NEW YORK UNIVERSITY TANDON SCHOOL OF ENGINEERING ROBOTIC DESIGN TEAM

2017-2018 SYSTEMS ENGINEERING PAPER

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ABSTRACT

NASA is on the brink of sending humans to Mars, but sustaining life will be impossible without harvesting the resources found natively on the planet such as ice and hydrated minerals found under 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 (Operational Robot Built in Tandon), is an autonomously operated, mining system capable of mining up to 50 kg of icy regolith simulant in the 10 minute test period. The NYU RDT utilized the Systems Engineering process, when designing, building and testing its system to ensure that its solution effectively addressed the competition requirements. The system is composed of three subsystems: the chassis, the mining assembly, and the control subsystem. Each subsystem was designed and tested according to the Systems Engineering Process, and thoroughly reviewed to minimize and mitigate possible points of failure and risks. This paper describes the System Engineering Process as used by the NYU RDT to construct ORBIT. A computer rendering of ORBIT system is shown below in Figure 1.

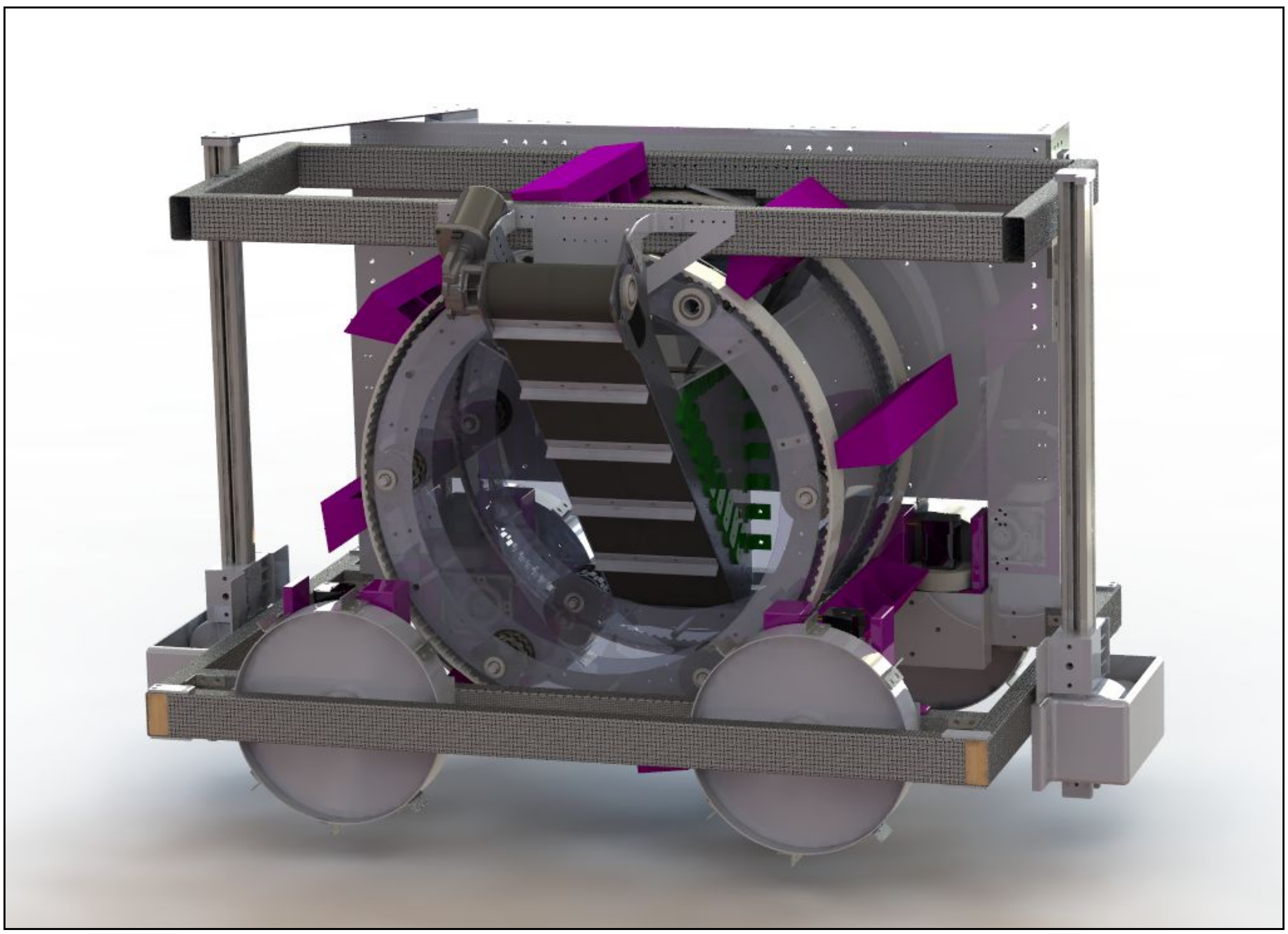

FIGURE 1: Rendering of ORBIT robotic mining system

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1. INTRODUCTION

1.1. Purpose Statement and Project Objectives

The NASA Robotic Mining Competition (RMC) is a national intercollegiate competition hosted by the United States National Aeronautics and Space Agency. The competition aims to encourage the development of systems to be employed in future in-situ resource utilization colonization missions to extra-terrestrial bodies such as the moon and Mars [1]. A focus of potential In-Situ Resource Utilization (ISRU) missions is the acquisition of water, which has been found to exist as a layer of frozen particulate (icy-regolith) beneath the surface of Mars and can be refined for human hydration, breathable oxygen, and rocket propellant. The competition thus challenges its 50+ participating teams to construct a rover that is efficient in mining icy-regolith simulant (gravel) from a test environment [1].

In addition to the mining portion of the competition, teams are judged on their respective efforts to promote the STEM (Science, Technology, Engineering, and Mathematics) fields within their local communities and through social media. Finally, the competition requires teams to submit a Systems Engineering Paper outlining the design process by which they developed their respective rover technologies. This paper fulfills that requirement by outlining the team's approach towards designing its rover, ORBIT: the decision to compete in the competition, addressing this year's new requirements, the design and fabrication process, and the subsequent testing of the manufactured systems [2].

In its seventh year participating in the competition, the New York University, Tandon School of Engineering Robotic Design Team seeks to fulfill the competition objective of designing an autonomous rover which effectively mines icy regolith through a rotating digging drum. While the utilization of the systems engineering process is required for the competition, it was embraced by the team as a rigorous project development tool. Using the Systems Engineering approach taught the team about the product realization process and the importance of careful planning towards the development of well engineered systems.

1.2. Problem Definition

Whereas in previous years, the goal of participating teams' rovers was to mine and deposit at least 10 kg of Martian dry regolith simulant, BP-1, this year, the competition's objectives have changed. Specifically, BP-1 is no longer the desired mining objective, rather, the icy-regolith simulant, located 0.3 m below the surface of the testing arena, is the target of the participating robotic miners. The testing arena, provided by the competition, is 3.78 m wide and 7.38 m long, and is divided into three zones: A) the "start zone" where robots are placed at a random position and orientation at the start of the 10 minute mining test period, B) the "obstacle zone" where three obstacles are randomly placed in order to obstruct robot motion prior to testing, and C) the "mining area," the only area in which teams' rovers are allowed to excavate icy regolith [2]. Additionally, teams must deposit collected regolith into collection bins located behind the wall bordering the start zone positioned 0.55 m above the surface of the test arena, and sized to 1.575m x 0.457m [2].

Teams are given 10 minutes to mine at least 1 kg of icy regolith simulant and earn points based on how much their rovers mine. Completing the task autonomously and other design factors such as the rover's dust tolerance are also also scored towards the total mining score [2]. Additionally, rovers face score deductions based on mass--measured prior to testing--average power consumption, and average bandwidth usage for communications sent between the rover and human operator control ground station. Robots are constrained to a volume no greater than 1.5 m x 0.75 m x 0.75 m [2].

1.3. Deliverables

The following deliverables will be provided by the team in accordance with the requirements of the NASA Robotic Mining Competition:

- A rover able to complete the objectives of NASA's RMC within the the imposed size and operations restrictions
- A video proving the aforementioned rover's operation
- An accompanying human operator console (ground station) and supporting communication infrastructure

- An on-site technical presentation and demonstration of the rover's functionality
- A Systems Engineering Report outlining the teams' adherence to the Systems Engineering Process during the design of its rover

2. Systems Engineering Process

The primary goal of this project is to develop a Martian mining system using a Systems Engineering approach, and to demonstrate the system's effectiveness at completing the NASA RMC objectives. The development process of the team's rover, ORBIT (Operational Robot Built in Tandon), through the Systems Engineering life cycle is the topic of this paper. The NASA Systems Engineering Handbook [3], and the Lunar Engineering Handbook written by David Beale [4] were utilized as guides for implementing the process of Systems Engineering. The team followed the seven phases of the Systems Engineering lifecycle which is visualized in Figure 2 and performed the general process requirements, shown in Figure 3.

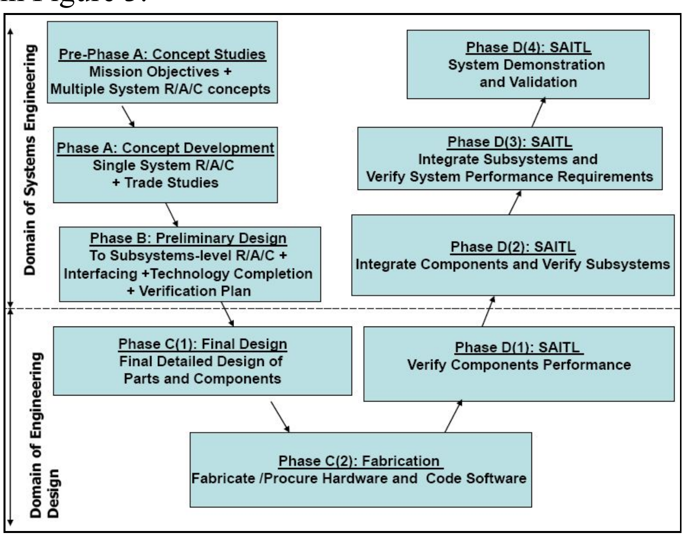

FIGURE 2: The System Engineering Lifecycle

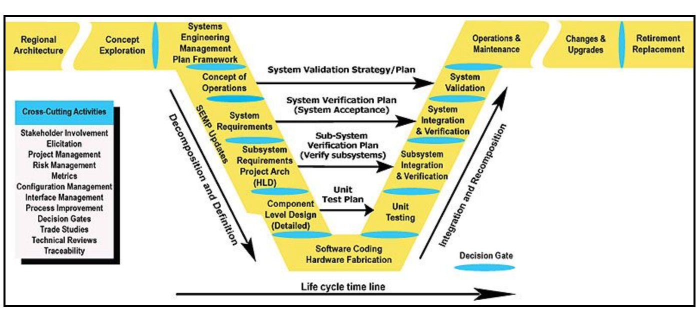

FIGURE 3: Activities during the Systems Engineering lifecycle

2.1. Pre-Phase A: Concept Studies

Pre-Phase A involves the identification of a potential project and concept that is both desirable and feasible for the team to undertake. This phase took place in early July, 2017 in which the team re-evaluated whether or not to continue competing in the NASA Robotic Mining Competition after previously competing in May, 2017.

The decision was made that RMC was a feasible choice for the group's selected project because of its six years of previous experience designing RMC rovers and the interest of its sponsoring university in funding that project. Furthermore, the introduction of the new icy-regolith rules was seen as a new, extra dimension to the challenge. The new rule would require additional design innovation compared to past years.

2.2. Phase A: Concept Development

Phase A involves a deeper analysis of the technical and logistical requirements of the project. A baseline mission concept is developed as a solution to the problems posed by the mission and in accordance with the mission requirements. To achieve the baseline mission concept, the overall system **r**equirements, top-level system **a**rchitecture, and **c**oncept of operation (ConOps) are identified and outlined within this phase (R/A/C). At the conclusion of the phase, a System Requirements Review is performed to verify that the Baseline Concept adequately answers the mission's needs.

2.2.1. Baseline Mission Concept

The overall objective of the ORBIT system is to efficiently fulfill the RMC technical requirements and maximize its achievable score based upon the RMC scoring guidelines (NASA RMC Rules and Rubric, 2018, Part II). To do so means optimizing three separate categories of scoring:

1) **Maximizing the amount of ice regolith collected** can be achieved by digging deeper where the density of icy regolith versus dust regolith is higher and, therefore, less effort is expended on mining BP-1.
2) **Minimizing deductions due to weight, bandwidth, and power consumption** can be achieved by choosing materials with a high strength to weight ratio and actuators with a low power consumption.

3) **Implementing autonomous function** is worth 33.3 kg of collected icy regolith and minimizes used bandwidth between the rover and ground station. Therefore full autonomy is another baseline design goal of the ORBIT system.

2.2.2. System Requirements

The system requirements are based upon the baseline mission concept established in the previous section in accordance with requirements derived from rules of the RMC. Table 1 outlines the ORBIT system's key requirements.

Table 1: Derived System Requirements

RMC System Requirement	Derived System Requirement
The system shall dig at least 30 cm below the surface to collect gravel.	The system shall excavate to a depth of 0.5 m
The system shall traverse chaotic terrain autonomously, or with teleoperation.	The system shall be able to navigate and traverse the test arena autonomously The system shall be able to excavate then deliver regolith to the collection bin autonomously
The system shall not exceed 80 kg.	The system shall weigh less than 50 kg (70 kg)*
The system shall deliver a minimum of 1 kg of icy gravel simulant in 10 min	The system shall spend at least 7 min mining The system shall deposit at least 120 kg (50 kg)* The system shall achieve a mining score of 1854 points
The system shall not exceed 1.5 m x 0.75 m x 0.75 m. The system shall be dust tolerant	**Same as RMS Requirements**
Self derived system requirements	The system shall be designed keeping in operation in an extraterrestrial environment The system shall utilize two rovers: one to mine and one to transport and deposit regolith*

* denotes system requirement altered during later reviews, final values denoted in parenthesis if applicable

2.2.3. System Architecture

The ORBIT system is divided into three distinct subsystems: 1) the chassis subsystem, 2) the mining assembly subsystem, and 3) the control subsystem.

The chassis subsystem serves as the ORBIT system's foundation; it is shall propel of the rover and shall provide structural support of the mining and control subsystems. The drivetrain, frame, electrical component enclosure, and main power source and distribution are all included in this subsystem.

The mining subsystem shall provide an infrastructure to excavate icy regolith, located 0.3 m below the surface of test arena. The mechanism to offload the collected regolith to the deposition bin is also included in this subsystem. The power supply for the subsystem's is derived from the chassis subsystem's power distribution.

The control subsystem shall be the mechanism by which the rover's actions and other subsystems are controlled, either by a human operator or autonomously through responses to environmental stimuli. Figure 4 is a visualization of ORBIT's system architecture.

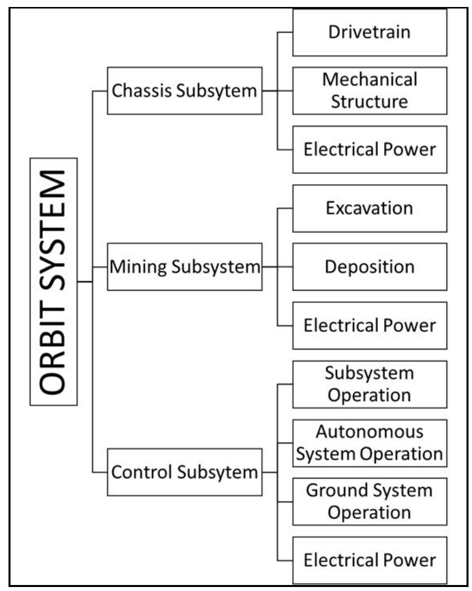

FIGURE 4: Top-Level System Architecture

2.2.4. Concept of Operations

The initial concept of operations decided upon was two robots in the arena: the mining rover and collector counterpart. The mining rover would reach a depth of 0.5 m and mine continuously, while the collector would ferry the payload until time runs out. This would be done autonomously. After testing and verification, this dual robot system was found to be infeasible.

The planned ORBIT system ConOps and its fulfilled system requirement is outlined in Table 2.

2.2.5. Proposed System Verification

To verify that the system requirements are met, the robot shall be tested before the competition. Each subsystem will be tested individually for their fulfillment of the baseline mission concept, and then

Table 2: Proposed System Concept of Operations

ConOps Step	Fulfilled System Requirement
Place the robot in starting position in the arena and set up the router	**Competition requirement**
Turn on the robot and establish connection to the ground station	The system shall traverse chaotic terrain with teleoperation.
Robot autonomously traverses the arena to mining area, avoiding obstacles and arena walls	The system shall be able to navigate and traverse the test arena autonomously.
Robot autonomously mines until reaching gravel at a depth of 0.3 m, while simultaneously offloading all collected BP-1	The system shall be able to excavate regolith autonomously.
Offloading stops upon penetration of icy regolith layer, robot continues autonomously mining until max depth is reached	The system shall excavate to a depth of 0.5 m.
While drum is still spinning, robot slowly moves backward autonomously to mine	The system shall be able to deliver regolith to the collection bin autonomously
When deposition bin is full, robot autonomously navigates to collection bin and deposits regolith.	The system shall deposit at least 50 kg.
Steps 4 through 7 repeated for 10 min run	The system shall spend at least 7 min mining.
If autonomy fails at any time, robot will change to manual control and the human operator at the ground station will complete the run	The system shall traverse chaotic terrain with teleoperation.

* denotes derived system requirement

in conjunction with the other subsystems. Preventative safety measures will be taken including redundancy, factor of safety, and dust resistance. The system will be tested as a whole in a homemade pit, the specifications of which are detailed in Appendix B.

2.2.6. Systems Requirements Review (SRR)

The SRR examines the functional and performance requirements defined for the system and the preliminary program or project plan and ensures that the requirements and selected concept will satisfy the mission [3]. In reviewing the system requirements, several design changes were made to optimize trade-offs based upon available project budget, time and human capital.

Initially, the ORBIT system's mining requirement was 120 kg of mined icy regolith, with the operation of two distinct rover units. However, during the first round SRR performed on October 9, 2017 that goal was deemed infeasible. As a result, the second rover unit was redeveloped in favor of a single miner. The regolith collection requirement was reduced from 120 kg to 50 kg. A trade study outlining the decision to pursue a single rover system is included in Appendix A, Table 1.

In the second round of SRR, which occured on October 23, 2017, the current baseline mission concept, and corresponding system R/A/C were accepted and the project progressed to Phase B.

2.3. Phase B: Preliminary Design

The Preliminary Design phase focuses on the development implementations of the individual subsystems described in section 2.2.3. Trade studies were performed to measure the applicability of design decisions made during the development of these subsystems. Each subsystem was given a set of system requirements to contribute to the fulfillment of the overall baseline mission concept. Each subsystems' interface with other subsystems was also outlined, with their effect on their individual subsystem RAC determined. Furthermore, each subsystem had a verification plan proposed to ensure both its operation within the system requirements and safety margins. By the end of Phase B, the system and its subsystems will be entirely defined and ready to be implemented in Phase C.

2.3.1. Project Baseline

This year's competition rover was developed independent of past designs, however, takes experience from the construction of previous rovers, including the use of carbon fiber as the primary construction material and the use of additive manufacturing (3D printing) to develop unique component geometries.

2.3.2. Subsystem RAC

2.3.2.1. Chassis Subsystem

The chassis shall be composed of three individual mechanisms: a motor actuated drivetrain responsible for rover propulsion, a structural frame responsible for the mechanical interface with the remaining subsystems, and containment of the rover's electrical components, and the electrical system to power the drivetrain and distribute said power to the remaining subsystems. It shall also address the general system requirements by maintaining an overall mass of less than 20 kg with little trade-off for structural strength.

The chassis should be able to move the robot fast enough to traverse the entirety of the testing arena in less than 30 sec in order to achieve the desired mining duration of 7 min, while it should not exceed greater than 100 W/h in average power consumption Additionally, it shall be able to either traverse the obstacles or navigate between them, requiring sufficient agility or wheel diameter. The chassis shall securely support and adequately protect both the rover's mining subsystem and electronics from impact and dust penetration.

The first design challenge posed during the development of the chassis subsystem was determining what drivetrain method would be built that would accomplish the system and subsystem requirements. Four drive train designs were discussed in a trade study (the decision matrix for which is located in Appendix A, Table 2): 1) an indirect belt drive in which motors actuate wheels indirectly via a timing belt, 2) a direct motor to wheel drive interface in which each motor would directly actuate a wheel via a linear planetary gearbox, 3) a rocker bogie system in which wheels and motors are mounted on articulating legs to ensure successful terrain traversal, and 4) an angled direct drive system in which motors directly interface with their driven wheel through a right angled gearbox. These four approaches are demonstrated in Figure 5.

The simplicity of a direct drive system as seen in approaches 2 and 4, compared to approaches 1 and 3, has the greatest intrinsic merit considering the weight of the minimized mass and constrained dimension system requirements. Approach 4, was ultimately chosen for its satisfaction of the minimal volume requirement, as the lack of a protruding gearbox and motor into the inner volume of the rover would leave a greater volume for the mining mechanism.

For the construction of the frame, carbon fiber was decided on for the primary construction material. Its main advantage is high strength to weight ratio which fulfills the minimum mass and mechanical robustness system requirements. Drawbacks include its machining difficulty, which was mitigated by the team's previous experience using the material, and its capital expense, which was deemed as an acceptable trade off.

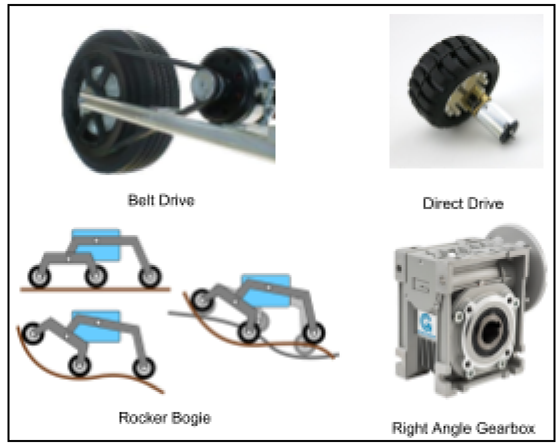

FIGURE 5: Comparison of the various drivetrain concepts

The proposed chassis subsystem verification plan involves testing the ability of the chassis to physically traverse a simulated test arena built by the team. Considerations during the testing of the rover include measuring the drivetrain power consumption, the system's dust tolerance, and its traversal speed across the regolith surface.

2.3.2.2. Mining Subsystem

The mining subsystem shall be able to excavate 50 kg of icy regolith within the allotted 10 min of testing time. The subsystem shall do so with minimal power consumption using components and materials which limits its overall mass to 25 kg. Additionally, the subsystem should be able to both contain collected regolith, minimize the amount of collected valueless BP-1 in comparison to icy regolith. After storing collected regolith, the mining subsystem shall be able to off load the collected regolith to the elevated collection bin with minimal residual loss (i.e. regolith left untouched by the deposition mechanism). The mining subsystem will therefore be composed of three mechanisms: the excavation mechanism, the deposition mechanism, and its power supply.

The development of the excavation mechanism centered around deciding upon an efficient digging methodology which would meet both the subsystem and system requirements. Four different mining approaches were considered for the excavation mechanism: 1) a drill utilizing an Archimedes screw to vertically displace regolith upwards, 2) a digging wheel that fit initially within the design dimension constraint, but whose spokes could expand during operation to achieve the desired mining depth, 3) a conveyor belt digger (dubbed "the worm") which features shovels on a pulley driven belt whose incident angle could be changed to achieve varying mining depths, and 4) a digging wheel actuated by motors placed at the apex of the wheel's circumference using a planetary gears to maximize available digging depth.

Approaches 2 and 4 were favored for their combination of the mining and containment subsystem requirements. Approaches 1 and 3 require actuators with high torque and therefore were discarded for violating the minimal power consumption and mass system requirements. Mathematical analysis of approach 2 determined that its capable mining volume would be insufficient to fulfill the 50 kg mined regolith requirement. After similar analysis (the graphical representation for which is shown in Figure 6), it was determined that approach 3 could be engineered to meet the all of the system requirements and was decided upon as the concept of the mining mechanism's operation. A decision matrix for this trade study can be found in Appendix A, Table 3.

The deposition mechanism would fulfill both the RMC system requirement of being able deposit mined regolith into an elevated container, and the independent system requirement of being able to interface with a possible second "containment rover." Special attention was given towards the development of a mechanism which did not add significant complexity and mass to the subsystem, yet would be able to quickly and completely displace collected regolith from within the rover to the collection bin.

A pulley driven, angled conveyor belt was chosen for its easy addition to the deposition mechanism. A tradeoff was made between the regolith containment volume within the excavation drum and the simplicity of the deposition mechanism.

While the deposition mechanism could be incorporated into the interior excavation drum volume, it would result in the reduction of the available volume within the drum from regolith containment. This tradeoff is within the bounds of the system requirements as the mechanism would still be capable of meeting the 50 kg collected regolith requirement (albeit with reduce margin for error), however, does fulfill the system mass minimization requirement and eventual compatibility with a second regolith transport rover.

Another topic of development during this phase was the planning of the verification process. The verification of the mining mechanism will involve testing the mining volume and power consumption of the subsystem in a constructed test pit for its adherence to the given system requirements, particularly its mined mass requirement.

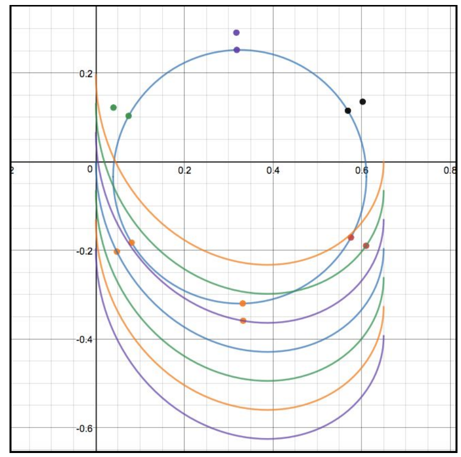

FIGURE 6: Mathematical model analysis of planetary digging wheel's expected mining capacity

2.3.2.3. Control Subsystem

The control subsystem shall be able to receive commands from both the human operator and autonomous processor, then translate said commands into operations for the various subsystems. The control subsystem shall also be designed to theoretically minimize possible disruption when exposed to extraterrestrial environmental conditions. Additionally, the control subsystem shall minimize bandwidth used for communication between the ground station and rover, while ensuring link integrity

The control subsystem shall be composed of three operational layers. The ground system operational layer shall be able to both maintain a reliable communication link and relay commands between the human operator and rover. It utilizes the Ground Control System (GCS) and communication link between the GCS and rover, facilitated via NASA's network and the team supplied router.

The autonomous operational layer shall be able to independently control the rover based on input from digital sensing, and includes the Central Processing Unit (CPU) and affiliated localization sensors.

The subsystem operational layer shall be able to translate commands received from the aforementioned layers to defined subsystem actions and distribute these signals to their respective subsystem. It includes the low-level Micro Processing Unit (MPU), signal distribution board, and busing between control units. Additionally, the control subsystem shall be powered in a manner that ensures the safety of the controlling hardware in the event of electrical failure. Figure 7 shows the relationship between these operational layers.

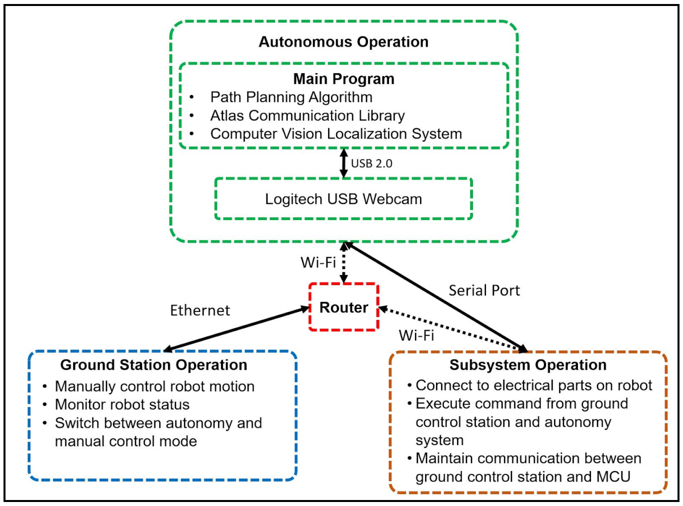

FIGURE 7: Control subsystem architecture

The development of the ground system operational layer's wireless communication protocol focuses on the minimization of utilized bandwidth. A trade study was conducted between various communication protocols which offered different levels of packet size and reliable data transfer (RDT) guarantees. A decision matrix outlining this trade study can be found in Appendix A, Table 4. Based upon adherence to both the system requirements and general system requirements, a compressed UDP packet with a "heartbeat" RDT protocol was chosen. Being a UDP based protocol, each segment's size has been minimized, therefore conserving bandwidth. The heartbeat protocol ensures reliable data transfer through the maintenance of an active link between the rover and GCS using RDT "heartbeat packets." Packet loss is indicated by the failure of a heartbeat packet to arrive within a given timeout window. Packet loss will pause robot operation until the link can be reestablished.

Another control system design decision was the determination of the strategy to be employed for autonomous localization, or the process of determining the rover's position in the test arena. The possible strategies to be employed are the use of commercial Light Detection and Ranging (LIDAR) systems, self-manufactured LIDAR systems, and computer vision (CV) systems utilizing optical aids (AprilTags). The main drawback posed by both LIDAR solutions is its capital cost. Specifically, commercial phase measurement LIDAR can cost greater than $4,000 and simple triangle LIDAR system costs greater than $1,000. A CV system can be accomplished with a $50 USB camera and inkjet printed AprilTags. While LIDAR systems are more accurate and reliable--CV solutions are dependent on ambient lighting conditions--CV systems are more versatile as they can be trained to identify both indicators like AprilTags or visually analyze its environment such as the identification of obstacles for path planning. Ultimately, CV was chosen as the ConOp for the autonomy mechanism. Appendix A, Table 5 outlines the decision matrix used for this trade study.

The final design consideration taken towards the development of the ConOps of the subsystem operational layer is the low level protocol utilized between the individual electrical components, the most important link connecting the MCU with the various motor controllers for the the subsystem actuators. A trade study was conducted comparing various signal level protocols, the decision matrix for which is shown Appendix A, Table 6. The final design decision made was to utilize a CAN (Controller Area Network) bus protocol for its electrical simplicity (it requires two wires for operation), expandability (subsequent additions to the control system output can be connected in series with previous components), and its electrical properties (in a simulated extraterrestrial environments, radiation poses the threat of "flipping bits" and corrupting signals, CAN being a differential protocol is unaffected by random bit flips compared to other protocols such as UART).

The proposed subsystem testing plan involves testing the autonomous pathfinding and localization algorithms first virtually using computer simulation, then on a miniature rover model, then finally using the complete ORBIT system within the simulated test arena.

2.3.3. Subsystem Interface

Subsystem interfaces are an important component of successful system design. Interfaces must abide within the subsystem and system requirements and fulfill the baseline mission concept. The following section identifies various subsystem interfaces and their role in the system preliminary design. Figure 8 identifies that various system interfaces

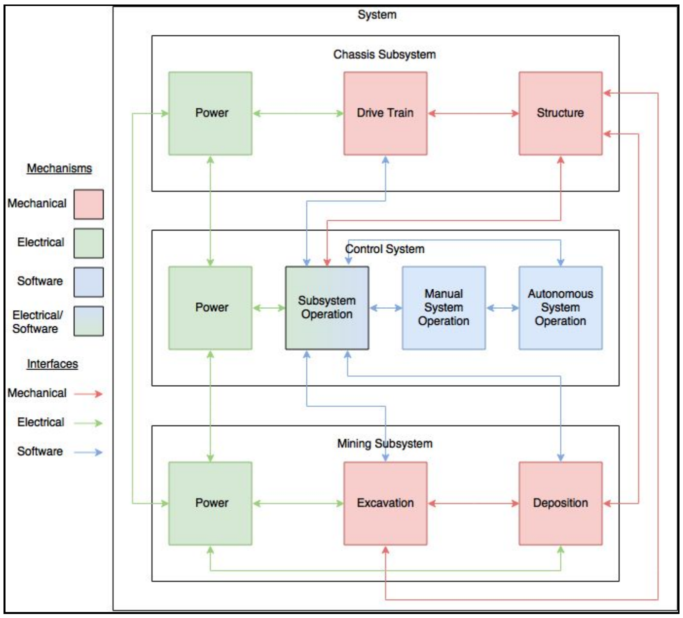

FIGURE 8: Diagram of System Interfaces.

2.3.3.1. Chassis - Mining

Being the foundational subsystem of the greater ORBIT system, the chassis subsystem is responsible for the structural support of the mining subsystem. Subsystem interfaces between the chassis and mining subsystems must ensure the robust function of both subsystems.

2.3.3.2. Control - Chassis

The control-chassis interface is bidirectional. Similar to the chassis-mining interface, the chassis subsystem is responsible for the structural support of the control subsystem including the protection of the rover's electrical components. The dust tolerance system requirement is therefore applicable to this interface.

The control system is responsible for the operation of the electro-mechanical components of the chassis subsystem, particularly, the command of the system by either the human operator or the autonomy system. As this interface dictates the autonomous operation of the ORBIT system, the system's autonomous operation requirement, specifically, that the robot shall be able to autonomously navigate the test area, is applicable to this interface.

2.3.3.3. Control - Mining

The control-mining interface involves the operation of the mining subsystem by either the human operator or autonomy system. As mentioned previously, this interface therefore must accomplish the autonomous mining system requirement as the control system must successfully integrate with the mining system to accomplish this task.

2.3.4. Safety Review

The safety of the robot's subsystems both in relation to its operation and environment was investigated. The proposed verification plan to test the subsystems' robustness is described in detail previously. Thus, the only points of jeopardy remaining to the operation of the rover are protections to its electrical systems, specifically its particular tolerance and current protection.

2.3.4.1. Particulate Tolerance

In the designing of electrical enclosures, especially fine particulate tolerant systems, a point of failure arises from the electrical interface between the interior and exterior of the enclosure. Therefore, constructing interfaces between the electrical enclosures' electronics and exterior subsystems must be closely monitored.

Investigation into chemicals to limit static attraction between the system and the regolith led to the discovery of a commercial product called Staticide for use on the system's surface.

2.3.4.2. Current Protection

Electrical failure cannot only damage the system's components, but can also jeopardize the operation of the system as a whole. Therefore, during the subsequent design phases of the subsystems, adequate measures must be take to ensure that high current circuits are kept separate from the more delicate circuits and that all electronics components are protected from current spikes and used only in application within their individual current ratings.

2.3.5. Preliminary Design Review (PDR)

The PDR demonstrates that the preliminary design meets all system requirements with acceptable risk, within the cost and schedule constraints, and establishes the basis for proceeding with detailed design [3]. On December 17, 2017, the team met to discuss the preliminary system design and status of the project's schedule, technical budgets, and capital budgets.

It was determined that the developed preliminary system design met the goals and requirements set out in Phase A. Furthermore, the proposed verification plans outlined could be utilized as a practical metric of each subsystem's application of the system requirements.

After a review of the project's progress, it was determined that the project was behind schedule by two weeks. This would be mitigated by committing to work more in the following university break. The current project's preliminary design, risk mitigation plans, and proposed verification plans were approved and the project progressed into Phase C.

2.4. Phase C: Final Design and Fabrication

Phase C involves the specific implementation of each subsystem's preliminary design plan. The mechanical and software fabrication of each mechanism was fully defined, planned, then executed in this Phase [3].

2.4.1. Chassis Subsystem

2.4.1.1. Structure

The carbon fiber is used to construct the frame consists of 2 in by 1 in rectangular tubes with 0.05 in thick walls, joined by a combination of carbon fiber L-brackets, plastic spacers, and aluminum straight gussets.

The tubes made the frame light, however, when other components were screwed on to the carbon fiber, the carbon fiber started to deform. By adding plastic spacers into the carbon fiber the issues was resolved. Since plastic was light and only placed in certain areas of high strain the frame was still light.

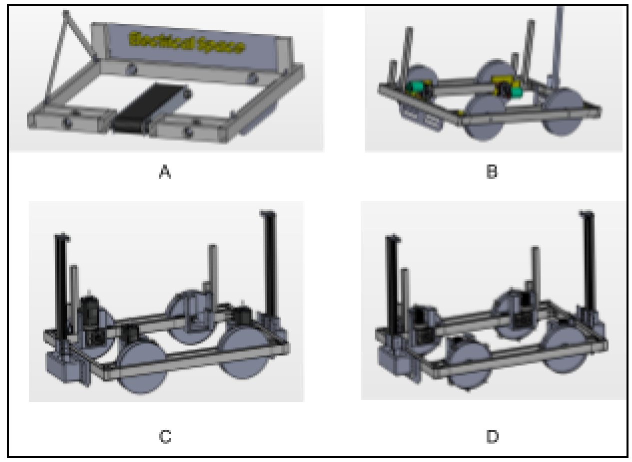

FIGURE 9: Evolution of the chassis subsystem. (A) First iteration, (B) 20th iteration, (D) 30th iteration (D) Final iteration

The square frame also experienced large shear strain when shear force was applied. By adding carbon fiber L-bracket to the inside corner of the frame, the frame's structural integrity increased while the weight of the system stayed minimal. Figure 9 demonstrates the development of the chassis frame.

2.4.1.2. Drive Train

Given the right angled gearbox chassis strategy chosen in the preliminary design phase, a four-wheeled drive system was designed that includes the wheel, gearbox and motor, which are interfaced with a shaft and hub. Figure 10 is a rendering of the wheel motor assembly.

The wheel is made from a single plate of honeycomb aluminum that is circumscribed by perforated steel metal which are both 0.125 in thick. The construction of the wheel was made to fit within the minimized system mass requirement. The wheel has small cleats that will help with traction when driving. The diameter of the wheel was chosen in conjunction with the diameter of the mining mechanism (section 2.4.2.1) to maintains the maximum dimension system requirement.

The motor was chosen based on two criteria, the torque and speed of the motor. The required torque was calculated using force analysis calculations. The torque calculated was 900 oz-in, however a operation margin of 1.5 was added to the calculation to account for uncertainties. The speed of the motor was determined by the 7 min digging requirement. The robot needs to travel to the digging area in 45 seconds. The RPM of the motor was calculated to be 28 RPM. Using the gear ratio calculator in (2.4.2.1) an appropriate gearbox reduction of 60:1 was chosen for the subsystem design.

Anaheim Automation, BLY172S-24V-2000 24V DC brushless motors were chosen for their satisfaction of the above torque and speed requirements, and their IP65 rating, a satisfaction of the dust tolerance system requirement. The motors are nominally rated for a torque of 28.3 oz-in at 2000 RPM. The chosen right angle worm gearbox 60:1 reduction, Grosschop P/N 926-30-0038, was chosen as it satisfied both the maximum dimension system requirement and the aforementioned torque / speed calculations. The combine motor-gearbox interface yields a nominal torque of 1700 oz-in--well above the targeted 1350 oz-in torque--and a speed of 33 RPM--again above the target speed of 28 RPM.

During the determination process of the right angled reduction, it was found that the such gearboxes with the desired reduction have a generally greater mass than its planetary gearbox alternative. However, if a planetary gearbox matching the desired specifications were used then the motor would protrude into the inner rover volume, reducing the space available for the mining mechanism and system's mining capacity. It was decided that increasing the weight of ORBIT was less detrimental towards the system requirements than decreasing its digging capacity.

2.4.1.3. Power

The drivetrain portion of the chassis subsystem is driven by four 24V brushless motors. As mentioned previously, the motors have a nominal power consumption of 41W (1.7A nominal current draw operating at 24V) and a maximum power consumption of 155W (6.4A at 24V).

Given these electrical properties, a motor controller was chosen which could accommodate the maximum current requirements of each individual motor, with a margin for subsystem safety, as well as provide accurate feedback control from the motor's Hall Effect sensors.

RoboteQ MBL1330 DC brushless motor controllers were used in the control circuit for the chassis drivetrain. The controllers are rated for 60V, 70A and feature feedback loop capabilities for accurate motor operation. Each motor controller receives a fused power connection from the power distribution unit (PDU).

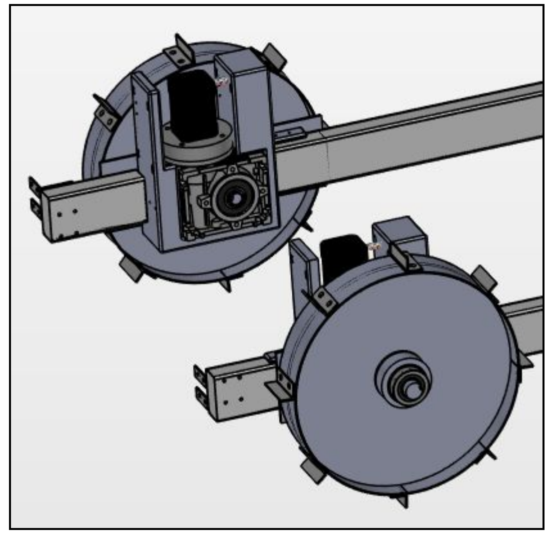

Figure 10: Two motor-wheel assemblies

The PDU consists of two marine bus bars (24V+ and GND) within an insulative, acrylic case. The PDU distributes the 24V lithium-ion battery input to each motor controller of the subsystem. XT-90 connectors, rated 90A, were used to interface the power distribution unit with motor controller wire leads. An XT-150, rated 150A, connector was used on the main power line from the battery to the power distribution unit. The schematic of the chassis power is show below in Figure 11.

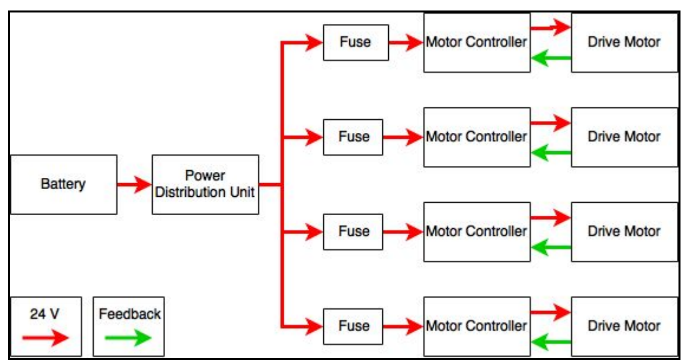

FIGURE 11: Chassis power and feedback distribution schematic

2.4.2. Mining Subsystem

2.4.2.1. Excavation

The Excavation mechanism was built in two parts, the polycarbonate polymer drum and the shovels. The drum consists of the planetary gear assembly and motors. The shovel is connected to the rotating ring of the drum. Figure 12 is a rendering of the planetary gear system.

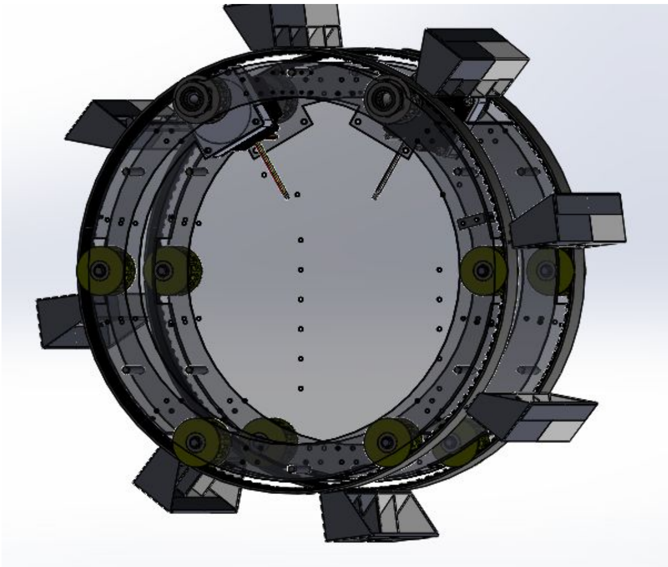

FIGURE 12: components of a planetary gear. The yellow pulleys are the planet gears and the gray ring is the ring gear.

To create the drum, a 140 tooth HTD timing belt is used as a ring gear and 3D printed HTD timing pulleys are used as planet gears. For the rest of the structure, polycarbonate was chosen for its high strength to weight ratio, thermal elasticity (hence relative bending ease), and low cost. The structure is composed of four parallel circular polycarbonate plates, and one polycarbonate plate rolled around the outside of the mining mechanism and heat treated to maintain its form. The development of the excavation mechanism is shown in Figure 13.

During mathematical analysis, careful equilibrium must be found between the shovels' rotational rate and the descent velocity of the entire mining mechanism: if the shovels excavation rate is too slow in comparison with the descent rate, the mechanism as a whole will collide with the excavated regolith surface, whereas if the shovels excavated regolith faster than the mechanism was lowered, time would be wasted mining an empty volume. The ideal drum's angular velocity is 1.57 rad/s whereas the balanced descent rate is 0.00762 m/s.

Part of the verification process for the designed excavation mechanism was the completion of a simulation of a smaller version of the drum used to mine a small sample of BP-1. The force required to mine the regolith was measured using a spring scale, from which the approximate torque requirement, for the excavation mechanism was derived.

A motor was chosen to most closely match the speed calculated in the simulation in Figure 6 and the torque found through prototyping. To compare different motors, a calculator was created to compare the speed, and current draw of each motor for various gear reductions at the calculated torque. The required torque and speed of the system (including safety margins) was determined to be 15 RPM and 16,913 oz-in.

Using the calculated torque and rotational velocity, the lightest motor with a relatively low current draw that could meet the expected digging rate was selected; two Anaheim Automation BLYSG342D-24V-3000 24V DC Brushless motor with a 12.5:1 spur gear reduction was chosen. It has a rated maximum torque of 3750 oz.in and a rated maximum speed of 160 RPM. The two motors combined with the planetary gear digging mechanism, would achieve a total system torque of 17,000 oz-in and 17 RPM, which is within the subsystem mechanical requirements. The calculator was used to choose other motors used on the robot, including those for the drive system, and the deposition system.

2.4.2.2. Deposition

The deposition bin contains a conveyor, a collection area and the actuators. The collection area carries all the gravel and BP-1 that the shovel deposits. The conveyor belt deposits the collected gravel to the collection bin and the actuator will move the entire mininning mechanism downward to dig and upward so it can deposit the gravel.

The conveyor belt is made with two timing belt and five pulleys. One pulley on each edge and a three in the middle. The middle pulley were added to disperse the load of the gravel. One of the pulleys on the edge is adjustable so the timing belt could be tensioned. Since the the timing belt has to transport the gravel at a 45 degree angle, cleats were added to force the gravel upwards.

The collection area is contained within the mining drum and guided onto the belt by two polycarbonate walls. In order to minimize manufacturing difficulty and effectively guide collected regolith onto the deposition belt, the containment assembly decreases the volume of gravel that can be carried.

Currently ORBIT's mining subsystem, can nominally contain 25 kg of gravel at once, therefore the ORBIT system must make two trips to collect the required 50kg of regolith.

The actuator part of the mining mechanism consists of two linear actuators and an upper rectangular carbon fiber frame. The frame supports the mining drum and interfaces with the linear actuator and chassis.

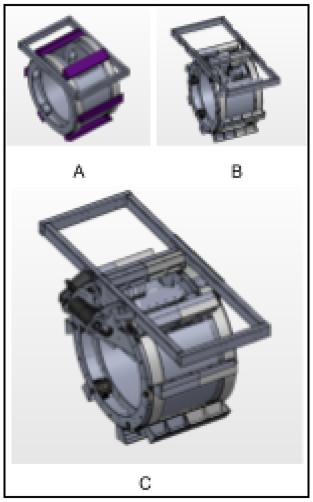

FIGURE 13: Evolution of the minging mechanism. (A) First iteration, (B) 20th iteration, (C) Final iteration

The linear actuators interface with the chassis with two printed plastic mounts. Given that the actuator mounts have only an inch of clearance, it is an optimal place to mount limit switches to mechanically detect obstacles and interface with the autonomous control operational layer of the control subsystem.

To support the linear actuator from the top, a brace was connected from the linear actuator to the electrical enclosure to ensure stability,

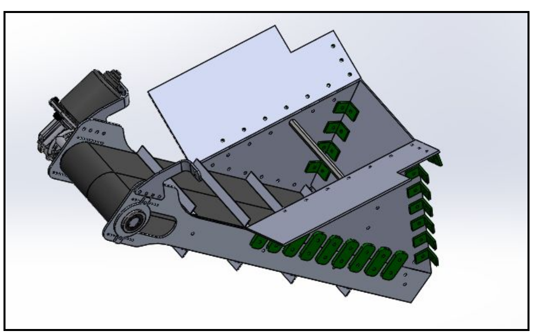

FIGURE 14: CAD rendering of the deposition system

2.4.2.3. Power

The mining subsystem includes two separate voltage levels: 24V and 12V (Figure 15). The digging motors have a nominal current draw of 4A and a peak current draw of 24A. To accommodate the maximum current draw and achieve the current safety system requirement, 60V, 70A RoboteQ brushless motor controllers were chosen for the system. These motor controllers receive its power input from the PDU and interface with 90A rated XT-90 connectors.

The deposition mechanism and linear actuators run on 12V and utilize brushed motors. The total, maximum current draw for the 12V system was 32A, therefore a 40A DC Buck 24V - 12V voltage converter was chosen. Although Buck converters (with the included heatsink) have a generally greater mass than linear or switching regulators, it was chosen for its 95% efficiency rating. The linear actuators and deposition pulley motors are run on 2, 24V 50A RoboteQ brush motor controllers. The linear actuators provide feedback into the system through a string potentiometer mounted between the upper frame and chassis frame.

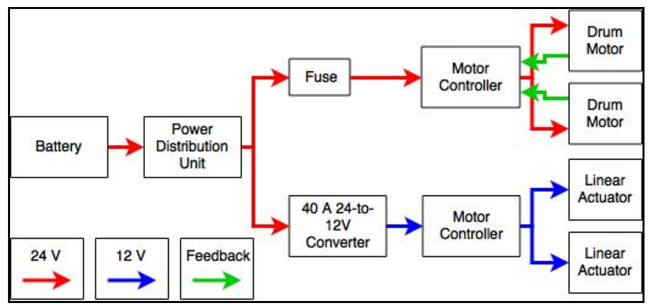

FIGURE 15: Power distribution schematic of the mining subsystem

2.4.3. Control Subsystem

2.4.3.1. Subsystem Operation

The subsystem operation layer is the combined hardware and low level software implementation of the control subsystem and the main interface between the control software and other subsystems.

The subsystem operation layer shall include hardware support for interfacing with ORBIT's various subsystems and their control peripherals, each requiring a specific communication protocol: 1) the multiple motor controllers (CAN bus), 2) the communication hardware, a WiFly 802.11b/g/n to UART bridge (UART Serial), the CPU (USB Serial), and the feedback devices (i.e. string potentiometers, and limit switches, and mining mechanism feedbacks, all running on an analog signal path). A 32-bit Allegro Microsystems ARM Cortex M3 microprocessor was chosen for the rover's MCU for its support of all of these protocols.

In addition to the MCU, more peripheral hardware is used for the embedded control, all of which is located on the control signals distribution motherboard: a CAN bus transceiver, a 5V and 3.3V regulator, a WiFly 802.11b/g/n to UART bridge, and indicator LEDs used for state debugging. The autonomous system operation is run on an Intel NUC7i5bnk, a portable, full featured x86 computer equipped with a low per rated Intel i5 processor and 16 GB of memory.

Aside from the control hardware, various protocols are used to communicate between the subsystems. Specifically, the CAN communication protocol was chosen to communicate between the microcontroller and the motor controllers because it uses only few wires for many devices and it is minimally affected by environmental noise and radiation. Devices are connected to a singular CAN bus with two wires, CAN High, and CAN Low. Data is sent in packets containing the node identifier, which specifies which device the message is being sent to, and the data payload. CAN is a differential communication protocol which makes it ideal for use in outer space. The value of a bit is determined by taking the differential of the CAN High and CAN Low lines meaning radiation or noise in space is likely to affect both lines, keeping the differential in the same.

The subsystem operation layer interfaces with the autonomy and ground control systems layers through a USB Serial connection between the MCU and CPU. Through this hardware interface, control subsystem layer receives critical control commands. These commands include: 1) fail safe mode or a full stop of subsystem activities resulting from packet loss, 2) operation commands from the autonomy/ ground control systems, and 3) start/stop commands generated by the transference of authority between the autonomous and ground control layers.

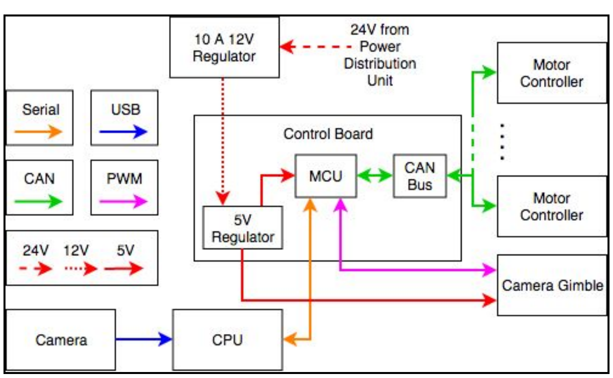

FIGURE 16: The control signal and power distribution schematics of the control subsystem

2.4.3.2. Ground System Operation

The ground system operation layer is the network application layer responsible for the maintenance of a reliable communication link between the GCS and rover. Specifically the GCS encapsulates inputs from an I/O peripheral such as a keyboard or joystick controller into a customized UDP packet. The input packets are then sent through the network link provided by NASA to the rover's network receiver (the 802.11b/g/n antenna on the CPU or redundant antenna connected to the MCU). The MCU / CPU will then decode the packet into subsystem commands which are passed on to the subsystem operation layer for distribution.

Additionally, the ground system operation layer interfaces with the autonomous operation layer as the latter sends monitoring statistics to the GCS while running through the same transport link described previously.

The Ground System Operation layer utilizes an application layer protocol (GSOAP) designed for robot operation. Said protocol (outlined in Figure 17) is optimized for faster response times, lower bandwidth usage and better exception handling, all core subsystem requirements derived from the greater bandwidth minimization requirement. The core of this protocol is the heartbeat mechanism and a customized UDP packet.

The heartbeat mechanism guarantees reliable data transfer (RDT) similar to a TCP transport protocol, but while maintaining limited bandwidth usage. The mechanism runs at a 30Hz refresh rate in which the GCS will send either a command data or empty UDP "heartbeat" packet. The rover system responds with either a data response or heartbeat of its own. In the event of transmission timeout, fail counter is incremented, otherwise, it is set to 0. When said counter crosses the fail threshold (initially set to 10) the robot initiates its fail safe mode described previously in the subsystem operation layer.

The custom UDP packet is identical to a standard UDP packet except for the present of flag byte indicating the packet type (0 = heartbeat, 1 = GCS data, 2 = rover data).

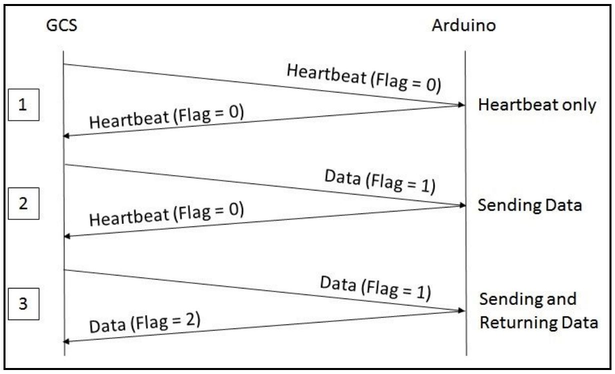

FIGURE 17: Network communication diagram for ground system for heartbeat protocol

The GSOAP runs on two primary end systems: the Ground Control System and the Rover Control Software. The Ground Control System is the software interface for the human operator to send commands to the rover via the Ground System Operation Transport Layer. It runs on a laptop within the mission control trailer.

The Rover Control Software runs on the MCU and consists of three layers: I/O manipulation, communication protocol and the customized RTOS. The rover's embedded platform is only able to support a sequential operation flow rather than multithreaded parallelism. To guarantee the speed of execution of said operations, a customized lightweight real-time operating system (RTOS) is designed for Control Hardware that supports the basic non-preemptive scheduling mechanisms. The communication protocol runs on the RTOS. It is responsible for receiving and pushing commands to and from the transport layer and parsing said commands into processable signals forwardable to the I/O manipulation layer. The I/O manipulation layer directly interfaces with the Control Subsystem layer to distribute parsed commands to the various subsystem control peripherals.

2.4.3.3. Autonomous System Operation

The autonomous system operation layer (auto layer) implements perceiving the environment, planning the optimized work path and generating the appropriate operation command. It also has the ability to handle emergency situation and stop the execution when irreversible emergency events occur. The architecture of auto layer is illustrated in Figure 18.

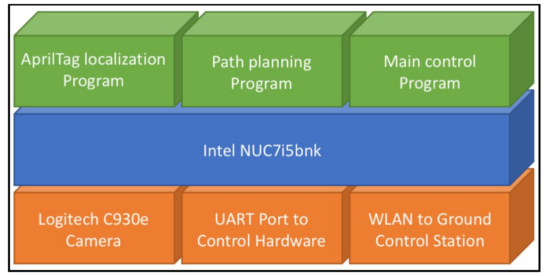

FIGURE 18: Autonomous System Operation Layer Architecture

The auto layer runs as a software program on the CPU and related peripherals which are discussed in full in the context of the Subsystem Operational Layer.

The localization program is based on the AprilTag localization library, developed by the April Lab from University of Michigan, Ann Arbor. This library provides the functions of detecting the presence of the QR code-style tag in the image and calculating the 3D transformation matrix from camera coordinate system to corresponding tag coordinate system.

To achieve the localization function, an AprilTag is attached on the wall of bin in the arena, which will be used as origin, and a camera will be installed on the robot on an articulating gimbal to maintain "eye contact" with the tag during operation.

Given the transformation matrix from camera coordinate to tag coordinate T^0_c, the transformation matrix from tag to camera will be $T^c_0 = inv(T^0_c)$, which can be solved by calculating the inverse of T^0_c. Then, with the size of tag as scale factor s, the 3D space position of robot (camera) is outlined in Equation 1.

$$x = sT^c_0(0,\ 3)\ /\ 2$$
$$y = sT^c_0(1,\ 3)\ /\ 2$$
$$z = sT^c_0(2,\ 3)\ /\ 2$$

EQUATION 1: Transformational matrix calculations

The code of this program is implemented in C++ using CV processing functions from the OpenCV library.

Based on the AprilTag localization to detect the position of the robot, the path planning program is used find the shortest path to the target. The path cost includes path distance and number of turns.

The algorithm uses a widely used shortest path algorithm: SPFA. However, the ORBIT system autonomous layer employs a more complex cost calculation function (Equation 2), which also takes into account the number of turns since it will cost a robot a lot of time to make a turn on the regolith surface. The time complexity for the SPFA path planning determination is *O(size(position in the graph))*.

$$f = w_1 \times cost_{dis} + w_2 \times cost_{turn}$$

EQUATION 2: SPFA cost analysis function

The main control program is the core of the autonomy system. It organizes the above two processes and interfaces with the Ground System Operation Layer. The main control program logic is demonstrated by the flowchart in Figure 19.

For detecting the obstacle, a bumper switch is installed in the front of the robot to detect the physical contact of obstacle. Once the switch is closed due to hitting of obstacle, a mark is placed in map to indicate the position of obstacle, and try to avoid it next time.

The main control program is controlled by the Ground System Operational Layer. Considering that the autonomy system is unreliable, once an emergency event happen (i.e. exceptions within the autonomy system), the autonomy layer will yield control of the system to the human operator.

2.4.3.4. Power

The control subsystem has three voltage requirements: the CPU which is powered on a 12V input, and the control peripherals (signal distribution buses, sensors, and CAN bus transceiver) which operate on a 5V logic level, and the MCU operates on 3.3V logic.

All inputs come from a 24V - 12V 10A DC Buck Converter which derives its power from the PDU. The signal distribution motherboard includes 12V - 5V and 5V - 3.3V linear regulators to achieve the desired logic level. Overall the potential reduction has a measured efficiency of 94%. The power distribution circuit is outlined in Figure 16.

2.4.1. Critical Design Review

On February 5th, 2018, the team met to discuss the final system design. This review looked at all of the subsystems, and the interfaces between them. At this review CAD models, mathematical models, prototypes, and simulations, like the ones described above were used to validate the design concepts. The whole system was evaluated against the system requirements. At the conclusion of this review, it was determined that the design was complete and fabrication began. Plans for testing and risk management were solidified. Specifications for the testing pit were finalized, and a location for the pit was acquired. Risk management is discussed in Section 2.5.2. The schedule and financial budget were updated. The detailed robot design is expected to meet the requirements, and without any high risk subsystems. The team progressed to Phase D.

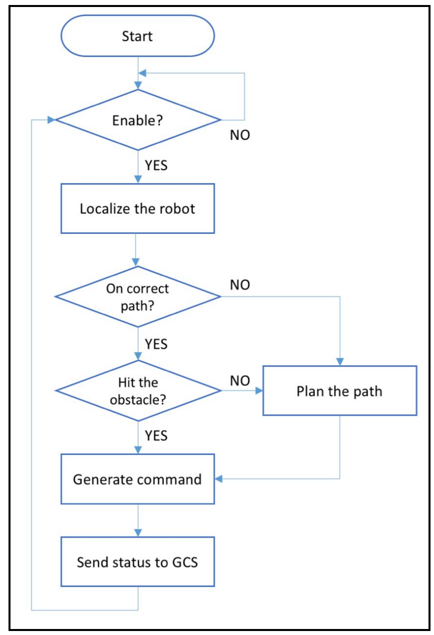

FIGURE 19: Auto layer operational state diagram

2.4.2. Subsystem Fabrication

Before assembling the full robot, each component of the robot were manufactured using fabrication methods specific to its material. Aluminum and polycarbonate components were machined using a Wardjet 24in x 24in waterjet cutter. The carbon fiber was either machined by hand via the use of a drill press, and circular saw, or machined using a 3-axis Shopbot CNC mill. Components that required a specific geometry whose fabrication would be too complex through subtractive methods--the linear actuator mounts, shovels, pulleys, and small support pieces--were fabricated from ABS plastic using fused deposition modeling 3D printing. For the electrical subsystem, PCBs were etched using a 2-axis CNC mill and treated with UV curable, film applied soldermask.

As a fabrication method, 3D printing, is a cheaper and simple method of making complex parts. However, 3D printed components are inherently weak since the manufacturing method cannot create one solid part. In order to reinforce the plastic, 0.1” thick aluminium 6061 sheet metal were affixed to the stressed parts of such components such as attacking edge of the shovels and the mounting interfaces (i.e. fastener holes) of the linear actuator mounts.

The software for the rover’s embedded systems and autonomy functions were coded in C++, while the GCS was programmed using Python.

2.5. Phase D: System Assembly, Integration, Test, and Launch

During Phase D, activities are performed to assemble, integrate, test, and launch the system [3]. The project is currently in this phase in Systems Engineering Process. The subsystems have been assembled and tested independently and now are being integrated into the complete system. Once the entire rover is assembled, testing will occur in a mock test arena.

The testing arena was built to be 8ft x 8ft x 3ft out of wood, and was filled with 0.3 m of a BP-1 simulant (see Appx B, Table 1 for the composition by mass of the mixture). As the testing location had low tolerance for possibly hazardous material (like coal fly ash, a common BP-1 replacement material), Metakaolin, a dehydrated form of the clay mineral kaolinite was utilized as it is not a respiratory irritant and is easier to source than fly ash. Below this a layer of gravel of 0.3m to simulate icy regolith was placed. The testing area information shared with all of the teams by Iowa State University was used to help develop safe testing procedures.

2.5.1. Chassis Subsystem Testing

The chassis subsystem testing involves testing both its drive train’s efficacy and its structural tolerances.

The first test performed verified the subsystem’s drivetrain mechanism. This includes how well can ORBIT move from the starting position to the ending. Three parts of the driving mechanism needs to be tested. First parts is traction. The amount of traction between the regolith and the wheel is proportional to the speed of ORBIT. If ORBIT cannot achieve the maximum speed that the motor is outputting, the wheel will be redesigned to increase traction. The second part is the ability to clear the obstacles. ORBIT was not designed to go around rocks, however, ORBIT needs to go over a crater in less than ten seconds. The third part is failure due to stall. There might be situation where one wheel on ORBIT will get stuck and cause the motor to stall. All driving components on ORBIT needs to handle the torsion force of the stalled motor.

The second verification evaluates the chassis’s structural tolerance. a structural test. This includes how well the different components of ORBIT will handle different loadings, and the chassis’s dust tolerance.

Mechanically, there are three main forces that ORBIT needs to withstand: the falling force of ORBIT falling into a crater, the force on ORBIT climbing over an obstacle and the impact force on ORBIT on a collision with a rock.

Dust tolerance, especially within the electrical enclosure is vital to successful system operation. Individual material tests with Staticide proved that treatment with the chemical made surfaces more resistant to regolith exposure. Appx B, Figure 1, demonstrates the effect of the application off staticide on the reduction of regolith retention on aluminum. Staticide will be applied to the entire system and tested for its efficacy in increasing dust tolerance.

To test the drivetrain and its structural integrity, the completed chassis subsystem was run inside of the test pit and these behaviors evaluated. Adjustments were made to the motor mounts to reduce torsion exerted on the wheels and frame. Otherwise, testing proved the design successful.

Upon successful system assembly, the aforementioned system verification points will be reevaluated to test the effects of subsystem interfaces on their performance.

2.5.2. Mining Subsystem Testing

The mining mechanism function is the collect, carry and dump gravel. Each function will be evaluated during subsystem testing.

The collect function is the combination of the drum, the shovels and linear actuator. Two properties of this function need to be tested. First is the ratio between the linear actuator velocity and the shovels angular velocity optimized and efficient as it was discussed in 2.4.2.1. The second property that needs to be tested is whether the drum motor will stall. As most of what the drum will dig up will be a combination of regolith and gravel, which makes the gravel loser and easier to dig then if it was just pure gravel. Therefore, the mining mechanism will attempt to dig pure gravel that has been compacted.

The carrying function involves the shovel and the collection area. The main thing that needs to be verified gravel and regolith debris leakage into other components and subsystems. This can be evaluated visually during subsystem testing.

The dumping function involves the conveyor belt offloading regolith into the collection bin. There are two parts of the conveyor belt that need to be tested. The first part is, whether the conveyor belt stalls when the entire collection area is filled with gravel. The second part is the alignment with the collection bin. Since the conveyor belt output is on ORBIT's side, aligning it with the collection bin will be difficult. Verification will need to include tests with different strategies to determined the most effective way to align with the collection bin (this involves successful interface with the chassis subsystem).

The mining subsystem is currently being tested individually within the test pit for the aforementioned functions with the purpose of validating the proposed goal of 25kg of regolith

2.5.3. Control Subsystem Testing

The control subsystem testing is focused on two main metrics: used bandwidth and autonomous operation errors.

To test the bandwidth used by the subsystem, the electronics of the subsystem were isolated and a test radio link between the rover and GCS was established. A ten minute test run was simulated with commands being sent back and forth over the GSOAP utilizing full teleoperation control. The bandwidth was measured from the GCS using the Wireshark packet trace utility (see Appx B, Figure 2. The average bandwidth usage was measured to be 26 kbps, with a maximum bandwidth utilization of 50 kbps.

To test the autonomy system, three verifications were utilized: computer based simulation, modelled simulation, and full system verification. During the computer based simulations unit test programs were developed to individually test the accuracy of the CV localization and path planning algorithm. Appx B, Figure 3 is a screenshot of the AprilTag Orientation unit test, while Appx B, Figure 4 is an annotated output of the path planning unit test.

After virtualization, the entire autonomy system was tested using a miniature test system, simulated on a Whippersnapper Runt Rover Test platform. The same sensors and webcam was used to successfully navigate a miniature test pit using the developed autonomy programs.

Finally, the autonomy system will be tested as a whole (both mining and driving subsystem interfaces) on the completed system upon full system assembly. This is the last step in the verification phase and is a culmination of previous subsystem verification and testing.

2.6. Phase E: Operations and Sustainment

2.5.1. Operations

At the competition ORBIT will perform the competition tasks. It will be clear whether the initial requirements are met based on the performance in the competition. When arriving at the competition the team will verify that the system is functioning correctly after shipping by participating in a practice run. Any perceived problems will be addressed. After each test run, ORBIT will be cleaned thoroughly to prevent any dust from entering the electronics enclosure during maintenance.

2.5.2. Risk Management

During operation there are undesired events and consequences that may occur which will have a negative impact ORBIT's performance. These risks have been identified and planned for. The risks that have been identified and classified are shown in Table 2. The failure classifications are specified in Table 3.

- **Communication Failure:** If the robot is disconnected from the ground station then tele-op control will be impaired. Communication failure is unlikely due to the heartbeat protocol used to check for connection consistently and actively reconnect at loss.
- **Obstacle Collision:** While navigating across the arena ORBIT will encounter rocks and craters. If not handled, collision could cause damage to the chassis or mining mechanisms. To make

sure this does not occur, a bumper sensor was added to the front and back of the frame.

- **Autonomy Failure:** ORBIT will be able to complete all of the tasks autonomously. In case of autonomy failure due to algorithm indecision the still will be switched to tele-operation for a significantly lower score, but task completion.
- **Bin Misalignment:** Due to the geometry of the rover frame, it may be difficult to align the robot deposition mechanism with the collection bin. If the rover cannot do this autonomously, tele-operation will occur. This may also be a difficult task for a human driver, and may cost time. To mitigate this risk the team will practice the bin alignment maneuver, and will utilize the individual control of each wheel.

Table 3: Risk Analysis

Risk Analysis		Failure Classification			
		1	2	3	4
Likelihood	4	Obstacle Collision			
	3		Bin Misalignment		
	2		Autonomy Failure		Robot Gets Stuck
	1	Comms Failure			Regolith on Electronics

Low Risk	Medium Risk	High Risk

Table 4: Failure Classification

Classification of Failure		
Level	**Name**	**Description**
1	Non-Critical	If this error occurs, the mission can still be completed without need for redundancy
2	Reduced Capability	If this error cannot be mitigated, the mission is still a success, but will need to be revisited to provide increased capability
3	Significantly Reduced Capability	If this error occurs, performance has decreased and cost will increase, but the mission can still be considered a success
4	Mission Failure	The mission will be a failure if this risk cannot be mitigated

- **Immobility:** A common risk that rovers face on regolith is getting stuck if the digging process clear too much regolith away to achieve a sufficient traction at the wheels. Immobility can lead to mission failure. However, this risk is mitigated by the path planning algorithm which should ensure that ORBIT avoids depressions in the regolith.
- **Regolith on Electronics:** If regolith enters the electronics enclosure, it could potentially damage the sensitive electrical components within. To prevent dust from entering the electronics enclosure, it has been designed to be dust-proof. All of its interfaces are rated for IP60, and the manufactured seams are sealed with silicone sealant. The enclosure need never be opened as all of the troubleshooting interfaces can be accessed externally via IP60 rated connectors.

2.7. Phase F: Closeout

After the competition, ORBIT will be shipped back to NYU Tandon and displayed in the NYU Makerspace. After that it will be stored in the team's lab. A post competition review will be conducted to analyze improvements that can be used for future systems (for RMC and elsewise)

3. Project Management

3.1. Schedule

The schedule for this project was designed to follow the phases of systems engineering. The major tasks were recorded on the schedule found in Appendix C, and the minor tasks were communicated through slack, posted in the robotics lab, and during meetings.

3.2. Team Organization

The team was organized into subteams based on interest and skill. The management structure is shown in Figure 20. Team members mostly worked within the subteams, the whole team met weekly to be informed about all aspects of the project. Team leadership would also meet weekly.

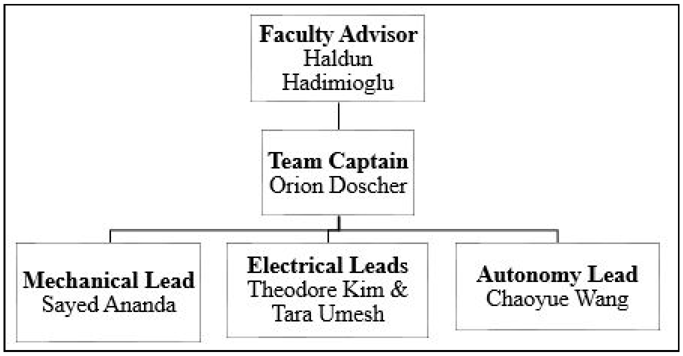

FIGURE 20: Team Leadership Organization Chart

3.3. Project Financials

The team was generously funded by the departments of the NYU Tandon School of Engineering from which the team members belong to. The Electrical and Computer Engineering (ECE) Department, Computer Science and Engineering Department, and the Mechanical Engineering Department funded the project. There was also a donation by Marc Haskelson of Compliancy Group towards the end of the project. The detailed budget is included in Appendix C, Table 1.

4. Conclusion

Using the systems engineering approach the team was able to develop ORBIT. There were challenges throughout the project, but the team persevered. The team expects the untested components and system to complete testing and meet the requirements in the coming weeks. The final test of the system will be at the 2018 Robotic Mining Competition in May 2018. The team expects to continue designing multidisciplinary robot systems, and will use the skills learned from the systems engineering process in future competitions, and projects.

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APPENDIX A: Trade Studies

Table 1: Decision Matrix for Multi-Rover System Implementation

Criteria	Weight	Two Rover System		One Rover System	
		Score	Total	Score	Total
Complexity	0.8	0.2	0.16	0.9	0.72
Weight	1	0.3	0.3	1	1
Cost	0.7	0.3	0.21	0.7	0.49
Efficiency	0.6	1	0.6	0.2	0.12
Manufacturing Time	0.7	0.5	0.35	0.6	0.42
TOTAL			**1.62**		**2.75**

Table 2: Decision Matrix for Drivetrain Mechanism Approach

Criteria	Weight	Belt Drive		Direct Drive		Rocker Bogie		Right angle oriented gearbox	
		Score	Total	Score	Total	Score	Total	Score	Total
Complexity	0.8	0.5	0.4	1	0.8	0.4	0.32	0.7	0.56
Size	1	0.5	0.5	0.3	0.3	0.5	0.5	1	1
Cost	0.5	0.7	0.35	1	0.5	0.5	0.25	0.5	0.25
Weight	0.8	0.5	0.4	1	0.8	0.5	0.4	0.5	0.4
Efficiency	0.5	0.8	0.4	1	0.5	0.5	0.25	0.5	0.25
Maneuverability	0.5	0.3	0.15	0.3	0.15	1	0.5	0.3	0.15
Dust Tolerance	1	0.1	0.1	0.5	0.5	1	1	1	1
TOTAL			**2.3**		**3.55**		**3.22**		**3.61**

Table 3: Decision Matrix for Excavation Mechanism Approach

Criteria	Weight	Drill		Expanding Wheel		Worm Belt		Planetary Wheel	
		Score	Total	Score	Total	Score	Total	Score	Total
Weight	1	0.8	0.8	0.6	0.6	0.2	0.2	0.4	0.4
Maneuverability	0.2	0.8	0.16	0.4	0.08	0.5	0.1	0.5	0.1
Stability	1	0.2	0.2	0.5	0.5	0.1	0.1	0.5	0.5
Versatility	0.5	0.6	0.3	0.3	0.15	0.1	0.05	0.5	0.25
Cost (time and money)	1	0.2	0.2	0.5	0.5	0.8	0.8	0.7	0.7
Electronic Accessibility	0.5	0.1	0.05	0.6	0.3	0.2	0.1	0.8	0.4
Power Consumption	0.5	0.5	0.25	0.5	0.25	0.1	0.05	0.5	0.25
Autonomous Integration	1	0.1	0.1	0.6	0.6	0.5	0.5	0.8	0.8
TOTAL			**2.06**		**2.98**		**1.9**		**3.4**

Table 4: Decision Matrix for Ground Station - System Operation Communication Protocol

Criteria	Weight	ROS integrated communication		TCP + raw protocol		UDP + compressed protocol		UDP + heartbeat + compressed protocol	
		Score	Total	Score	Total	Score	Total	Score	Total
Reliability	0.9	0.9	0.81	0.8	0.72	0.2	0.18	0.9	0.81
Bandwidth	0.8	0.2	0.16	0.3	0.24	0.9	0.72	0.8	0.64
Simplicity	0.6	0.4	0.24	0.7	0.42	0.4	0.24	0.3	0.18
Completion time	0.6	0.5	0.3	0.5	0.3	0.7	0.42	0.4	0.24
Versatility	0.4	0.8	0.32	0.2	0.08	0.7	0.28	0.7	0.28
TOTAL			**1.83**		**1.76**		**1.84**		**2.15**

Table 5: Decision Matrix for Autonomous System Operation Localization Approach

Criteria	Weight	Commercial LiDAR		Simple LiDAR		AprilTag	
		Score	Total	Score	Total	Score	Total
Reliability	0.9	1	0.9	0.6	0.54	0.8	0.72
Accuracy	0.9	1	0.9	0.6	0.54	0.8	0.72
Cost	0.8	0.1	0.08	0.3	0.24	0.7	0.56
Simplicity	0.7	0.3	0.21	0.3	0.21	0.8	0.56
Speed	0.6	0.7	0.42	0.4	0.24	0.6	0.36
Versatility	0.5	0.5	0.25	0.3	0.15	1	0.5
TOTAL			**2.76**		**1.92**		**3.42**

Table 6: Decision Matrix for Subsystem Operation Communication Protocol

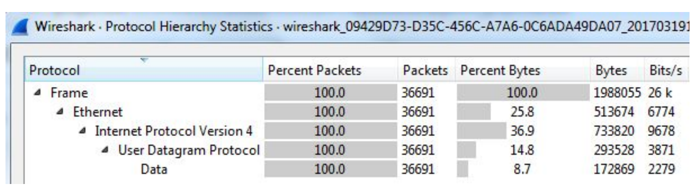
Criteria	Weight	PWM		CAN		UART	
		Score	Total	Score	Total	Score	Total
Signal Reliability	0.9	0.5	0.45	1	0.9	0.5	0.45
Documentation	0.6	0.8	0.48	0.5	0.3	0.8	0.48
Implementation Simplicity	0.4	0.5	0.2	1	0.4	0.3	0.12
Speed	0.2	0.8	0.16	0.4	0.08	0.6	0.12
Expandability	0.2	0.5	0.1	0.7	0.14	0.7	0.14
TOTAL			**1.39**		**1.82**		**1.31**

APPENDIX B: Testing and Verification Methodologies

Table 1: Regolith Simulant Composition by Mass

Material	Material Source	Mass Ratio	Mass Utilized
Portland Cement	Portland Type I-II Cement, Home Depot	5	1000 lbs
Metakoalin	Povier Pozz Metakoalin, Fishstone Concrete Supplies	3	600 lbs
Fine Play Sand	Quikrete Fine Play Sand, Home Depot	1	200 lbs
Decorative Gravel (icy regolith)	Sakrete All Purpose Gravel, Home Depot	8	1600 lbs

FIGURE 1: Staticide treatment testing on 6061 aluminum. Left: untreated, pre-regolith aluminum sheet, center: untreated aluminum after regolith exposure, right: treated aluminum after regolith exposure



Wireshark · Protocol Hierarchy Statistics · wireshark_09429D73-D35C-456C-A7A6-0C6ADA49DA07_20170319

Protocol	Percent Packets	Packets	Percent Bytes	Bytes	Bits/s
Frame	100.0	36691	100.0	1988055	26 k
Ethernet	100.0	36691	25.8	513674	6774
Internet Protocol Version 4	100.0	36691	36.9	733820	9678
User Datagram Protocol	100.0	36691	14.8	293528	3871
Data	100.0	36691	8.7	172869	2279

FIGURE 2: Control Subsystem - Ground System Operation Layer Application Protocol Bandwidth testing using Wireshark packet analysis

FIGURE 3: Control Subsystem - Autonomous Operation Layer - AprilTag Localization Testing

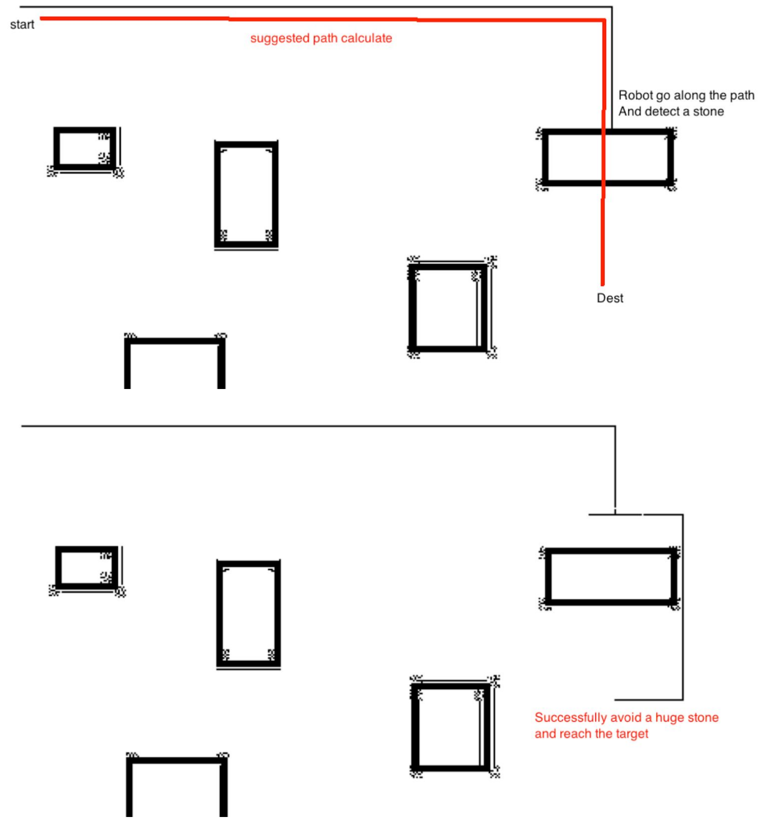


FIGURE 4: Control Subsystem - Autonomous Operation Layer - Path finding algorithm simulations

APPENDIX C: Project Budget and Schedule

Table 1: Project P&L Summary

RDT 2017-2018 Profit and Loss	
Income	
University Grants	$25,000
Corporate Sponsorships	$1,000
Private Donations	$1,000
Total Income	**$26,000**
Expenses	
Robot Systems	$11,234.16
Travel and Accomodations	$8,960.00
Community Outreach	$1,231.87
Shipping Costs*	$1,000.00
Lab Expenses**	$3,050.93
Total Expense	**$25,476.96**
Net Income	**$523.04**

*Anticipated Costs
** Includes Test Pit

Table 2: Robot Expense Summary

Robot Systems Cost		
Category		**Cost**
Mechanical	Chassis	$3,139.12
	Mining	$1,979.89
	Deposition	$430.94
	Subtotal	$5,549.95
Electrical	Control	$2,899.27
	Power	$665.15
	Enclosure	$690.40
	Subtotal	$4,254.82
Autonomy	Autonomous	$1,163.61
	Control	$265.78
	Subtotal	$1,429.39
Robot Total:		**$11,234.16**

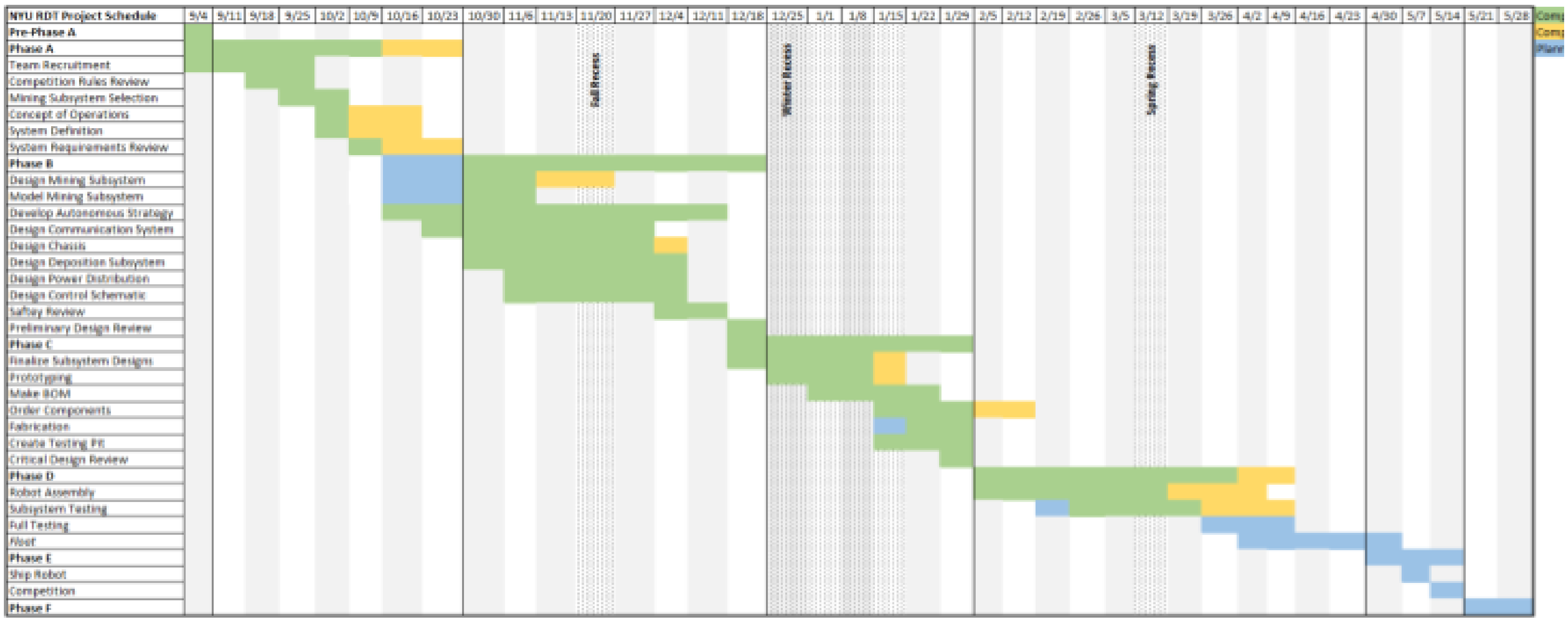


FIGURE 1: RDT Project Gantt Chart
