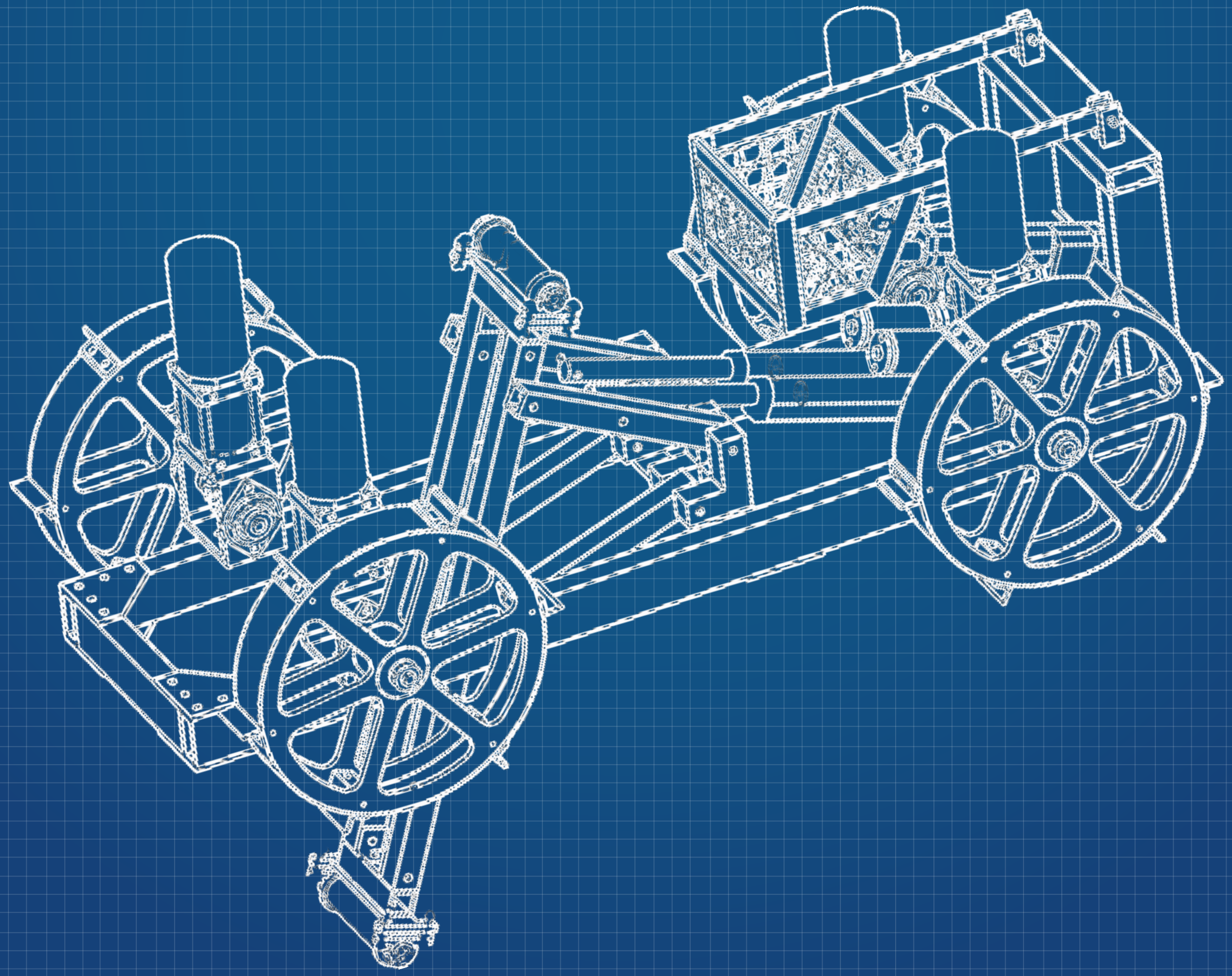
Illinois Institute
of Technology

NASA

Scarlet Spacehawks
NASA RMC, 2021 Systems Engineering Report

Gregory Bonnema
Andrea de Fonseca
Eyob Ghebreiesus
Cameron Haley
Jiyeoun Jang
Peter Kwiecinski
Anil Kumar
Jordan Lauer
Daberechi Onyeacholem
Kristin Petersen
Mohammed Razzak

This report submitted to and approved by Faculty Advisor Dr. Mahesh Krishnamurthy.



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1 - Introduction

1.1 Team Introduction

Scarlet Spacehawks is composed of students from different STEM backgrounds and various experience levels. Below is the breakdown of the team.

Name	Role on Team	Major
Kristin Petersen	Systems Engineer	Mechanical Engineering
Gregory Bonnema	Chief Electrical Engineer	Computer Engineering
Andrea de Fonseca	Chief Mechanical Engineer	Aerospace Engineering
Cameron Hailey	Chief Software Engineer	Computer Engineering
Jordan Lauer	Treasurer & Mechanical Sub-team	Mechanical Engineering
Mohammed Razzak	Electrical Sub-team	Physics & Aerospace Engineering
Jiyeoun Jang	Mechanical Sub-team	Mechanical Engineering
Daberechi Onyeacholem	Mechanical Sub-team	Mechanical Engineering
Anil Kumar	Mechanical Sub-team	Mechanical & Manufacturing Eng.
Peter Kwiecinski	Software Sub-team	Physics & Aerospace Engineering
Eyob Ghebreiesus	Software Sub-team	Aerospace Engineering

Table 1.1: Team Organizational Chart

1.2 Why Use Systems Engineering

To guide systems engineering, the team used a combination of the Vee Chart Process Model of the Life Cycle by David Beale and Joseph Bonometti[1] and Table 2-2.1 Phases Pre-A thru D from the NASA Systems Engineering Handbook[2] as the table offered more detailed information on the mission life cycle. Utilizing systems engineering created an opportunity to ask questions and minimize consequences of the design and operations. This allowed the team to guide the engineering of each sub-system and reduce cost and operational risk through proper planning and coordination. A copy of the tables referenced can be found in Appendix A.

2 - Systems Engineering

2.1 - Pre-Phase A: Concept Studies

2.1.1 Mission Overview

America will land the first woman and next man on the Moon by 2024, fulfilling a goal of the Artemis Program. These astronauts could one day work on the Moon testing new technologies and developing areas such as in-situ resource utilization (ISRU). Excavation of regolith will be one of the first challenges to overcome in developing ISRU. With the knowledge gained from lunar excavation, NASA can take the next step and send astronauts to Mars. To facilitate lunar excavation technologies, NASA created The Robotic Mining Competition (RMC): Lunabotics. The goal of RMC is to train university students in methods not often taught in schools, such as systems engineering and its applications in designing, building, and operating lunar excavation systems. The 2021 competition is expected to host 59 university teams in creation of excavator prototypes. These prototypes will act as a proof-of-concept for future lunar missions through the Artemis Program and directly benefit NASA by promoting clever ideas and solutions from students. Teams are encouraged to foster relationships with their local and this year, worldwide, communities through the promotion of STEM outreach events. Scarlet Spacehawks will be returning for their fifth year of the competition with a brand-new excavator and collections design. The objective of the team is to develop an autonomous robot capable of successfully functioning in the competition and inspire future designs for NASA lunar excavators. This report will encapsulate the systems engineering approach taken to develop the autonomous robot, Scoops.

2.1.2 Mission Statement

The goal of this team is to support the Artemis mission by designing an autonomous robot for excavation of simulated lunar regolith. With the data received from this mission, the team will further the development of autonomous robotic mining to create a sustainable presence on the Moon and other off-world locations.

2.1.3 Stakeholders

The following stakeholders were identified as potential researchers interested in vehicular excavation, the Illinois Institute of Technology (IIT), and NASA. Potential stakeholders primarily include researchers interested in vehicular excavation, lunar morphology data scientists, and various private research facilities. At the conclusion of the competition, data gathered from the stress analysis performed on the robot will be publicized for any who find this information valuable for current or future excavation robots. IIT is the primary provider of both the team's electrical and mechanical labs as well as financial backing. The experience that RMC provides such as the practical application of educational courses and involvement within the local community through outreach, was highly supported by the University. As the sponsor of the RMC competition and facilitator of applicable competition resources, such as the rules and FAQs updates, NASA is another primary stakeholder. All stakeholders expect a functioning excavation robot in time for the May 2021 competition.

2.1.4 Design Philosophy

With the COVID-19 procedures in place, many workshops on campus were unavailable to students during the first and much of the second half of the school year. As such, the design philosophy was based on "making the best use of what we have." The team's main goal was to recycle as many parts as possible, this included sourcing materials from the inventory such as scrap metal and disassembling previous robots for parts. These savings are referenced in section 2.7.2. If materials had to be purchased, they were purchased with the knowledge that fabrication may need to occur with equipment that could be operated safely in the teams' small lab space, such as drills, grinders, and soldering irons. Workshop availability was planned based on hours provided by shop facilitators, which were only available in the Spring semester. This scheduling was factored in with the teams SRR meeting and tentatively displayed in the Gantt chart of section 2.7.1.

2.1.5 Design Optimization Criteria

In the context of systems engineering, the design focused on optimizing the system to satisfy the Full Autonomy category by completing, at minimum, two cycles and depositing 1 kg of icy regolith. As autonomy is primarily achieved through the software team, the Design Philosophy was satisfied since year-round access was available for software's primary tools: computers, GitHub, and the LiDAR.

<table>
<tr><th colspan="4">Stakeholder Requirements</th></tr>
<tr><td colspan="4">The robot shall excavate simulated regolith at the 2021 Robotic Mining Competition</td></tr>
<tr><th>Code</th><th>Driving Requirements</th><th>Sub-System</th><th>Verification</th></tr>
<tr><td>F</td><td>The robot shall mine, transport, and deposit simulated regolith</td><td>Electrical
Mechanical
Software</td><td>Analysis
Test
Demonstration</td></tr>
<tr><td>F</td><td>The robot shall report the amount of energy consumed after each run</td><td>Electrical
Software</td><td>Analysis
Test</td></tr>
<tr><td>PH</td><td>The total mass of the robot shall be less than 60.0 kg</td><td>Mechanical</td><td>Inspection</td></tr>
<tr><td>PH</td><td>The robot shall be contained within 1.0 m length x 0.5 m width x 0.5 m height before operations</td><td>Mechanical</td><td>Inspection</td></tr>
<tr><td>PH</td><td>The robot shall not extend 2.5 m height when in dumping mode</td><td>Mechanical</td><td>Inspection</td></tr>
<tr><td>F</td><td>The robot shall have a reliability plan in place in case of system component failure</td><td>Electrical
Mechanical
Software</td><td>Analysis
Test</td></tr>
<tr><th>Code</th><th>Requirements to Satisfy Optimization Criteria</th><th>Sub-System</th><th>Verification</th></tr>
<tr><td>P</td><td>The robot shall mine a minimum of 1.0 kg of rock in autonomy mode</td><td>Mechanical
Software</td><td>Test
Demonstration</td></tr>
<tr><td>P</td><td>The robot shall mine a minimum of two cycles in autonomy mode</td><td>Mechanical
Software</td><td>Test
Demonstration</td></tr>
<tr><td>PH</td><td>The robot shall include dust protection</td><td>Mechanical</td><td>Inspection</td></tr>
</table>

Table 2.1: System Requirements

2.1.6 System Requirements

The driving requirements are derived from the RMC rules[3] and the requirements necessary to satisfy the Design Optimization Criteria. The requirements are coded according to their requirement type: Functional (F), Performance (P) and Physical (PH), then further broken out to include the associated Sub-System and Verification process performed to ensure all requirements are satisfied.

2.1.7 Concept Studies

With a focus on the design philosophy, the team met to perform a study on three types of excavation designs with the knowledge that each could be built from materials primarily sourced in-house. The point values were on a feasibility scale from 0 to 3: 0 = no impact/parts owned, 1 = most feasible, 2 = less feasible, 3 = least feasible. The design with the least number of points would be the design the team proceeded with.

Excavation Design	Autonomy	Excavation Capacity	Weight	Size	System Integration	Cost	Total
Auger	1	3	3	3	2	0	**12**
Dump Bucket	3	1	2	2	3	1	**12**
Conveyor Belt	2	2	1	1	1	1	**8**

Table 2.2: Concept Studies

Within the concept studies meeting, issues of risk and reliability were briefly addressed based on notes from past years' excavation designs. It was noted that a previous teams conveyor belt had not performed properly due to insufficient torque supply from the motor system and the system was unable to recover. The team chose to address this and other risks during the SDR meeting. Therefore, based on the results, the team proceeded with the conveyor belt excavation, a new design.

2.1.8 Design Updates and New Elements

The design for this robot was primarily chosen based on the ability to source materials in house. In doing so, Scoops utilized a former robot's chassis and wheel system design. To meet the size constraints for the 2021 competition the chassis and wheel systems were remodeled and rebuilt. The newer addition to the system's design includes the collections hopper, excavator, electrical box (E-box), and autonomous software. The new systems are described in detail further in this report.

2.1.9 Mission Concept Review (MCR)

Each sub-team held a team MCR where they defined system requirements and technical performance measurements (TPM) relevant to their sub-system, as well as any verification and validation approaches. The entire team then gathered at a general body meeting, via Zoom, to approve the Pre-Phase A, sections 2.1.1 - 2.1.7 as well as the preliminary financial budget as discussed in section 2.7. Some key details were mentioned during the meeting which included the problem of the past conveyor belt's attempt and failure. The team decided since the cause of the failure was known, it could be avoided, and the design could proceed. Once each member had agreed on these sections, as shown by a vote of hands, the team could continue to Phase A: Concept Development.

2.2 - Phase A: Concept Development

2.2.1 System Hierarchy

As seen in Appendix A, the requirements of the Scoops system are divided into three sub-systems: Electrical, Mechanical and Software. The Electrical sub-system contains the microelectronics and power source. Electrical will interface with Mechanical and Software to determine how and how much power to supply to the motor components and the autonomy system. The Mechanical sub-system includes the mobility, frame, excavation, and collections systems. This sub-system is defined by the physical design and fabrication of the robot. The Software sub-system consists of motor controls, autonomous operation algorithms, and communication between a front-end control center and the robot. All sub-systems need to communicate with one another in an efficient manner for the rover to work at optimal speed. Each interface is further discussed within the sub-system sections of Phase B and Phase C.

2.2.2 Concept of Operations

The basic Concept of Operations (ConOps) for Scoops is adapted from the RMC rules with further analysis about the operation of the robot during a Fully Autonomous competition attempt:

- Setup required wireless network, target is attached to the collector sieve frame, and robot is positioned in the starting zone.

- Power on robot and establish network connection
- Divulge the method of autonomy sensing to the judges
- At competition start, demonstrate autonomy by travelling from the starting point and navigating the arena while avoiding collisions with obstacles and arena walls
- Autonomously deploy the excavation system and mine the regolith
- Autonomously navigate to the sieve frame and deposit regolith
- Repeat the autonomy procedure until the 15 minutes competition run ends
- Should the autonomy procedure fail, operator will be ready to intervene utilizing manual controls
- At the end of the 15 minutes competition run, the actual energy consumed will be shown to the judges
- Power down robot and remove from arena
- Perform maintenance as needed
- Store network hardware and robot until the next competition run

2.2.3 System Requirements & Definitions Review (SRR & SDR)

Due to time constraints, the SRR and SDR meetings were both held in early November 2020. The team met via Zoom and the meeting was broken into two sessions, the first of which was the SDR and the second for the SRR. The goals of these meetings were to ensure that the design criteria were followed, and the stakeholder requirements were upheld. After each session, team members confirmed the understanding of all elements discussed and advancement to Phase B: Preliminary Design was approved.

2.2.3.1 System Definition Review (SDR)

Within this meeting, the Systems engineer ensured that the design so far follows the stakeholder requirements. The Treasurer also confirmed funding and potential costs based on the design philosophy to reuse all applicable materials. Sub-teams confirmed verification methods as provided in section 2.1.6, with a special emphasis given to the plans to perform stress analysis of various components of the robot.

2.2.3.2 System Requirements Review (SRR)

The goal of this meeting was to ensure that the Systems Engineer addressed the system requirements flow and ensured that they were well defined and followed the proposed design plan as previously discussed in the MCR meeting. ConOps was also confirmed to align with the mission.

2.3 - Phase B: Preliminary Design

2.3.1 Electrical

The initial design of the electrical sub-system looked to create a simple, reliable electrical system. As a starting point, the team looked back to the previous years' final robot. The initial design reached from this starting point, which can be seen in Fig. 2.1, featured an ASUS Tinkerboard controlling an inertial measurement unit along with four Sabertooth 2x60 motor controllers, one of which was configured to run a pair of linear actuators rather than motors. There was circuitry for the control of the two LiDAR, and two DC-DC converters that handled the regulation of power to the Tinkerboard and LiDAR. The system was powered by a single battery, using a solid-state relay to toggle power to the robot, and a wattmeter to measure power. With this working as an effective starting point, Electrical established the sub-system hierarchy as seen in Appendix A. This hierarchy is the foundation of the Electrical sub-system.

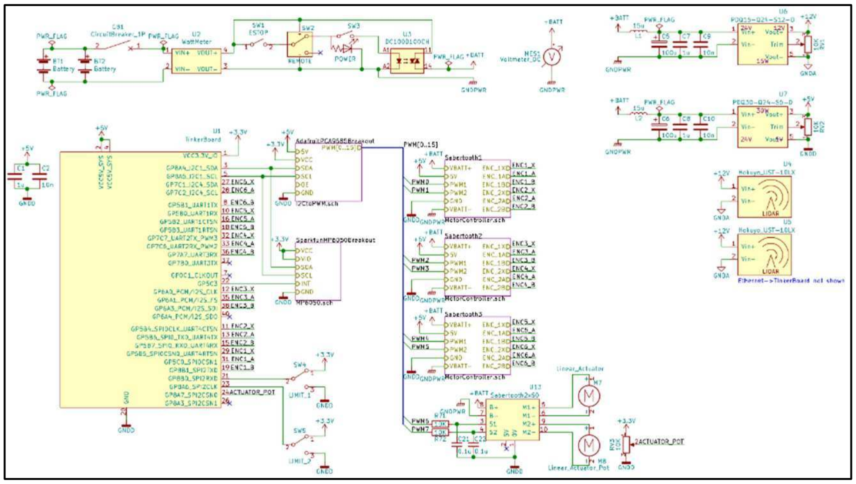


Fig. 2.1: Electrical preliminary design

2.3.2 Mechanical

Preliminary designs for the mechanical team were based around previous years' final robots, keeping successful component designs, and altering or redesigning less-than-optimal components, keeping in line with the Design Philosophy of "work with what we have." Decisions on what was successful and what needed to be altered stemmed from needing to satisfy Full Autonomy, working with the electronic and software system hierarchies. With these requirements, the mechanical team put together the sub-system hierarchy as shown in Appendix A.

With overlapping components, the team ensured all sub-systems worked together. Outside of Full Autonomy, several sub-goals were outlined, and the following solutions were found:

2.3.2.1 Mobility

The robot must move from the starting position to the excavation zone to the collection bin. The team decided to proceed with a 4-wheel drive system based on its previous effectiveness. Adhering to the Design Philosophy, components from previous years' builds were used which allowed for financial savings. Based on the time, torque values, and size constraints, CIM motors with a stall torque of 2.32 Nm were chosen for the wheels. A 3-stage planetary gear box from BaneBots with 64:1 gear ratio was chosen to be used with these motors. To transmit the torque, a right-angle gearbox was needed. The torque output at peak power output is 1.05 N-m. With a 64:1 gear increase this makes the theoretical torque output at 67.2N-m. Software sub-team provided the LiDAR that helps move the robot around obstacles (further details in Software section 2.4.3). The gearbox consists of a milled-out block of aluminum and a clear square of plastic to cover the large top opening. This allows the team to monitor any problems that may occur while also acting as a seal from arena debris. [Fig. 2.2]

2.3.2.2 Frame

The robot frame must be under the size restraint of [1 x 0.5 x 0.5] m, smaller than previous years. Space between the chassis and the ground is tightened to achieve size restraint goals, and the drive system is on top of the chassis, tangent to the wheels. Components of the robot were designed to fit these size restraints while working harmoniously with other system components. [Fig. 2.3]

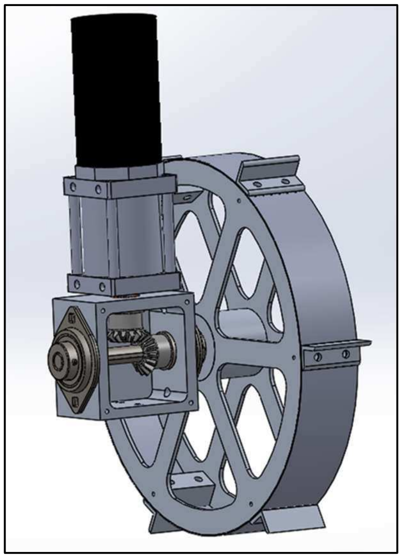


Fig. 2.2: Mobility on SCOOPS. Note the clear side of gearbox for easy viewing.

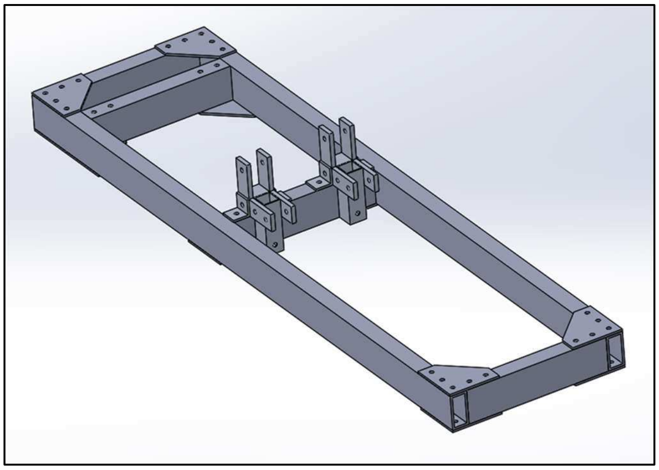


Fig. 2.3: Frame on SCOOPS. Compact to adhere to regulations.

2.3.2.3 Excavation

The excavation system must go through the BP-1 layer approximately 30 cm deep and collect the regolith approximately within the next 15 cm of depth. The excavation mechanism must then deposit the regolith into the collections system. In previous years, the team was able to use an auger system. Based on the results of a trade study performed on the excavation system that factored in the new size constraints, a new conveyor system was designed in the form of a trench digger composed of a belt, frame, and buckets. The trench digger uses a two-linkage linear actuator system that allows the rover to constrain the digger's movement and make the depth required for regolith extraction, controlled through the Electronics' E-box via the Software Team's coding. [Fig. 2.4]

2.3.2.4 Collections

The requirement of the collections system (hopper) is that it must store the regolith collected and deposit it into the collection bin in the arena. To solve this, a gearmotor is utilized to lower the height of the hopper to be situated underneath the buckets of the trench digger, allowing the regolith to fall from the open buckets into the hopper. A rod connects the motor to the basket arms. The same motor, when instructed via Software sub-team coding, will rotate the rod to lift fully and deposit the regolith into the final collection bin of the arena. Due to tight constraints placed on the robot, the hopper is utilizing a compact, lightweight design to fit between the wheel motors and far back enough to clear the excavation system. [Fig. 2.5]

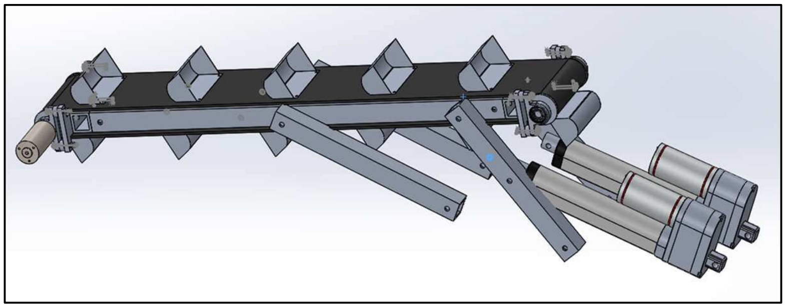


Fig. 2.4: Excavation: flexible arms and actuators allow for deep digging.

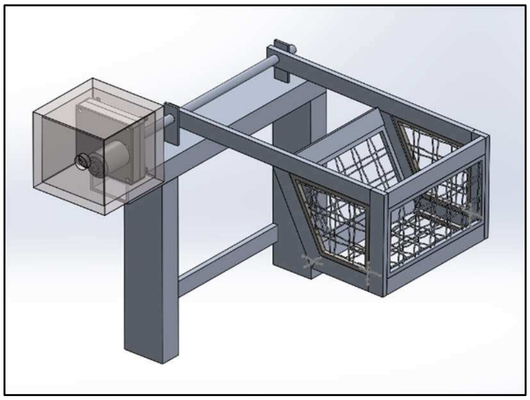


Fig. 2.5: Collection's basket (hopper): a powerful motor cuts down on space and allows the full turn needed to empty the collections basket.

2.3.3 Software & Autonomy

The software team targeted a fully autonomous robot; the initial preliminary design proved to be of utmost importance to ensure this was accomplished. To structure the plans, a hierarchy was created, as seen in Appendix A.

2.3.4.1 Autonomy

For the robot to complete the objective autonomously, it was determined that there are three major tasks it must perform: pathfinding, obstacle detection, and localization. Localization would allow the robot to determine where it is in the arena at any given time; this was decided to be the most important factor in autonomous operation. Once the location and the orientation of the robot is known, the robot must be able to detect obstacles and craters in its path. To accomplish both localization and obstacle detection, LiDAR's were utilized. The LiDAR of choice is the Hokuyo UST-10LX, a 2D LiDAR capable of accurately detecting distance and reflectivity for up to 10 meters.

Finally, to take the location and obstacle data and turn it into a set of instructions for the robot to carry out, a pathfinding algorithm needed to be used. In the previous competition, the A* algorithm was used; however, this algorithm assumes the state of the map is known ahead of time and needs complete recalculation if a new obstacle is added. A trade study was performed and, due to the terrain being unknown, an incremental search algorithm was chosen that is capable of efficiently updating the path upon receiving new data. This path can then trivially be converted into motor control movements, allowing the robot to navigate to and from the mining area safely.

2.3.4.2 Controls

Regardless of whether the control type is autonomous or manual, the robot must be able to control the wheels and trench digger to complete the objectives. The motor section of the software code should control and manage the driving speed, turn angle, and braking of the robot. The motor controls must be reliable enough to follow the predefined path that will be given by the Autonomous module. Similarly, the control of the linear actuators must be capable of reliably operating the mining aspects of the robot.

Additionally, in case of autonomous failure, the robot must have the capability to be controlled manually. To do so, an XBOX Controller is used that is connected to the Control Center, which then wirelessly transmits commands to the robot. The robot then interprets these commands appropriately and moves the robot.

2.3.4.3 Control Center

The final task that the software team found to be critical to a successful mission was the ability to receive, send, and visualize live data from the robot. To achieve this goal, the team opted for creating a web application that communicates with a WebSocket server on the robot. Through this connection, commands can be invoked from the client to the robot, performing tasks such as disabling autonomy and taking over manual control in case of failure. To this end, one of the major goals of the Control Center is to be as simple and understandable as possible, without sacrificing robustness or security. This, in conjunction with the XBOX Controller, will allow manual operation in the case of autonomous failure, ensuring that the robot is always operable.

2.3.5 Preliminary Design Review (PDR)

The PDR was held in December 2020 and the Systems Engineer confirmed the sub-systems preliminary designs met the system requirements and the stakeholder objectives. The schedule constraints were deemed appropriate. Interfacing between the sub-systems was also confirmed as accurate. Prior to the meeting, the Mechanical sub-team found the desired motor, one that was already owned by the team, would not provide enough torque to properly function within the conveyor belt system. The financial budget was adjusted to include a new motor, but due to budget constraints, the order was delayed. This delay was appropriately factored into the current Gantt chart [Appendix A]. The new motor also affected the mass and power budgets referenced in sections 2.6.2.1 and 2.6.2.2 as both the total mass and power consumption would increase due with the new motor.

2.4 - Phase C: Final Design and Fabrication

2.4.1 Electrical

The final design of the Electrical sub-system [Fig. 2.6] was significantly modified and expanded relative to the preliminary design. The first major change made was the addition of a second battery and solid-state relay. This change was made to mitigate problems of brownout caused by excessive power draw. With these additions, it was also necessary to add a second wattmeter to maintain accurate power draw data. The next major change was made at the behest of the Software sub-team to switch out the ASUS Tinkerboard for a Raspberry Pi. An analog-digital converter was also added in order to better facilitate the use of the linear actuators and servos, as the preliminary design lacked the ability to read the positional data that these parts were capable of returning. Two current sense resistors were added to help with testing and better optimize the system's power draw.

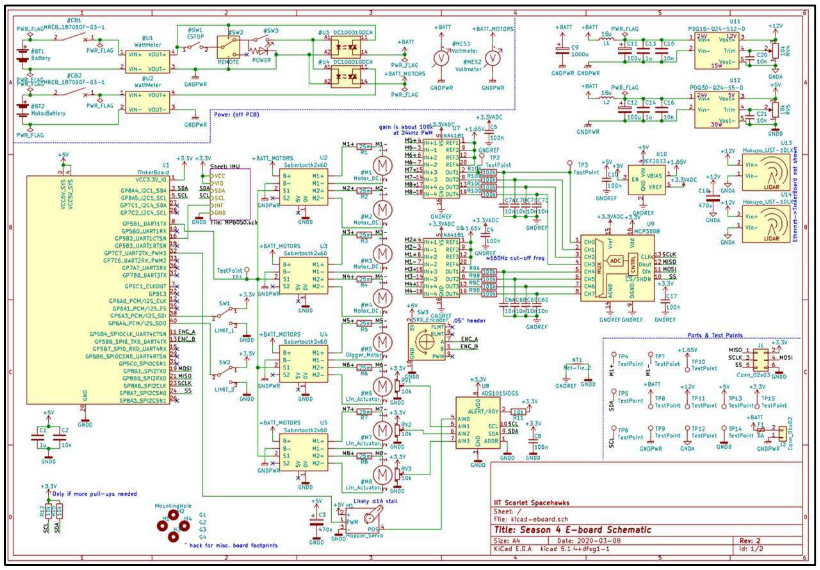


Fig. 2.6: Electrical Final Design. Here you can see the changes made from the preliminary design in Fig. 2.1.

2.4.2 Mechanical

Preliminary designs in SolidWorks showed a clearance for each sub-system component [Fig. 2.7] and fabrication commenced. Aluminum 6061 was the main material of choice due to several reasons stated throughout the following sections—to name a few: lightweight, low cost, and malleability.

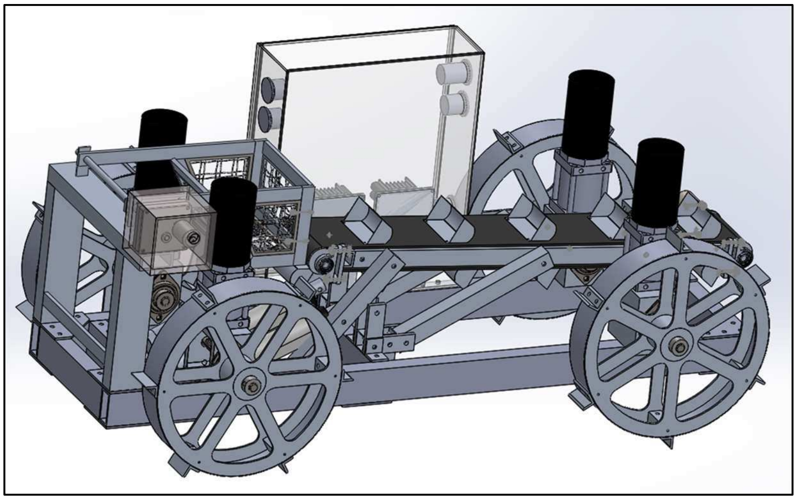


Fig. 2.7: Completed CAD of SCOOPS shows a clearance of all components.

2.4.2.1 Mobility & Frame

The main frame of the robot is made from a 51x25mm thick wall extruded 6061 aluminum bars butted together at the corners and fastened with plates on top and bottom of each joint. Bars are hollowed to cut down on mass and weight. Drilling holes in the bars was considered, but due to the malleable nature of aluminum 6061, solid frames were chosen to keep structural integrity, prioritizing the flexible material over the slight additional weight from not removing excess. 6mm diameter bolts are used to fasten the plates through the long side of the bar, with three bolts on the long bar and two on the short one which are then tightened with nylon-insert locking nuts. All mounted features used this mounting system. The use of thick wall aluminum allowed these fasteners to be tightened heavily without deformation of the material.

The wheels consist of the grousers, blocks, rim, axle, and wheel face with an overall diameter of approximately 305mm. The wheel is made entirely of aluminum for strength and weight, therefore cutting down on costs. The axles are milled, and the wheel faces are press-fit together and welded to the axles. Due to the low melting point of aluminum 6061, welding the wheel faces to the axels caused slight warping. Attaching the wheel faces to the blocks helped force them in place. As aluminum 6061 can lose up to 40% of strength with welding if not properly heat treated afterwards, a stress analysis was conducted (see section 2.6.4) to properly analyze possible loss of strength.

2.4.2.2 Excavator

The excavator component consists of a belt and frame, rollers and mounting assemblies, buckets, and a two-linkage linear actuator system, which allows the Electrical and Software sub-teams to constrain the diggers movement and get the depth required for regolith extraction. Custom-fabricated mounting brackets are designed for the belt's supporting linkages. This system was designed to fit inside of the robot frame while moving and extend out while stationary.

The final belt chosen for the excavator is made of neoprene rubber material with 3.05mm thickness and is flexible yet strong enough for excavation needs. The Bodine 24A Series Permanent Magnet DC Motor was chosen because it hit all the specs calculated for the digger system, including necessary Hp, torque, RPM, and voltage. It also is compact enough to fit in the confined space between edge of digger and chassis.

One issue faced was the buckets popping off the flexible belt material due to the rivets being undersized. Scoop buckets were reattached, trading out the simple rivets used and replacing them with fasteners with a larger diameter. Due to this change, the buckets can hold more weight.

2.4.2.3 Collections

The hopper beams are made of 6x19mm aluminum with a 23-gauge wire with 6mm square mesh opening that allows any BP-1 to be released and regolith to remain. The body was welded together instead of bolted. These decisions helped cut down on space and weight, which took stress off the motor. The collection's gear-motor was handed down—saving on finances—and tested to ensure required torque strength. A trade study was performed comparing motors and actuators and a motor was chosen in place of the originally intended actuator. The actuators would not have extended far enough to move the basket 90° to deposit the regolith.

Due to the low melting point of the aluminum and the size of the rod, a screw rod with nuts and epoxy is utilized to connect the motor to the basket arms. A coupler connects the motor to the screw rod to move the collection system.

The gear-motor needed to be held in place while being protected from the BP-1 and so a polycarbonate housing was constructed to cover the motor and connect it to the chassis [Fig. 2.8], while allowing electrical components to easily make their way to the Electrical sub-team E-box.

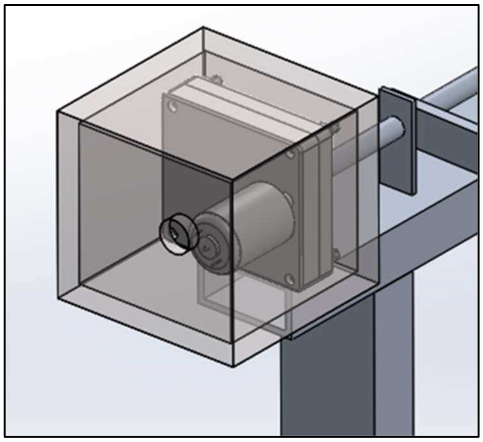


Fig. 2.8: Polycarbonate housing to keep BP-1 off the motor.

2.4.3 Software & Autonomy

The ideal end-goal of the robot was full autonomy achieved utilizing the two on-board LiDAR's to both identify the robot's current location as well as detect incoming obstacles in relation to the robot. Thus, creating an effective map of the entire arena. Exactly how this was achieved is detailed in the following sections.

2.4.3.1 Autonomy

Localization was successfully carried out using a LiDAR on the back of the rover and a target that has stripes of retro-reflective tape.

The LiDAR can detect the boundaries between the stripes due to the rapid change in reflectivity, which can then be used to find the coordinates and orientation of the robot with respect to the target through trigonometry. However, especially at larger distances, these numbers can become unreliable. To fix this problem, a Kalman Filter was implemented to reduce the error of the output. The basic functionality of a Kalman Filter is detailed in Fig. 2.9.

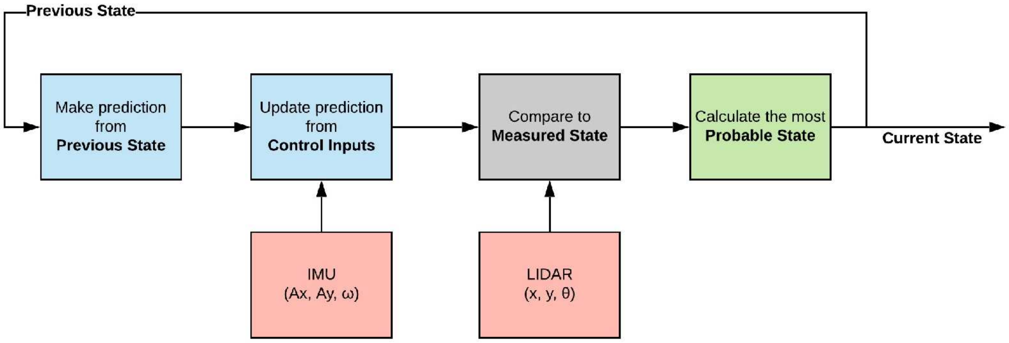


Fig. 2.9: Kalman filter functionality

With the implementation of this filter, the standard deviation of the measurement noise fell from around 50cm to around 10cm. This filtered data could now be used for obstacle detection. Another LiDAR was used on the front of the robot to scan the general terrain. Then, by setting a distance threshold, obstacles can be detected and can have their locations determined by first calculating the distance relative to the robot, and then using the localization data to determine the absolute position from the target, which is the universal origin. Boundaries of the obstacles were then successfully detected.

With the knowledge of the robot's location and obstacles' locations, the D* Lite algorithm was implemented to reliably navigate through the terrain and efficiently update the path when new obstacles are detected. D* Lite was chosen over other options, such as the more common A* algorithm, because it quickly recalculates only the affected areas of the sub-optimal nodes instead of all the node points, thus significantly reducing the necessary processing time. This is expected to decrease necessary processing time, allowing computational power to be used for other modules of the rover.

2.4.3.2 Controls

To meet the requirements, set forth in Phase B: Preliminary Design, various libraries were used to interface between the higher-level software code written and the Sabertooth motor drivers. From here, higher levels of abstractions were made, allowing for two main driving functions - Arcade Drive and Tank Drive. These functionalities map well onto the XBOX Controller; the arcade drive mode uses the left joystick to go forward and back with the right joystick turning the robot left and right, while the tank drive uses the left joystick and right joystick to control the left wheels and the right wheels, respectively. The mode can be switched in the Control Center.

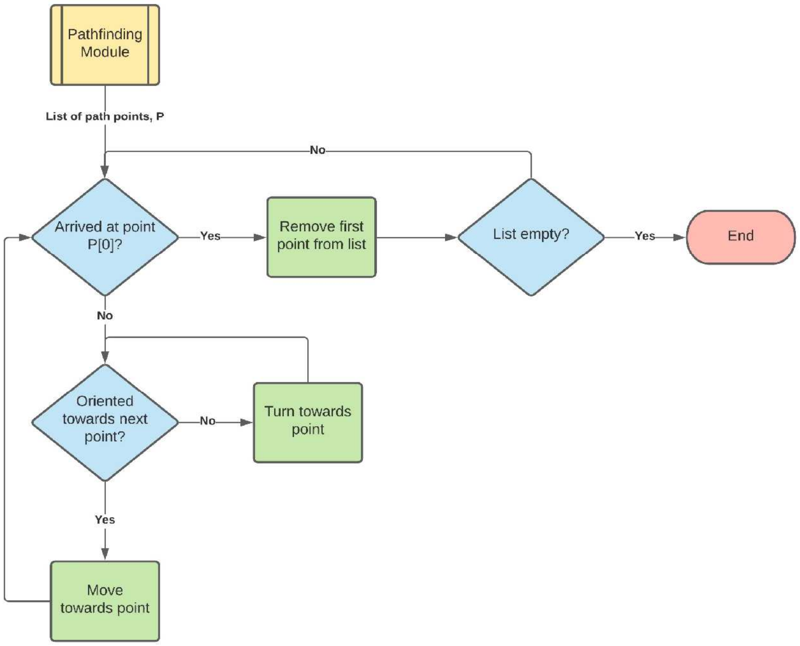


Fig. 2.10: Pathfinding module followed by the robot

For autonomous operation, the robot will take the path provided by the Pathfinding module [Fig. 2.10], which will be distilled into a list of points, and then navigates from point to point, using the Localization module to check before each movement. Consistently checking whether the robot is headed towards the point, ensures that terrain conditions, small measurement errors, or any other sources of inconsistencies do not affect the robot's navigation along the path.

2.4.3.3 Control Center

To have reliable monitoring of the robot and the data it is collecting (e.g., localization data, obstacle data, path data), a control center was constructed. The basic architecture of the final control center, and how it interfaces with the robot is seen in Fig. 2.11.

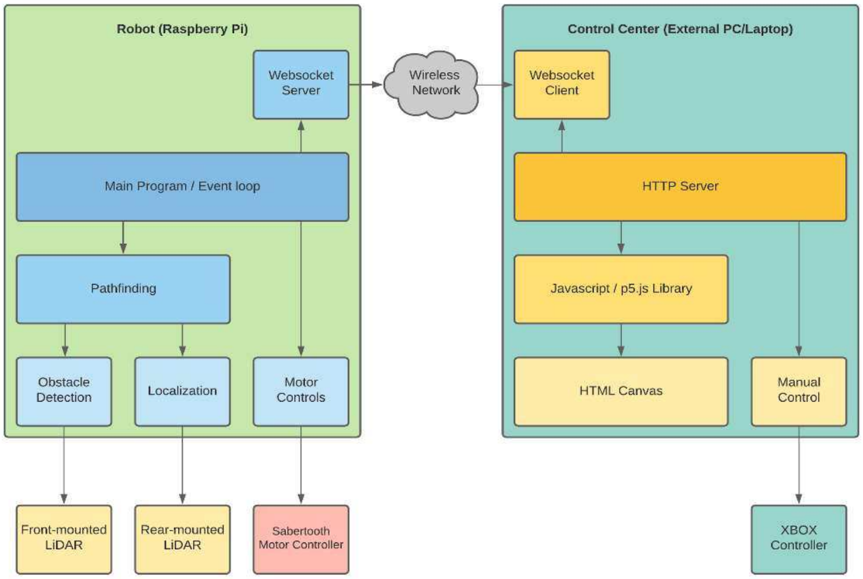


Fig. 2.11: Control center architecture

The Control Center uses a library called p5.js, which is a wrapper for the HTML Canvas JavaScript API. This allows the map to be plotted in real-time, allowing observation of the map vicariously through the robot, but with a much lower data impact than using a camera. This application also allows the XBOX Controller to manually control the robot in the event of an autonomy failure. To communicate efficiently, a simple command structure was generated.

In the future, the team hopes to expand the features of the Control Center even further to include any useful metrics on the robot, like temperature. The team will also convert the command structure into binary data instead of text to further reduce data transmission, including using Huffman coding to minimize the command type.

2.4.4 Interfaces

Preliminary design processes focused on sub-system interfaces between Mechanical, Electrical, and Software sub-teams. Previous years showed little to no consideration to this process and therefore multiple iterations of different components were rebuilt throughout the fabrication and testing process. Focusing on compatible interfaces from the beginning design phase and throughout saved on time and materials.

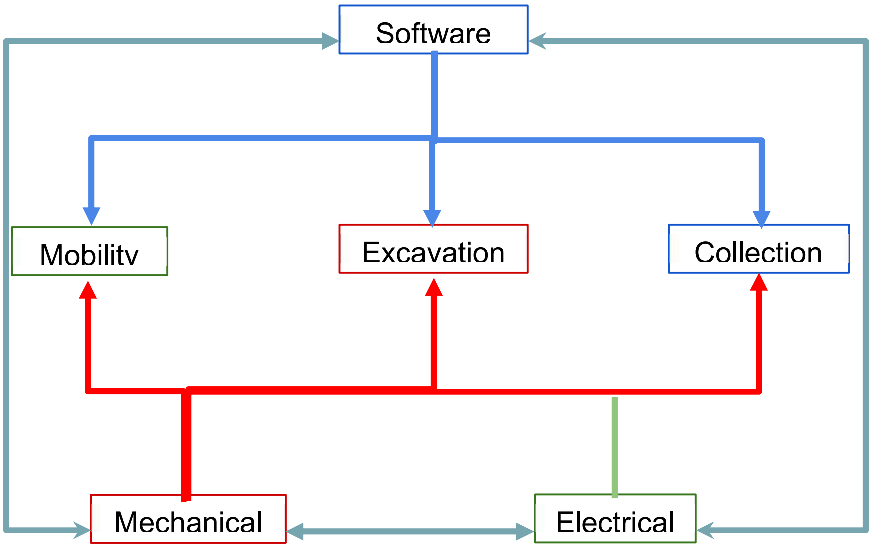


Fig. 2.12: Interfacing between sub-systems

2.4.4.1 Electrical

The electrical design of the robot was focused on the facilitation of the core design, and as such feature's heavy integration with both the Mechanical and Software sub-systems. The microelectronics portion of the design was focused on the Software sub-system. The goal of the design was to effectively pass along the requisite data to and from the on-board computer. Specifically, the microelectronics system passed along data from the inertial measurement unit and LiDAR to the raspberry pi, facilitating the mobility of the robot. After Software sub-system processes this data, commands for the motors are sent out and routed through the custom printed circuit board to the motor controllers. The power section of the design was focused primarily on enabling the Mechanical sub-system, but also maintains the functionality of the Software sub-system. The primary source of power draw in the system are the motors, which are controlled by four Sabertooth 2x60 motor controllers. These controllers' interface with all of the motors on the robot, allowing for functionality of the excavation, collections, and mobility systems. The power system must maintain proper power delivery to all these motors while also maintaining power to the microelectronics.

2.4.4.2 Mechanical

The core of interfacing for Scoops lies in the E-box, which connects power and programming to mechanical components. Each motor has its own wiring into the E-box, which allows for performance of mobility, excavation, and collections. The E-box interior was designed by Electrical to include quick-connects for any line coming out of the box. The exterior was designed by Mechanical to fit specific design parameters of the robot and prevent dust collection and the entire system was designed to interface with Software's Sabertooth motor controllers, allowing for both manual and autonomous operations to occur. While much of the Mechanical Sub-system was designed prior to E-box completion, final wiring of the robot and fastening of the E-box are expected to go smoothly due to the consideration placed on sub-system interfacing.

2.4.4.3 Software

The ability to detect obstacles and calculate the robot's current location can change drastically depending on the LiDAR location. While there are many methods with which to complete the mission, the mechanical components were decided before the final positions of the two LiDARs used to guide the robot. The Software sub-system interfaced with both Mechanical and Electrical in deciding an optimal location so that each device performs to the best of its ability and facilitates mobility without interfering with collections and excavation. The localization LiDAR was placed on the back of the chassis, at a sufficient height to always see the target; the obstacle detection LiDAR was placed on the front underside of the chassis so as to easily detect obstacles.

2.4.5 Critical Design Review (CDR)

In mid-January 2021, CDRs corresponding to the different levels of the systems hierarchy were held. The Systems Engineer determined it was best to conduct these reviews first with each sub-team then a final CDR with the entire team. The CDRs were held with a lower level to top-level approach to reflect the integration process in Phase D. In each sub-team CDR, the Systems Engineer verified if the maturity of the design was appropriate to support the fabrication, assembly, integration, and test of that system. The schedule, costs and resources allotted for each sub-system were also verified and progression to Phase D was approved.

2.4.6 Fabrication

Space exploration is full of constraints, yet technology is still produced, and missions still performed because successful engineers make it work. Scarlet Spacehawks robotics team is constrained to tight working spaces and incredibly limited finances. One way these constraints were combatted was by seeking sponsorships. The team received sponsorships from both CAD software companies and manufacturers to laser cut the wheel faces. Personal and school 3D printers were utilized to create custom parts. Ingenuity comes from what is lacking and following the design philosophy of “work with what we have,” each sub-team did just that.

2.5 - Phase D: System Assembly, Integration, Test

2.5.1 Assembly & Integration

2.5.1.1 Electrical

Integration began with the assembly of the PCB. Many of the components were contained and controlled through a custom PCB designed by the team and printed by an external vendor. With the PCB printed, the parts were soldered on and the functionality was validated, which will be discussed further in section 2.5.2.1. Once the PCB was validated, the Mechanical sub-team assembled an E-box out of polycarbonate that would house all electrical components. It was decided that as many electrical components as possible would be housed in this sealed box to protect the systems from dust. The box’s shape was chosen based on the dimensions of all the electrical components and their optimal placement for least use of wires and excess jumper cables. The assembly also needed to consider the connections between the Mechanical and Software sub-system. The Mechanical sub-system needed the electrical box placement to be efficient and optimal for volume constraints. The Software sub-system needed the electrical sub-system placement to work in a manner that the LiDAR has easy access to the computing software and the connections are reliable and safe. The integration of the electronics bay took this and any environmental hazards into account.

2.5.1.2 Mechanical

Mechanical components were assembled prior to electrical wiring to ensure mining maneuvers can perform in the optimal positioning. Some components, such as the collections bin and the wheels are currently being tested with Electrical. Mechanical sub-team is ensuring components do not interfere with LiDAR placement and testing while Electrical sub-team is ensuring wiring compliments mechanical components. Integration between these sub-systems is pivotal to ensure the robot can perform without any interference between components and wires.

2.5.1.3 Software

Software utilized several currently available programming techniques. To this end, the D* lite pathfinding algorithm served as the base for autonomously navigating the robot. Further, a Kalman Filter was used to filter high ambient noise from localization and obstacle detection data involving the LiDARs.

For software development, the entire coding system is organized by folders and component functions. There are three main folders. First one being frontend, which handles the interface and the web socket for the main interface used to control the robot. Second one is pathfinding, which handles path determination, planning, and detection. The last one is the Robot folder which contains, the main function, the actuator function, motor drive and the Kalman filter. All these are coded in Python and sync across the GitHub server. Doing so allows the Software sub-team to debug, comment or edit the block codes over the internet. It is only then assembled and compiled using the raspberry pi server at the lab. That way it is easier for testing, re-designing, and making the necessary changes to the overall program.

2.5.2 Testing

The Scoops robot is currently undergoing Phase D testing starting with the bottom of the sub-system hierarchy. Once each sub-system has been individually tested, the whole system will be tested in a controlled environment as a proof of life demonstration.

2.5.2.1 Electrical

The Electrical sub-system follows the sub-system hierarchy starting from the bottom up to the top of the sub-system. The initial tests for the components that were outsourced were performed by the manufacturers and a simple i/o test. The components made in house, such as the wiring and the PCB, were tested thoroughly to ensure that there was continuity in the circuit and the system could handle the power usage of the motors. Each motor controller was checked separately for continuity and then checked with an in-house motor to confirm the motor controller worked. After the entire sub-system was put together, the system was checked for any power surge, over the limit temperatures, and dead zones in the wiring. The testing revealed that there were none of these present in the system. With the sub-system tested, the next step was to integrate with other sub-systems and test in the same way. This was done by running a low power test on the system to see if there were any electrical issues with the system.

2.5.2.2 Mechanical

Testing for the different sub-systems included SolidWorks simulations and hands-on testing with Electrical and Software sub-teams to determine:

- **Mobility & Frame**

  Wheel deflection: if, when the max load is applied to the robot using weights, will the measured difference between the position of the frame relative to the ground vary greatly with load and without.
  Rotation: if the robot can turn 360 degrees about its center.
  Obstacle: if the robot is capable of driving out of a crater or around an obstacle

- **Excavator**

  Movement: if the trench digger can move in all required directions without interfering with other components.
  Lift: if the actuators can hold and maintain the digging angle of the trench digger.
  Digging: if the trench digger can successfully dig through both layers without putting strain on the robot frame or becoming stuck in the regolith.

- **Collections**

  Lift: if the motor can lift the hopper, loaded, in the required direction without interfering with other components.
  Depositing: if the hopper, with the max load, can repeatedly lift and dump test regolith.

Once individual sub-systems pass all tests successfully, it is ready for implementation. If not, adjustments will be made accordingly. When excavation and collection systems are individually operational, they will be tested as a complete system. If either the trench digger or collections system cannot function as a system, adjustments will be made and tested again.

2.5.2.3 Software

- **Live Localization Test**

  A live localization test of the data collected by the LiDAR was carried out by setting up the reflective target some measured distance from the LiDAR and viewing the robot's estimated localization values. Initial tests revealed the calculated values had too much variation in both axes. Thus, a Kalman Filter was added to reduce measurement noise, which succeeded in reducing the observed error.

- **Obstacle Detection Test**

  Obstacle detection tests involved using the LiDAR to develop a live visualization map of every identified obstacle. Initial tests had the software read back every point that it identified within range of the LiDAR. The control center visualization proved extremely helpful for ensuring obstacle detection was effective to the degree necessary for success by allowing the team to view obstacle data in real-time.

2.6 - Technical Management

2.6.1 - Interface Management

As there were three sub-teams working remotely this year, the team decided it would be best to implement an interface management process. Throughout the Spring semester, following the CDRs, the Systems Engineer attended select sub-system meetings to verify each sub-team was following the appropriate sub-system hierarchy. Verification that each sub-system interoperates with the other sub-systems was the main priority. As such, the full team held a weekly meeting on Tuesday nights to discuss and further verify interfaces would follow the system requirements. Sub-teams were able to interact and introduce any concerns, reducing the possibility of potential risks to arise. The weekly all member meetings proved to be so beneficial, they will be implemented into the Scarlet Spacehawks systems engineering approach for all future builds.

2.6.2 - Power, Mass, and Localization Accuracy Budgets

2.6.2.1 Mass

Per the NASA RMC rules the cost to send 1 kg of mass to space is $1.2 million. Competition regulations limit the weight of the robot to 60 kg. The Mechanical sub-team focused on keeping the design as simple and lightweight as possible. The team opted for aluminum 6061 for most of the robot because it is not only a malleable and sturdy material, but because it is extremely lightweight.

By adhering to the design philosophy and keeping materials minimum, Scoops functions at an extremely low cost to stakeholders with an estimated cost of $39.8 million.

Sub-system	Weight (kg)
Collections	2.38
Frame	1.75
Wheels + Motors	20.8
E-box	2.5
Excavator	5.74
TOTAL	**33.17 kg**

Table 2.3: Mass Budget

2.6.2.2 Power

The electrical sub-team was responsible for the management of power draw in the robot. Many of the decisions made in the design of the electrical sub-team were framed as a compromise between power draw and reliability. The most extreme example of this decision comes in the mitigation of brownouts. The motor controllers used led to spikes of power draw that were rather excessive, and when all four of the motor controllers spiked simultaneously it was quite possible for the robot to brownout. To avoid this issue without radically adjusting the design, it was decided to add a second battery and accept the power draw spikes. While this does not optimize effectively for power draw, which will affect the robot's performance and ability to operate for long periods of time, it does vastly improve the robot's reliability in operation. By choosing to prioritize reliability over power draw, the overall performance of the system has been optimized. This is, of course, not to say that the team did not optimize the system for power draw. Using current sensing resistors, the team measured the current going through the motors and attempted to allow the system to see it was stalled and stop wasting power.

Overall, the priority of the electrical sub-team ended up shifting towards reliability over the course of time, but the team still agrees the overall power draw of the robot stays within acceptable limits.

2.6.2.3 Localization Accuracy

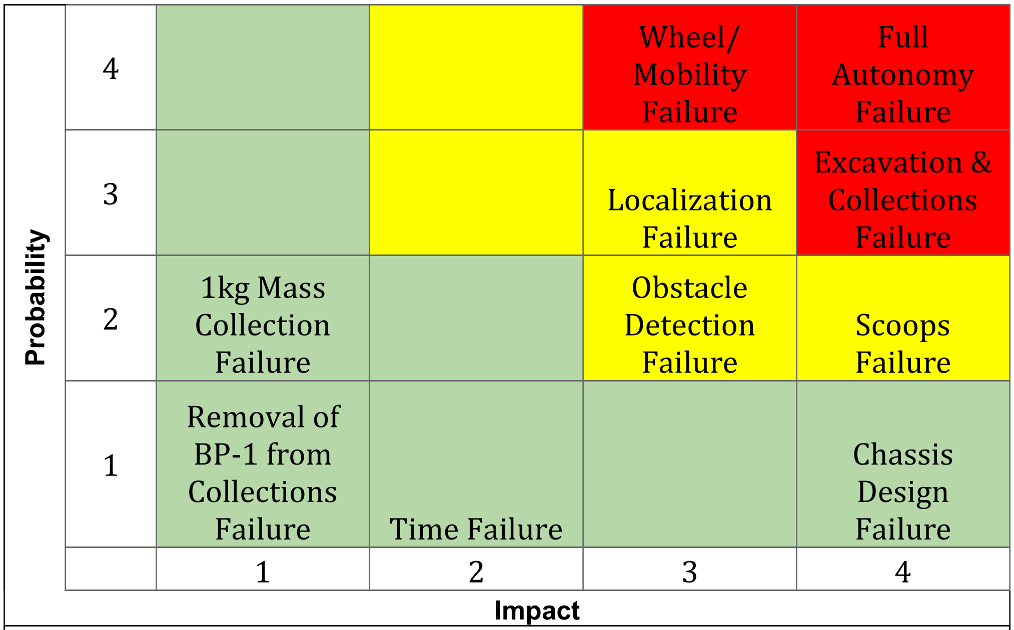
As per the NASA rules and rubric section 7.5, scoring, a team can earn up to 300 points for a completely autonomous run. As a result, the software team sought to ensure the accuracy of the Localization module, as it was determined to be the cornerstone of autonomous operation. During the Preliminary Design, the aim was to have an error of at most +/-15cm at a distance of 3.6 meters, which is specified as the beginning of the mining area. This goal remained constant throughout the entire design process.

During the initial run with the LiDAR data alone, the error was closer to 50cm, which is a non-starter for complete autonomy, and would almost certainly result in an autonomous failure. However, after tweaking the calculations and implementing the Kalman Filter, the observed error dropped down to roughly +/- 10cm, which is within the goal range.

2.6.3 - Risk and Reliability

Several risks were noted by each sub-team during the preliminary design phase and within each major review of the robot. Starting with the system hierarchy and the overarching goal of Full Autonomy, Chief Engineers rated highest risk to lowest risk of having a fully autonomous system. With a Probability vs. Impact chart the team ordered risks to focus on the most important.

On the Y-axis is Probability: the likelihood of failure with 1 being lowest, and 4 being highest probability of failure. On the X-axis is Impact: what that failure would mean for the robot, with 1 being lowest impact, and 4 being highest impact on the robot. Since Full Autonomy, Wheel/Mobility, and Excavation & Collections have components that include all three sub-teams of Mechanical, Electrical, and Software, there are far more possibilities of failure, so those systems were colored in RED; if they fail, the robot fails.



Probability					
	4	🟩	🟨	🟥 Wheel/ Mobility Failure	🟥 Full Autonomy Failure
	3	🟩	🟨	🟨 Localization Failure	🟥 Excavation & Collections Failure
	2	🟩 1kg Mass Collection Failure	🟩	🟨 Obstacle Detection Failure	🟨 Scoops Failure
	1	🟩 Removal of BP-1 from Collections Failure	🟩 Time Failure	🟩	🟩 Chassis Design Failure
		1	2	3	4
		Impact			

Table 2.4: Probability vs. Impact chart used to rate possible risks

The highest risk mitigation went toward Full Autonomy in mobility, excavator, and collections. Without any one of these three, the robot is non-functional.

Failures in any one of these systems would be catastrophic therefore mitigation went primarily toward those sub-systems in Mechanical, Electrical, and Software.

Full Autonomy: One of the biggest ways that the software team accounted for possible autonomous failure is through the construction of the Control Center (see section 2.4.3.3). The Control Center allows the team to monitor the robot and ensure the data it is collecting is conducive to a successful run. It also enables an easy way to detect if it gets stuck, is caught in a loop, or some other unforeseen error. This helps tremendously during testing, as any errors in the autonomous operation can be detected and fixed. During an actual mission, though, the Control Center will allow the team to recover from an autonomy failure by taking over manual control of the robot, mitigating the risk involved. Once the robot has recovered, the robot can be put back into autonomous mode.

Excavation & Collections: Both sub-systems were designed to keep over-engineering at bay; with fewer parts, the fewer risks, and failures there were. In place of an actuator lifting the Collections basket, a housed motor was installed, cutting down on possible BP-1 building in the actuator and causing jams. A simple conveyor belt design was chosen to cut down on moveable parts, adding "jaws" to the scoop buckets to help pick up regolith. Only two actuators and one motor are needed to dig and deposit in the Collections basket.

Wheel/ Mobility: Each wheel was equipped with its own motor not only ensuring enough power to help other wheels overcome obstacles, but to make up for a possible failed motor.

2.6.4 - Stress Management

ANSYS was utilized to ensure proper loading and stress response of each sub-system. With aluminum 6061-T6 having a yield strength of at least 240 MPA, there was little fear of failure; but with the metal bars of the chassis being reused and the design remaining simple, analysis would confirm the bars could withstand the forces. Only a small amount of higher stress (in yellow) was visible near the center bar and the team was confident the chassis could withstand the weight of the various system components.

As welding can cause aluminum 6061 to lose a significant amount of yield strength, stress analysis on the wheels was conducted. Pre-welding, the material has a yield strength of 290 MPa so in analysis 160 MPa was used to reflect the possible 40% loss in strength. In Fig. 2.23 of Appendix C, where the red looks alarming, the total deformation is negligible. To ensure shareholders that, over time, the wheels would perform, reinforcement blocks were installed.

In response to the buckets catching on the conveyor and popping off the neoprene belt, the excavation sub-system was the next component tested. The model was numerically analyzed on ANSYS and the geometry was refined by focusing on two subsequent buckets of the conveyor belt to justify the computational time. The stresses were generated on the localized high concentration areas and with the analysis confirming reinforcement procedures, the buckets were attached with large area washers with no fear of the neoprene failing.

Next, the hopper was analyzed to ensure the motor could lift the basket with a 20N force down and to ensure the threaded rod could endure the force. The structure was verified with the torque 2.6 N-m from the motor to carry the weight in hopper basket of 20 N. The analysis was modeled locally on the hopper and the geometry was focused on a static structural approach. In order of ensure structural safety, a load with twice the magnitude was considered. As seen from the images in Appendix C, all stresses stayed well within a safe range, ensuring the hopper would perform as expected.

2.7 - Project Management

2.7.1 - Schedule of Work

Initially, the team believed the build could proceed as it had in the past, but due to the COVID-19 environment, it became apparent this would not be the case. With a new mindset, the team created the planned Gantt chart, found in Appendix B, which included tentative shop days based on school sanctioned working hours and group size allotment as well as the original RMC competition days. This chart also included some Outreach events that were cancelled due to unfortunate circumstances. Since the Fall semester was dedicated to Pre-Phase A through some of Phase C, many deadlines were hit as they could be completed remotely. As such, no changes were made to the Gantt chart and the schedule was followed closely. The Spring semester is where the changes occurred and the revised Gantt chart, found in Appendix B, was tentatively followed. Electrical sub-team faced an issue when their space was suddenly combined with another on-campus organization. The team took initiative and created a Calendly to schedule all meeting times for both Scarlet Spacehawks and the other organization. In doing so, school group guidelines were followed and Electrical could proceed without interruption. The Mechanical sub-team faced a similar situation for scheduled shop days. The on-campus mechanical shop is run by one faculty member and unfortunately, this led to the shop being closed and reservations being cancelled multiple times throughout the semester. Since much of the system integration of the robot revolved around certain mechanical components being in place and functioning, Scoops was not completed by the initial completion date of March 15th, 2021. Scoops will be completed in time to perform a proof of life demonstration for the competition and satisfy stakeholders requirements.

2.7.2 - Financial Budget

The Scarlet Spacehawks have received funding from the Illinois Institute of Technology Student Government Association (SGA) Financial Board. Because of the COVID-19 situation, the team reached out to fewer sponsors which led to a smaller budget than past years. This factor helped the team create the design philosophy of “using what we had.” During the fabrication process, used parts were utilized which led to the total money

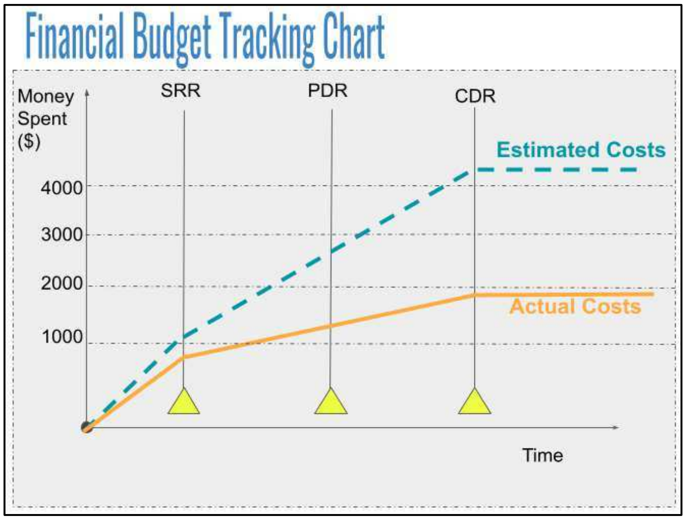
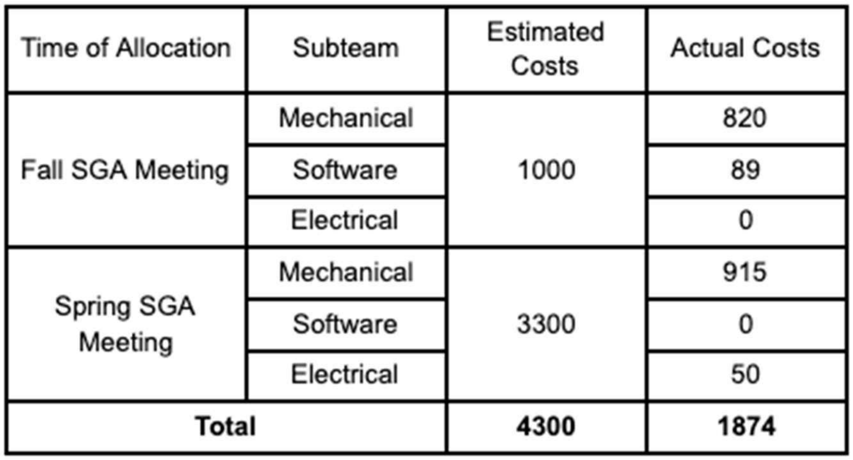


Fig. 2.13: Financial Budget Tracking Chart

spent to be much less than the estimated budget. Table 2.5 and Fig. 2.16 show team spending throughout the year-long project.

The Treasury Lead assumed the responsibility of purchasing the project equipment with the approval of at least one other executive board member, documenting each purchase, and keeping track of all accounts to ensure that the project stayed under budget. The Treasury Lead was also responsible for attending the SGA finance meeting to request money for the project. The budget was then re-organized based on the approved funds.

There were additional estimated travel expenses for the competition at the Kennedy Space Center which would be funded by the school; however, these funds were no longer needed once the in-person portion of the competition was canceled.



Time of Allocation	Subteam	Estimated Costs	Actual Costs
Fall SGA Meeting	Mechanical	1000	820
	Software		89
	Electrical		0
Spring SGA Meeting	Mechanical	3300	915
	Software		0
	Electrical		50
Total		**4300**	**1874**

Table 2.5: Budget including Estimated and Actual costs

3 - Conclusion

Scarlet Spacehawks developed Scoops, an excavating robot proof-of-concept for future NASA missions. The team created a design philosophy to recycle as many materials as possible and adhered to this philosophy throughout every phase. Due to the Concept Studies, a new design was chosen based on a conveyor belt system. The new system, along with the collections hopper, excavator, electrical box (E-box), and autonomous software have been integrated to form a working excavator. Through every review meeting, both the financial budgets and technical performance measurements were reviewed and adjusted based on any new findings. By adhering to a system engineering approach, problems were addressed before they could occur, saving the team valuable time and money in the build. The final system validation will be performed in early April as a demonstration and will confirm a successful mission, satisfying both the system requirements and stakeholders.

4 - References

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Appendix A - Systems Engineering Model & Hierarchies

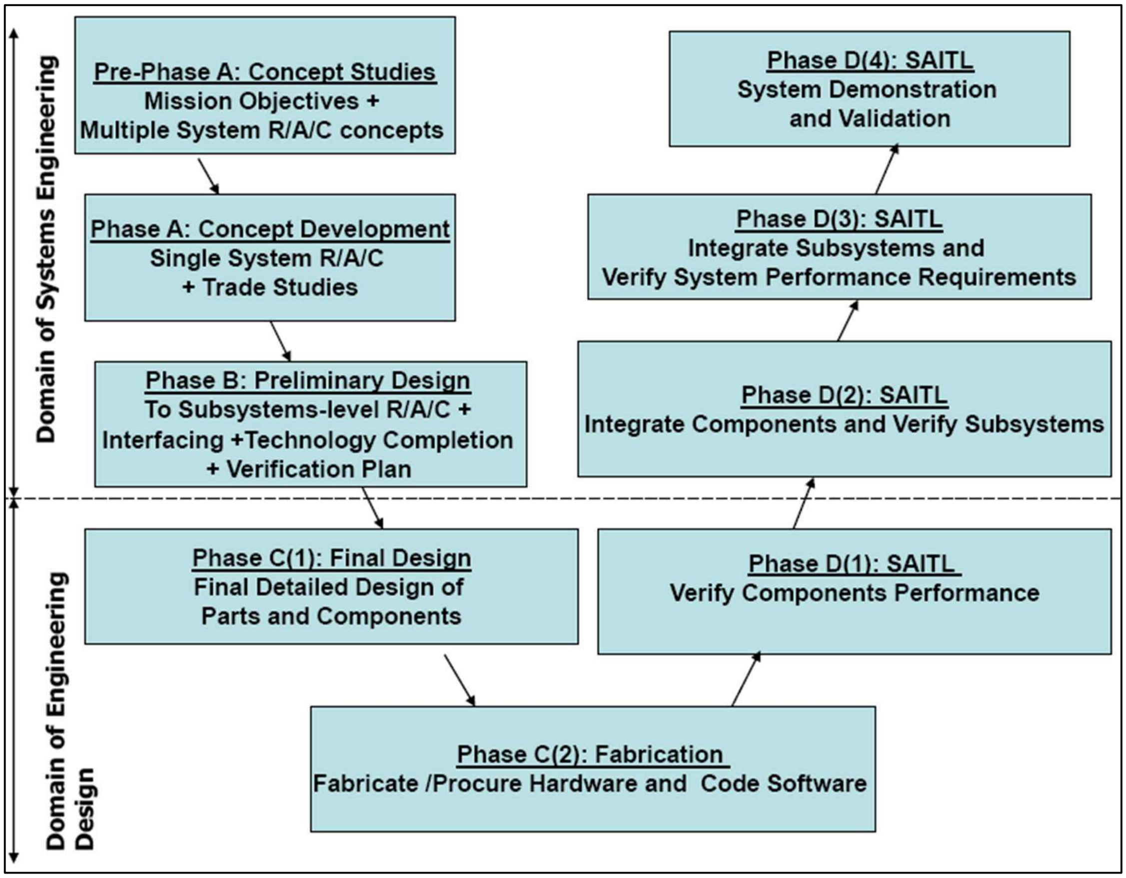


Fig. 2.14: Vee Chart Process Model of the Life Cycle

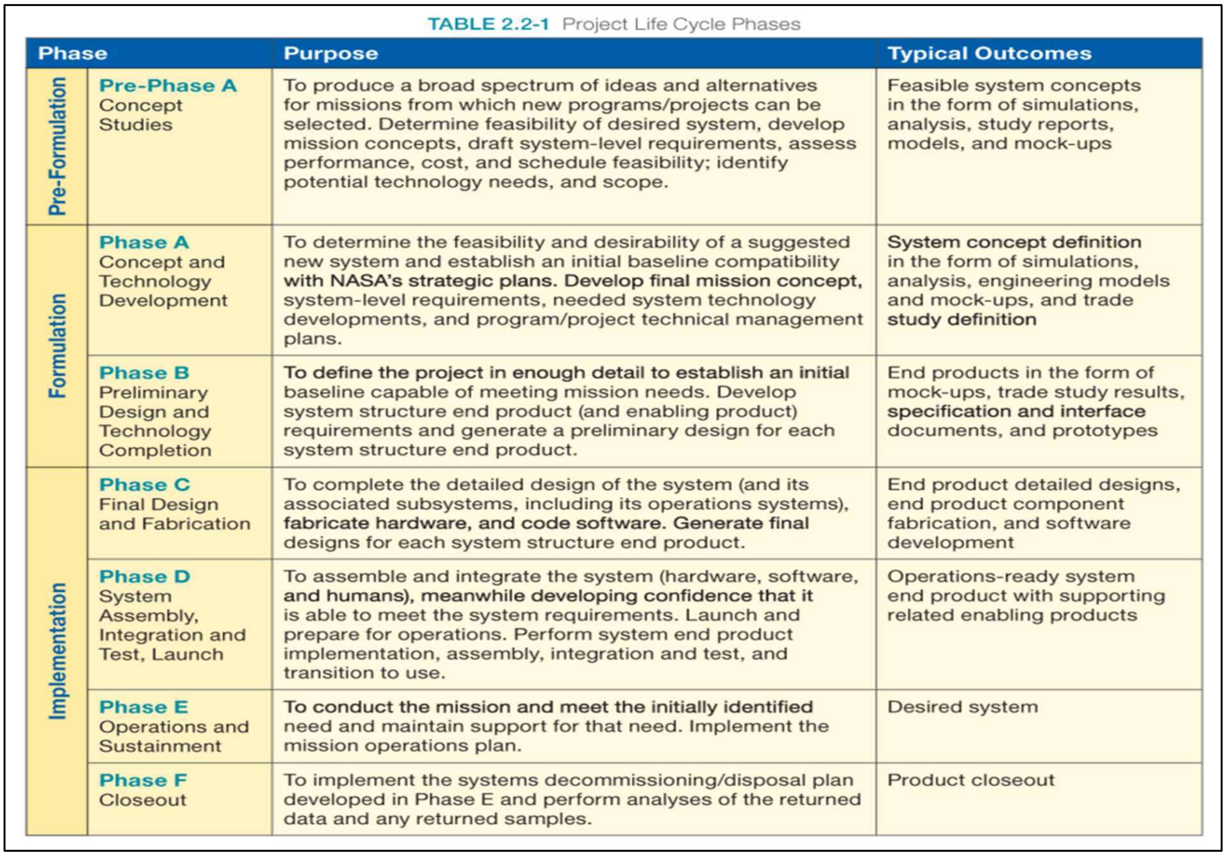


TABLE 2.2-1 Project Life Cycle Phases

Phase		Purpose	Typical Outcomes
Pre-Formulation	**Pre-Phase A** Concept Studies	To produce a broad spectrum of ideas and alternatives for missions from which new programs/projects can be selected. Determine feasibility of desired system, develop mission concepts, draft system-level requirements, assess performance, cost, and schedule feasibility; identify potential technology needs, and scope.	Feasible system concepts in the form of simulations, analysis, study reports, models, and mock-ups
Formulation	**Phase A** Concept and Technology Development	To determine the feasibility and desirability of a suggested new system and establish an initial baseline compatibility with NASA's strategic plans. Develop final mission concept, system-level requirements, needed system technology developments, and program/project technical management plans.	System concept definition in the form of simulations, analysis, engineering models and mock-ups, and trade study definition
	Phase B Preliminary Design and Technology Completion	To define the project in enough detail to establish an initial baseline capable of meeting mission needs. Develop system structure end product (and enabling product) requirements and generate a preliminary design for each system structure end product.	End products in the form of mock-ups, trade study results, specification and interface documents, and prototypes
Implementation	**Phase C** Final Design and Fabrication	To complete the detailed design of the system (and its associated subsystems, including its operations systems), fabricate hardware, and code software. Generate final designs for each system structure end product.	End product detailed designs, end product component fabrication, and software development
	Phase D System Assembly, Integration and Test, Launch	To assemble and integrate the system (hardware, software, and humans), meanwhile developing confidence that it is able to meet the system requirements. Launch and prepare for operations. Perform system end product implementation, assembly, integration and test, and transition to use.	Operations-ready system end product with supporting related enabling products
	Phase E Operations and Sustainment	To conduct the mission and meet the initially identified need and maintain support for that need. Implement the mission operations plan.	Desired system
	Phase F Closeout	To implement the systems decommissioning/disposal plan developed in Phase E and perform analyses of the returned data and any returned samples.	Product closeout

Fig. 2.15: Table 2-2.1 Phases Pre-A thru D

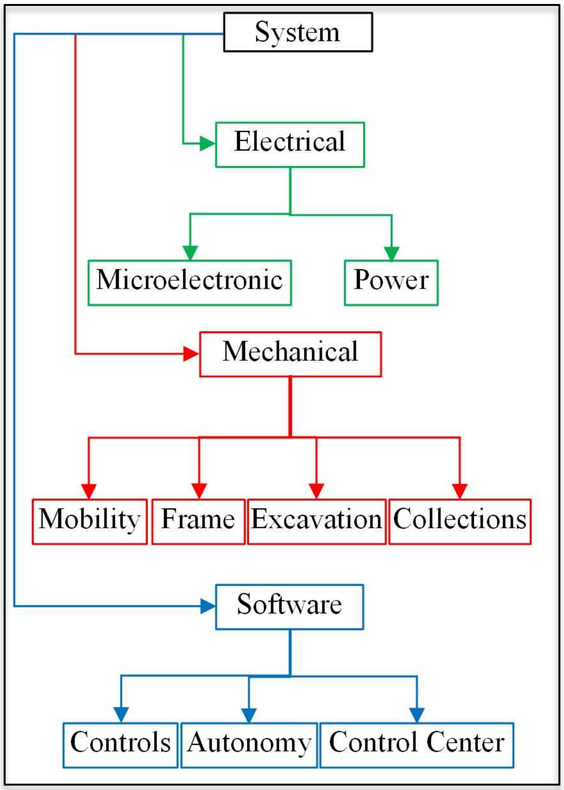


Fig. 2.16: System Hierarchy

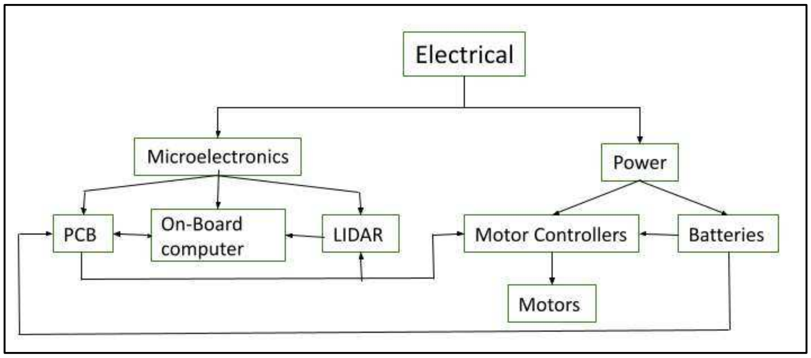


Fig. 2.17: Electrical sub-system hierarchy breakdown in two main components: Microelectronics and Power

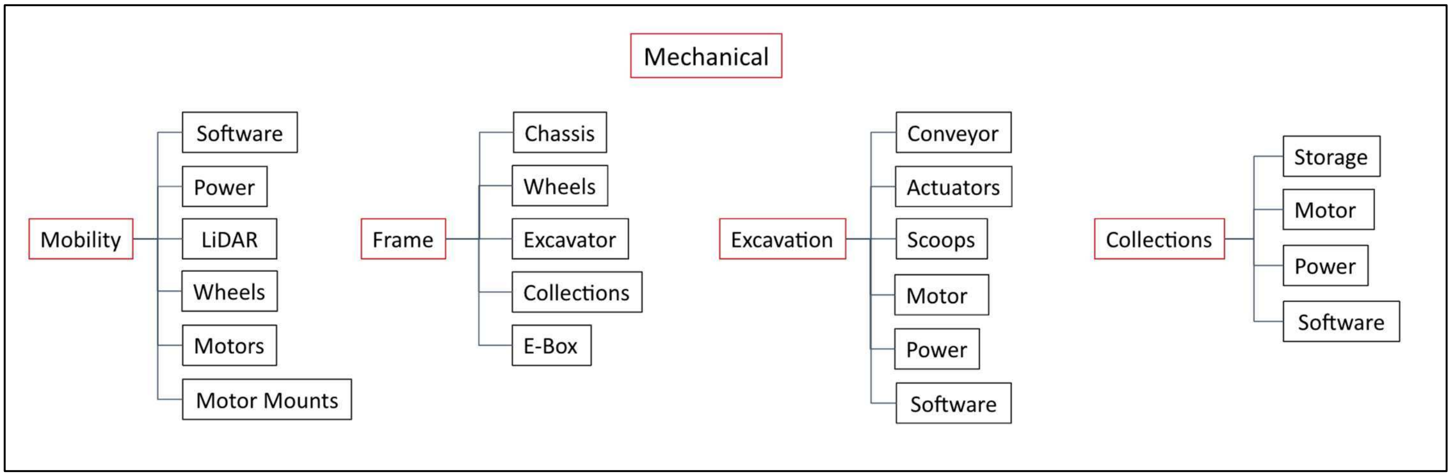


Fig. 2.18: Mechanical sub-team system hierarchy breakdown in four main components: Mobility, Frame, Excavation, & Collections

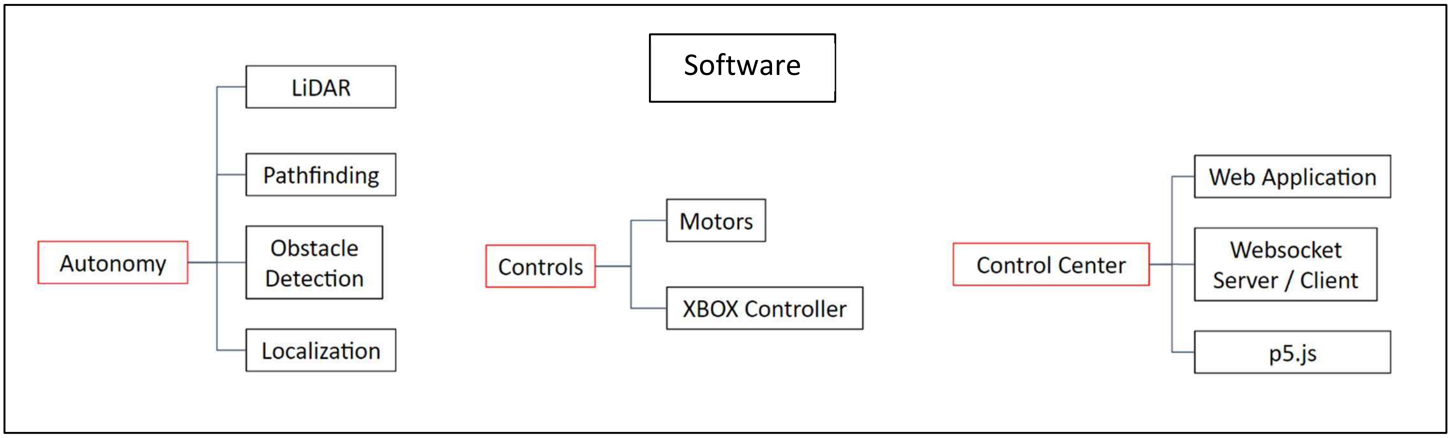
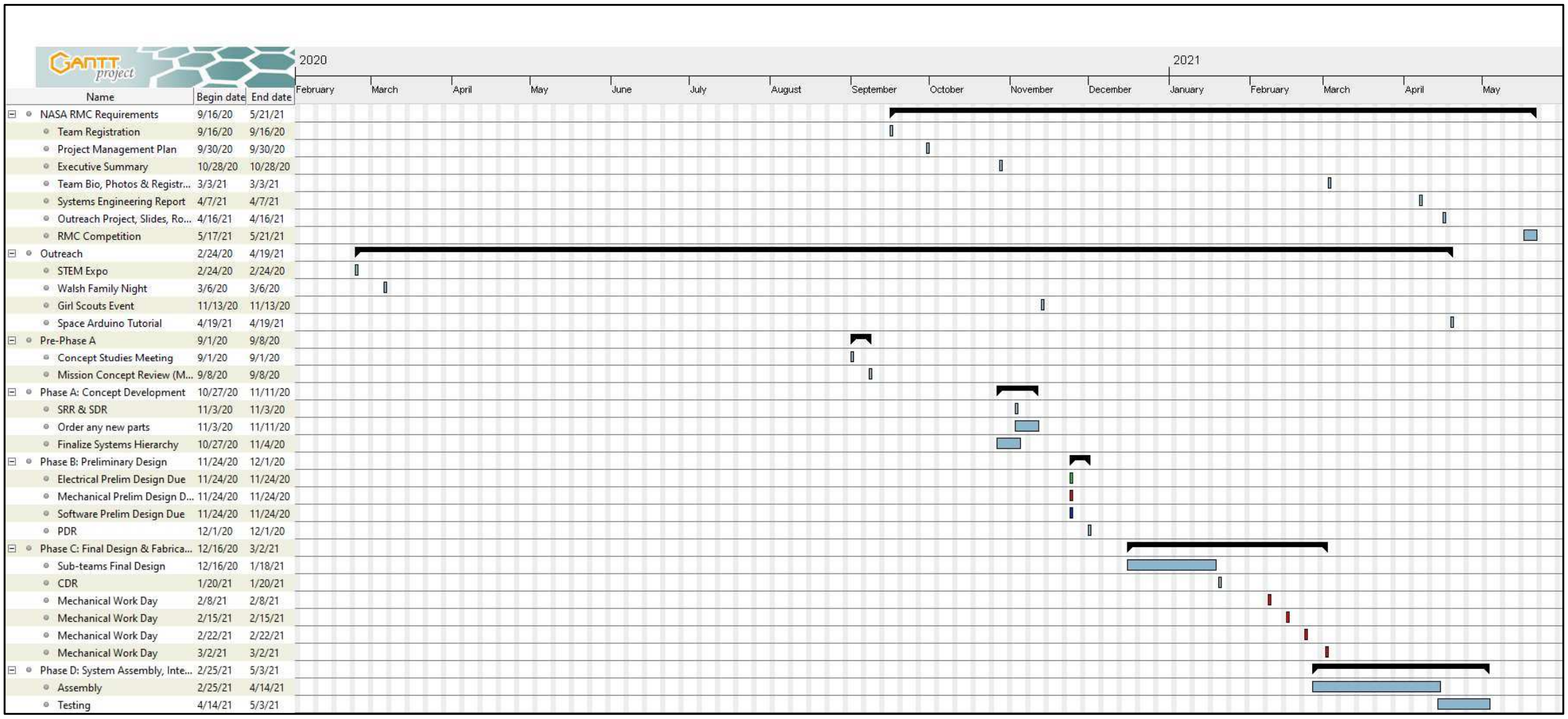


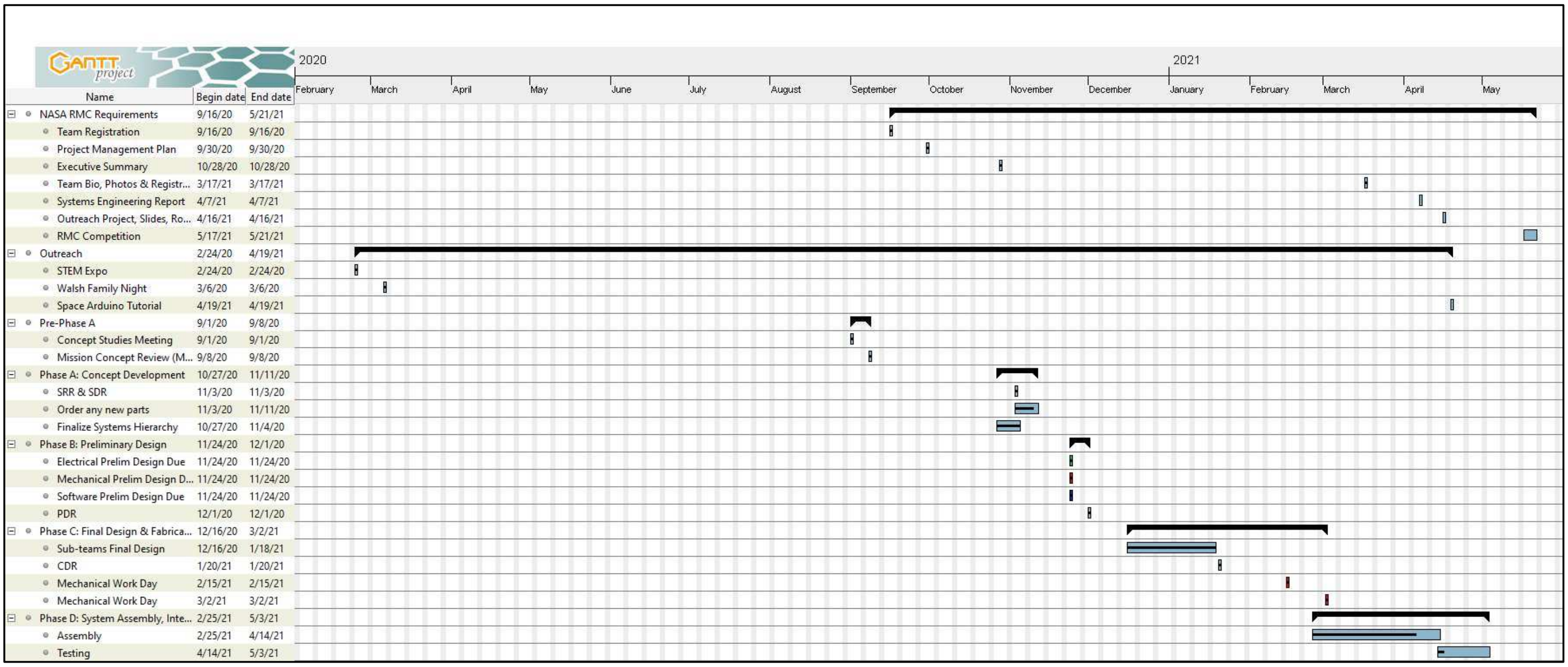
Fig. 2.19: Software sub-team system hierarchy breakdown in three main components: Controls, Autonomy, and Control Center

Appendix B – Gantt Charts



Name	Begin date	End date
NASA RMC Requirements	9/16/20	5/21/21
Team Registration	9/16/20	9/16/20
Project Management Plan	9/30/20	9/30/20
Executive Summary	10/28/20	10/28/20
Team Bio, Photos & Registr...	3/3/21	3/3/21
Systems Engineering Report	4/7/21	4/7/21
Outreach Project, Slides, Ro...	4/16/21	4/16/21
RMC Competition	5/17/21	5/21/21
Outreach	2/24/20	4/19/21
STEM Expo	2/24/20	2/24/20
Walsh Family Night	3/6/20	3/6/20
Girl Scouts Event	11/13/20	11/13/20
Space Arduino Tutorial	4/19/21	4/19/21
Pre-Phase A	9/1/20	9/8/20
Concept Studies Meeting	9/1/20	9/1/20
Mission Concept Review (M...	9/8/20	9/8/20
Phase A: Concept Development	10/27/20	11/11/20
SRR & SDR	11/3/20	11/3/20
Order any new parts	11/3/20	11/11/20
Finalize Systems Hierarchy	10/27/20	11/4/20
Phase B: Preliminary Design	11/24/20	12/1/20
Electrical Prelim Design Due	11/24/20	11/24/20
Mechanical Prelim Design D...	11/24/20	11/24/20
Software Prelim Design Due	11/24/20	11/24/20
PDR	12/1/20	12/1/20
Phase C: Final Design & Fabrica...	12/16/20	3/2/21
Sub-teams Final Design	12/16/20	1/18/21
CDR	1/20/21	1/20/21
Mechanical Work Day	2/8/21	2/8/21
Mechanical Work Day	2/15/21	2/15/21
Mechanical Work Day	2/22/21	2/22/21
Mechanical Work Day	3/2/21	3/2/21
Phase D: System Assembly, Inte...	2/25/21	5/3/21
Assembly	2/25/21	4/14/21
Testing	4/14/21	5/3/21

Fig. 2.20: Preliminary Gantt chart



Name	Begin date	End date
NASA RMC Requirements	9/16/20	5/21/21
Team Registration	9/16/20	9/16/20
Project Management Plan	9/30/20	9/30/20
Executive Summary	10/28/20	10/28/20
Team Bio, Photos & Registr...	3/17/21	3/17/21
Systems Engineering Report	4/7/21	4/7/21
Outreach Project, Slides, Ro...	4/16/21	4/16/21
RMC Competition	5/17/21	5/21/21
Outreach	2/24/20	4/19/21
STEM Expo	2/24/20	2/24/20
Walsh Family Night	3/6/20	3/6/20
Space Arduino Tutorial	4/19/21	4/19/21
Pre-Phase A	9/1/20	9/8/20
Concept Studies Meeting	9/1/20	9/1/20
Mission Concept Review (M...	9/8/20	9/8/20
Phase A: Concept Development	10/27/20	11/11/20
SRR & SDR	11/3/20	11/3/20
Order any new parts	11/3/20	11/11/20
Finalize Systems Hierarchy	10/27/20	11/4/20
Phase B: Preliminary Design	11/24/20	12/1/20
Electrical Prelim Design Due	11/24/20	11/24/20
Mechanical Prelim Design D...	11/24/20	11/24/20
Software Prelim Design Due	11/24/20	11/24/20
PDR	12/1/20	12/1/20
Phase C: Final Design & Fabrica...	12/16/20	3/2/21
Sub-teams Final Design	12/16/20	1/18/21
CDR	1/20/21	1/20/21
Mechanical Work Day	2/15/21	2/15/21
Mechanical Work Day	3/2/21	3/2/21
Phase D: System Assembly, Inte...	2/25/21	5/3/21
Assembly	2/25/21	4/14/21
Testing	4/14/21	5/3/21

Fig. 2.21: Final Gantt chart – revised to show the cancelled Mechanical Work Days and Outreach event

Appendix C – Stress Analysis Results

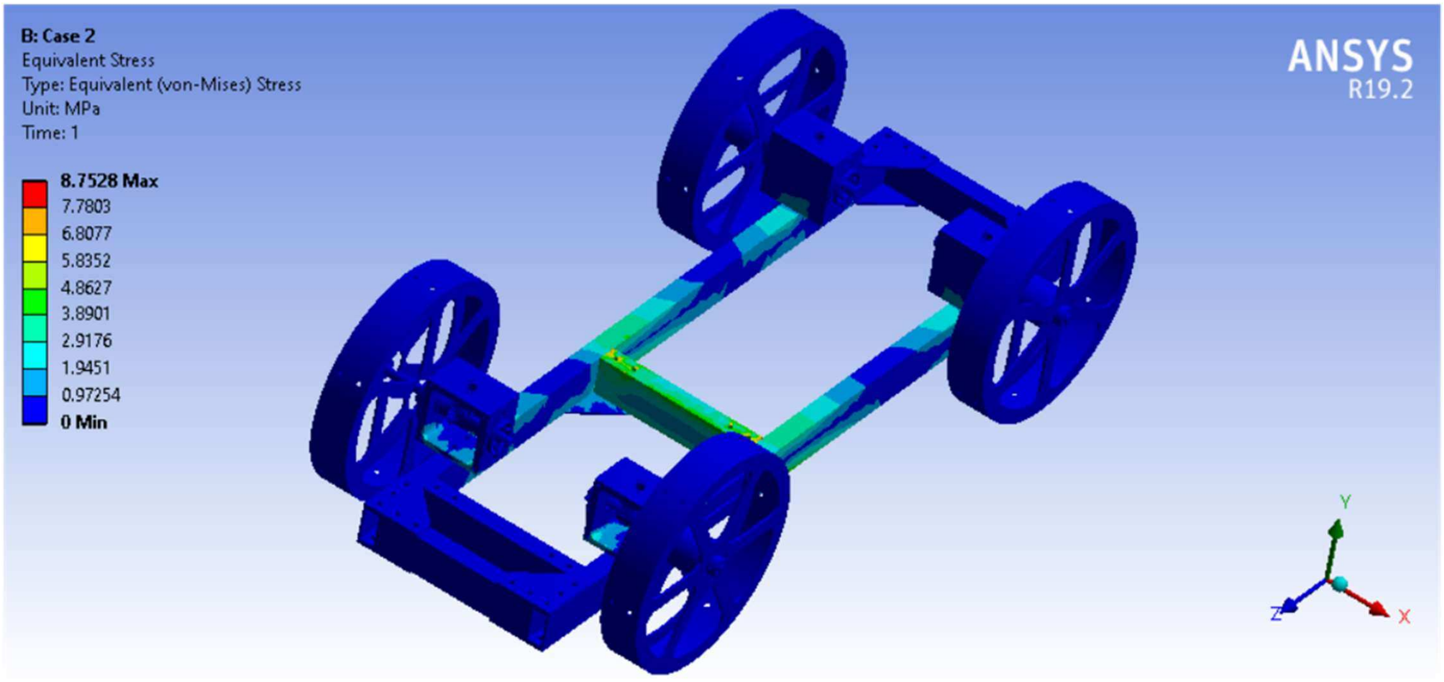


Fig. 2.22: Results of the stress analysis performed on the chassis.

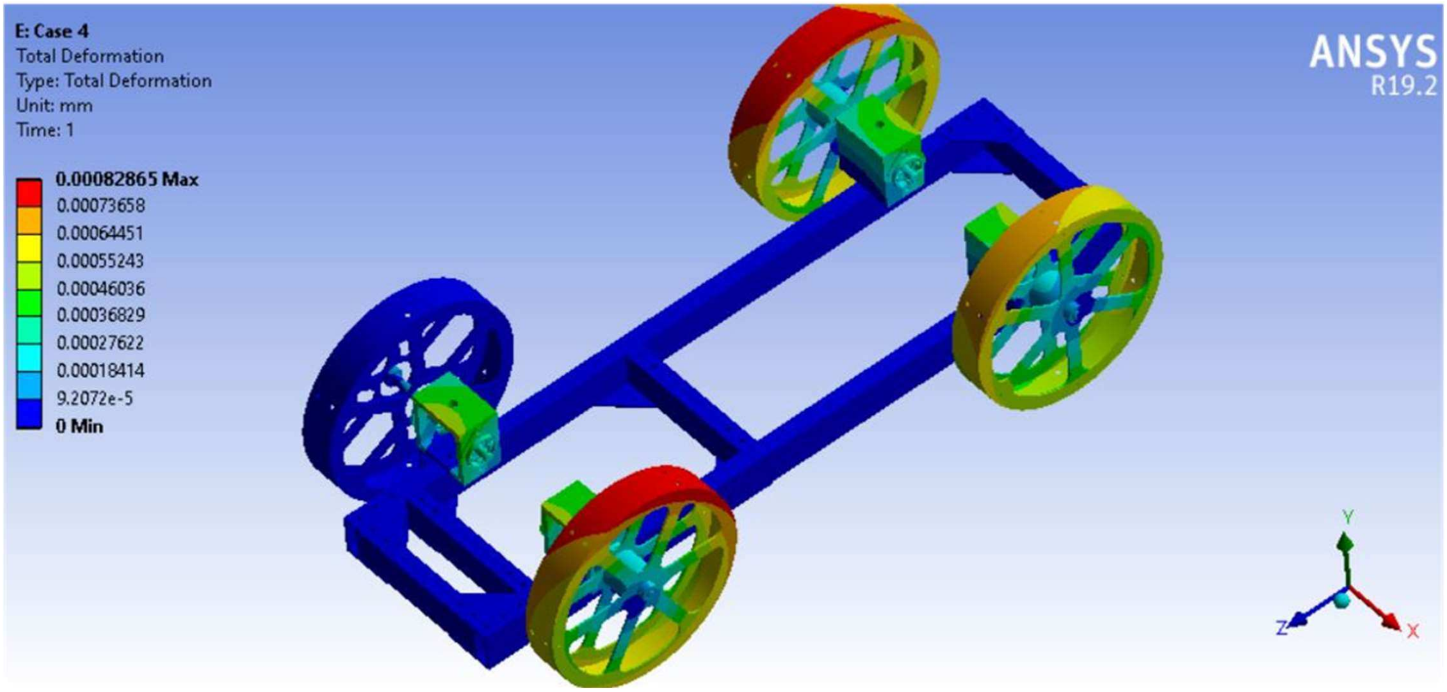
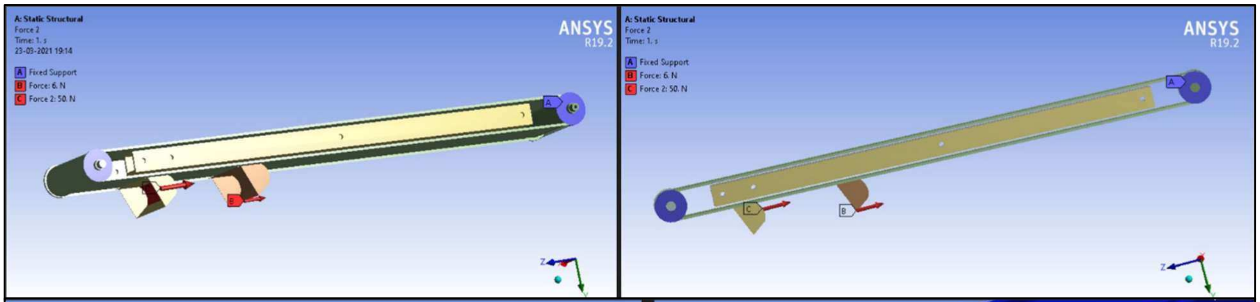


Fig. 2.23: Results of the stress analysis performed on the wheels.



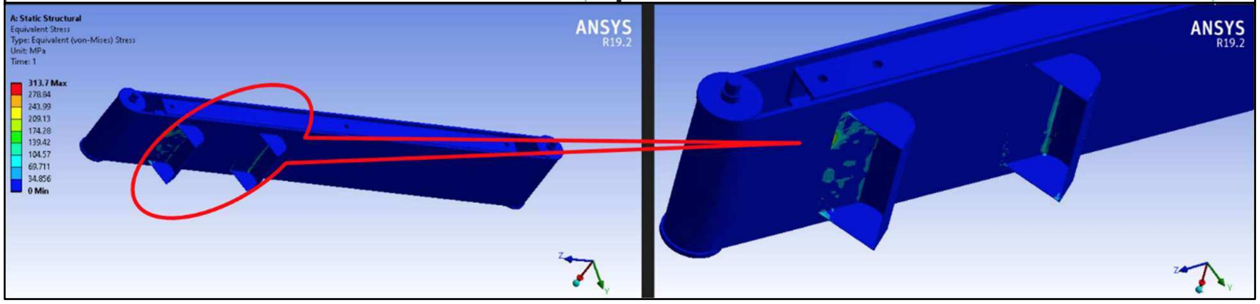
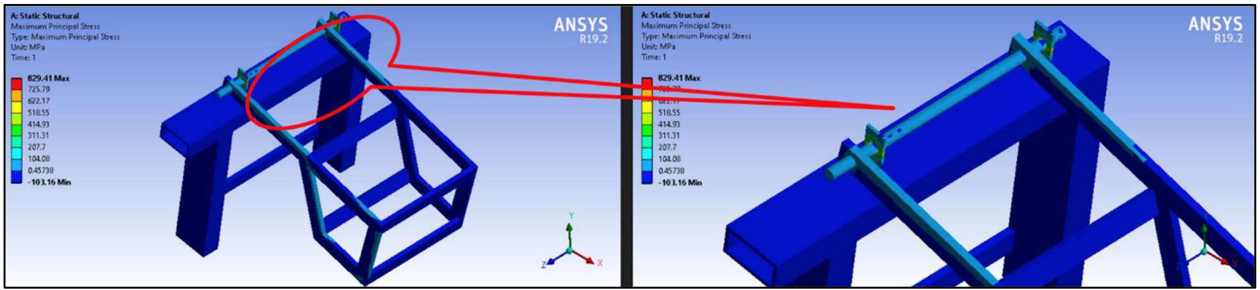


Fig. 2.24: Top Images: A 50N force was placed on buckets.

Fig. 2.25: Bottom Images: Reaction analysis shows where most of the stress is placed.



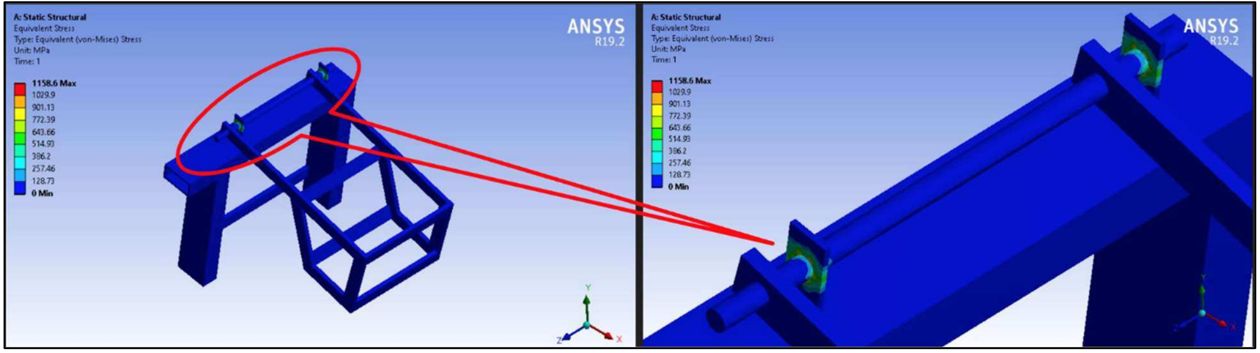


Fig. 2.26: Top Images: The threaded rod, attachment bars, and arms of the hopper took the most stress from the applied force downward from the regolith collected.

Fig. 2.27: Bottom Images: The attachment bars took the most stress from the motor.