Conceptual Design Review Report

Lunar ROADSTER

Team I

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December 12, 2024

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1 Project Description

Humanity is preparing to return to the Moon, with the Artemis missions focusing on exploring the South Pole—a region rich in sites of interest. Establishing a circumnavigating route around the lunar pole will serve as a critical "highway" connecting these sites and enabling key activities such as transportation, human settlement, and resource extraction.

A solar-powered rover capable of sun-synchronous circumnavigation could achieve perpetual operation by avoiding lunar sunsets. At high latitudes, this is feasible at low speeds, as shown in Table 1. However, these assumptions rely on the terrain being flat and traversable, free from major topographical challenges. A mission to manipulate the lunar regolith in the circumnavigating path to make it more traversable for future missions is thus, a clear step forward. A robotic system can be designed to conduct these operations efficiently for extended durations.

Table 1: Average Speed Required to Circumnavigate at Different Latitudes on the Moon

Latitude	**Distance (km)**	**Speed (kph)**
Equator	11,000	16
50°	7,040	10
60°	5,500	8
70°	3,700	6
75°	2,800	4
80°	1,870	3
81°	1,529	2.5

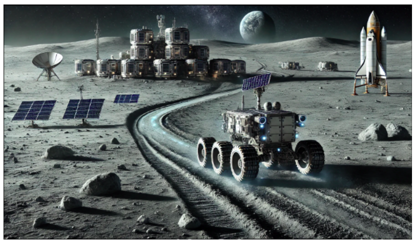
The Lunar Robotic Operator for Autonomous Development of Surface Trails and Exploration Routes (Lunar ROADSTER) is an autonomous moon-working rover, capable of finding exploration routes and grooming the lunar surface to develop traversable surface trails. These groomed trails will become the backbone for the colonization of the Moon by enabling transportation, logistics, and enterprise development.

2 Use Case

The conceptual system is visualized in Figure 1. The process begins with the system receiving detailed maps of the user-specified latitude from prior exploration missions, such as orbiters or exploratory rovers. Using this data, the system plans an optimal path around the latitude. This path avoids un-gradable terrain and obstacles while selecting craters and dunes as targets for regolith manipulation.

Once deployed, the system localizes itself using its surroundings and autonomously follows the planned path. Upon reaching a designated crater, the system plans the grooming motion for its tools and begins manipulating the regolith. The rover pushes regolith from the crater rim into the crater to fill it, smoothing the terrain.

(a)



(b)

Figure 1: Conceptual System Graphic Representation (Credits: DALL.E)

After completing the initial grooming, the system retreats to evaluate the groomed crater. If the terrain remains too steep or unsatisfactory for trail usability, the system autonomously returns to re-groom the crater. This grooming-evaluating cycle continues iteratively until the desired surface quality is achieved. Throughout this process, the system updates the mission status in real-time for the user.

Once the surface meets the criteria, the system validates the completed work, informs the user, and resumes its navigation along the planned path. This process repeats until the system reaches its final goal, leaving behind a groomed and navigable trail.

3 System-Level Requirements

The system requirements for the Lunar ROADSTER project are derived from a comprehensive understanding of the problem statement, its use cases, and the high-level objectives. These objectives shown in Figure 2, informed by inputs from stakeholders, provide a clear framework for defining the system requirements.

The requirements are organized into mandatory and desirable categories, further classified into functional, performance, and non-functional requirements. The mandatory requirements form the core functionalities essential for the project's success, while the desirable requirements, though initially out of scope, aim to enhance the system's overall performance. The requirements may evolve as the system develops, further research is conducted, and tests refine the design. The team will focus on meeting all mandatory requirements by project deadlines while working to implement desirable ones as resources permit.

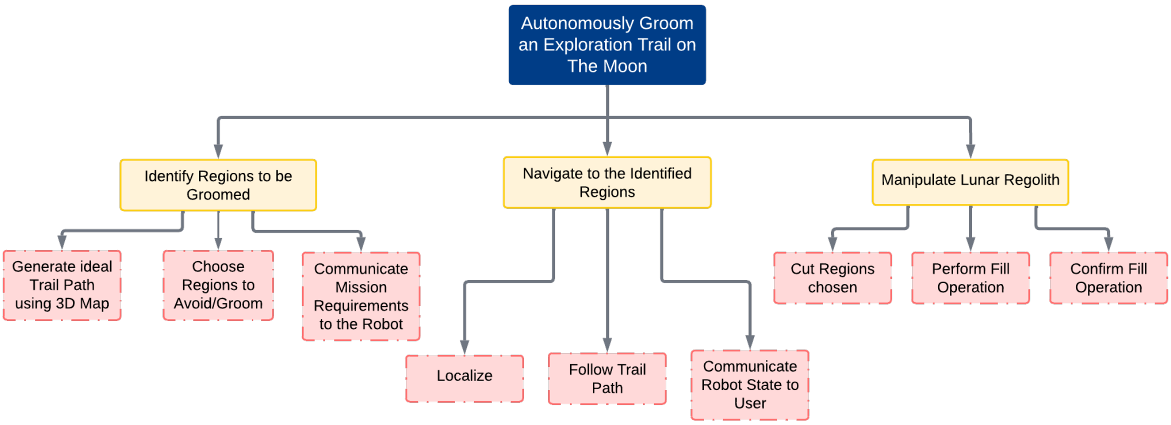


Figure 2: Objectives Tree

3.1 Mandatory Requirements

3.1.1 Mandatory Functional Requirements

Table 2: Mandatory Functional Requirements

Sr.No.	Mandatory Functional Requirement (Shall)
M.F.1	Perform **trail path planning**
M.F.2	Operate **autonomously**
M.F.3	**Localize** itself in a GPS denied environment
M.F.4	**Navigate** the planned path
M.F.5	Traverse **uneven terrain**
M.F.6	Choose craters to **groom and avoid**
M.F.7	**Grade** craters and **level dunes**
M.F.8	**Validate grading** and trail path
M.F.9	**Communicate** with the user

3.1.2 Mandatory Performance Requirements

Table 3: Mandatory Performance Requirements

Sr.No.	Performance Metrics (Will)
M.P.1	Plan a path with **cumulative deviation of** $\leq$ 25% from chosen latitude's length [4]
M.P.2	**Follow planned path** to a maximum deviation of **10%**
M.P.3	**Climb gradients up to** 15° and have a **contact pressure of less than 1.5 kPa** [5]
M.P.4	**Avoid craters** $\geq$ 0.5 **metres** and **avoid slopes** $\geq$ 15°
M.P.5	Fill craters of **up to 0.5 meters** in diameter and **0.1 meter** in depth [1]
M.P.6	Groom the trail to have a **maximum traversal slope of** 5°

3.1.3 Mandatory Non-Functional Requirements

Table 4: Mandatory Non-Functional Requirements

Sr.No.	Parameter	Description
M.N.1	Weight	The rover must weigh **under 50 kg**
M.N.2	Cost	The cost for the project must **be under $5000**
M.N.3	Computing Capacity	The onboard computer should be able to **run all required tasks**
M.N.4	Size/Form Factor	The rover should measure **less than 1 meter** in all dimensions

3.2 Desirable Requirements

3.2.1 Desirable Non-Functional Requirements

Table 5: Desirable Non-Functional Requirements

Sr.No.	Parameter	Description
D.N.1	Technological Extensibility	The system will be **well documented** and designed so that future teams can easily access and build on the work
D.N.2	Aesthetics	Requirement from sponsor, the rover must **look presentable and lunar-ready**
D.N.3	Modularity	To enable **tool interchangeability**, the tool assemblies must be modular and easy to assemble/disassemble
D.N.4	Repeatability	The system will **complete multiple missions without the need of maintenance**

4 Functional Architecture

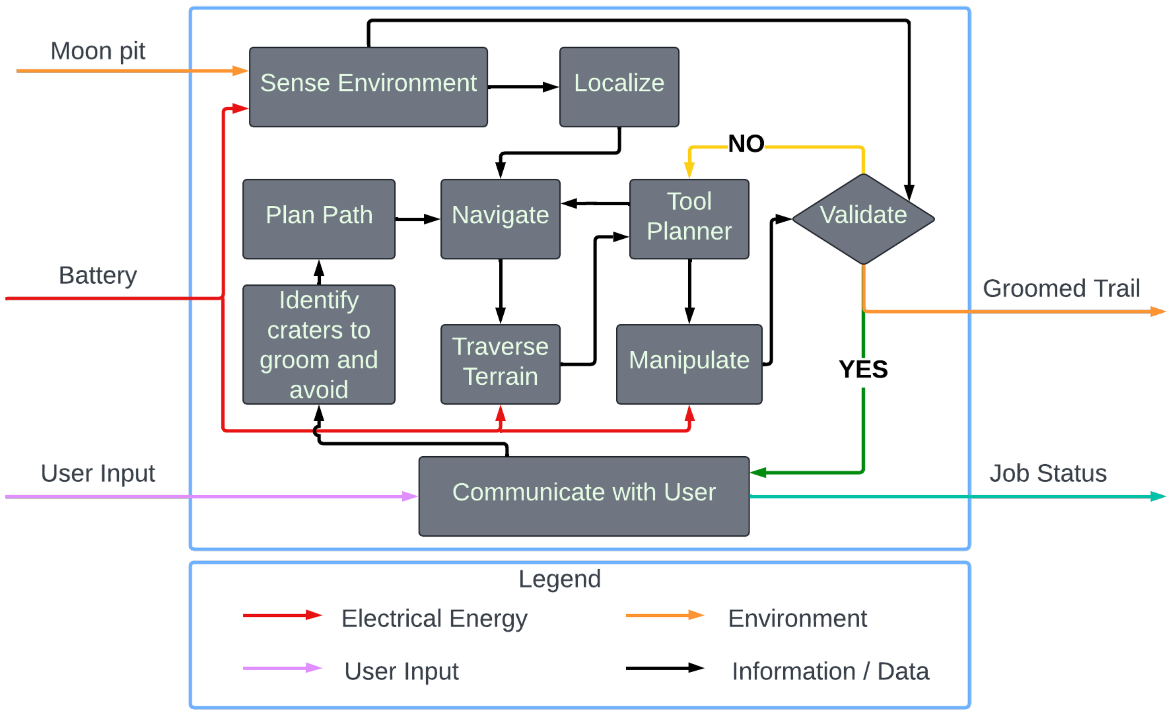


Figure 3: Functional Architecture

Figure 3 illustrates the functional architecture of our system. The system receives three types of input: user input in the form of a map of the environment from the operational terminal, battery input as the electrical energy that powers the components, and environment input from the moonpit (worksite).

The `Communicate with User` block serves as the critical interface between the user and the system. It transmits the map to the `Plan Path` algorithm and updates the user with real-time job status information for active monitoring. The `Plan Path` algorithm processes environmental information from the map to identify craters to groom and avoid. These constraints are defined in the performance requirements (M.P.4 and M.P.5). Based on this analysis, it generates precise waypoints near the craters requiring grooming and sends them to the `Navigate` block. Before initiating navigation, the robot undergoes localization through the `Localize` block, using information from the sensor stack to accurately determine its position within the environment. The `Navigate` block translates the planned waypoints into motor commands for the chassis, which are executed by the `Traverse Terrain` block, enabling the robot to maneuver through the moonpit and approach the target crater effectively.

Once positioned near the crater, the `Tool Planner` is activated, sending motor commands to the `Manipulate` block to initiate tool operations, such as excavation and grading. The grooming process is then evaluated by the `Validate` block to determine if the crater meets the specified grooming criteria, as defined in the performance requirements (M.P.6). If validation fails, the system repeats the cycle, navigating the robot back to the position near the crater and restarting the tool operation. If grooming is successful, the `Communicate with User` block updates the user with the job status, and the system outputs a groomed trail. This iterative and modular workflow ensures precise grooming operations while maintaining active user monitoring and operational reliability.

5 System and Subsystem-Level Trade Studies

Trade studies are an integral part of decision making in the systems engineering process. It identifies the most balanced technical solution among a set of proposed viable solutions and determines which viable architecture or system we should use. Rigorous trade studies were performed on the systems-level and important subsystems to determine the most viable solutions. A summary of the chosen architecture from the conducted trade studies can be found in the morphological chart in Figure 4.

5.1 Systems-Level Trade Study: Lunar Grader

A systems-level trade study was conducted to determine which lunar grader concept is best suited for meeting our performance requirements. Figure 5 identifies 4 potential concepts to use for a lunar grader. The criteria and weight factors were obtained via a weighted objectives tree and can be found in Appendix A.1.

Based on available concepts, we identified 3 different autonomous rovers suitable for lunar grading. They are the Lunar ROADSTER, Crater Grader (made by MRSD 2022 Team A), and the Offworld Dozer (made by Offworld.ai). We also include a benchmark and compare against human performance. Since lunar earth-working is a very dangerous task, we determined that safety should be of utmost importance. This is why it has a

Morphological Chart	Option 1	Option 2	Option 3	Option 4	Option 5
Path Planning	**A***	Dijkstra's Graph Search	Greedy Best First	D*-Lite	
Localization Method	**Total Station, IMU**	Sun/Star Sensor, Visual Odometry, Wheel Odometry, IMU	LRO Correspondences, Wheel Odometry, IMU	Motion Capture, IMU	Visual Odometry, Wheel Odometry, IMU
Navigate	Pure Pursuit	RRT	**Dynamic Window**	Incremental Search	
Wheels	Air Filled	**Metal**	Plastic	Treads	
Chassis	Space Frame	**Ladder Frame**	Unibody	Monocoque	
Suspension	Rocker Bogie	**Double Rocker**	Multi-Link	Trailing/Leading Arm	Macpherson Strut
Motors	BDC	**BLDC**			
Drive System	**Gearbox**	Belt Drive	Chain Drive		
Powertrain	**Lithium Based Battery**	Solar Cells	Isotope		
Decision Architecture	**Finite state machine**	Single state machine			
Cut/Fill Methodology	**Custom Algorithm**	Kubla Software			
Manipulate	Front loader	Front grader	Chassis grader	**Front loader & chassis grader**	
Validate	**Depth Camera on belly of rover**	LiDAR	Camera on top	IR Sensor on belly of rover	RADAR
Communicate With User	2.4 GHz Wi-Fi	**5 GHz Wi-Fi**	Bluetooth		
Sensor Fusion Method	**Extended Kalman Filter**	Particle Filter	Bayes Filter		

Figure 4: Morphological Chart of Cyberphysical Architecture

Trade Studies	Systems Level	Lunar Grader			
Value Ratings *	Concept	Lunar ROADSTER	Crater Grader	Offworld Dozer	Human
0: Inadequate		LUNAR ROADSTER			
2: Tolerable					
4: Adequate					
6: Good					
8: Excellent					
10: Perfect					
* Subjective Value Method					
Criteria	Weight Factor	Value (1 - 10) *			
Safety	12	7	7	9	0
Navigate autonomously	11	8	8	9	5
Ability to localize	11	8	7	9	1
Ability to grade	8.25	9	9	0	3
Ability to excavate	8.25	9	0	9	3
Traversability	8.25	7	7	5	8
Reliability	6	7	7	8	9
Weight	6	8	10	2	6
Cost	6	10	10	3	2
Tool Size	6	7	2	9	4
Repeatability	6	5	5	7	7
Operation time	4.95	7	7	9	2
Ability to communicate	3.3	8	8	8	8
Adaptability	3	6	5	5	10
Final Score	100	7.673	6.6105	6.8145	4.158

Figure 5: Systems-Level Trade Study on Lunar Grader Concept

weight factor of 12%. The 3 rovers are comparatively safe since they can operate autonomously. Contrastingly, the benchmark scores very low in safety due to human-prone accidents and a high fatality rate from space suit punctures and explosive decompression.

The ability to localize itself and navigate autonomously is also highly prioritized. This is because the aim of our system is to create a circular lunar polar highway. The concept needs to be able localize and navigate by itself so the path created does not deviate too far from its objective path. Additionally, the tool planner and the navigation planner both requires accurate localization to be able to function effectively. The three rovers all tend to perform well in these aspects, with the commercial Offworld Dozer arguably performing slightly better due to the use of commercial-grade sensors. However, the human benchmark performs poorly in this criteria. Without the proper navigational tools, humans can quickly become lost in the relatively featureless lunar surface.

Our next priority is the concept's ability to grade and excavate while maintaining traversability. This is what differentiates the Lunar ROADSTER concept from the other rover concepts. The Lunar ROADSTER concept can both grade and excavate, whereas the Crater Grader concept can only grade, and the Offworld Dozer and only excavate. The versatility of having both a grader and an excavator prove to be highly appropriate for our functional requirement of grading craters and leveling dunes (M.F.7). In the end, this is arguably the deciding factor to use the Lunar ROADSTER concept.

5.2 Subsystems-Level Trade Study: Manipulation

A trade study on which manipulation subsystem to implement is shown in Figure 6. This is arguably our most important subsystem as it pertains to our primary objective of grooming an exploration trail on the lunar surface.

Trade Studies	Sub-Systems Level	Manipulation			
Value Ratings *	Concept	Front loader	Front grader	Chassis grader	Front loader & chassis grader
0: Inadequate					
2: Tolerable					
4: Adequate					
6: Good					
8: Excellent					
10: Perfect					
* Subjective Value Method					
Criteria	Weight Factor	Value (1 - 10) *			
Excavation volume	17.5	9	1	1	7
Grading area	17.5	1	8	9	7
Manipulation effort	15	5	6	7	4
Dust contamination	12	1	5	7	7
Controllability	10	4	5	6	6
Degrees of freedom	10	7	5	5	9
Size	9	5	5	4	4
Weight	4.5	5	7	7	4
Cost	4.5	5	5	5	4
Final Score	100	4.62	5.065	5.64	6.11

Figure 6: Subsystems-Level Trade Study on Manipulation Concept

For the manipulation subsystem, we put heavy emphasis on the concept's excavation volume and grading area. This is because our path can be groomed faster when the excavation volume and grading area is large. Comparing the different concepts, the front grader and chassis grader have a high grading area, but negligible excavation volume. Contrastingly, the front loader has a high excavation volume, but is not able to grade efficiently. While not being able to perform at the level of the specialized concepts, the front loader plus chassis grader concept uniquely can achieve both a high excavation volume and a high grading area. This is the differentiation factor from the other 3 specialized concepts.

However, one drawback of the dual-machinery concept is that it requires a higher manipulation effort to operate. The size and weight of the rover chassis will also need to be larger to accommodate both a grader and loader. Despite this, the advantages of having two tools on trail grooming efficiency greatly outweigh its downsides. Thus, we have decided to use a combination of a front loader plus a chassis grader for our manipulation subsystem.

5.3 Subsystems-Level Trade Study: Localization Method

Our second most important subsystem is the localization method. This is because virtually all aspects of our rover requires accurate localization for it to function effectively. The tool planner subsystem requires localization to plan motor commands, whereas the navigation planner subsystem requires it to plan trajectories and paths. A trade study on which localization method to use is shown in Figure 7.

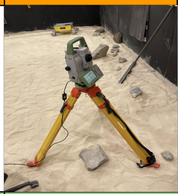
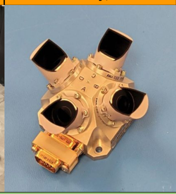
Trade Studies	Sub-Systems Level	Localization Method				
Value Ratings *	Concept	Total Station, IMU	Sun/Star Sensor, Visual Odometry, Wheel Odometry, IMU	LRO Correspondences, Wheel Odometry, IMU	Motion Capture, IMU	Visual Odometry, Wheel Odometry, IMU
0: Inadequate 2: Tolerable 4: Adequate 6: Good 8: Excellent 10: Perfect * Subjective Value Method						
Criteria	Weight Factor	Value (1 - 10) *				
Accuracy	30	8	4	6	9	4
Robustness	18	8	4	6	8	2
Computational efficiency	12	8	2	3	7	2
Lunar transferability	12	4	9	9	1	9
Reliability	12	8	5	7	9	6
Ease of use	8	9	5	5	7	2
External infrastructure dependency	8	3	9	1	1	9
Final Score	100	7.2	4.96	5.64	6.82	4.48

Figure 7: Subsystems-Level Trade Study on Localization Method

An accurate and robust localization is a necessity. This is why these two criterion constitute 48% of the total weight factor. The total station and motion capture concepts score highly in these categories due to their low localization errors. The motion capture system arguably scores slightly higher due to its ability to discern both location and orientation whereas the total station can only determine location. The sun/star sensor, Lunar Reconnaissance Orbiter (LRO), and visual odometry concepts all score relatively low due to their high localization error rates.

However, a downside of the total station and motion capture system is that they are highly dependent on external infrastructure. The total station requires at least 1 surveyor whereas the motion capture system requires at least 4 cameras to function. This is why both score relatively low in external infrastructure dependency and lunar transferability. Despite this, a total station setup is relatively reasonable for a well-established moon station. In conjunction with its high localization accuracy and robustness, we have decided to utilize a total station as our localization method.

6 Cyberphysical Architecture

The Cyberphysical architecture, depicted in Figure 8, shows how our Lunar rover is physically realized. It integrates a network of the following major subsystems: Sensors, Computations, External Infrastructure, Mechanical subsystem, Actuation and Electronics, and Electrical Power. Each component plays a specific role, with all of them working together in unison to meet the unique demands of lunar surface operations.

6.1 Sensors

The rover relies of the following set of sensors for the essential data, which are crucial for navigating and executing tasks:

- Wheel motor encoders

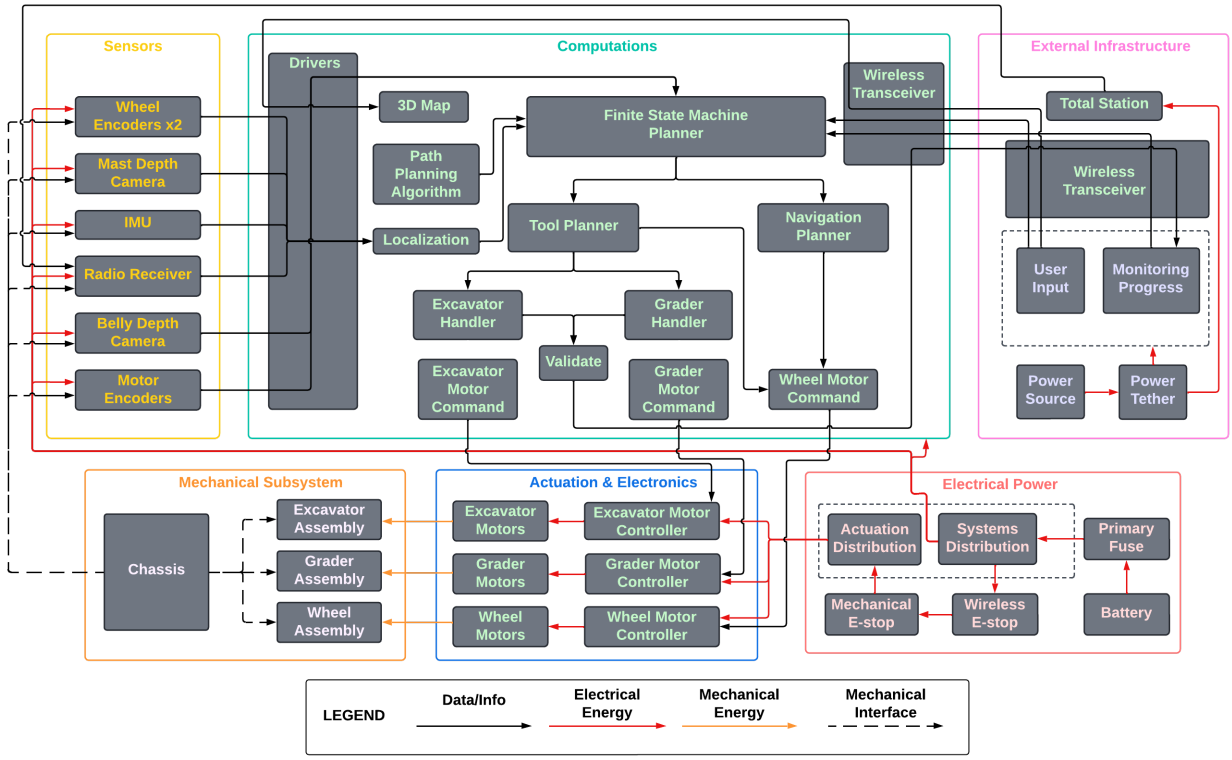


Figure 8: Cyberphysical Architecture

- Mast depth camera
- Inertial Measurement Unit (IMU)
- Radio receiver
- Belly depth camera
- Tool motor encoders

These sensors provide critical feedback on the rover's position, orientation, and material to manipulate.

6.2 External Infrastructure

The extrernal infrastructure comprises the Total Station, a Wireless Transceiver, and an Operations Terminal. The robotic total station provides precise robot pose estimates, and the operations terminal allows for seamless communication between the rover and mission control through the wireless transceiver, by providing a user interface to monitor progress and receive updates.

6.3 Computations

The computations subsystem is the processing powerhouse of the rover, where data from sensors are transformed into actions. It includes the following components:

1. The drivers form the interface between sensors and processing units.
2. A 3D map is fed into the 3D Map block through a wireless transceiver from the operations terminal. A path-planning algorithm is used to create a navigational path for the rover to follow. These tasks are done in the base station/in our laptops, and is directy fed into the brain of the rover.

3. A robotic total station in the external infrastructure, which provides precise robot pose, sends its data to the localization block.
4. The data from the total station is fused with the data from wheel encoders, mast depth camera, and IMU, and sent to the localization block, which keeps track of the rover's position on the lunar surface.
5. The FSM Planner manages high-level decision-making and receives inputs from the localization block, the belly depth camera and tool motor encoders for manipulating the regolith, and the path that the robot has to follow. The planner chooses between 2 states - the Tool Planner and Navigation Planner.
6. Tool Planner and Navigation Planner are used to coordinate tool operations and movement respectively.
7. The Tool Planner then divides into the Excavator Handler and Grader Handler to manage the specific tool functions - excavating and grading the surface. So they give the excavator motor commands and the grader motor commands respectively.
8. The two handlers also pass information into the validate block, which passes the data to the operations terminal through the wireless transceiver. At the operations terminal, the progress of excavating and grading is monitored, and is sent back into the FSM Planner as feedback, i.e., whether the surface has been excavated or graded satisfactorily.

6.4 Actuation and Electronics

This subsystem translates electrical signals into physical movements. The excavator motor controller receives commands from the excavator motor command block in the computations subsystem. The grader motor controller receives commands from the grader motor command block in the computations subsystem. And similarly, the wheel motor controller receives commands from the wheel motor command block in the computations subsystem. These controller blocks provide signals to the respective excavator, grader, and wheel motors, which then make the respective assemblies connected to them in the mechanical subsystem move.

6.5 Mechanical Subsystem

It forms the structural backbone of the rover. The main components include the Chassis, Excavator Assembly, Grader Assembly, and Wheel Assembly. This subsystem provides both the physical support required for the rover and the mechanisms needed to interact with the lunar surface. All the sensors and hardware sit on the chassis of the rover, and the excavator and grader assemblies are used to groom the trail on the Moon.

6.6 Electrical Power

This subsystem is responsible for supplying energy to the entire rover. In the operations terminal, a power source supplies power to the robotic total station as well as the operations terminal via a tether. On the rover, a battery provides the electrical power and is connected to the Power Distribution Board (PDB) through a primary fuse for safety. The PDB allocates power to the Systems Distribution block and the Actuation Distribution block. The systems distribution block supplies power to all the subsystems on the rover, and the Actuation Distribution block supplies power to the actuators – motor controllers and motors. We also have a wireless emergency stop (E-stop), which translates to a mechanical E-stop to cut off all power to the actuators in case of an emergency.

7 Subsystem Descriptions

7.1 Rover

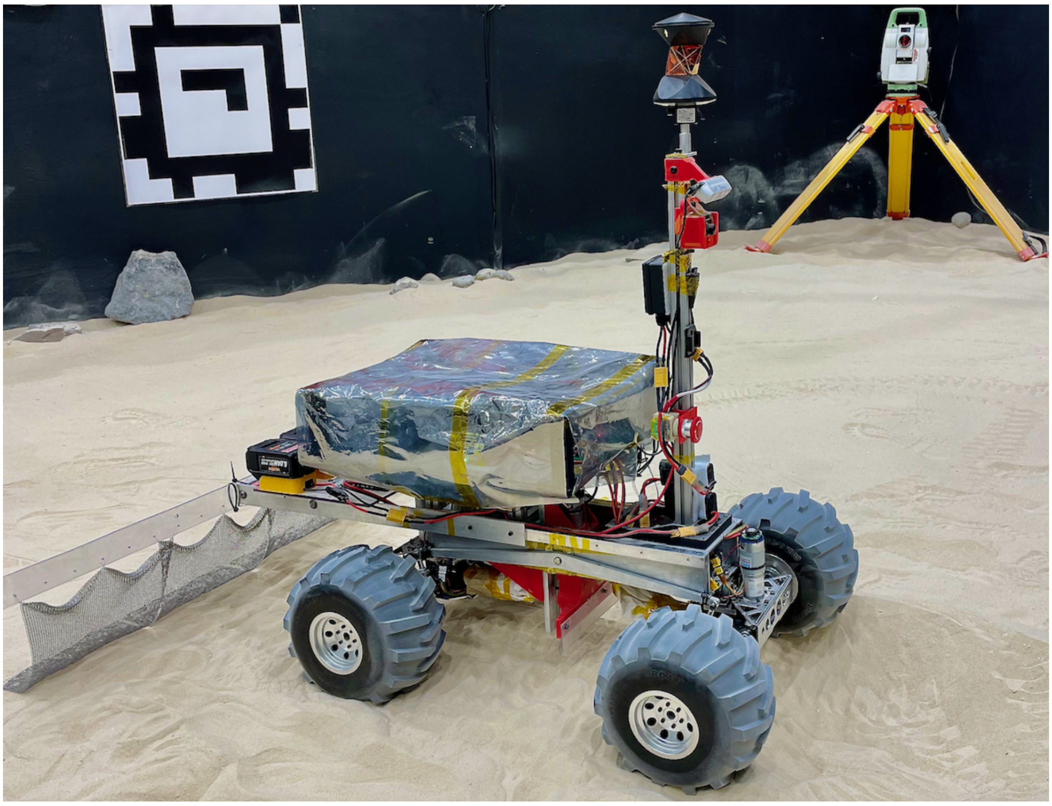


Figure 9: Crater Grader Rover

Building up on the work of the MRSD 2022 Team CraterGrader [3], we will be using the same RC4WD chassis as our Lunar rover. Its wheels are driven through front and rear differentials, with independent steering of the front and rear axles in a double Ackermann configuration. The rover will house all the sensors, excavator and grader tool assemblies, electronics and compute required to perform the autonomous trail grooming tasks.

The Moon's terrain is relatively flat with 67% of routes at less than 5° in slope and 91% less than 10°. It is possible for rovers to traverse over $15 - 20°$ slopes, although for angles exceeding 15°, the slip would likely exceed 30% [2]. Taking this into consideration and also our desirable vehicle mass of less than 50 kilograms, we will be sourcing appropriate wheels for the rover, so as to match our requirements.

7.2 Excavator and Grader

From our subsystem-level trade study on choosing the best Moon-working manipulation option, we have decided to use a combination of a front loader as well as a chassis grader to perform the grooming operations. This strategy draws on proven practices from Earth-working machines used for construction and mining. On Earth, these machines are usually paired up and used to move material quickly and refine surfaces to high precision. By adapting this terrestrial knowledge to the Moon, where conditions are harsher and maintenance opportunities are limited, using such excavator and grader tool assemblies provides significant advantages for effective trail preparation.

The excavator will be present at the front of the rover and will perform the bulk handling of the Lunar regolith. The grader will be mounted on the belly of the rover and will help in fine surface shaping and leveling. We will be designing both the excavator and grader assemblies with multiple degrees of freedom (DOFs) to enable flexible and fast grooming operations on the varied Lunar terrain. Their operation will depend on several functional parameters, which include:

- The assemblies will adjust their position and orientation based on the unevenness of the terrain
- The assemblies will dynamically adjust their angles and positions relative to the rover's pitch, roll, and yaw to maintain proper contact with the ground
- Both assemblies will adjust their operation to achieve the desired grooming metrics

7.3 Sensors and Electronics

A ZED 2i stereo camera will be mounted on the mast of the rover at an optimal height and facing the ground for active mapping of the environment. The height will be carefully chosen so that the camera's field of view (FOV) is not hindered by the front excavator assembly. An IMU sensor will be mounted at a position that will minimize exposure to vibrations due to system operation. Wheel encoders will be used to determine wheel velocities, and tool encoders to control the excavator and grader assemblies. Roboclaw motor controllers will be used to control the motors. In order to validate the grooming operation, we plan on having another depth camera placed on the belly of the rover, pointing vertically downward. However, this approach is still under exploration, with potential consideration of alternative sensors for improved validation.

7.4 Software

The software architecture of the system is structured into four key modules: localization, perception, planning and control. We will be using an NVIDIA Jetson AGX Xavier Dev Kit running ROS2 for the primary computations, along with an Arduino Due for lower-level interface with the sensors and actuators. Communication between the Jetson and the Arduino will be facilitated by Micro-ROS.

A FARO Survey LiDAR will be used on the MoonYard to generate a 2.5-D map of the demo area, providing a detailed representation of the terrain. This map will serve as the basis for a path-planning algorithm to compute a navigational path for the rover to follow. These tasks will be performed in the operations terminal, that is, our laptops, which will then be fed into the rover.

Sensor data from the IMU, motor encoders, and pose estimates from the robotic total station, will be subjected to pre-processing to reduce noise. This data, along with data from the mast depth camera are fused together using an Extended Kalman Filter to localize the rover within the work site.

A finite state machine (FSM) planner will manage the high-level decision making by switching between the tool planner and the navigation planner. Within the tool planner, the excavator handler and the grader handler will manage the specific manipulation tasks of excavating or grading the Lunar surface. They will individually plan the required depth of cut, assembly velocity, and the velocity of the mobile base to excavate or grade the surface. The navigation planner will include a heuristic-based graph search planner that can plan a feasible path to the desired robot pose for filling the crater and grooming the surface. The mast depth camera, which is used for actively mapping the environment, will aid in navigation. The planners send motor commands to the motor controllers.

Once a grooming operation is completed, another depth camera will be used to validate the grooming, i.e., whether the crater has been excavated or graded to a satisfactory extent according to our performance requirements. This information is fed back into the FSM planner as feedback, which repeats the entire process if necessary.

All the three planners – excavator planner, grader planner, and navigation planner, will first be simulated on Gazebo, and then deployed into the real world.

7.5 External Infrastructure

The external infrastructure includes elements which are not present on the rover but are essential for operation. It comprises a robotic total station, which provides precise robot pose estimates to localize the robot within the environment by tracking a prism placed on its mast, a wireless transceiver, and an operations terminal for seamless communication between the rover and mission control, by providing a user interface to monitor progress and receive updates. It also includes a FARO Survey LiDAR to map the environment and also to evaluate the worksite configuration.

7.6 Integration and Testing

The project will be tested in the MoonYard, a sandbox situated in the Planetary Robotics Lab (PRL) at CMU, which is commonly used to test Space Robotic systems. Adopting a V-model for system development, we will rigorously test every unit, subsystem, and the fully integrated system at each stage of the project. Unit and subsystem tests will be considered successful based on their functionality and performance against design expectations. The success of the system level tests will be based on the metrics or performance requirements that we have set and the rover's overall performance for grooming operations will be evaluated using the FARO LiDAR. We also aim to document every detail of the project so that future teams can easily build upon our work.

8 Project Management

8.1 Work Plan and Tasks

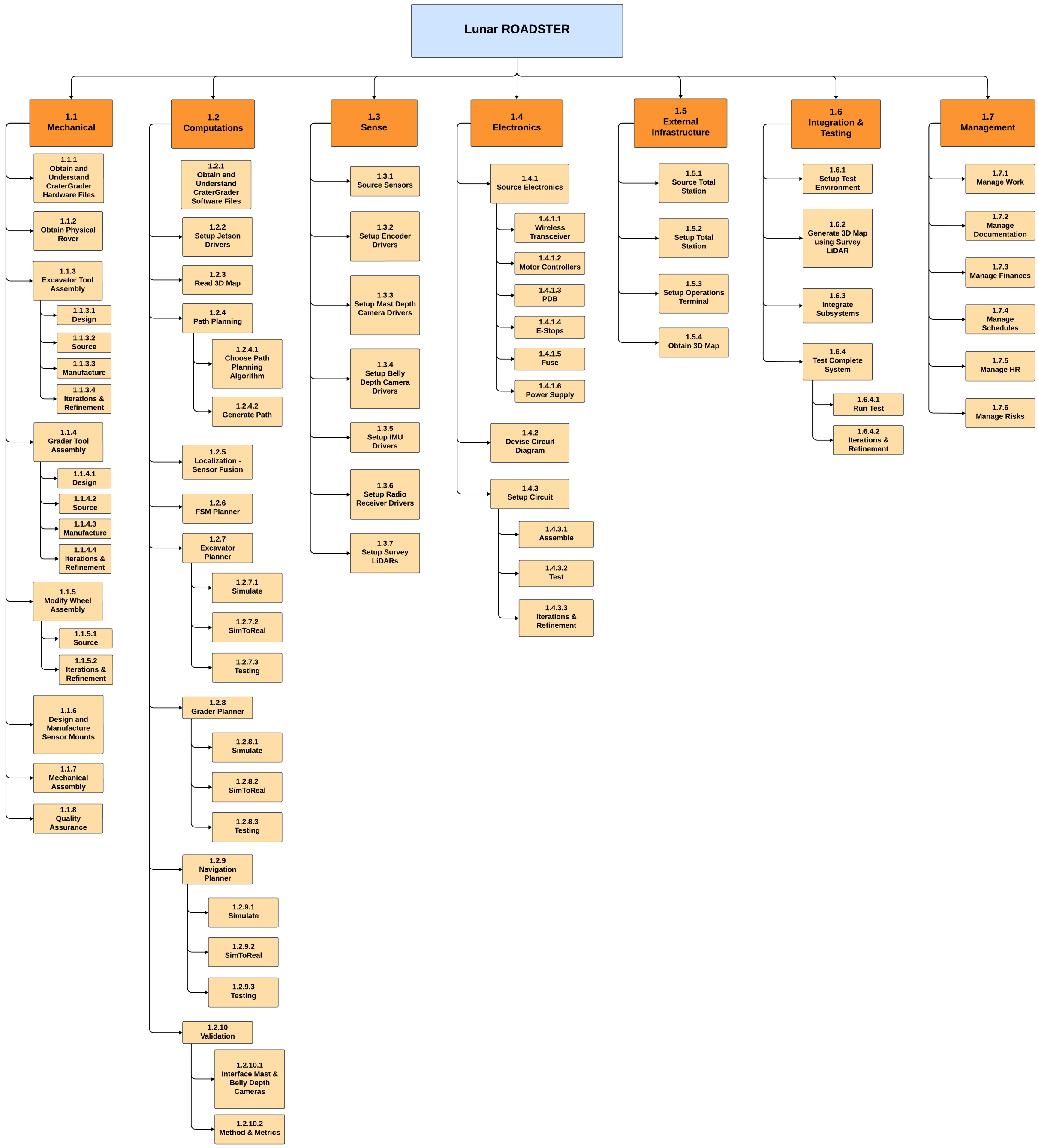


Figure 10: Level 4 WBS

Figure 10 shows the Level 4 Work Breakdown Structure of the Lunar ROADSTER Project. It is a product-based WBS that is derived from the cyber-physical architecture. The work blocks were created by breaking down the individual blocks in the cyber-physical architecture into tasks required to be completed. A subsystem-wise breakdown is shown in Appendix A.2.

Some key highlights are:

- The Excavator and Grader Tool Assembly tasks are split into a general methodology of design, source and manufacture. The team added Iterations and Refinement blocks based on the advice of our sponsors to ensure that we can enable an iterative design process.

- The Localization task will consist of several interdependent tasks. To maintain flexibility, the team has kept this task as an umbrella term directly.
- The 3 planners - Excavator, Grader, Navigation, all follow a uniform Simulate, Sim2Real, Testing process to allow effective scheduling and progress tracking.
- The Validation task involves novel work regarding the method and metrics. This task will require extensive brainstorming and multiple team meetings.
- Throughout the Sense tasks, the team will focus on documentation to achieve the target of technological extensibility as well as quick replacement of sensors if required.

8.2 Schedule and Key Milestones

Based on stakeholder advice, past experiences and correspondences with Crater Grader, the team estimated the hours that each task will take. Based on this estimate, a split between the SVD and FVD was devised, as shown in Table 6.

Table 6: SVD and FVD Split

Spring Validation Demo	Fall Validation Demo
ROADSTER uses the excavator to groom one or two craters on a simple, straight path in the MoonYard.	ROADSTER uses both grader and excavator to create a circuitous path around the MoonYard.
This will be our Minimal Viable Product with simplified localization and path planning.	This will include more ambitious tasks such as Lunar-accurate environments and localization through Visual Odometry/ Structure for Motion.

8.2.1 Spring Semester Schedule

Based on this split, the team decided 2 key internal milestones for the Spring Semester and devised the project schedule

- **Completion of Hardware Implementation** - February 12^{th} 2025
- **Completion of Software Stack** - March 20^{th} 2025

To estimate the time taken by each subsystem, the team followed a bottom-up schedule. Each task was based on the estimated time along with buffers to ensure that the schedule is achievable. The full schedule is shown in Figure 11. A subsystem-wise breakdown is shown in Appendix A.3.

8.2.2 Fall Semester Schedule

Based on the FVD Split, the team devised two broad milestones for the Fall semester shown in Table 7. The contents of these milestones are highly dependent on the performance in the Spring and they will be defined further into the project.

Table 7: Milestones for Fall 2025

Milestone	Estimated Timeline
Lunar ROADSTER v1.0	October 5^{th}
Lunar ROADSTER v2.0	November 2^{nd}
Fall Validation Demo	November 17^{th}

Figure 11: Schedule for Spring 2025

8.3 System Validation Experiments

8.3.1 Spring Validation Demonstration

Table 8: System Validation Demonstrations for Spring 2025

Objective	**F.R.**	**Success Criteria**
Traversability	M.F.5	Will climb gradients up to 15° and have a contact pressure of less than 1.5 kPa. [M.P.3]
Tool Operation	M.F.6, M.F.7	Will fill craters of up to 0.5 meters in diameter and 0.1m in depth. [M.P.5]
Navigation	M.F.3, M.F.4	Will localize itself and follow planned path to a maximum deviation of 10%. [M.P.2]
Autonomous Operation	M.F.2, M.F.9	Will operate autonomously and communication robot state and mission status to the user.

Demonstration Plan

- **Location**: MoonYard in the Planetary Robotics Lab. Craters constructed to emulate a possible straight groomed path.
- **Needed Equipment**: ROADSTER with Tools, Total Station, Operations Terminal, Survey LiDAR to build 3D Map.
- **Procedure**: 3D Map of the MoonYard is fed to the rover along with a pre-planned straight path. ROADSTER autonomously grooms the trail while the user monitors the mission using the operations terminal.

8.3.2 Fall Validation Demonstration

In addition to the SVD objectives,

Table 9: System Validation Demonstrations for Fall 2025

Objective	**F.R.**	**Success Criteria**
Trail Path Planning	M.F.1	Will plan a path with cumulative deviation of <= 25% from chosen latitude's length. Will avoid craters >= 0.5 metres and avoid slopes >= 15°[M.P.1, M.P.4]
Validation	M.F.8	Will groom and validate the trail to have a maximum traversal slope of 5° [M.P.6]

Demonstration Plan

- **Location**: MoonYard in the Planetary Robotics Lab. Craters constructed to emulate a circuitous/semi-circuitous path.

- **Needed Equipment**: ROADSTER with Tools, Total Station, Operations Terminal, Survey LiDAR to build 3D Map.
- **Procedure**: 3D Map of the MoonYard is fed to the rover along with a pre-planned ideal path. ROADSTER autonomously grooms the trail while the user monitors the mission using the operations terminal. The path is validated and a mission complete signal is sent to the user.

8.4 Team Member Responsibilities

The following responsibilities are designated to each team member based on their strengths, past experiences, and learning interests.

Table 10: Team Member Responsibilities

Team Member	Primary Responsibility	Secondary Responsibility
Ankit Aggarwal	Controls, Actuation, Planning, Project Management	Mechanical Design
Deepam Ameria	Mechanical Design, Integration, System Testing	Controls, Planning
Bhaswanth Ayapilla	Perception, Navigation, Localization	Electronics, Project Management
Simson D'Souza	Navigation, Perception, Software Development	Electromechanical Design
Boxiang (William) Fu	Sensing, Localization, Planning	Controls

8.5 Parts Lists and Budget

Table 11 outlines the provisional budget statement and the inventory list we currently have on hand. Parts with an asterisk denote items provided to us free of charge by our supervisor and the Crater Grader MRSD team from 2022. They do not expend the $5,000 MRSD budget. Parts with an circumflex denote items already purchased.

Table 11: Provisional Budget Statement

ID	Part Name	Description	Unit	Quantity	Total
B01	NVIDIA Jetson	Computing board	$800	1	$800*
B02	VN-100 IMU	IMU	$800	1	$800*
B03	Planetary Gear Motor	Actuator	$60	4	$240*
B04	RoboClaw 2x30A	Motor Controller	$135	2	$270*
B05	Vanon DCB200	Battery	$20	8	$160*
B06	Arduino Due	Microcontroller	$48.4	2	$96.8^
B07	Vanon Charger	Battery Charger	$103	1	$103^
B08	ZED 2i	Stereo Camera	$533	1	$533^
B09	Zed 2i Cable	Camera Cable	$29	1	$29^
B10	Excavator Assembly	Manufacture Tool	$1000	1	$1000
B11	Grader Assembly	Manufacture Tool	$1000	1	$1000
B12	Chassis	Source Chassis	$500	1	$500
B13	Wheel Assembly	Source Wheels	$100	4	$400
B14	Validation Camera	Source Camera	$500	1	$500
B15	Power Distribution Board	Manufacture Board	$200	1	$200
B16	Miscellaneous	Miscellaneous	$500	1	$500
				MRSD Budget Total:	**$4861.80**
				Grand Total:	**$7131.80**
				*Excluded from MRSD budget, ^Already purchased	

8.6 Risk Management

Our top 5 greatest risks are shown in this section. A full list of identified risks can be found in Appendix A.4. We also provide a preliminary mitigation plan for each identified risk and any actions that are taken to address each risk.

8.6.1 Excavator and Grader Tool Planner takes Longer than Expected to Deliver

This risk has an unmitigated **likelihood of 5 and consequence of 5**. Our autonomous trail grooming rover requires the use of both an excavator tool and a grader tool. This requires the integration of both the hardware and software components for each tool. If integration takes longer than expected, we may be unable to meet the SVD deadline, thus requiring us to make changes in our performance requirements.

The first mitigation action taken was to shift requirements for SVD and only integrate the grader during Fall semester. This was decided upon and implemented on Nov 28th, 2024 and the performance requirements were updated accordingly. A second action is to potentially use off-the-shelf code if available, preferably from Crater Grader. The adoption of these actions results in a mitigated **likelihood of 2 and consequence of 5**.

8.6.2 Integration Issues between Subsystems

This risk has an unmitigated **likelihood of 3 and consequence of 5**. Since our rover has many complex moving parts, subsystem integration and communication between the subsystems may be flawed. This could result in integration delays causing scheduling overruns, requirement changes and failure of the demo.

Some mitigation actions we planned to act upon include performing unit testing and subsystem validation continuously while only integrating one subsystem at a time. Additionally, we plan to use a common framework (e.g. ROS2 interfaces) for communication between subsystems and to have at least 5 weeks for testing and integration. The adoption of these actions results in a mitigated **likelihood of 2 and consequence of 5**.

8.6.3 Delay in Arrival and Manufacture of Hardware Components

This risk has an unmitigated **likelihood of 3 and consequence of 5**. Shipping delays of components ordered and/or manufacturing delays on custom made components can severely delay hardware integration, causing push backs in scheduling, software development, and potentially failing to meet performance requirements.

Our first mitigation action is to order and design components during Winter break. We completed the ordering on Dec 9^{th}, 2024 and will start designing components on the 12^{th}. We also plan to use off-the-shelf components to reduce lead times. The adoption of these actions results in a mitigated **likelihood of 2 and consequence of 5**.

8.6.4 Mast Depth Camera Field of View (FOV) is Blocked

This risk has an unmitigated **likelihood of 5 and consequence of 4**. The mast depth camera's FOV can be blocked, partially or completely, due to dust, misalignment of camera, or interference from the rover's own excavator assembly. This hinders the rover's ability to perceive its surroundings accurately, resulting in navigation errors and inefficiencies in excavation tasks.

To mitigate this, we plan to conduct field tests to choose an optimal height to place the depth camera such that dust does not reach it and it can clearly see in front of the rover, despite the presence of the excavator assembly. The adoption of these actions results in a mitigated **likelihood of 3 and consequence of 4**.

8.6.5 Too Many Performance Requirements

This risk has an unmitigated **likelihood of 5 and consequence of 5**. We originally had 9 performance requirements scheduled for SVD. Delays in testing and validation may impact project timelines and we may not be able to meet all the requirements for SVD.

To reduce this risk, we met with the Crater Grader MRSD '22 team on Dec 2nd, 2024 to discuss what is feasible in the given time. We then had a team meeting on Dec 4th, 2024 and agreed to revise the performance requirements down to 6. We further undertook revisions of our schedule and plan to follow it diligently. The adoption of these actions results in a mitigated **likelihood of 2 and consequence of 5**.

9 References

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[2] John O. Elliott Jennifer Heldmann. *INSPIRE IN situ Solar system Polar Ice Roving Explorer*. https://smd-cms.nasa.gov/wp-content/uploads/2023/10/inspire-lunar-polar-volatiles-rover.pdf. 2023.

[3] Ryan Lee et al. “CraterGrader: Autonomous Robotic Terrain Manipulation for Lunar Site Preparation and Earthmoving”. In: *arXiv preprint arXiv:2311.01697* (2023).

[4] P. Muñoz, P. Bellutta, and M. D. R-Moreno. “Proposing new path-planning metrics for operating rovers on Mars”. In: *Scientific Reports* 13 (2023), p. 22256. DOI: 10.1038/s41598-023-49144-8. URL: https://doi.org/10.1038/s41598-023-49144-8.

[5] Laurent Sibille et al. *Lunar Regolith Simulant Materials: Recommendations for Standardization, Production, and Usage*. Tech. rep. NASA/TP-2006-214605. NASA Marshall Space Flight Center, 2006. URL: https://ntrs.nasa.gov/api/citations/20060051776/downloads/20060051776.pdf.

A Appendices

A.1 Weighted Objectives Tree

The following weighted objectives trees were conducted at the system and subsystem-level to determine the criteria and weight factors used for the trade studies.

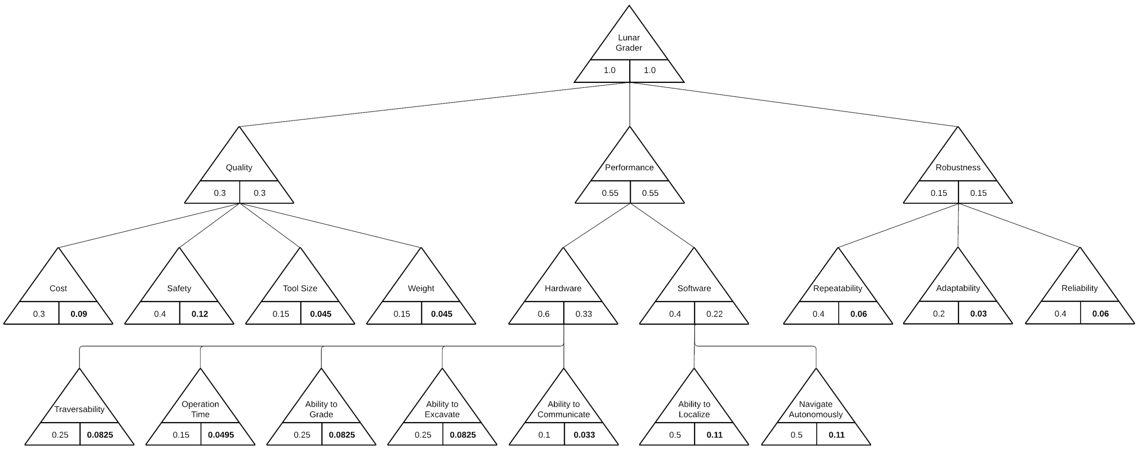

Figure 12: Systems-Level Weighted Objectives Tree for Lunar Grader Concept

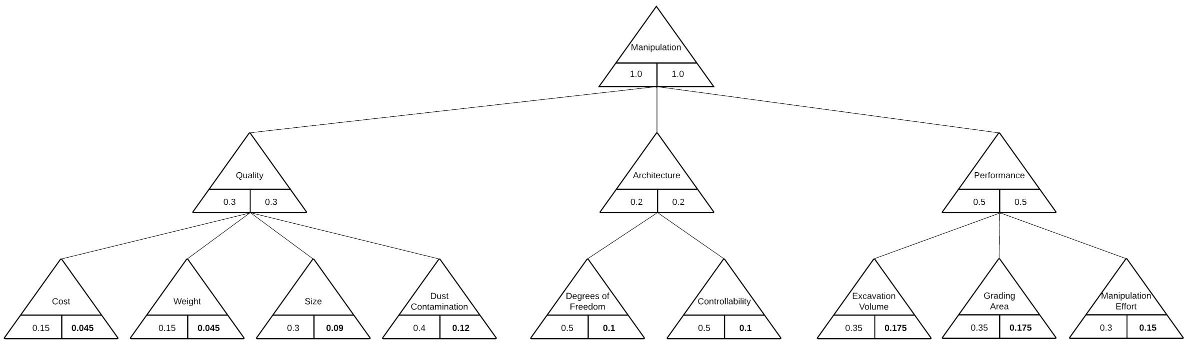

Figure 13: Subsystems-Level Weighted Objectives Tree for Manipulation Concept

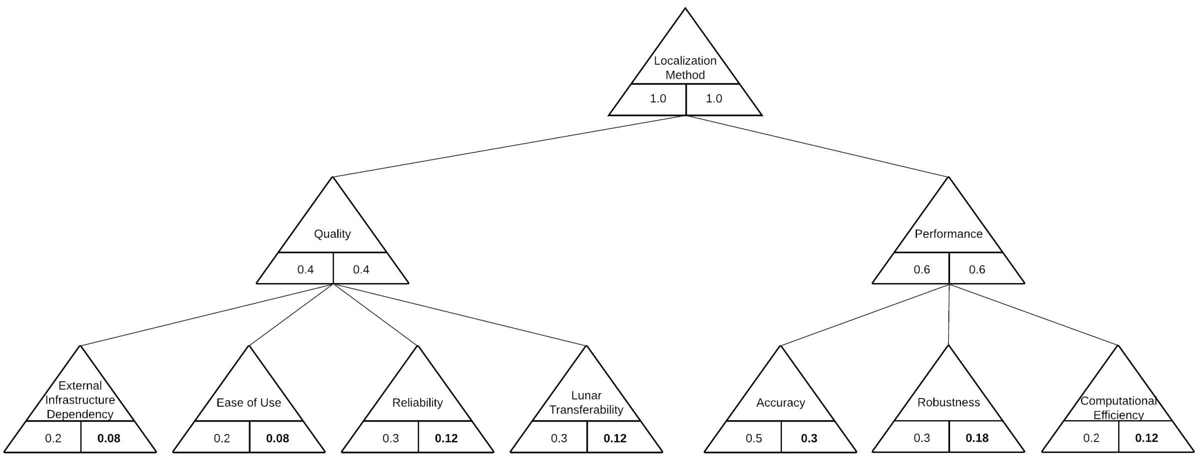

Figure 14: Subsystems-Level Weighted Objectives Tree for Localization Method

A.2 Subsystem-Wise Detailed WBS

A.2.1 Mechanical

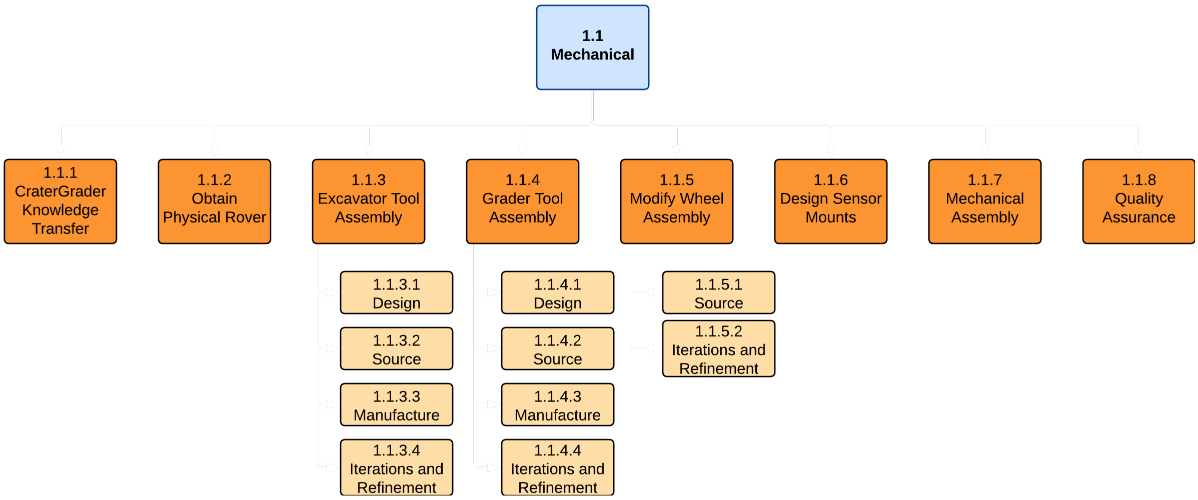

Figure 15: Level 4 WBS for Mechanical Subsystem

Figure 15 shows the Level 4 Work Breakdown Structure for the Mechanical Subsystem. The tasks shown are:

- Crater Grader Knowledge Transfer and obtaining Physical Rover involve reading through the documentation, going through CAD files and assessing the condition of the robot.
- The Modify Wheel Assembly task will involve sourcing new wheels and working on integrating them with the current drive system of the rover.
- The Mechanical Assembly task will involve mounting all created sub-assemblies onto the main rover chassis.
- The Quality Assurance block will involve unit testing to ensure that the created assemblies meet the desired standards of functionality and robustness.

A.2.2 Computations

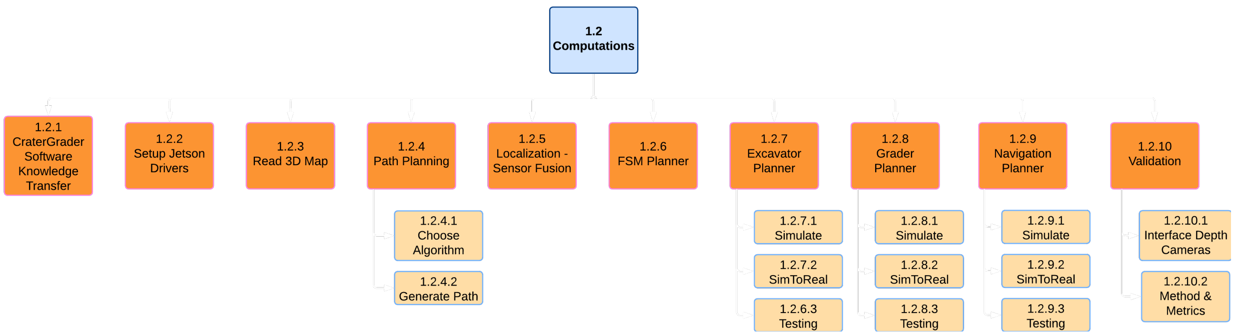

Figure 16: Level 4 WBS for Computations Subsystem

Figure 16 shows the Level 4 Work Breakdown Structure for the Computations Subsystem. The tasks shown are:

- The first 3 tasks are initial setup tasks involving research, setting up drivers and obtaining initial data.
- The Path Planning task will follow a regular pipeline of choosing an algorithm and generating a path

A.2.3 Sense

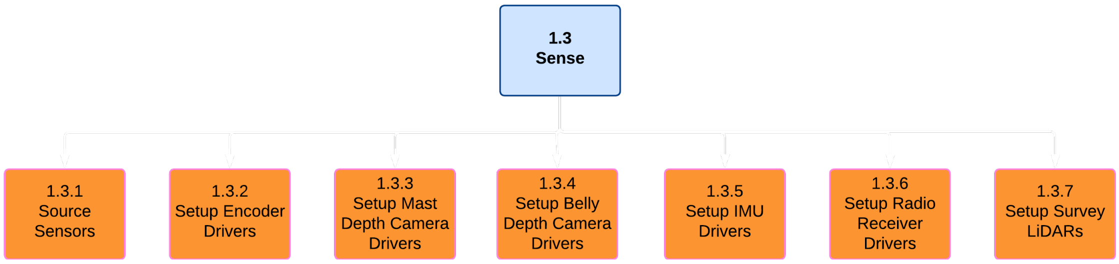

Figure 17: Level 4 WBS for Sense Subsystem

Figure 17 shows the Level 4 Work Breakdown Structure for the Sense Subsystem. The tasks shown are:

- This subsystem involves sourcing our sensor stack - Encoders, Depth Cameras, IMU, Radio Receivers and Survey LiDARs.
- The tasks also include setting up the required drivers and obtaining data using the desired communication method.

A.2.4 Electronics

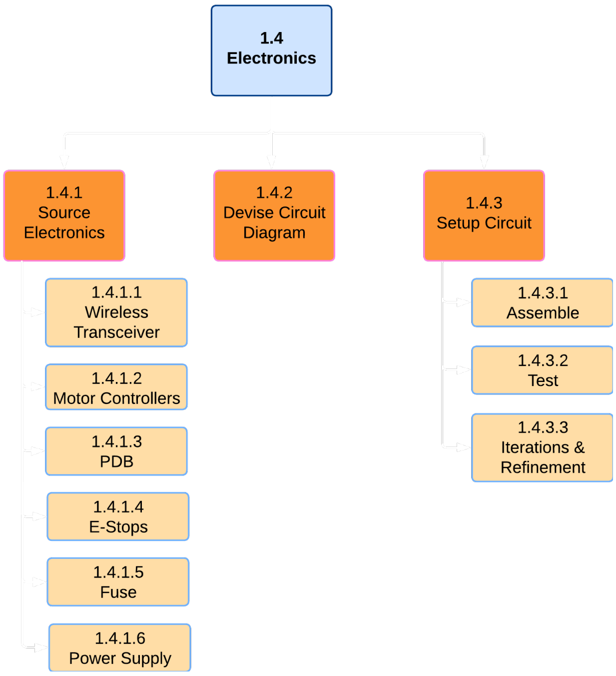

Figure 18: Level 4 WBS for Electronics Subsystem

Figure 18 shows the Level 4 Work Breakdown Structure for the Electronics Subsystem. The tasks shown are:

- The Source Electronics task involves sourcing electronic components - Wireless Transceiver, Motor Controllers, Power Distribution Board, E-Stops, Fuses and Power Supply.
- The Devise Circuit Diagram involves creating and optimal circuit to connect all components to their required inputs and outputs.
- Setup Circuit will consists of assembling, testing and iterating the circuit to ensure robustness.

A.2.5 External Infrastructure

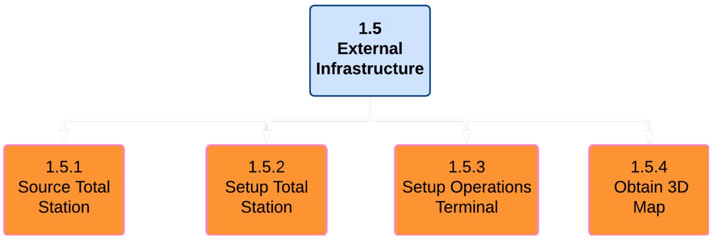

Figure 19: Level 4 WBS for External Infrastructure Subsystem

Figure 19 shows the Level 4 Work Breakdown Structure for the External Infrastructure Subsystem. This consists of all components of the project that are not on the rover. The tasks shown are:

- Sourcing and Setting up total station will require training with FRC Technicians. It will involve calibrating and tracking the rover's postion during the mission.
- The Operations Terminal will be the team's laptops, emulating the Moon Station. This station will be used to monitor the mission and check for the validation conditions.
- Obtain 3D Map involves obtaining a map of the Moon Yard using the Survey LiDAR. This map will be used to plan the trail path to be groomed by the ROADSTER.

A.2.6 Integration and Testing

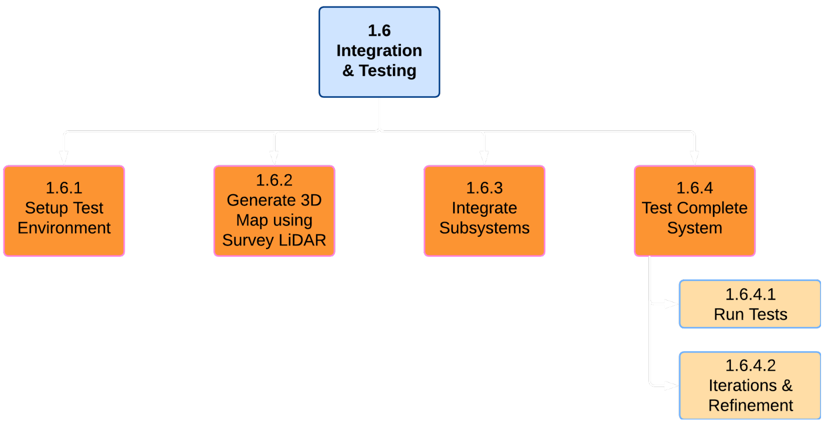

Figure 20: Level 4 WBS for Integration and Testing Subsystem

Figure 20 shows the Level 4 Work Breakdown Structure for the Integration and Testing Subsystem. The tasks shown are:

- All tasks involve ensuring that all subsystems can work together as a cohesive unit.
- The team will setup concrete testing plans with varying environments to test the ROADSTER
- The Iterations and Refinement block will allow the team to improve overall functionality of the rover, focusing on robustness and repeatability.

A.2.7 Management

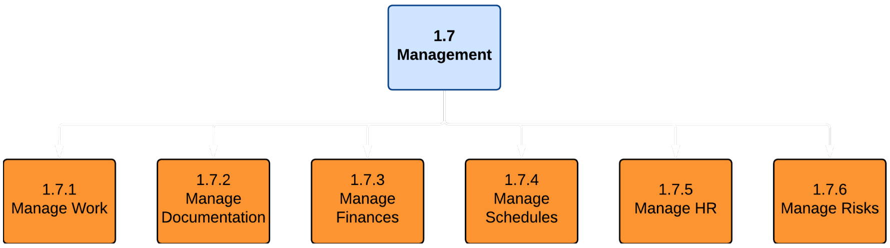

Figure 21: Level 4 WBS for Management Subsystem

Figure 21 shows the Level 4 Work Breakdown Structure for the Integration and Testing Subsystem. The Program Manager will be responsible for all tasks in the Management Subsystem. The tasks shown are:

- Manage Work involves tracking progress of the assigned tasks to each member.
- Manage Documentation will cover all reports, presentations and process documentations through the work period.
- Manage Finances involves managing purchases and allocating adequate budget to every subsystem.
- Manage Schedules involves tracking the overall timeline of the project and ensuring that the team follows the planned schedule.
- Manage HR is a task where the team will allocate some time every week to uplift team morale and maintain motivation.
- Manage Risks involves identifying and mitigating any potential risks in the project.

A.3 Detailed Schedule

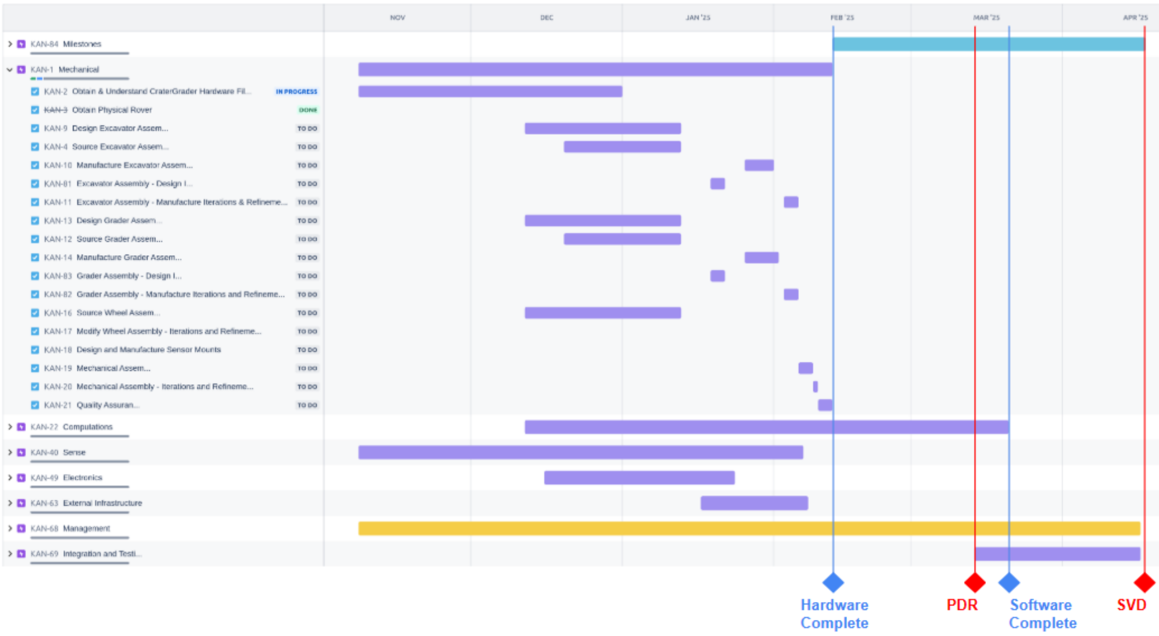

Figure 22: Mechanical Subsystem Schedule for Spring 2025: December and Early January will be used to complete the bulk of the design tasks to ensure that implementation can begin as soon as the Spring Semester starts.

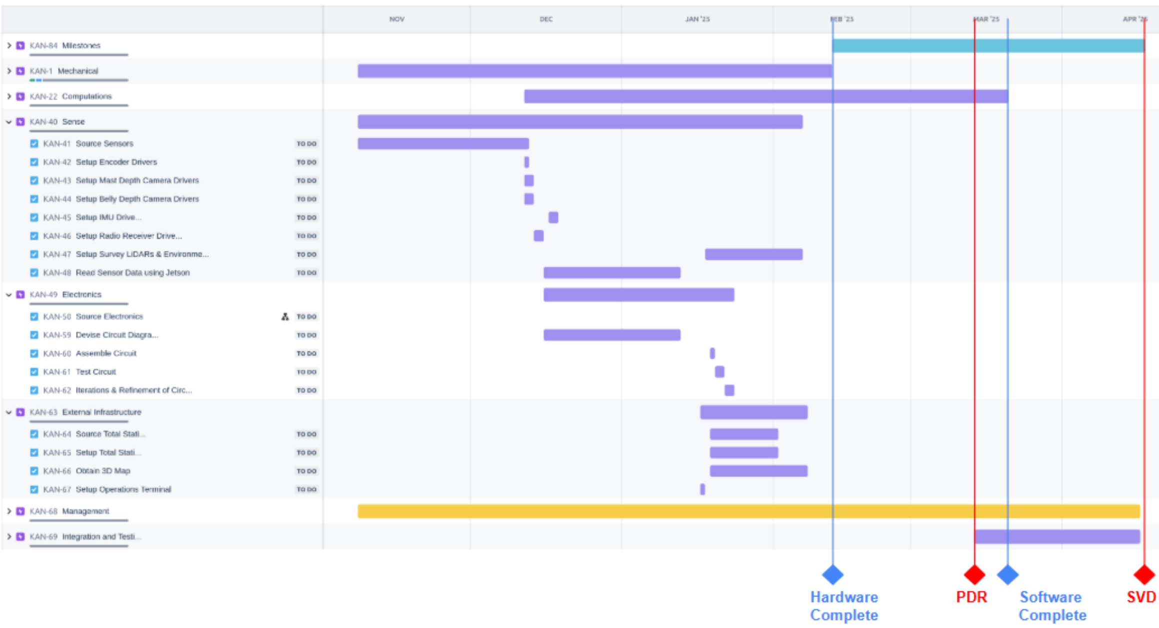

Figure 23: Sense, Electronics and External Infrastructure Subsystems Schedule for Spring 2025: Simultaneously, the team will be working on sensing and electronics to meet the hardware milestone. Tasks will be split between members based on specializations and interests. Tasks which require learning from FRC Technicians will require all members to participate.

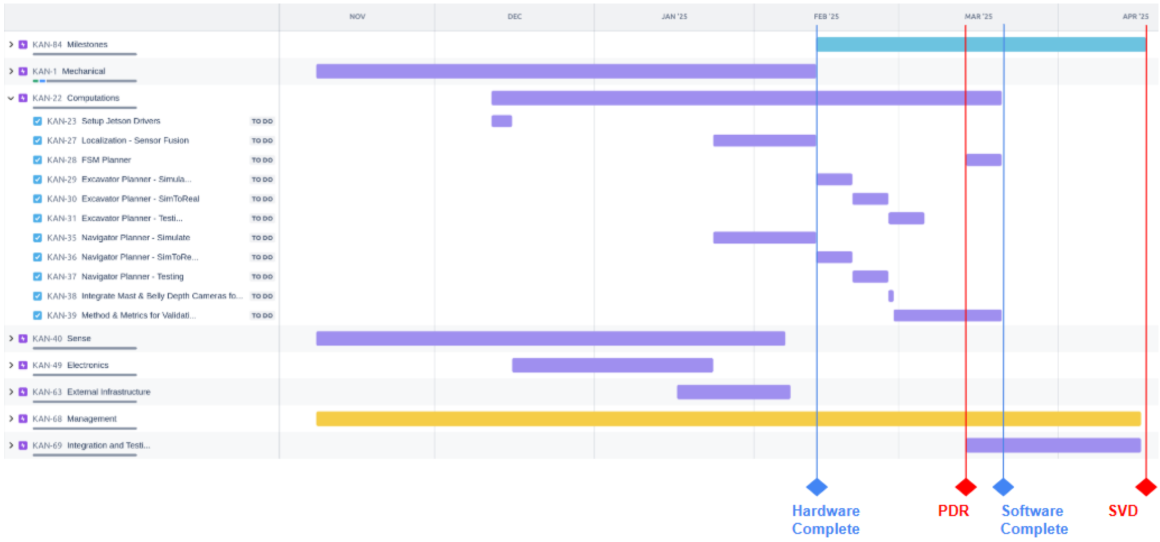

Figure 24: Computations Subsystem Schedule for Spring 2025: After hardware completion, the team will collectively work on computational design. All tasks will have atleast 2 members collaborating to ensure well researched and deliberated computational decision making.

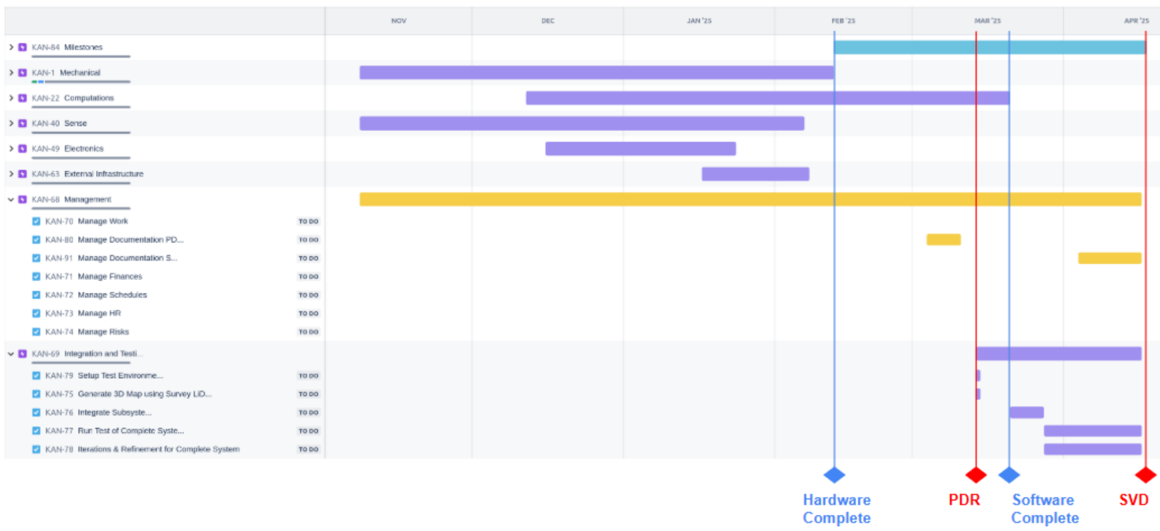

Figure 25: Management and Integration Subsystems Schedule for Spring 2025: The team will begin testing and integrations as soon as the software stack is ready. The team plans to run multiple iterations of the SVD to ensure robustness and repeatability.

A.4 Identified Risks

The following risks are identified during our preliminary risk management analysis. Potential mitigation actions are put in place to minimize these risks.

Risk ID	Risk Title	Risk Owner	Date Added	Date Updated
R1	PRL Testbed Scheduling	Ankit	11/27/2024	11/27/2024
Description			**Original Likelihood**	**Original Consequence**
PRL Testbed unavailable due to scheduling conflicts with other high priority projects			2	4
Consequence			**Mitigated Likelihood**	**Mitigated Consequence**
No testbed available for testing and/or SVD			1	4
Risk Reduction Plan Summary			**Risk Type:**	Scheduling
Action/Milestone		**Success Criteria**	**Date Planned**	**Date Implemented**
Devise and discuss a testing and demo plan with Red and other stakeholders of the PRL testbed beforehand and reserve slots		Successfully reserve slots for using the PRL Testbed	11/30/2024	
Reach out to external testing facilities like Astrobotic or CAT for a backup testing facility		Communicate and discuss possibility of using other testbeds if PRL falls through		
Schedule tests at night		Schedule tests at off-hours to avoid clashes		
Comments				

Figure 26: PRL Testbed Scheduling

Risk ID	Risk Title	Risk Owner	Date Added	Date Updated
R2	Excavator and grader tool planner takes longer than expected to deliver	Simson	11/27/2024	11/27/2024
Description			**Original Likelihood**	**Original Consequence**
Integration of the excavator and grader software with hardware takes longer than expected			5	5
Consequence			**Mitigated Likelihood**	**Mitigated Consequence**
Unable to meet SVD deadline and potential requirements change			2	5
Risk Reduction Plan Summary			**Risk Type:**	Technical
Action/Milestone		**Success Criteria**	**Date Planned**	**Date Implemented**
Shift requirements for SVD		Working prototype for SVD	11/28/2024	11/28/2024
Integrate the grader during Fall semester		Working excavator and grader for FVD	11/28/2024	
Potentially use off-the-shelf code if avaliable, preferably from CraterGrader		Successful integration of off-the-shelf components		
Comments				
Decided to move delivery of grader tool planner to the Fall semester				

Figure 27: Excavator and Grader Tool Planner takes Longer than Expected to Deliver

Risk ID	Risk Title	Risk Owner	Date Added	Date Updated
R3	Integration issues between subsystems	Deepam	11/27/2024	11/27/2024
Description			**Original Likelihood**	**Original Consequence**
Subsystems work individually, but integration and communication between the subsystems are flawed			3	5
Consequence			**Mitigated Likelihood**	**Mitigated Consequence**
Delay in integration causing scheduling overruns, requirements change and failure of the demo			2	5
Risk Reduction Plan Summary			**Risk Type:**	Technical
Action/Milestone		**Success Criteria**	**Date Planned**	**Date Implemented**
Perform unit testing and subsystem validation continuously		Successful testing of all major subsystems	11/30/2024	
Integrate one subsystem at a time		Successful integration of all major subsystems	11/30/2024	
Use a common framework (e.g. ROS2 interfaces) for communication between subsystems to reduce bugs		Adoption of common framework for communications	11/30/2024	
Keep to planned schedule and have at least 5 weeks for testing and integration		Successful integration of all major subsystems	11/30/2024	
Comments				

Figure 28: Integration Issues between Subsystems

Risk ID	Risk Title	Risk Owner	Date Added	Date Updated
R4	Belly depth sensor is not suitable for validation	Bhaswanth	11/27/2024	11/27/2024
Description			**Original Likelihood**	**Original Consequence**
The belly depth camera is used to validate if a groomed crater is satisfiable. The sensor may not be able to adequately determine depth variations suitable for validation			**4**	**3**
Consequence			**Mitigated Likelihood**	**Mitigated Consequence**
Will result in major revision and changes to the validation architecture and functional requirement, causing delays in scheduling			**2**	**2**
Risk Reduction Plan Summary			**Risk Type:**	Technical
Action/Milestone		**Success Criteria**	**Date Planned**	**Date Implemented**
Mount the depth camera at another location on the rover (e.g. on a mast)		Acceptable validation specifiied by performance requirement		
Use another sensor to determine depth variations (e.g. LIDAR, visual odometry, IR sensor)		Acceptable validation specifiied by performance requirement		
If all else fails, use the total station for validation		Acceptable validation specifiied by performance requirement		
Comments				

Figure 29: Belly Depth Sensor is not Suitable for Validation

Risk ID	Risk Title	Risk Owner	Date Added	Date Updated
R5	Unable to get Crater Grader to perform autonomous crater filling	Bhaswanth	11/27/2024	11/27/2024
Description			**Original Likelihood**	**Original Consequence**
Our rover builds on top of the work acomplished by Crater Grader. If we cannot get Crater Grader to perform autonomous crater filling, we may need to spend time on the navigation stack and design the entire pipeline			**3**	**3**
Consequence			**Mitigated Likelihood**	**Mitigated Consequence**
Extra time commitment to start from scratch or obtaining a suitable replacement			**2**	**2**
Risk Reduction Plan Summary			**Risk Type:**	Technical
Action/Milestone		**Success Criteria**	**Date Planned**	**Date Implemented**
Thoroughly go through Crater Grader's code and the mechanical schematics provided		Thoroughly understand Crater Grader's operations	11/27/2024	
Test each component and wiring to see if they are working		Validate all components and replace broken ones	11/28/2024	
If it is still not working, inherit only the software component from Crater Grader and build hardware ourselves		Working prototype for SVD		
Comments				

Figure 30: Unable to get Crater Grader to Perform Autonomous Crater Filling

Risk ID	Risk Title	Risk Owner	Date Added	Date Updated
R6	Delay in arrival and manufacture of hardware components	William	11/27/2024	11/27/2024
Description			**Original Likelihood**	**Original Consequence**
Shipping delays of components ordered and/or manufacturing delays on custom made components			**3**	**5**
Consequence			**Mitigated Likelihood**	**Mitigated Consequence**
Delays in hardware integration, causing pushbacks in schduling and software development			**2**	**5**
Risk Reduction Plan Summary			**Risk Type:**	Scheduling
Action/Milestone		**Success Criteria**	**Date Planned**	**Date Implemented**
Use off-the-shelf components that are avaliable on hand (e.g. from CMU labs or Red's workshop)		Obtain components before end of December		
Start ordering and designing components during Winter break so there is adequate leeway for delivery and manufacturing before Spring semester starts		Order components before end of December	11/27/2024	12/09/2024
Use simulations to work on software components while we wait for the components to be delivered and/or manufactured		Successful integration of all subsystems on schedule		
Implement other subsystems that are independent from the subsystem that is missing parts		Successful integration of all subsystems on schedule		
In case of delay in wheels, work with the existing wheels and proceed with the timeline while waiting for the new ones to arrive		Successful integration of all subsystems on schedule		
Comments				

Figure 31: Delay in Arrival and Manufacture of Hardware Components

Risk ID	Risk Title	Risk Owner	Date Added	Date Updated
R7	Lack of proper simulation environment	Simson	11/27/2024	11/27/2024
Description			**Original Likelihood**	**Original Consequence**
Inability to accurately simulate the rover in a Lunar-like environment can lead to suboptimal performance			3	3
Consequence			**Mitigated Likelihood**	**Mitigated Consequence**
The rover's performance in the Moon Pit may be compromised, leading to inefficiencies, mission delays, or potential failure in achieving key objectives			1	2
Risk Reduction Plan Summary			**Risk Type:**	Technical
Action/Milestone		**Success Criteria**	**Date Planned**	**Date Implemented**
Ask CraterGrader how they ran all their simulations and gather resources		Meet with CraterGrader team	11/28/2024	12/2/2024
Explore LunarSim - https://github.com/PUTvision/LunarSim and check how useful this will be, during the winter break		Working simulation	12/12/2024	
Develop Gazebo environment		Working simulation		
Comments				

Figure 32: Lack of Proper Simulation Environment

Risk ID	Risk Title	Risk Owner	Date Added	Date Updated
R8	Mast depth camera field of view (FOV) is blocked	William	11/27/2024	11/27/2024
Description			**Original Likelihood**	**Original Consequence**
Mast depth camera's FOV can be blocked, partially or completely, due to dust, misalignment of camera, or interference from the rover's own excavator assembly.			5	4
Consequence			**Mitigated Likelihood**	**Mitigated Consequence**
Hinders the rover's ability to perceive its surroundings accurately, resulting in navigation errors and inefficiencies in excavation tasks			3	4
Risk Reduction Plan Summary			**Risk Type:**	Technical
Action/Milestone		**Success Criteria**	**Date Planned**	**Date Implemented**
Conduct field tests to choose an optimal height to place the depth camera such that dust does not reach it and it can clearly see in front of the rover, despite the excavator assembly. Ensure that visual data such as depth perception and object detection should not be compromised		Working mast depth camera with a clear FOV		
Comments				

Figure 33: Mast Depth Camera Field of View (FOV) is Blocked

Risk ID	Risk Title	Risk Owner	Date Added	Date Updated
R9	Too many performance requirements	Ankit	11/27/2024	11/27/2024
Description			**Original Likelihood**	**Original Consequence**
We have a lot of performance requirements and we may not be able to meet all of them by April for SVD			5	5
Consequence			**Mitigated Likelihood**	**Mitigated Consequence**
Delays in testing and validation, impacting project timelines and April SVD Demo results			2	5
Risk Reduction Plan Summary			**Risk Type:**	Technical, Scheduling
Action/Milestone		**Success Criteria**	**Date Planned**	**Date Implemented**
Have revised performance requirements separately for SVD and FVD (focus more on SVD)		Achievable Performance Requirements	11/28/2024	12/4/2024
Talk to CraterGrader and discuss what is feasible and what is not in the given time		Meeting conducted	11/28/2024	12/2/2024
PM should track schedule properly and team members have to push to meet the timeline		Project follows the schedule	11/28/2024	
Comments				

Figure 34: Too Many Performance Requirements

Risk ID	Risk Title	Risk Owner	Date Added	Date Updated
R10	Drive system wear-and-tear causes malfunction	Deepam	11/27/2024	11/27/2024
Description			**Original Likelihood**	**Original Consequence**
The transmission and steering assembly might be worn out, leading to suboptimal vehicle dynamics, and potentially mechanical failure			**4**	**4**
Consequence			**Mitigated Likelihood**	**Mitigated Consequence**
Rover drive system fails and may require a lot of repair and maintenance			**2**	**2**
Risk Reduction Plan Summary			**Risk Type:**	Technical
Action/Milestone		**Success Criteria**	**Date Planned**	**Date Implemented**
Thoroughly check the Crater Grader's assembly and carry out maintenance of any worn-out parts		Successfully understand and carry out maintenance of existing parts and assemblies		
Completely replace the assembly parts with the same/similar new parts for better performance and reliability		Order and stock spares		
Add limit switches to avoid steering gears to operate beyond their limits		Limit switches added		
Comments				

Figure 35: Drive System Wear-and-Tear Causes Malfunction

Risk ID	Risk Title	Risk Owner	Date Added	Date Updated
R11	Dust ingress	William	11/27/2024	11/27/2024
Description			**Original Likelihood**	**Original Consequence**
Due to significant sand manipulation, the flying sand/dust can enter and accumulate over sensitive electronics (PDB, drivers, Arduino) and sensors (cameras, IMU), leading to component failure or incorrect sensing			**5**	**3**
Consequence			**Mitigated Likelihood**	**Mitigated Consequence**
Component failure during testing or demonstrations. Highly inhibits all future scheduled tasks			**3**	**3**
Risk Reduction Plan Summary			**Risk Type:**	Technical, Cost
Action/Milestone		**Success Criteria**	**Date Planned**	**Date Implemented**
Design proper sand enclosures and mounts for sensitive components		Successfully design and manufacture enclosures		
Review placement of components		Components are placed aptly, away from dust		
Review scale and speed of sand manipulation to eliminate root-cause of flying sand/dust		Select the sweet spot for apt tool speed with least flying dust/sand		
Allocate contingency budget and order spares of the sensitive components in case of component failure		Order and stock spares		
Comments				

Figure 36: Dust Ingress

Risk ID	Risk Title	Risk Owner	Date Added	Date Updated
R12	Code version control	Simson	11/27/2024	11/27/2024
Description			**Original Likelihood**	**Original Consequence**
Code modifications or config parameter changes during testing might not be saved, affecting the final demo. Reverting to a stable version is difficult if changes do not work as expected			**3**	**4**
Consequence			**Mitigated Likelihood**	**Mitigated Consequence**
Delay in code integration and implementation			**1**	**4**
Risk Reduction Plan Summary			**Risk Type:**	Technical
Action/Milestone		**Success Criteria**	**Date Planned**	**Date Implemented**
Implement GitHub version control to store and retrieve the best versions of code and configuration		Successful tracking of code changes		
Use Google Drive to back up important documentation explaining setup processes		Reduces delays during testing due to quick access to setup processes		
Comments				

Figure 37: Code Version Control

Risk ID	Risk Title	Risk Owner	Date Added	Date Updated
R13	Items missing	Ankit	11/27/2024	11/27/2024
Description			**Original Likelihood**	**Original Consequence**
Critical project items may go missing if not stored properly or tracked. Items may be misplaced or borrowed without proper logging			**4**	**3**
Consequence			**Mitigated Likelihood**	**Mitigated Consequence**
Delay in hardware implementation			**2**	**2**
Risk Reduction Plan Summary			**Risk Type:**	Logistics
Action/Milestone		**Success Criteria**	**Date Planned**	**Date Implemented**
Maintain an inventory tracking spreadsheet		Ensures availability of required tools and materials		
Include spare inventory		Reduces downtime caused by missing or damaged items		
Comments				

Figure 38: Items Missing

Risk ID	Risk Title	Risk Owner	Date Added	Date Updated
R14	Sensor ROS packages not available	William	11/27/2024	11/27/2024
Description			**Original Likelihood**	**Original Consequence**
Finalized sensors might lack compatible ROS packages, leading to delays or significant changes in the software architecture			**3**	**3**
Consequence			**Mitigated Likelihood**	**Mitigated Consequence**
Delay in software implementation			**1**	**3**
Risk Reduction Plan Summary			**Risk Type:**	Technical, Scheduling
Action/Milestone		**Success Criteria**	**Date Planned**	**Date Implemented**
Perform trade studies to pick sensors that are compatible with ROS versions before finalizing		Sucessful sensor-ROS compatibility		
Select sensors and ROS versions that minimize potential conflicts		Streamlined integration with minimal issues		
Comments				

Figure 39: Sensor ROS Packages not Available

Risk ID	Risk Title	Risk Owner	Date Added	Date Updated
R15	Lunar-accurate cut/fill regions are not possible to groom	Simson	11/27/2024	11/27/2024
Description			**Original Likelihood**	**Original Consequence**
The rims of the craters may not be enough to fill the whole crater. Going to a different region to carry the sand to the crater may prove to be inefficient			**3**	**3**
Consequence			**Mitigated Likelihood**	**Mitigated Consequence**
The basic assumption of sand availability fails. We may need to rethink the basic concept of tool planner to fit the new parameters of the environment.			**2**	**2**
Risk Reduction Plan Summary			**Risk Type:**	Technical
Action/Milestone		**Success Criteria**	**Date Planned**	**Date Implemented**
Accurately create the environment and assess if the rims are enough to fill		Assessment gives us adequate information		
If not, modify PRs accordingly		Achievable Performance Requirements		
Comments				

Figure 40: Lunar-Accurate Cut/Fill Regions are not Possible to Groom

Risk ID	Risk Title	Risk Owner	Date Added	Date Updated
R16	Sensor data is too noisy to fulfill performance requirements	William	11/27/2024	11/27/2024
Description			**Original Likelihood**	**Original Consequence**
Performance requirements are tough and ambitious, sensor noise may prevent us from achieving it			**4**	**4**
Consequence			**Mitigated Likelihood**	**Mitigated Consequence**
Failure to demonstrate performance requirements may cause us to lose marks in the demonstrations			**2**	**4**
Risk Reduction Plan Summary			**Risk Type:**	Technical
Action/Milestone		**Success Criteria**	**Date Planned**	**Date Implemented**
Relax the performance requirements enough to ensure that they are achievable		Achievable Performance Requirements		
Ensure enough testing time to tune parameters		Fully planned testing cycle	11/28/2024	
Comments				

Figure 41: Sensor Data is too Noisy to Fulfill Performance Requirements

Risk ID	Risk Title	Risk Owner	Date Added	Date Updated
R17	Off-the-shelf wheels don't interface with the rover	Ankit	11/27/2024	11/27/2024
Description			**Original Likelihood**	**Original Consequence**
No off-the-shelf wheels fit the rover, We'll have to redesign wheel hubs and mountings as per the new wheels.			**3**	**3**
Consequence			**Mitigated Likelihood**	**Mitigated Consequence**
Continue with sub-optimal wheels that the rover currently has, thus, not meeting one of the non-functional requirements			**2**	**3**
Risk Reduction Plan Summary			**Risk Type:**	Technical
Action/Milestone		**Success Criteria**	**Date Planned**	**Date Implemented**
Shift requirements to FVD		Updated SVD and FVD requirements for wheels		
Good enough market research to see find the best fit, with least amount of changes		Finding and replacing current wheels with new wheels, with least modifications		
Comments				

Figure 42: Off-the-Shelf Wheels don't Interface with the Rover