# 2020-2021 Systems Engineering Report


University of Arkansas - Fayetteville

Razorbotz

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# 1 - INTRODUCTION

## 1.1 - Purpose

The annual Lunabotics Competition was established by NASA in 2010. It was formerly known as the Robotic Mining Competition. NASA created this competition in order to challenge college students to design and build robots that can perform various tasks on the Moon's surface. A large emphasis of the project was placed on the Artemis Mission that NASA has planned, the purpose of which is to have another Moon landing by 2024. Additionally, this competition seeks to increase the awareness and excitement of space, robotics, and STEM fields by reaching out to elementary, middle, and high school students.

## 1.2 - Objective

The primary objective of the University of Arkansas Razorbotz team was to design a functional, fully modular robot that was able to maneuver on the arena terrain, collect the maximum amount of icy regolith within the time limit, and operate autonomously. Secondary objectives included gaining experience with efficient hardware design and software-architecture planning, learning the processes involved in using the Systems Engineering method, and obtaining valuable engineering skills for future careers.

## 1.3 - Reason for Using Systems Engineering

Systems engineering is generally known as the interdisciplinary field that incorporates engineering with management by focusing on the complex system of an engineering endeavor. The more layman definition we use at the University of Arkansas is that it is the leadership-oriented side of engineering. The most important aspect of systems engineering that was used by the team was the planning aspect of systems engineering. A lot of work was put in on the front end by the team leaders to ensure that the teammates under their command knew the project timeline for their specific part within the project. The main benefit this provided to the team was a clear understanding of the project timeline, and an unexpected benefit was a better understanding of how other sub-teams within the project connected and relied upon one another.

## 1.4 - Sub-System Breakdown

Five separate sub-teams come together to form the Arkansas Razorbotz team. The first sub-team is Excavation, whose purpose was to focus on the system that collects the gravel/regolith mixture, and be able to separate it. The second sub-team is the Chassis team, whose mission was to improve upon the chassis in terms of strength and weight. The third sub-team is Computer Systems, whose mission was to create the code needed to give the robot autonomy. The fourth sub-team is Electrical, whose mission was to ensure that the electrical system within the robot worked properly. The last sub-team is Testing, whose mission was to create a testing environment similar to the one NASA provides for the competition, and test the robot's capabilities.

## 2 - DESIGN INFORMATION

### 2.1 - Optimization

The Arkansas Razorbotz team focused on three parts to optimize: rate of collection, mobility, and autonomy. There were plenty of reasons for why the team decided to optimize these three things. Concerning the first component the team wanted to optimize, the rate of collection was very slow when competing in the NASA robotic competition two years ago. The robot used a scoop system, and was able to only get one scoop in before returning to the dropoff point. Due to the obvious inefficiency in this process, the team wanted to optimize the rate of collection.

The second component the Razorbotz team planned to optimize was mobility. In the competition two years ago, the robot moved at a fairly slow pace. While this is one component of the robot that the team wanted to improve, it is not what the team wanted to optimize for this year's competition. The team wanted to optimize the speed at which the different components within the robot move. Examples of this include how quickly the robot can deploy and retract its auger, and also how quickly the robot can deposit the gravel/regolith mixture at the drop-off site.

The third component that the Razorbotz team planned to optimize was autonomy. Autonomy was uncharted territory for the Razorbotz team. While it had been planned for the previous iteration of the robot, it was never included in the design due to time crunches. There are a lot of things that have to go correctly in order for the robot to function properly with full autonomy, so the team wanted to optimize the robot by including as much autonomy within it as possible.

### 2.2 - Design of Robot

The robot system used by the Razorbotz team is an entirely new design. The team arrived at this decision quickly due to one main reason. The reason was that the robot of two years ago performed poorly during its competition, and last year's robot, which was the same design, performed poorly during testing. As mentioned beforehand, the first thing the team changed was the scoop.

The following is how the scoop system worked. The arm holding the scoop would become vertical, then the scoop would extend down to make contact with the ground. Once the scoop was in contact with the ground, the scoop would curve inward to collect the regolith/gravel mixture. The arm holding the scoop would then be brought backwards onto a sifter, where the regolith would fall below and the gravel would remain. This gravel was then dropped in a box and delivered to the competition dropoff point. This was deemed as an inherently slow method because the scoop could only gather one set of the regolith/gravel mixture, and then had to be used in order to transport the mixture to the sifter. Therefore, with the creation of the new robot, the team decided to use an auger system in order to collect the regolith/gravel mixture. This auger system included an auger bit as well as a slide that used gravity in order to feed the mixture into the sifter. There are two clear benefits to using this system to collect the mixture. The auger bit was designed to be in continuous use, so instead of having a scoop perform one long action to collect one set of the regolith/gravel mixture, the auger bit can continuously bring up the mixture while reaching further into the ground of the competition floor. While this is a direct upgrade with regards to the rate of collection, another added benefit of this system is that the process for collecting the mixture and transporting it to the sifter was designed to occur at the same time. Instead of having a two-step process where the scoop has to perform two separate actions, each part of the auger system can perform a one step action that continuously occurs. This was the first major improvement in the design.

The second major change in design was the chassis of the robot. The team concluded that this needed to change due to two main reasons. The first reason was that the new auger system necessitated a different structure in order to appropriately use said auger system. The second reason was due to the rule changes implemented for this year's competition. In order to meet these new requirements, the chassis of the new robot needed to be smaller. The main way in which the team sought to achieve this goal was to move the gearbox to the inside of the chassis, whereas for the previous robot it had been on the outside of the chassis.

The last major change to the new robot over the previous robot was to make the new robot autonomous. The team wanted to focus on adding autonomy to the new robot for two reasons. Firstly, there was the simple fact that extra points are added for having autonomy within the robot. While this was certainly an extra motivator, the main reason was that autonomy would drastically increase the efficiency of the robot. This goal was not to be realized in one year, as autonomy is a large undertaking considering that this would be the first year attempting to incorporate autonomy into the robotic system of operations. The goal for this semester was to automate the excavation process. By learning the lessons of automation and the difficulties that come with it, the team planned to put the future of the Razorbotz team in a very good spot moving forward.

### 2.3 - Major Reviews

The process for reviews changed dramatically for the Razorbotz team when compared to previous years. The ongoing COVID-19 pandemic presented a number of challenges when trying to set up Major Reviews for the proposed design of the robot. Due to these local COVID-19 concerns, only one external review was able to be set up. However, in order to make sure the team created a viable robotic design while embracing the concept of systems engineering, internal reviews were conducted for the System Requirements Review (SRR), Preliminary Design Review (PDR), and the Critical Design Review (CDR).

The SRR and PDR were both conducted as internal reviews. A major goal of these reviews was to find a new design to replace the excavation method used by the previous robot. For the SRR internal review, five designs were presented to the team. These designs were all unique and thoroughly discussed by the team, until only three designs remained. The main takeaway from the SRR was that the old system of using a scoop method was eliminated from the running.

As stated previously, the PDR was also conducted internally. Three prototype robots were created for the PDR based off of the three contenders that remained from the SRR. It was during the PDR that the auger system for the excavation process demonstrated its efficiency and effectiveness. It was because of the PDR that the team decided to move forward with the auger system for the new excavation process.

The CDR was conducted in person with safety requirements in place. Because the SRR and PDR focused solely on the excavation system of the robot, the purpose of the CDR was to expose the remaining systems of the robot to industry partners in the area and glean all advice that could be gathered. The CDR had many impacts on the design of the robot moving forward. The following two examples are the design suggestions that had the largest impact on the design of the robot. The first impact was related to the Mobility sub-team. It was decided that the tracks used by the previous robot were inadequate for the new excavation process, and so plans for a redesigned track were put into motion. The new tracks were shrunk in width by 5%. While a seemingly small change, it ensured that the robot remained within the width requirements of the competition, maintained the high level of traction the previous set of tracks excelled in, and removed all interfering problems between the tracks and the auger excavation system. Another major impact the CDR had was to increase the sensor loadout on the robot. It was discovered by the team that there were no sensors located on the robot to determine the mass of regolith collected by the robot. The team immediately made plans to add this sensor following the CDR.

**2.4 - Schedule of Work**

A full list of the team's proposed schedule of work can be found in Appendix 1. However, this section will seek to give a good understanding of the overview and intent of the Razorbotz schedule of work. The first month of the project, from August 24 to September 30, 2020, was focused on the planning and paperwork of the robotic systems. This included acquiring funding, forming the sub-teams, starting the GUI/CI design, and so on. Construction of the robot itself was planned and did begin on October 1, 2020. However, at this point the team encountered multiple difficulties and set-backs. The month of October 2020 had many important milestones that needed to be completed, such as designing, fabricating, and assembling the new gearboxes, creating the auger shell, mounting the wheels, gear boxes, and electrical boxes. However, during the period of October 2020 only one project was completed on time, which was the complete construction of the test arena on October 17, 2020.

In total, there were 12 objectives that were planned to be met in October, but were pushed back and completed at a later date. One objective was completed at a later date still within October 2020, two were completed in November 2020, two were completed in December 2020, and the remaining were completed past January 2021. This chain of pushbacks had a definite effect on how the project would be handled moving forward. The good news for the team was that this was an aggressive schedule in its initial form. As can be seen in Appendix 1, nearly every objective past February pertained to preparing paperwork and preparing data for the competition in May. This aggressive schedule allowed the team "wiggle-room" when the team did encounter problems that ultimately pushed back portions of the timeline. The two main pushbacks were the assembly of the chassis by the mobility team and the assembly of the Auger system by the excavation team.

The Mobility team was able to complete assembly of the chassis on April 10, 2021. This was a long push-back considering that completion of the chassis was meant to be completed on October 17, 2020. Two major factors that led to this outcome were parts related. In one case the wrong hardware was sent to the Mobility team with a gearbox that was ordered, and in a second instance an acrylic part that was being attached to the robot broke during that process. These issues added onto the whole assembly process taking approximately a month longer than expected added to why the chassis was completed at such a late date.

The Excavation team also had a long setback, with their team completing assembly of the Excavation system April 17, 2021. The planned date for completion of the Excavation system was on February 20, 2021. A key problem that led to this eventuality included certain key parts not being shipped on time. In one instance the wrong size bolts were shipped to the chassis team, meaning that they could not attach the motor properly. A second problem was that the collection bin that the Auger deposited its reogilth-gravel mixture into came in months late. These problems, plus the assembly taking approximately two weeks longer than expected led to the Excavation system assembly being delayed. Despite these setbacks, the Razorbotz team was able to be flexible and achieve its goals, albeit with a longer timeframe.

## 2.5 - Budget

The team was very diligent in setting up and in keeping track of the budget for the 2020-2021 Lunabotics Competition. It was broken up into multiple components, as can be seen in Table 1.

| Project/SubTeam | Budget (Remaining) | | SPENT | Budget (Initial) |
|---|---|---|---|---|
| Autonomy | $730.01 | 73% | $269.99 | $1,000.00 |
| Body (Chassis, etc) | $140.72 | 28% | $359.28 | $500.00 |
| Cart & Stand | $750.00 | 100% | $0.00 | $750.00 |
| Excavation | $660.07 | 66% | $339.93 | $1,000.00 |
| Testing | -$163.28 | 5% | $663.28 | $500.00 |
| Tools & Supplies | $468.07 | 94% | $31.93 | $500.00 |
| Misc Other | $431.00 | 77% | $69.00 | $500.00 |
| Travel | $7,000.00 | 100% | $0.00 | $7,000.00 |
| Total | $10,016.59 | | $1,733.41 | $11,750.00 |

*Table 1, Budget as of 01/30/21*

On the right side of the table, the initial budget is shown in its entirety, as well as in its individual components. The total initial budget was $11,750. The largest portion of the budget (&7000) went towards travel costs. As of 01/30/21, when this screenshot was taken, most sub-teams had not used a large portion of their budget. The exception to this was the Testing sub-team, which was $163.28 over the initial budget for their sub-team. In order to rectify this situation, it was decided that some of the resources needed to be reallocated. $200 was moved from the Misc Other section and into the Testing sub-team budget in order to accomplish this. This is also why the amount of budget remaining is at 5% for the testing sub-team, as opposed to a negative percentage. The updated budget as of 01/30/21 can be seen in Table 2.

| Project/SubTeam | Budget (Updated) |
|---|---|
| Autonomy | $1,000.00 |
| Body (Chassis, etc) | $500.00 |
| Cart & Stand | $750.00 |
| Excavation | $1,000.00 |
| Testing | $700.00 |
| Tools & Supplies | $500.00 |
| Misc Other | $300.00 |
| Travel | $7,000.00 |
| Total | $11,750.00 |

*Table 2, Updated Budget as of 01/30/21*

Following the turn to January, the team was able to stay on budget throughout the rest of the duration of the project. The travel expenses of $7000 were planned to be rolled into next year's project, giving the Razorbotz team much more wiggle room for future endeavors into the competition.

# 3 - Robotic Operations

## 3.1 - Concept of Operations

The following is the concept of operations planned by the Razorbotz team. The first step is to properly set up the robot and network infrastructure within the competition area. Step two is to power up the robot, power up the network, and connect them. Once the competition begins, step three is to autonomously navigate towards the mining area. Step four is to autonomously mine the regolith/gravel mixture with the auger excavation system. Step five is to autonomously maneuver the robot to the drop-off location. Step six is to repeat steps 3-5 until the time limit expires. Note that at any time if the autonomy fails, manual control will be immediately used for the duration of the competition time. Step seven is to measure the energy usage of the robot, and report it properly. Step eight is to safely turn off the robot and network. Step nine is to inspect the robot and record any noted malfunctions or aberrations. Step ten is to pack up the robot and network infrastructure with intent to transport it.

## 3.2 - System Hierarchy

The Razorbotz team broke the system architecture into two main components: Software systems and Mechanical/Electrical Systems. The Software Systems components can itself be broken into three distinct parts. Diagrams of the System hierarchy can be found in Appendix 2

The first section of Software Systems is Manual Control & Operator Interface. This section of Software Systems focused on the controls within the robotic structure, the networking, and the operator interface. It was vital that the team place these systems under the Manual Control & Operator Interface because these all directly impact how the team interacts with the robot. This is most on the nose with the Operator Interface, which determines how the interface will look and operate when a team member may have to control the robot manually. The section section of Software Systems was Navigation. This section focused on the autonomy that was planned to be integrated into the robot. The four ways the Navigation planned to achieve this was by breaking its autonomy down into global positioning, environmental detection, positioning, and path planning. The sensors on the robot would also fall under this section, due to the importance of them in regards to Navigation. The last section of Software Systems was the Excavation/Dumping system. As the name implies, this sub-section focused on the excavation procedure and the dumping procedure of the robot. While both of these processes were planned to be operated, they warranted their own section in the hierarchy because of the possibility that these processes may have to be accomplished manually. The team wanted to make certain that it could be accomplished both autonomously and manually, and therefore instead of putting it under one of these sections, put it in its own section under Software Systems.

The second section of the System Hierarchy was the Mechanical/Electrical Systems. This section was broken up into two sub-sections, the larger of the two being Mobility and the smaller of the two being Testing.

While smaller than the other sub-section, the Testing sub-section was vital to what we accomplished here at Razorbotz. The Testing sub-section was responsible for the testing bed location, its design, and for developing the testing procedures. It was decided that the most important of these was the testing procedures. The team needed a method that would fully test the robot, while not creating new problems that may affect the robot. The larger of the two sub-sections was

Mobility. The Mobility sub-section accomplished its goals by focusing on the chassis, wheels, sensor mounting, electrical boxes, and motors of the robot. Essentially, this sub-section was concerned with the remaining physical aspects of the robot that had not yet been addressed. This sub-section was also vital to making sure that the robot remained within the set mission parameters for the competition. Again, please see Appendix 2 to see diagrams of the System Hierarchy.

### 3.3 - Interfaces

The main interface used to connect all of the aforementioned systems within the System Hierarchy was the Networking subsystem. This subsystem was one of the components underneath to the Manual Control and Operator Interface section. The Networking subsystem was responsible for all interfacing between the electrical components of the robot, including but not limited to the packet layout of the robot and continually searching for connection failures. This subsystem was essential in maintaining the connection to the entire Navigation section in the System Hierarchy, as well as making certain that the Excavation/Dumping system operated properly. The sections the Networking subsystem did not connect to were the Testing section and the Mobility section, because both of these were connected by physical properties and not electrical systems.

### 3.4 - Requirements

There were six requirements that the Razorbotz team set forth at the beginning of the project. The first requirement was that the robot shall fit within the volume requirements as set by the Lunabotics Competition. The second requirement was that the robot shall have a lower mass limit than set forth by the Lunabotics Competition. The third requirement was that the robot shall move autonomously in an efficient manner. The fourth requirement was that the robot shall quickly mine and efficiently dispel regolith. The fifth requirement stated that the robot shall efficiently mine and retain icy regolith (i.e. gravel). The last requirement was that the robot shall deposit icy regolith quickly and efficiently. These early requirements were vital in determining the technical performance measurements of the robot.

### 3.5 - Technical Performance Measures

Six different technical performance measurements were determined by the Razorbotz team at the beginning of the project. The first technical performance measurement was the responsibility of the Mobility and Excavation sub-teams, and stated “Full robot must fit within the starting volume of 0.5m x 0.5m x 1m”. The second technical performance measurement was the collective responsibility of the Excavation, Mobility, and Computer Systems sub-teams, and stated that the “Full robot mass cannot exceed 60 kg”. The third technical performance measurement was the sole responsibility of the Computer Systems subteam, and stated that the robot must “Navigate obstacle field in 1 minute and 30 seconds or less”. The fourth technical performance measurement was the joint responsibility of the Excavation, Testing, and Computer Systems sub-teams, and stated that the robot will “Mine 32cm of Regolith in 2 minutes or less”. The fifth technical performance measurement was the responsibility of the Excavation and Computer Systems sub-teams, and stated that the robot shall “collect 1kg of Icy Regolith (minimum) in 2 minutes”. The sixth, and last, technical performance measurement of the robot was the joint responsibility of the Computer Systems and Excavation sub-teams, and stated that the robot would “Deposit Icy Regolith in the collection area in 30 seconds or less”. A detailed list of the technical performance measurements, as well as additional information on each, can be found in Appendix 3.

### 3.6 - Trade Studies

Using trade studies was vital to determining the functions of the robot, and in determining which functions of the robot should be placed over other functions. The method of trade studies helped the Razorbotz team determine two of the three major systems that were to be optimized. The first trade study applied was to the previous scoop system vs the (at that time) hypothetical auger system, with regards to excavation speed and efficiency. Both by raw score and by weighted score, the auger system was determined to be more efficient as well as faster than the previous scoop system. The second trade study applied was to the autonomy system. This trade study compared the efficiency and speed of a manually controlled system compared to two different autonomous systems. The first one was a fully autonomous robot, whereas the second was a semi-autonomous robot. The semi-autonomous robot was defined as having autonomy for the excavation/dumping process, while having manual control for the mobility aspect of its design. Ranked from highest to lowest in the trades study, the full autonomous robot scored highest, followed by the semi-autonomous robot, with the manually controlled robot coming in last. After performing this trade study, the team sought to add as much autonomy to the new robot as possible. Since most of the other systems were carried over conceptually from the previous robotic design, no other trade studies were conducted.

### 3.7 - Reliability

Designing the robot with safety considerations in mind was the top priority when designing the robot. While the team ultimately wanted the robot to perform well during the competition, it would mean nothing if the robot ended up harming people, property, or itself in the process. As per competition requirements, the robot has a large red kill switch on the top of itself that will immediately shut off all electrical functions when pressed down. In addition to this, the sensors within the system can also detect overload feedback, regardless of whether this overload is caused by electrical or mechanical problems. In the case of an overload, the robot is designed to shut down on its own, so that no individual has to go up to the robot to initiate the kill switch. Of course in a case where this happens, the team plans to go up to the robot and press the kill switch in order to make absolutely certain that the robot is shut down.

In case something drastic happened to the robot, the team also took precautionary steps to ensure that the robot can “bounce back”. The vast majority of the parts of the robot are either interchangeable, can be easily/cheaply replaced, or modified. This was accomplished through the use of finding cheap yet reliable parts that can be used in a variety of situations, and by 3-D printing many parts on the robot. Additionally, the parts of the robot were mounted in such a way that they are, for the most part, easy to get to and detach if a problem does occur with them.

### 3.8 - Verification of Robotic Systems

A practical route was taken by the team in order to assure that the system requirements were up to the standards sought beforehand. The Testing sub-team was responsible for setting up a testing environment that emulated the mining layout for the mining portion of the competition. The first test carried out occurred on 03/16/21. The test was conducted in order to make certain the drivetrain worked with manual controls on the chassis. The chassis was able to rotate both to the left and the right within a reasonable time period, and be able to move at a quick pace due to how light the chassis was during testing.

As of the writing of this paper, no further tests have been conducted. However, two tests have been planned for the future. The first test will take place on April 16, 2021, and will train the neural networks of the autonomous system with identifying the rocks on the testing course. The second test will be a full systems test and will occur on May 1, 2021.

## Appendix 1

*Table 1, Initial Project Schedule of Work*

| Activity | Sub-Team Responsible | Responsibility | Due / Completion Dates |
|---|---|---|---|
| Project Start | Management | Project Manager | August 24, 2020 |
| Team Funded | Management | Faculty Advisor | August 24, 2020 |
| GUI/CI Design Started | Software Systems | Software Systems Lead | September 1, 2020 |
| Sub-Team Formation | Full Team | PM & Leads | September 4, 2020 |
| Complete Team Registration | Management | Project Manager | September 4, 2020 |
| System Requirements Review | Full Team | PM & Leads | September 16, 2020 |
| Budget Submitted for Approval | Management | Project Manager | September 16, 2020 |
| Complete Team Design Goal Development | Full Team | Sub-Team Leads | September 23, 2020 |
| Assess parts on Fusion vs what is on hand/what we still need | Excavation | Excavation team lead | September 26, 2020 |
| GUI Design Review | Software Systems | Software Systems Lead | September 26 2020 |
| Systems Engineering - Plan for Project Systems Engineering (submit by this date to be eligible for additional 2 pts) | Management | Project Manager | September 30, 2020 |
| GUI Programming/Code Rewrite Started | Software Systems | Software Systems Lead | October 1, 2020 |
| Start Manual Controls | Software Systems | Software Systems Lead | October 1, 2020 |
| Assess/Redesign Gear Boxes and Electrical Boxes | Mobility | Mobility Lead | October 3, 2020 |
| Update fusion file with proper constraints and movements | Excavation | Excavation team lead | October 3, 2020 |
| Fabricate Gear Boxes | Mobility | Mobility Lead | October 9, 2020 |
| Auger shell should be made | Excavation | Excavation team lead | October 10, 2020 |
| Fabricate Electrical Boxes and Supports | Mobility | Mobility Lead | October 10, 2020 |
| Preliminary Design Review | Full Team | Sub-Team Leads | October 10, 2020 |
| Assemble Gear Boxes | Mobility | Mobility Lead | October 14, 2020 |
| Complete construction of test arena | Testing | Testing Lead | October 17, 2020 |
| Mount Wheels and Gear Boxes | Mobility | Mobility Lead | October 17, 2020 |
| Assemble and Mount Electrical boxes | Mobility | Mobility Lead | October 17, 2020 |
| Finish assembly | Mobility | Mobility Lead | October 17, 2020 |
| Start assembly | Excavation | Excavation team lead | October 24, 2020 |
| Testing | Mobility | Mobility Lead | October 27, 2020 |

| | | | |
|---|---|---|---|
| Assembly complete | Excavation | Excavation team lead | November 28, 2020 |
| Finish Manual Controls | Software Systems | Software Systems Lead | December 18, 2020 |
| Finish GUI/CLI Design Overhaul | Software Systems | Software Systems Lead | December 18, 2020 |
| Revisit Scope of Project | Software Systems | Software Systems Lead | January 23, 2021 |
| Start Autonomy Macro for Excavation | Software Systems | Software Systems Lead | January 23, 2021 |
| Start Sensor Implementation | Software Systems | Software Systems Lead | January 23, 2021 |
| Start Camera Implementation | Software Systems | Software Systems Lead | January 23, 2021 |
| Systems Engineering report review | Writing | Writing Lead | February 15, 2021 |
| Team Roster | Management | Project Manager | March 3, 2021 |
| Team Biography (200 words maximum) | Management | Project Manager | March 3, 2021 |
| Team Photo with Faculty (jpeg format only) | Management | Project Manager | March 3, 2021 |
| Corrections to NASA generated Team Roster | Management | Project Manager | March 3, 2021 |
| Systems Engineering report rough draft | Writing | Writing Lead | March 24, 2021 |
| Finish Excavation Macro | Software Systems | Software Systems Lead | March 27, 2021 |
| Final Team Roster (no changes after this date) | Management | Project Manager | March 29, 2021 |
| Systems Engineering report | Writing | Writing Lead | April 7, 2021 |
| Outreach Project Report | Outreach | Outreach Team Lead | April 16, 2021 |
| Slide Presentation and Demonstration | Full Team | PM & Leads | April 16, 2021 |
| Robot Details and Proof of Life Submission | Full Team | PM & Leads | April 16, 2021 |
| Finish Final Testing of Camera/Sensors | Software Systems | Software Systems Lead | April 24, 2021 |
| Ready for competition | Excavation | Excavation team lead | May 1, 2021 |
| Supplemental Data Submitted | Full team | Project Manager | May 14, 2021 |
| Project Completion Date | Full Team | Project Manager | May 21, 2021 |

# Appendix 2

*Diagram 1, Manual Control and Operator Interface System Hierarchy*

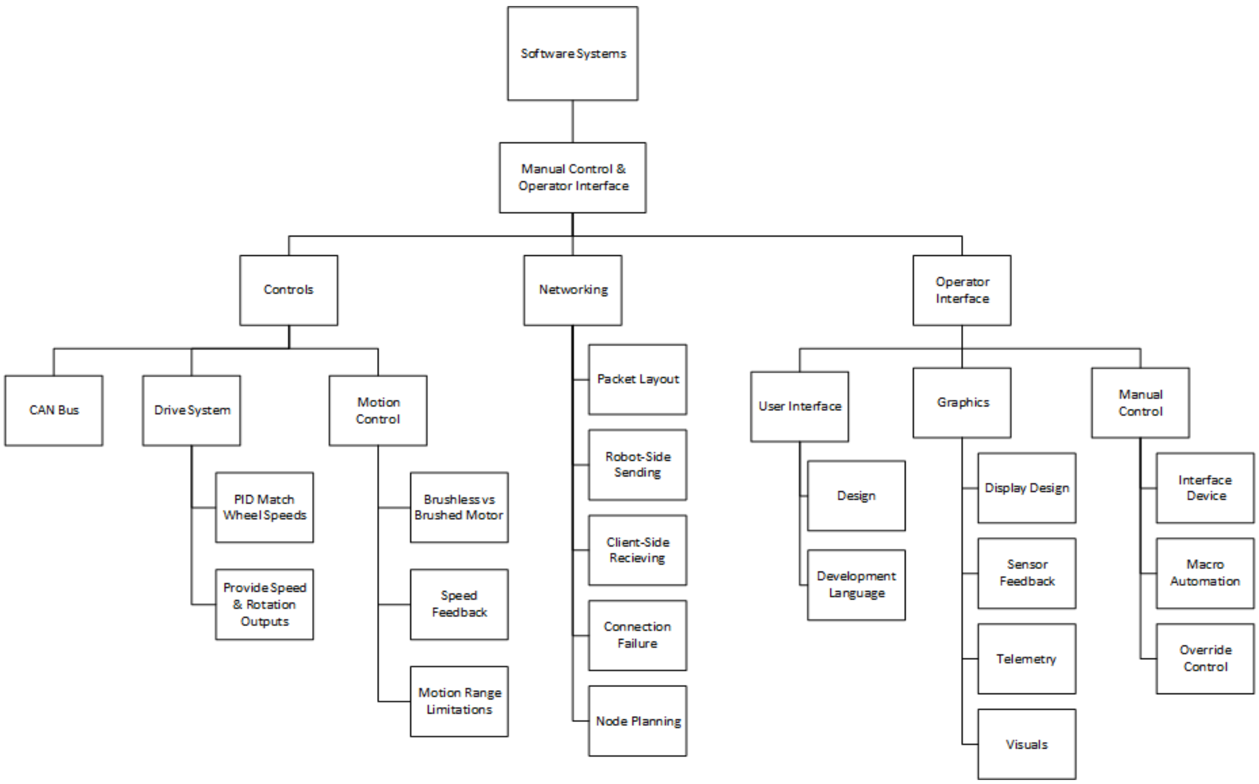



*Diagram 2, Navigation System Hierarchy*

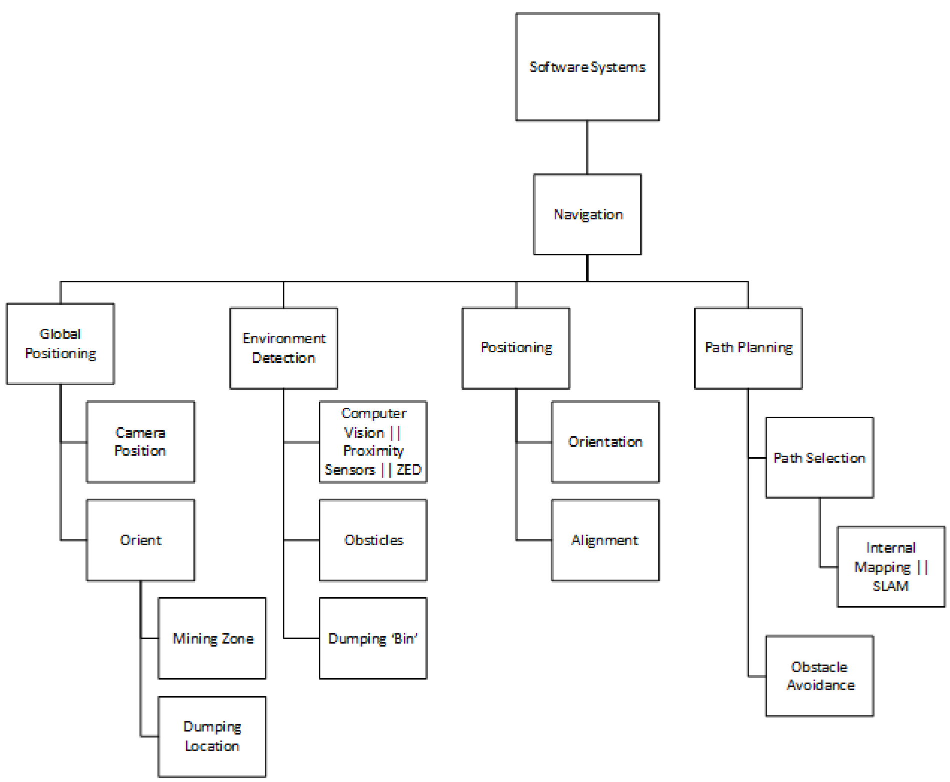


*Diagram 3, Excavation & Dumping System Hierarchy*

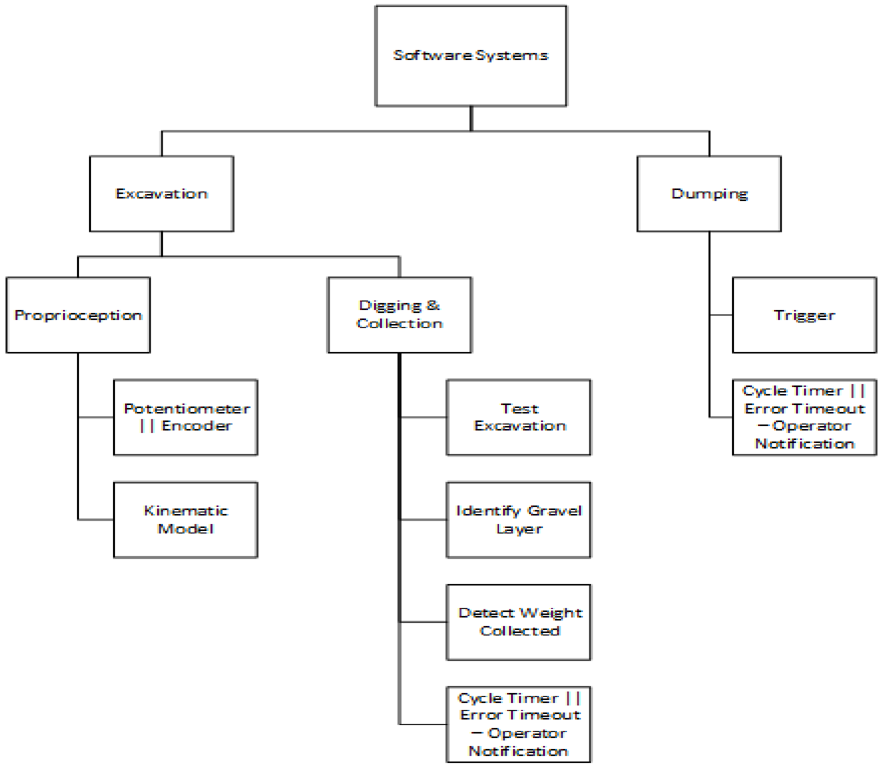



*Diagram 4, Testing System Hierarchy*

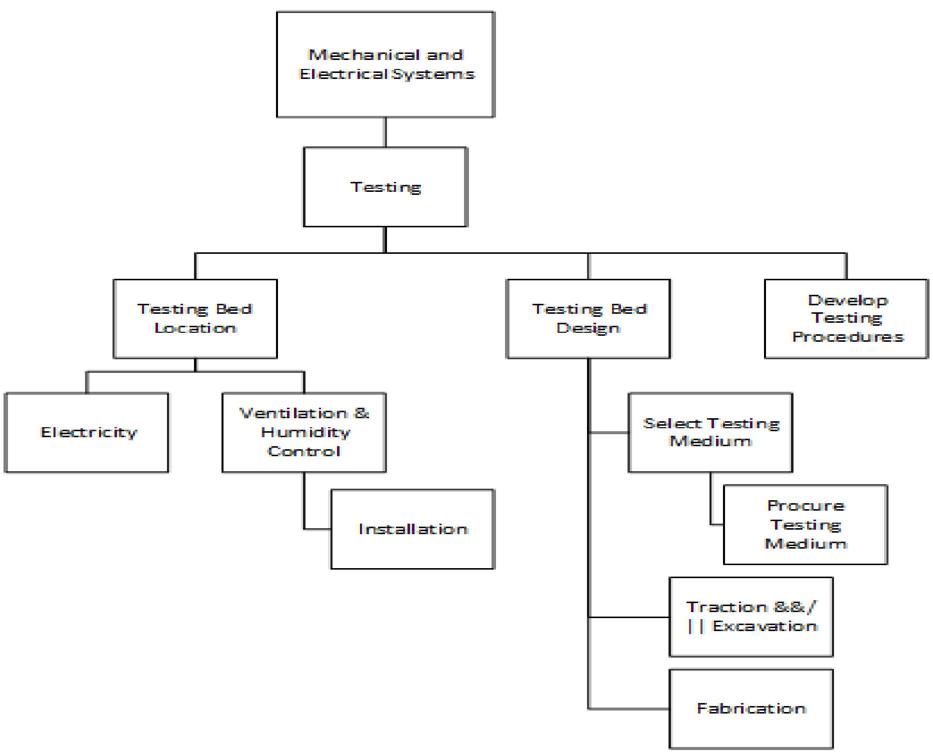
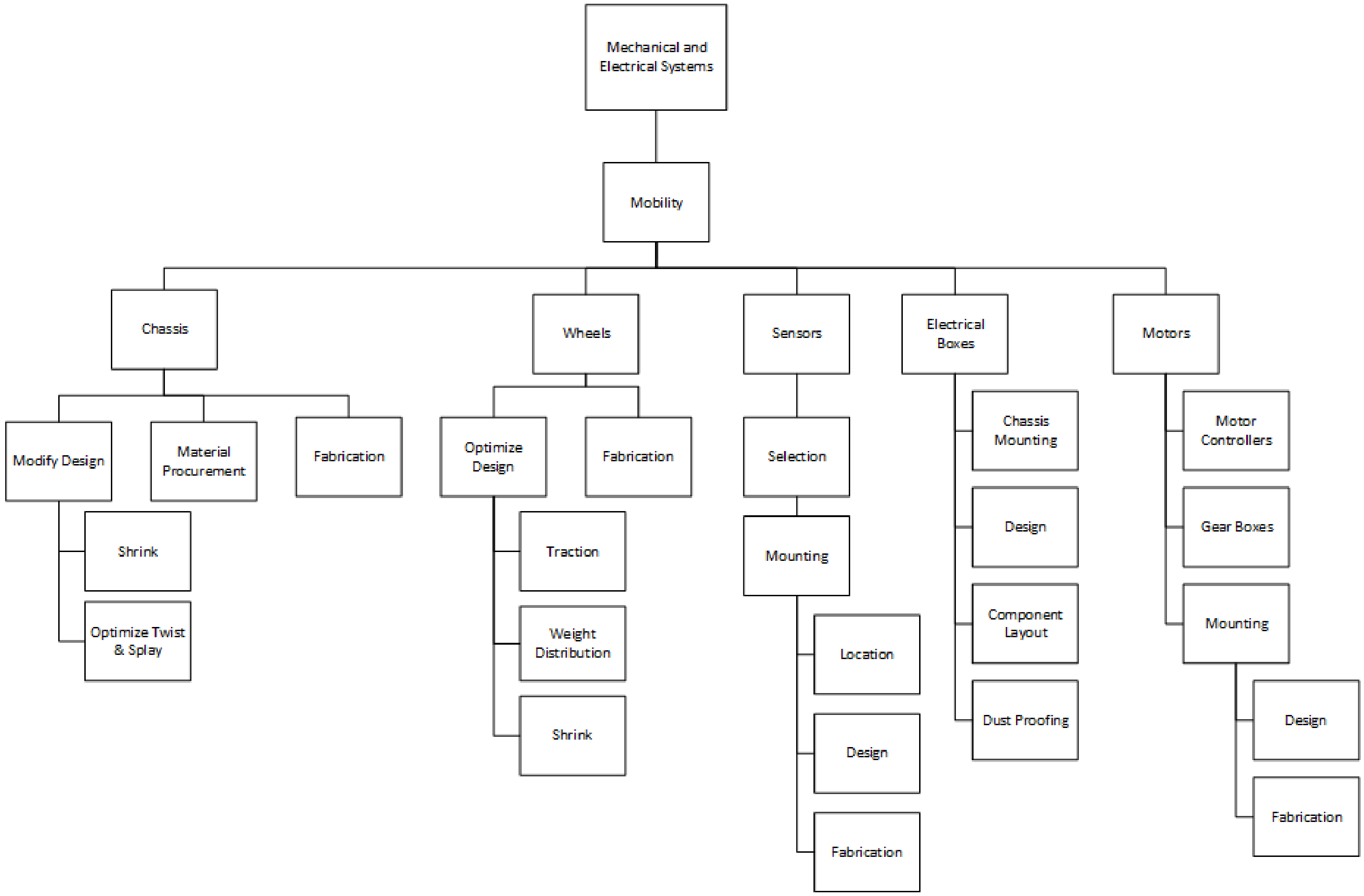


*Diagram 5, Mobility System Hierarchy*



**Appendix 3**

*Table 2, Technical Performance Measurements*

| Technical Performance Measures | System Hierarchy | Measurement Method | Measurement Time |
|---|---|---|---|
| Full Robot Must Fit Within Starting Volume (.5m x .5m x 1m) | Mobility | 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 60 kg | Excavation | CAD Model Analysis | Excavation Critical Design Review |
| | Mobility | 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 32cm 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 |