



Lunar ROADSTER

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



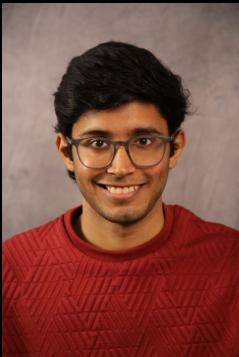
“Starting with a foothold on the Moon, we pave the way to the cosmos”



The Team



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Simson D'Souza

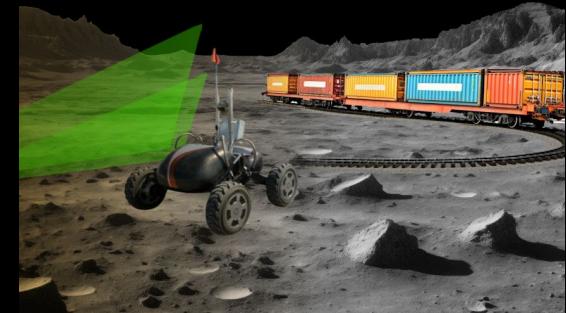
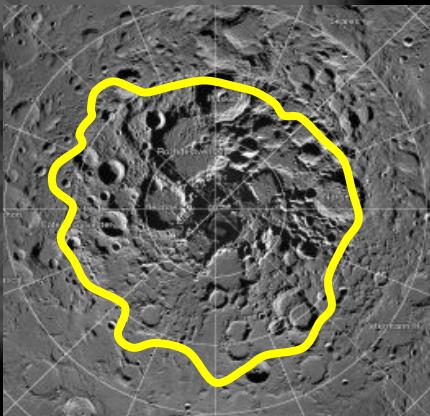


Boxiang (William) Fu



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**



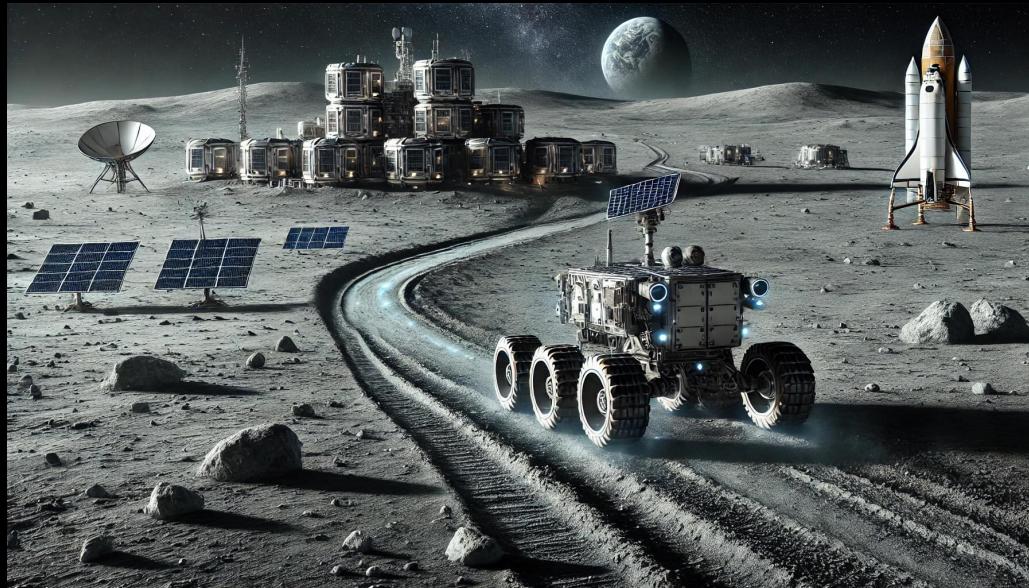
The Project: Lunar ROADSTER

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

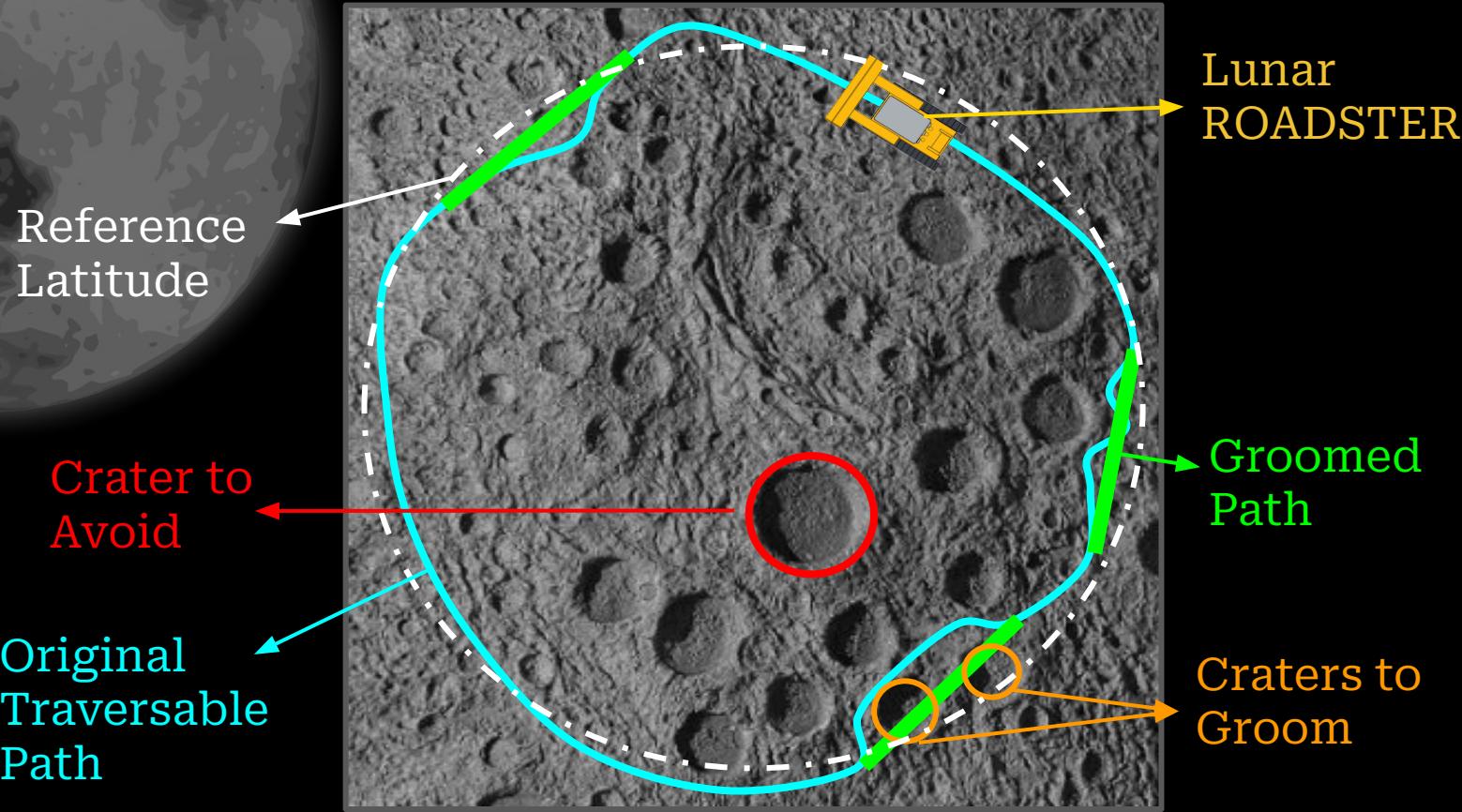
By **grooming trail paths**, rovers with less traversing capabilities will be able to travel at higher speeds and higher power efficiencies.

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

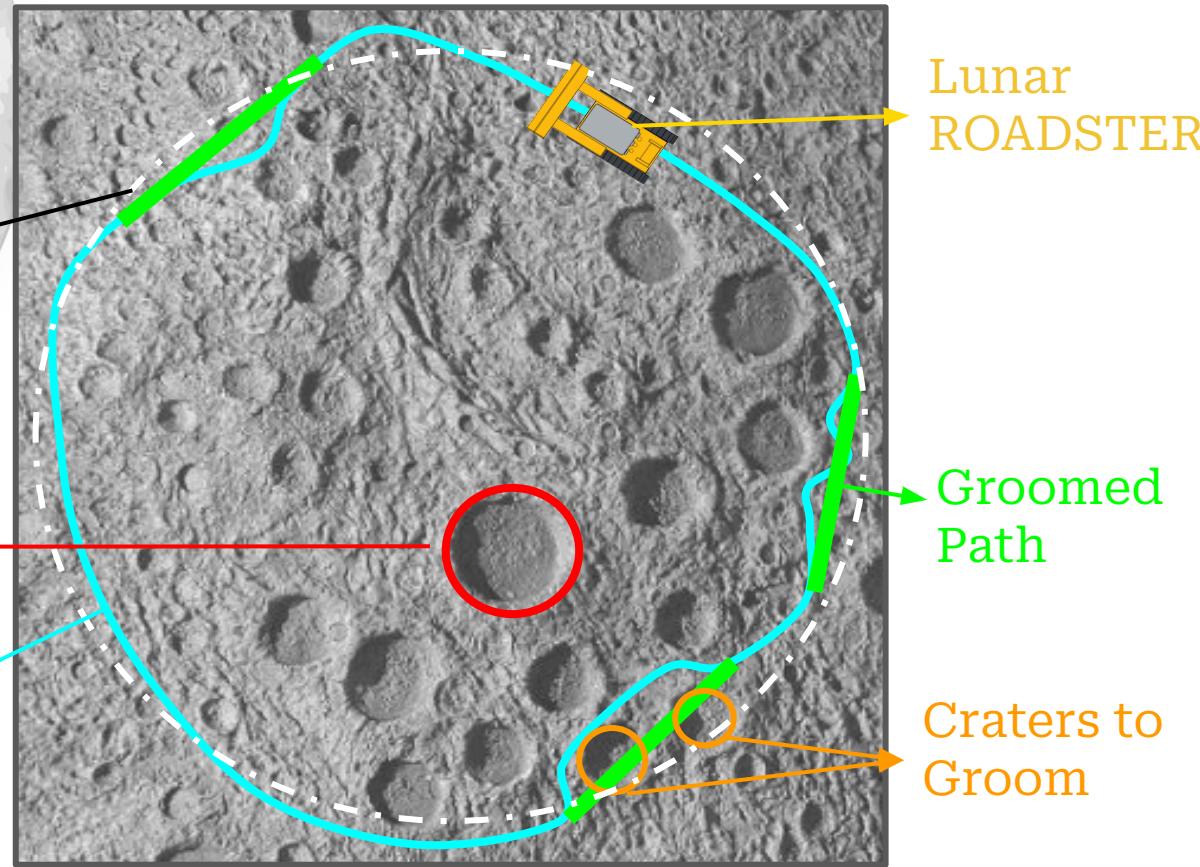
The groomed trails will become the **backbone for colonization** of the Moon by enabling transportation, logistics and enterprise development.



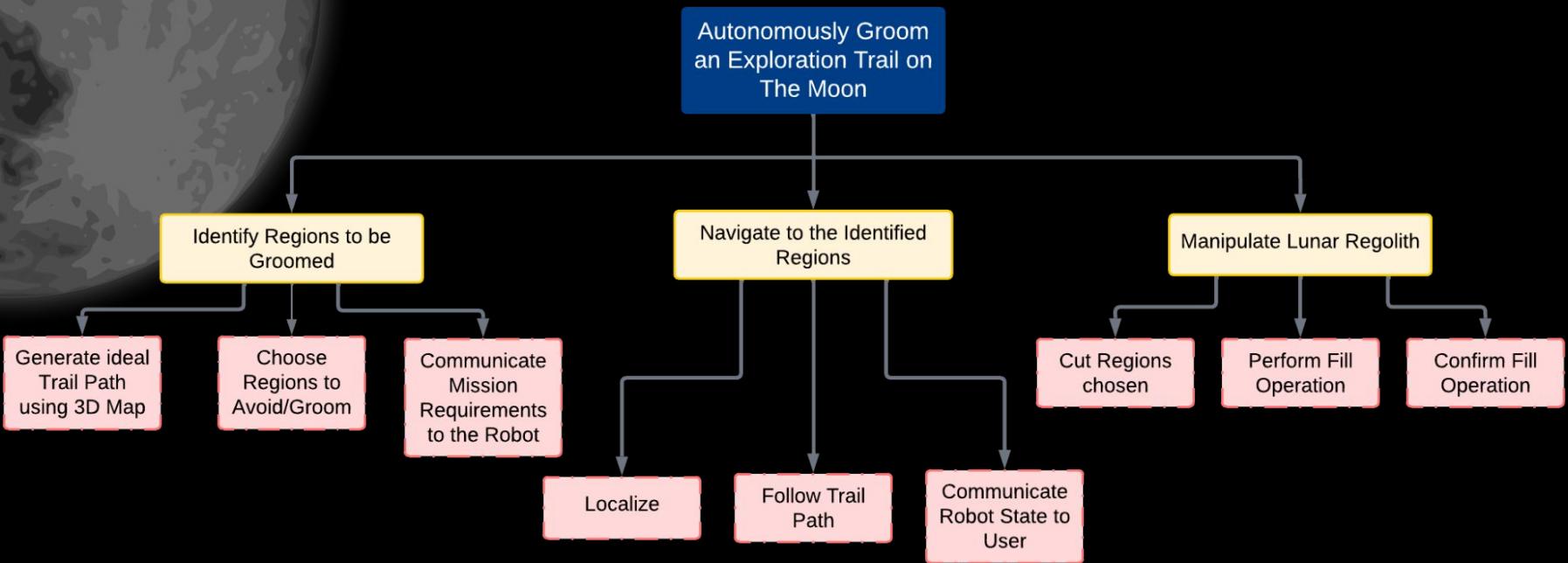
Use Case: Circular Path Grooming



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)

Modified

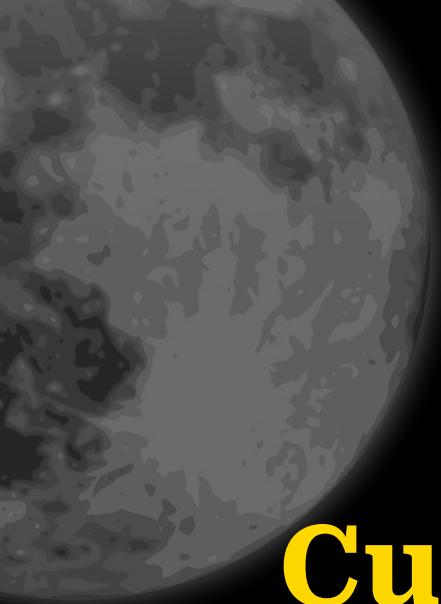
Sr. No.	Parameter	Description
M.N.1	Weight	The rover must weigh under 50kg
M.N.2	Cost	The cost for the project must be under \$5000
M.N.3	Computing Capacity	The onboard computer should be able to run all required tasks
M.N.4	Size/Form Factor	The rover should measure less than 1m in all dimensions

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) Modified

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°



Current System Status

Subsystem Completion Status

Subsystem	Completion %	Future Work
Sensors	100%	None
Computations	60%	
1. Jetson and Docker	100%	None
2. Localization Stack	85%	Tune and improve Skycam based localization
3. Navigation Stack	60%	Test and tune navigation stack (global + local)
4. Perception Stack	60%	Fine tune, integrate with planning and navigation
5. Validation Stack	100%	None
6. Planning Stack	40%	Obtain Robot poses
7. Behavior Executive Node	40%	Integrate all computation units into FSM
External Infrastructure	100%	None
Mechanical	100%	
1. Dozer Assembly	100%	None
2. Wheel Assembly	100%	None
Actuation	100%	None
Electrical Power	100%	None

Description: Sensors Subsystem



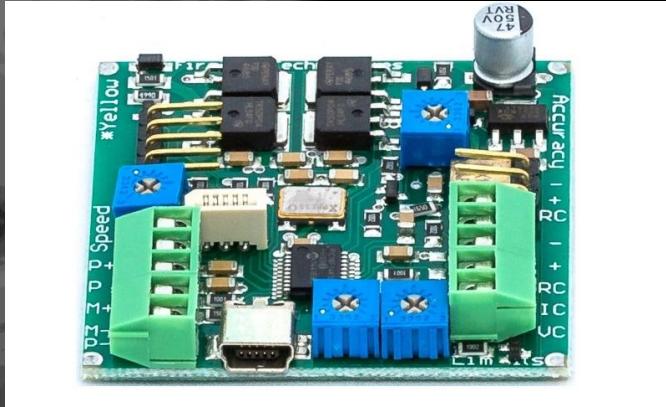
Description: All sensors used on the rover for computations.

Requirements:

- Wheel Encoders (x4)
- Mast Depth Camera (ZED 2i) - **New!**
- 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



```
williamfbx@williamfbx-ubuntu: ~/Lunar-ROADSTER/lr_ws
williamfbx@williamfbx-ubuntu:~/Lunar-ROADSTER/lr_ws$ ros2 topic list
/parameter_events
/rosout
/vectornav/gnss
/vectornav/imu
/vectornav/imu_uncompensated
/vectornav/magnetic
/vectornav/pose
/vectornav/pressure
/vectornav/raw/attitude
/vectornav/raw/common
/vectornav/raw/gps
/vectornav/raw/gps2
/vectornav/raw/imu
/vectornav/raw/ins
/vectornav/raw/time
/vectornav/temperature
/vectornav/time_gps
/vectornav/time_pps
/vectornav/time_startup
/vectornav/time_syncin
/vectornav/velocity_aiding
/vectornav/velocity_body
williamfbx@williamfbx-ubuntu:~/Lunar-ROADSTER/lr_ws$
```

Implementation:

- IMU implemented using VectorNav ROS package
- Wheel Encoder parsed using micro-ROS
- Purchased actuator has a feedback potentiometer
- Obtained point cloud feed using ZED 2i wrappers

Challenges:

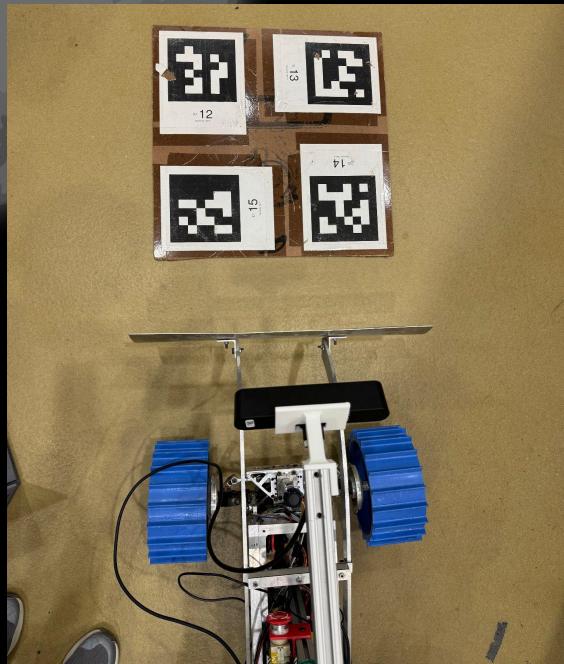
- CUDA compatibility issues with ZED SDK on Jetson Xavier – tackled by upgrading to Orin
- IMU issues – tackled by purchasing new IMU

Status:

100% Complete

IMU, wheel encoder, and linear actuator finalized.
Upgraded RealSense to ZED 2i during summer.

Evaluation: Sensors Subsystem



Modelling:

- New 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 ZED 2i is much denser than Realsense

Testing:

- Fall T09: CPU/GPU Usage of Autonomous Stack is Below Orin Compute Limits
- Fall T10: Maintenance, Reliability and Quality Assurance Test

Description: Computations Subsystem Jetson and Docker



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

Requirements:

- NVIDIA Jetson Orin – **New!**
- 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

A screenshot of a terminal window titled "Tilix: root@ubuntu:~/Lunar_ROADSTER/lr_ws". The terminal shows the command "lunarroadster@ubuntu:~\$ docker start -i lunar_roadster_dev_orin" being run. The output of the command shows several square brackets indicating the status of the Docker container. The bottom of the terminal shows the path "/Lunar_ROADSTER/lr_ws" and the user "root@ubuntu".

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
- Tmux used for master launcher

Challenges:

- Setup of a VNC server for remote GUI access

Status: 100% Complete
Integrated ZED SDK drivers

Evaluation: Computations Subsystem Jetson and Docker Unit

Lunar-ROADSTER / lr_ws / docker / lrdev_jetson_zed.dockerfile ▾

LunarROADSTER updated dockerfiles

Code Blame Executable File · 251 lines (208 loc) · 9.85 KB

```
1  # ----- ZED Camera SDK -----
2  FROM deepamaria/zed_ros2_sdk:36.4.0
3
4  # ----- ROS 2 Humble image -----
5  # FROM dustynv/ros:humble-desktop-l4t-r36.2.0
6
7  # Set environment variables
8  ENV DEBIAN_FRONTEND=noninteractive \
9    ROS_DISTRO=humble \
10   WORKSPACE=/root/Lunar_ROADSTER/lr_ws
11
12 # ----- NVIDIA Libraries Configuration -----
13 # Ensure NVIDIA drivers and CUDA libraries are accessible inside the container
14 ENV NVIDIA_VISIBLE_DEVICES=all
15 ENV NVIDIA_DRIVER_CAPABILITIES=all
16 ENV LD_LIBRARY_PATH=/usr/local/cuda/lib64:/usr/lib/aarch64-linux-gnu:/usr/lib/aarch64-linux-gnu/tegra:$LD_LIBRARY_PATH
17
18
19 COPY ./ $WORKSPACE
20
21 # ----- Base environment configuration -----
22 # Setup shell
23 COPY docker/.p10k.zsh /root/.p10k.zsh
24 ENV TERM=xterm-256color
25 RUN apt-get update && apt-get install -y zsh bash wget \
26   && PATH="$PATH:/usr/bin/zsh" \
27   # Install Oh-My-Zsh with default theme
28   && sh -c "$(wget -O https://github.com/deluan/zsh-in-docker/releases/download/v1.1.3/zsh-in-docker.sh)" \
29   # Zsh Autocomplete
30   && git clone https://github.com/zsh-users/zsh-autosuggestions ${ZSH_CUSTOM:-~/root/.oh-my-zsh/custom}/plugins/zsh-autosuggestions \
31   && echo "ZSH_AUTOSUGGEST_HIGHLIGHT_STYLE='fg=#777777'" >> ~/.zshrc \
32   # Initialize custom zsh theme
33   && echo "[[ ! -f ~/p10k.zsh ]] || source ~/p10k.zsh >> ~/.zshrc \
34   # Source ROS
35   && echo '# ROS' >> /root/.zshrc \
36   && echo '# ROS' >> /root/.bashrc \
37   && echo 'source /opt/ros/$ROS_DISTRO/setup.zsh' >> /root/.zshrc \
```

Modelling:

- Created custom Dockerfile built on ZED SDK image that installs all required system packages

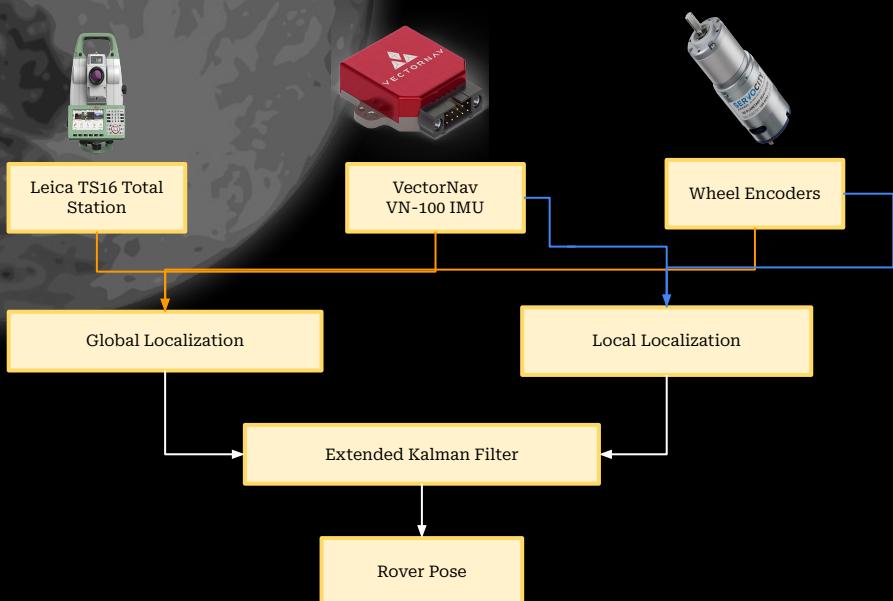
Analysis:

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

Testing:

- Fall T01: Rerun Spring Validation Demonstration
- Fall T09: CPU/GPU Usage of Autonomous Stack is Below Orin Compute Limits

Description: Computations Subsystem Total Station Localization



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

Total Station Localization



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
- Fixed frame shifts issue caused by total station battery replacement by using resection method (uses 3 total station prisms instead of 2)

Challenges:

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

Status: 100% Complete

Evaluation: Computations Subsystem

Total Station Localization

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

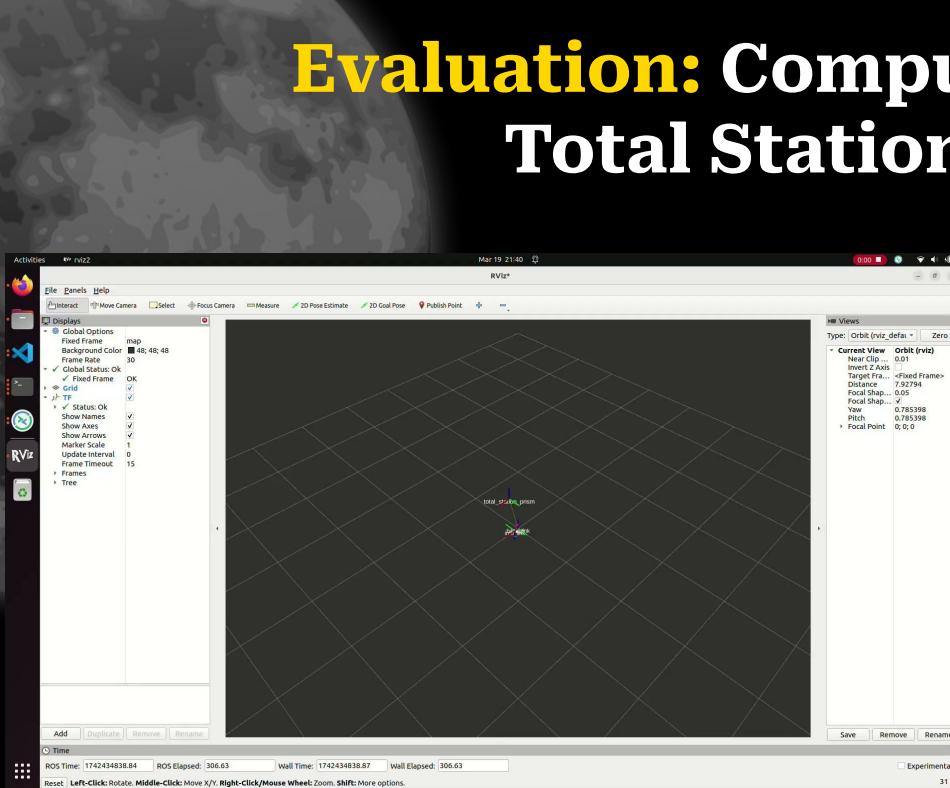
Analysis:

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

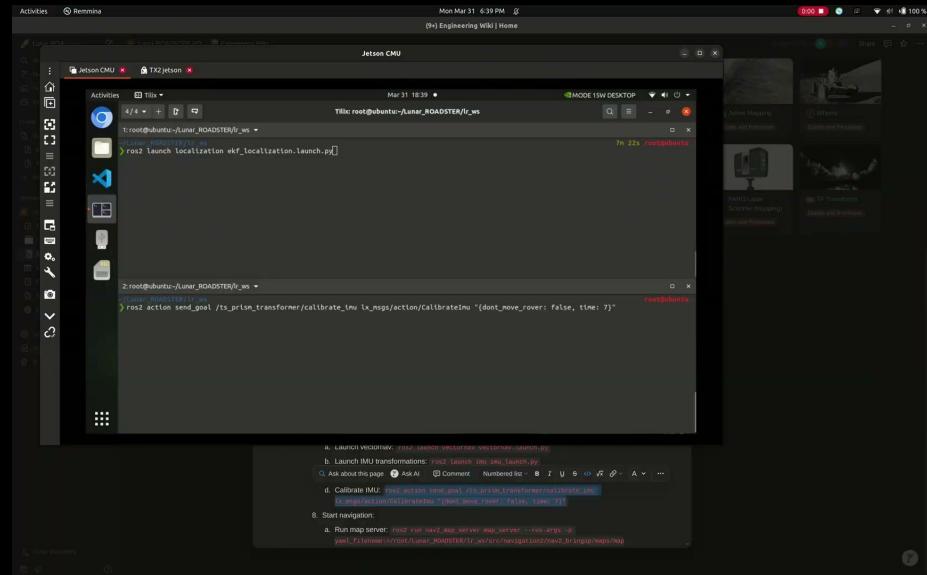
Testing:

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

Evaluation: Computations Subsystem Total Station Localization



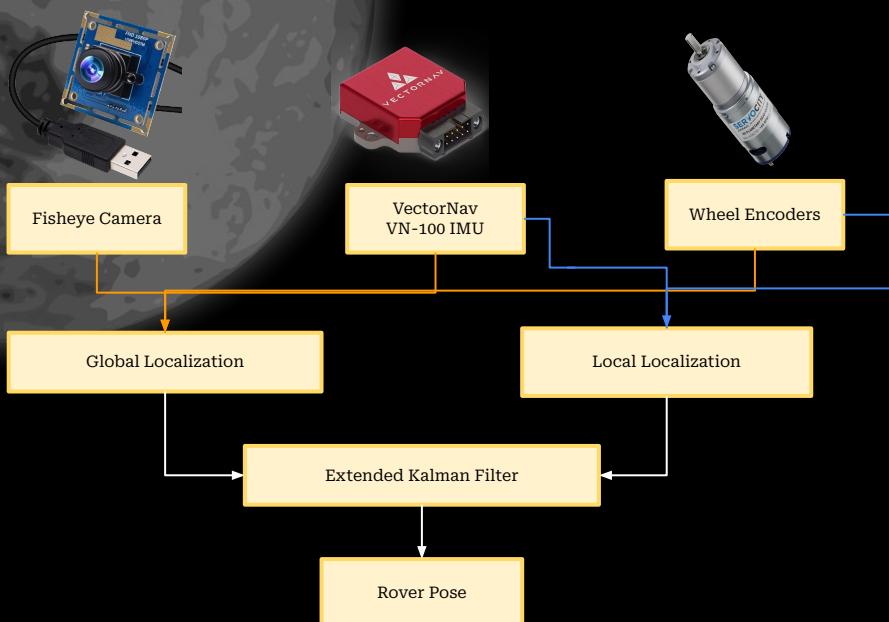
Localization drift issue



Drift corrected + Yaw calibrated

Description: Computations Subsystem

Skycam Localization



Description: Localize the rover in the Moon Yard using rover mounted Skycam – New!

Requirements:

- Fisheye camera (Skycam)
- VectorNav IMU
- Wheel Encoders

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

Status: Computations Subsystem

Skycam Localization



Implementation:

- **Data Collection Pipeline:** Saves and indexes raw Skycam camera images along with ground truth localization provided by total station
- **Training Pipeline:** Train a neural network using PyTorch by regressing camera image against position
- **Deployment Pipeline:** Deploys network to a ROS node at runtime

Challenges:

- Trained model is inaccurate (MSE localization error is ~1 meter)
- Corners of Moon Yard is recently covered, need to retake training data to account for this

Status:

85% Complete

- Tune MSE localization error to be below 10cm

Evaluation: Computations Subsystem

Skycam Localization

Modelling:

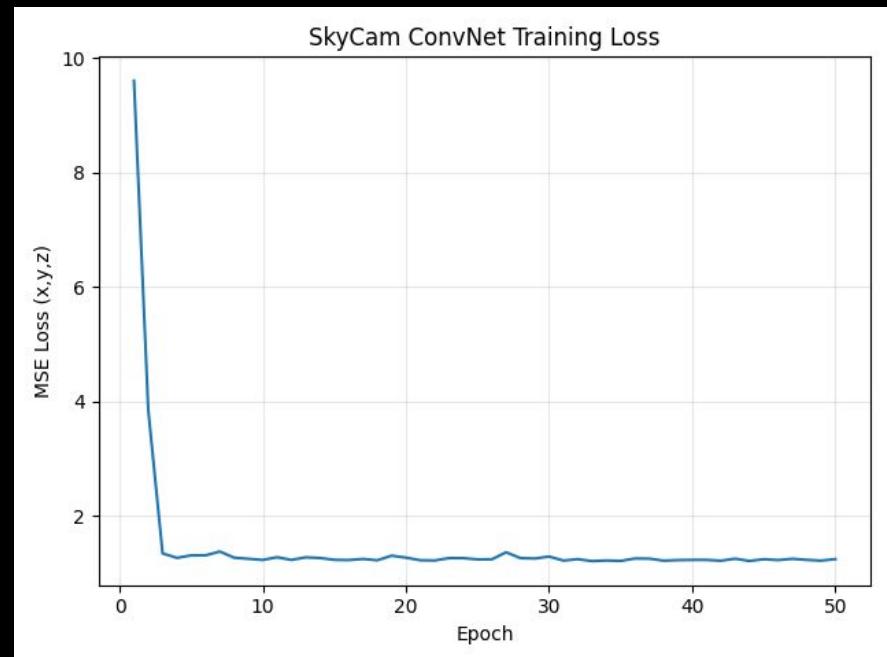
- Tried different neural network architectures (vanilla, ConvNet, etc)

Analysis:

- Split the training data into training and validation datasets
- Analyzed the localization MSE loss on validation dataset
- Compared localization error against total station method

Testing:

- Fall T08: SkyCam Localization Validation



Description: Computations Subsystem Navigation Stack



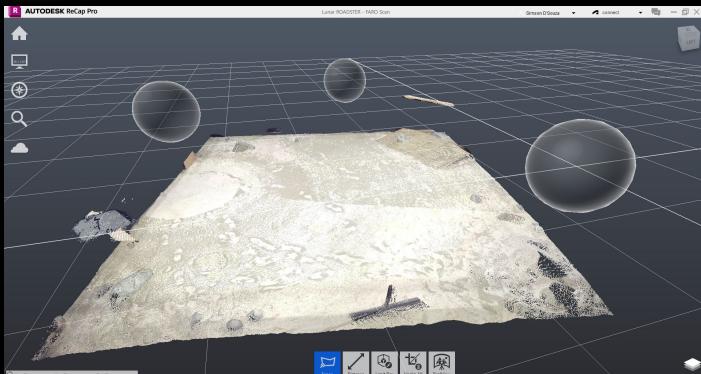
Description: Obtain a global plan between craters based on target poses and navigate the rover to their locations

Requirements:

- FARO Laser Scanner
- NVIDIA Jetson Orin
- ZED 2i Depth Camera
- Rover
- Team laptop (operations terminal)

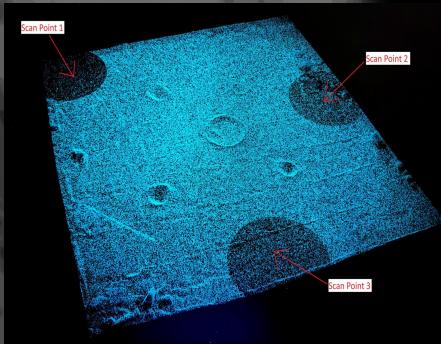
Expected Functionality:

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

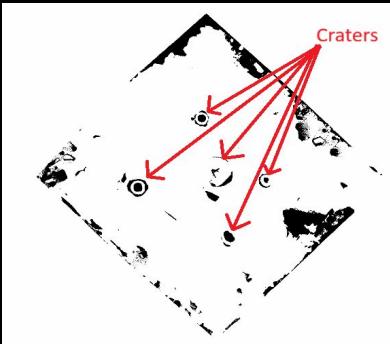


Status: Computations Subsystem

Navigation Stack



Moon Yard Scan
Visualization



Global Costmap

Implementation:

- FARO Laser Scanner used to map the Moon Yard and obtain a high density point cloud
- The point cloud is converted into an occupancy grid using RANSAC and thresholding – contains craters centroid and diameter information
- Global Path Planner uses the occupancy grid map to compute a smooth trajectory between craters, taking into account Ackermann primitives and ring bias
- Pure Pursuit Global Controller executes the planned path and reaches the desired goal (close to the crater)
- MPC Local Controller uses information from perception and planning stacks to reach desired target poses
- Navigation stack is integrated with tool planner to perform transport assignments

Challenges:

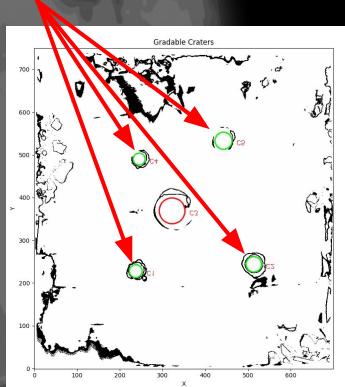
- FARO output file (.fls) was incompatible with the PCL library and ROS.
- Fine-tune global planner and global/local controller parameters for optimal performance on our robot

Status: 60% Complete (Tune Navigation Stack)

Evaluation: Computations Subsystem

Navigation Stack

Gradable Craters



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
- Custom Global Path Planner that takes into account various costs and heuristics for optimal planning
- Custom Global and Local Controllers to allow more control over robot movement
- Used RViz extensively to visualize and debug transformations and paths

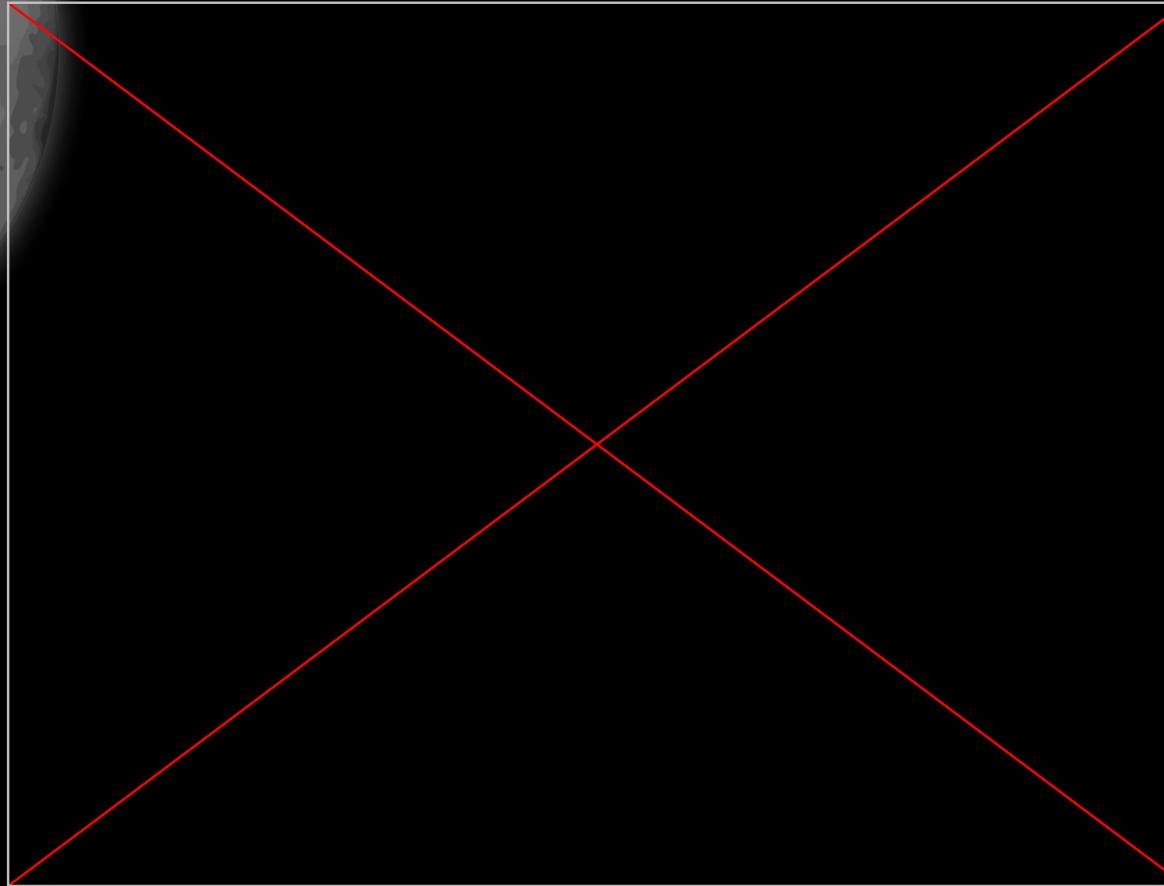
Analysis:

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

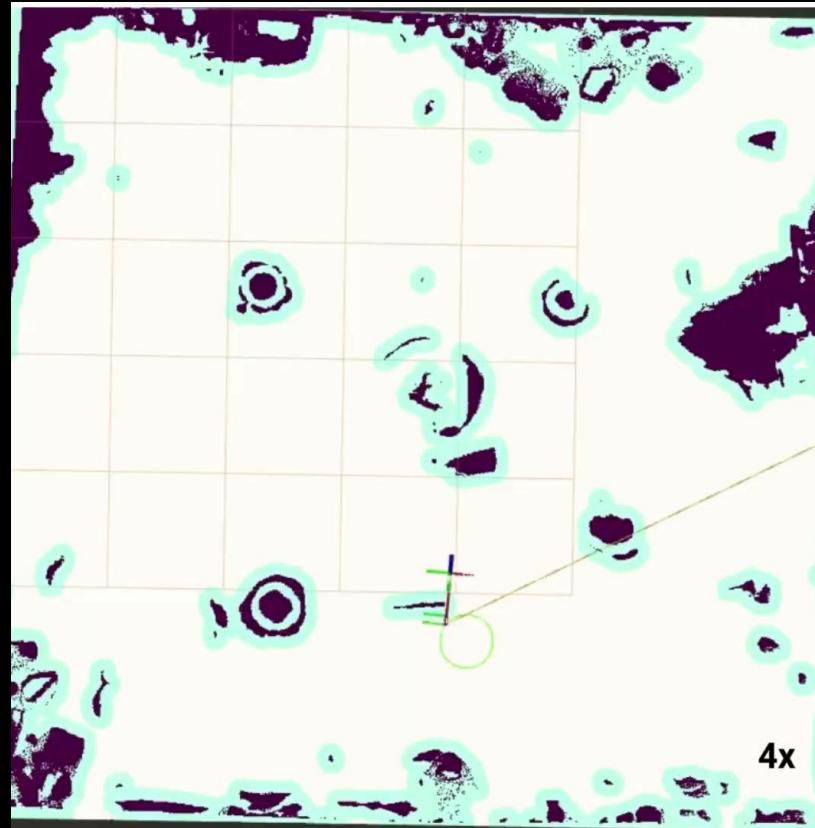
Testing:

- Fall T02: Global Path Planner Accuracy Test
- Fall T03: Filtering and Selection of Gradable Craters
- Fall T04: Navigation planner maximum deviation test
- Fall T06: Repeatability Test of Local Navigation Controller
- Fall T11: Fall Validation Demo Preparation Test

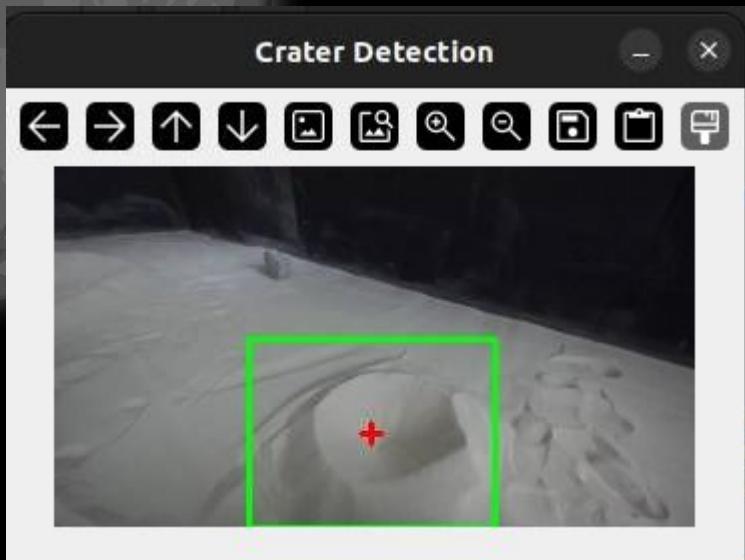
Evaluation: Computations Subsystem Navigation Stack



Evaluation: Computations Subsystem Navigation Stack



Description: Computations Subsystem Perception Stack



Description: Uses RGB-D sensor to detect craters and extract coordinates for planning and navigation subsystems.

Requirements:

- ZED 2i stereo camera
- Camera driver packages/ROS2 Wrappers
- Jetson Orin

Expected Functionality:

- Output coordinates of the detected crater(s) in the world frame.

Status: Computations Subsystem

Perception Stack

Implementation:

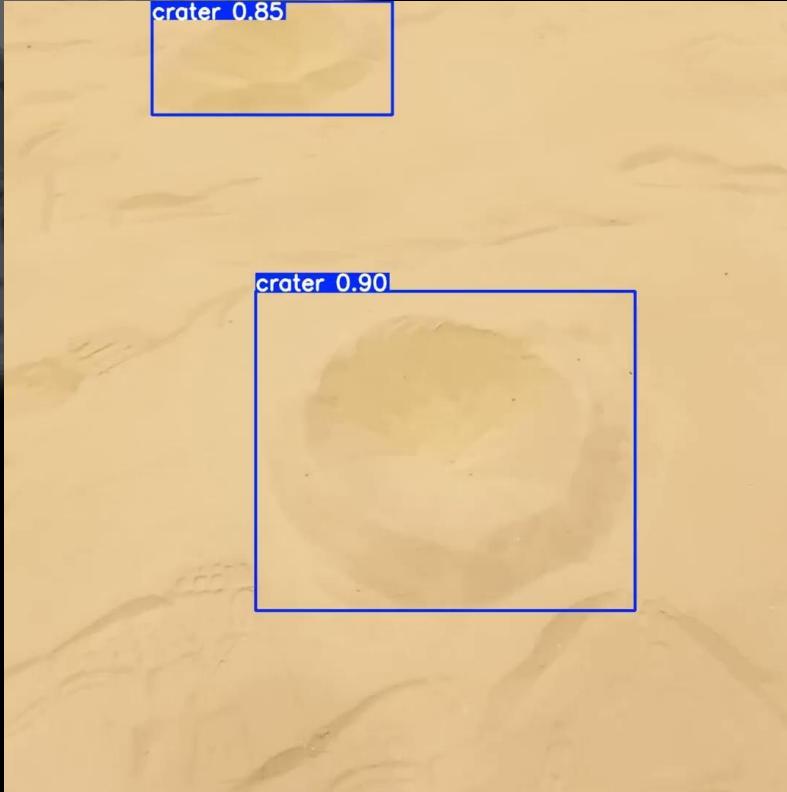
- Collect data for training and validating a CNN Object Detection Model
- Load the trained model on edge compute
- Obtain RGB raw images from ZED Camera over ROS topics
- Detect craters in real-time
- Obtain centroid of crater and publish on ROS topic for planning and navigation stacks

Challenges:

- Rover mast moves due to rover suspension. May cause jitter in coordinates.
- Compute or inference is not optimized for real-time detection

Status: 60% Complete

Evaluation: Computations Subsystem Perception Stack



Modelling:

- Collected dataset and annotated using Roboflow Annotation Tool
- Trained YOLO v8 and validated on test videos
- Transferred to Orin for online real-time perception and inference
- Used bounding box analysis to determine crater centre coordinates

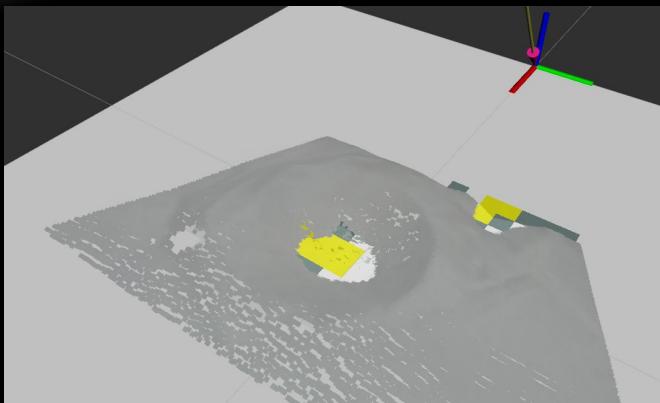
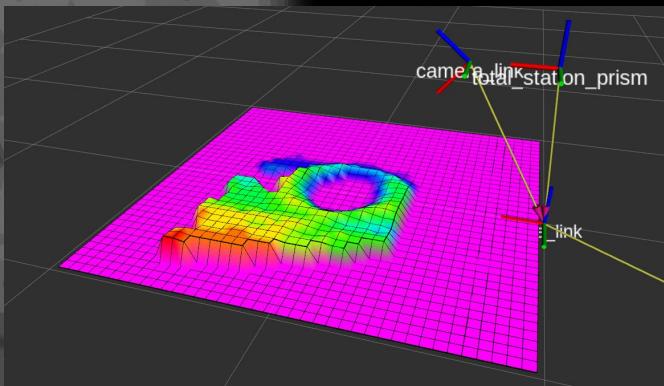
Analysis:

- Inference is laggy and requires optimization and smoothening for persistent detection

Testing:

- Fall T05: Perception Stack Crater Geometry Extraction Test

Description: Computations Subsystem Validation Stack



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

Requirements:

- ZED 2i stereo camera
- Camera driver packages
- Jetson Orin

Expected Functionality:

- Outputs boolean of grading success or failure plus additional gradient information in FOV region

Status: Computations Subsystem Validation Stack

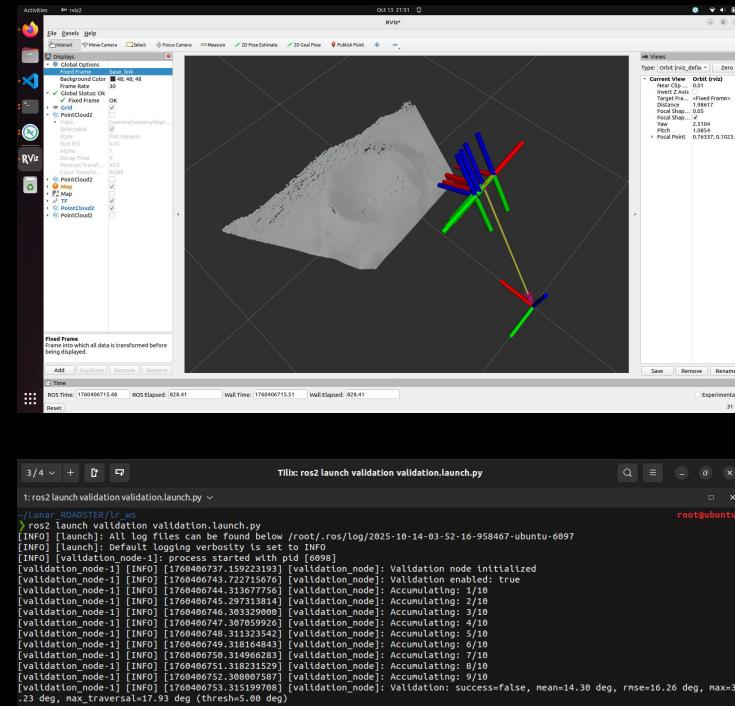
Implementation:

- Obtains most recent point cloud feed from the ZED camera
- Voxel downsampling, and builds a KdTree
- Surface normal estimation and calculate per-point slope from the vertical z-axis
- Nearest neighbor smoothing and masking to filter out phantom points and walls/edges
- Compute aggregate slope statistics over several frames

Challenges:

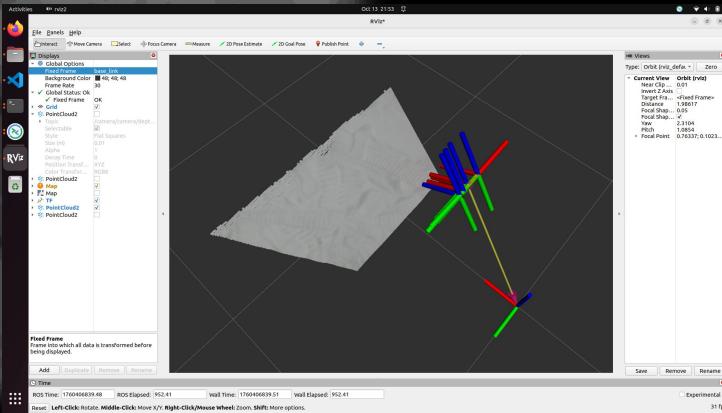
- Rover mast moves due to rover suspension
- Phantom points in point cloud data sometimes causes erroneous gradient estimates

Status: 100% Complete



Validation before grooming

Evaluation: Computations Subsystem Validation Stack



Modelling:

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

Analysis:

- Analyzed accuracy and robustness of output on different terrains (crater, flat ground, smoothed sand, facing wall, facing rock)

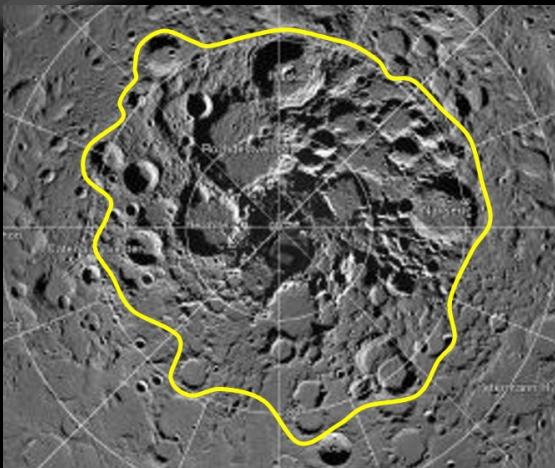
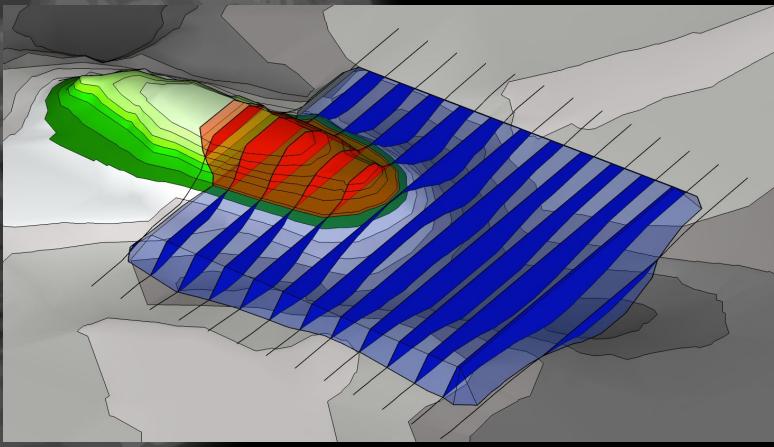
```
tilix: ros2 launch validation validation.launch.py
[1]: ros2 launch validation validation.launch.py
[1]root@ubuntu:~/catkin_ws/src/rover/computations$ ./validation_node
[INFO] [validation_node-1]: All log files can be found below: /root/.ros/log/2025-10-14-03:54:10-850300-ubuntu-6261
[INFO] [validation_node-1]: default logging verbosity is set to INFO
[INFO] [validation_node-1]: process started with pid [6263]
[validation_node-1]: [INFO] [1760406863.014576] [validation_node]: Validation node initialized
[validation_node-1]: [INFO] [1760406863.014576] [validation_node]: Validation enabled: true
[validation_node-1]: [INFO] [1760406858.315576] [validation_node]: Accumulating: 1/10
[validation_node-1]: [INFO] [1760406859.31649754] [validation_node]: Accumulating: 2/10
[validation_node-1]: [INFO] [1760406860.31970053] [validation_node]: Accumulating: 3/10
[validation_node-1]: [INFO] [1760406861.31300352] [validation_node]: Accumulating: 4/10
[validation_node-1]: [INFO] [1760406862.31415516] [validation_node]: Accumulating: 5/10
[validation_node-1]: [INFO] [1760406863.31422979] [validation_node]: Accumulating: 6/10
[validation_node-1]: [INFO] [1760406864.32142991] [validation_node]: Accumulating: 7/10
[validation_node-1]: [INFO] [1760406865.32232383] [validation_node]: Accumulating: 8/10
[validation_node-1]: [INFO] [1760406866.32322383] [validation_node]: Accumulating: 9/10
[validation_node-1]: [INFO] [1760406867.31645493] [validation_node]: Validation: success=true, mean=2.82 deg, rmse=2.92 deg, max=4.55 deg, max_traversal=1.73 deg (thresh=5.00 deg)
```

Validation after grooming

Testing:

- Fall T07: Trail Grooming Slope Validation

Description: Planning Stack



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

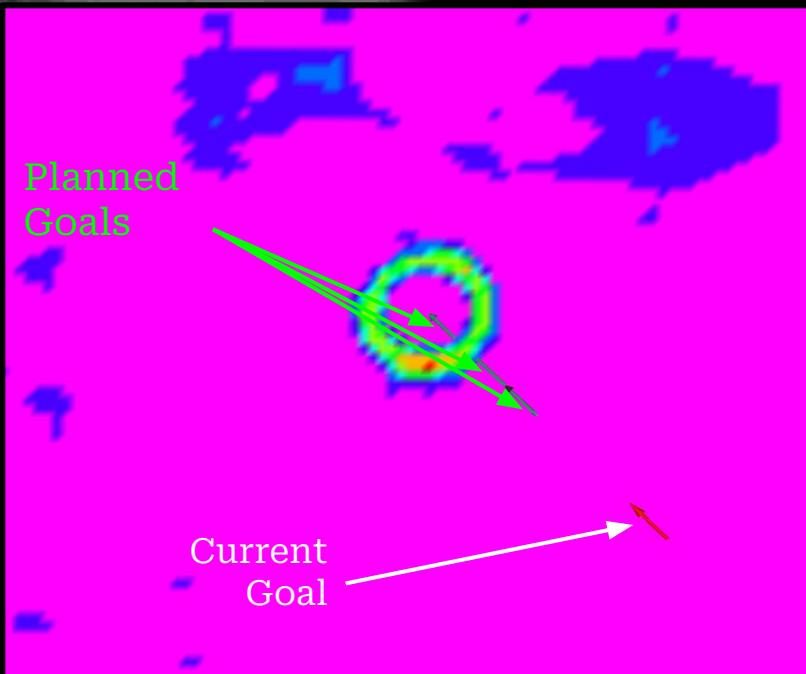
Requirements

- Jetson Orin
- 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: Planning Stack



Implementation:

- The new planning stack will be using the geometry of the crater as obtained by the perception stack.
- The diameter and coordinates of the crater's centroid will be used to create robot poses for manipulation
- The tool height will be determined by the depth data obtained from the ZED

Challenges:

- Accurate crater geometry will be needed
- Robot poses are an estimate of an estimate, meaning they will need to be tuned

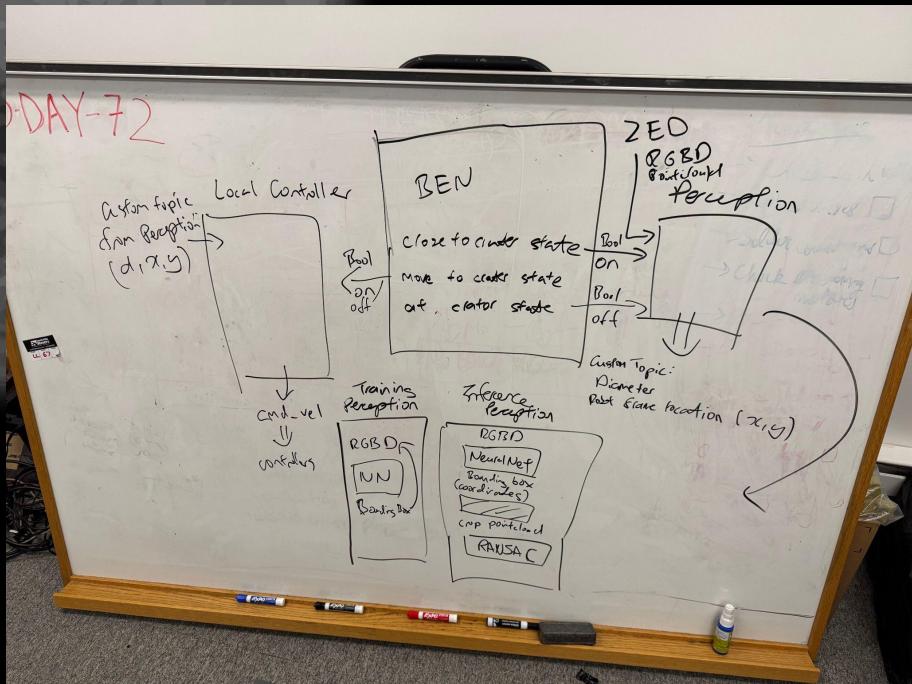
Status: 40% complete

Evaluation: Planning Stack



4x

Description: Computations Subsystem Behavior Executive Node



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

Initial Methodology for Integration

Status: Computations Subsystem Behavior Executive Node

Implementation:

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

Challenges:

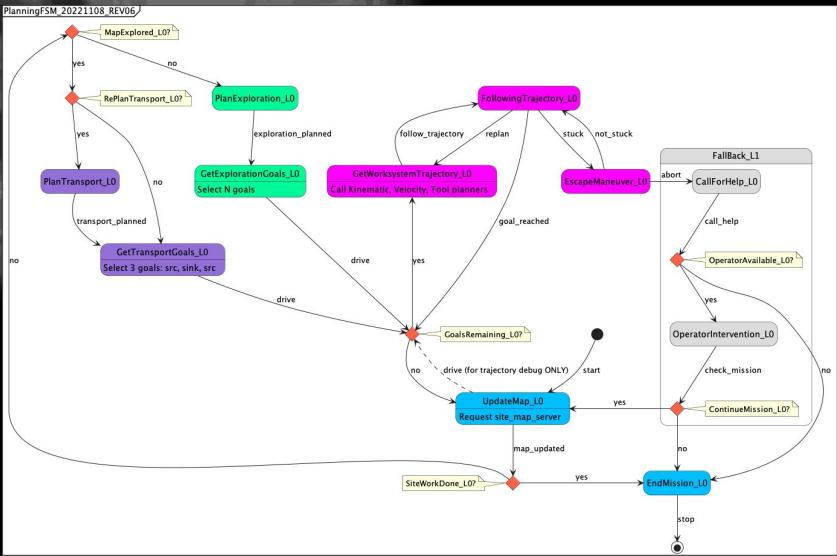
- Compute may not be sufficient with new modules

Status: 40% Complete

(Integrate new navigation, perception and validation unit into FSM)

Evaluation: Computations Subsystem

Behavior Executive Node



Modelling:

- Initial FSM design sourced from Crater Grader. Adapted and modified design based on our needs to include all new packages

Analysis:

- Computations take too long. Rover often completely stops for calculations
- Sometimes topic messages gets missed due to high network layer traffic

Testing:

- Fall T09: CPU/GPU Usage of Autonomous Stack is Below Orin Compute Limits
- Fall T11: Fall Validation Demo Preparation Test

Description: External Infrastructure Subsystem



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

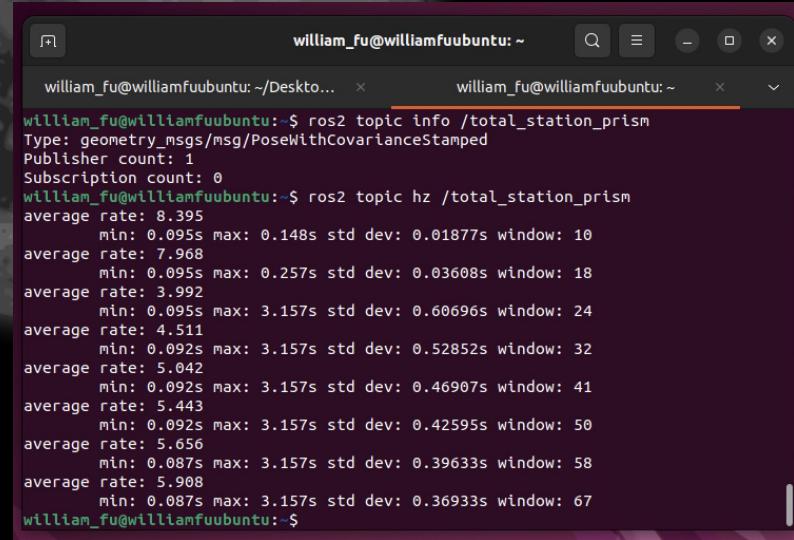
Requirements:

- 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:~/Desktop...  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:

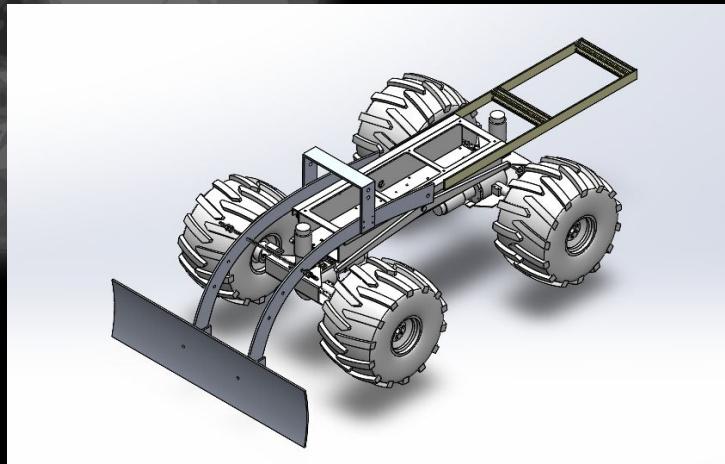
- Incorrect Jetson Docker network permissions blocked two-way communication

Status: 100% Completed

Analysis: Investigated network permission issues inside Jetson Docker

Testing: Spring T05: External Infrastructure Test

Description: Mechanical Subsystem Dozer Assembly



Description: Lunar terrain manipulation tool

Requirements:

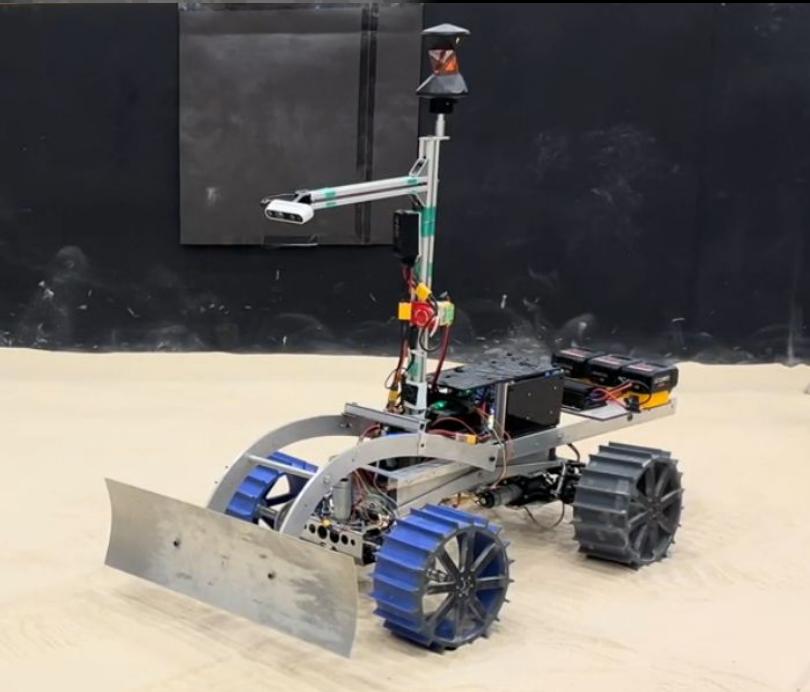
- Dozer blade
- Dozer arms assembly
- Linear actuator
- Arduino Due

Expected Functionality:

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

Status: Mechanical Subsystem

Dozer Assembly Unit



Implementation:

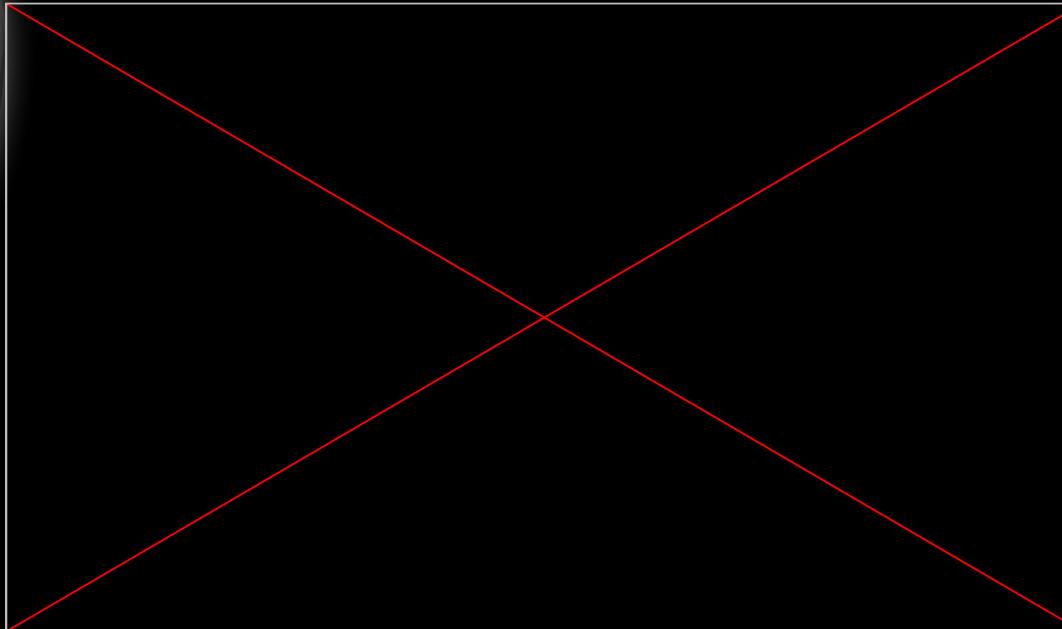
- Research: Dozer shapes and sizes, actuation methodologies.
- Designed the dozer assembly (blade, arms, yoke, mounts) using SolidWorks.
- Shortlisted linear actuators of different gear ratios.
- Manufactured and assembled all parts on the rover.
- Testing with different actuators

Challenges:

- Fabrication problems
- Limited access to FRC Workshop

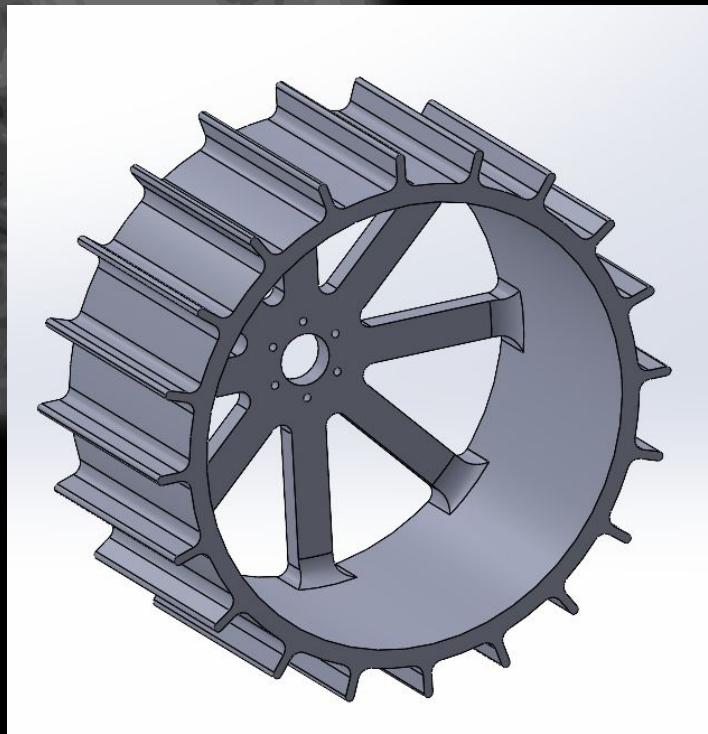
Status: 100% Completed

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

Description: Wheel Assembly Unit



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

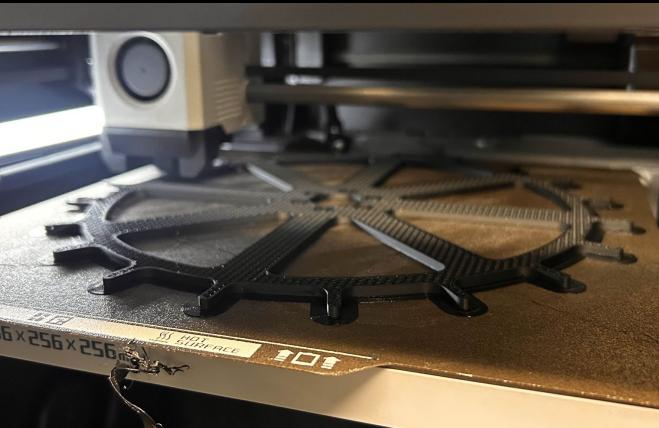
Requirements:

- 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:

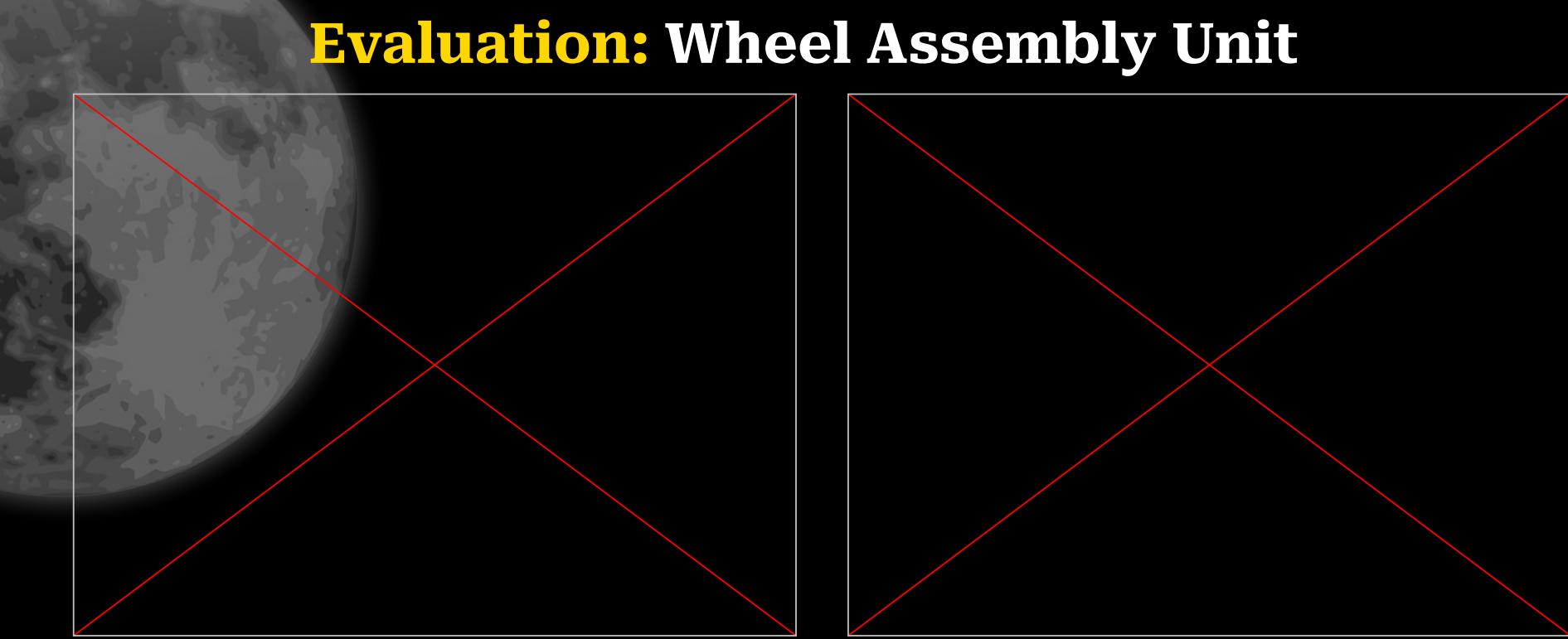
- 3D Printing the wheel is a long process with frequent failures
- Steering system of the rover is fragile and frequently disengages - solved.

Status:

Completed

- Demonstrated mobility and pushing power with 4 printed wheels in SVD

Evaluation: Wheel Assembly Unit



Great performance in traction and generating pushing power in all tests

Description: Actuation Subsystem



Description: Power transfer methodologies for rover mechanisms.

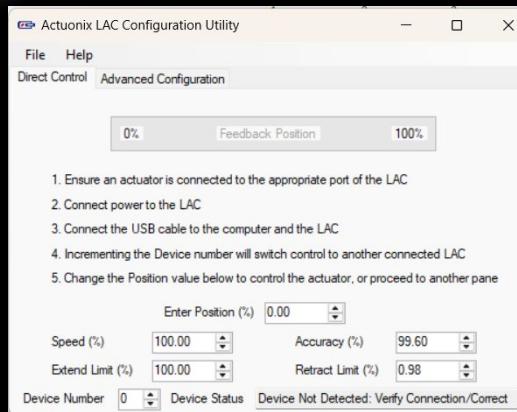
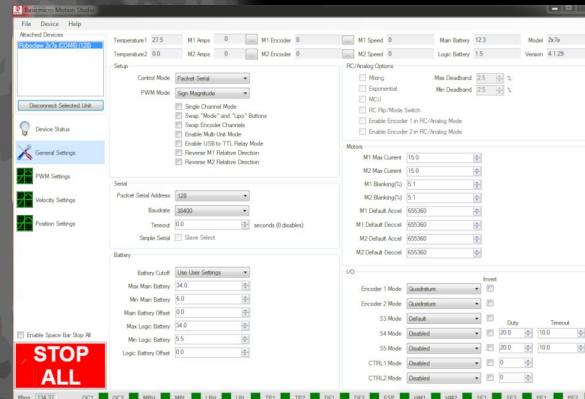
Requirements:

- 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:

- Worn-out pinion gears
- Hard-to find spares (resolved)

Status:

100% Complete

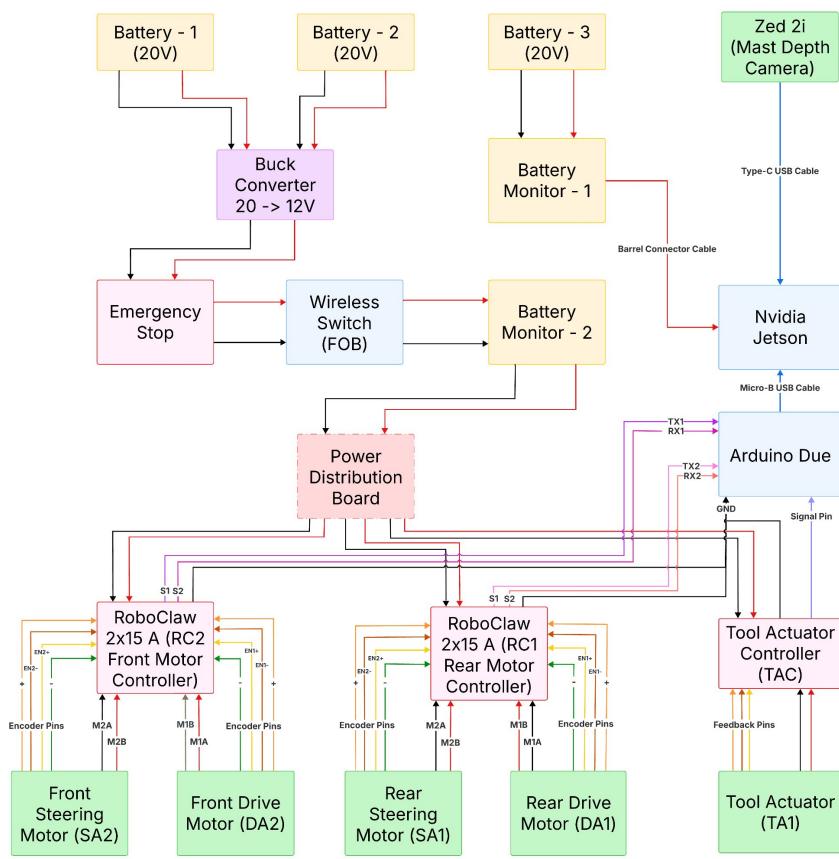
- Demonstrated enhanced steering and driving in SVD
- Linear actuator has been tuned by switching to analog control, eliminating oscillations

Evaluation: Actuation Subsystem



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

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:

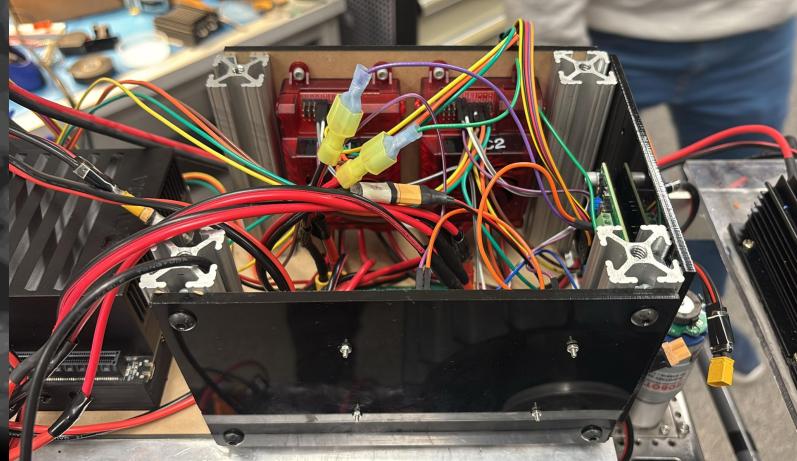
- Integrated new electrical components and designed a custom Power Distribution Board (PDB) based on updated power requirements
- Designed a compact and accessible electronic box to streamline the electrical subsystem setup
- Successfully integrated and tested the PDB within the rover's electrical system
- Created robust connections by replacing jumper wires with screw terminals and lever wire connectors

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: 100% Completed

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:

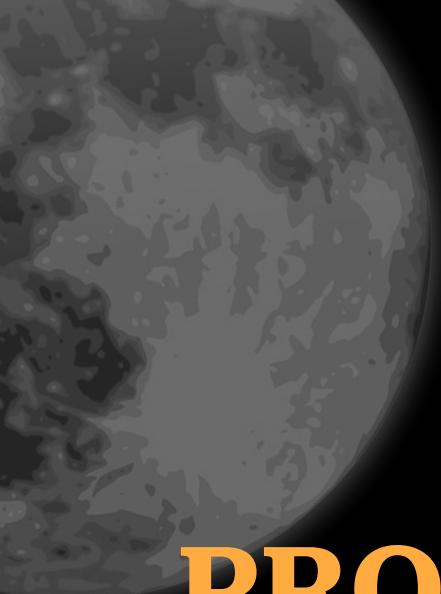
- Fall T10: Maintenance, Reliability and Quality Assurance Test

Video Excerpt

Pose 3 - Sink



2x Speed



PROJECT MANAGEMENT

Schedule

Major Milestones:

- Implemented Objectives and Key Results (OKR) to track Progress Review Goals
- Achieved promised goals during PRs

Current Status:

- Achieved all promised goals for SVD
- On track with planned schedule
- Delays in planned Continuous Integration Continuous Testing approach due to hardware issues – made up for this in Fall break

Plan to Improve:

- Extreme testing until FVD to ensure hardware robustness
- Testing and tuning navigation, perception and planning stacks
- CICT

Fall Test Plan

Date	Event	Capability Milestones	Tests	Requirements
09/10	PR7	<ul style="list-style-type: none"> Hardware and software refinement 	Validate hardware upgrades, software fixes, and system stability improvements	M.F.2 M.F.3 M.F.4 M.F.5 M.F.7 M.F.9
09/24	PR8	<ul style="list-style-type: none"> Validation stack setup Navigation stack setup Obtain gradable craters location 	Detect craters that meet grading criteria based on diameter and depth, and determine their poses	M.F.6
10/08	PR9	<ul style="list-style-type: none"> Perception stack detects craters accurately and provides waypoints Validate grading Rover navigates to goal location accurately 	Test navigation accuracy and perception stack geometry extraction	M.F.1 M.F.2 M.F.3 M.F.4 M.F.6 M.F.8 M.F.9

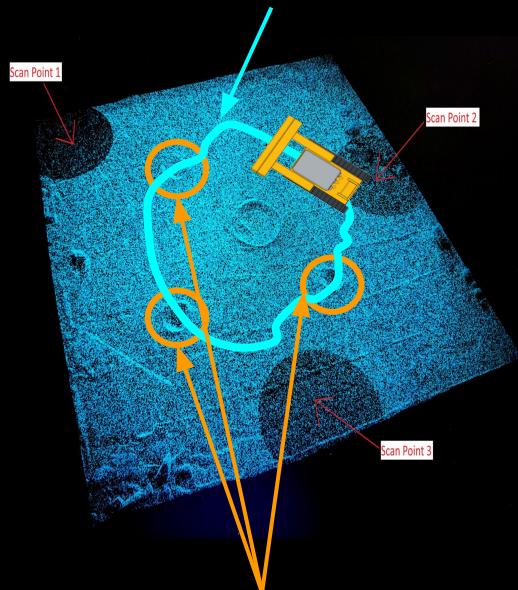
Fall Test Plan

Date	Event	Capability Milestones	Tests	Requirements
10/29	PR10	<ul style="list-style-type: none"> SkyCam-based localization for improved global positioning Ensure compute usage is below orin limits Tool Planner stack completed and integrated with necessary subsystems 	Test SkyCam-based localization by checking rover's ability to self-localize accurately with / without external infrastructure and compute usage	M.F.3 M.F.7
11/12	PR11	<ul style="list-style-type: none"> Full system integration Conduct quality assurance testing 	Check all subsystems and units are functioning correctly	M.F.1 M.F.6 M.F.2 M.F.7 M.F.3 M.F.8 M.F.4 M.F.9 M.F.5
11/17 11/24	PR12 (FVD and FVD Encore)	<ul style="list-style-type: none"> 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.F.6 M.F.2 M.F.7 M.F.3 M.F.8 M.F.4 M.F.9 M.F.5

Fall Validation Demonstration

Test Location
Planetary Robotics Lab Moon Yard
Sequence of Events
Prior Setup: <ol style="list-style-type: none">1. Prepare the Moon Yard with several craters and dunes in a circular path.2. Perform a FARO scan of the environment and preprocess the scan to generate a map used for identifying gradable crater poses and for navigation planning.3. Set up the external infrastructure by positioning the Leica total station at the corner of the Moon Yard, configuring the LAN router, and connecting the Jetson TX2 relay.4. Position the rover in the Moon Yard and perform localization calibration. During Demonstration: <ol style="list-style-type: none">1. Switch the rover to autonomous mode and run the start-up procedure.2. Observe the rover autonomous grade craters and level dunes in a circular path.3. After each dozed crater, use the ZED camera to validate whether the dozing satisfies the performance requirements.4. Monitor the job status through the GUI, and use the emergency stop button if any unexpected behavior occurs.
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 have a contact pressure of less than 1.5 kPa M.P.4: Will avoid craters >= 0.5 metres 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°

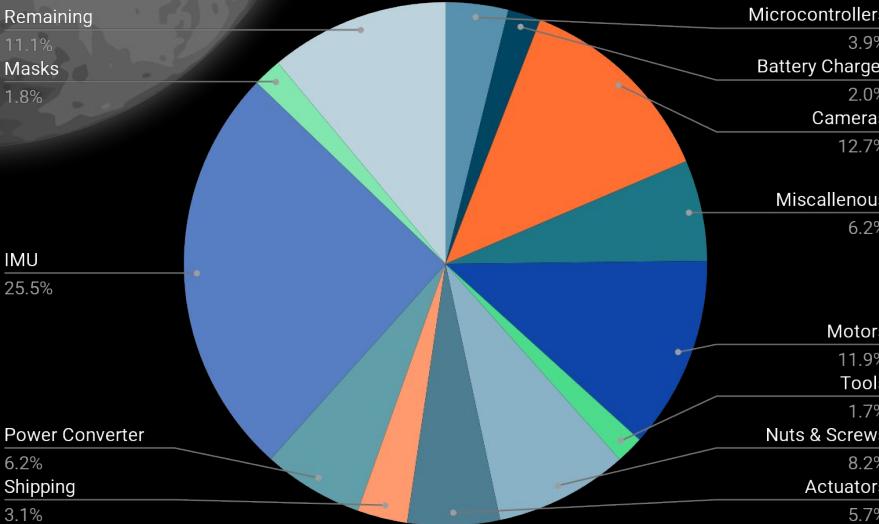
Follow a circular path



Groom several craters in a circular path

Budget

MRSD Budget	MRSD Budget Spent (\$)	MRSD Budget Spent (%)	Total Budget Spent*	Remaining Balance
\$5,000	\$4,437.09	88.7%	\$7507.09	\$562.91



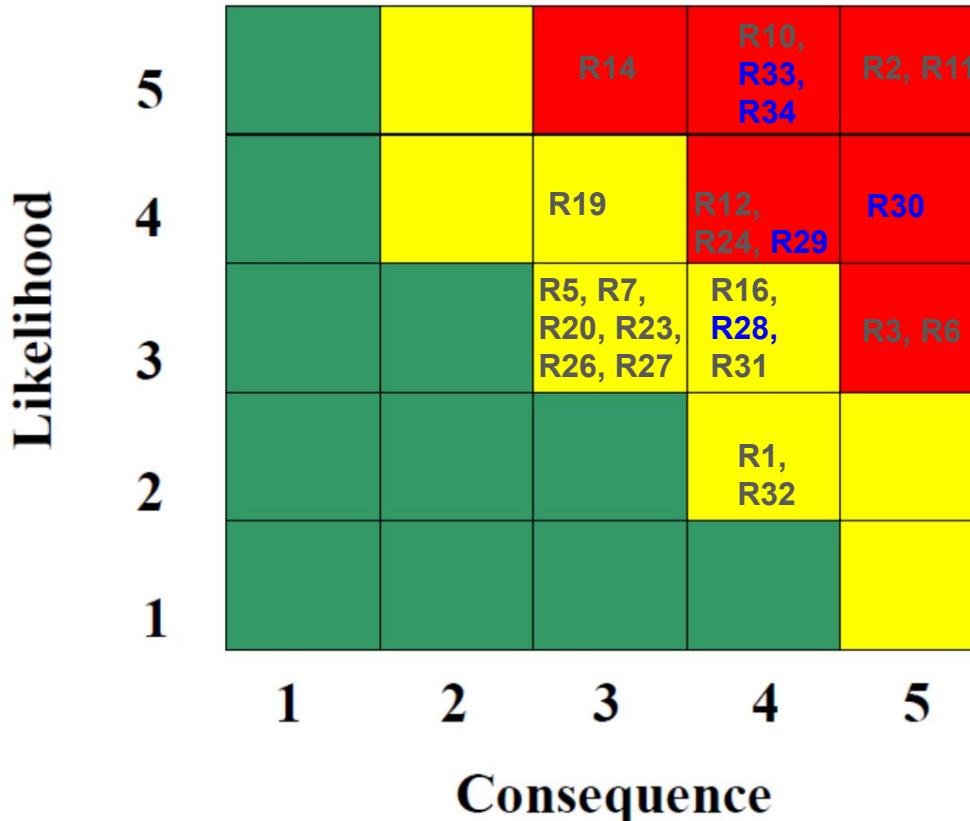
Critical Parts	Extra Stock
Steer motor	2 Units
Drive motor	2 Units
Pinions	8 Units
IMU	2 Units
Chassis	1 Disassembled

Emergency Budget: Red

* Includes \$3,070 worth of items inherited from Crater Grader and Supervisor

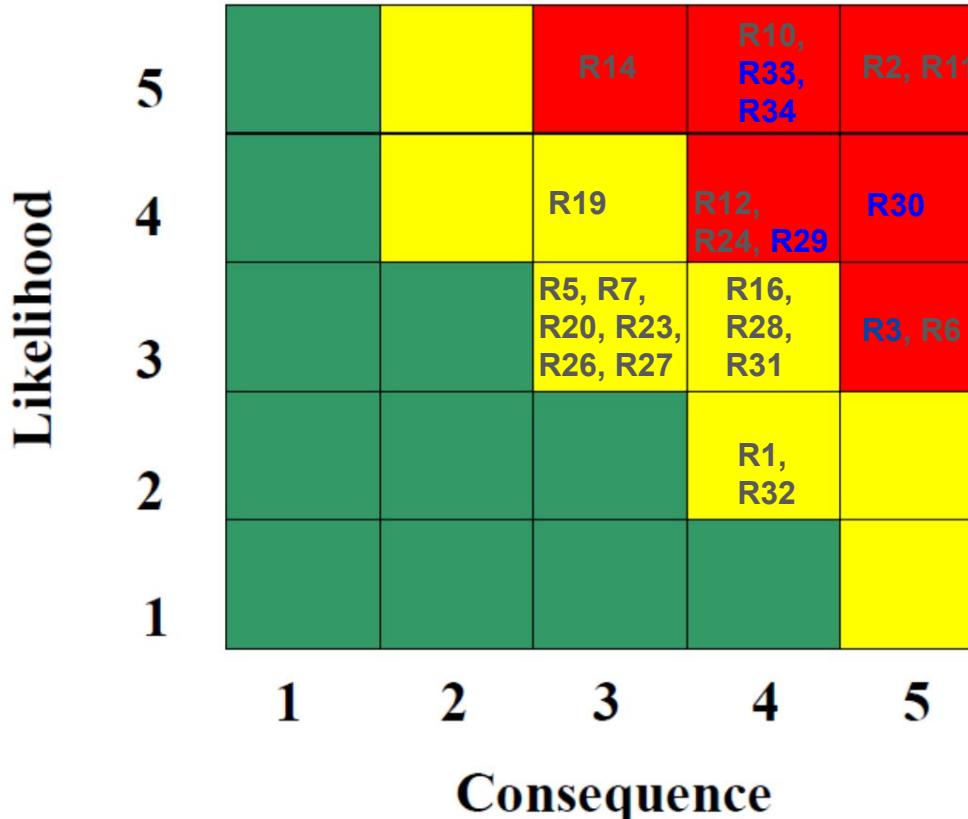
Risk Management (Updated)

Risk Summary



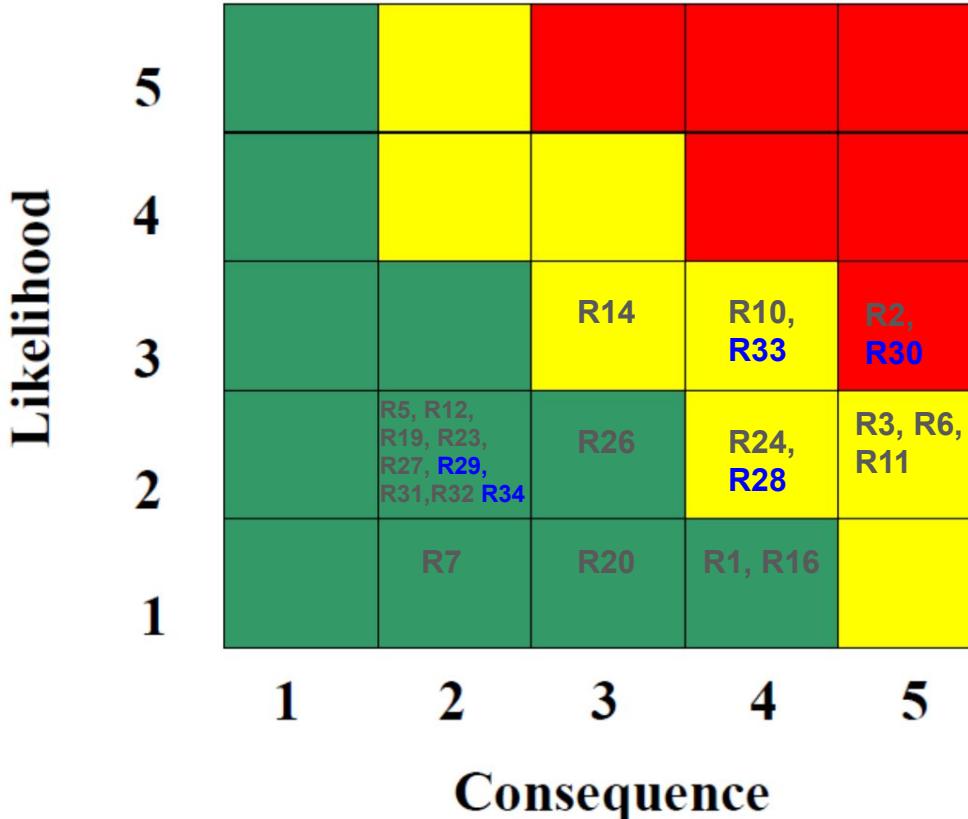
Risk Management (Updated)

Risk Summary



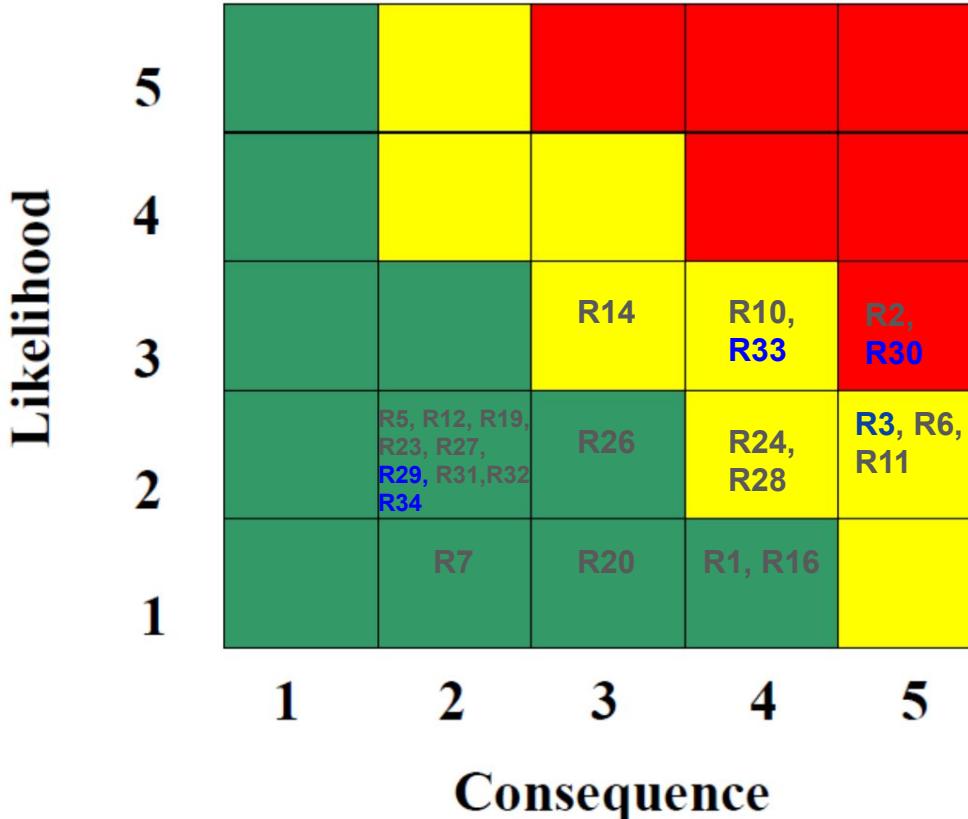
Risk Management (Updated)

Reduced Risk Summary



Risk Management (Updated)

Reduced Risk Summary



Risk Management

Risk ID	Risk Title	Risk Owner	Risk Type:	Logistics
R30	No spares available	Team		
Description	Date Added	Likelihood	Consequence	
Discontinued model, spare parts unavailable	3/4/2025	5		
Date Updated	9/22/2025	4		
Consequence	The whole project falling through, or redo almost all subsystems on a different rover.	3		
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	9/22/2025	
Check out and stock similar parts if not same	Successfully find and stock similar parts	3/6/2025	9/22/2025	
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	
Find similar parts - a slightly smaller pinion and motor set	Spares problem will be solved	9/10/2025	9/22/2025	

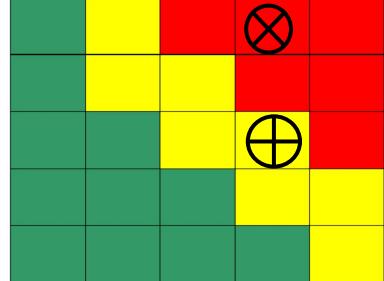
Risk Management

Risk ID	Risk Title	Risk Owner	Risk Type:	Logistics
R36	PRL Moonyard Access	William		
Description		Date Added	Likelihood	
Securing Moonyard access for testing/demos will be restricted and challenging		8/29/2025		
Consequence		Date Updated		
No testbed available for testing and/or FVD		9/30/2025		
			1 2 3 4 5	Consequence
			1 2 3 4 5	Likelihood
Action/Milestone	Success Criteria	Date Planned	Date Implemented	
Devise and discuss a testing and demo plan with Prof. Red and Prof. David Wettergreen beforehand and reserve slots	Successfully meet and discuss the schedule of high priority projects	9/11/2025	9/11/2025	
Complete Medical Evaluation to get unrestricted but controlled access	Successfully complete the Medical Evaluation and get unrestricted access to the Moonyard	9/5/2025	9/11/2025	
Respirator Training	Complete training and get custom masks	9/30/2025	9/30/2025	

Risk Management

Risk ID	Risk Title	Risk Owner	Risk Type:	Technical
R34	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		
		9/7/2025		
Consequence			Likelihood	
Slows down setup time and impacts operational readiness, delaying mission start and mode transitions.			5	
			4	
			3	
			2	
			1	
				Consequence
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	9/5/2025	
Verify that Arduino is connected via USB 3.0 instead of USB 2.0 port	Ensure stable high-speed communication	4/26/2025	9/5/2025	
Check for ROS node frequency mismatches causing packet loss to Arduino	Match ROS publish/subscribe rates	4/26/2025	9/5/2025	
Implement a software reset trigger	Reset can be called from the operations terminal	9/7/2025		

Top Risks

Risk ID	Risk Title	Risk Owner	Risk Type:	Technical		
R33	Localization frame shift after total station battery swap	Bhaswanth	Likelihood			
Description		Date Added				
		3/4/2025				
		Date Updated				
		9/12/2025				
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	9/12/2025			
Explore and test alternative localization methods (using SkyCam)	Successfully maintain localization accuracy	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

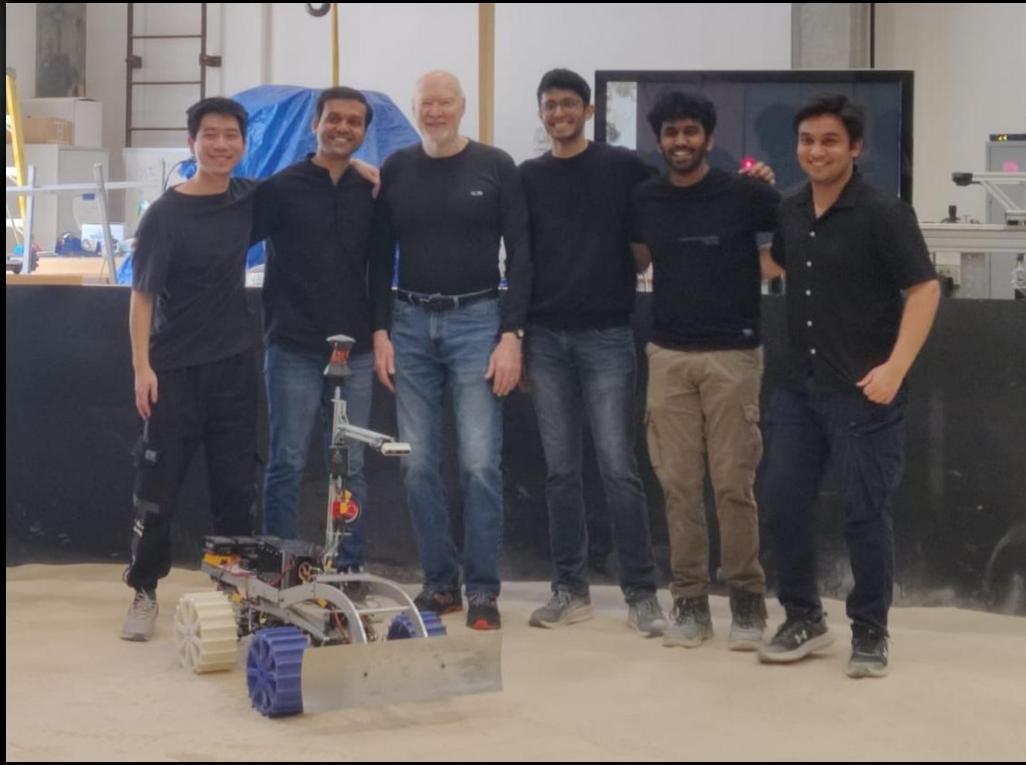
Colonize the Moon!

- Team *Lunar ROADSTER*



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

Thank You!



<https://mrsdprojects.ri.cmu.edu/2025team/>

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 $15.5/30 \approx 0.5$ 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	<p>Thoroughly go through Crater Grader's code and the mechanical schematics provided</p> <p>Test each component and wiring to see if they are working</p> <p>If it is still not working, inherit only the software component from Crater Grader and build hardware ourselves</p>
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	<p>Use off-the-shelf components that are available on hand (e.g. from CMU labs or Red's workshop)</p> <p>Start ordering and designing components during Winter break so there is adequate leeway for delivery and manufacturing before Spring semester starts</p> <p>Use simulations to work on software components while we wait for the components to be delivered and/or manufactured</p> <p>Implement other subsystems that are independent from the subsystem that is missing parts</p> <p>In case of delay in wheels, work with the existing wheels and proceed with the timeline while waiting for the new ones to arrive.</p>
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	<p>Ask CraterGrader how they ran all their simulations and gather resources</p> <p>Explore LunarSim - https://github.com/PUTvision/LunarSim and check how useful this will be, during the winter break</p> <p>Develop Gazebo environment</p>

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

Risk Management (Extra)

R27	TX2 Integration	William	Technical	Unable to login to TX2 and interface with a LAN network for transmitting data over WiFi to 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