING WHEEL, AUGER.

B. Locomotion Subsystem

Several design decisions regarding the structure of the locomotion chassis were examined during the trade study, specifically the use of a static chassis without a suspension mechanism and a rocker-bogie chassis with an articulated wheel suspension. Both breadboards were constructed using LEGO Mindstorm components and evaluated on the MOEs defined in Table 6.

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

The rocker-bogie chassis has a suspension system, and therefore would be able to traverse obstacles easier, but would be more complex to fabricate and have more mass.

The static chassis was chosen for its lower mass and complexity. In order to mitigate the risk of failure as a result of a collision, this design requires larger wheels and a more robust autonomous strategy. Table 8 lists the scaled scores of each concept based upon the established subsystem MOEs in Table 6 and Figure 4 shows the breadboarded concepts.

TABLE 8
LOCOMOTION DESIGN CONCEPT TRADE STUDY RESULTS

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

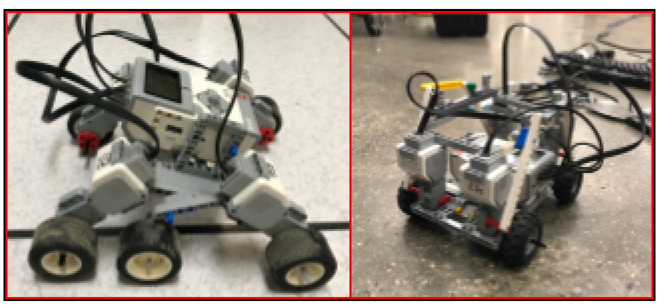


FIGURE 4
LOCOMOTION SUBSYSTEM DESIGN CONCEPTS. FROM LEFT TO RIGHT: ROCKER BOGIE, STATIC FRAME

C. Deposition Subsystem

The primary technology involved in the deposition subsystem is the means of transferring the collected regolith from the storage subsystem to the collection bin. Four concepts were examined during the trade study: expanding bin, expanding tube, 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 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.

TABLE 9
DEPOSITION DESIGN CONCEPT TRADE STUDY RESULTS

Measure of Effectiveness	Decision Weight	Design Concepts			
		Expanded Tube	Expanded Bin	Tipping	Chute
DeMOE1	5	< 15%	< 10%	< 5%*	< 5%*
DeMOE2	3	7.5 Wh	10 Wh	4 Wh*	8 Wh
DeMOE3	5	8 sec	5 sec	2.5 sec	2 sec*
DeMOE4	2	5kg	8kg	2kg*	2kg*
DeMOE5	2	> 98%	> 97%	> 80%	> 95%*

* indicates best performing metric

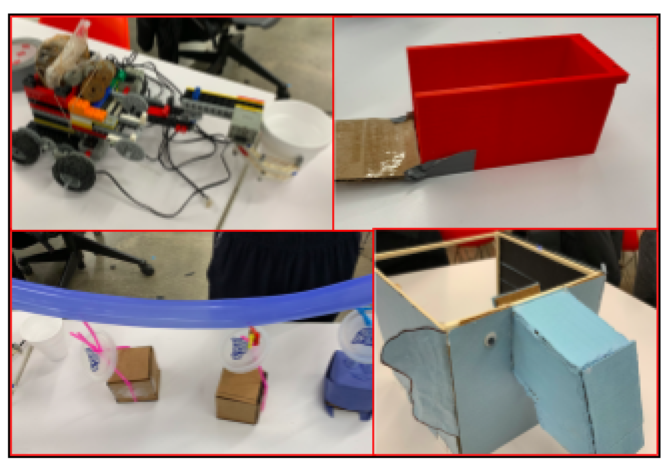


FIGURE 5
DEPOSITION SUBSYSTEM DESIGN CONCEPT. FROM LEFT TO RIGHT: (TOP ROW) EXPANDING BIN, TIPPING, (BOTTOM ROW) EXPANDED TUBE, CHUTE

The final design concept chosen was tipping for its efficiency of operation and simplicity of its implementation. Table 9 shows the scaled results of the trade study for each design concept and Figure 5 shows images of design concept breadboards.

D. Storage / Differentiation Subsystem

The primary technology developed for the storage and differentiation subsystem was the means by which the icy and BP-1 regolith would be separated. The regolith is differentiated to maximize the storage capacity of the rover without having to maximize the physical volume of the storage container. The 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 tiered inclined plane system. Both breadboards were constructed from balsa and evaluated based upon the MOEs defined in Table 6.

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 tiered inclined plane involves the use of several inclines in an enclosed container. BP-1 regolith falls onto the inclines and, due to its fluidic properties, flows out of the filter, as the gravel falls downwards into the storage container. While more complex and less efficient at differentiation, it is a passive system and allows for a greater inflow rate. The lack of actuation implies no power consumption.

The tiered incline plane concept was chosen for its minimal power consumption and greater inflow rate over the vibrating sieve. Table 10 shows the results of the trade study and Figure 6 shows the breadboard for the tiered incline plane concept.

TABLE 10
STORAGE DESIGN CONCEPT TRADE STUDY RESULTS

		Design Concepts	
Measure of Effectiveness	Decision Weight	Vibrating Sieve	Tiered Inclined Plane
StMOE1	2	< 2 Wh	0 Wh*
StMOE2	4	0.5 kg / sec	2 kg / sec*
StMOE3	5	> 90%*	70 - 80%

* indicates best performing metric

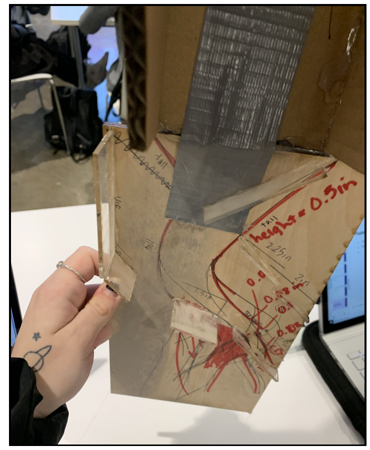


FIGURE 6
STORAGE / DIFFERENTIATION SUBSYSTEM DESIGN CONCEPT, TIERED INCLINED PLANE

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
- 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
- 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.

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 7 is a generalized flow chart showing the 1.5 rover system concept.

TABLE 11
SYSTEM DESIGN CONCEPT TRADE STUDY RESULTS

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.

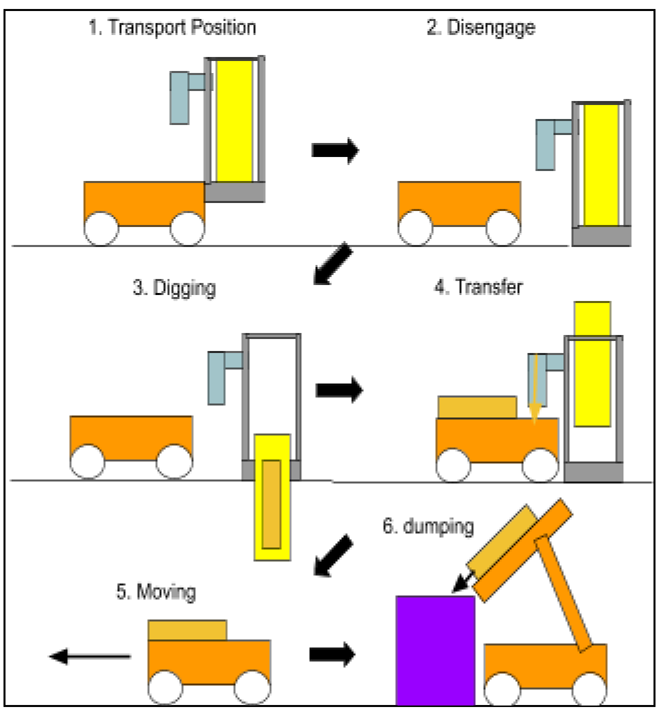


FIGURE 7
CHOSEN SYSTEM DESIGN CONCEPT (1.5 ROBOTS). STEPS IN OPERATION CONCEPT NUMBERS IN CHRONOLOGICAL ORDER

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 1.5 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 18, 2018, with the end of the PDR and ended on March 31, 2019, with the completion of the fabrication process.

I. Design Process and Philosophy

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

The mechanical component of the design process focused on producing the physical forms of the functional mechanisms of the system as well as to perform element analysis to determine the best fabrication method for each component. The electrical and software components of the design process involved the identification of feedback measures, the creation of an autonomy procedure based on the system Concept of Operations, and identifying the necessary actuators for the subsystem. Table 12 lists the system design goals and their traceability to the system requirements and measures of effectiveness.

Mechanical engineering designs were completed using SolidWorks, a solid modeling and computer-aided design and engineering (CAD / CAE) software provided by the company to the team under an educational license. SolidWorks was also utilized for design testing (mechanical stress simulations and weight estimations). Electrical engineering designs were completed using EagleCAD, software produced by Autodesk and utilized for electrical schematic and printed circuit board design, under an educational license. No specific tool was utilized for the software design process.

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 each 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 and parallelism by reducing inter-subsystem dependency.	SR11, SR12

A. Digging Subsystem

The final design of the digging subsystem was a refinement of the concept developed during the previous phase as well as the design used in the previous year's system, ORBIT 1. The final CAD render of the subsystem is included in Figure 8. The primary challenges faced during the development of a final design was making the digging subsystem into an independently operating rover. Specifically, designing the drum, a concept which has a large dimensional and mass requirement, within the constraints of the system.

The design of the subsystem is largely unchanged from that of ORBIT 1 (RMC 2018). It consists of a large, central digging wheel mounted on two linear actuators. The digging wheel consists of seven shovels mounted on two ring gears. Each ring is actuated using a motor and four idler gears. The linear actuators lower the wheel downwards as it excavates regolith from the surface below it.

The changes made to the subsystem from previous year's systems is primarily aimed to reduce the mass and volume of the subsystem, especially given the two rover system concept. For example, the aluminum backings to the shovels are replaced with carbon fiber, reducing the mass by 12%. Furthemore, the rolled polycarbonate that served to hold the halves of the drum together are replaced with aluminum standoffs, resulting in an 8% reduction of mass. The width of the drum (i.e. distance from the faces of the cylinder) is reduced from 39 cm to 31 cm to fit within the second rover, however, the shovel design spans the entire width of the drum, compared to ORBIT 1 whose shovels were only 32 cm long (approximately 82% of the total width of the drum).

Based upon modelling performed both during the design of ORBIT 1 and earlier during the preliminary design concept trade studies, the maximum digging rate was estimated to be approximately 0.5 kg/sec for BP-1 regolith and 0.3 kg/sec for gravel given a rotational speed of 15 RPM.

The digging subsystem provides feedback of the rotational speed of the digging wheel and the position and speed of the drum vertically on the linear actuators (i.e. digging depth). The digging subsystem uses a minimal amount of actuators (two) to enable motion on all necessary tasks.

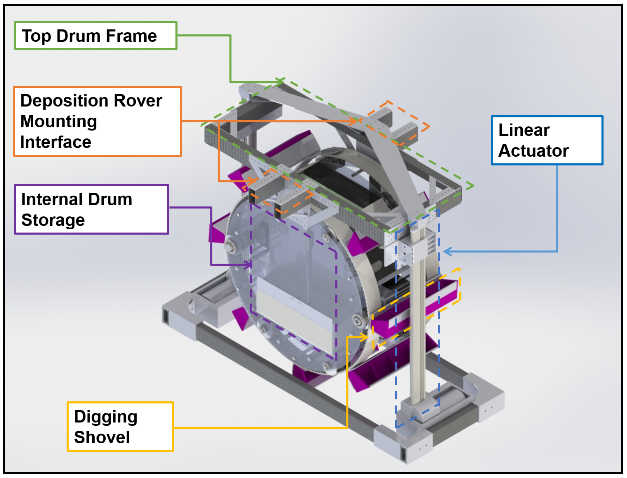


FIGURE 8
FINAL COMPUTER RENDERING OF THE DIGGING SUBSYSTEM

B. Locomotion Subsystem

The locomotion subsystem (the deposition rover excluding the deposition subsystem) faced dimensional constraints as imposed by the digging subsystem and system constraints. The locomotion subsystem would have to provide a structurally secure interface between the two rovers as well as maintain stability when operating independently. Therefore, most of the subsystem needed to be designed from scratch. Another key consideration for the design of the subsystem was building the chassis such that the lack of a suspension mechanism would not inhibit its ability to traverse the obstacle field. Figure 9 shows the final locomotion subsystem.

The wheel design utilized in the system is a derivative of the wheels used in the ORBIT 1 system. Similar to Atlas VII, the wheels' motors are mounted within the center volume of the wheel to reduce the width of the overall assembly. A difficult point for other competing teams at RMC is the low coefficient of friction of BP-1. As observed on ORBIT 1, adding cleats to the wheels increases the wheel traction. The major change in this year's system is elevating the chassis above the wheels in order to increase the rover's clearance. 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.

Another design decision made was to make the deposition rover's chassis a "U-shape" in order to place the digging rover within its center cavity (Figure 10). This would increase the stability of the joined rovers during the initial phase of its operation.

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). While an accelerometer and encoders on the drive motors provide limited motion feedback, a more complete sensing solution is needed to provide accurate information for an autonomous program: computer vision. Rather than mounting the vision system on the rover, the cameras are mounted to an assembly placed on the collection bin and elevated above the arena to provide the maximum viewing angle of the arena. The vision system provides the absolute position and orientation of the two rovers within the arena.

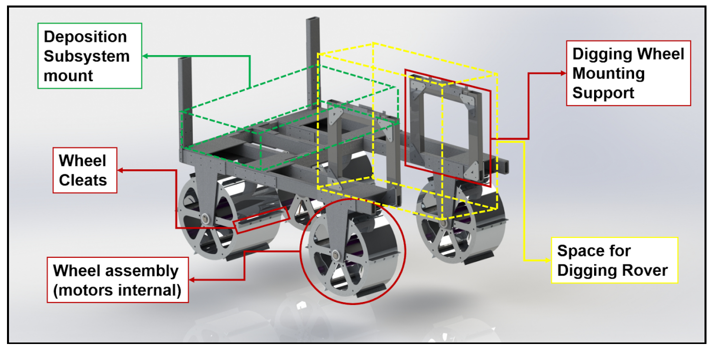


FIGURE 9
FINAL COMPUTER RENDERING OF THE LOCOMOTION SUBSYSTEM

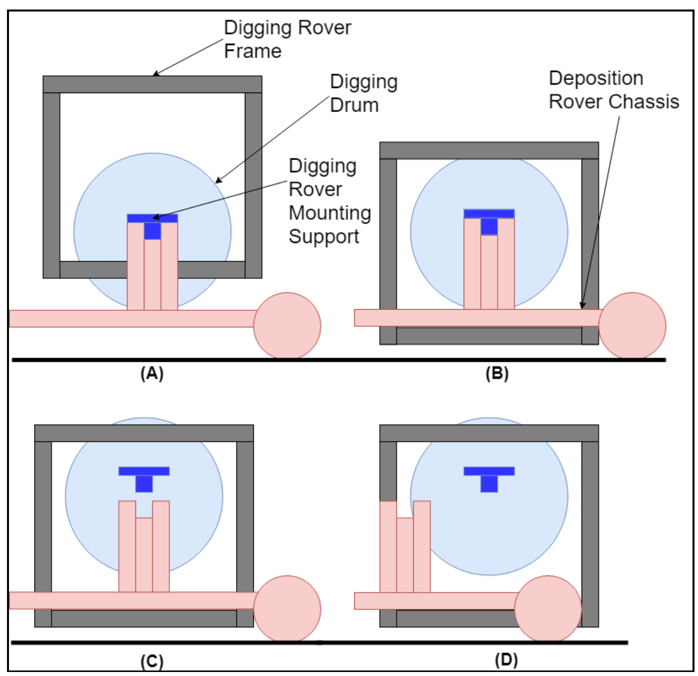


FIGURE 10
DISENGAGEMENT MECHANISM:
(A) THE DRUM IS IN A LOWERED POSITION AND ITS MOUNTING SUPPORT IS ENGAGED WITH THE DEPOSITION ROVER, (B) THE DRUM IS RAISED AND THE FRAME RESTS ON THE GROUND, (C) THE DRUM IS FULLY RAISED AND THE SUPPORTS ARE DISENGAGED, (D) THE DEPOSITION ROVER SEPARATES BY DRIVING AWAY

C. Deposition Subsystem

The deposition subsystem design concept was changed significantly during the final design phase as a result of new dimensional constraints introduced by the actual design of the system and its interfaces as well as the formulation of explicit Design Goals (specifically DG1).

Rather than employ a tipping design (similar to a dump truck), the deposition subsystem employs a "pushing design" in which a plunger mounted on a rack and pinion gear pushes the collected regolith up an inclined plane and into the collection bin. The container be raised and lowered using two linear actuators mounted to the front of the deposition rover chassis.

The original concept required that the digging mechanism is raised in excess of 45 centimeters to accommodate the top of the deposition container. This task would have required two additional actuators in order to lift the digging drum to the desired height. The decision to change the deposition concept was accompanied by a thorough trade study in which brassboarded prototypes of the original and new concepts were compared for their compliance with the deposition MOEs and design goals. The new concept achieves the same efficiency as the original concept, with fewer actuators, a simpler interface with the digging subsystem, and only a small sacrifice in capacity. Figure 11 shows the final deposition subsystem.

The feedback provided to the subsystem are the vertical position of the container, the linear position of the plunger, the proximity of the rover to the collection bin, and the capacity of the container. The subsystem has two actuation directions and accomplishes this with a minimal amount of actuators.

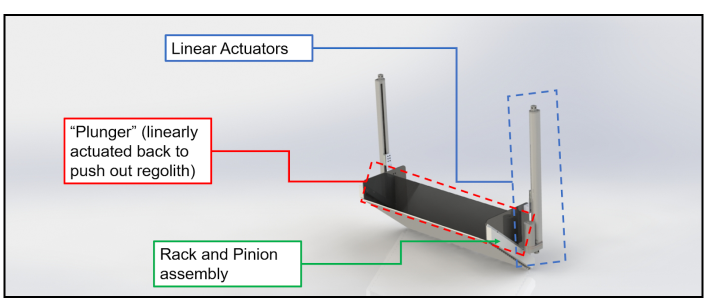


FIGURE 11
FINAL COMPUTER RENDERING OF THE DEPOSITION SUBSYSTEM

D. Storage / Differentiation Subsystem

The primary challenge to the final design of the storage and differentiation subsystem was the integration of the design concept into a manufacturable mechanism. Furthermore, the storage subsystem must interface with the digging mechanism and the deposition mechanism, and provide feedback to provide control signals to the other subsystems.

Figure 12 demonstrates the intended operation of the storage subsystem. The gravel / BP-1 mixture will enter from the digging subsystem from the top of the device. The filtration system at the top of the system will differentiate the BP-1 and gravel such that the BP-1 will fall from the top chute and out the rear of the storage container. The separated gravel will then fall into the bottom of the container. Upon interface with the deposition subsystem, an actuated door at the base of the bottom chute will open and the gravel will fall from the chute into the aligned deposition container.

Upon testing the design, its efficiency was calculated to be approximately 75%. Hence, the storage container would have a maximum capacity of 12 - 15kg (depending on the gravel density).

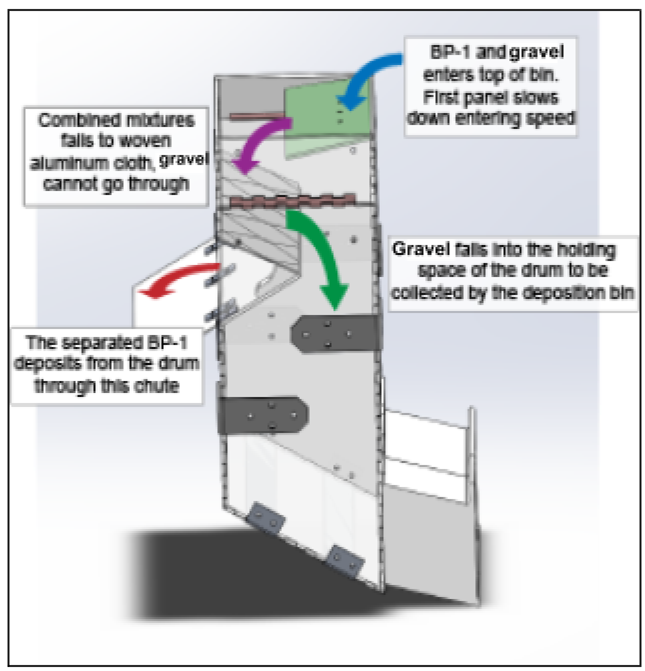


FIGURE 12
FINAL COMPUTER RENDERING OF THE STORAGE SUBSYSTEM

The storage container provides feedback for both the capacity of the storage container (as a means to control the initiation and termination of digging) and the efficiency of the differentiation mechanism/ composition of the contained regolith. The storage mechanism uses a single actuator to open and close the gravel chute for transfer into the deposition rover.

E. Subsystem Interfaces

There are three primary functional interfaces of the system in need of final design: the interface between the two rovers (the "disengagement mechanism"), the interface between storage mechanism and the deposition subsystem, and the communications interface between the various subsystems.

The disengagement mechanism is one of the most critical components of the system. It must provide a stable connection between the two rovers as well as reliable disengagement between the two rovers. In addition, it must comply with the defined design goals. The final design for the interface utilizes no additional actuators and operates similarly to a forklift. Lowering the drum assembly rests the forks on the supports of the deposition rover and raises the digging rover's base upwards so that the digging rover is fully supported by the deposition rover. The interface is demonstrated in Figure 10. Prior to the finalization of the interface concept, it was brassboarded using wooden models. The models were stress tested to ensure stability of the design and the reliability of its usage.

The interface between the storage and the deposition subsystem is similarly critical as the regolith from the storage mechanism must be completely transferred to the deposition mechanism. Alignment between the two rovers is crucial. Several design factors ensure the reliability of the interface. Mechanically, the deposition container is significantly wider than the storage container interface to ensure horizontal alignment. Alignment is further ensured via an infrared proximity sensor on the front of the deposition container and the collection bin mounted vision system. Once again, thoroughly modeled testing of the interface was conducted to ensure the viability of the design.

The final interface is the communication between the two rovers, the bin mounted processing component, and the ground control station (GCS). This interface must not exceed the bandwidth requirement (SR4) but similarly allow for a robust autonomous program. Rather than develop a distributed system, communication and computational resources are centralized. A central server on the collection bin assembly (which houses the vision system) runs the primary control architecture of the system. Instead of treating the two rovers as independent systems, they are treated as contributing devices to the master server. The GCS is yet another contribution endpoint in the network and simply delivers commands to the server to relay to the rovers. Given that the bandwidth limitation is only imposed on the communication between the GCS and arena, the bandwidth between the server (located within the arena) and the rovers is not limited and more flexible.

To ensure simplicity of implementation and parallelism, each subsystem will be controlled by their own MCU and electrical circuit and isolated from the other subsystems. Therefore, each subsystem communicates directly with the main server. The connection between the GCS and the main server is conducted over a low bandwidth protocol developed for the Atlas rovers. During autonomous operation, communication between the GCS and server is limited to the start and stop commands and basic reporting of state changes and errors. The communication architecture was prototyped to measure its capabilities, latencies, and efficiency. Figure 13 shows the diagram of the rover's network and Figure 14 shows its autonomous processing infrastructure.

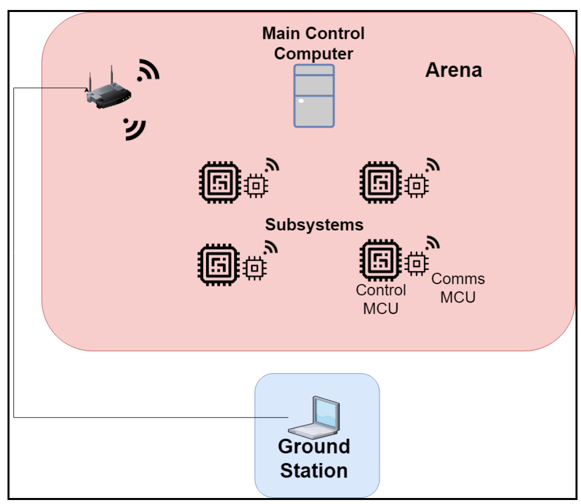


FIGURE 13
CONTROL SYSTEM INTERFACE DIAGRAM

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 and Interface placement

- The rigidity of the system

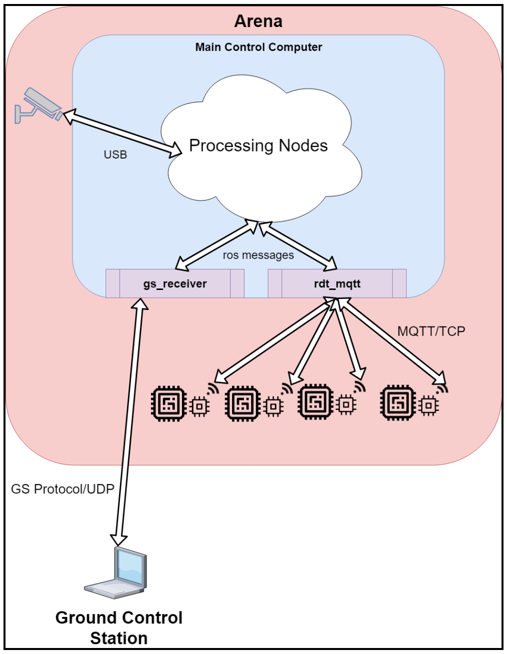


FIGURE 14
AUTONOMOUS PROGRAM INTERFACE / CONTROL FLOW DIAGRAM

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 27, was conducted on February 7, 2019. The reviewing panel was comprised 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 7123.1B, 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
- 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 protect 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 31, 2019. Phase D ends on May 1, 2019, when the final system must be delivered to NASA for operation (in the form of the proof of life video deliverable). Three main activities that are performed during Phase D are integration, verification, and validation.

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

I. System Integration

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

As of March 31, 2019, the digging subsystem was 90% integrated and the storage subsystem 80% integrated (according to their integration plans). Given the two rover nature of the system, emphasis was put into completing integration of these two subsystems first so that the completed digging rover could be verified and validated during the integration of the locomotion subsystem. Integration of the entire system should occur by April 14, 2019.

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**).

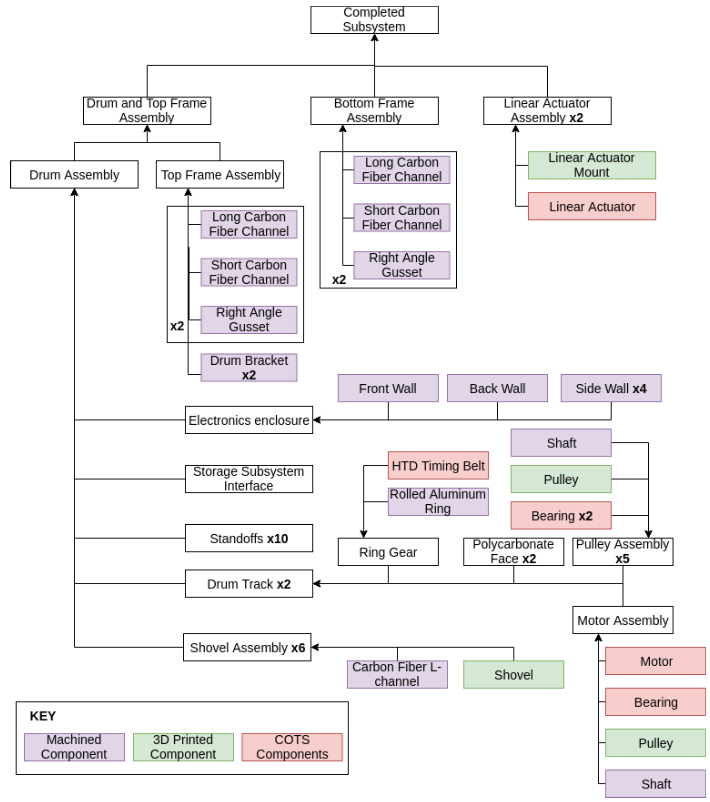


FIGURE 15

SIMPLIFIED DIGGING SUBSYSTEM COMPONENT HIERARCHY AND INTEGRATION PLAN

Figure 16 shows the partially integrated digging subsystem.

FIGURE 16
PARTIALLY INTEGRATED DIGGING SUBSYSTEM (MARCH 28, 2019)

Initially, each subsystem was verified individually for compliance with their subsystem's allocated requirements. 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 ORBIT 1, the rover utilized for the 2018 RMC.

IV. System Delivery

The completed system is delivered to NASA on May 1, 2019. 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 system is also delivered to New York University, another important stakeholder in the project, as a demonstration of the robot at NYU's annual research exposition in late April.

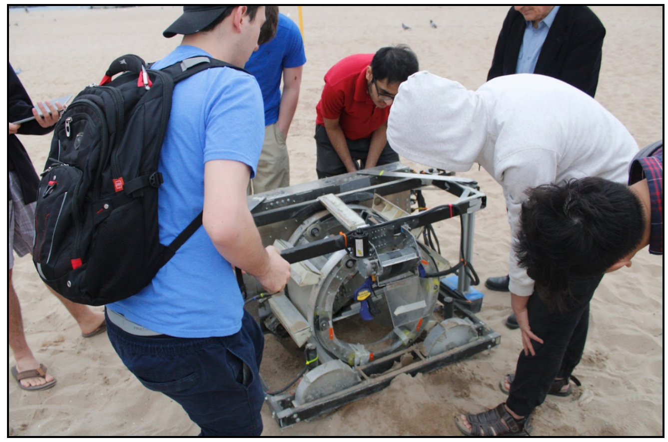


FIGURE 18

Validation of ORBIT 1, which will be Similar to the validation process of ORBIT 2.

Project Management

The New York University Robotic Design Team is a group of 40 undergraduate and graduate students currently enrolled in New York University. The students represent a diverse set of engineering disciplines. The team is advised by Dr. Haldun Hadimioglu. The team's student lead and lead systems engineer is Theodore Kim.

Given the scope of the project and organization of the system, the team is organized into a matrix divided into functional and project teams. Each subteam is led by a student leader. Functional teams are composed of all individuals working on a similar engineering aspect of the robot (software, electrical and mechanical engineering), while the project teams are composed of individuals from the three functional groups, working collaboratively on a single subsystem. This approach is meant to encourage interdisciplinary collaboration. See Figure 19 for a diagram of the team's organization.

I. Technical Requirements Management

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

Faculty Advisor Dr. Haldun Hadimioglu — **Student Lead** Theodore Kim

	Mechanical Sayed Ananda	**Software** Marcus Barbu	**Electrical** Tara Umesh
Locomotion Muhammad Fahad	Emilia Bianchini Lucia De Jesus Min Joo Kim Peter Paik	Jackie Chen Sarjak Thakkar Dan Shafman	Marzuqa Ahmed Carlos Lopez Akhil Subramanya
Digging Jion Fairchild	Duhee Han Michael Linares Srivatsan Ramesh Julie Ryoo	Sofiia Barysheva Jack Zheng	Angy Lara Brandon LeMay Phoebe Zhu
Storage / Differentiation Kiersten Page	Allie Karakosta Anusha Rungta	Charles Chan	Masuma Sonji
Deposition Ziyao Shangguan	Stephen Scott Caroline Cho Jasee Balajadia Rosa Choi	Jin Su	Zachary Atwood Jess Hochron Jiacheng Wang

FIGURE 19

TEAM ORGANIZATIONAL STRUCTURE (NAMES UNDER BOLDED TEAM NAME ARE STUDENT LEADS)

II. Interface Management

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

III. Configuration Management

The project's configuration items include: the code for the software developed for the system (autonomy, communications, and the embedded systems), the mechanical system's CAD files, and the electrical and embedded systems' schematics and CAD files. All of this data is required for the completion of the project (technical reviews, determining sources of errors, etc.) as well as for guidance for future year's project development. Figure 20 shows the configuration management workflow utilized by the project team.

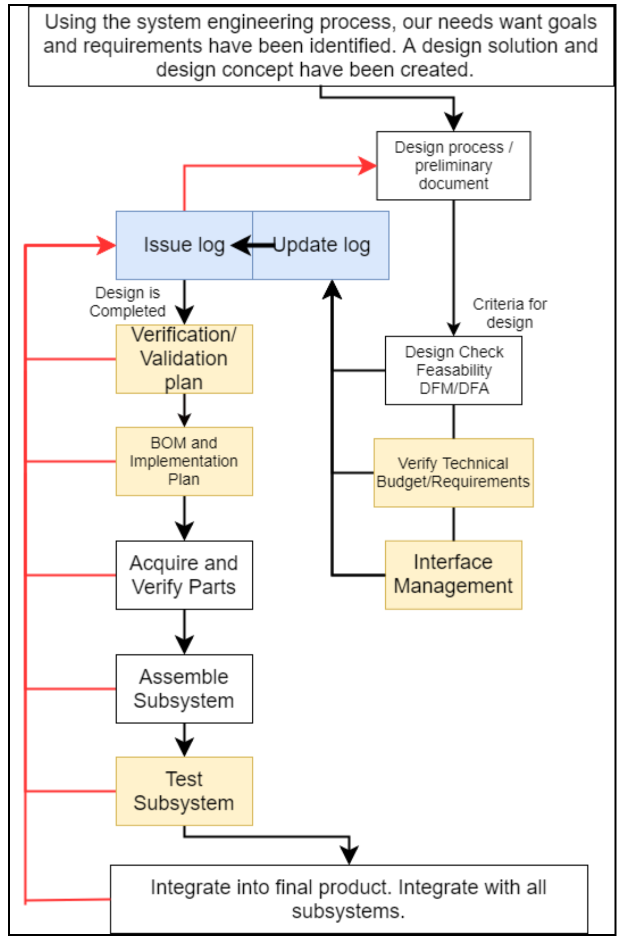


FIGURE 20

CONFIGURATION MANAGEMENT WORKFLOW EMPLOYED BY THE TEAM

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

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

IV. Technical Risk Management

Risk management was performed throughout the project lifecycle. Risks were classified as either operational risks (i.e. risks associated with the project) or a functional risk (i.e. risks associated with the function of the rover). Risks were tracked in a risk matrix which identified the risk classification, severity, discovery date, mitigation plan, and mitigation result. This risk matrix is included in Table E1, **Appendix E**. At each of the major reviews, the subsystem leads and the systems engineer reviewed the risk classifications from previous stages of the project. Furthermore, new risks were identified given the progress and development of the system.

V. Technical Data Management

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

VI. Technical Planning

The technical planning process involves the management and tracking of the progress made by the project and its team. The project's technical planning was conducted by the student leads and systems engineer. The primary product of the technical planning process was the project schedule, which was baselined during the Concept Development Phase (prior to the submission of the Plan for Systems Engineering deliverable). It was then regularly revisited and revised. Figure F1, **Appendix F** includes the proposed project schedule (Gantt Chart) for the project and the actual progression of the project lifecycle.

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

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

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

FIGURE 21

Kanban Board utilized by the team in managing the technical planning process.

VII. Technical Assessment and Decision Analysis

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

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

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

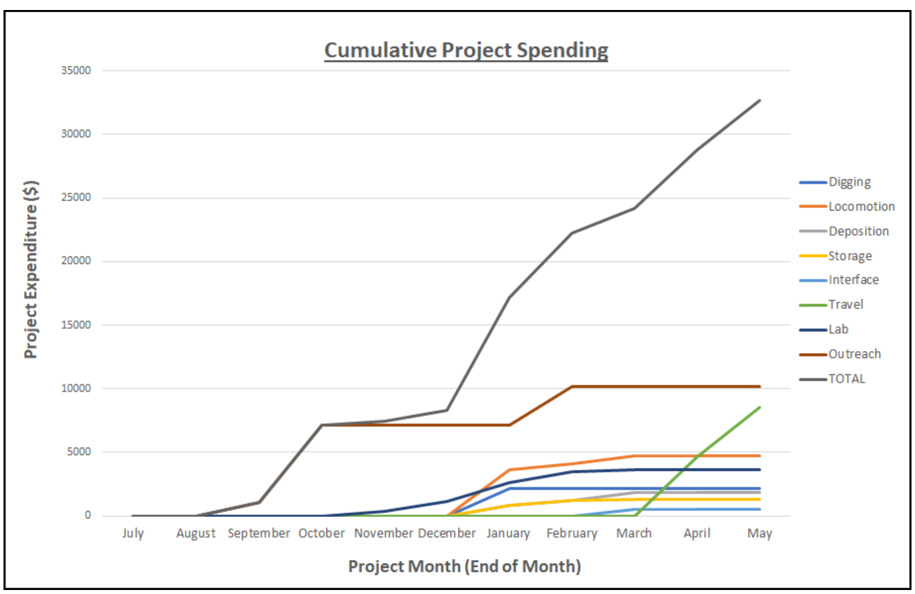
VIII. Budget Management

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

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

TABLE 13:
FINAL PROJECT BUDGET

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



References

[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. 6, 2018). *NASA RMC Registration, Rules, and Rubrics*.

[4] National Aeronautic and Space Administration (Dec. 2018). *RMC Archive 2017 - 2018*. Retrieved from **https://www.nasa.gov/content/rmc-archive-2018**

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

Appendix A: Technical Measures

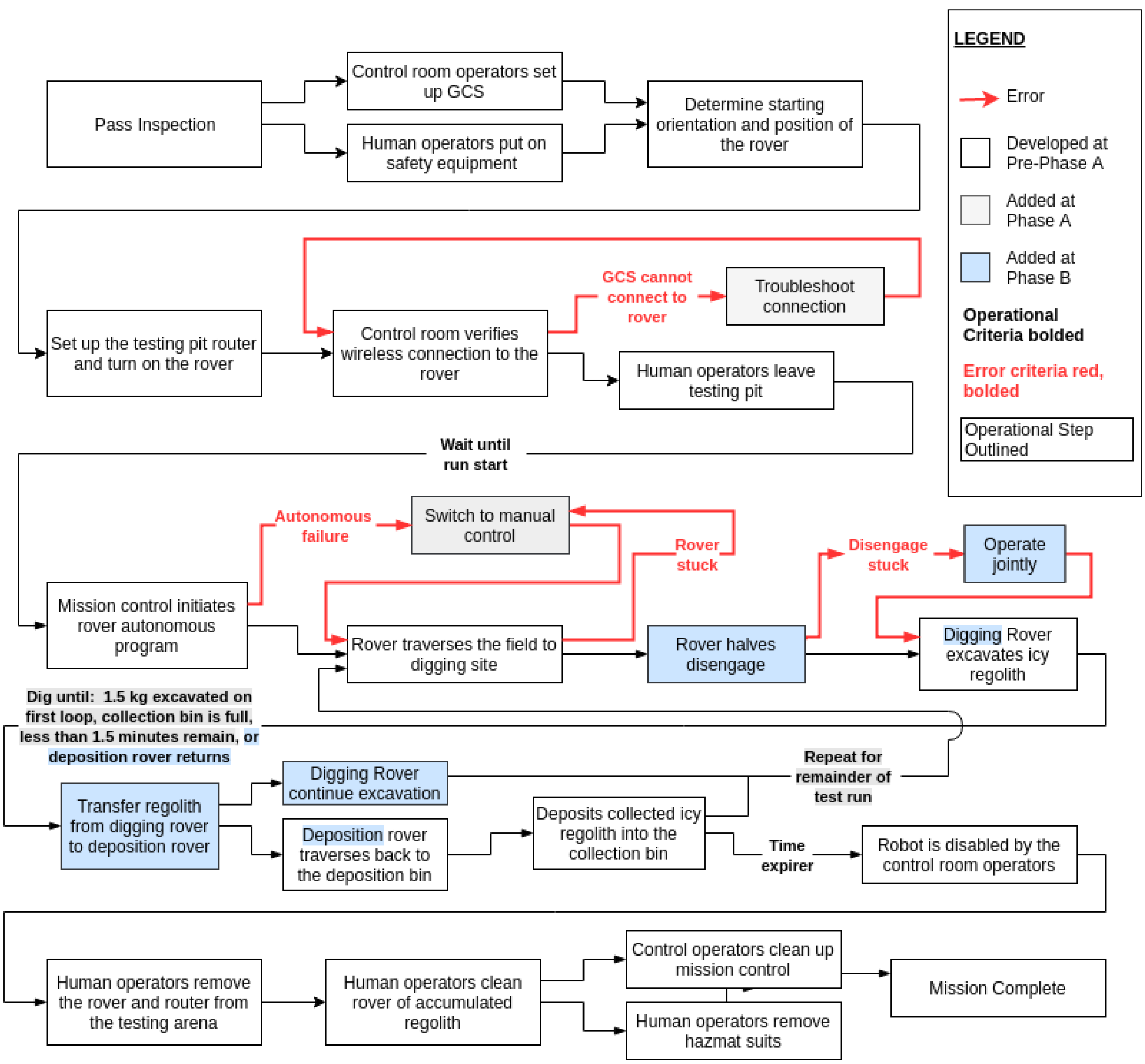
TABLE A1
System Measures of Effectiveness

Measure of Effectiveness	Traced from
MOE1: Capability to differentiate gravel icy regolith from BP-1 regolith	Ob7, C1
MOE2: Able to collect at least 20 kg of gravel in 10 minutes	C2
MOE3: Capable of operating fully autonomously consistently (as defined by NASA RMC Rules and Rubrics)	G1, Ob9
MOE4: System has a mass less than 80kg	Ob1
MOE5: System uses less than 40 Wh of electrical power	Ob8
MOE6: System uses less than 15 Mbps bandwidth for communication	Ob4
MOE7: System is capable of operating in the target environment	C6, 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 (2kg) and the second to deliver the remaining 18 kg.	MOE2
MOP3: System mass is less than 70 kg	MOE4
MOP4: Provide capability for the system to perform without GCS input	MOE6
MOP5: System provides the capability to protect critical components against dust intrusion.	MOE7

Appendix B: Mission Concept of Operations



Appendix C: Technical Budgets

TABLE C1

Initial Technical Budget (October 20, 2018)

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
Deposition 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
Digging Subsystem Allocation	30	5	10	4000	240	0.35 m mining depth 0.16 kg/s digging rate	0.25
Locomotion - Digging Interface (Structural)	6	*N/A*	*N/A*	150	*N/A*	*N/A*	*N/A*[3]
Locomotion - Storage Interface (Structural)	5	*N/A*	*N/A*	150	*N/A*	*N/A*	*N/A*[3]
Locomotion - Deposition Interface (Structural)	5	*N/A*	*N/A*	150	*N/A*	*N/A*	*N/A*[3]
Digging - Storage Interface	2	0[1]	2.5	250	240[4]	Will allow for 0.16kg/s	*N/A*[3]
Storage - Deposition Interface	2	0[1]	2.5	250	90[4]	Will allow for 0.833 kg/s	*N/A*[3]

TABLE C2

Actual Technical Budget (February 7, 2019)

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
Deposition Subsystem Allocation	10	0[5]	4.3	1816	120	0.8333 kg/s offload rate	0.03
Storage / Differentiation Subsystem Allocation	8	0[5]	0	1272	10[1]	40 kg payload capacity	0.09
Digging Subsystem Allocation	15	0[5]	12.3	2142	300	0.35 m mining depth 0.16 kg/s digging rate	0.28
Locomotion - Digging Interface (Structural)	1	*N/A*	*N/A*	79	*N/A*	*N/A*	*N/A*[4]
Locomotion - Storage Interface (Structural)			***-----INTERFACE WAS REMOVED IN FINAL DESIGN----***				
Locomotion - Deposition Interface (Structural)	1	*N/A*	*N/A*	64	*N/A*	*N/A*	*N/A*[4]
Collection Bin Mounted Controller	2	15	5	496	600[1]	*N/A*	0.04
Digging - Storage Interface	N/A	0[3]	0	0	240[2]	Will allow for 0.16kg/s	*N/A*[4]
Storage - Deposition Interface	N/A	0[3]	0	0	90[2]	Will allow for 0.833 kg/s	*N/A*[4]

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

Appendix D: Requirements Verification

TABLE D1

Requirements Verification Matrix

Require-ment No.	Shall Statement	Verification Success Criteria	Verification Method	Phase	Results
SR1	The system shall have a mass of 70kg	The system mass is less than or equal to 70kg.	Individual components are measured for compliance with the sum / final system is weighed	C and D	Estimates place the mass at 69 kg.
SR2	The system shall have a maximum dimension of 1.5m x 0.75m x 0.75m	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 15 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 15 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 < 15 kbps	C and D	Individual subsystems have been controlled manually from the GCS. Final system manual control testing has yet to take place.
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 March 31, 2019)
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 simultaneously	The system is able to operate in parallel	Develop system concepts that provide parallelism. Verification will ensure parallelism	B, C and D	Final system operation still untested (as of March 31, 2019)
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 March 31, 2019)

Appendix E: Project Risk Management Matrix

TABLE E1

Risk Management Matrix

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

* Statuses are as of March 31, 2019 and can possibly be: identified (risk has been identified and mitigation strategy developed, however, mitigation has not been implemented), in progress (risk mitigation strategy being implemented), in review (mitigation strategy being verified for effectiveness), and retired (risk successfully mitigated)

Appendix F: Project Schedule

PROJECT TITLE	2019 Robotic Mining Competition	COMPANY NAME	NYU Robotic Design Team
PROJECT MANAGER	**Student Lead:** Theodore Kim **Faculty Advisor:** Haldun Hadimioglu	PROJECT DATES	July 1, 2018 - May 29, 2019

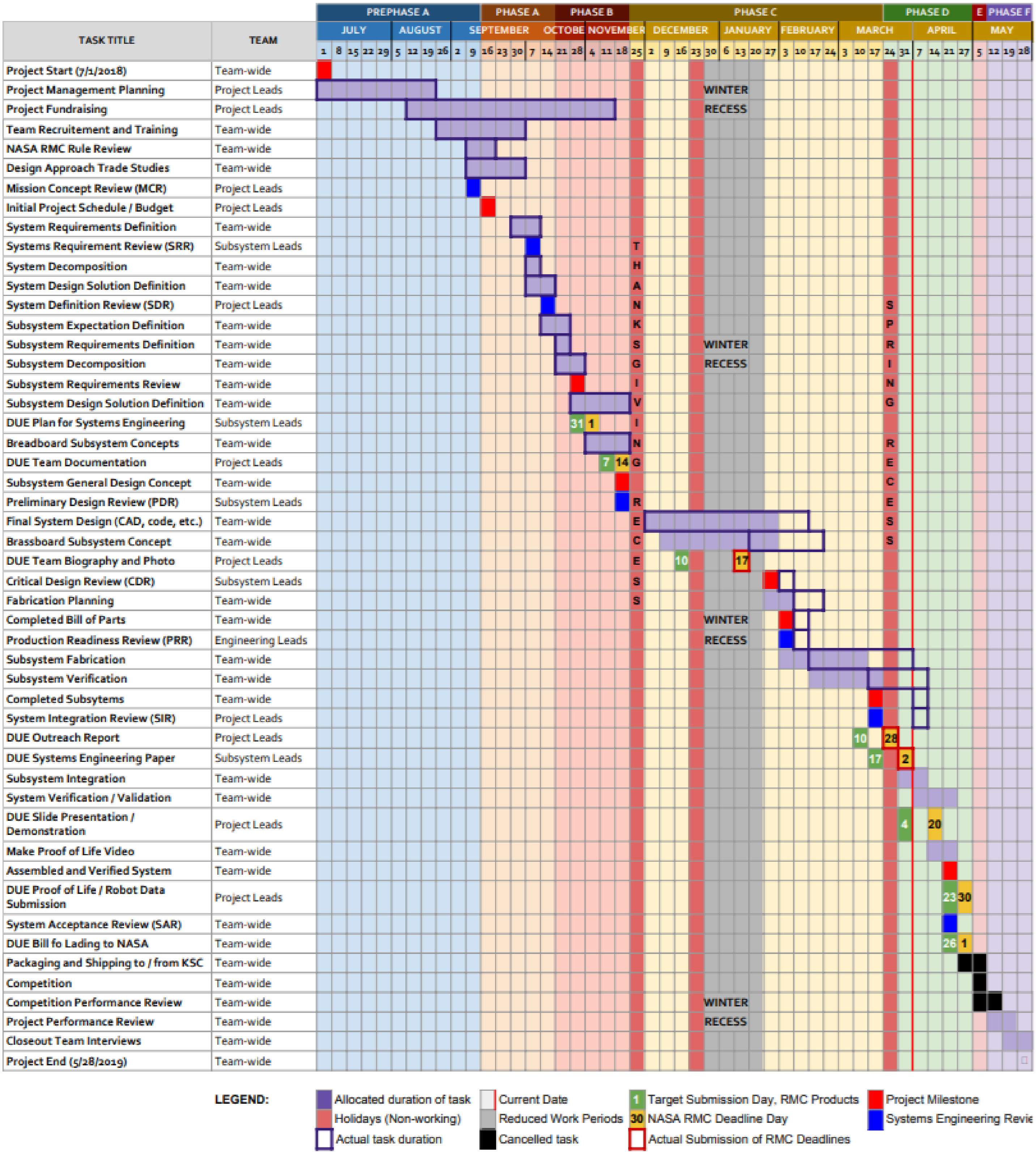


FIGURE F1
Project Schedule (Gantt Chart).