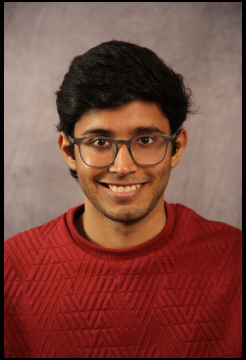
Lunar ROADSTER

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

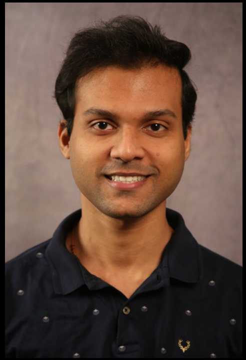
“Starting with a foothold on the Moon, we pave the way to the cosmos”

The Team


Ankit Aggarwal


Deepam Ameria

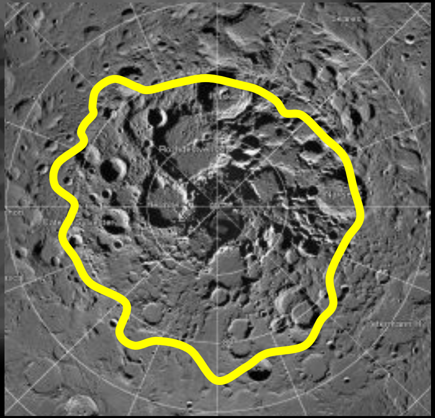

Bhaswanth Ayapilla

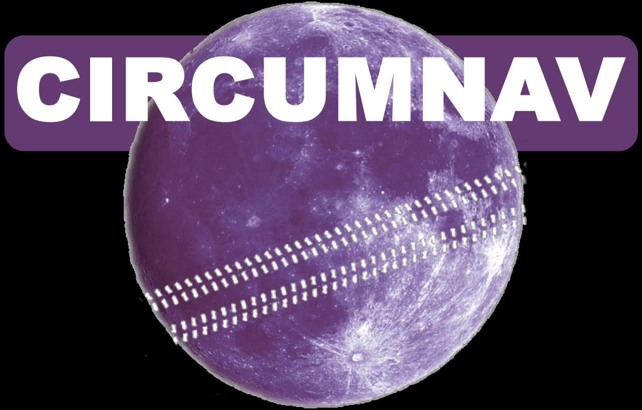

Simson D'Souza

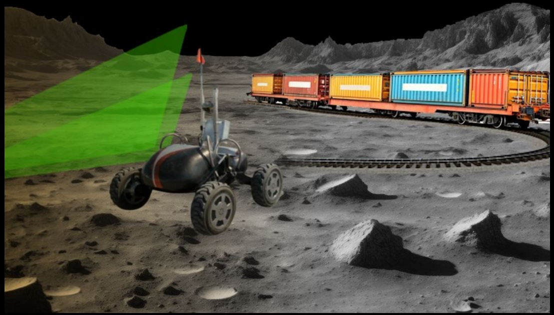

Boxiang (William) Fu


Dr. William "Red" Whittaker

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

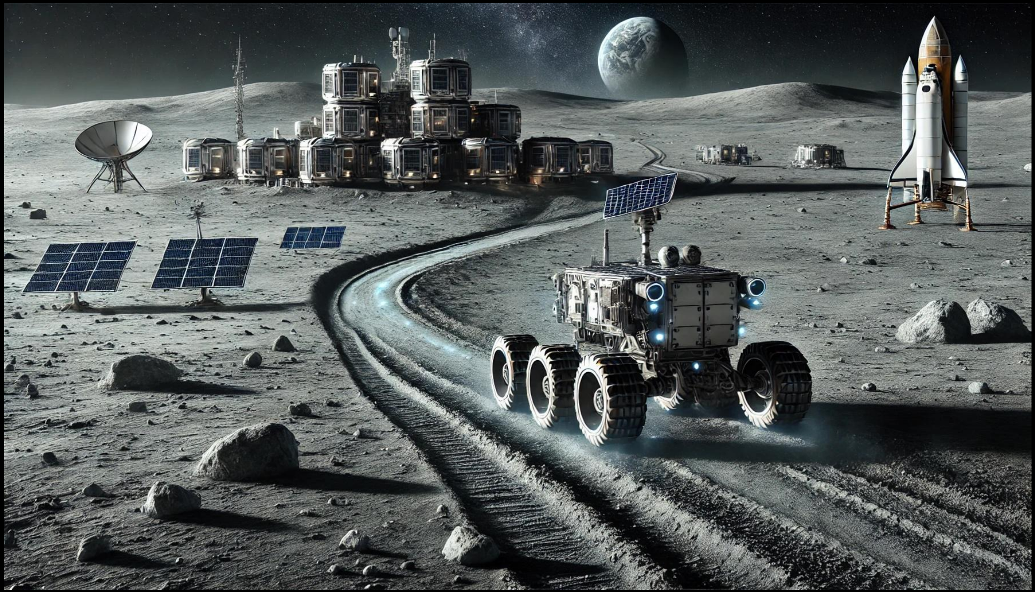
The Project: Lunar ROADSTER

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

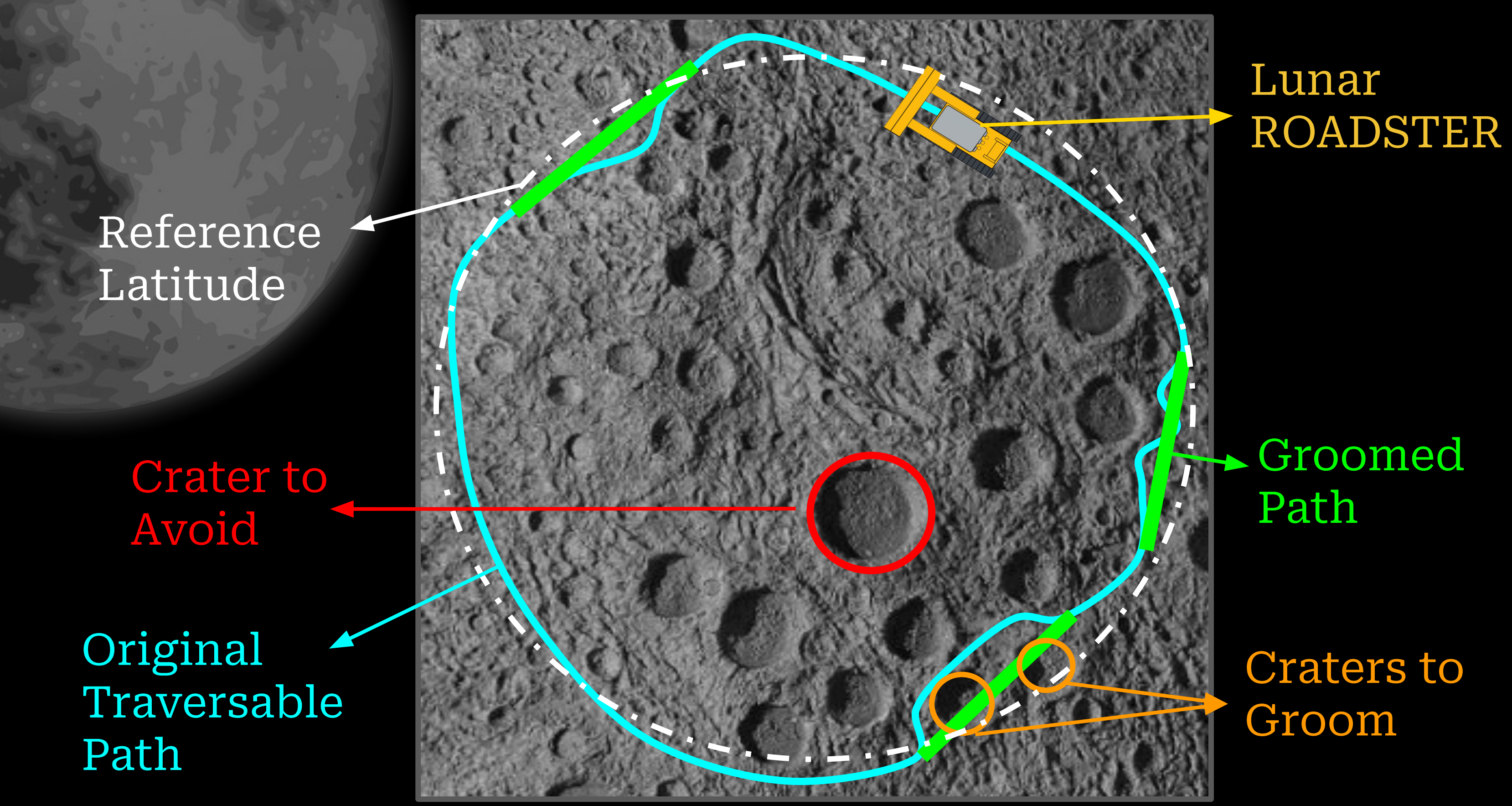
By grooming trail paths, rovers with less traversing capabilities will be able to travel at higher speeds and higher power efficiencies.

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

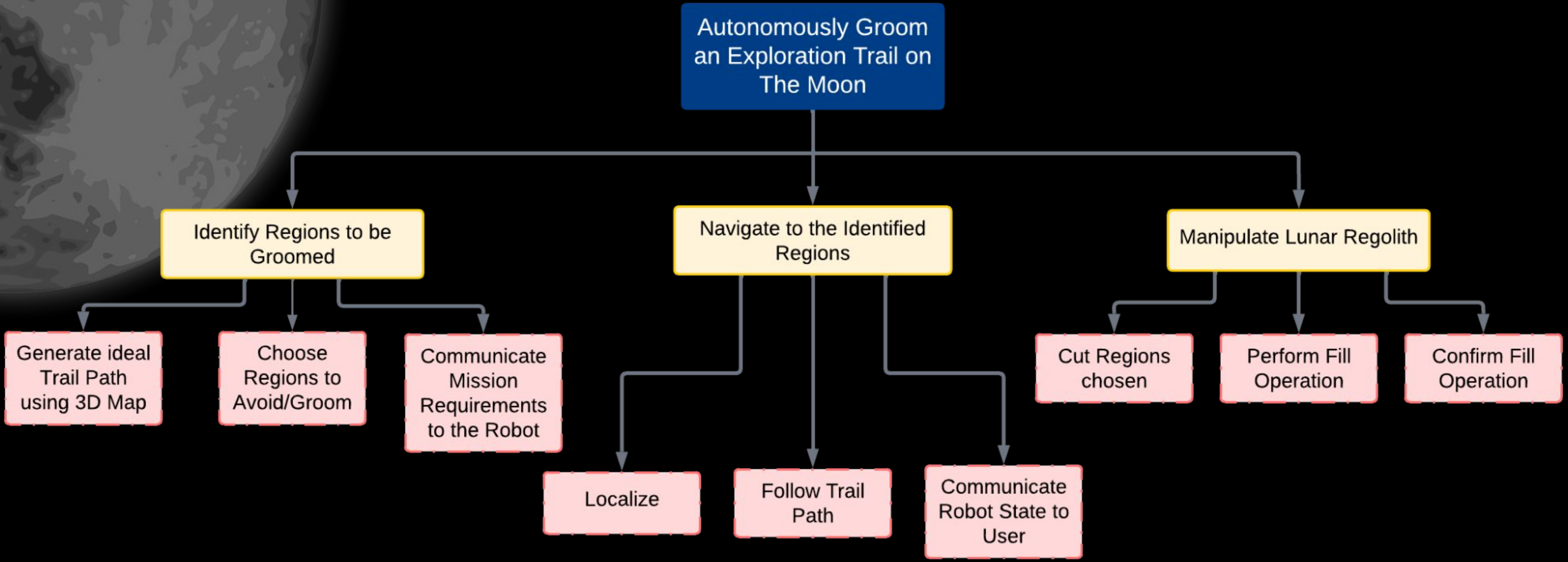
The groomed trails will become the backbone for colonization of the Moon by enabling transportation, logistics and enterprise development.



Use Case: Circular Path Grooming



Objectives Tree



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

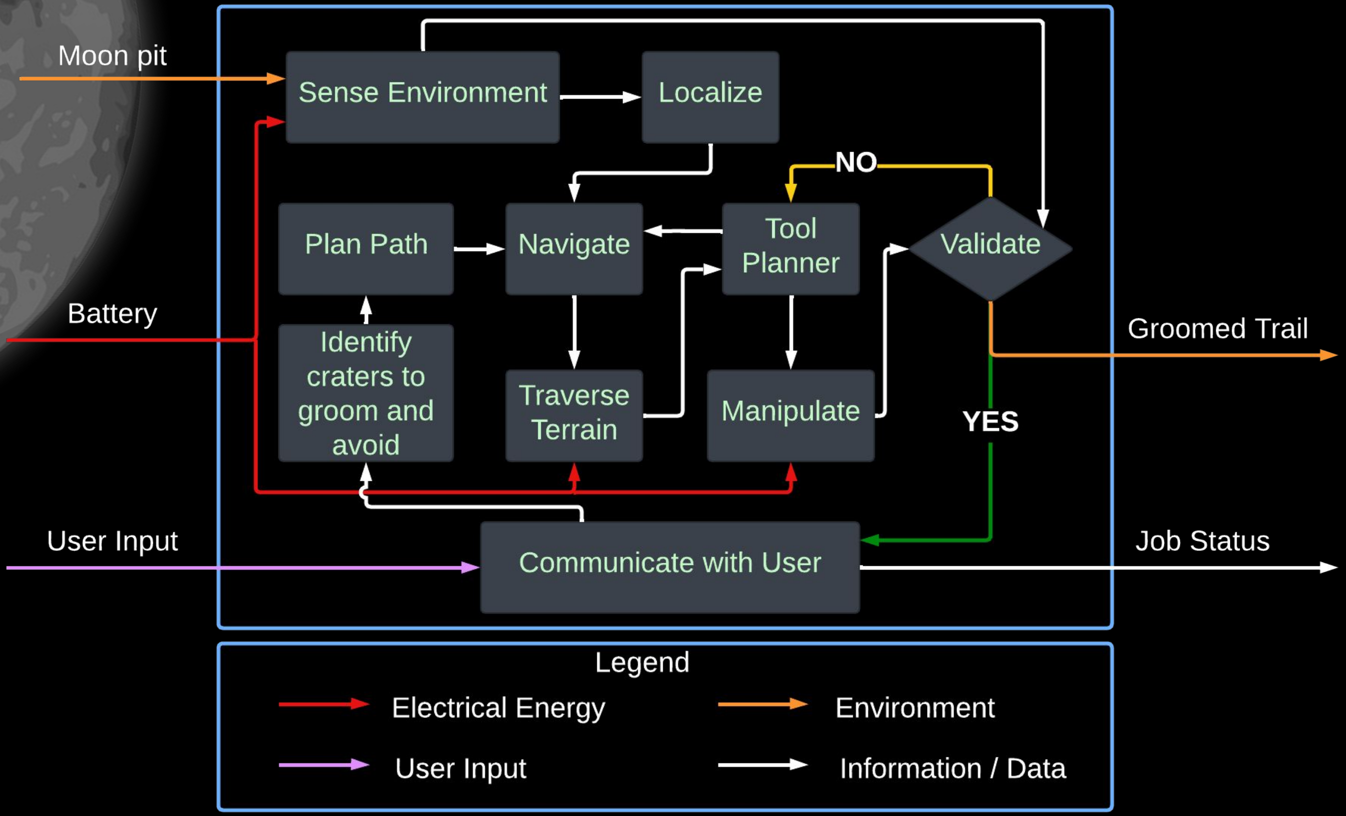
Non-Functional Requirements (Desirable)

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

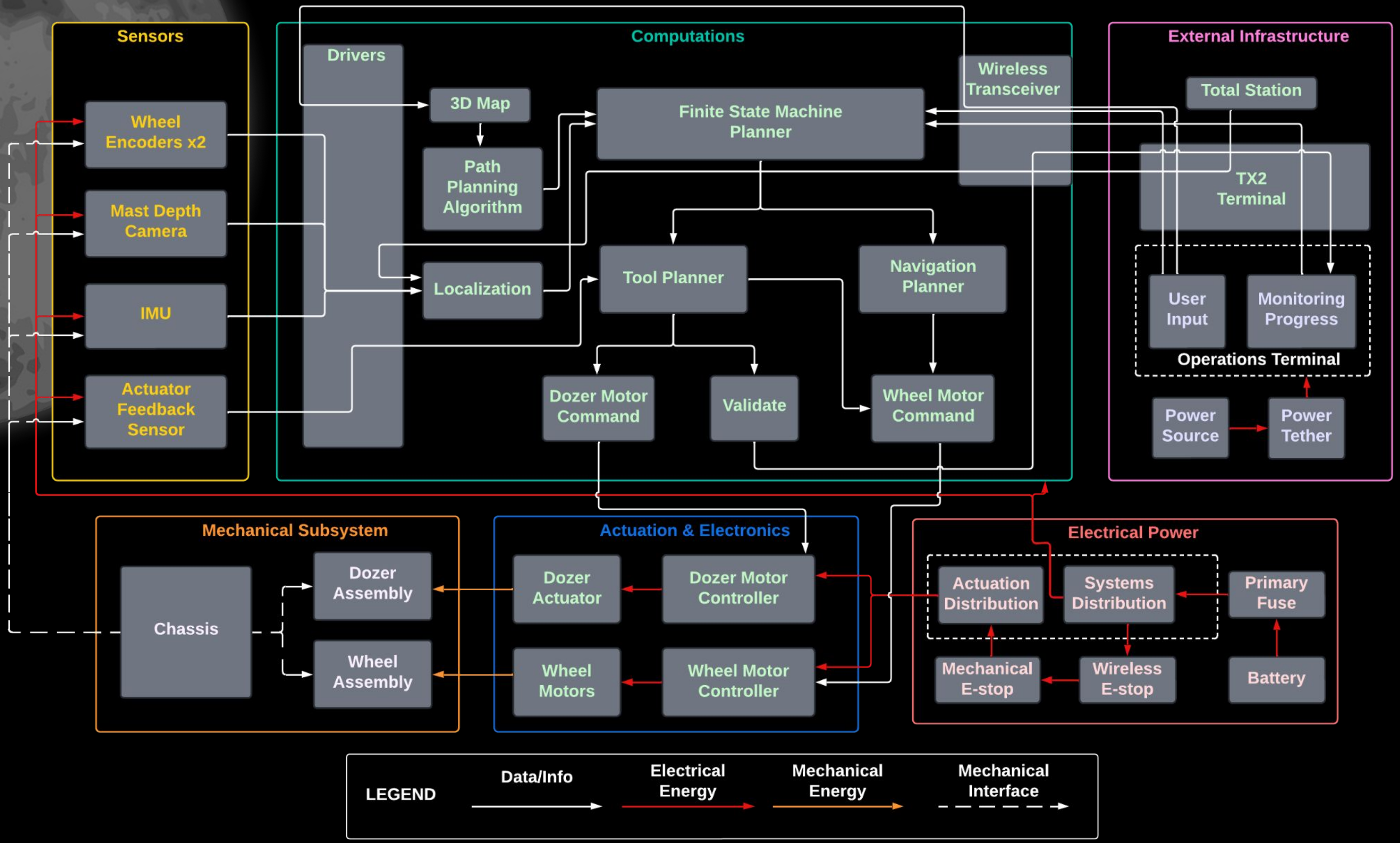
Performance Requirements (Mandatory)

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°

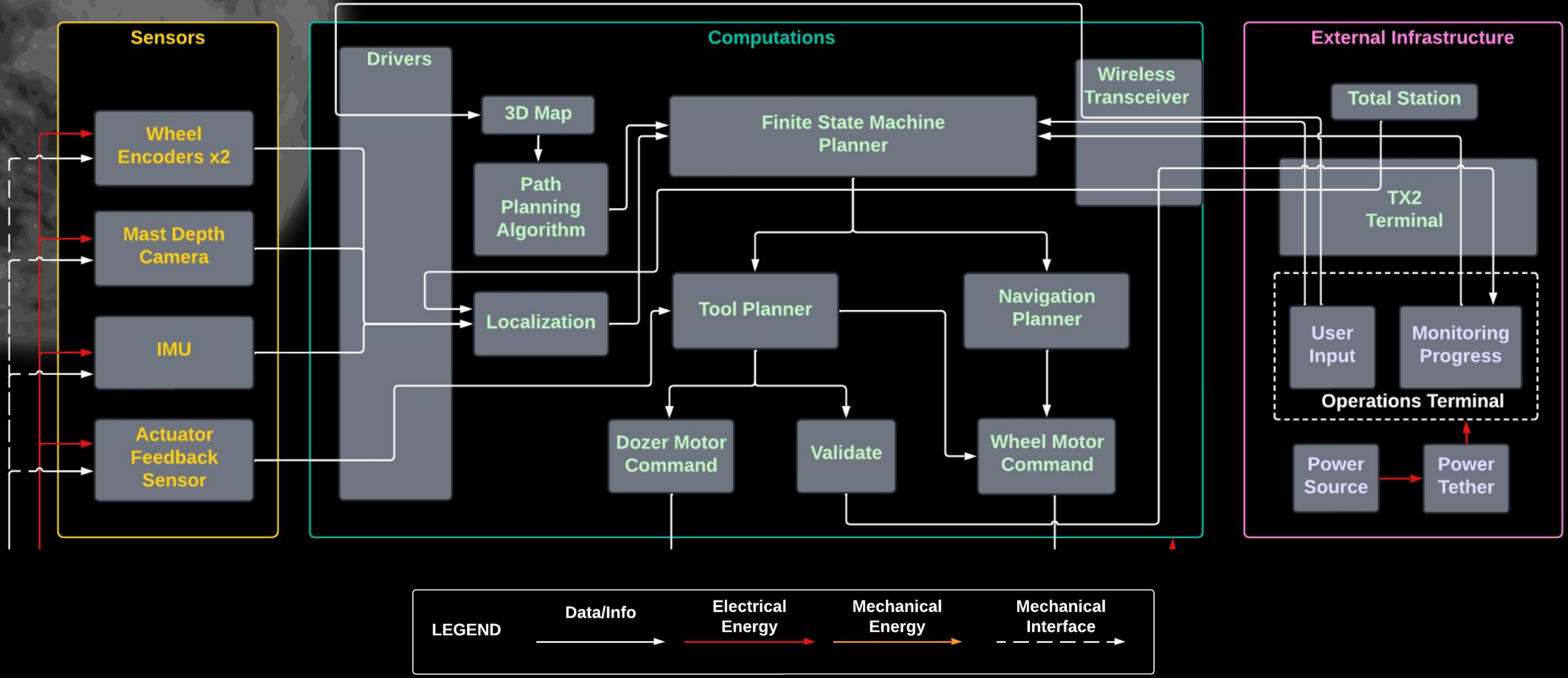
Functional Architecture



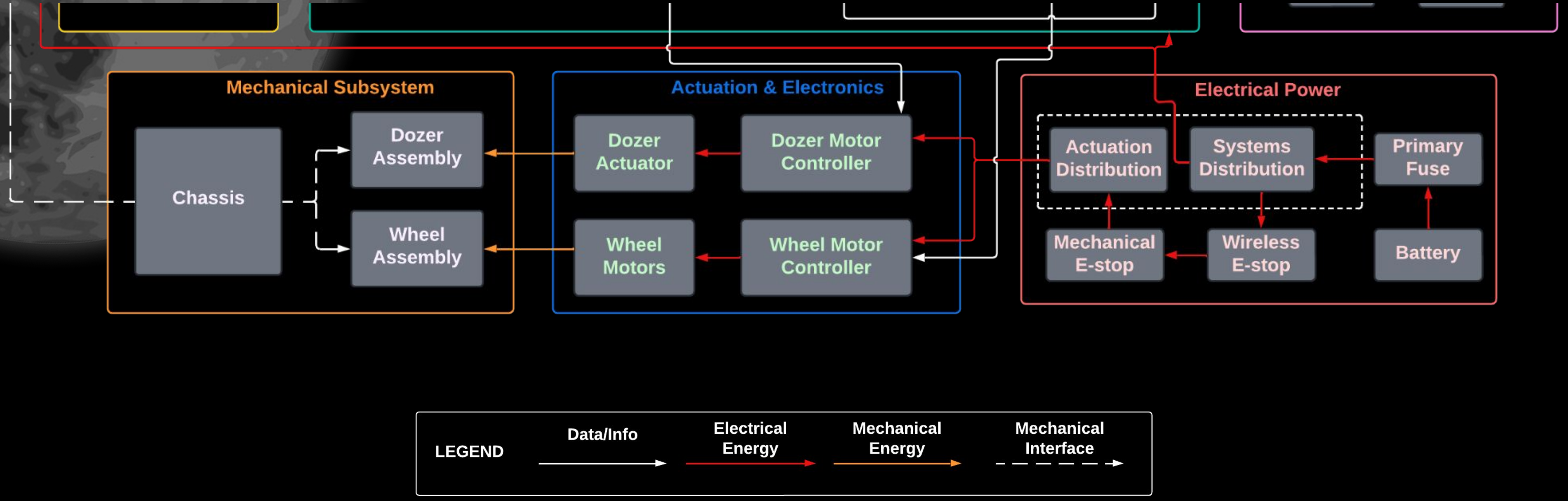
Cyber-Physical Architecture

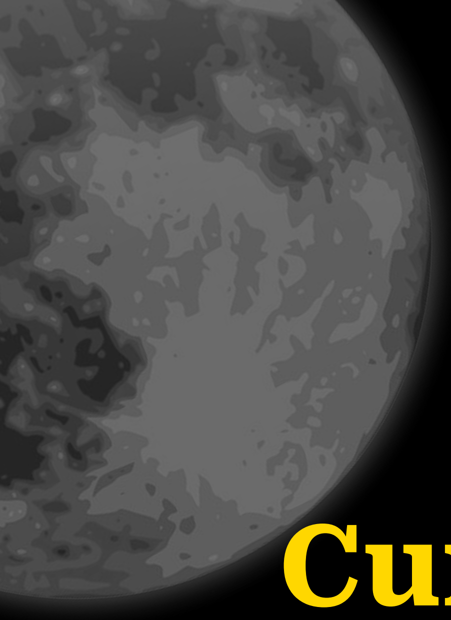


Cyber-Physical Architecture



Cyber-Physical Architecture





Current System Status

Targeted Requirements in Spring

Requirement	Description	Status
M.P.1	Will plan a path with cumulative deviation of <= 25% from chosen latitude's length	Achieved
M.P.2	Will follow planned path to a maximum deviation of 10%	Demonstrated
M.P.4 (Part 1)	Will avoid craters >= 0.5 metres	Demonstrated
M.P.5	Will fill craters of up to 0.5 meters in diameter and 0.1m in depth	Demonstrated
M.N.1	Weight - The rover must weigh under 50kg	Achieved
M.N.4	Size - The rover should measure less than 1m in all dimensions	Missed
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	Achieved
D.N.2	Aesthetics - Rover must look presentable and lunar-ready	Demonstrated

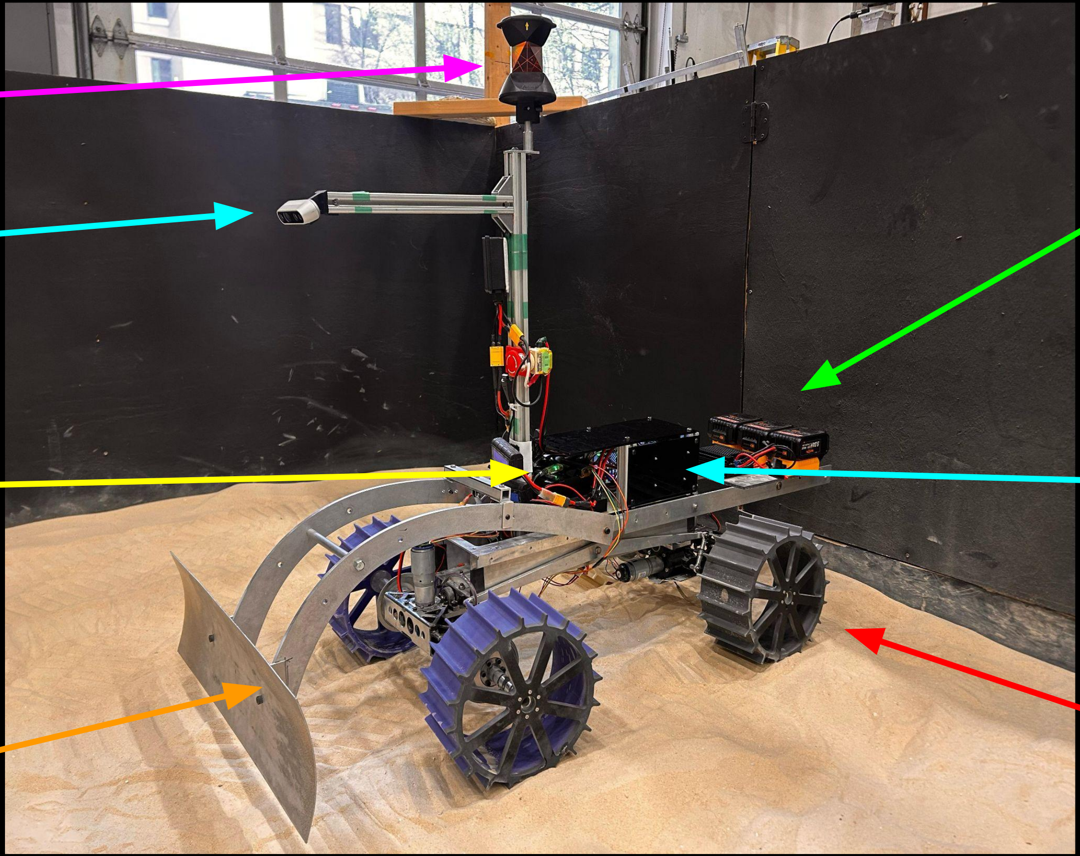
Overall System Depiction - Hardware

Leica Prism

Intel Realsense D235i

Jetson Xavier AGX

Custom Dozer Blade

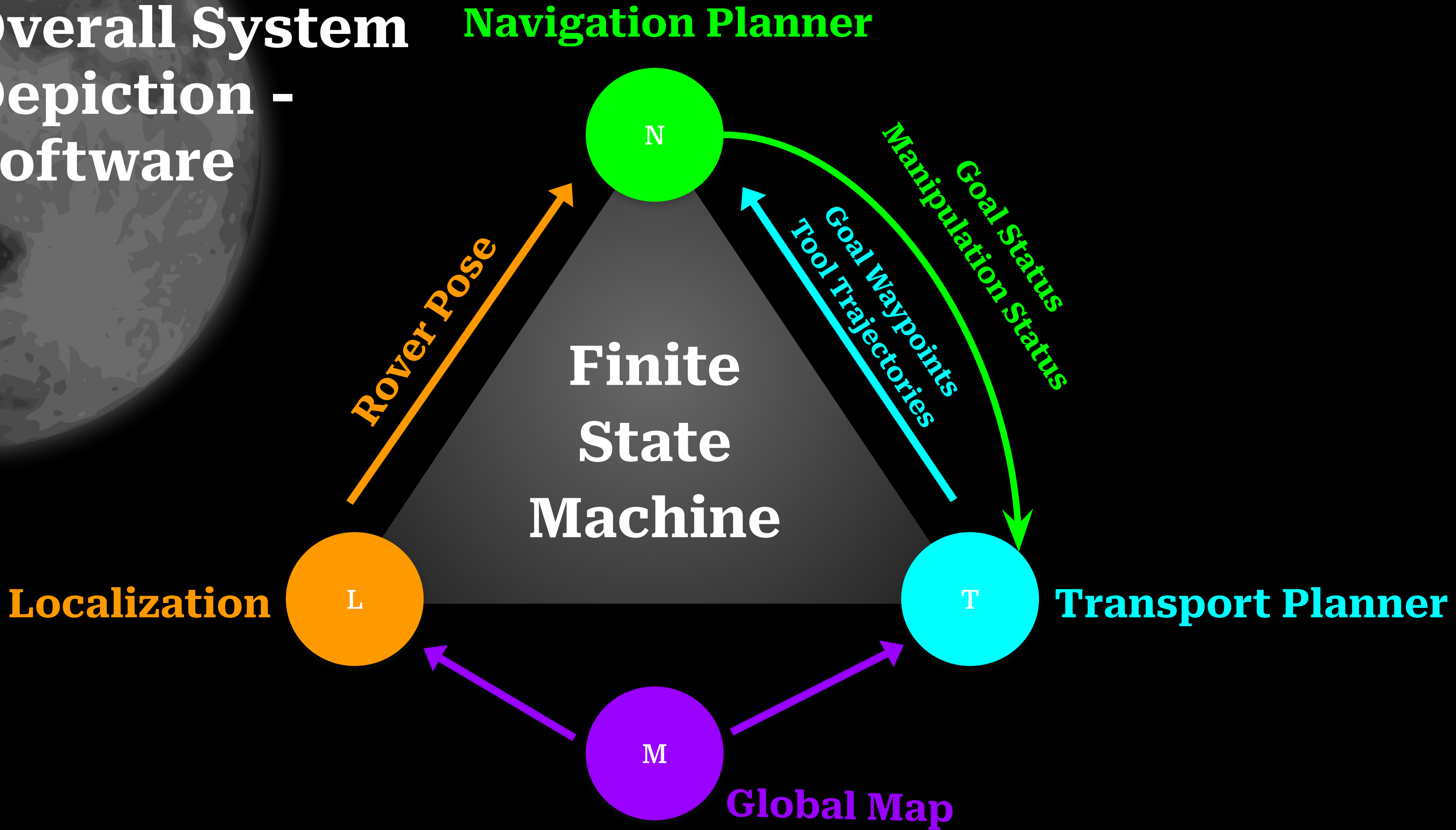


20V Batteries x3

Electronics Box

Custom Wheel Design

Overall System Depiction - Software



Subsystem Completion Status

Subsystem	Completion %	Future Work
Sensors	75%	Upgrade RealSense D235i to ZED 2i stereo camera
Computations	60%	
1. Jetson and Docker	95%	Integrate ZED drivers
2. Localization Unit	85%	Address frame shifts caused by battery replacements
3. Transport Planner Unit	60%	Implement unit
4. Navigation Planner Unit	90%	Tune navigation stack
5. FSM Planner Unit	95%	Integrate validation unit into FSM
6. Validation Unit	10%	Implement unit
External Infrastructure	100%	None
Mechanical	90%	
1. Dozer Assembly	90%	Refinement of dozer
2. Wheel Assembly	90%	Wheel design iterations, final manufacturing
Actuation	80%	Linear actuator upgrade/tuning, torque sensing
Electrical Power	90%	Change battery placement

Description: Sensors Subsystem

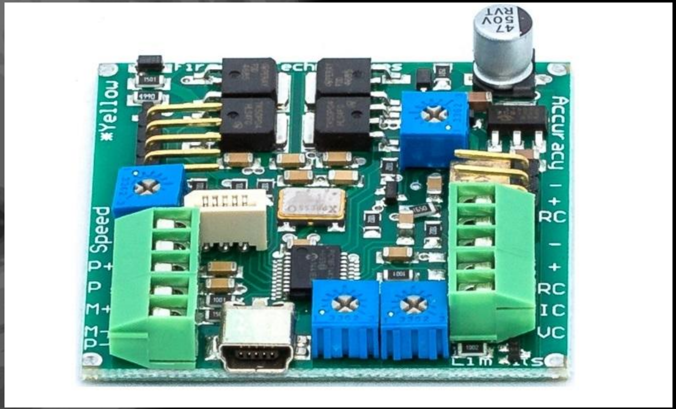
Description: All sensors used on the rover for computations.

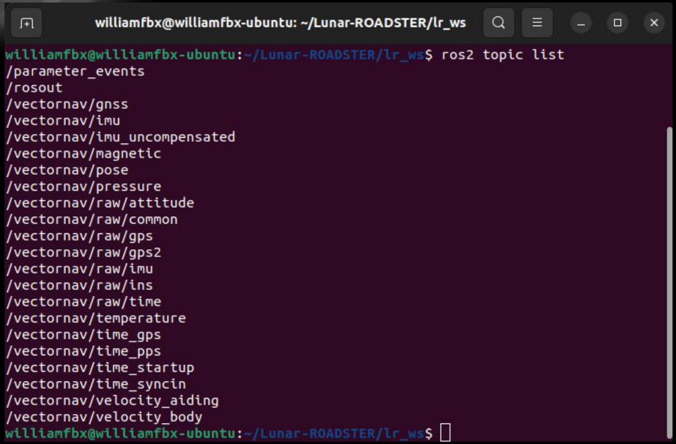
Requirements:

- Wheel Encoders (x4)
- Mast Depth Camera (RealSense D435i)
- IMU (VectorNav)
- Actuator Feedback Sensor

Expected Functionality: The sensor data is published to various ROS topics and can be used inside the Docker container to perform computations.

Status: Sensors Subsystem





Implementation:

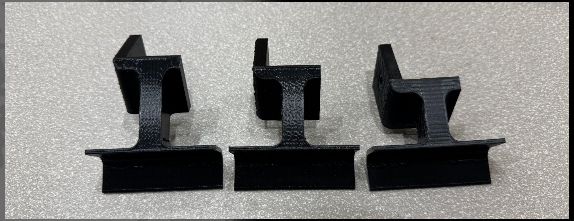
- IMU implemented using VectorNav ROS package
- Wheel Encoder parsed using micro-ROS
- Purchased actuator has a feedback potentiometer
- Obtained RealSense point cloud feed using RealSense ROS wrappers

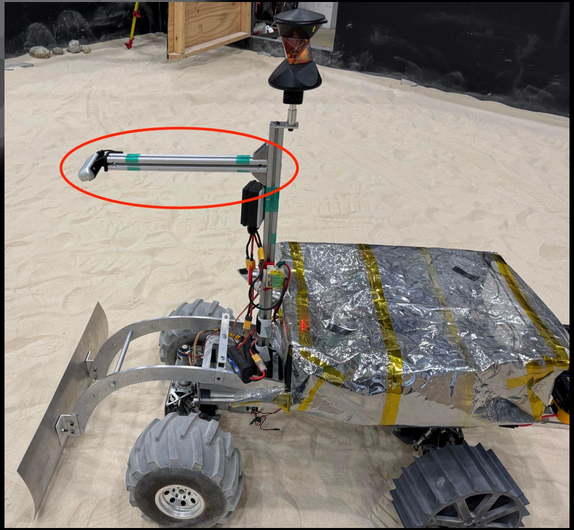
Challenges:

- Difficulty integrating ZED SDK with docker container due to CUDA compatibility issues
- Reverted back to using RealSense, which did not require CUDA
- IMU firmware drivers were outdated

Status: 75% Complete
IMU, wheel encoder, and linear actuator finalized.
Upgrade RealSense to ZED 2i in Fall semester

Evaluation: Sensors Subsystem





Modelling:

- CAD designed and 3D printed mast depth camera mounts of 30, 40, 45, and 50 degree angles relative to mast

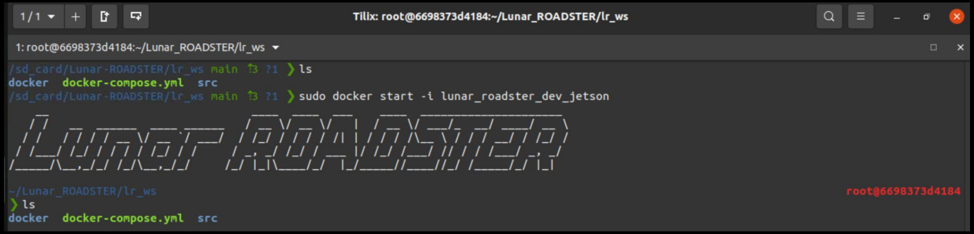
Analysis:

- 50 degree angled camera mount gives the best view of craters
- However, if tool height is above 15%, occlusion occurs
- Point cloud obtained from RealSense is not as dense as ZED 2i

Testing:

- T10: Optimal Mast Depth Camera Placement Test
- T14: Maintenance, Reliability and Quality Assurance Test

Description: Computations Subsystem Jetson and Docker Unit



Description: Set up the Jetson AGX Xavier with Docker to host and run all critical system packages

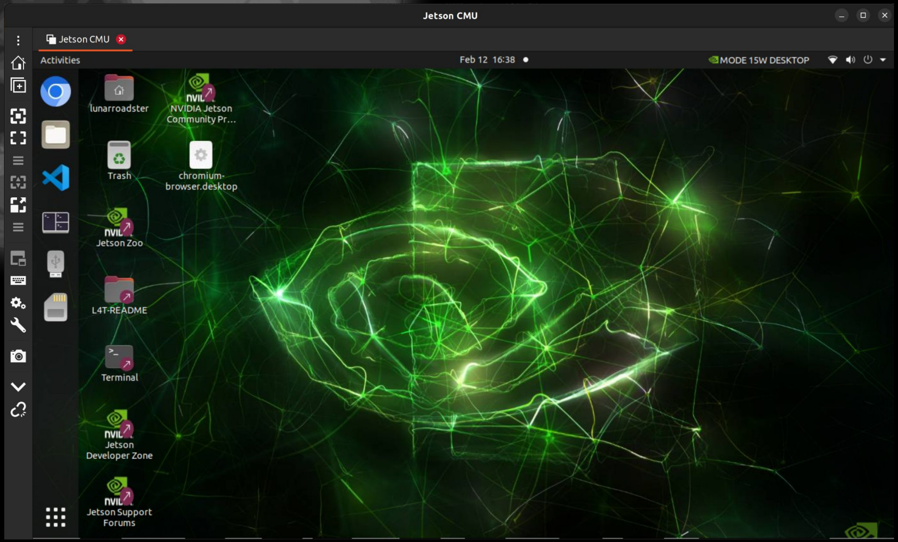
Requirements:

- NVIDIA Jetson AGX Xavier
- LAN Router
- Team laptop (operations terminal)

Expected Functionality:

- Acts as primary on-board compute
- Runs ROS2 Humble
- Runs micro-ROS
- Hosts and manages all necessary packages and device drivers inside Docker containers

Status: Computations Subsystem Jetson and Docker Unit



Implementation:

- Connect Jetson to rover's power system
- Assigned static IP on the LAN to enable SSH-based remote access from operations terminal
- Start docker container and initialize all core services and packages

Challenges:

- Setup of a VNC server for remote GUI access

Status: 95% Complete
Need to integrate ZED SDK drivers

Evaluation: Computations Subsystem
Jetson and Docker Unit

Lunar-ROADSTER / lr_ws / docker / lrdev_jetson.dockerfile

LunarROADSTER added realsense drivers

Code | Blame | Executable File · 189 lines (161 loc) · 7.31 KB

```
# ------- ZED Camera SDK --------
# FROM stereolabs/zed:4.2-runtime-cuda12.1-ubuntu22.04
# FROM stereolabs/zed:4.2-runtime-jetson-jp6.1.0
FROM stereolabs/zed:4.2-devel-jetson-jp6.1.0

# ------- ROS 2 Humble image --------
# FROM dustynv/ros:humble-desktop-l4t-r36.2.0

# Set environment variables
ENV DEBIAN_FRONTEND=noninteractive \
  ROS_DISTRO=humble \
  WORKSPACE=/root/Lunar_ROADSTER/lr_ws

# --------------- NVIDIA Libraries Configuration ------------------------
# Ensure NVIDIA drivers and CUDA libraries are accessible inside the container
ENV NVIDIA_VISIBLE_DEVICES all
ENV NVIDIA_DRIVER_CAPABILITIES all
ENV LD_LIBRARY_PATH=/usr/local/cuda/lib64:/usr/lib/aarch64-linux-gnu:/usr/lib/aarch64-linux-gnu/tegra:$LD_LIBRARY_PATH

# Copy ZED SDK from the source image
# COPY --from=zed_sdk /usr/local/zed /usr/local/zed

# Add ZED SDK environment variables
# ENV LD_LIBRARY_PATH=$LD_LIBRARY_PATH:/usr/local/zed/lib
# ENV PATH=$PATH:/usr/local/zed/bin

COPY ./ $WORKSPACE

# --------------- Base environment configuration ------------------------
# Setup shell
COPY docker/.p10k.zsh /root/.p10k.zsh
ENV TERM=xterm-256color
RUN apt-get update && apt-get install -y zsh bash wget \
  && PATH="$PATH:/usr/bin/zsh" \
```

Modelling:

- Created custom Dockerfile that installs all required system packages

Analysis:

- Verified that all required nodes and drivers start successfully inside the container

Testing:

- T03: Depth Camera Connectivity Test

Upgrade to higher performance Jetson – Fall Goal

Description: Computations Subsystem Localization Unit

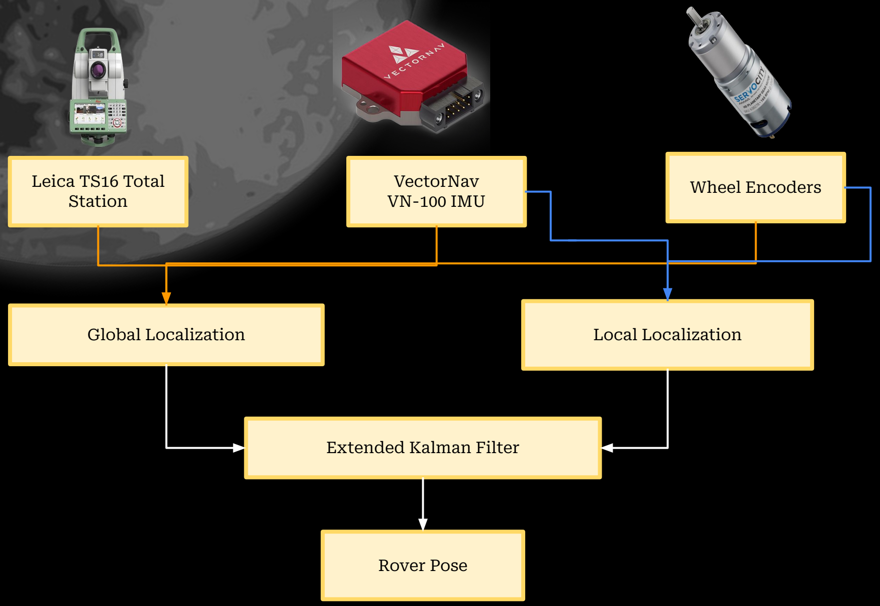
Description: Localize the rover in the Moon Yard

Requirements:

- Leica TS16 Total Station
- NVIDIA TX2 Relay Chip + LAN
- VectorNav IMU
- Wheel Encoders

Expected Functionality: Accurately localize rover pose inside the Moon Yard, to be used further for navigation

Status: Computations Subsystem
Localization Unit



Implementation:
- On-board IMU and encoders used for local localization
- Total station data fused with IMU and encoders for global localization
- EKF running on Jetson using robot_localization package, now tuned to prevent odometry drift
- Yaw calibration to ensure IMU data is w.r.t map frame

Challenges:
- Incorrect Jetson Docker network permissions blocked two-way communication
- Minor offset introduced when total station battery is replaced, causing frame inconsistencies

Status: 85% Complete
Address frame shifts caused by total station battery replacements

Evaluation: Computations Subsystem Localization Unit

Modelling:

- Configured and tuned EKF to fuse sensor inputs
- Set up frame transforms to ensure all sensor data aligns properly at base_link frame
- Performed yaw calibration to ensure consistent orientation data from IMU

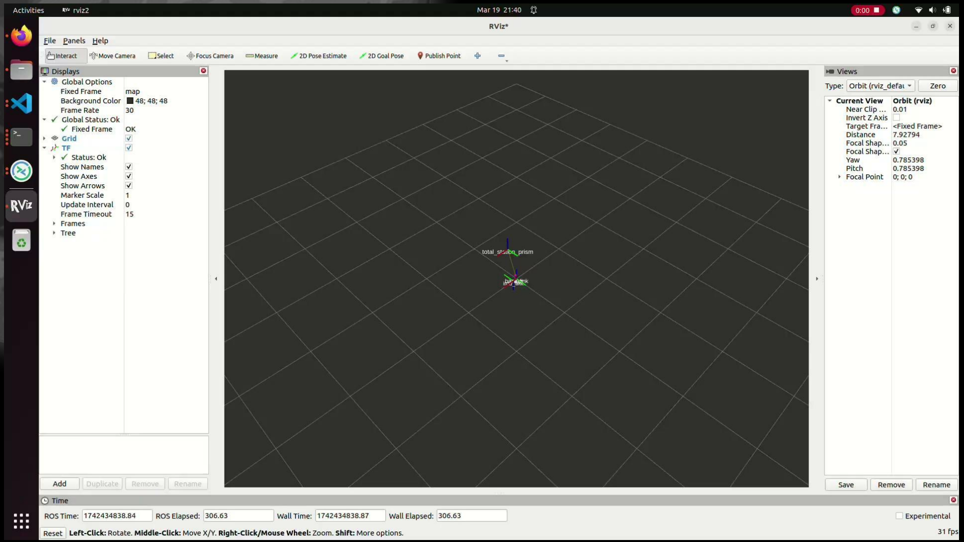
Analysis:

- Analyzed pose stability and drift over time during testing
- Analyzed sensor noise and measurement delays, tuning EKF parameters to minimize odometry drift
- Assessed effect of total station resections and battery swaps on accuracy

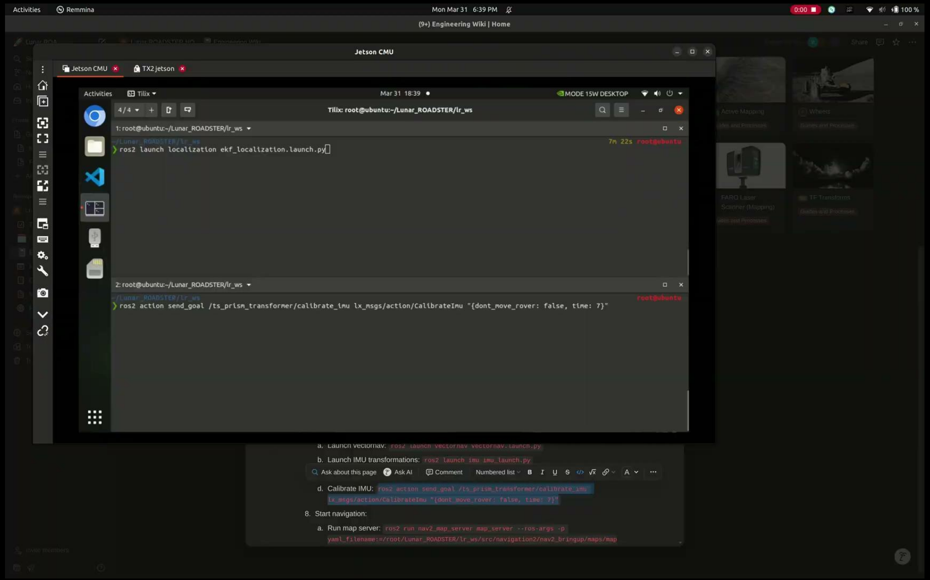
Testing:

- T09: Rover can localize itself accurately
- T15: Spring Validation Demo Test

Evaluation: Computations Subsystem Localization Unit



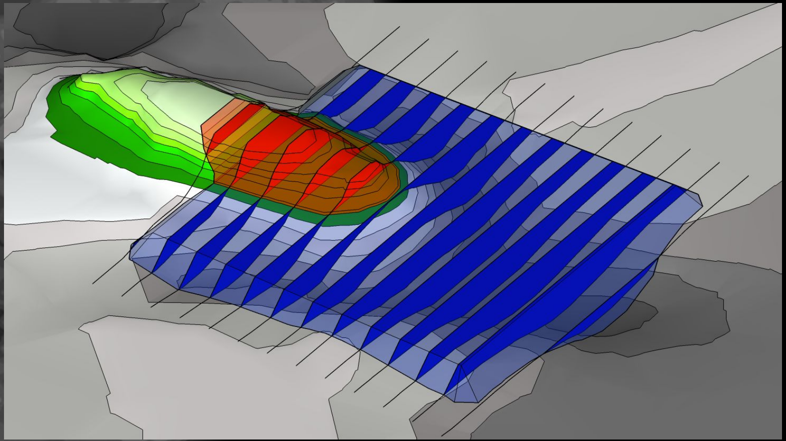
Localization drift issue

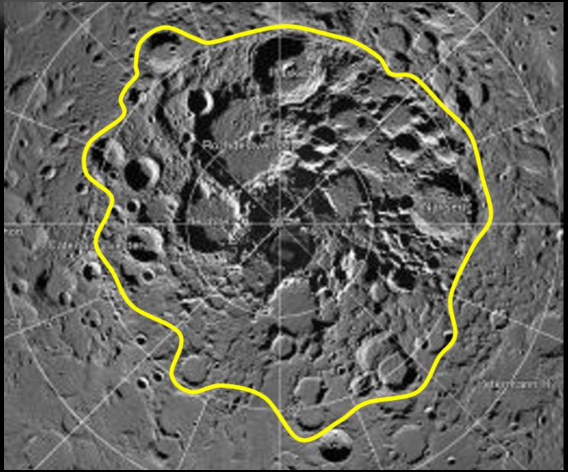


Drift corrected + Yaw calibrated

New localization method using SkyCam to be implemented to remove total station dependency – Fall Goal

Description: Transport Planner Unit





Description: Subsystem that plans sand manipulation by using the tool and drive train.

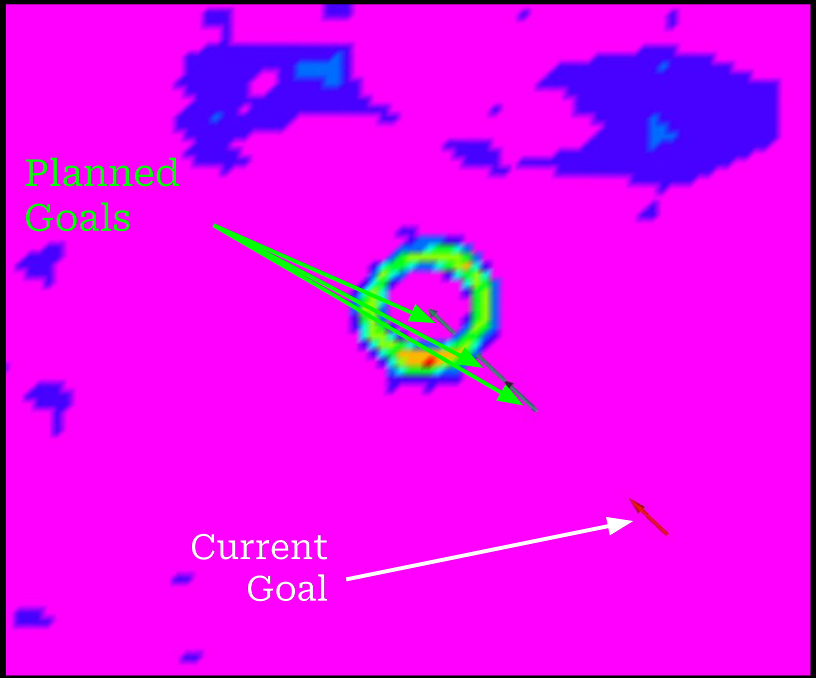
Requirements

- Jetson Xavier AGX
- Dozer Assembly
- Drivetrain (with Wheel Assembly)
- Global Map

Expected Functionality

- Plans a control input for the tool
- Plans a trajectory for the rover for manipulation
- Outputs waypoints and tool trajectories to the navigation planner

Status: Transport Planner Unit



Implementation:

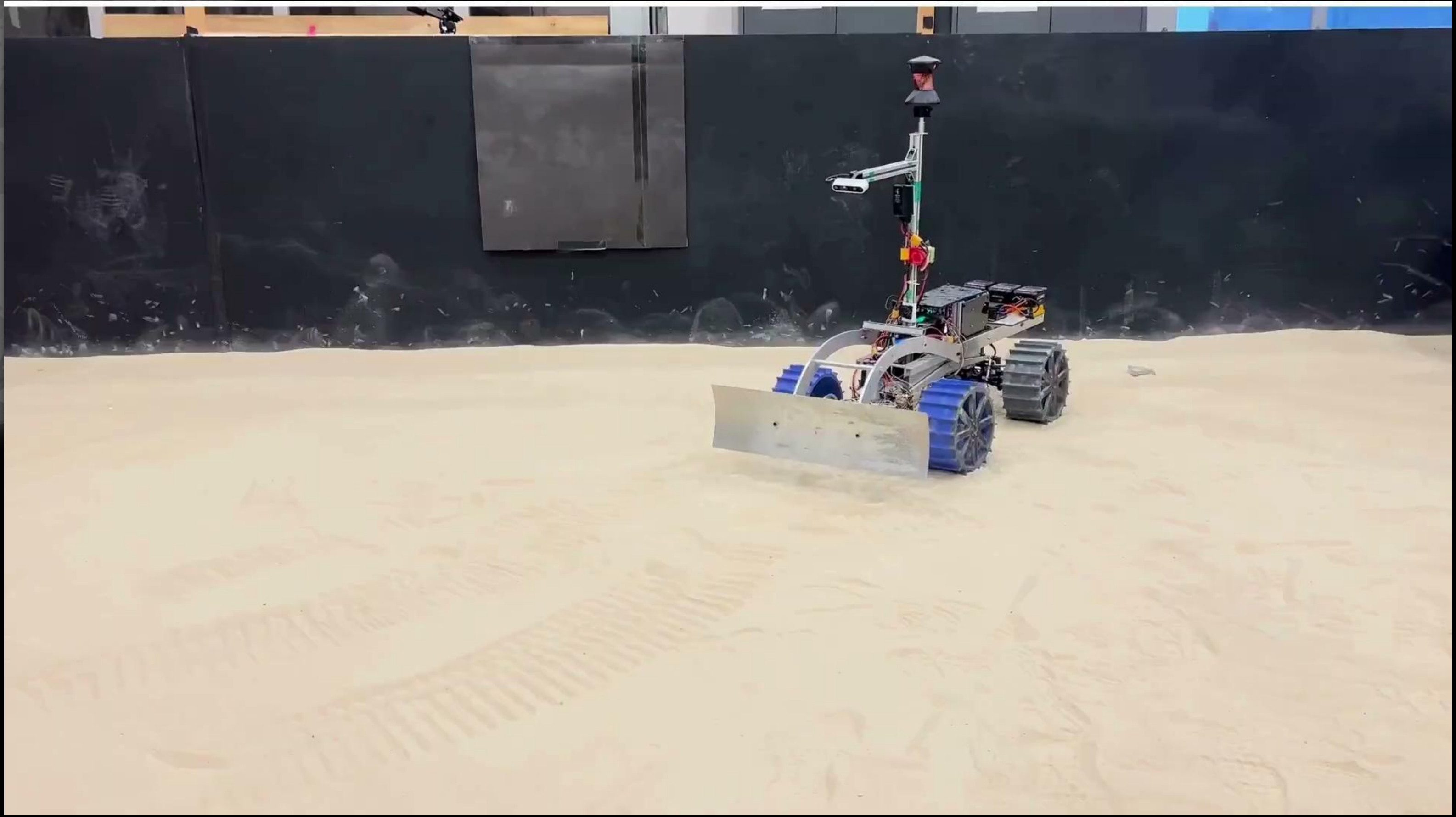
- Global Map is used to identify source and sink nodes.
- Transport Assignments are generated between sources and sinks, based on minimizing a cost function
- ROADSTER Waypoints are obtained from the filtered assignments to generate paths and tool trajectories.
- Methodology needs to be adapted for multiple craters

Challenges:

- Processing a dense point cloud
- Modelling tool size within the subsystem for optimal plans

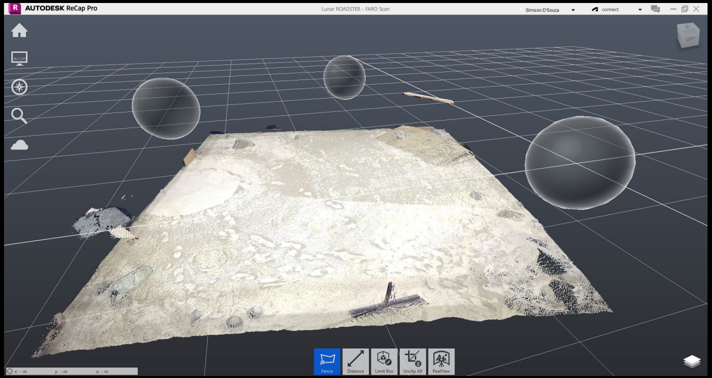
Status: 60% complete

Evaluation: Transport Planner Unit



4x

Description: Computations Subsystem Navigation Planner Unit



Description: Identify gradable craters, obtain coordinates, and navigate the rover to their locations

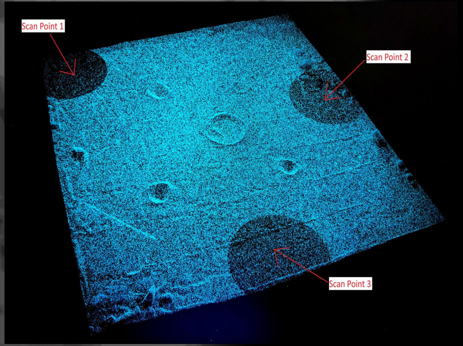
Requirements:

- FARO Laser Scanner
- NVIDIA Jetson AGX Xavier
- Team laptop (operations terminal)

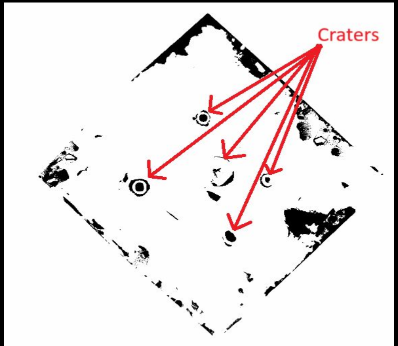
Expected Functionality:

- Accurately detect and classify gradable craters
- Ensure no gradable crater is overlooked
- Compute an optimal navigation path while avoiding obstacles (non-gradable craters and rocks)
- Navigate and reach the goal location correctly

Status: Computations Subsystem Navigation Planner Unit



Moon Yard Scan Visualization



Global Costmap

Implementation:

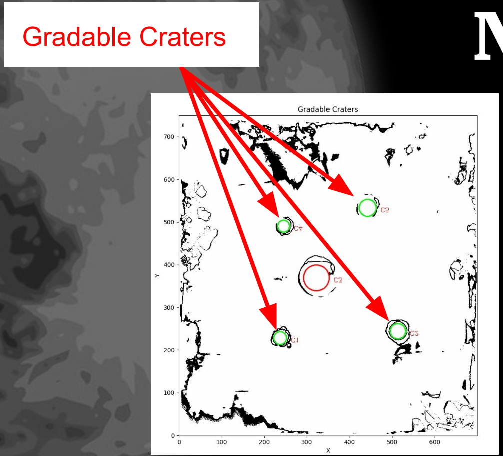
- Mapped the Moon Yard using the FARO Laser Scanner to generate a point cloud.
- Converted the point cloud file into a ROS-compatible format.
- Applied RANSAC for plane fitting and implemented thresholding to generate a 2D costmap for navigation.
- Identified craters based on diameter and depth, extracting their coordinates.
- Integrated navigation with tool planner to perform transport assignments

Challenges:

- FARO output file (.fls) was incompatible with the PCL library and ROS.
- Plane fitting for identifying gradable craters was challenging due to uneven terrain.
- Accurately classifying gradable craters based on diameter and depth.
- Fine-tune Nav2 parameters for optimal performance on our robot and ensure accurate robot localization

Status: 90% Complete (Tune Navigation Stack) - Fall Goal

Evaluation: Computations Subsystem
Navigation Planner Unit



Identified Gradable Craters

```
Gradable Craters Location
Crater C1: Diameter = 0.300 meters
  Centroid of Crater C1: X = 2.380 m, Y = 2.289 m

Crater C2: Diameter = 0.360 meters
  Centroid of Crater C2: X = 5.131 m, Y = 2.443 m

Crater C3: Diameter = 0.600 meters

Crater C4: Diameter = 0.280 meters
  Centroid of Crater C4: X = 2.453 m, Y = 4.909 m

Crater C5: Diameter = 0.400 meters
  Centroid of Crater C5: X = 4.421 m, Y = 5.335 m
```

Gradable Craters Location

Modeling:

- Generated dense point cloud maps by taking multiple FARO scans and updated the map origin for consistent localization and navigation frames
- Tuned Nav2 parameters to suit Ackermann steering kinematics.
- Used RViz extensively to visualize and debug transformations and paths

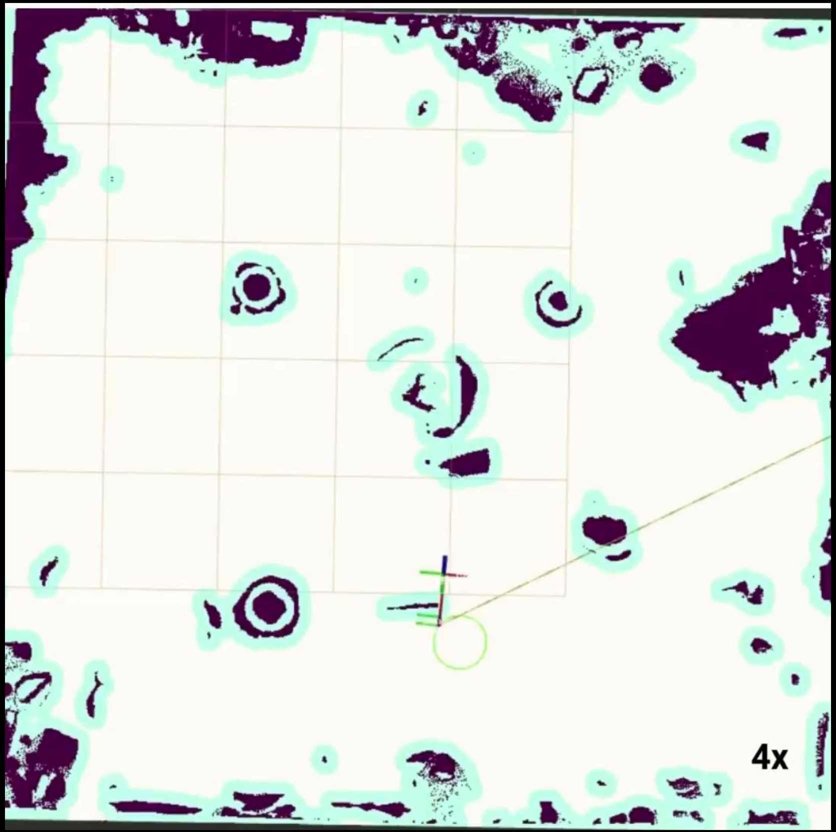
Analysis:

- Evaluated planned paths for smoothness, obstacle avoidance, and feasibility
- Analyzed factors affecting navigation: localization noise, data delay, computation load, and parameter tuning

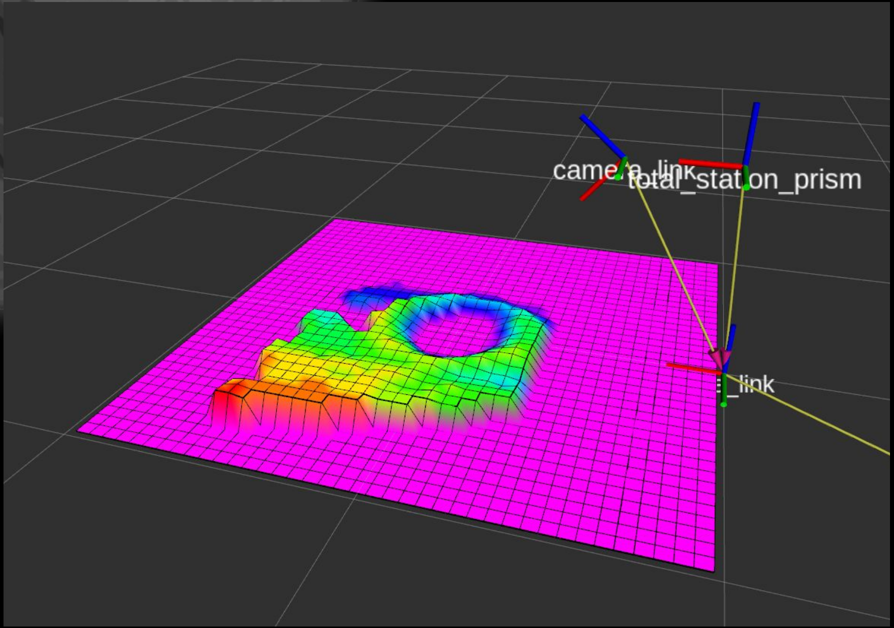
Testing:

- T08: Mapping the Moon Yard and visualize the point cloud data
- T11: Navigate and reach the goal location correctly
- T15: Spring Validation Demo Test

Evaluation: Computations Subsystem Navigation Planner Unit



Description: Computations Subsystem Validation Unit



Description: Validates if groomed crater satisfies maximum traversability requirement (M.P.6)

Requirements:

- RealSense D235i or ZED 2i stereo camera
- Camera driver packages
- Jetson Xavier AGX

Expected Functionality:

- Outputs trail RMSE elevation error and/or maximum traversal slope

Status: Computations Subsystem Validation Unit

Implementation:

- Preliminary implementation for SVD Encore by calculating RMSE relative to mean elevation
- Will implement full unit in Fall semester using mast camera

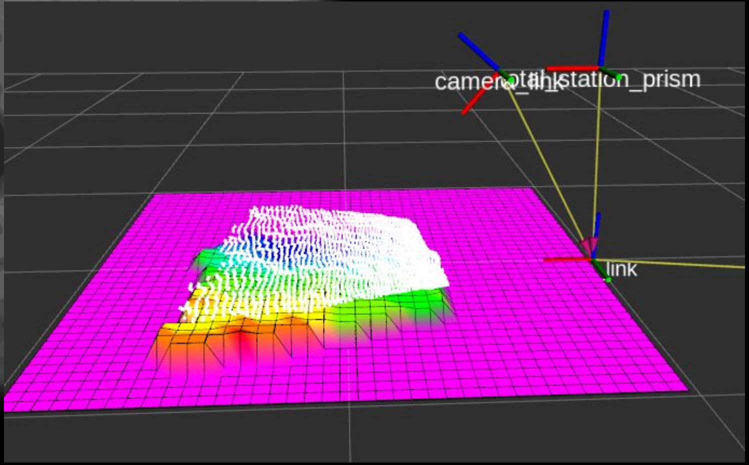
Challenges:

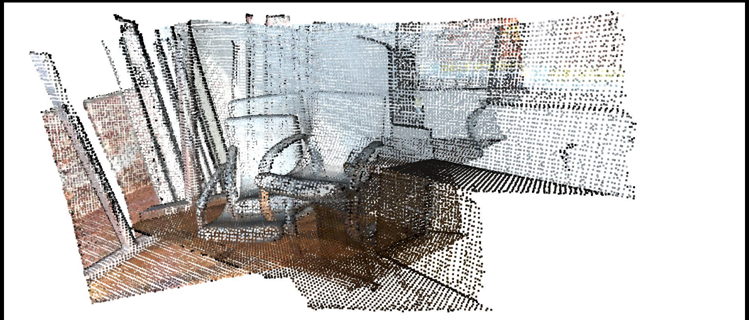
- Rover mast moves due to rover suspension. May cause errors in estimating the ground plane
- Compute is not enough for RealSense point cloud feed at 30 FPS

Status: 10% Complete

```
[info_logger_node-1] [INFO] [1745446813.600659910] [info_logger_node]: Mean Elevation:      1.41 cm
[info_logger_node-1] [INFO] [1745446813.600924924] [info_logger_node]: Elevation RMSE:      2.91 cm
[info_logger_node-1] [INFO] [1745446933.590001611] [info_logger_node]: Mean Elevation:      0.99 cm
[info_logger_node-1] [INFO] [1745446933.590321099] [info_logger_node]: Elevation RMSE:      1.90 cm
```

Evaluation: Computations Subsystem Validation Unit





Modelling:

- Calibrated camera {X, Y, Z, R, P, Y} so that flat ground has zero elevation and no rotation

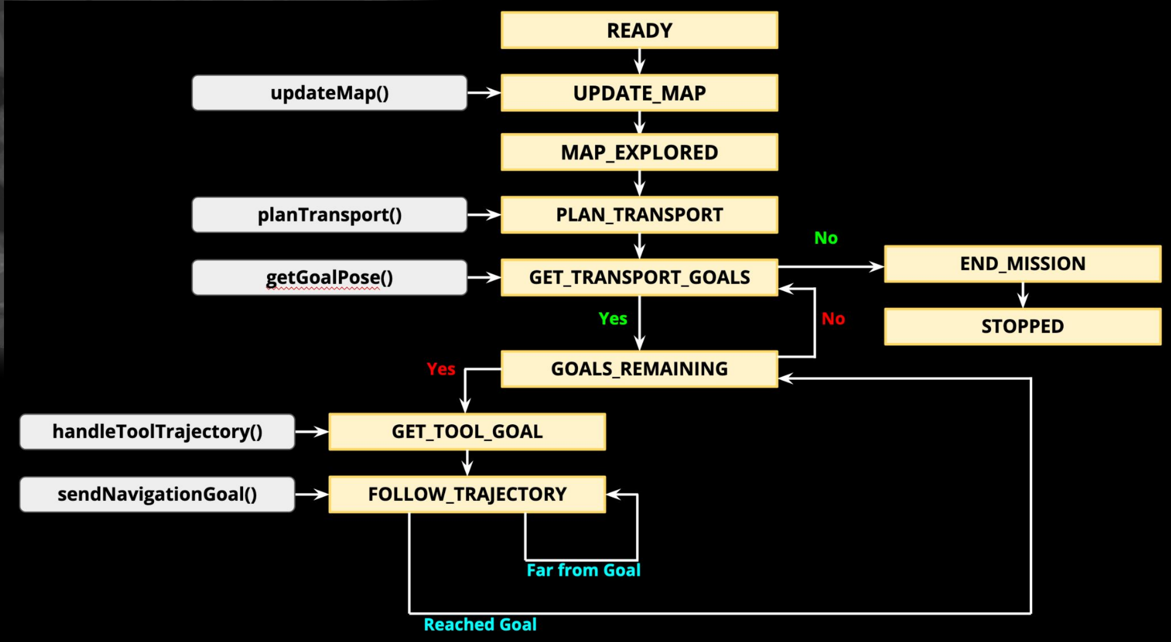
Analysis:

- Point cloud obtained from RealSense is not as dense as ZED 2i. May not be adequate for validation requirements

Testing:

- Milestone deadline set for PR8

Description: Computations Subsystem Finite State Machine Unit



Description: High level behaviour tree for entire autonomy stack

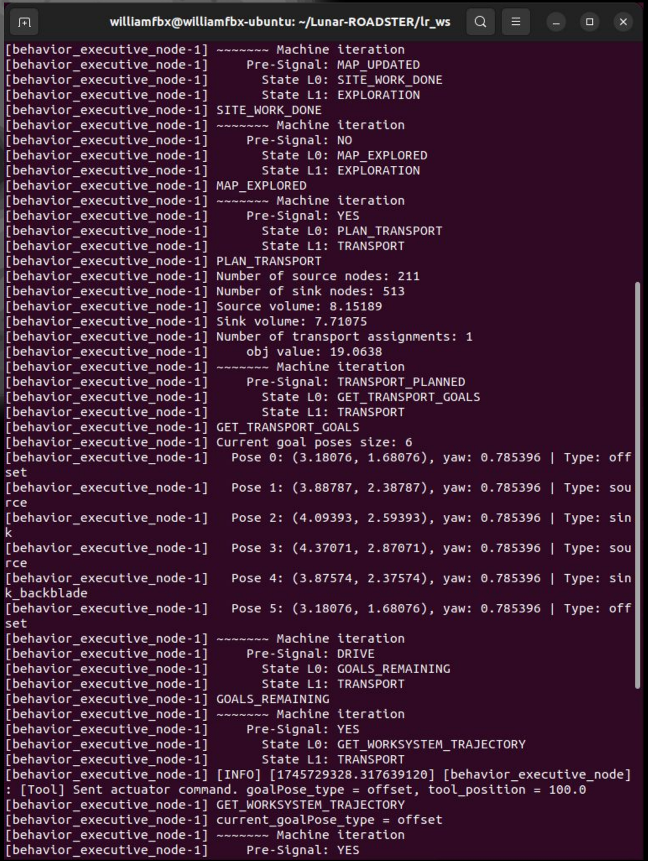
Requirements:

- Sensors subsystem
- Computations subsystem
- External infrastructure
- Mechanical subsystem
- Actuation subsystem
- Electrical power subsystem

Expected Functionality:

- Entire system is able to grade craters autonomously

Status: Computations Subsystem Finite State Machine Unit


williamfbx@williamfbx-ubuntu: ~/Lunar-ROADSTER/lr_ws

```
[behavior_executive_node-1] ~~~~~~~ Machine iteration
[behavior_executive_node-1]     Pre-Signal: MAP_UPDATED
[behavior_executive_node-1]       State L0: SITE_WORK_DONE
[behavior_executive_node-1]       State L1: EXPLORATION
[behavior_executive_node-1] SITE_WORK_DONE
[behavior_executive_node-1] ~~~~~~~ Machine iteration
[behavior_executive_node-1]     Pre-Signal: NO
[behavior_executive_node-1]       State L0: MAP_EXPLORED
[behavior_executive_node-1]       State L1: EXPLORATION
[behavior_executive_node-1] MAP_EXPLORED
[behavior_executive_node-1] ~~~~~~~ Machine iteration
[behavior_executive_node-1]     Pre-Signal: YES
[behavior_executive_node-1]       State L0: PLAN_TRANSPORT
[behavior_executive_node-1]       State L1: TRANSPORT
[behavior_executive_node-1] PLAN_TRANSPORT
[behavior_executive_node-1] Number of source nodes: 211
[behavior_executive_node-1] Number of sink nodes: 513
[behavior_executive_node-1] Source volume: 8.15189
[behavior_executive_node-1] Sink volume: 7.71075
[behavior_executive_node-1] Number of transport assignments: 1
[behavior_executive_node-1]     obj value: 19.0638
[behavior_executive_node-1] ~~~~~~~ Machine iteration
[behavior_executive_node-1]     Pre-Signal: TRANSPORT_PLANNED
[behavior_executive_node-1]       State L0: GET_TRANSPORT_GOALS
[behavior_executive_node-1]       State L1: TRANSPORT
[behavior_executive_node-1] GET_TRANSPORT_GOALS
[behavior_executive_node-1] Current goal poses size: 6
[behavior_executive_node-1]   Pose 0: (3.18076, 1.68076), yaw: 0.785396 | Type: off
set
[behavior_executive_node-1]   Pose 1: (3.88787, 2.38787), yaw: 0.785396 | Type: sou
rce
[behavior_executive_node-1]   Pose 2: (4.09393, 2.59393), yaw: 0.785396 | Type: sin
k
[behavior_executive_node-1]   Pose 3: (4.37071, 2.87071), yaw: 0.785396 | Type: sou
rce
[behavior_executive_node-1]   Pose 4: (3.87574, 2.37574), yaw: 0.785396 | Type: sin
k_backblade
[behavior_executive_node-1]   Pose 5: (3.18076, 1.68076), yaw: 0.785396 | Type: off
set
[behavior_executive_node-1] ~~~~~~~ Machine iteration
[behavior_executive_node-1]     Pre-Signal: DRIVE
[behavior_executive_node-1]       State L0: GOALS_REMAINING
[behavior_executive_node-1]       State L1: TRANSPORT
[behavior_executive_node-1] GOALS_REMAINING
[behavior_executive_node-1] ~~~~~~~ Machine iteration
[behavior_executive_node-1]     Pre-Signal: YES
[behavior_executive_node-1]       State L0: GET_WORKSYSTEM_TRAJECTORY
[behavior_executive_node-1]       State L1: TRANSPORT
[behavior_executive_node-1] [INFO] [1745729328.317639120] [behavior_executive_node]
: [Tool] Sent actuator command. goalPose_type = offset, tool_position = 100.0
[behavior_executive_node-1] GET_WORKSYSTEM_TRAJECTORY
[behavior_executive_node-1] current_goalPose_type = offset
[behavior_executive_node-1] ~~~~~~~ Machine iteration
[behavior_executive_node-1]     Pre-Signal: YES
```

Implementation:

- FSM callbacks implemented at 2 Hz
- Heavy computations parallelized and detached from main thread to not block FSM node from iterating

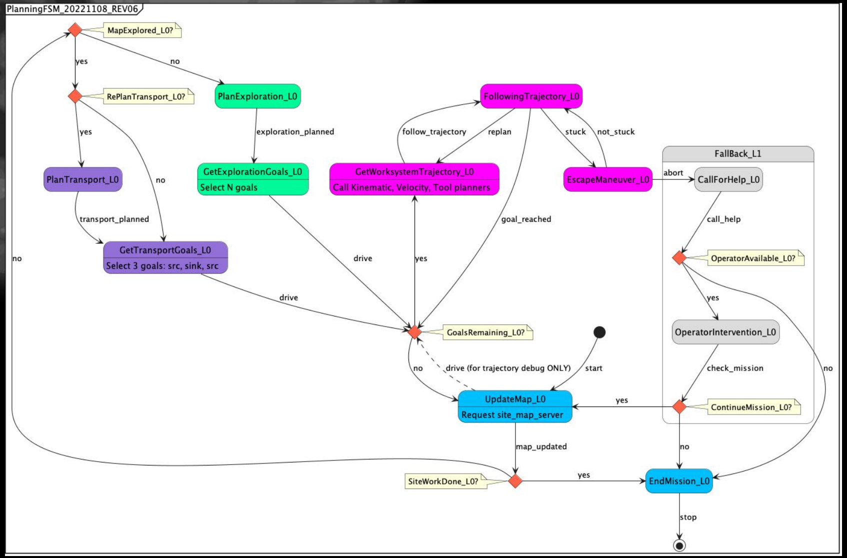
Challenges:

- Compute not sufficient for active mapping using RealSense

Status: 95% Complete

Integrate validation unit into FSM – Fall Goal

Evaluation: Computations Subsystem Finite State Machine Unit



Modelling:

- Initial FSM design sourced from Crater Grader. Adapted design for our needs

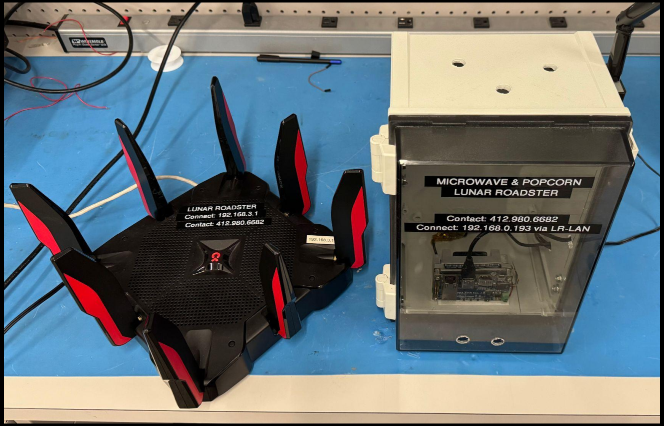
Analysis:

- Computations take too long. Rover often completely stops for calculations
- Integrating active mapping sometimes causes topic messages to be missed due to high network layer traffic

Testing:

- T13: Integration Test
- T15: Spring Validation Demo Test

Description: External Infrastructure Subsystem



Description: Mission components deployed offboard the rover to support localization and communication

Requirements:

- Leica TS16 Total Station
- NVIDIA TX2 Relay Chip
- LAN Router
- Team laptop (operations terminal)

Expected Functionality:

- Accurately localize {X, Y, Z}-coordinates of the rover inside Moon Yard
- Establish two-way communication

Status & Evaluation: External Infrastructure Subsystem

```
william_fu@williamfuubuntu: ~
william_fu@williamfuubuntu: ~/Deskto...    william_fu@williamfuubuntu: ~
william_fu@williamfuubuntu:~$ ros2 topic info /total_station_prism
Type: geometry_msgs/msg/PoseWithCovarianceStamped
Publisher count: 1
Subscription count: 0
william_fu@williamfuubuntu:~$ ros2 topic hz /total_station_prism
average rate: 8.395
        min: 0.095s max: 0.148s std dev: 0.01877s window: 10
average rate: 7.968
        min: 0.095s max: 0.257s std dev: 0.03608s window: 18
average rate: 3.992
        min: 0.095s max: 3.157s std dev: 0.60696s window: 24
average rate: 4.511
        min: 0.092s max: 3.157s std dev: 0.52852s window: 32
average rate: 5.042
        min: 0.092s max: 3.157s std dev: 0.46907s window: 41
average rate: 5.443
        min: 0.092s max: 3.157s std dev: 0.42595s window: 50
average rate: 5.656
        min: 0.087s max: 3.157s std dev: 0.39633s window: 58
average rate: 5.908
        min: 0.087s max: 3.157s std dev: 0.36933s window: 67
william_fu@williamfuubuntu:~$
```

Implementation:

- Total Station sends rover coordinates to TX2 relay chip, forwards data packet via LAN network to rover
- Established static IP on LAN network so operations terminal can communicate via SSH

Challenges:

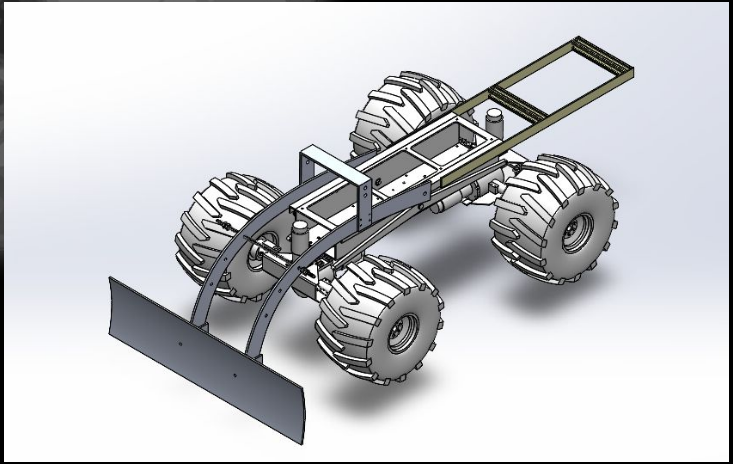
- Unable to obtain access to the TX2 relay chip login details
- Incorrect Jetson Docker network permissions blocked two-way communication

Status: Completed

Analysis: Investigated network permission issues inside Jetson Docker

Testing: T05: External Infrastructure Test

Description: Mechanical Subsystem Dozer Assembly

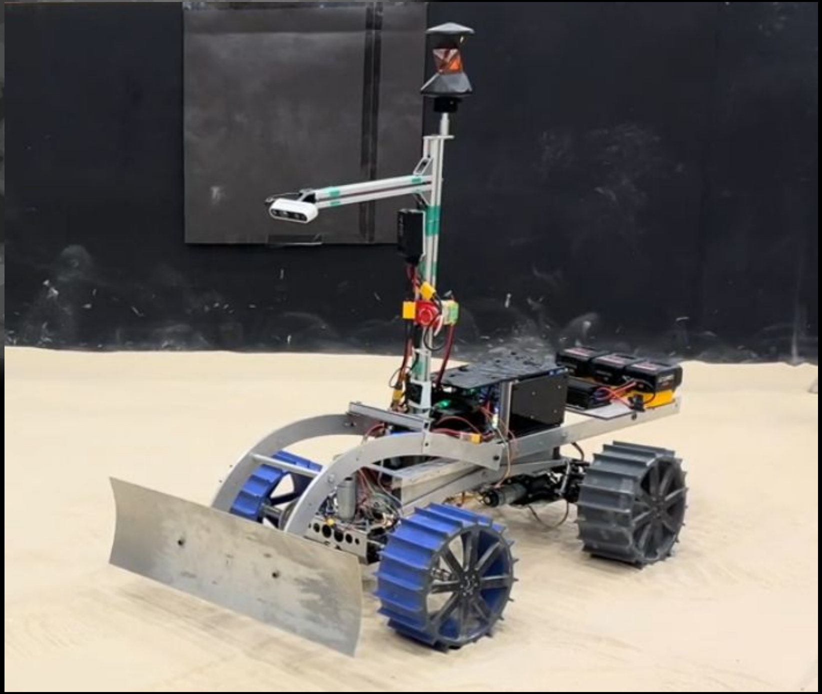


Description: Lunar terrain manipulation tool

Requirements:
- Dozer blade
- Dozer arms assembly
- Linear actuator
- Arduino Due

Expected Functionality:
- Perform dozing of sand
- Perform backblading
- Actuate automatically based on commands from tool planner

Status: Mechanical Subsystem Dozer Assembly Unit



Implementation:

- Research: Dozer shapes and sizes, actuation methodologies.
- Designed the dozer assembly (blade, arms, yoke, mounts) using SolidWorks.
- Shortlisted linear actuators of different gear ratios.
- Manufactured and assembled all parts on the rover.
- Testing with different actuators

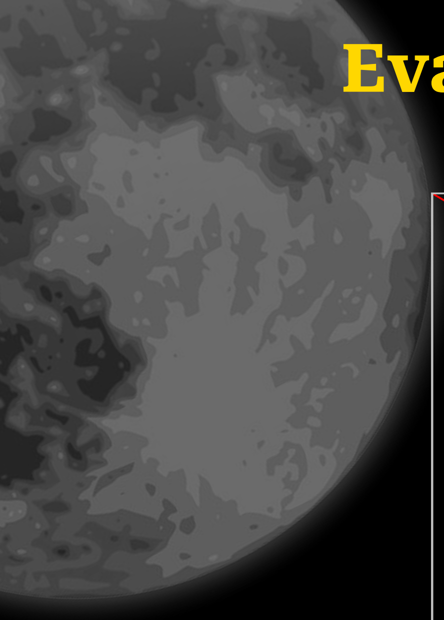
Challenges:

- Fabrication problems
- Limited access to FRC Workshop

Status: 90% Complete

- Demonstrated automatic dozing and backblading capabilities of the assembly in SVD
- Refine the assembly by remanufacturing certain components

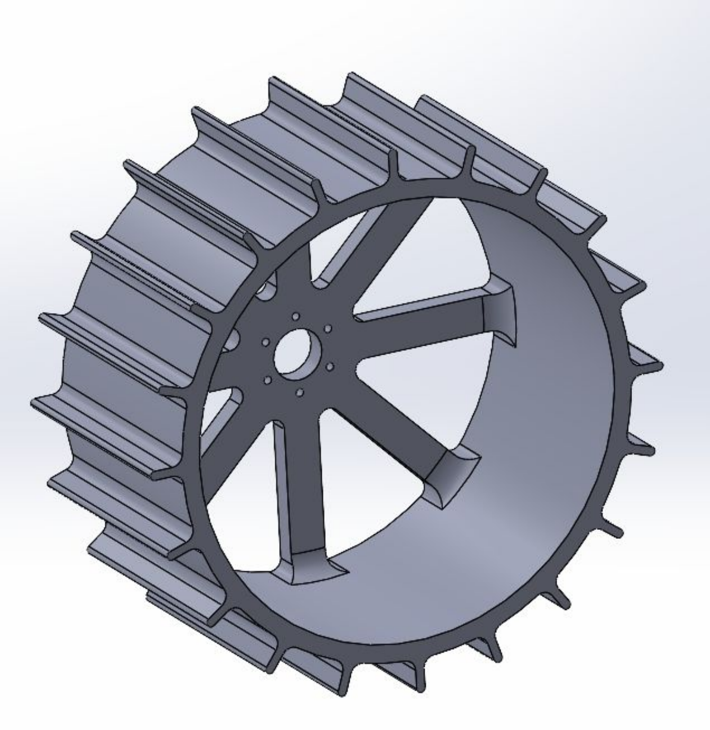
Evaluation: Mechanical Subsystem Dozer Assembly Unit



Excellent pushing and grading capability, owing to the shape and size of the blade, and the robust dozer arms

Improved yoke/actuator arch to be manufactured in Fall based on the actuator

Description: Wheel Assembly Unit



Description: Assembly that enables movement of the rover by acting as an interface between the drivetrain and ground.

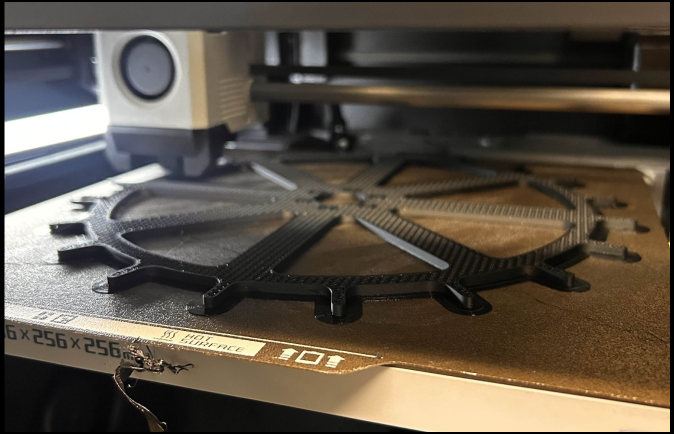
Requirements:

- Wheel (3D Printed - PLA)
- Mounting Assembly to the Suspension
- Drive Train (Differential and Steering)
- Motors

Expected Functionality:

- Provide required traction for movement and grading of sand
- Minimize wheel slip
- Allow for steering in sand
- Desirable - Use materials that can function on the Lunar Surface

Status: Wheel Assembly Unit



Implementation:

- Design single-part iterations in SolidWorks
- 3D-print designs and test in the MoonYard
- Observe and re-design until the design is satisfactory

Challenges:

- 3D Printing the wheel is a long process with frequent failures
- Steering system of the rover is fragile and frequently disengages - solved.

Status: 90% Complete

- Demonstrated mobility and pushing power with 4 printed wheels in SVD
- Next iteration in Fall to make the design lighter.
- Integration of current sensing to measure wheel torque.

Evaluation: Wheel Assembly Unit

Great performance in traction and generating pushing power in all tests

Torque feedback to be integrated in the Fall to estimate traction and slip

Design can be optimized to be lighter - Fall goal

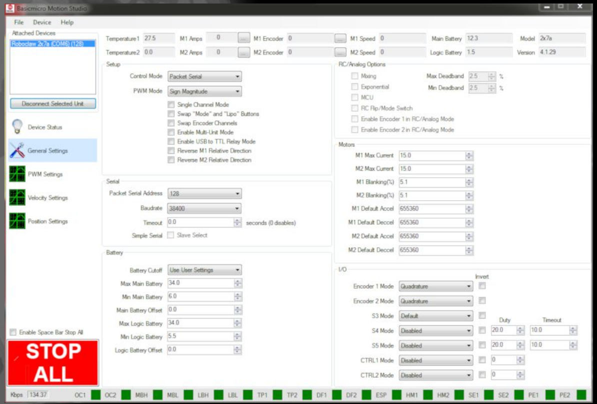
Description: Actuation Subsystem

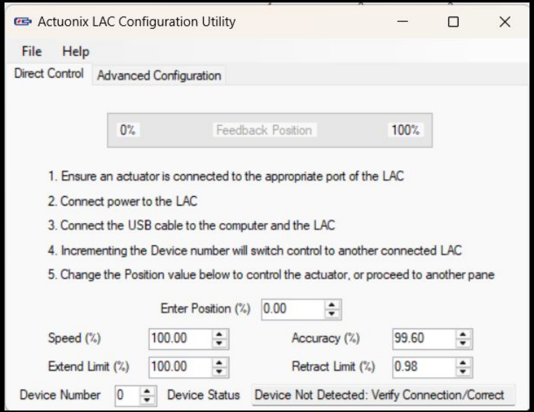
Description: Power transfer methodologies for rover mechanisms.

Requirements:
- DC Motors with Encoders (x4)
- Linear Actuator (with feedback)

Expected Functionality:
- Deliver power to wheels for mobility
- Steer the front and rear wheels
- Actuate the dozer assembly to facilitate mobility and dozing

Status: Actuation Subsystem





Implementation:

- Selected drive motors with higher torque for better traction and mobility
- Selected linear actuator for dozer assembly
- Interfaced drive motors and steering motors with Roboclaw motor controller
- Interfaced Actuator with Linear Actuator Controller Board and Arduino Due

Challenges:

- Mismatched gearing in motors caused non-uniform steering in front and rear
- Worn-out pinion gears
- Oscillations near setpoint of linear actuator under load.

Status: 90% Complete

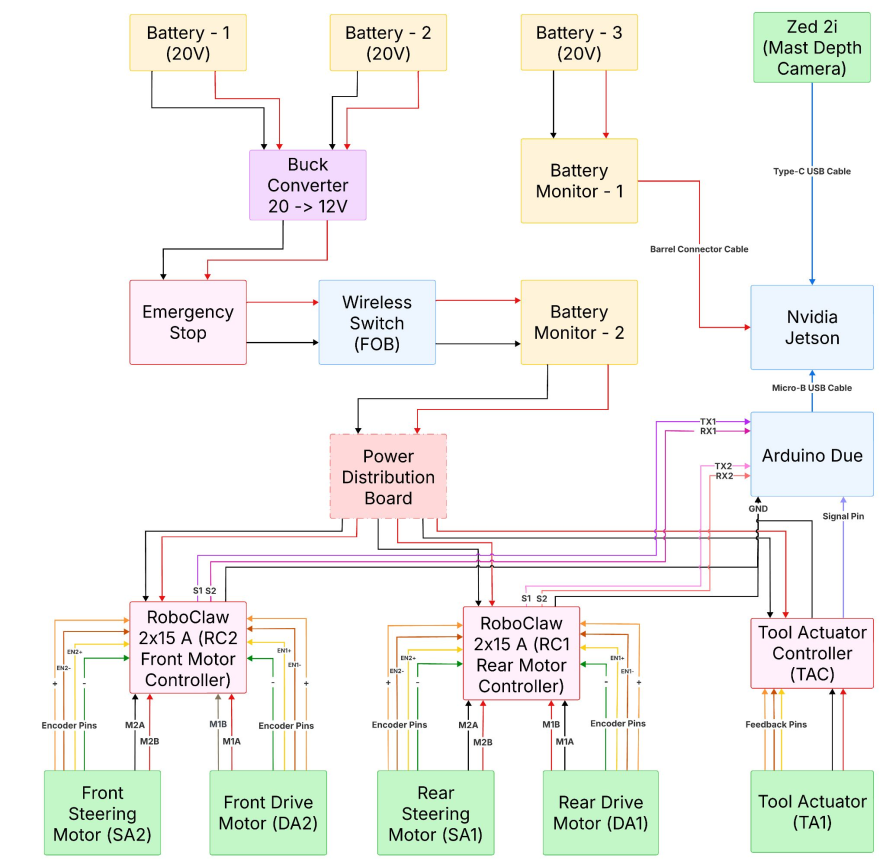
- Demonstrated enhanced steering and driving in SVD
- Upgrade/tune linear actuator

Evaluation: Actuation Subsystem

New drive motors provide adequate motion in the Moonyard. Actuator has the capability to lift the rover, as demonstrated in SVD.

Replace actuator for better and smoother performance - Fall goal

Description: Electrical Subsystem



Description: Rover's power and logic circuitry.

Requirements:

- Buck Converter (20 V -> 12 V)
- Power Distribution Board (PDB)
- RoboClaw Motor Controller - 2
- Linear Actuator Controller
- Linear Actuator
- Zed 2i Depth Camera
- E-Stop
- Wireless Switch
- IMU - VectorNav VN100
- Arduino Due
- Nvidia Jetson Xavier AGX
- Wireless Receiver for Joystick
- DC motors with Encoders

Expected Functionality:

- Distribute power efficiently to all rover components
- Ensure stable voltage levels for uninterrupted operation

Status: Electrical Subsystem

Implementation:

- Integrated new electrical components and designed a custom Power Distribution Board (PDB) based on updated power requirements
- Designed a compact and accessible electronic box to streamline the electrical subsystem setup
- Successfully integrated and tested the PDB within the rover's electrical system

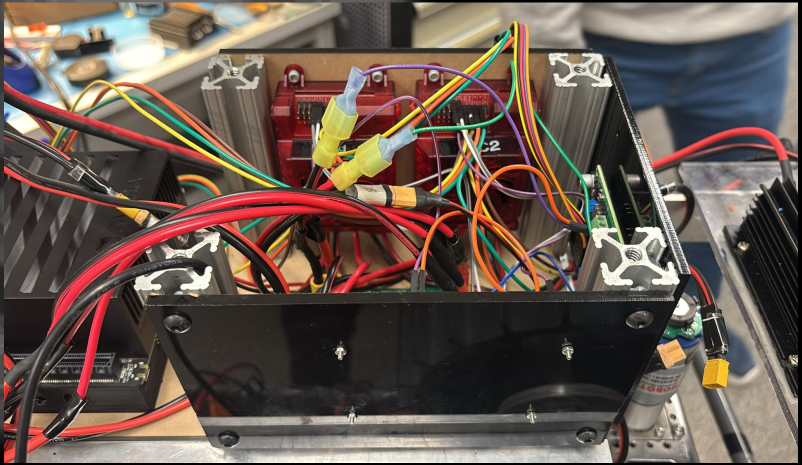
Challenges:

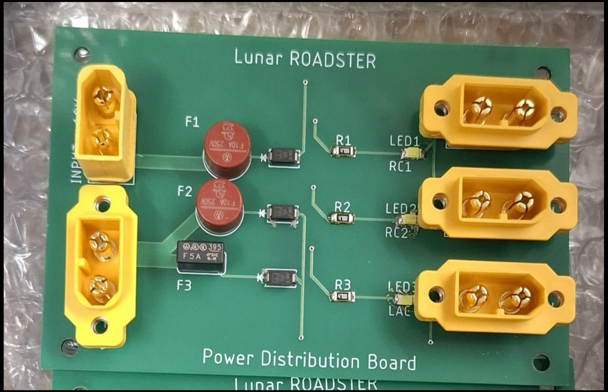
- Understanding and adapting to the existing circuit design and limitations.
- Ensuring the compact design of the electronic box while maintaining accessibility and proper cooling.

Status: 90%

Integrating torque feedback sensing and updating battery position – Fall Goal

Evaluation: Electrical Subsystem





Modeling:

- Developed detailed circuit diagram integrating existing and new electrical components
- Modeled custom PDB with over-current, reverse-voltage, and power indication features
- Designed electronics box for minimal footprint, cooling, and accessibility

Analysis:

- Verified voltage and current demands for each subsystem component to ensure PDB output stability
- Assessed cable routing and hardware quality assurance

Testing:

- T07: Complete Hardware Test

Performance Evaluation in SVD

What went well?

1. Mechanical Design
2. Electronics Box Design
3. Transport Planner
4. Navigation Planner
5. Finite State Machine

What didn’t go well?

1. Reliability of Autonomy
2. Demonstrating Performance Metrics
3. System Improvement for Encore

What needs to improve?

1. Codebase (Bloated, heavy compute)
2. Localization Accuracy
3. Wiring
4. Pre-demo setup methodology

Performance Evaluation in SVD

Req.	Description	Status	Score
M.P.1	Cumulative deviation from latitude	Achieved - Global path planning methodology has been set up. We were only able to demonstrate a straight line for a single crater.	5/10
M.P.2	Navigation Accuracy	Demonstrated - The ROADSTER followed the generated global path to an average deviation of 8.16%. Metric will also improve with localization.	9/10
M.P.4 (Part 1)	Crater Avoidance	Demonstrated - Methodology for identification of craters to avoid set up. Shown in sim during SVD	8/10
M.P.5	Crater Grooming	Demonstrated - Groomed craters in both autonomous and teleop. Built a strong, capable machine for crater grooming	10/10

Performance Evaluation in SVD

Req.	Description	Status	Score
M.N.1	Weight	Achieved - The rover weighs 25kg. This number may increase with additions during the Fall. Need to demonstrate.	8/10
M.N.4	Size	Missed - The size of the dozing arms were increased to allow for backblading. The battery mounting extension arms need to be removed to meet this requirement.	3/10
D.N.1	Technological Extensibility	Achieved - We have maintained an Engineering Wiki and extensively documented our entire design process. Need to demonstrate.	8/10
D.N.2	Aesthetics	Demonstrated - Sponsor requirement. Design look is satisfactory with minor changes in cable management and colour schemes	9/10

Performance Evaluation in SVD

Presentation / Management

9/10

Hardware

9/10

Software

6/10

Video Excerpt

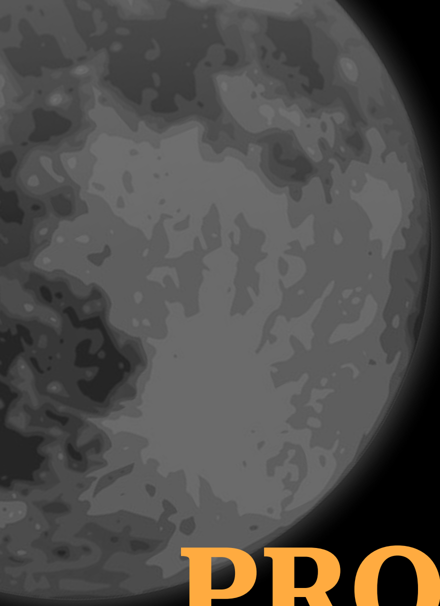
Conclusions after SVD

STRENGTHS

- Robust Tool Subsystem
- Compact E-Box
- Wheels
- Power Distribution Board (PDB)
- Management and Presentation
- External Infrastructure
- Software Integration

WEAKNESSES

- Mechanical Vulnerability
- Electrical Unreliability
- Compute Bottleneck
- Reliability of autonomy
- Demonstrating performance metrics



PROJECT MANAGEMENT

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 Dozer Tool Assembly
  - 1.1.4 Modify Wheel Assembly
  - 1.1.5 Design and Manufacture Sensor Mounts
  - 1.1.6 Mechanical Assembly
  - 1.1.7 Quality Assurance
  - ~~Grader Design~~
- **1.2 Computations**
  - 1.2.2 Setup Jetson Drivers
  - 1.2.4 Slip Estimation
  - 1.2.5 Localization - Sensor Fusion
  - 1.2.6 FSM Planner
  - 1.2.7 Dozer Planner
  - 1.2.8 Navigation Planner
  - 1.2.9 Grooming Validation
  - ~~Grader Planner~~
- **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 IMU Drivers
  - 1.3.5 Setup Survey LiDARs
  - 1.3.6 Read Sensor Data using Jetson
- **1.4 Electronics**
  - 1.4.1 Source Electronics
  - 1.4.2 Devise Circuit Diagram
  - 1.4.3 Setup Circuit
  - 1.4.4 Power Distribution Board
- **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
  - 1.5.5 Setup TX2 Terminal
- **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

Schedule

Major Milestones:

- All major spring milestones completed ahead of SVD
- Systems require improvement to meet FVD goals

Current Status:

- Achieved all promised goals for SVD
- Slight delays due to additional development for SVD Encore (higher compute requirements)

Plan to Improve:

- Upgrade to a higher-performance Jetson during summer
- Make final system adjustments to ensure system robustness before PR6

Fall Test Plan

Date	Event	Capability Milestones	Tests	Requirements
09/10	PR7	• Hardware and software refinement	Validate hardware upgrades, software fixes, and system stability improvements	M.F.5 M.F.9 M.N.3
09/24	PR8	• Validation stack setup • Wheel torque measurement • Navigation tuning	Detect robot stalling through torque measurement, adjust tool height, and verify smooth navigation through path execution tests	M.F.2 M.F.3 M.F.4 M.F.8 M.F.9
10/08	PR9	• Autonomous grading of multiple craters	Verify autonomous grading performance across multiple craters	M.F.2 M.F.3 M.F.4 M.F.5 M.F.6 M.F.7 M.F.9

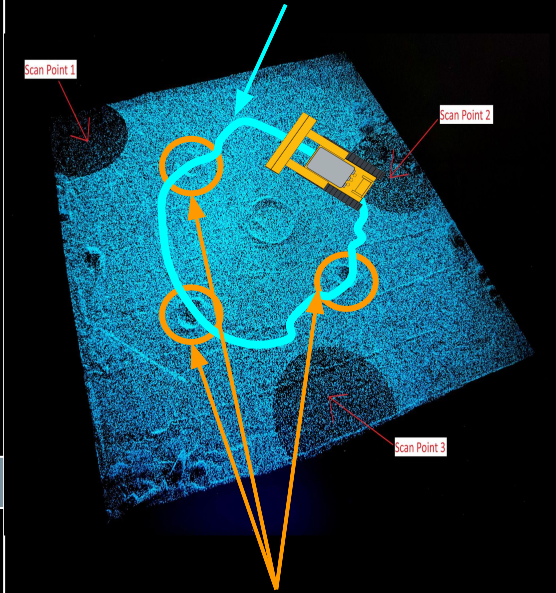
Fall Test Plan

Date	Event	Capability Milestones	Tests	Requirements
10/29	PR10	• SkyCam-based localization for improved global positioning	Test SkyCam-based localization by checking rover's ability to self-localize accurately with / without external infrastructure	M.F.3
11/12	PR11	• Full system integration • Quality assurance testing	Check all subsystems and units are functioning correctly	M.F.2 M.F.3 M.F.4 M.F.5 M.F.6 M.F.7 M.F.8 M.F.9
11/17 11/24	PR12 (FVD and FVD Encore)	• Final system demonstration involving autonomous grading of multiple craters	Demonstrate full autonomous operation by detecting, avoiding ungradable craters, and grading multiple suitable craters according to mission specs	M.F.1 M.P.1 M.F.2 M.P.2 M.F.3 M.P.3 M.F.4 M.P.4 M.F.5 M.P.5 M.F.6 M.P.6 M.F.7 M.F.8 M.F.9

Fall Validation Demonstration

Test Location
Planetary Robotics Lab Moon Yard
Sequence of Events
Prior Setup: 1. Prepare the Moon Yard with several craters and dunes in a circular path. 2. Scan the Moon Yard with a FARO Scanner to obtain a global map for navigation. 3. Attach and connect all the components and subsystems of the rover. 4. Place the rover in the Moon Yard and calibrate its localization using a star-sun tracker, visual odometry, and/or total station. **During Demonstration:** 5. Switch the rover to autonomous mode and use goal poses with offsets to plan the path. 6. Observe the rover autonomously grade craters and level dunes in a circular path. 7. After each dozed crater, use the ZED camera to validate whether the dozing satisfies the performance requirements. 8. If anything unexpected occurs press the emergency stop button.
Quantitative 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°

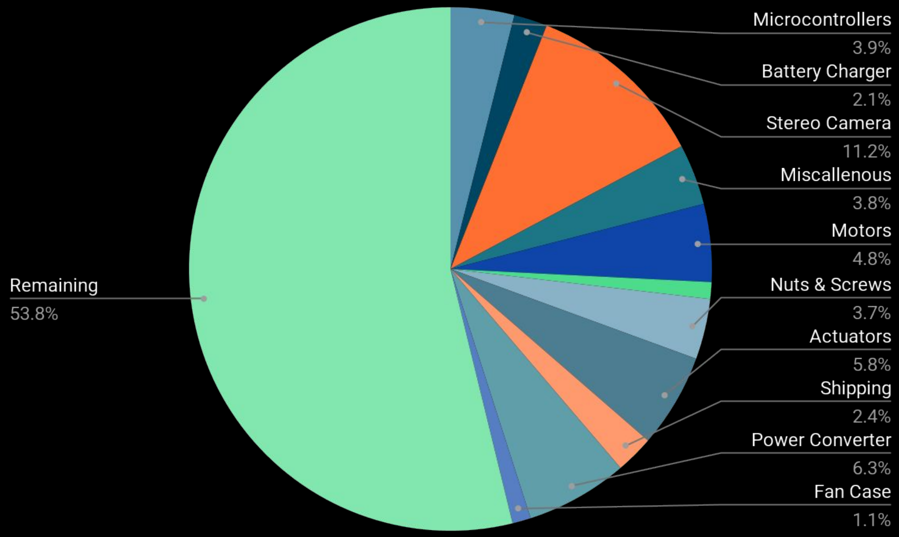
Follow a circular path



Groom several craters in a circular path

Budget

Major Items	Units	Total Price
ZED 2i Stereo Camera	1	$562.00
DC/DC Power Converter	1	$315.51
Linear Actuators	3	$290.00
Planetary Gear Motors	4	$239.96

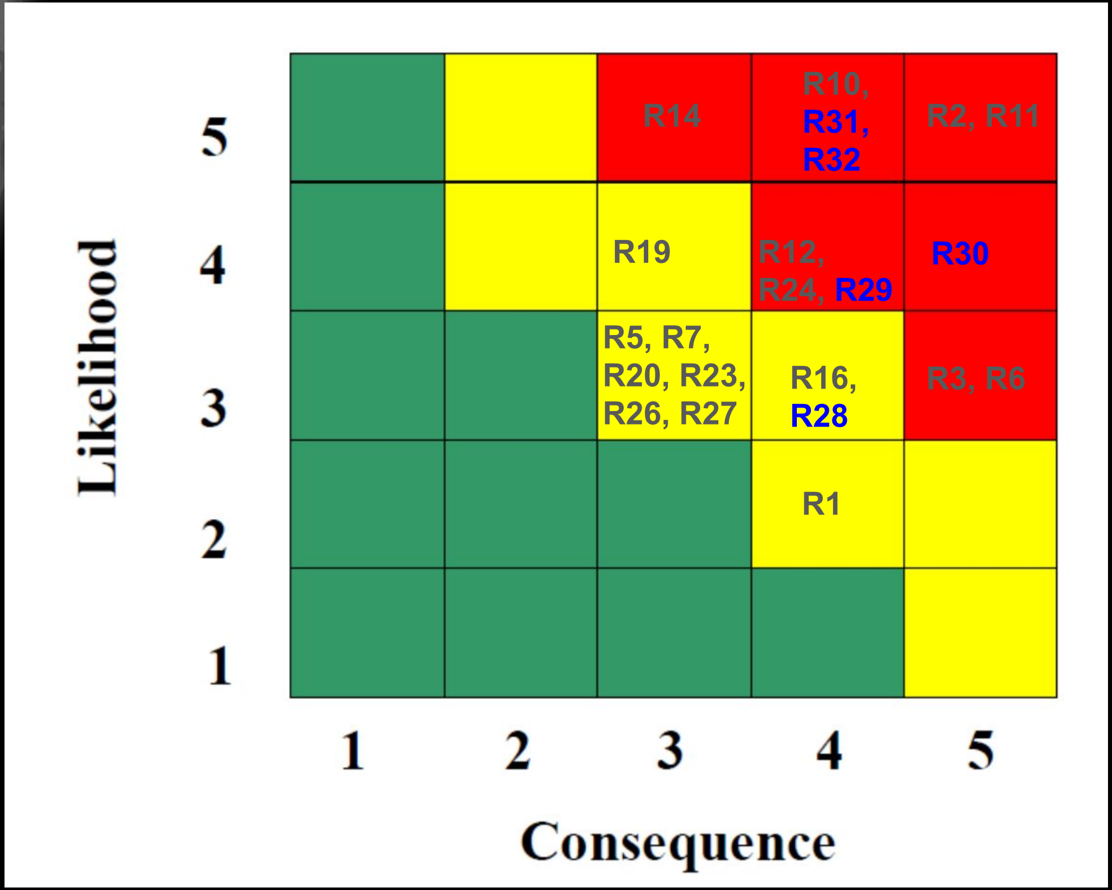


MRSD Budget	MRSD Budget Spent ($)	MRSD Budget Spent (%)	Total Budget Spent*	Remaining Budget Balance
$5,000	$2,309.07	46.2%	$5,379.07	**$2690.93**

* Includes items inherited from Crater Grader and Supervisor

Risk Management (Updated)

Risk Summary



Risk Management (Updated)

Reduced Risk Summary

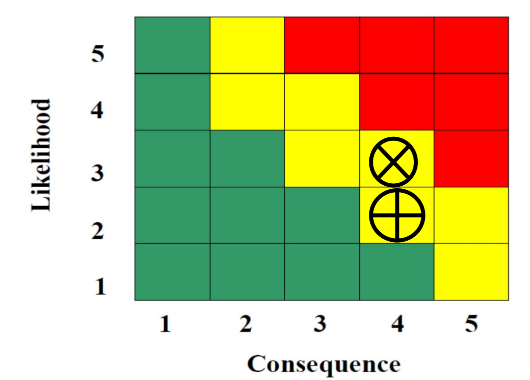
Likelihood					
5					
4					
3			R14	R10, R31	R2, R30
2		R5, R12, R19, R23, R27, R29, R32	R26	R24, R28	R3, R6, R11
1		R7	R20	R1, R16	
	1	2	3	4	5
			Consequence		

Top Risks

Risk ID	Risk Title	Risk Owner	Risk Type:	Technical, Logistics
R28	Electrical Hardware Finalization	Ankit		

Description	Date Added
E-box Design dependence on to-be manufactured PDB.	2/14/2025
	Date Updated
	4/06/2025

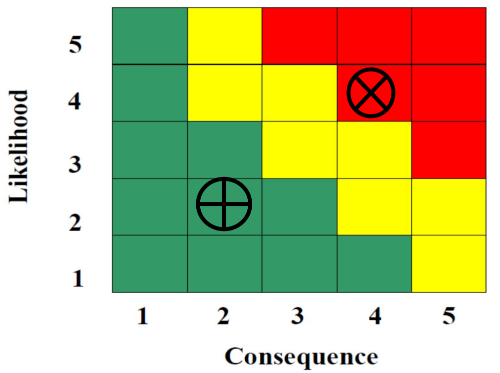
Consequence
Not meeting the hardware deadline



Action/Milestone	Success Criteria	Date Planned	Date Implemented
Use previous knowledge and account for a placeholder in the design.	Successfully design and manufacture E-box compatible with the new PCB using placeholder PCB design	02/14/2025	04/06/2025
Order PCB and components (and spares) outside of MRSD schedule	Successfully order and assemble the PCB	03/26/2025	04/04/2025

Top Risks

Risk ID	Risk Title	Risk Owner	Risk Type:	Logistics
R29	Access to FRC Workshop	Deepam		
Description		**Date Added**		
Without access, no hardware fabrication/repairs can be carried out in the absence of Tim		2/7/2025		
		Date Updated		
		2/7/2025		
Consequence				
Not meeting the hardware deadline				



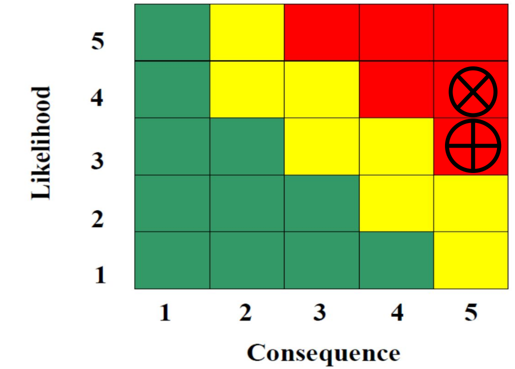
Action/Milestone	Success Criteria	Date Planned	Date Implemented
Try other fab-labs on campus.	Successfully access other fab-labs and manufacture components	2/9/2025	4/4/2025
Request Tim, John or Red for getting temporary access, if not permanent	Successfully get temporary/permanent access to FRC Workshop	2/12/2025	

Top Risks

Risk ID	Risk Title	Risk Owner	Risk Type:	Logistics
R30	No spares available	Team		

Description	Date Added
Discontinued model, spare parts unavailable	3/4/2025
	Date Updated
	4/10/2025

Consequence
The whole project falling through, or redo almost all subsystems on a different rover.



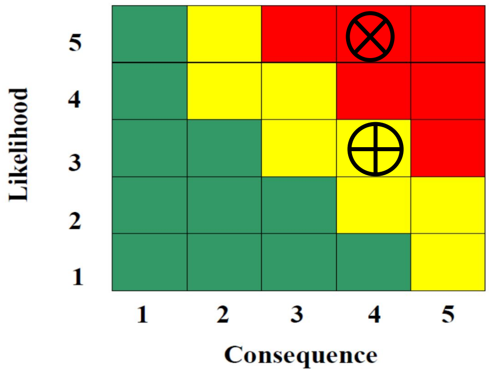
Action/Milestone	Success Criteria	Date Planned	Date Implemented
Check out eBay and other similar platforms for spares	Successfully find exact spares on these platforms	3/6/2025	
Check out and stock similar parts if not same	Successfully find and stock similar parts	3/6/2025	
Find a twin rover that was used by a previous team on campus	Successfully find the twin rover and scavenge parts	3/6/2025	3/7/2025
Maintain all parts, especially mechanical parts	Successfully avoid future breakdowns and part failures	3/7/2025	4/10/2025

Top Risks

Risk ID	Risk Title	Risk Owner	Risk Type:	Technical
R31	Localization frame shift after total station battery swap	Bhaswanth		

Description	Date Added
Battery replacement in the total station causes small frame offsets, leading to localization inaccuracies.	3/4/2025
	Date Updated
	4/10/2025

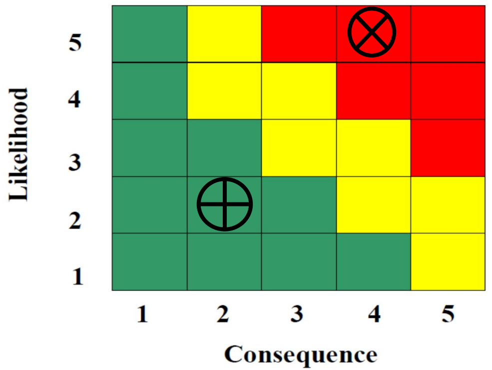
Consequence
Leads to poor navigation performance and risk of missing the crater during grading operations.



Action/Milestone	Success Criteria	Date Planned	Date Implemented
Implement resection method using three known prism locations instead of orientate-to-line	Successfully fix the frame consistently after battery swaps	4/26/2025	
Explore and test alternative localization methods (using SkyCam)	Successfully maintain localization accuracy	4/26/2025	

Top Risks

Risk ID	Risk Title	Risk Owner	Risk Type:	Technical
R32	Arduino requires reset before operation	Bhaswanth		



Description	Date Added
Arduino needs to be manually reset each time before starting autonomy or switching between autonomy and teleoperation modes.	3/4/2025
	Date Updated
	4/10/2025

Consequence
Slows down setup time and impacts operational readiness, delaying mission start and mode transitions.

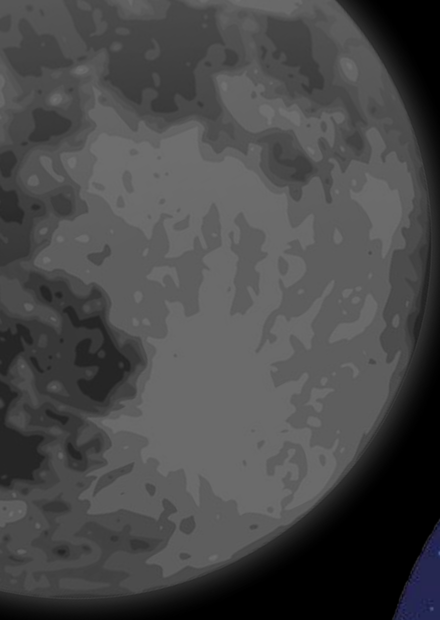
Action/Milestone	Success Criteria	Date Planned	Date Implemented
Check USB port permissions and drivers issues on Jetson	Successfully establish consistent serial connection without reset	4/26/2025	
Verify that Arduino is connected via USB 3.0 instead of USB 2.0 port	Ensure stable high-speed communication	4/26/2025	
Check for ROS node frequency mismatches causing packet loss to Arduino	Match ROS publish/subscribe rates	4/26/2025	

Lessons Learned

- Check for common issues online while choosing hardware (Jetson and Zed issue)
- Schedule based on resource availability such as lab access and lead times
- Plan for Progress Review goals at the beginning of the semester
- Have a proper plan for demo split between SVD and SVD Encore
- Do not choose a project where you have to build both software and hardware from scratch :)

Fall Activities

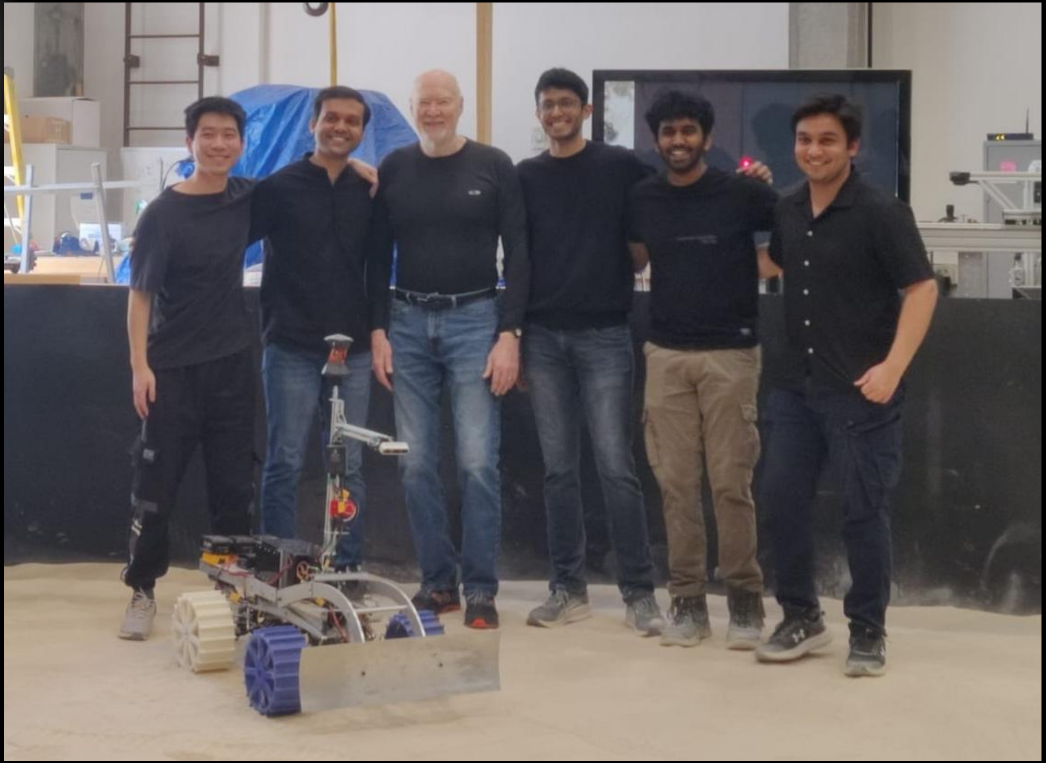
- Integrate and test continuously
- Improve tool actuator
- Wheel torque feedback
- Tune overall software stack
- Solution to compute problem (new Jetson/code optimization)
- New localization method - SkyCam
- Planning for grooming multiple craters



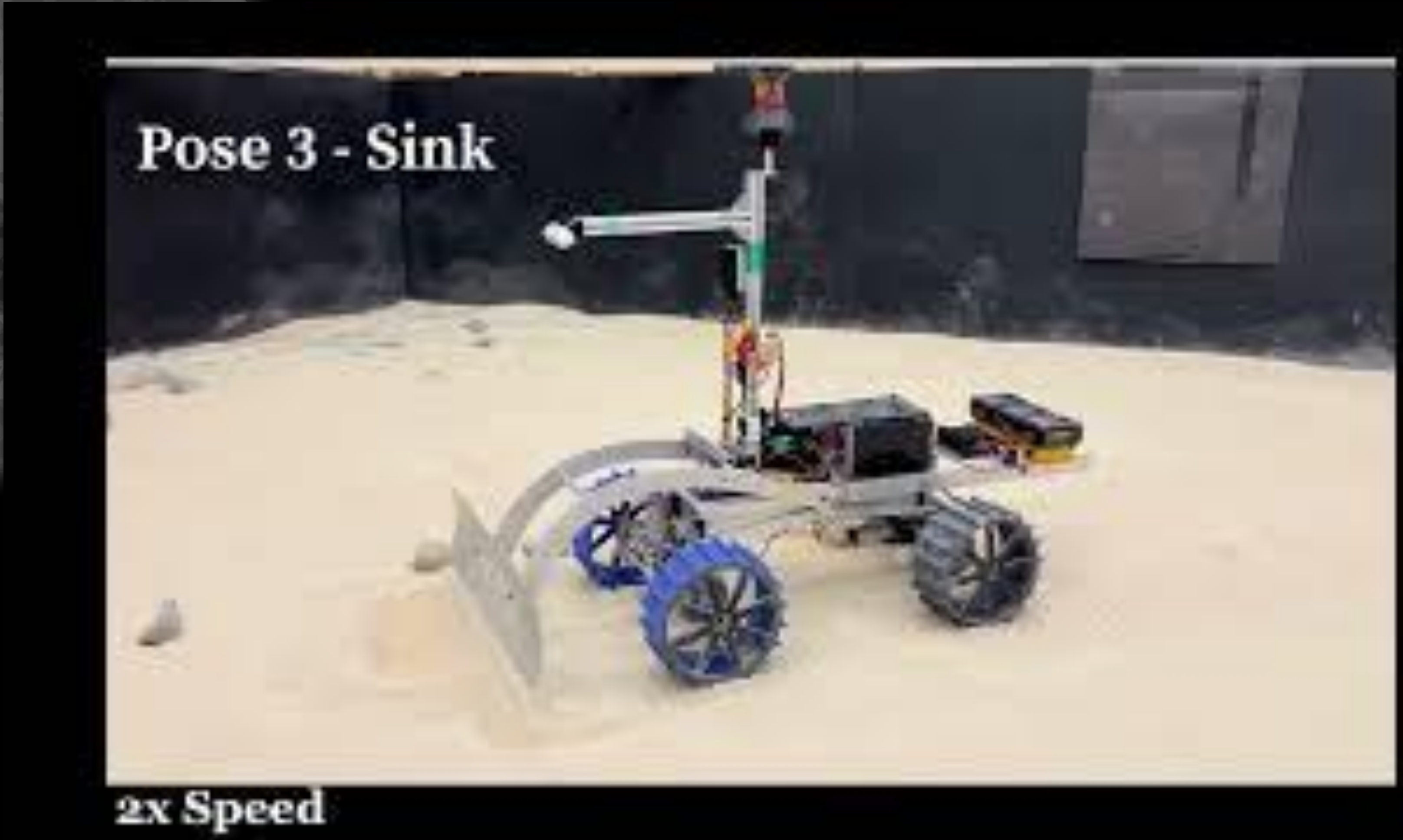
Colonize the Moon!
- *Team Lunar ROADSTER*

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

Thank You!



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


Pose 3 - Sink
2x Speed

Appendices

A.1. Derivation for M.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 M.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 M.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

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)

<table>
<tr><th>Risk ID</th><th>Risk Title</th><th>Risk Owner</th><th>Type</th><th>Description</th><th>Consequence</th><th>Risk Reduction Plan</th></tr>
<tr><td rowspan="2">R24</td><td rowspan="2">Sensor data is too noisy to fulfill performance requirements</td><td rowspan="2">William</td><td rowspan="2">Technical</td><td rowspan="2">Performance requirements are tough and ambitious, sensor noise may prevent us from achieving it</td><td rowspan="2">Failure to demonstrate performance requirements may cause us to lose marks in the demonstrations</td><td>Relax the performance requirements enough to ensure that they are achievable</td></tr>
<tr><td>Ensure enough testing time to tune parameters</td></tr>
<tr><td rowspan="2">R26</td><td rowspan="2">Off-the-shelf wheels don't interface with the rover</td><td rowspan="2">Ankit</td><td rowspan="2">Technical</td><td rowspan="2">No off-the-shelf wheels fit the rover, We'll have to redesign wheel hubs and mountings as per the new wheels.</td><td rowspan="2">Continue with sub-optimal wheels that the rover currently has, thus, not meeting one of the non-functional requirements</td><td>Shift requirements to FVD</td></tr>
<tr><td>Good enough market research to see find the best fit, with least amount of changes</td></tr>
</table>

Risk Management (Extra)

R27	TX2 Integration	William	Technical	Unable to login to TX2 and interface with a LAN network for transmitting data over WiFi ro Jetson	Delay in finalizing localization stack	Set up a new TX2 (Re-flash the TX2). Reach out to previous teams to understand their methodology and retrieve credentials
R28	Electrical hardware finalization	Ankit	Technical	E-box Design dependence on to-be manufactured PDB.	Not meeting the hardware deadline	Use previous knowledge and account for a placeholder in the design
R29	Access to FRC Workshop	Deepam	Logistics	Without access, no hardware fabrication/repairs can be carried out in the absence of Tim	Not meeting the hardware deadline	Try other fab-labs on campus. Request Tim, John or Red for getting temporary access, if not permanent
R30	No spares available	Team	Logistics	Discontinued model, spare parts unavailable	The whole project falling through, or redo almost all subsystems on a different rover.	Check out eBay and other similar platforms for spares Check out and stock similar parts if not same Find a twin rover that was used by a previous team on campus Maintain all parts, especially mechanical parts