Lunar **ROADSTER**

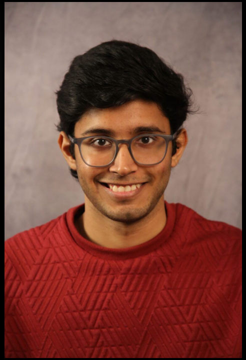
(Robotic Operator for Autonomous Development of Surface Trails and Exploration Routes)

“Starting with a foothold on the Moon, we pave the way to the cosmos”

CARNEGIE MELLON UNIVERSITY
PITTSBURGH PENNSYLVANIA 1900

The Team


Ankit Aggarwal


Deepam Ameria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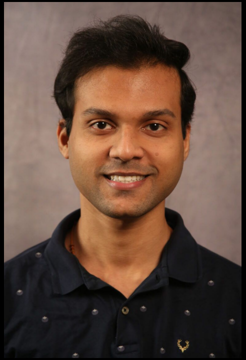
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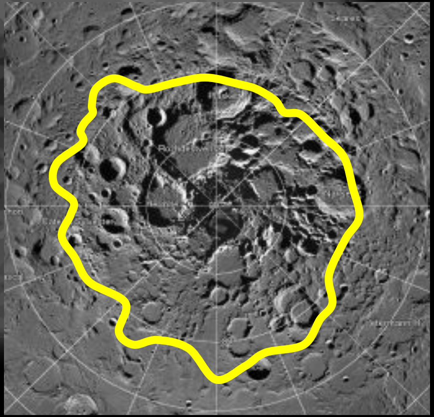
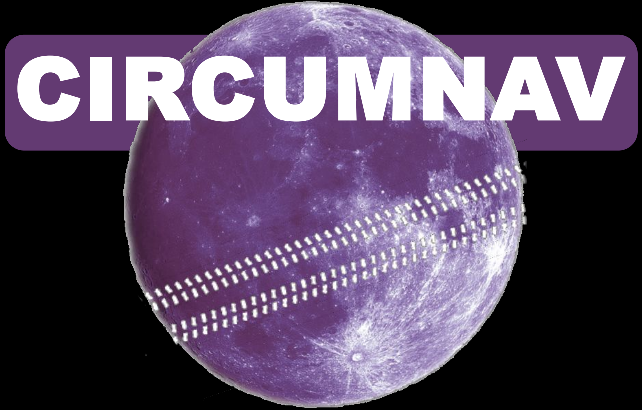
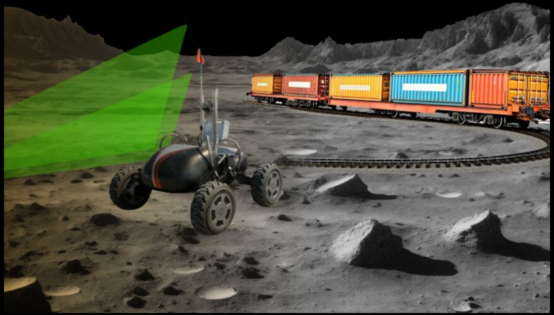
Motivation: The Lunar Polar Highway







Is it possible for a solar-powered rover to repeatedly drive around the Moon and never encounter a sunset?

Motivation: The Lunar Polar Highway

Sun-synchronous circumnavigation around Moon at
28 days x 24 hr = 672 hour sun rotation

At equator	11,000 km	16 kph
At 50 deg	7,040 km	10 kph
At 60 deg	5,500 km	8 kph
At 70 deg	3,700 km	6 kph
At 75 deg	2,800 km	4 kph
At 80 deg	1,870 km	3 kph
At 81 deg	1,529 km	2.5 kph

Jogging speed if the route was flat, circular and traversable

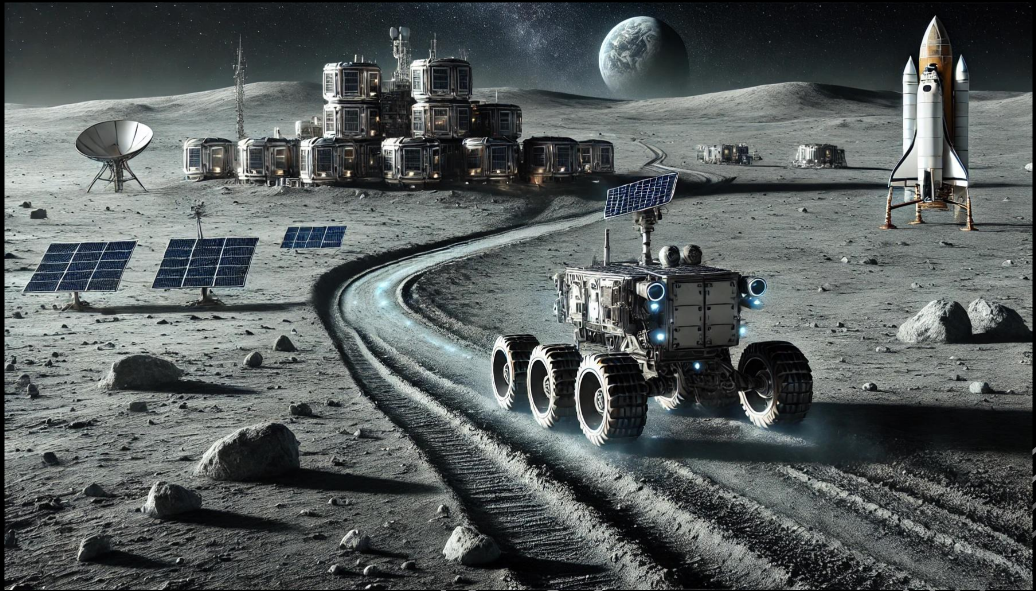
The Project: Lunar ROADSTER

An autonomous moon-working rover capable of finding ideal exploration routes and creating traversable surface trails.

By grooming trail paths, rovers with less traversing capabilities will be able to travel at higher speeds and higher power efficiencies.

A traversable and circuitous trail path will allow rovers to maintain sun-synchronicity, thereby allowing machines to run for much longer.

The groomed trails will become the backbone for colonization of the Moon by enabling transportation, logistics and enterprise development.



Use Case 1:

A road is being built to connect two lunar bases on the polar region of the moon. At the lunar base, the Lunar ROADSTER is given a detailed map of the lunar polar region.

The rover calculates a suitable path that connects the two bases that is free from large obstacles and craters. Once outside, the Lunar ROADSTER observes its surroundings and localizes its position. It then departs the lunar base and follows the planned trajectory.

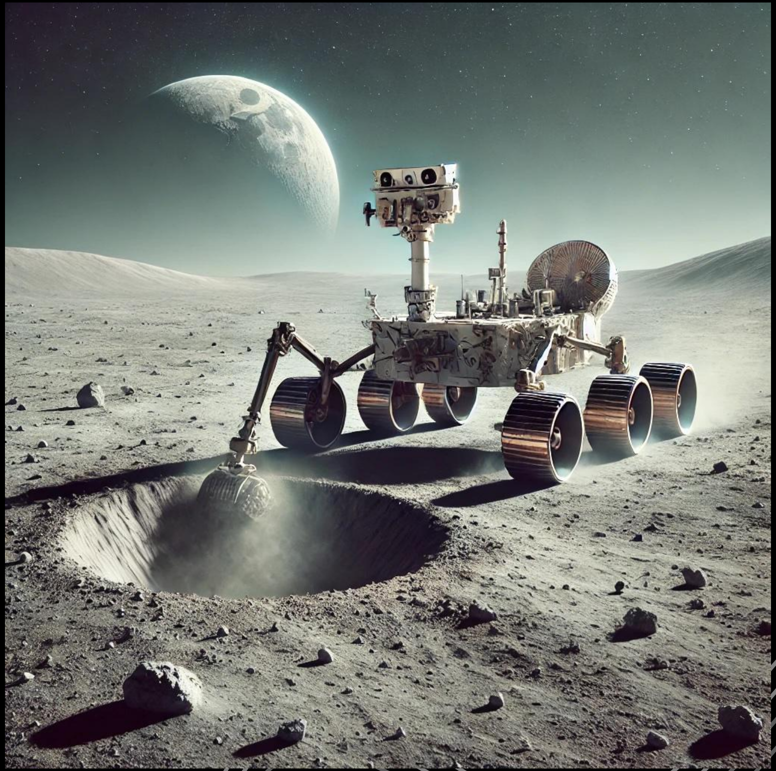
However, after traversing 500 meters, the rover notices a large obstacle in the path of the trajectory. The rover adjusts its planned path to navigate around the obstacle and alerts the lunar base of the updated trajectory.

Use Case 2:

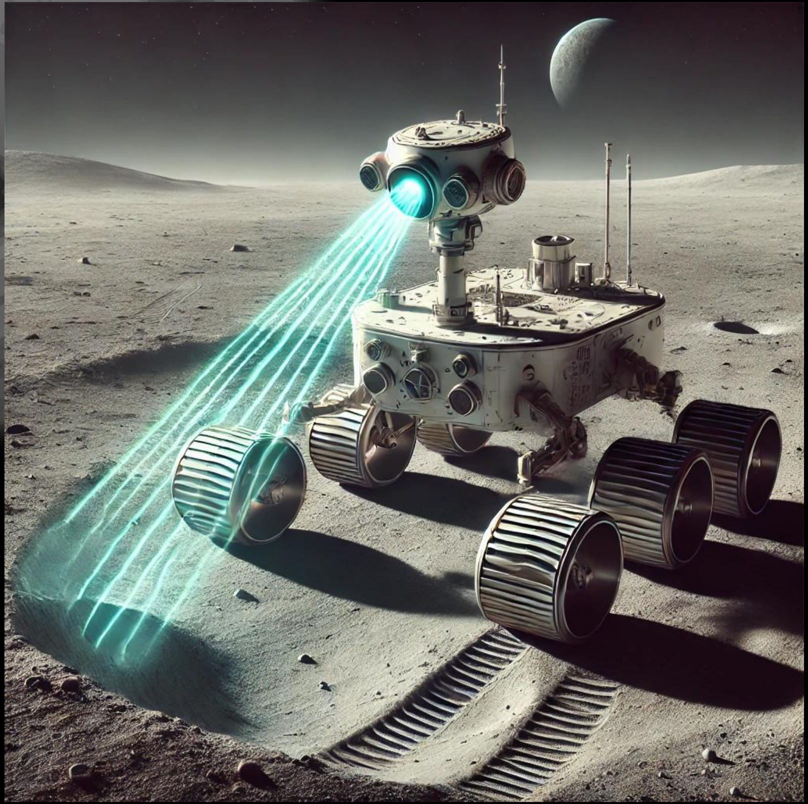
The Lunar ROADSTER approaches a shallow crater in the route of the planned path. After already determining that it is not feasible to adjust to a new path that circumvents the crater, the rover beings to fill in the crater.

Luckily, the periphery of the crater has some excess regolith to fill in the crater. The rover takes the excess regolith from the dune and pushes them into the crater. During excavation, the rover slipped on the loose regolith and falls into the crater.

Luckily, the rover was built for such rugged terrains and easily climbs out of the crater and continues on excavating. Finally, it grooms the filled in crater to make it smooth.



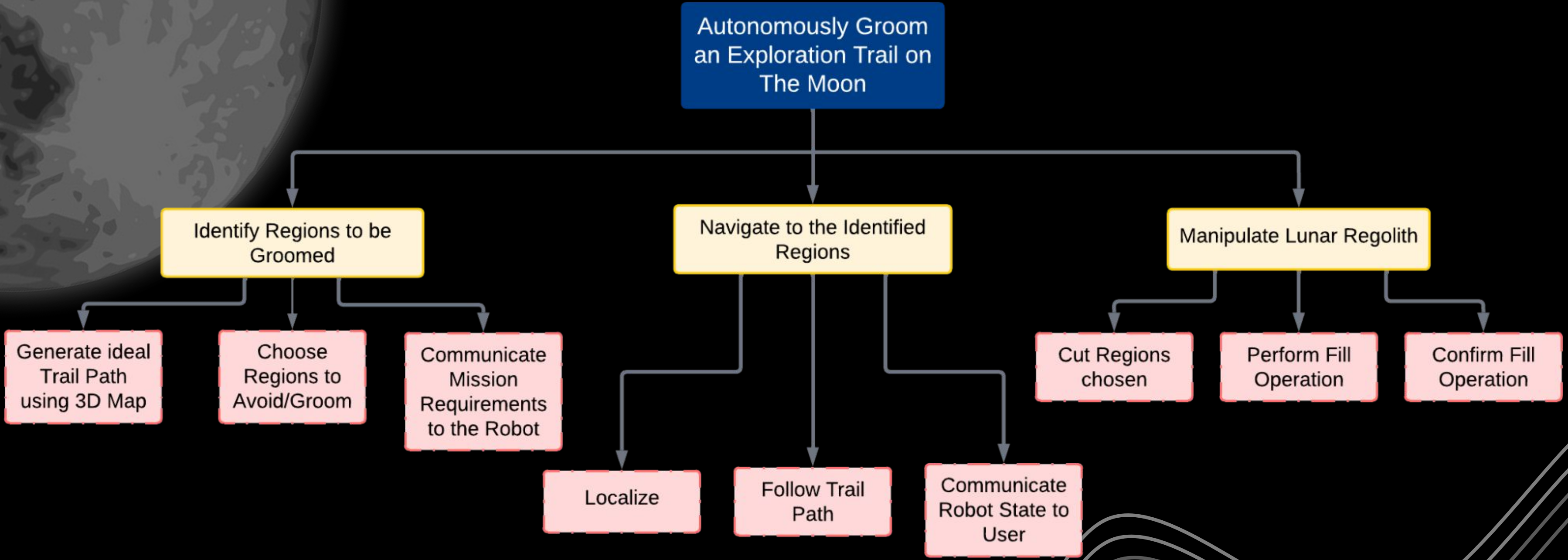
Use Case 3:



After smoothing the crater, the rover backs up to view the groomed crater and validate the job. However, the rover determines that the groomed crater is still to steep and does not make a satisfactory trail. The rover returns to the crater location to re-groom the crater and make it smoother.

After the second attempt, the rover validates that the trail is now satisfactory. It sends this information to the user and continues on navigating the planned path.

Objectives Tree



Autonomously Groom an Exploration Trail on The Moon

Identify Regions to be Groomed

Generate ideal Trail Path using 3D Map

Choose Regions to Avoid/Groom

Communicate Mission Requirements to the Robot

Navigate to the Identified Regions

Localize

Follow Trail Path

Communicate Robot State to User

Manipulate Lunar Regolith

Cut Regions chosen

Perform Fill Operation

Confirm Fill Operation

Functional Requirements (Mandatory)

Sr. No.	Mandatory Functional Requirement
M.F.1	Shall perform trail path planning
M.F.2	Shall operate autonomously
M.F.3	Shall localize itself in a GPS denied environment
M.F.4	Shall navigate the planned path
M.F.5	Shall traverse uneven terrain
M.F.6	Shall choose craters to groom and avoid
M.F.7	Shall grade craters and level dunes
M.F.8	Shall validate grading and trail path
M.F.9	Shall communicate with the user

Non-Functional Requirements (Mandatory)

Sr. No.	Parameter	Description
M.N.1	Weight	The rover must weigh under 50kg
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 1m in all dimensions

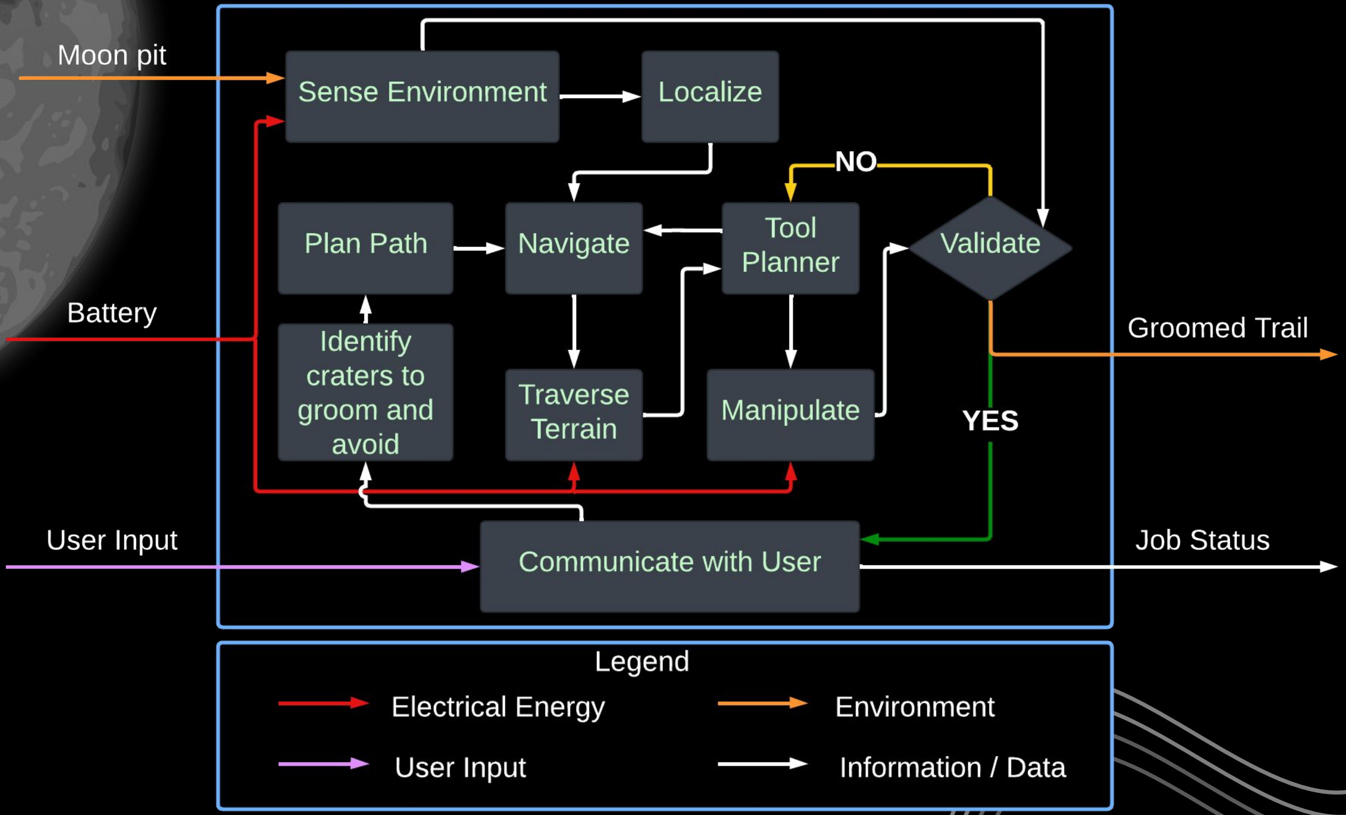
Non-Functional Requirements (Desirable)

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

Performance Requirements (Mandatory)

Sr. No.	Performance Metrics
M.P.1	Will plan a path with cumulative deviation of <= 25% from chosen latitude's length
M.P.2	Will follow planned path to a maximum deviation of 10%
M.P.3	Will climb gradients up to 15° and have a contact pressure of less than 1.5 kPa
M.P.4	Will avoid craters >= 0.5 metres and avoid slopes >= 15°
M.P.5	Will fill craters of up to 0.5 meters in diameter and 0.1m in depth
M.P.6	Will groom the trail to have a maximum traversal slope of 5°

Functional Architecture



Moon pit

Battery

User Input

Sense Environment

Localize

Plan Path

Navigate

Tool Planner

Validate

NO

YES

Identify craters to groom and avoid

Traverse Terrain

Manipulate

Communicate with User

Groomed Trail

Job Status

Legend

Electrical Energy

Environment

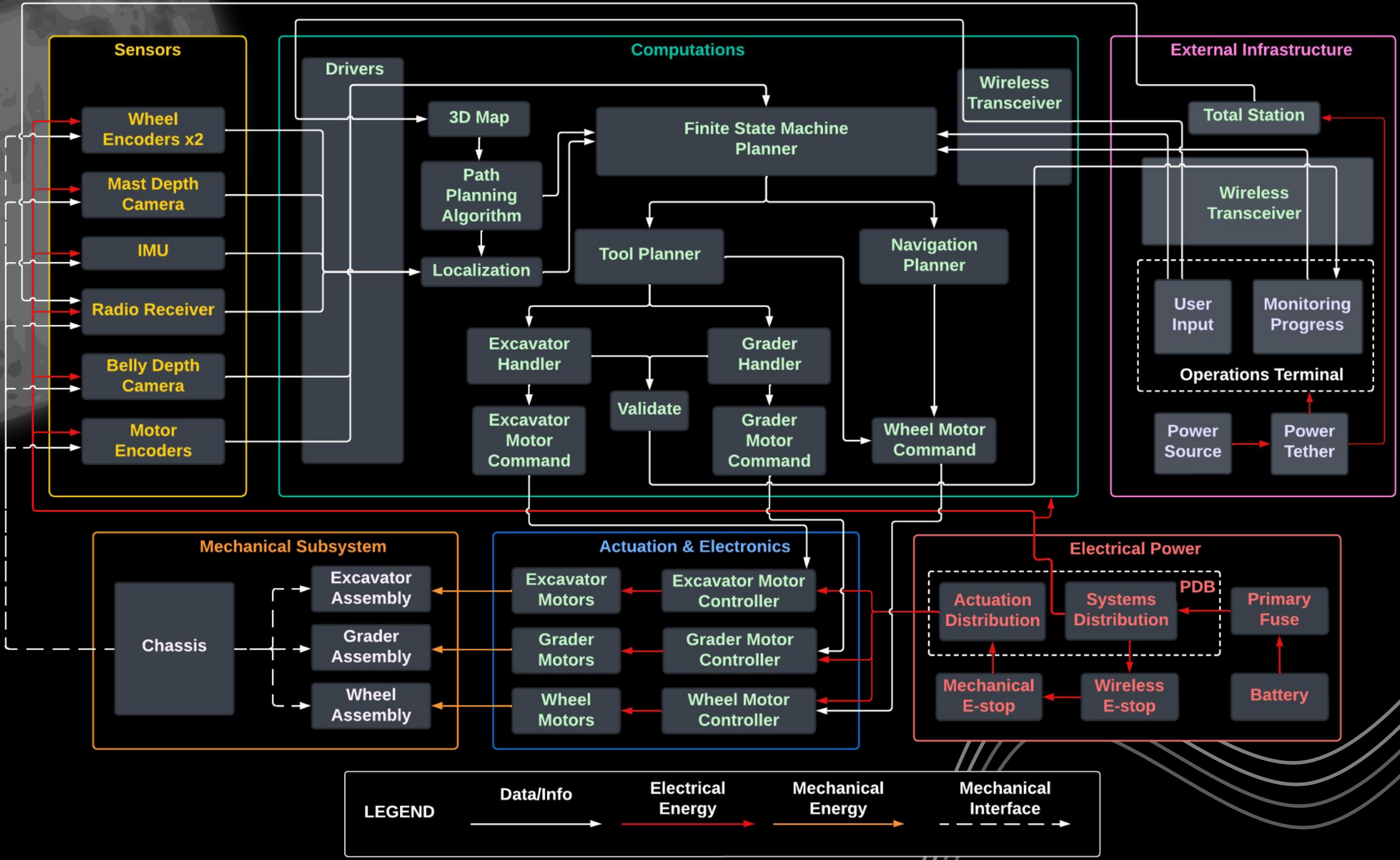
User Input

Information / Data

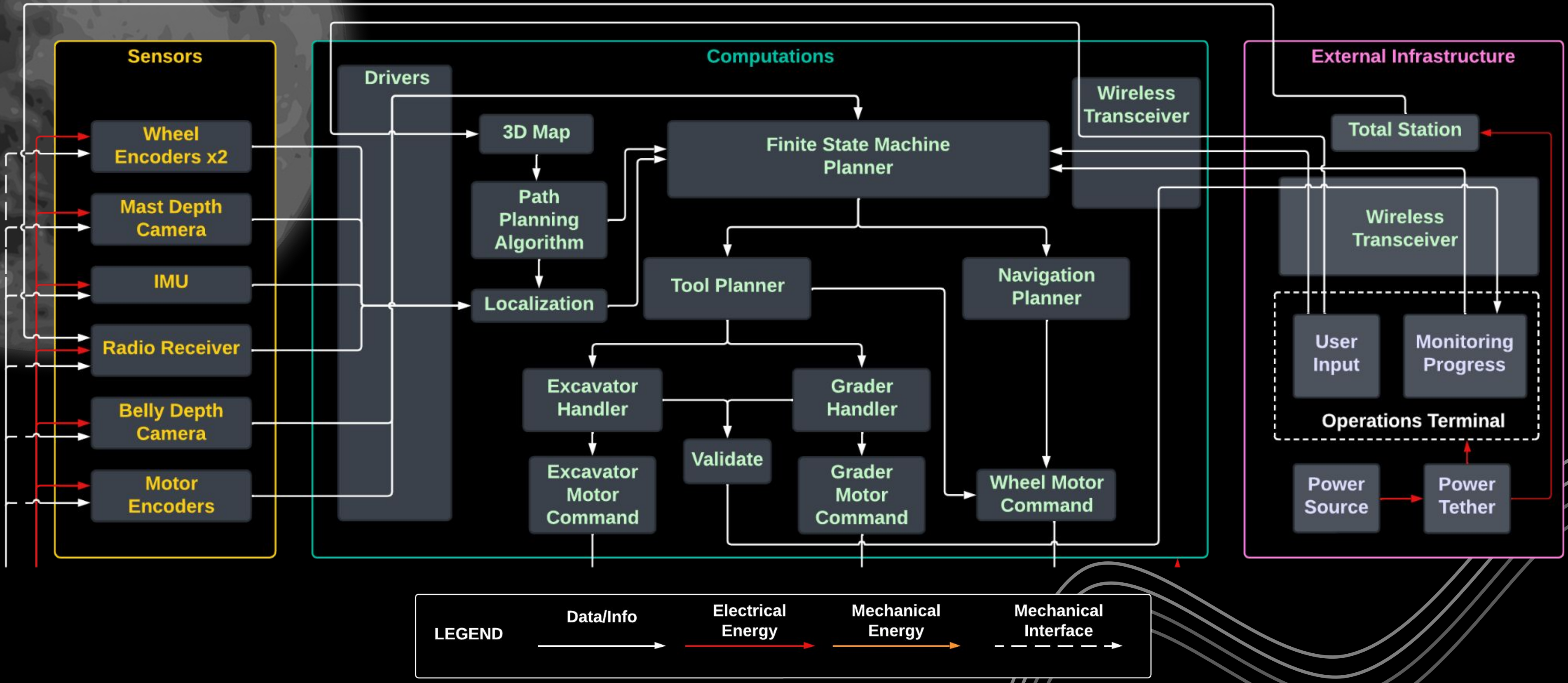
Morphological Chart

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		

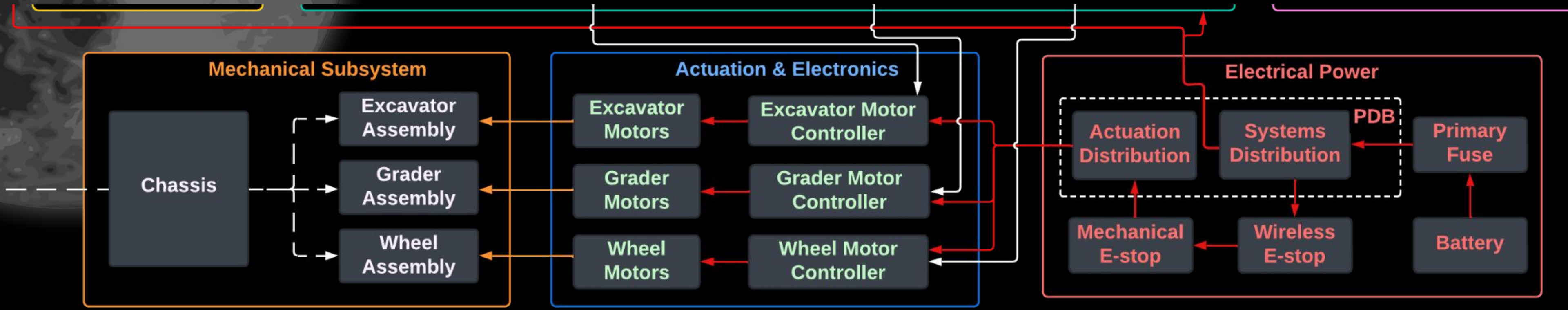
Cyber-Physical Architecture

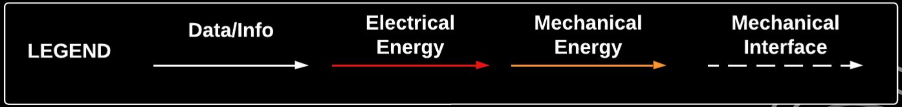


Cyber-Physical Architecture

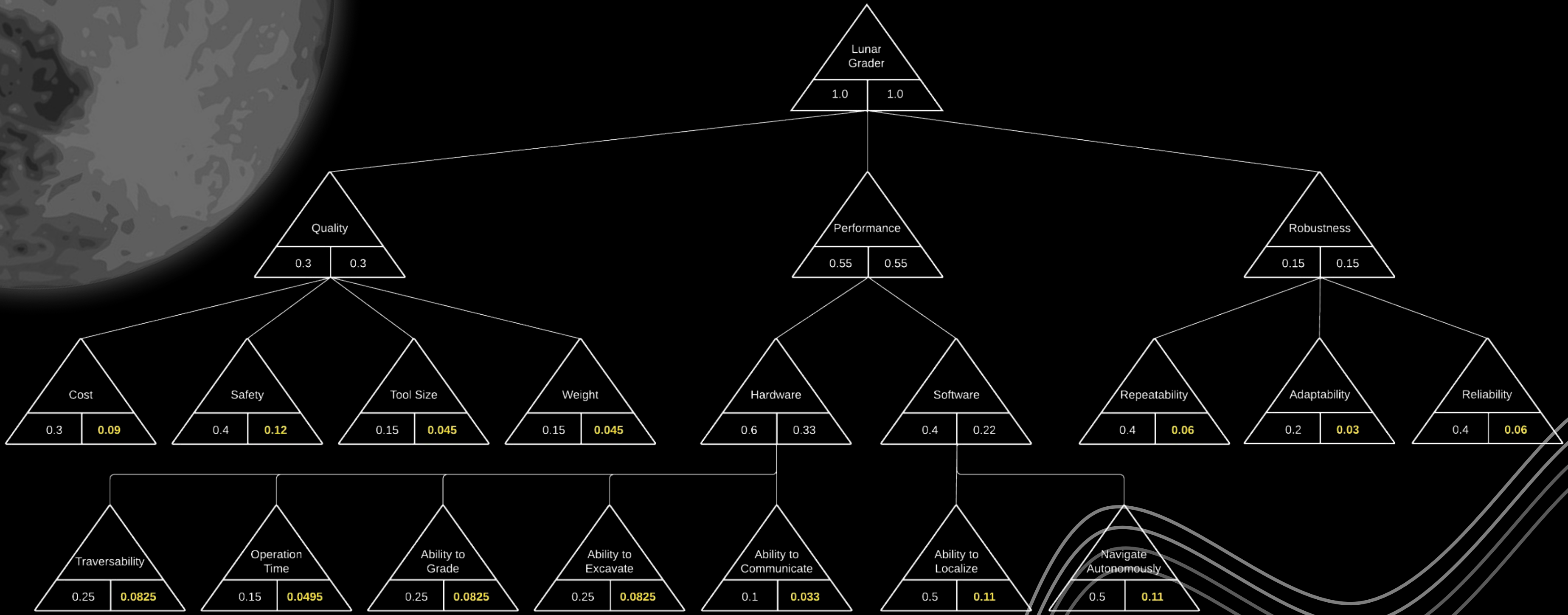


Cyber-Physical Architecture



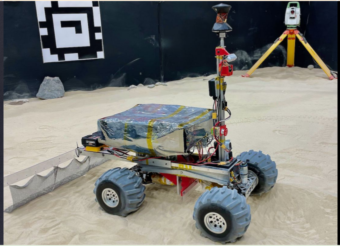


Systems Level Weighted Objectives Tree

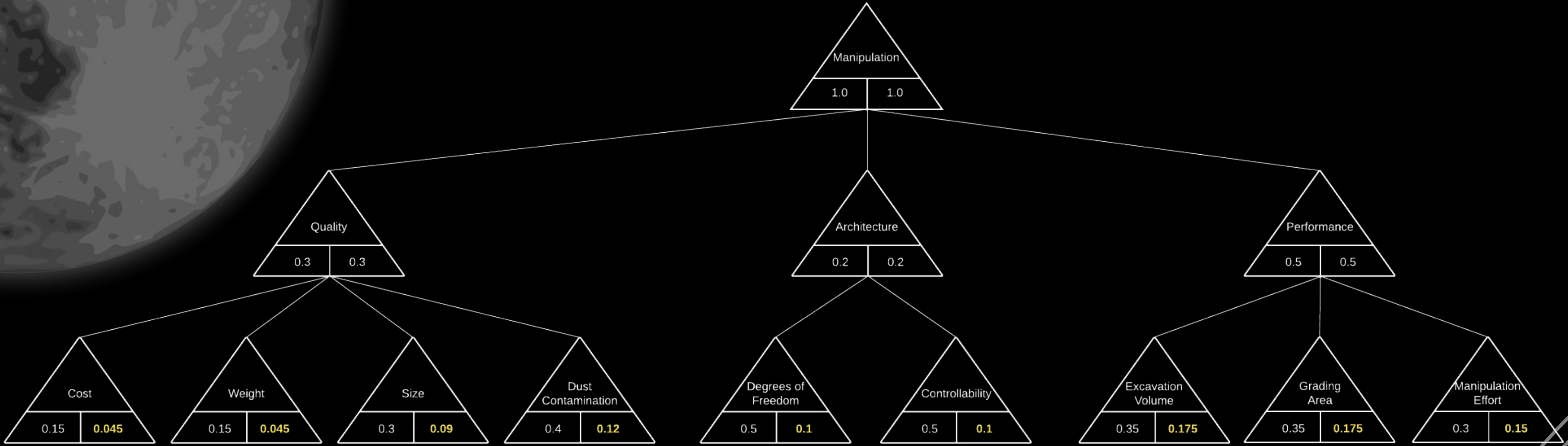


- Lunar Grader 1.0 | 1.0
  - Quality 0.3 | 0.3
    - Cost 0.3 | **0.09**
    - Safety 0.4 | **0.12**
    - Tool Size 0.15 | **0.045**
    - Weight 0.15 | **0.045**
  - Performance 0.55 | 0.55
    - Hardware 0.6 | 0.33
      - Traversability 0.25 | **0.0825**
      - Operation Time 0.15 | **0.0495**
      - Ability to Grade 0.25 | **0.0825**
      - Ability to Excavate 0.25 | **0.0825**
      - Ability to Communicate 0.1 | **0.033**
    - Software 0.4 | 0.22
      - Ability to Localize 0.5 | **0.11**
      - Navigate Autonomously 0.5 | **0.11**
  - Robustness 0.15 | 0.15
    - Repeatability 0.4 | **0.06**
    - Adaptability 0.2 | **0.03**
    - Reliability 0.4 | **0.06**

Systems Level Trade Study

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**

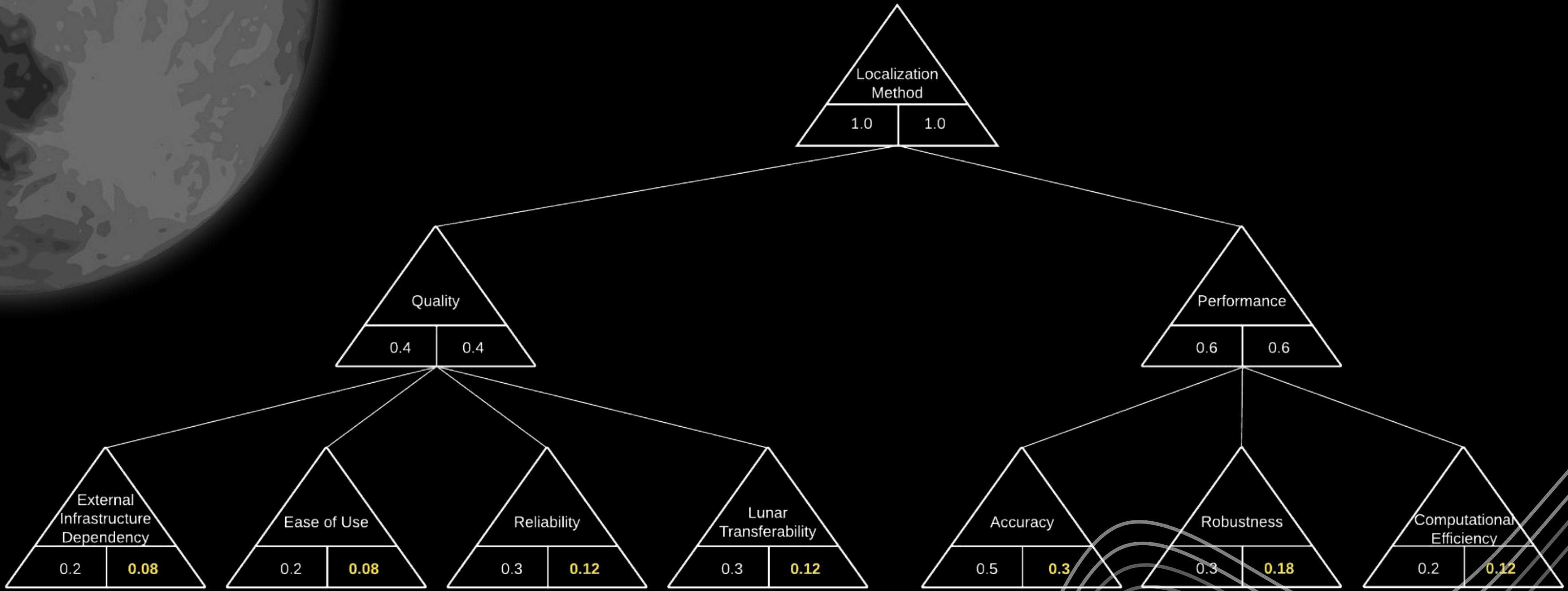
Sub-Systems Level Weighted Objectives Tree (1)



Sub-Systems Level Trade Study (1)

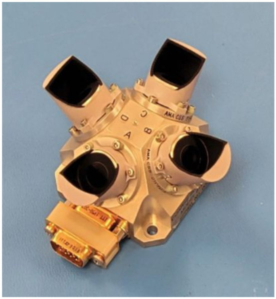
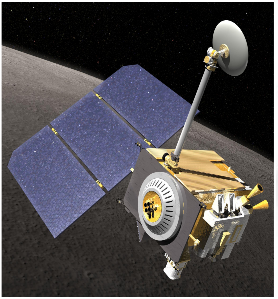
Trade Studies	Sub-Systems Level	Manipulation			
Value Ratings *	Concept	Front loader	Front grader	Chassis grader	Front loader & chassis grader
0: Inadequate					
2: Tolerable					
4: Adequate					
6: Good					
8: Excellent					
10: Perfect					
*** Subjective Value Method**					
Criteria	Weight Factor	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**

Sub-Systems Level Weighted Objectives Tree (2)



- Localization Method 1.0 1.0
  - Quality 0.4 0.4
    - External Infrastructure Dependency 0.2 **0.08**
    - Ease of Use 0.2 **0.08**
    - Reliability 0.3 **0.12**
    - Lunar Transferability 0.3 **0.12**
  - Performance 0.6 0.6
    - Accuracy 0.5 **0.3**
    - Robustness 0.3 **0.18**
    - Computational Efficiency 0.2 **0.12**

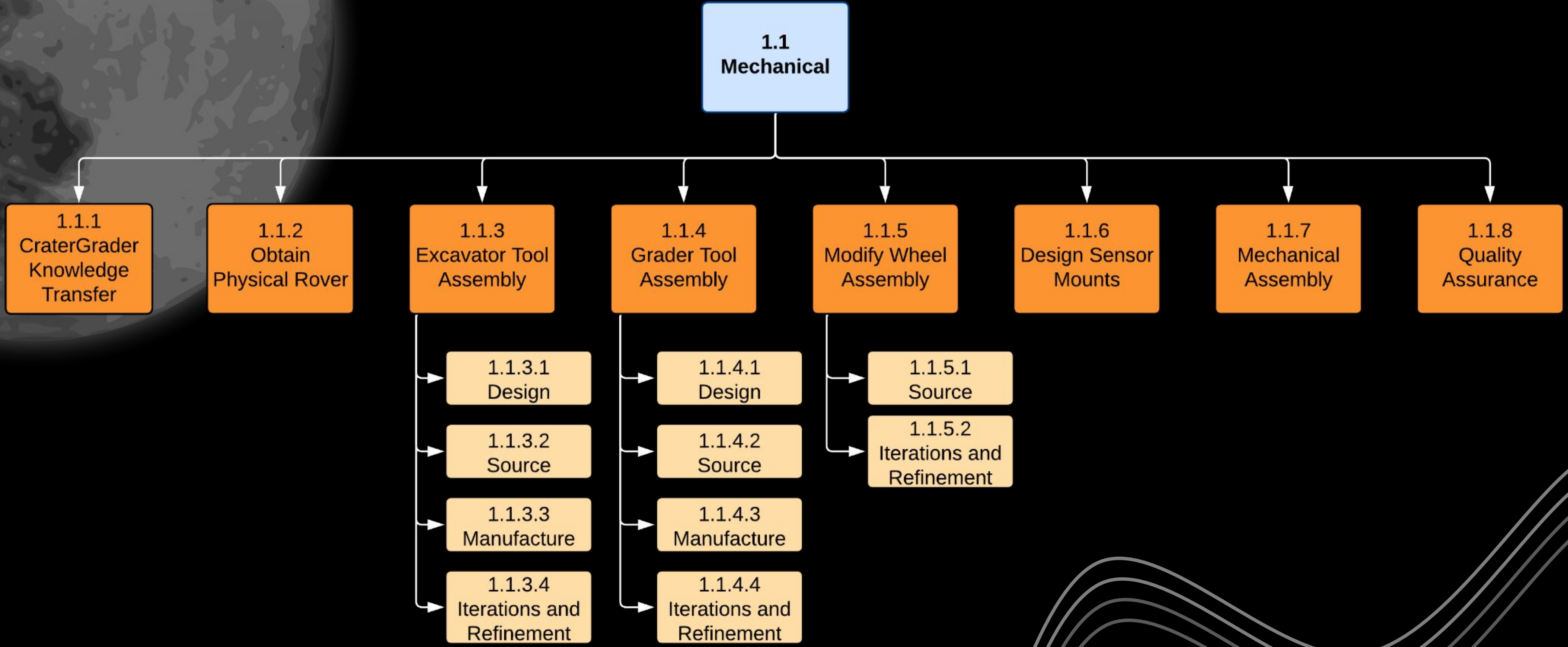
Sub-Systems Level Trade Study (2)

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**

Work Breakdown Structure

- Lunar ROADSTER
  - 1.1 Mechanical
    - 1.1.1 Obtain and Understand CraterGrader Hardware Files
    - 1.1.2 Obtain Physical Rover
    - 1.1.3 Excavator Tool Assembly
    - 1.1.4 Grader Tool Assembly
    - 1.1.5 Modify Wheel Assembly
    - 1.1.6 Design and Manufacture Sensor Mounts
    - 1.1.7 Mechanical Assembly
    - 1.1.8 Quality Assurance
  - 1.2 Computations
    - 1.2.1 Obtain and Understand CraterGrader Software Files
    - 1.2.2 Setup Jetson Drivers
    - 1.2.3 Read 3D Map
    - 1.2.4 Path Planning
    - 1.2.5 Localization - Sensor Fusion
    - 1.2.6 FSM Planner
    - 1.2.7 Excavator Planner
    - 1.2.8 Grader Planner
    - 1.2.9 Navigation Planner
    - 1.2.10 Validation
  - 1.3 Sense
    - 1.3.1 Source Sensors
    - 1.3.2 Setup Encoder Drivers
    - 1.3.3 Setup Mast Depth Camera Drivers
    - 1.3.4 Setup Belly Depth Camera Drivers
    - 1.3.5 Setup IMU Drivers
    - 1.3.6 Setup Radio Receiver Drivers
    - 1.3.7 Setup Survey LiDARs
  - 1.4 Electronics
    - 1.4.1 Source Electronics
    - 1.4.2 Devise Circuit Diagram
    - 1.4.3 Setup Circuit
  - 1.5 External Infrastructure
    - 1.5.1 Source Total Station
    - 1.5.2 Setup Total Station
    - 1.5.3 Setup Operations Terminal
    - 1.5.4 Obtain 3D Map
  - 1.6 Integration & Testing
    - 1.6.1 Setup Test Environment
    - 1.6.2 Generate 3D Map using Survey LiDAR
    - 1.6.3 Integrate Subsystems
    - 1.6.4 Test Complete System
  - 1.7 Management
    - 1.7.1 Manage Work
    - 1.7.2 Manage Documentation
    - 1.7.3 Manage Finances
    - 1.7.4 Manage Schedules
    - 1.7.5 Manage HR
    - 1.7.6 Manage Risks

Work Breakdown Structure - Mechanical



1.1 Mechanical

1.1.1 CraterGrader Knowledge Transfer

1.1.2 Obtain Physical Rover

1.1.3 Excavator Tool Assembly
- 1.1.3.1 Design
- 1.1.3.2 Source
- 1.1.3.3 Manufacture
- 1.1.3.4 Iterations and Refinement

1.1.4 Grader Tool Assembly
- 1.1.4.1 Design
- 1.1.4.2 Source
- 1.1.4.3 Manufacture
- 1.1.4.4 Iterations and Refinement

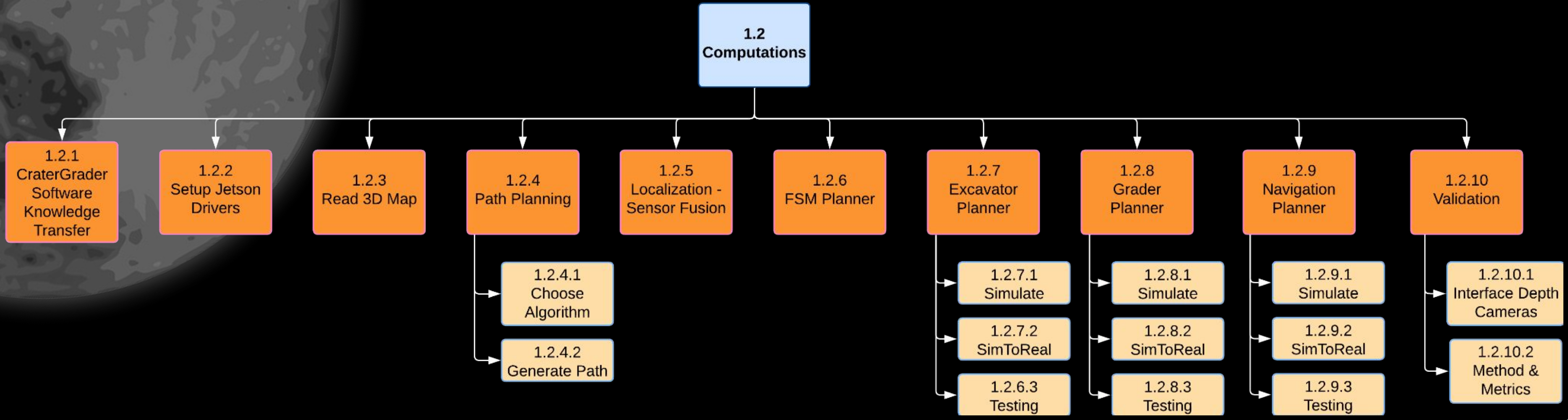
1.1.5 Modify Wheel Assembly
- 1.1.5.1 Source
- 1.1.5.2 Iterations and Refinement

1.1.6 Design Sensor Mounts

1.1.7 Mechanical Assembly

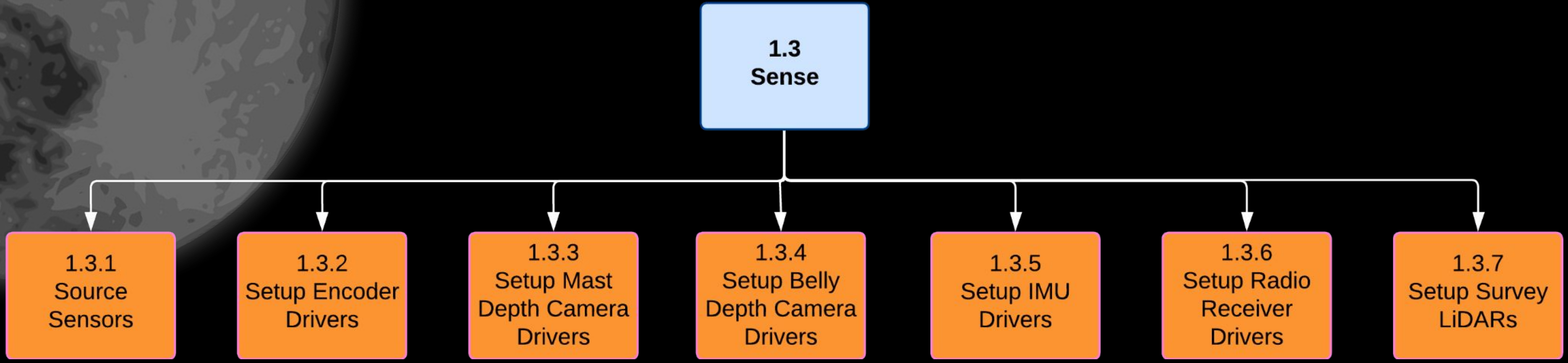
1.1.8 Quality Assurance

Work Breakdown Structure - Computations



- 1.2 Computations
  - 1.2.1 CraterGrader Software Knowledge Transfer
  - 1.2.2 Setup Jetson Drivers
  - 1.2.3 Read 3D Map
  - 1.2.4 Path Planning
    - 1.2.4.1 Choose Algorithm
    - 1.2.4.2 Generate Path
  - 1.2.5 Localization - Sensor Fusion
  - 1.2.6 FSM Planner
  - 1.2.7 Excavator Planner
    - 1.2.7.1 Simulate
    - 1.2.7.2 SimToReal
    - 1.2.6.3 Testing
  - 1.2.8 Grader Planner
    - 1.2.8.1 Simulate
    - 1.2.8.2 SimToReal
    - 1.2.8.3 Testing
  - 1.2.9 Navigation Planner
    - 1.2.9.1 Simulate
    - 1.2.9.2 SimToReal
    - 1.2.9.3 Testing
  - 1.2.10 Validation
    - 1.2.10.1 Interface Depth Cameras
    - 1.2.10.2 Method & Metrics

Work Breakdown Structure - Sense



1.3
Sense

1.3.1
Source Sensors

1.3.2
Setup Encoder Drivers

1.3.3
Setup Mast Depth Camera Drivers

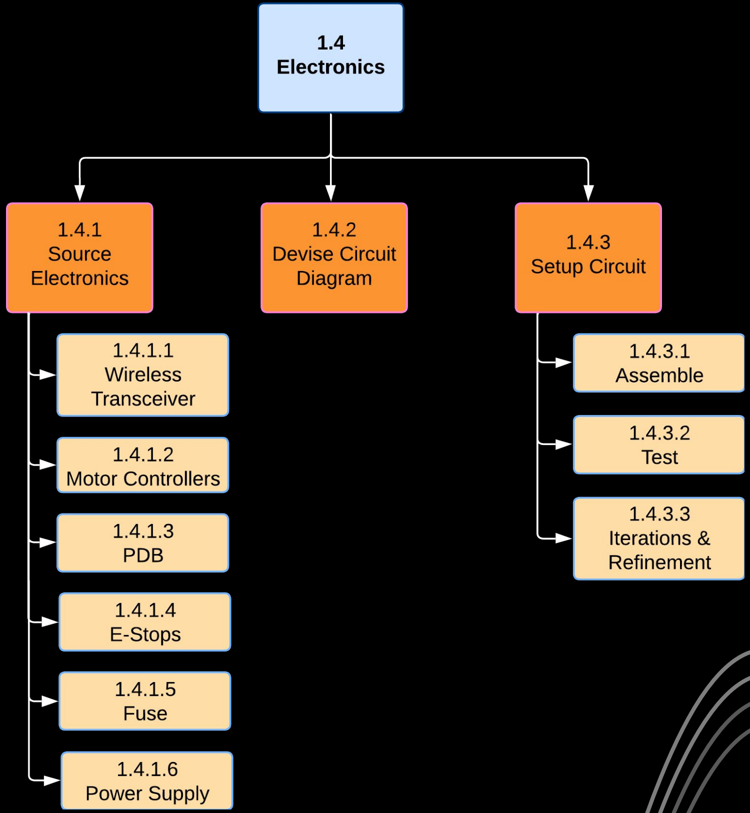
1.3.4
Setup Belly Depth Camera Drivers

1.3.5
Setup IMU Drivers

1.3.6
Setup Radio Receiver Drivers

1.3.7
Setup Survey LiDARs

Work Breakdown Structure - Electronics



1.4
Electronics

1.4.1
Source Electronics

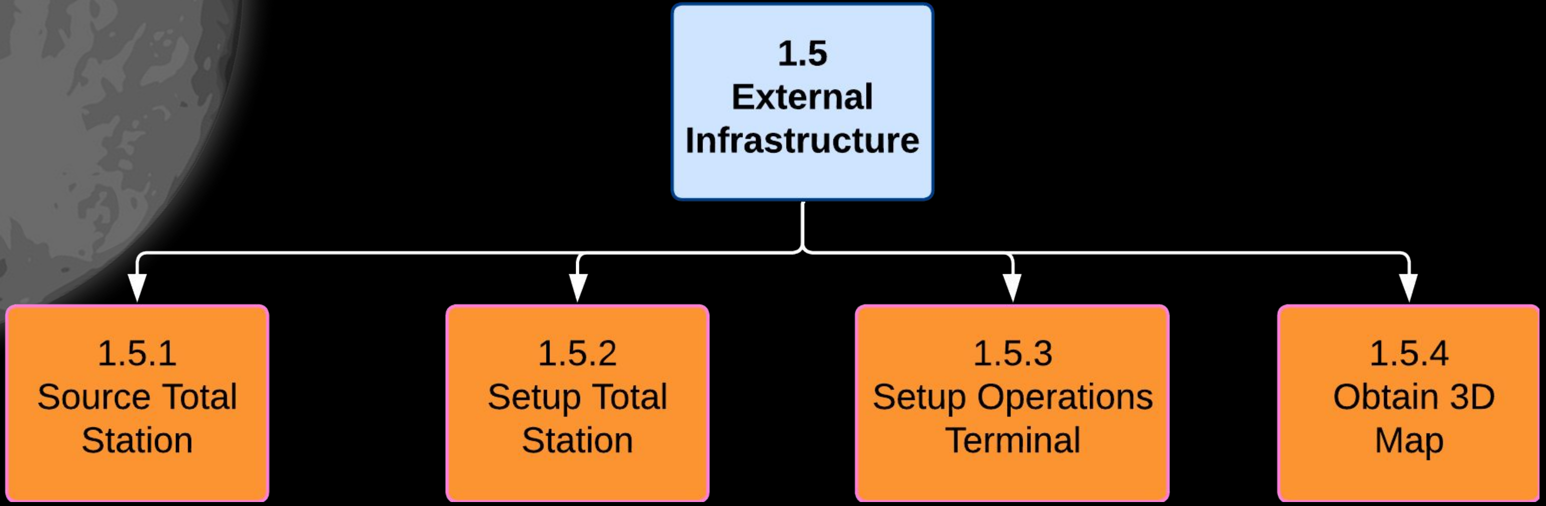
- 1.4.1.1 Wireless Transceiver
- 1.4.1.2 Motor Controllers
- 1.4.1.3 PDB
- 1.4.1.4 E-Stops
- 1.4.1.5 Fuse
- 1.4.1.6 Power Supply

1.4.2
Devise Circuit Diagram

1.4.3
Setup Circuit

- 1.4.3.1 Assemble
- 1.4.3.2 Test
- 1.4.3.3 Iterations & Refinement

Work Breakdown Structure - External Infrastructure



1.5
External Infrastructure

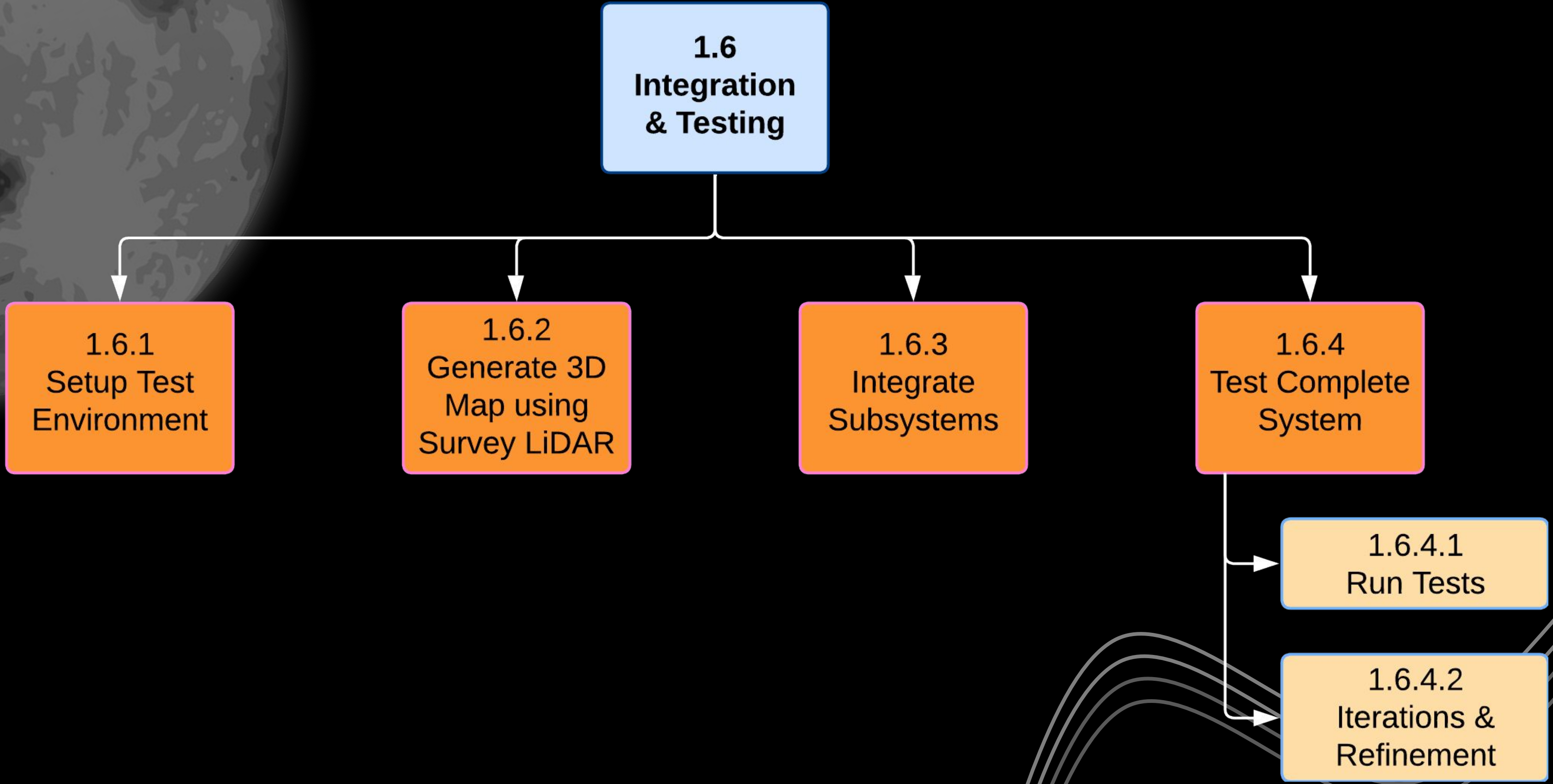
1.5.1
Source Total Station

1.5.2
Setup Total Station

1.5.3
Setup Operations Terminal

1.5.4
Obtain 3D Map

Work Breakdown Structure - Integration & Testing



1.6
Integration & Testing

1.6.1
Setup Test Environment

1.6.2
Generate 3D Map using Survey LiDAR

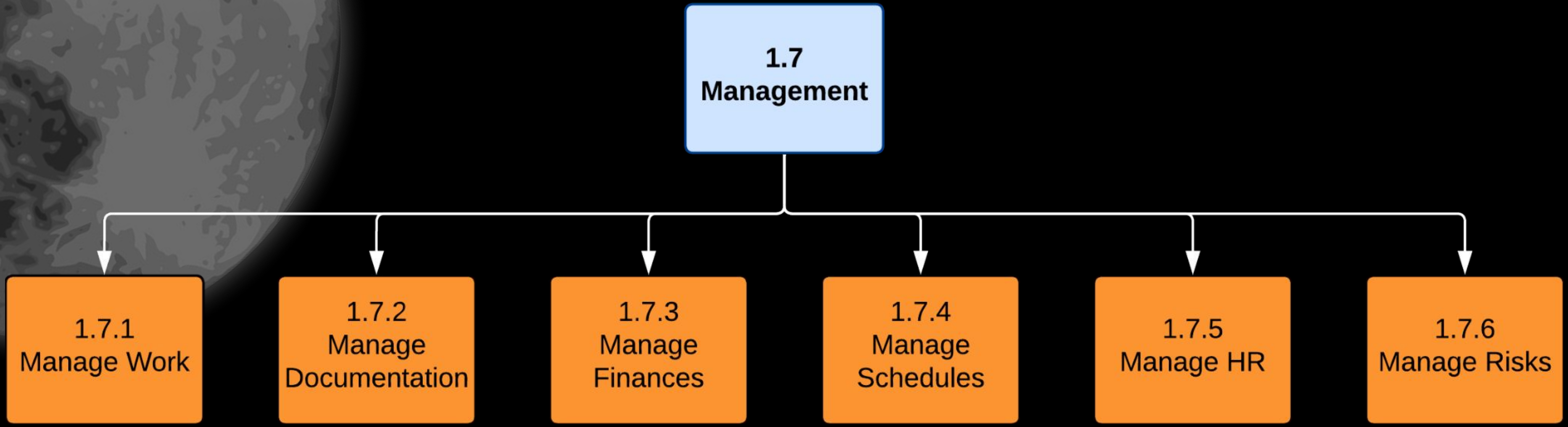
1.6.3
Integrate Subsystems

1.6.4
Test Complete System

1.6.4.1
Run Tests

1.6.4.2
Iterations & Refinement

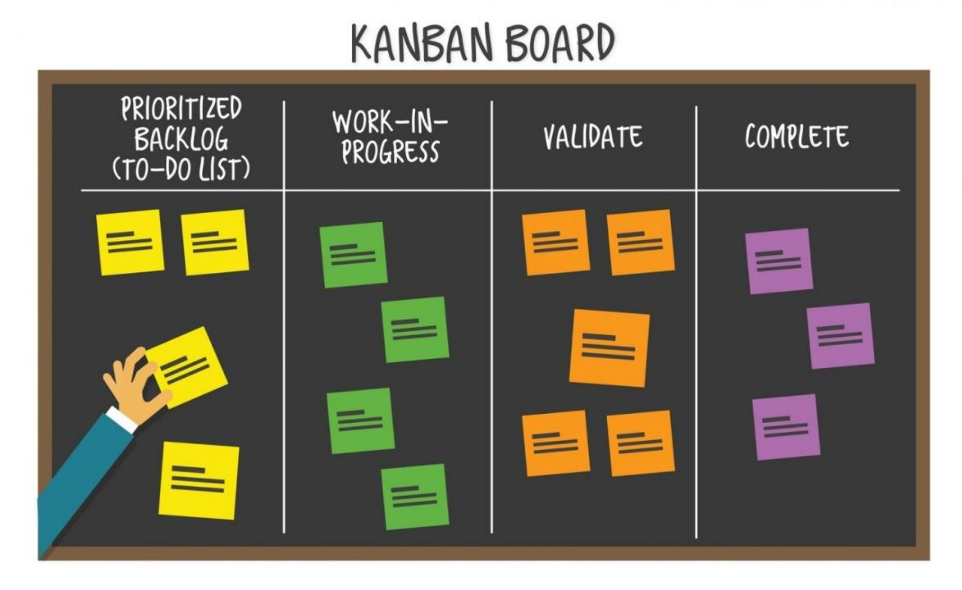
Work Breakdown Structure - Management



1.7 Management

- 1.7.1 Manage Work
- 1.7.2 Manage Documentation
- 1.7.3 Manage Finances
- 1.7.4 Manage Schedules
- 1.7.5 Manage HR
- 1.7.6 Manage Risks

Estimating Hours per Task



We estimated the time each task will take to complete on the basis of:

- CraterGrader’s Timeline
- Advice from Red
- Advice from Dimi
- Prior Experiences

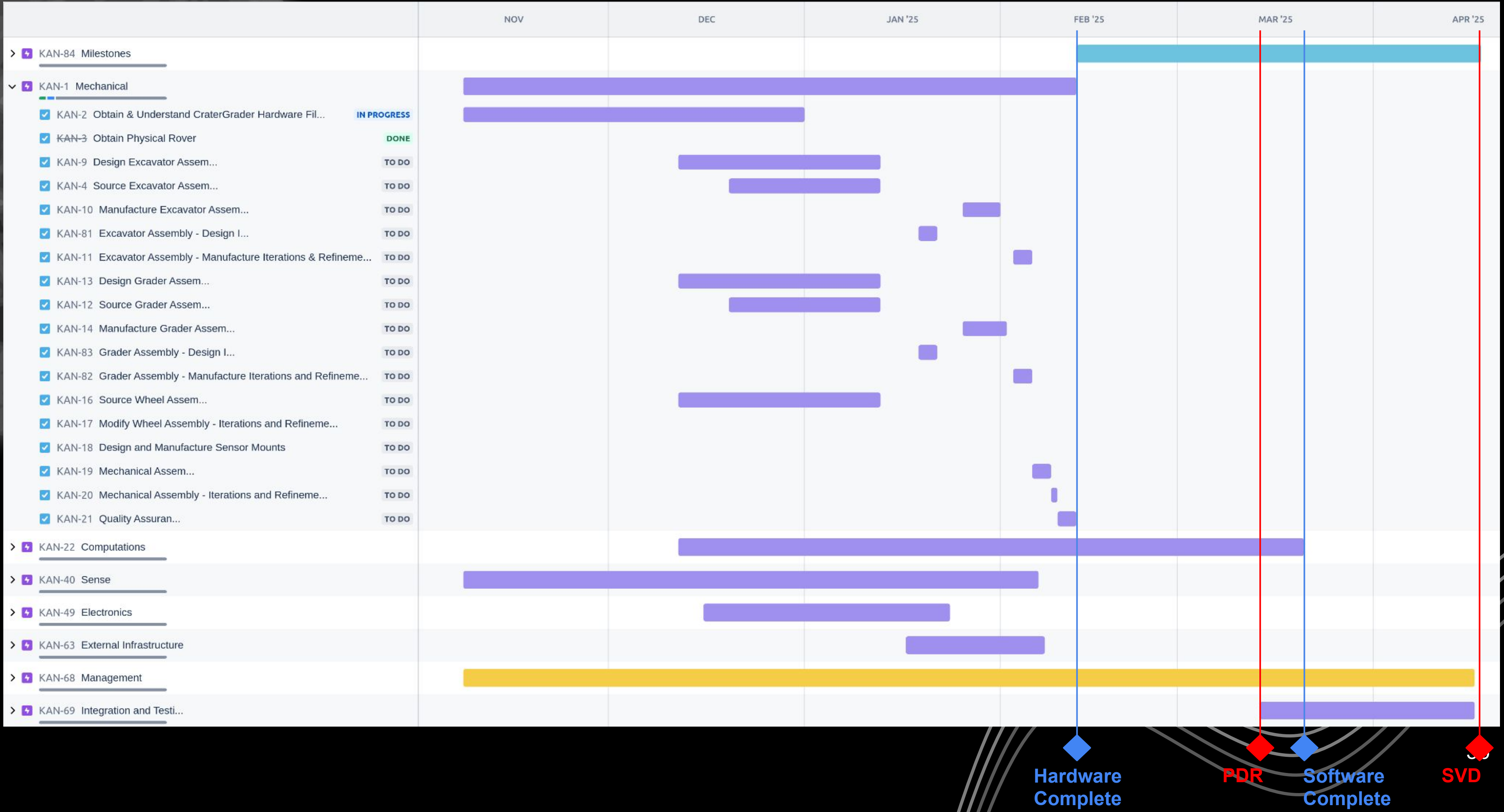
Based on this, we were able to devise the SVD and FVD split.

SVD and FVD Split

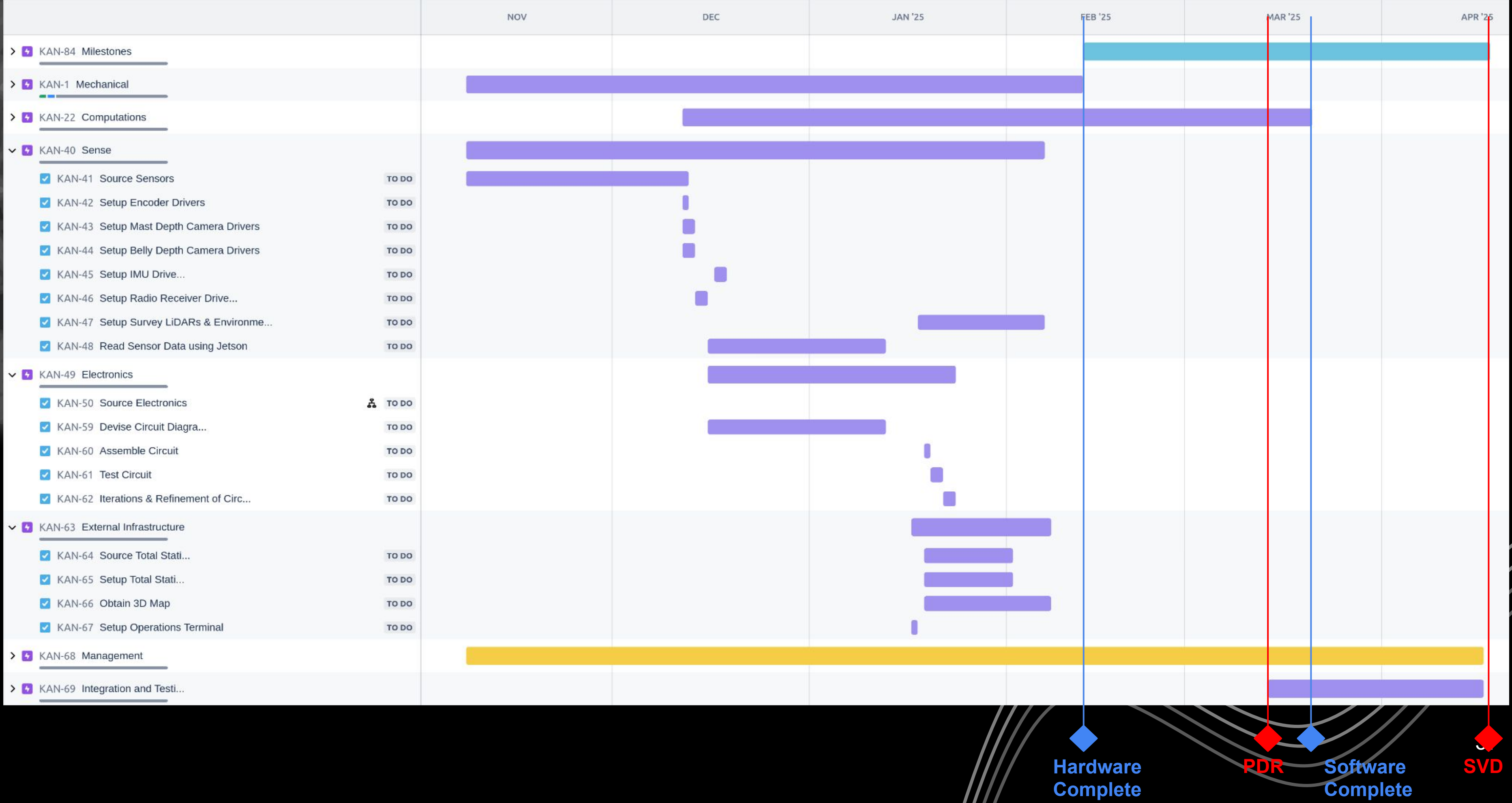
Spring Validation Demo	Fall Validation Demo
ROADSTER uses the excavator to groom one or two craters on a simple, straight path in the MoonYard.	ROADSTER uses both grader and excavator to create a circuitous path around the MoonYard.
This will be our Minimal Viable Product with simplified localization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

Schedule

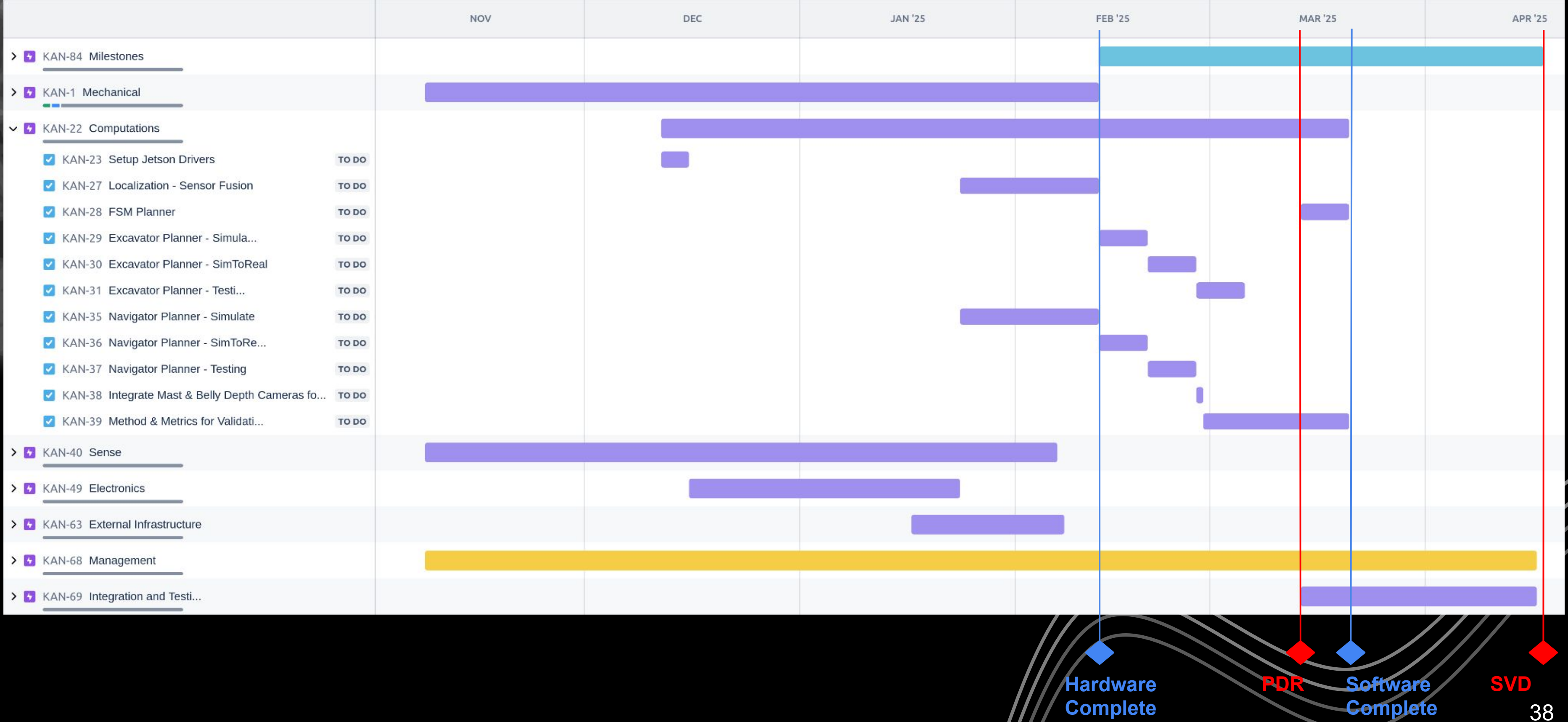

NOV
DEC
JAN '25
FEB '25
MAR '25
APR '25
KAN-84 Milestones
KAN-1 Mechanical
KAN-22 Computations
KAN-40 Sense
KAN-49 Electronics
KAN-63 External Infrastructure
KAN-68 Management
KAN-69 Integration and Testi...
Hardware Complete
PDR
Software Complete
SVD



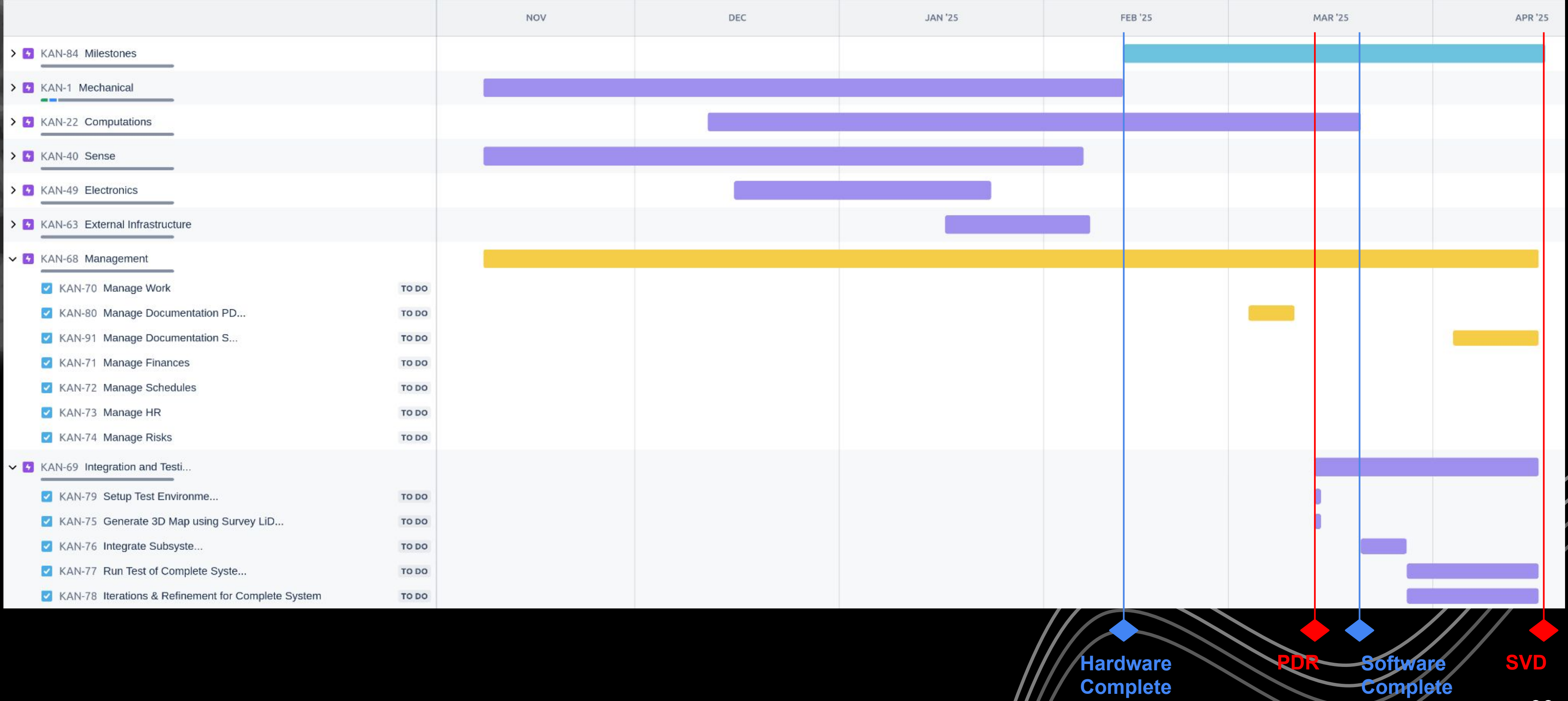
KAN-84	Milestones	
KAN-1	Mechanical	
KAN-2	Obtain & Understand CraterGrader Hardware Fil...	IN PROGRESS
~~KAN-3~~	Obtain Physical Rover	DONE
KAN-9	Design Excavator Assem...	TO DO
KAN-4	Source Excavator Assem...	TO DO
KAN-10	Manufacture Excavator Assem...	TO DO
KAN-81	Excavator Assembly - Design I...	TO DO
KAN-11	Excavator Assembly - Manufacture Iterations & Refineme...	TO DO
KAN-13	Design Grader Assem...	TO DO
KAN-12	Source Grader Assem...	TO DO
KAN-14	Manufacture Grader Assem...	TO DO
KAN-83	Grader Assembly - Design I...	TO DO
KAN-82	Grader Assembly - Manufacture Iterations and Refineme...	TO DO
KAN-16	Source Wheel Assem...	TO DO
KAN-17	Modify Wheel Assembly - Iterations and Refineme...	TO DO
KAN-18	Design and Manufacture Sensor Mounts	TO DO
KAN-19	Mechanical Assem...	TO DO
KAN-20	Mechanical Assembly - Iterations and Refineme...	TO DO
KAN-21	Quality Assuran...	TO DO
KAN-22	Computations	
KAN-40	Sense	
KAN-49	Electronics	
KAN-63	External Infrastructure	
KAN-68	Management	
KAN-69	Integration and Testi...	



KAN-84	Milestones	
KAN-1	Mechanical	
KAN-22	Computations	
KAN-40	Sense	
KAN-41	Source Sensors	TO DO
KAN-42	Setup Encoder Drivers	TO DO
KAN-43	Setup Mast Depth Camera Drivers	TO DO
KAN-44	Setup Belly Depth Camera Drivers	TO DO
KAN-45	Setup IMU Drive...	TO DO
KAN-46	Setup Radio Receiver Drive...	TO DO
KAN-47	Setup Survey LiDARs & Environme...	TO DO
KAN-48	Read Sensor Data using Jetson	TO DO
KAN-49	Electronics	
KAN-50	Source Electronics	TO DO
KAN-59	Devise Circuit Diagra...	TO DO
KAN-60	Assemble Circuit	TO DO
KAN-61	Test Circuit	TO DO
KAN-62	Iterations & Refinement of Circ...	TO DO
KAN-63	External Infrastructure	
KAN-64	Source Total Stati...	TO DO
KAN-65	Setup Total Stati...	TO DO
KAN-66	Obtain 3D Map	TO DO
KAN-67	Setup Operations Terminal	TO DO
KAN-68	Management	
KAN-69	Integration and Testi...	



KAN-84 Milestones	
KAN-1 Mechanical	
KAN-22 Computations	
KAN-23 Setup Jetson Drivers	TO DO
KAN-27 Localization - Sensor Fusion	TO DO
KAN-28 FSM Planner	TO DO
KAN-29 Excavator Planner - Simula...	TO DO
KAN-30 Excavator Planner - SimToReal	TO DO
KAN-31 Excavator Planner - Testi...	TO DO
KAN-35 Navigator Planner - Simulate	TO DO
KAN-36 Navigator Planner - SimToRe...	TO DO
KAN-37 Navigator Planner - Testing	TO DO
KAN-38 Integrate Mast & Belly Depth Cameras fo...	TO DO
KAN-39 Method & Metrics for Validati...	TO DO
KAN-40 Sense	
KAN-49 Electronics	
KAN-63 External Infrastructure	
KAN-68 Management	
KAN-69 Integration and Testi...	



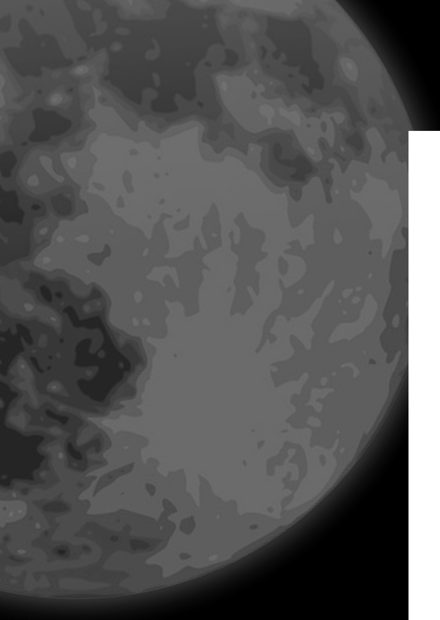
KAN-84 Milestones
KAN-1 Mechanical
KAN-22 Computations
KAN-40 Sense
KAN-49 Electronics
KAN-63 External Infrastructure
KAN-68 Management
- KAN-70 Manage Work TO DO
- KAN-80 Manage Documentation PD... TO DO
- KAN-91 Manage Documentation S... TO DO
- KAN-71 Manage Finances TO DO
- KAN-72 Manage Schedules TO DO
- KAN-73 Manage HR TO DO
- KAN-74 Manage Risks TO DO

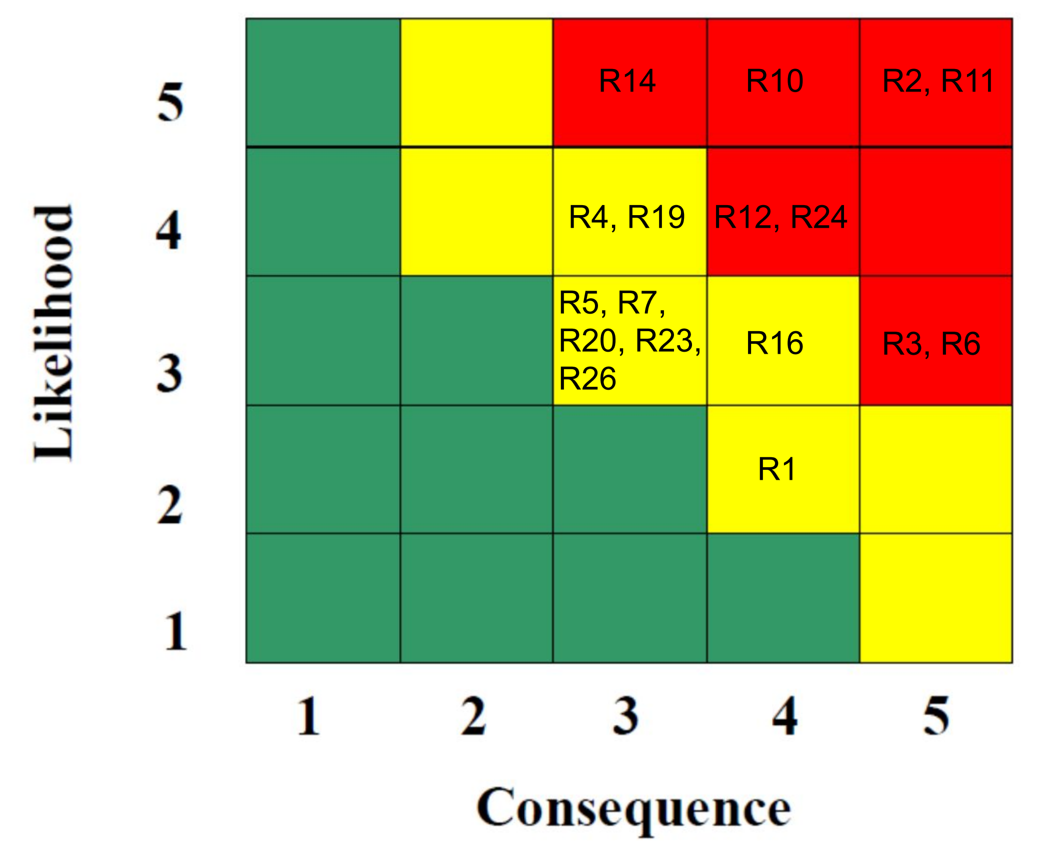
KAN-69 Integration and Testi...
- KAN-79 Setup Test Environme... TO DO
- KAN-75 Generate 3D Map using Survey LiD... TO DO
- KAN-76 Integrate Subsyste... TO DO
- KAN-77 Run Test of Complete Syste... TO DO
- KAN-78 Iterations & Refinement for Complete System TO DO

Fall Schedule

Milestone	Estimated Timeline
Lunar ROADSTER V1	October First Week
Lunar ROADSTER V2	November First Week
Fall Validation Demo	November 3rd Week

Risk Summary



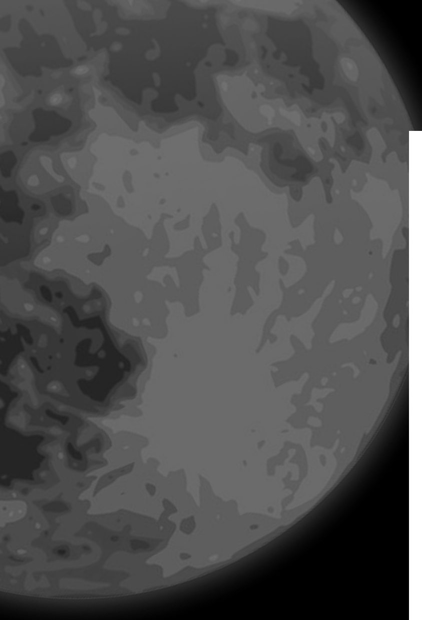


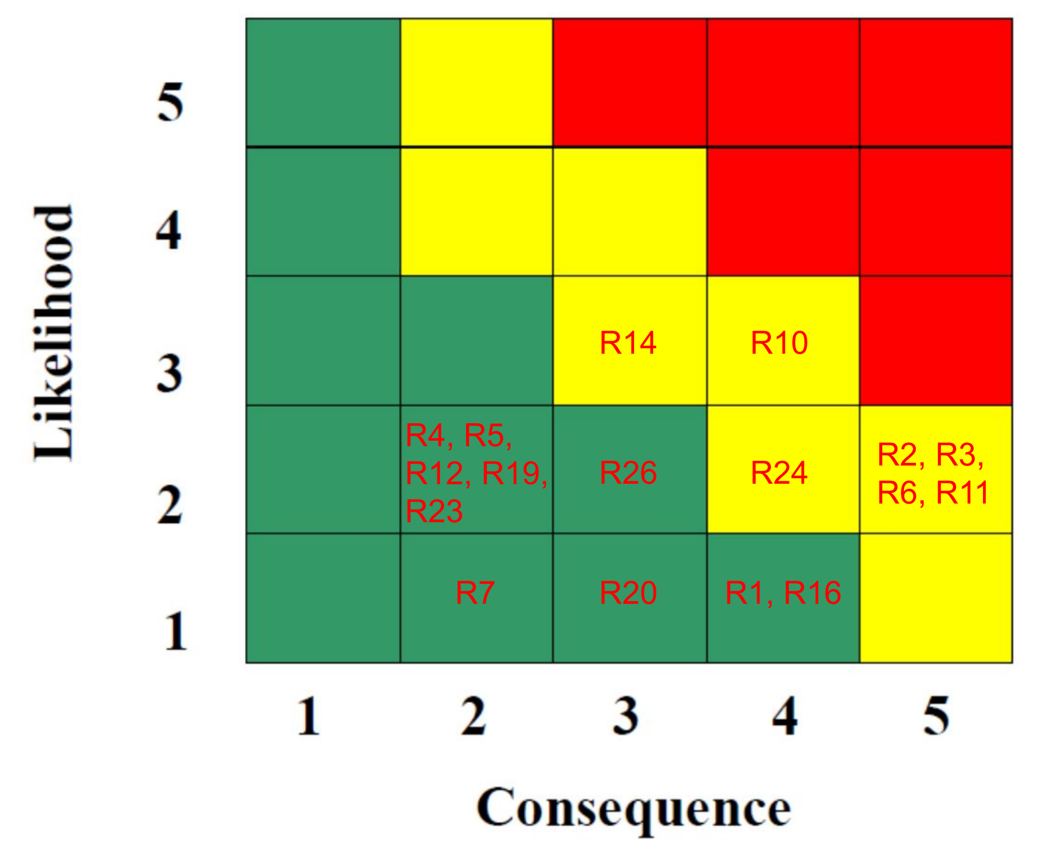
Likelihood

5	🟩	🟨	🟥 R14	🟥 R10	🟥 R2, R11
4	🟩	🟨	🟨 R4, R19	🟥 R12, R24	🟥
3	🟩	🟩	🟨 R5, R7, R20, R23, R26	🟨 R16	🟥 R3, R6
2	🟩	🟩	🟩	🟨 R1	🟨
1	🟩	🟩	🟩	🟩	🟨
	1	2	3	4	5

Consequence

Reduced Risk Summary





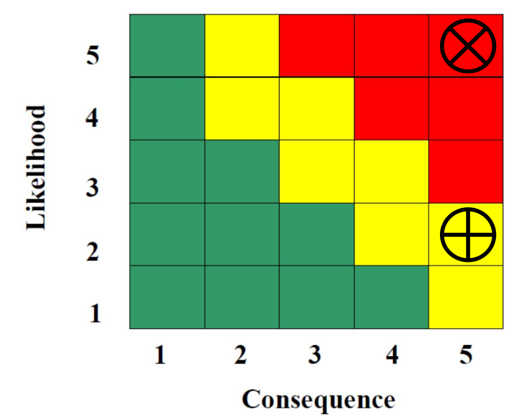
Likelihood					
5	🟩	🟨	🟥	🟥	🟥
4	🟩	🟨	🟨	🟥	🟥
3	🟩	🟩	🟨 R14	🟨 R10	🟥
2	🟩	🟩 R4, R5, R12, R19, R23	🟩 R26	🟨 R24	🟨 R2, R3, R6, R11
1	🟩	🟩 R7	🟩 R20	🟩 R1, R16	🟨
	1	2	3	4	5
	Consequence				

Risk Management

Risk ID	**Risk Title**	**Risk Owner**	**Risk Type:**	Technical
R2	Excavator and grader tool planner takes longer than expected to deliver	Simson		

Description	**Date Added**
Integration of the excavator and grader software with hardware takes longer than expected	11/27/2024
	Date Updated
	11/27/2024

Consequence
Unable to meet SVD deadline and potential requirements change



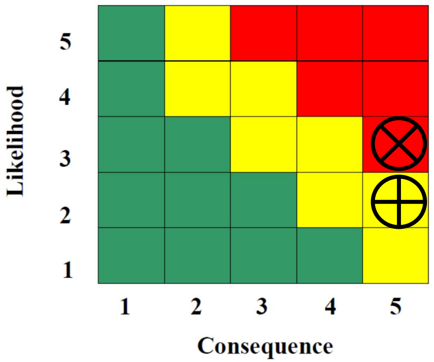
Action/Milestone	**Success Criteria**	**Date Planned**	**Date Implemented**
Shift requirements for SVD	Updated performance requirements	11/28/2024	11/28/2024
Integrate the grader during Fall semester	Working excavator and grader for FVD	11/28/2024	
Potentially use off-the-shelf code if available, preferably from CraterGrader	Successful integration of off-the-shelf components		

Risk Management

Risk ID	Risk Title	Risk Owner	Risk Type:	Technical
R3	Integration issues between subsystems	Deepam		

Description	Date Added
Subsystems work individually, but integration and communication between the subsystems are flawed	11/27/2024
	Date Updated
	11/27/2024

Consequence
Delay in integration causing scheduling overruns, requirements change and failure of the demo



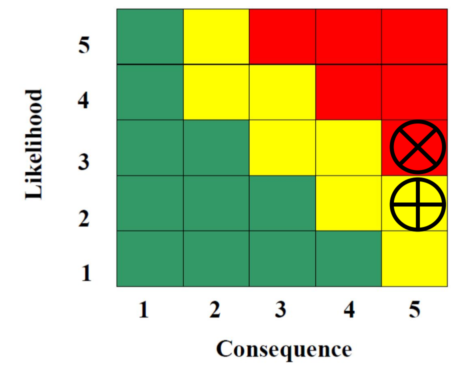
Action/Milestone	Success Criteria	Date Planned	Date Implemented
Perform unit testing and subsystem validation continuously	Successful testing of all major subsystems	11/30/2024	
Integrate one subsystem at a time	Successful integration of all major subsystems	11/30/2024	
Use a common framework (e.g. ROS2 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	

Risk Management

Risk ID	Risk Title	Risk Owner	Risk Type:	Schedule
R6	Delay in arrival and manufacture of hardware components	William		

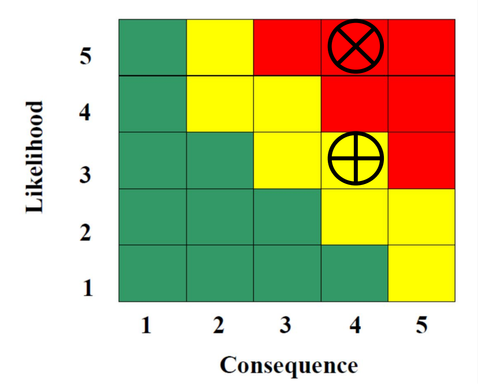
Description	Date Added
Shipping delays of components ordered and/or manufacturing delays on custom made components	11/27/2024
	Date Updated
	11/27/2024

Consequence
Delays in hardware integration, causing push backs in scheduling and software development

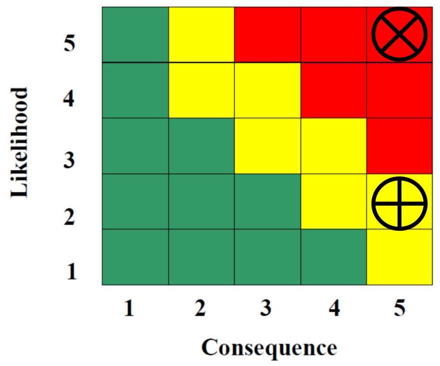


Action/Milestone	Success Criteria	Date Planned	Date Implemented
Use off-the-shelf components that are available on hand (e.g. from CMU labs or Red's workshop)	Obtain components before end of December		
Start ordering and designing components during Winter break so there is adequate leeway for delivery and manufacturing before Spring semester starts	Obtain components before end of December	11/27/2024	
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		
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		

Risk Management

Risk ID	**Risk Title**	**Risk Owner**	**Risk Type:**	Technical
R10	Mast depth camera FOV is blocked	William		
Description		**Date Added**		
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		11/27/2024		
		Date Updated		
		11/27/2024		
Consequence				
Hinders the rover's ability to perceive its surroundings accurately, resulting in navigation errors and inefficiencies in excavation tasks				
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		Visual data such as depth perception and object detection is not compromised.		

Risk Management

<table>
<tr><th>Risk ID</th><th>Risk Title</th><th>Risk Owner</th><th>Risk Type:</th><th>Technical</th></tr>
<tr><td>R11</td><td>Too many performance requirements</td><td>Ankit</td><td colspan="2" rowspan="7"> </td></tr>
<tr><td colspan="2">Description</td><td>Date Added</td></tr>
<tr><td colspan="2" rowspan="3">We have a lot of performance requirements and we may not be able to meet all of them by April for SVD</td><td>11/27/2024</td></tr>
<tr><td>Date Updated</td></tr>
<tr><td>11/27/2024</td></tr>
<tr><td colspan="3">Consequence</td></tr>
<tr><td colspan="3">Delays in testing and validation, impacting project timelines and April SVD Demo results</td></tr>
<tr><th colspan="2">Action/Milestone</th><th>Success Criteria</th><th>Date Planned</th><th>Date Implemented</th></tr>
<tr><td colspan="2">Have revised performance requirements separately for SVD and FVD (focus more on SVD)</td><td>Achievable Performance Requirements</td><td>11/28/2024</td><td>12/04/2024</td></tr>
<tr><td colspan="2">Talk to CraterGrader and discuss what is feasible and what is not in the given time</td><td>Meeting conducted</td><td>11/28/2024</td><td>12/02/2024</td></tr>
<tr><td colspan="2">PM should track schedule properly and team members have to push to meet the timeline</td><td>Project follows the schedule</td><td>11/28/2024</td><td></td></tr>
</table>

Risk Management (Extra)

Risk ID	Risk Title	Risk Owner	Type	Description	Consequence	Risk Reduction Plan
R1	PRL Testbed Scheduling	Ankit	Scheduling	PRL Testbed unavailable due to scheduling conflicts with other high priority projects	No testbed available for testing and/or SVD	Devise and discuss a testing and demo plan with Red and other stakeholders of the PRL testbed beforehand and reserve slots
						Reach out to external testing facilities like Astrobotic or CAT for a backup testing facility
						Schedule tests at night
R2	Excavator and grader tool planner takes longer than expected to deliver	Simson	Technical	Integration of the excavator and grader software with hardware takes longer than expected	Unable to meet SVD deadline and potential requirements change	Shift requirements for SVD
						Integrate the grader during Fall semester
						Potentially use off-the-shelf code if available, preferably from CraterGrader
R3	Integration issues between subsystems	Deepam	Technical	Subsystems work individually, but integration and communication between the subsystems are flawed	Delay in integration causing scheduling overruns, requirements change and failure of the demo	Perform unit testing and subsystem validation continuously
						Integrate one subsystem at a time
						Use a common framework (e.g. ROS2 interfaces) for communication between subsystems to reduce bugs
						Keep to planned schedule and have at least 5 weeks for testing and integration
R4	Belly depth sensor is not suitable for validation	Bhaswanth	Technical	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	Will result in major revision and changes to the validation architecture and functional requirement, causing delays in scheduling	Mount the depth camera at another location on the rover (e.g. on a mast)
						Use another sensor to determine depth variations (e.g. LIDAR, visual odometry, IR sensor)
						If all else fails, use the total station for validation

Risk Management (Extra)

Risk ID	Risk Title	Risk Owner	Type	Description	Consequence	Risk Reduction Plan
R5	Unable to get Crater Grader to perform autonomous crater filling	Bhaswanth	Technical	Our rover builds on top of the work accomplished by Crater Grader. If we cannot get Crater Grader to perform autonomous crater filling, we may need to spend more time working on the navigation stack and designing the entire pipeline	Extra time commitment to start from scratch or obtaining a suitable replacement	Thoroughly go through Crater Grader's code and the mechanical schematics provided
						Test each component and wiring to see if they are working
						If it is still not working, inherit only the software component from Crater Grader and build hardware ourselves
R6	Delay in arrival and manufacture of hardware components	William	Schedule	Shipping delays of components ordered and/or manufacturing delays on custom made components	Delays in hardware integration, causing pushbacks in scheduling and software development	Use off-the-shelf components that are available on hand (e.g. from CMU labs or Red's workshop)
						Start ordering and designing components during Winter break so there is adequate leeway for delivery and manufacturing before Spring semester starts
						Use simulations to work on software components while we wait for the components to be delivered and/or manufactured
						Implement other subsystems that are independent from the subsystem that is missing parts
						In case of delay in wheels, work with the existing wheels and proceed with the timeline while waiting for the new ones to arrive.
R7	Lack of proper simulation environment	Simson	Technical	Inability to accurately simulate the rover in a Lunar-like environment can lead to suboptimal performance	The rover's performance in the Moon Pit may be compromised, leading to inefficiencies, mission delays, or potential failure in achieving key objectives	Ask CraterGrader how they ran all their simulations and gather resources
						Explore LunarSim - https://github.com/PUTvision/LunarSim and check how useful this will be, during the winter break
						Develop Gazebo environment

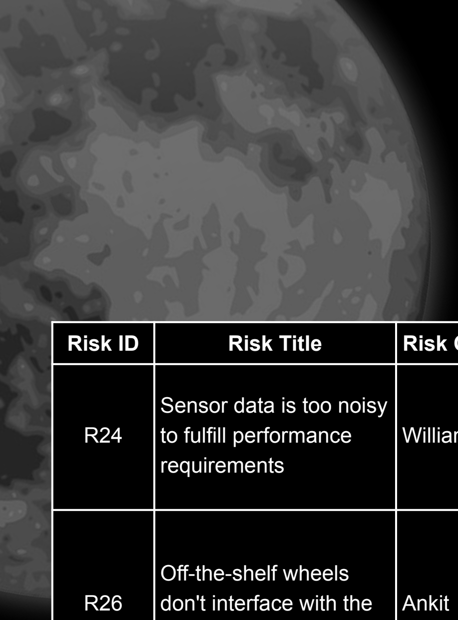
Risk Management (Extra)

Risk ID	Risk Title	Risk Owner	Type	Description	Consequence	Risk Reduction Plan
R10	Mast depth camera FOV is blocked	William	Technical	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.	Hinders the rover's ability to perceive its surroundings accurately, resulting in navigation errors and inefficiencies in excavation tasks	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
R11	Too many performance requirements	Ankit	Technical, Schedule	We have a lot of performance requirements and we may not be able to meet all of them by April for SVD	Delays in testing and validation, impacting project timelines and April SVD Demo results	Have revised performance requirements separately for SVD and FVD (focus more on SVD) Talk to CraterGrader and discuss what is feasible and what is not in the given time PM should track schedule properly and team members have to push to meet the timeline
R12	Drive system wear-and-tear causes malfunction	Deepam	Technical	The transmission and steering assembly might be worn out, leading to suboptimal vehicle dynamics, and potentially mechanical failure	Rover drive system fails and may require a lot of repair and maintenance	Thoroughly check the Crater Grader's assembly and carry out maintenance of any worn-out parts Completely replace the assembly parts with the same/similar new parts for better performance and reliability Added limit switches to avoid steering gears to operate beyond their limits
R14	Dust ingress	William	Technical, Cost	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	Component failure during testing or demonstrations. Highly inhibits all future scheduled tasks	Design proper sand enclosures and mounts for sensitive components Review placement of components Review scale and speed of sand manipulation to eliminate root-cause of flying sand/dust Allocate contingency budget and order spares of the sensitive components in case of component failure

Risk Management (Extra)

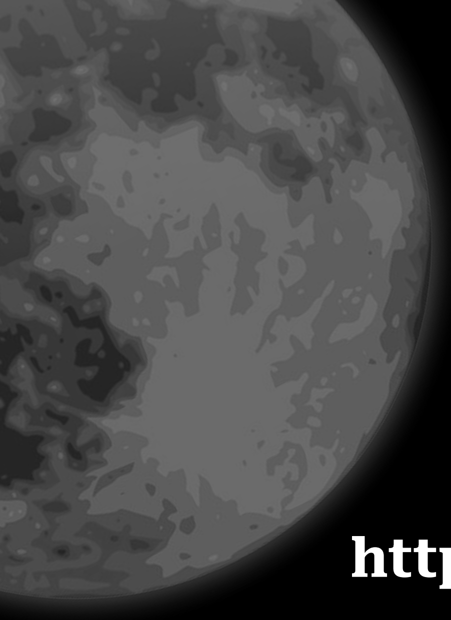
Risk ID	Risk Title	Risk Owner	Type	Description	Consequence	Risk Reduction Plan
R16	Code version control	Simson	Technical	Code modifications or config parameter changes during testing might not be saved, affecting the final demo. Reverting to a stable version is difficult if changes do not work as expected.	Delay in code integration and implementation	Implement GitHub version control to store and retrieve the best versions of code and configuration Use Google Drive to backup important documentation explaining setup processes
R19	Items missing	Ankit	Logistics	Critical project items may go missing if not stored properly or tracked. Items may be misplaced or borrowed without proper logging	Delay in hardware implementation	Maintain an inventory tracking spreadsheet Include spare inventory
R20	Sensor ROS packages not available	William	Technical, Schedule	Finalized sensors might lack compatible ROS packages, leading to delays or significant changes in the software architecture	Delay in software implementation	Perform trade studies to pick sensors that are compatible with ROS versions before finalizing Select sensors and ROS versions that minimize potential conflicts
R23	Lunar-accurate cut/fill regions are not possible to groom	Simson	Technical	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	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	Accurately create the environment and assess if the rims are enough to fill If not, modify PRs accordingly

Risk Management (Extra)



Risk ID	Risk Title	Risk Owner	Type	Description	Consequence	Risk Reduction Plan
R24	Sensor data is too noisy to fulfill performance requirements	William	Technical	Performance requirements are tough and ambitious, sensor noise may prevent us from achieving it	Failure to demonstrate performance requirements may cause us to lose marks in the demonstrations	Relax the performance requirements enough to ensure that they are achievable Ensure enough testing time to tune parameters
R26	Off-the-shelf wheels don't interface with the rover	Ankit	Technical	No off-the-shelf wheels fit the rover, We'll have to redesign wheel hubs and mountings as per the new wheels.	Continue with sub-optimal wheels that the rover currently has, thus, not meeting one of the non-functional requirements	Shift requirements to FVD Good enough market research to see find the best fit, with least amount of changes

Q&A



Thank You!

https://mrsdprojects.ri.cmu.edu/2025teami/

Appendices

A.1. Derivation for P.5:

- Chang'e-4's landing site was surveyed and found that 97.5% of nearby craters were below 15.5 meters in diameter.
- Our rover is approximately 1/30th the size of a commercial grader, so it shall be able to grade 15.5/30 ≈ 0.5 meter craters at least.
- Source: DOI 10.3390/rs14153608

A.2. Derivation for P.3:

- Average depth-to-diameter (DtoD) ratio of 0.07 near the North pole
- Assuming worst-case scenario of a crater with twice DtoD ratio of 0.14, the gradient is $\theta = \arctan(0.14*2) \approx 15$ degrees
- Contact pressure requirement follows recommendation from NASA
- Source: DOI 10.1029/2022GL100886, NASA/TP—2006–214605

A.3. Derivation for P.1:

- Recommendation from Nature paper on extraterrestrial path-planning metrics
- Source: DOI 10.1038/s41598-023-49144-8

Credits for images:

- Generative AI
- Google Images
- Dr. William Red Whittaker's slides