2021 – 2022 Systems Engineering Report

University of Arkansas - Fayetteville Razorbotz Team

Faculty Advisor

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I, Dr. Uche Wejinya, have read and reviewed this document prior to submission.

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Introduction

1.1- Purpose

Formerly the Mining Robotics Competition, the NASA Lunabotics Challenge was established in 2010 to engage college students in the field of robotics. The emphasis of the challenge is based on the upcoming Artemis moon mission planned by NASA to occur in 2024. The competition aims to challenge college students to work together to solve complex problems using the knowledge obtained through life experiences and the classroom. Furthermore, we have a responsibility to spread awareness and generate excitement with regards to space exploration, robotics, and STEM among K – 12 students.

1.2 - Objective

The University of Arkansas Razorbotz team had two overall objectives we worked to achieve through the 2021 – 2022 NASA Lunabotics Challenge. The first objective relates to working as a team to satisfy the requirements of the competition. We manufactured a mobile mining robot within a set of dimensional parameters that is capable of traversing the competitive arena to mine icy regolith simulant and deposit it within the allotted time limit. As a group, we aimed to foster a close-knit community comprised of multiple engineering disciplines and gain applicable experience that would allow us to become leaders in the future. Each sub-teams' individual objectives played a role in this success. The second objective is to facilitate the growth of the STEM field within our community. Through service events at local schools, we have spread awareness of the Artemis missions and generated interest in robotics amongst impressionable youth.

1.3 - Reason for Systems Engineering

The purpose of this systems engineering report is to provide a deliverable that showcases the processes undergone by our team to plan, design, manufacture, and test a functional and competitive lunar mining robot. Documenting goals, timelines, budgets, shortcomings, successes, and other parameters is important in both the short and long-term duration of the project. In the short term, it is important to have a model to follow in order to complete our prototype in a timely manner under our available budget and resources. In the long term, data gathered from previous iterations of the mining robots at the University of Arkansas allows us to make improvements on our design to satisfy the goals of the competition year after year.

1.4 - Subsystem Breakdown

The University of Arkansas Razorbotz team is composed of 5 sub-teams. The first sub-team is excavation, whose duty is to design, build, and test the regolith digging and collection system. The chassis team is responsible for the design and manufacturing of the frame and wheels of the robot. The computer systems team is tasked with programming the controls and autonomous operation of the robot. The electrical team is designated to handle the connections between the power supply and the individual motors. The writing team is responsible for documenting the progression of the robot and writing the technical reports required for the competition. While separate, all sub-teams work together to accomplish the teams' objective.

Project Management Merit

2.1 Design optimization Criteria

The newest iteration of the Razorbotz Lunabotics mining rover is designed to further improve upon the excavation and autonomy capabilities of its predecessors. Regarding the excavation process, we plan to optimize the speed and collection capacity of the system. The autonomous operation will be utilized as applicable for navigation across the competition arena and engagement of the excavation system. Implementation of these into design and operation will provide us with a competitive advantage through increased regolith collection and autonomous control point contributions.

2.2 - New/Updated design

The sub-teams and subsystems for this year's competition were consistent with the organization of last year's team. Subsystems were broken down between excavation, chassis, electrical, and computer systems. However, the design of this year's competition did have differences from last year's prototype. In terms of the emphasis of last year's robot, a system hierarchy of the mobility of the robot is provided below.

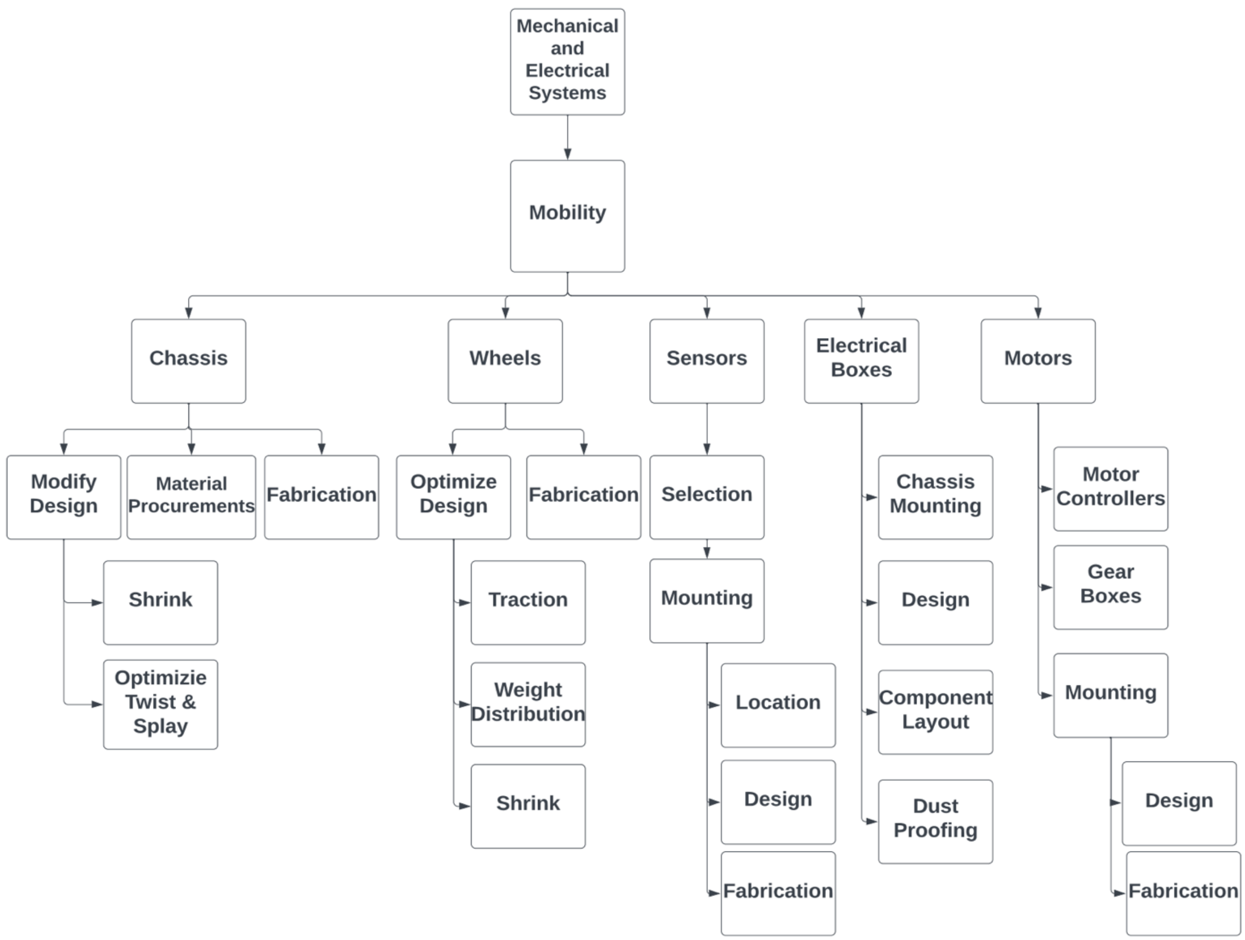

Figure 1: Mobility systems hierarchy of last year's robot.

Last year’s team focused on reducing the size of the robot due to competition requirements. Motors were used to power each of the wheels as well as two rectangular tubes made up the chassis frame. Beginning with the chassis subsystem for how this year’s design differed from last year’s prototype, a drivetrain was utilized to power the front wheels. Incorporating a drivetrain eliminated motors to be positioned towards the front of the robot. Instead, two motors were used to maneuver the robot opposed to last year’s design of using four motors. The reason this year's team decided to use a drivetrain was to improve the operability of the robot during the competition. Issues in past competitions of the robot struggling to traverse throughout the arena is the reason this year’s team decided to change the design of the chassis subsystem. This in turn would open more space for the excavation team to collect regolith as well as make it easier for computer systems team members to program and operate the robot. Therefore, programming the robot to move on command and autonomously for the competition certainly changed this year as well. In addition, the frame of the robot differed from last year’s design. Rather than using two rectangular tubes for the chassis subsystem, McMaster T-slot aluminum parts were used as connection tools for the robot. T-slot aluminum parts for the frame of the robot made the design process easier for each sub-team as parts could slide within the rails and be tightened by applying pressure. Although the weight substantially increased compared to last year’s design, the team decided that improving operability as well as making it easier to connect and move parts would be prioritized for this year’s design.

Lastly, the excavation sub-team decided to change the design of the robotic arm compared to last year. The previous Razorbotz team used both ends of the excavation arm to perform either digging or picking up regolith. One end of the robotic arm was composed of 3D printed blades capable of digging through the layer of BP-1. The other end was a metal bucket that could be used to dig up the exposed icy regolith simulant. However, this year’s Razorbotz team decided to use a bucket drum system with small holes to allow the mining robot to both collect regolith and filter out the BP-1 simultaneously. The change in excavation design was motivated by researching and observing previous successful Lunabotics robots that used a bucket drum for their excavation system.

To better visualize this year’s design, the final computer-aided design of the robot is shown below.

Figure 2: 1st view of finalized CAD model of this year’s robot.

Figure 3: 2nd view of finalized CAD model of this year's robot.

2.3 - Major Reviews

Systems Requirements Review - SRR

Formal meetings were conducted amongst members, team leads, project coordinators, and our advisor to progress through the product design process. With regards to the systems requirements review, each sub-team communicated to form a conceptual design that satisfied the constraints and goals of the competition. The initial concept was composed of a series of theoretical ideas and rough sketches that would be polished during the preliminary design phase using trade studies and computer design modeling. This phase was focused on macro-design with little attention to detail related to micro-design. The initial concept was then approved by the project coordinators and advisor to progress into the preliminary design phase. The allotted time set aside for macro-design was appropriate for generating an initial concept and put the team ahead of schedule moving forward into micro-design. No purchases were made during the systems requirements phase. As a result, the budget was not affected.

Preliminary Design Review - PDR

As part of the preliminary design review, detailed design was pursued. Trade studies were first conducted to make informed mechanical design and part selection decisions. Each sub-team made use of the trade studies to form a complete computer-aided design model of the rover. Conceptual functionality and interfaces at each hierarchical level were analyzed consistent with satisfying the engineering requirements and accomplishing the mission objective [1]. Concerns were raised due to the quantity of parts intended to be 3D printed and accessibility to 3D printers on the University of Arkansas campus. However, cost saving and available time in schedule to produce the parts made it justified. Communication between sub-teams was stressed by the advisor and project leads to ensure the limited space within the chassis frame was fully maximized to contain all excavation, electrical and computer system components. The preliminary design was approved by our advisor and project coordinators to proceed to critical design.

CDR - Critical Design Review

The critical design review phase analyzed the top-level prototype assembly. This includes the integration of individual components into separate subassemblies and the incorporation of each subassembly into a singular prototype assembly. This phase also involved the 3D printing of micro-level designs. Due to a significant number of 3D parts, delays in our schedule occurred while waiting for printed models. In addition, multiple iterations of the same 3D printed parts extended our schedule even further during the integration phase. To make up for this, groups began meeting 3-4 times a week to prevent from getting significantly behind schedule. With regards to changes in the budget, all sub-teams outside of excavation were within their proposed budget. Miscellaneous funds set aside during early budget planning allowed for the team to finance excavation's extra expenses. Approval within the critical design review proceeded forward with plans for component and system assembly, integration, and testing.

2.4 - Work Schedule

The project schedule was established early in the project life cycle utilizing a Gantt chart. The original schedule is shown below.

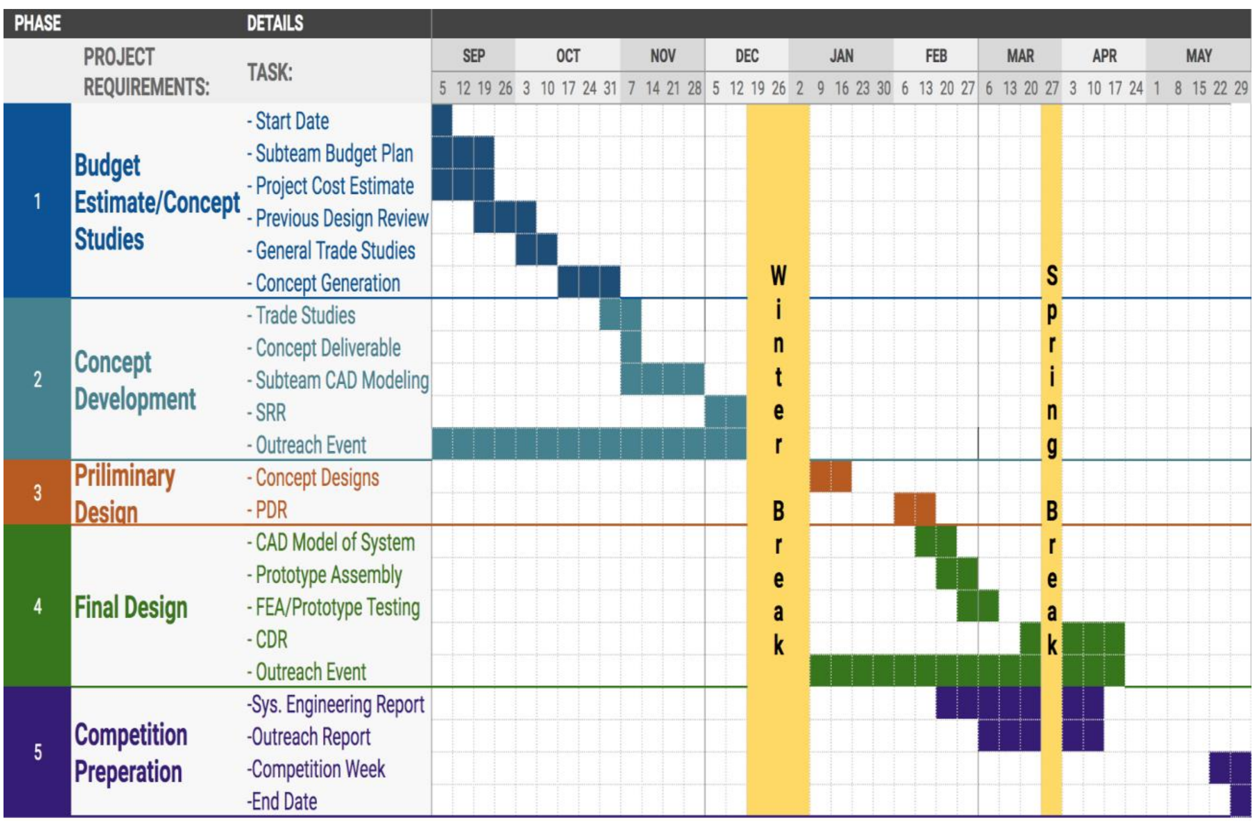

Figure 4: Original Project Schedule

For the duration of the project, sub-teams met 2 to 4 times a week with opportunities for additional meetings as applicable. Fridays were established as general meetings to provide project coordinators with sub-team progression updates. Saturdays served as designated build days. Meeting days stayed consistent throughout but weekly objectives for each sub-team evolved from the initial schedule. The finalized project schedule is shown below in Fig. 5.

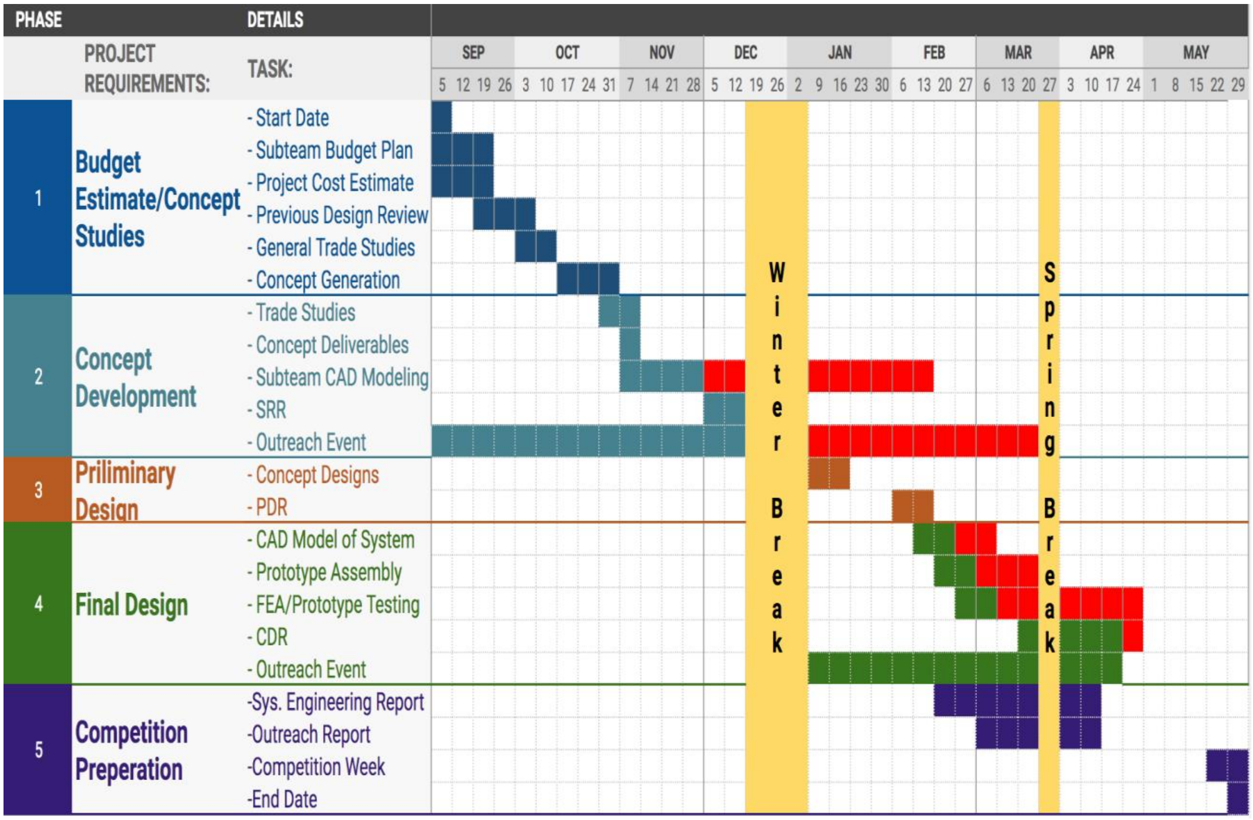

Figure 5: Final Project Schedule

The deadline extensions are shown in red. The state of the ongoing pandemic limited the outreach possibilities early in the project lifecycle. As a result, we had to push events to a later date extending into the Spring semester. Developing a full system CAD file took longer than expected which in turn extended the assembly of the prototype. Manufacturer shortages and purchasing parts with the wrong dimensions also contributed to the delay of the team's prototype. Such delays required groups to meet on a more frequent basis to complete the project.

2.5 - Cost Budget

The total project cost was estimated at $15,600. The cost estimate was divided by sub-teams in addition to allocations for travel and miscellaneous expenses.

Table 1: Initial Cost Budget

Project / Sub-Team	Initial Budget	Project / Sub-Team	Initial Budget	Project / Sub-Team	Initial Budget
Chassis Expenses	$900	Electrical Expenses	$1,500	Testing Expenses	$700

Excavation Expenses	$1,000	Computer Systems Expenses (Autonomy)	$2,000	Miscellaneous Expenses	$500
Travel Expenses	$9,000	**Total Project Cost Estimate**		**$15,600**	

An excel spreadsheet was created to track the spending of each sub-team. The leaders would request parts/equipment to order and provide details to links of the products. The items would then be approved by the budget personnel hierarchy based on the necessity and cost. In cases of disapproval, meetings were set to suggest alternative solutions. Part orders were placed weekly at noon on Saturdays.

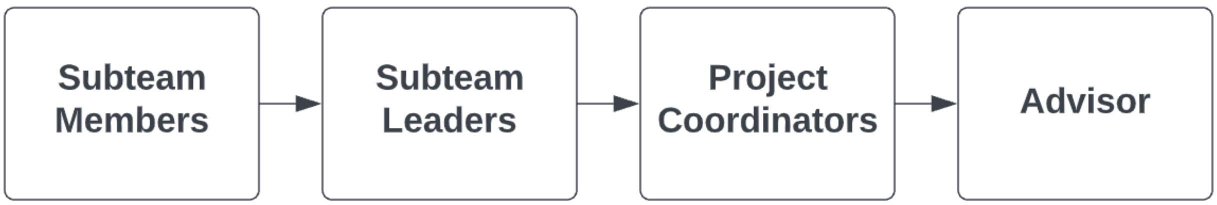

Figure 6: Budget Personnel Hierarchy

Table 2: Final Cost Budget

Sub-team	Initial Budget	Total Spent	Remaining Budget
Chassis	$900.00	$575.36	$324.64
Excavation	$1,000.00	$1,346.46	-$346.46
Electrical	$1,500.00	$1,214.36	$285.64
Computer Science	$2,000.00	$815.93	$1,184.07
Testing	$700.00	$0.00	$700.00
Misc Other	$500.00	$42.50	$457.50
Travel Expenses	$9,000.00	$9,000.00	$0.00
Total	**$15,600.00**	**$12,994.61**	**$2,605.39**

The final cost budget displayed above shows the finalized expense breakdown by sub-team. As it stands, the excavation team is the only sub-team currently over their allocated budget. Fortunately, over $2,500 was remaining for the team's budget with the assumption that travel expenses would be used in its entirety. Therefore, the excavation team exceeding their initial budget expectation was not an issue.

Systems Engineering Merit

3.1 - Concept of Operations

To operate the robot throughout the competition, the robot was divided into mechanical and electrical systems to achieve functionality. The electrical systems division was composed of the computer systems and electrical engineering sub-teams. The electrical team provided power to the system as well as made it feasible to operate the robot by utilizing circuit boards, batteries, and wires. The hardware of the robot was housed inside two boxes to protect the system's circuits from any foreign object debris. Computer systems made it feasible to communicate to the robot so that collection of regolith and direction of travel could be controlled. Although a few features of the robot were programmed to make autonomous decisions, the majority of operating the robot was scripted to be teleoperated. The purpose of splitting control of the robot between teleoperation and autonomy was to achieve extra mining points while still being confident of completing the competition.

The mechanical systems division was formed by the excavation and chassis sub-teams. The chassis team focused on how the robot would traverse throughout the competition arena using wheels, motors, and a drive train. In addition, the chassis sub-team was responsible for designing a frame that was durable and could have several features attached such as the wheel assembly, excavation arm, and electrical engineering boxes. Collecting and dispensing regolith was the excavation team's responsibility. How the entire system would operate is shown below [2].

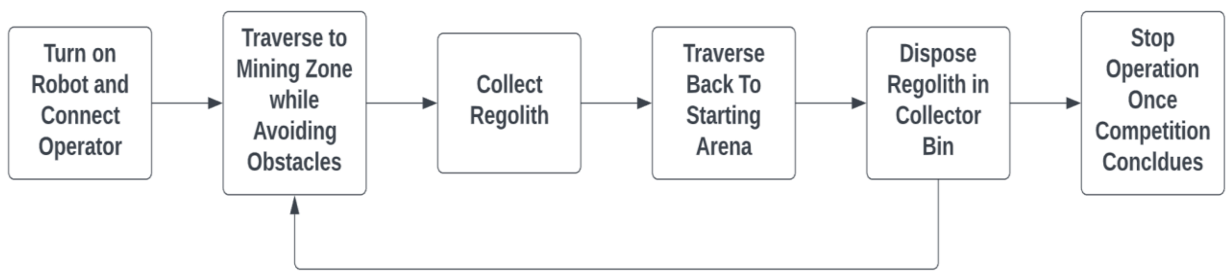

Figure 7: Concept of Operations

A major focus for this year's competition was to have an effective excavation subsystem that collects and dispenses regolith throughout the duration of the competition. The arm of the excavation subsystem had the capability to traverse above and below the robot's chassis by using a linear actuator, aluminum tubes, and two Falcon 500 motors. Once the arm is below the frame of the robot with the bucket drum touching the floor of the arena, the bucket drum assembly (powered by two other Falcon 500 motors) spins within the regolith and collects deposits from the arena. Holes are displaced throughout the outer layer of the bucket drum so that only the icey regolith is collected. It is important to note that the figure below does not provide the metal rims that will be attached to the edges of each bucket drum. The reason metal rims will be placed towards the edges of each bucket drum is so that the metal is initially contacting the regolith. The bucket drum is a 3D printed part made from ABS filament which could be damaged as the bucket drum spins and collects regolith. Therefore, metal rims on the edges of the bucket drum will prevent cracks that could occur to the plastic drum.

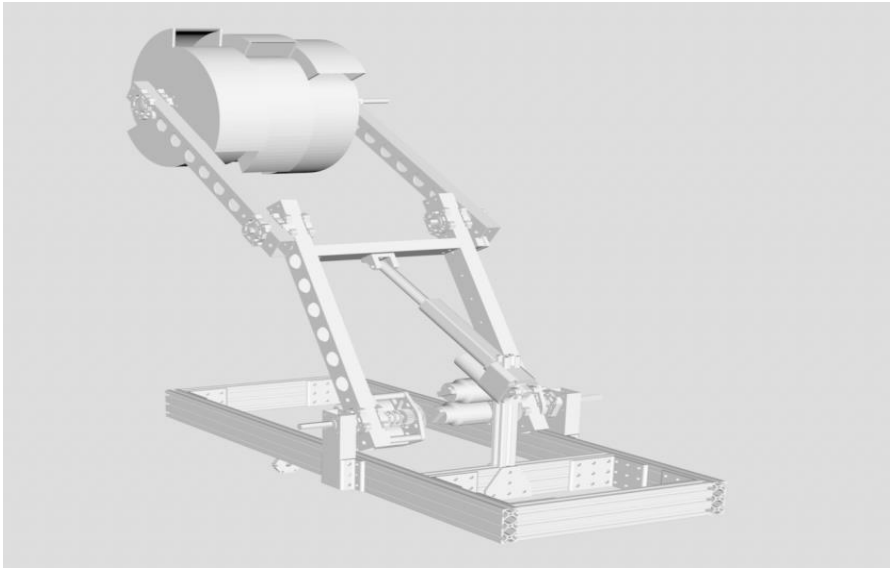

Figure 8: Assembly of Excavation Subsystem

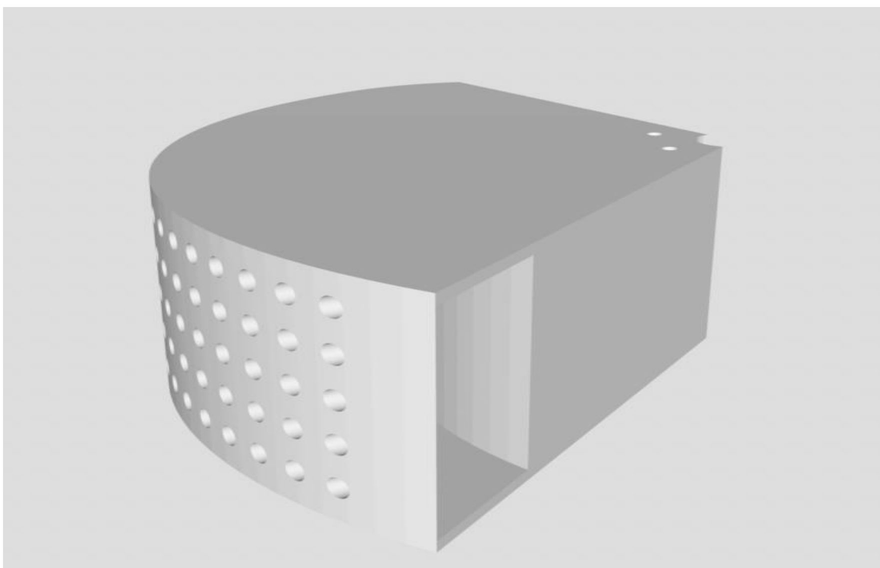

Figure 9: View of an Individual Bucket-Drum Component

A secondary focus for the team was further developing the software used for the robot. In the past, the software has been thrown together to facilitate the movement of the robot, while ignoring good practices of software development. To ensure that future teams would have an easier time starting the project, the computer systems team implemented a version control system, enacted documentation standards for all files in the system, and refactored old versions of the code to bring them up to standard. The system was designed to navigate autonomously using a stereo camera mounted on the front of the robot, while streaming video back to the client. Input from the driver would be prioritized, allowing the driver to override the autonomy program and manually control the robot if anything malfunctioned.

3.2 - System Hierarchy

The system hierarchy corresponding to the Razorbotz mining rover is shown below. The complete robot can be broken down into a series of mechanical and electrical subsystems each corresponding to a specialized group within the Razorbotz team. Chassis team is responsible for the frame, wheels, and gearbox. Excavation team must determine the design for the arms and bucket-drum. Electrical must form the electrical and battery boxes and facilitate the connections. Computer systems are responsible for autonomy and teleoperation user controls. Throughout the development process, the system hierarchy became more detailed and complex. Within each sub-team, individual responsibilities were given to team members to create or obtain certain parts and manufacture multiple levels of assemblies. Beginning with the systems requirements review, high level design was initiated with the forming of the high-level system architecture. Moving forward into preliminary design, the focus was to begin the process of micro-level, detailed design. Individual parts comprised within a particular assembly or subsystem were planned and designed during the preliminary design phase. The critical design phase is where the complete top-level design was compiled to display a finished virtual prototype.

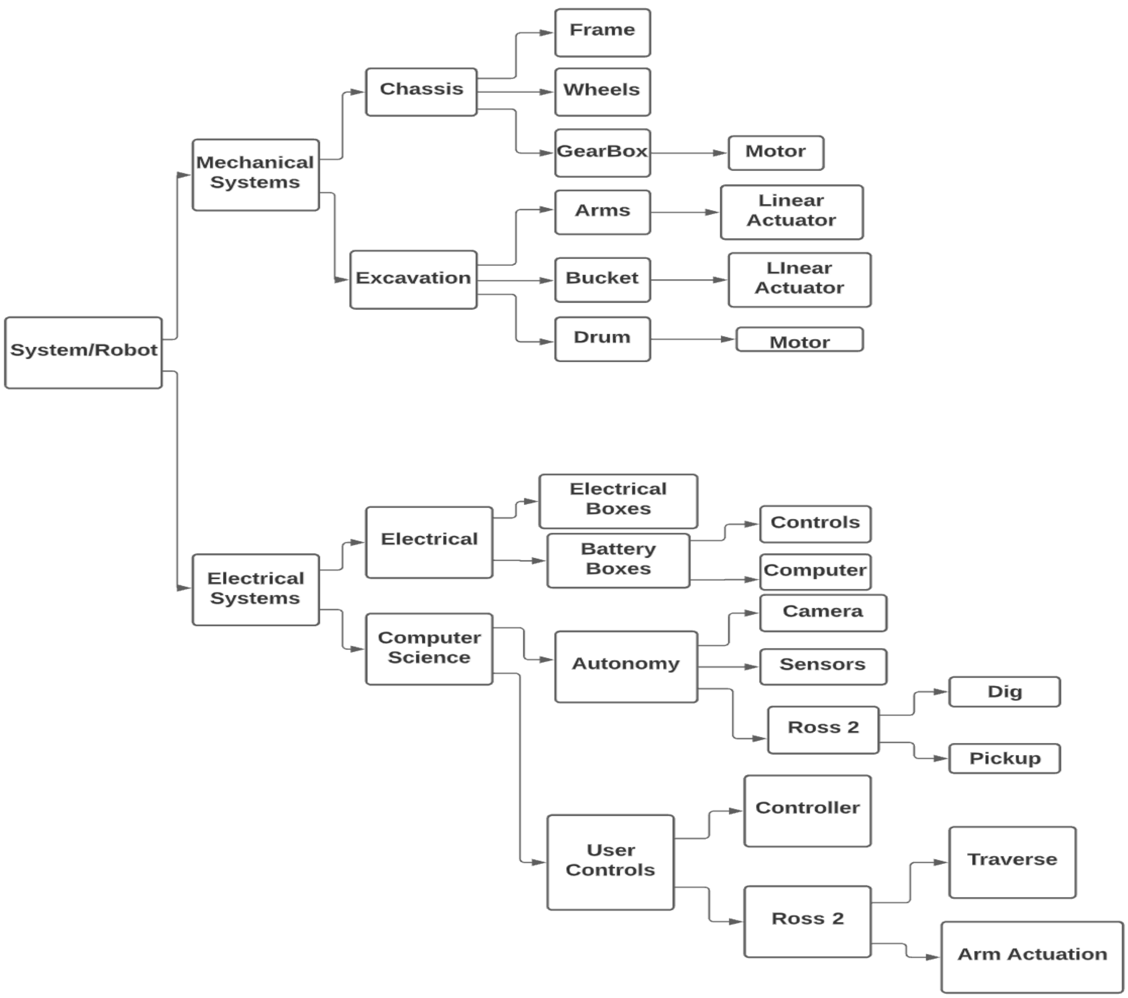

Figure 10: System Hierarchy [3]

3.3 - Interfaces

Below depicts a N squared chart that illustrates the inputs and outputs from each function that contribute to the system completing its mission [4]. The most common input that will initiate the robot's course of action is the teleoperator utilizing ROS 2 to control the system. Making sure each function fulfilled its purpose was beneficial during the design phase of the system because members were goal orientated while developing the robot. By organizing chronologically, the individual tasks the robot will perform, members of the Razorbotz team had to ensure while designing the system that the robot could fulfill its functions and operation.

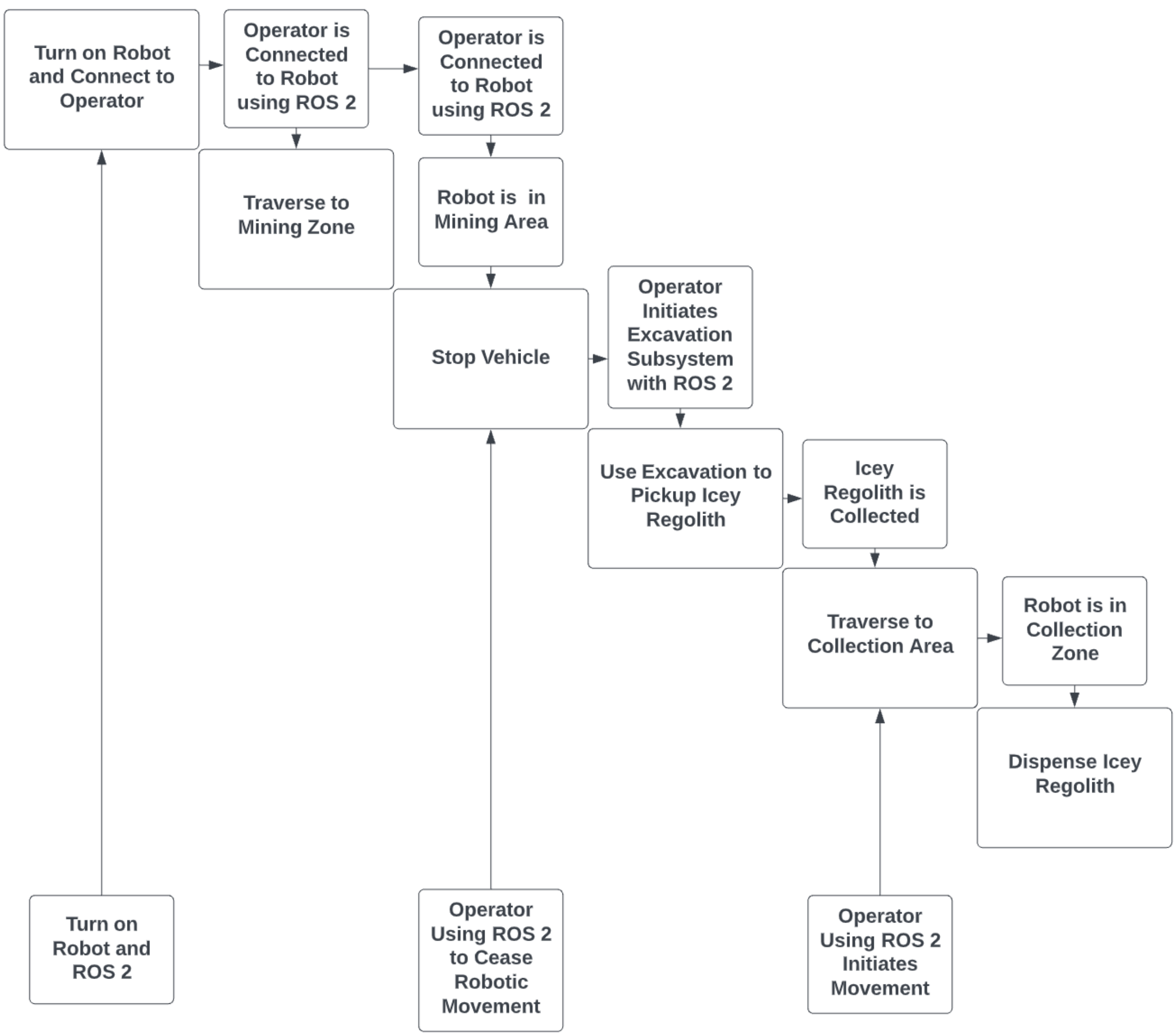

Figure 11: N squared chart describing system interfaces.

The combination of developing a systems hierarchy and N squared interfaces chart was helpful in breaking down the design phase of the robot and making sure each subassembly would complete its function and contribute to the successful operation of the robot.

3.4 - Requirements

The requirements implemented by the Razorbotz team were a culmination of NASA mission requirements as well as goals developed by the Razorbotz team. To be within the bounds of NASA's competition rules, the requirements below were strictly followed.

Table 3: Requirements enforced by the NASA Lunabotics Challenge [5].

Baseline Requirements
The dimensions of the robot shall be a maximum of 1.1 m length x 0.6 m width x 0.6 m height.
The maximum weight of the robot shall be 80 kg.
A kill switch shall be on the robot that is easily accessible for users to press.
The robot shall use its own onboard power without any auxiliary or facility power.
The robot shall not operate any actions that would be physically impossible on any off-world mission.
The Razorbotz shall submit all forms and papers in a timely manner before deadlines enforced by NASA expire.

Table 3 provides the baseline requirements that were followed by the Razorbotz team so that the option to compete would be possible. In addition, the Razorbotz created their own set of standards so that each sub-system would function as intended.

Table 4: Requirements developed by the Razorbotz for operation of the robot.

Requirements for Operation of Robot
The computer science subsystem shall program the robot to be teleoperated during competition with a few autonomous features to improve the efficiency of the robot.
The chassis subsystem shall be responsible for the robot's capability of traversing throughout the mining zone during competition time. Wheels, motors, and a drive train shall be connected with one another to provide the ability for the robot to move.
The excavation subsystem of the robot shall have the ability to sufficiently collect and dispense regolith during competition time.
The electrical subsystem shall connect each subsystem together using wires, batteries, and circuit boards. Power and operability of the robot shall be made possible because of the electrical subsystem's assembly of electrical boxes on the robot.

3.5 - Technical Performance Measurement

Technical performance measures were formed from a set of engineering requirements established early in the product lifecycle and geared towards achieving individual design optimization criteria. The two main optimization goals for our newest edition Lunabotics rover have been placed on maximizing autonomous navigation with the ability for teleoperation as necessary, and a more effective excavation system in both speed and carry capacity. Technical performance measures align directly with our optimization goals as well as maintain the necessary specifications which allow us to compete. Such technical performance measures include physical constraints such as size and weight established for the competition, arena navigation, and regolith excavation and collection. All the performance measures are described in Table 5 below. Each measure is interdisciplinary and involves input and analysis by multiple sub-teams to verify. Progressing review documentation such as the systems requirements, preliminary design, and critical design, documented changes in the design and verified our ability to accomplish and measure the technical performances. Scheduling and budgeting an allotted amount of time and resources towards different measuring methods such as technical reports, virtual models, and physical prototypes served as a proof of concept that the desired technical performance measures could be achieved. The volume and weight constraint were one such technical performance measure which we constantly had to look back on throughout the design process. It was a limiting factor with which each sub-team needed to work from. Beginning with the chassis team, they set the physical length and width of the robot based upon the size of the frame and wheelbase. From there, the excavation, electrical and computer system sub-teams had to communicate to fit all their necessary components within the robot base. A percentage of the weight of the robot was allocated amongst each sub-teams based on material weight estimates. 40% of the total weight was set aside for both chassis and excavation sub-teams with the other 20% percent split between electrical and computer system sub-teams. Much of the verification process was accomplished utilizing virtual solid modeling software. A complete computer-aided design model was formed prior to prototype construction. Further weight verification would be done by tracking the weight of assemblies and subassemblies as they were put together to form the complete robot. Once the prototype was constructed, physical testing in our custom arena would serve as the measuring method for navigation and excavation. In the instance of a technical performance measure not reaching the desired target, assistance would be provided by other sub-teams to fulfill the requirement and remain in the competition. Similarly, sub-teams ahead of schedule are encouraged to communicate with other sub-teams and aid in pressing tasks as applicable.

Table 5: Requirements developed by the Razorbotz for operation of the robot.

Technical Performance Measures	System Hierarchy	Measurement Method	Measurement Time
Full Robot Must Fit Within Starting Volume (.6m x .6m x 1.1m)	Chassis	CAD model of the full robot must fit within volume representation	Mobility & Excavation Critical Design Reviews
	Excavation	Physical Measurement	During & After Fabrication
Full Robot Weight Cannot Exceed 80 kg	Excavation	CAD Model Analysis	Excavation Critical Design Review

	Chassis	Material & Component Weight Calculation	Before Beginning Fabrication
	Computer Systems	Physical Measurement	During & After Fabrication
Navigate Obstacle Field in 1 Minute and 30 Seconds or Less	Computer Systems	Test run using a simulated environment and robot model	During and After Navigation Software Programing
		Testing the robot physical system response through a simulated environment	Pre and Post Fabrication
Mine 32 cm of Regolith in 2 Minutes or Less	Excavation	Physical testing	Excavation Design Selection
	Testing		Excavation Critical Design Review
	Computer Systems	Simulation Testing	During and After Excavation Software Programming
Collect 1kg of Icy Regolith (Minimum) in 2 minutes	Excavation	Physical testing	Excavation Design Selection
			Excavation Critical Design Review
	Computer Systems	Simulation Testing	During and After Excavation Software Programming
Deposit Icy Regolith in Collection Area in 30 Seconds or Less	Computer Systems	Simulation Testing	During and After Dumping Software Programming
	Excavation	Physical Testing	After Fabrication
Design Review	Full team	Physical Measurement	Before Fabrication

3.6 - Trade Studies

Razorbotz' first major decision over the construction of this year's robot was regarding the chassis design. The excavation team initially proposed to the rest of the robotics team to use 2"x1" tubing for the frame of the robot and use slotted extrusion for the cross braces to make electronic and excavation subsystem mounting easier. The purpose of using a thinner frame was so that the robot would be lighter weight and in turn, move quicker during competition. In addition, using slotted extrusion would make mounting the excavation arm and motors much easier. Ultimately, the design concept sponsored by the excavation team would allow for a better design of the excavation arm with a better mounting area and could lead to the Razorbotz becoming much more competitive during the robotics competition. However, the team leader for the chassis team rebuked the design concept because the modularity of the robot would decline. Making any adaptations requested by NASA during the school year much harder to approach. The team leader for the chassis team introduced a design concept that showed a thicker frame with an additional aluminum tube that will cover the drive chain. The major difference between the first and second design concepts is the weight of the robot. With an additional aluminum tube proposed by the chassis team leader, the weight of the robot would be much heavier than the first concept. Because of this, the robot will most likely drive slower during competition. However, the increase in modularity from the chassis leader's design concept would make the robot more adaptable to adjustments from NASA. Furthermore, designing the robot would become much easier for each sub-team with modularity as a priority.

With two conceptual designs of the frame of the robot, Razorbotz held a team vote to decide which frame design to pursue. Both leaders of the excavation and chassis team created rough models of each design concept on Fusion 360 and listed the pros and cons to the rest of the team. A week of thought was given to all Razorbotz team members before the official vote was cast. The table below was a useful tool when choosing the optimal design concept by using several criteria to prioritize the functions of the robot. The second design idea regarding a thick frame and aluminum tube above the wheels won by popular vote.

Table 6: Evaluation Criteria Results for Chassis Design

Evaluation Criteria	Platform In-Line with Wheels	Platform Above Wheels
Scoring Criteria (1 = Least Desirable, 5 = Most Desirable)		
Adaptability	2	5
Reliability	4	4
Maintenance	2	5
Sturdiness	4	4
Weight	5	3
Total	17	21

In addition, a major trade study that occurred was the excavation team deciding which concept design to pursue for their arm system. The excavation team was dissatisfied by the execution of the previous auger excavation system that was implemented by the 2019-2020 Razorbotz Team. As a result, they desired a complete redesign beginning a concept generation phase in early September. They drew inspiration from the rotating drum design implemented by the University of Arkansas 2017-2018 Lunabotics team. The drum is capable of sifting through the layer of BP-1 to collect the gravel below which acts as the icy regolith simulant. Several design concepts were generated utilizing the rotating drum as the primary excavation tool. Some designs implemented single or two bar arms with incorporated linear actuators to control the movement of the system remotely. With regards to the single bar design, issues arose related to the strength and the mobility of the arms strictly limiting access for the drum to reach the desired depth. A two-bar arm was then discussed which would allow the robot to achieve the desired depth.

Table 7: Evaluation Criteria Results for Excavation Design

Evaluation Criteria	Single Bar Arm	Double Bar Arm
Scoring Criteria (1 = Least Desirable, 5 = Most Desirable)		
Durability	2	5
Mobility	3	4
Speed	3	3
Reliability	2	3
Performance	4	5
Total	14	20

Through a series of team meetings and group discussions amongst team members, project coordinators, and our advisor, it was decided to take the initial design concept to a sub-team vote. Members using the evaluation criteria to base their judgment was beneficial to choosing the excavation design. The excavation sub-team concluded that a two-bar system would allow for appropriate access to the regolith and that a two-connected drum design would be adequate for the collection process while adhering to the size constraints set by the competition and resulting chassis.

3.7 - Reliability

To ensure the robotic system operates in a safe manner, the Razorbotz team divided what each main engineering specialty was, related to developing the robot, and possible failures that could occur with each subsystem. As stated earlier, the engineering specialties were broken down between electrical, computer systems, excavation, and chassis sub-teams. Each subsystem has a pivotal impact on ensuring that the overall system could function as planned. Therefore, all four subsystems were responsible for not only designing a section of the robot, but also predicting potential failures that could occur with their subsystem during the competition. The reason for predicting possible failures for each subsystem was to be ready to safely troubleshoot the robot during competition and make sure that dangers from any malfunction of the robot could be safely addressed by the Razorbotz team.

A risk analysis chart was used to quantify the most impactful issues that could occur between each engineering specialty [6]. Units were allocated from 2 being a low risk of severity and likelihood to 9 being very dangerous. Quantifying and applying the severity and likelihood of a major issue that could occur among each subsystem prepared the Razorbotz team to develop a reliable structure and mitigate any problems during competition. A list of each potential problem with each subsystem is listed below.

Table 8: Evaluation Criteria Results for Chassis Design

	SEVERITY		
LIKELIHOOD	LOW (1)	MEDIUM (2)	HIGH (3)
LOW (1)		FAILURE WITH ELECTRIC BOARDS	FAILURE TO TELEOPERATE THE ROBOT
MEDIUM (2)		MALFUNCTION OF ROBOT'S WHEELS	ISSUE WITH COLLECTING REGOLITH
HIGH (3)			

1. Starting with the chassis subsystem, the sub-team decided that the most probable issue that could occur is failure of the robot to move throughout the arena. Malfunction of the wheels resulted with a score of 4. To prevent any issue related to failure to move the robot during competition, the Razorbotz team purchased two brushless motors that could provide more than enough power during operation. Each motor has the capability to provide 406 Watts of power and a free speed of 5676 rotations per minute. Just in case motors provided too much power and incited any danger during competition, the computer systems team programmed to teleoperate parts of the robot. Thus, shutting down the system if its movement can't be controlled.
2. Problems with collecting regolith from the excavation's subsystem resulted with 5 units. The severity from failure of the excavation system was in the high region since the focus of the Lunabotics Challenge is to collect and transport regolith. However, the likelihood of the buckets to fail to collect regolith prevented this issue from receiving a 9 score. Concept, design, and integration of the excavation subsystem has led the team to become confident in the robot's ability to collect the required items during competition. 3D printers were used to enlarge the bucket and drum parts so that a relatively large quantity of regolith could be collected at once. Like the chassis subsystem, the excavation team made sure to utilize motors that could provide more than enough power to the bucket and drums. In addition, if the arm of the excavation system had to be lowered, linear actuators were integrated to extend and contract the arm subsystem. Teleoperation of the excavation system ensured that movement of the buckets and drums could be shut down if its motion incited any danger during competition.
3. The computer systems team discussed that the major issue that could affect their subsystem is failure to teleoperate the robot. Although issues with teleoperating the robot would result

in a highly severe consequence, the probability of such an issue is relatively low. Fortunately, the computer systems sub-team is composed of experienced mechanical and computer engineers who have been involved with the team for more than a year. The programs used to teleoperate the system have been relied on for the past several years: ROS 2, C++, and Python. A kill switch and teleoperated program is implemented to shut down the system if lack of control of the robot causes any danger during competition.

4. A problem that could arise from the electrical subsystem is failure from circuit boards and wires. For safety measures and to eliminate foreign object debris, the devices associated with the electrical sub-team were all stored in two 3D printed, rectangular cases. Cases were made to mitigate any safety issue that could occur from a circuit failure.

3.8 - Verification of system meeting requirements

The baseline requirements were verified in the same area the prototype was constructed. A designated room in the mechanical engineering building at the University of Arkansas allowed for team meetings to occur among the Razorbotz team and for each sub-team to build in the same area. Once the prototype was assembled, the requirements enforced by NASA were verified using a tape measure and scale. Regarding the mechanical subsystems of the robot, movement of the wheels and excavation arm were also tested in the same room the prototype was assembled. Basic motion from the excavation subsystem and wheel assembly were verified so that the Razorbotz team was at least assured the robot has the capability to move. Before physical testing, connections among assemblies on the chassis frame were verified to ensure parts would not abruptly disconnect. Parts and assemblies attached to the system's frame consisted of front and back wheel gear boxes, L brackets connecting frame, both electrical boxes, and the excavation base. Physical testing of the robot was operated in a room located at the engineering research center at the University of Arkansas. The testing room is set up to simulate the environment of the competition arena. Sand was distributed among the room and operation of the robot was pivotal to verify that the electrical and mechanical systems were able to achieve its function. The purpose for testing the robot in a simulated environment was to make sure the system achieved functionality and to locate sources of error among subsystems.

Figure 12: Image of simulated environment to test the robot's functionality.

Appendix

4.1 - Appendix A: Original Work Schedule

Activity/Goal/Description	Original Start Date	Original Deadline	Updated Start Date	Updated Deadline
Start Date	8/25/21	8/25/21	N/A	N/A
Community Outreach Event	9/1/21	12/12/21	1/18/22	4/1/22
Budget Estimate	9/22/21	9/27/21	N/A	N/A
Project Management Plan	9/28/21	10/6/21	N/A	N/A
December Budget Update	10/01/21	10/05/21	N/A	N/A
Concept Generation	10/15/21	10/25/21	N/A	N/A
Solid Modeling	10/26/21	11/25/21	N/A	N/A
December Budget Update	12/1/21	12/6/21	N/A	N/A
System Requirements Review	12/1/21	12/6/21	N/A	N/A
Community Outreach Event	1/18/22	4/20/21	N/A	N/A
Preliminary Design Review	1/23/22	2/2/22	N/A	N/A
February Budget Update	2/1/22	2/2/10/22	N/A	N/A
Finalized CAD Drawing	2/14/22	2/24/22	2/14/22	3/14/22
Fabrication	2/25/22	3/7/22	1/18/22	4/3/22
FEA/Prototype Testing	3/8/22	3/18/22	4/4/22	4/22/22
Critical Design Review	3/19/22	3/29/22	N/A	N/A
Systems Engineering Report	2/3/22	4/10/22	N/A	N/A
System Engineering Report Deadline	4/11/22	4/11/22	N/A	N/A
Outreach Report	2/13/22	4/12/22	N/A	N/A
Outreach Report Deadline	4/13/22	4/13/22	N/A	N/A
Proof of Life	4/28/22	4/28/22	N/A	N/A

April Budget Update	4/1/22	4/7/22	N/A	N/A
Competition	5/23/22	5/27/21	N/A	N/A
Completion Date	5/28/21	5/28/21	N/A	N/A

Table 9: Simplified table of the team's original Gantt chart, used for the sake of brevity.

4.2 - Appendix B: References

[1] "Systems Engineering for University-level Engineering Projects and Competitions". 2021. NASA: Kennedy Space Center. <https://www.nasa.gov/content/systems-engineering-for-university-level-engineering-projects-and-competitions>

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