Lunar ROADSTER

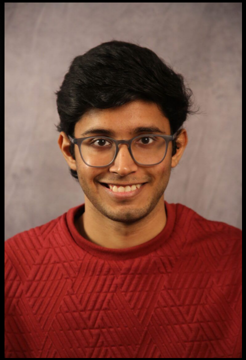
(Robotic Operator for Autonomous Development of Surface Trails and Exploration Routes)

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

CARNEGIE MELLON UNIVERSITY
PITTSBURGH PENNSYLVANIA 1900

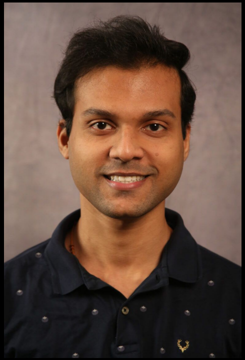
The Team

Ankit Aggarwal



Deepam Ameria

Bhaswanth Ayapilla

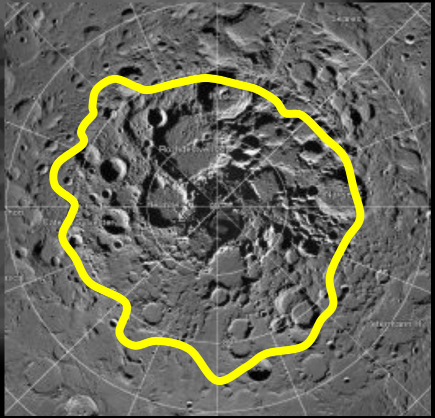


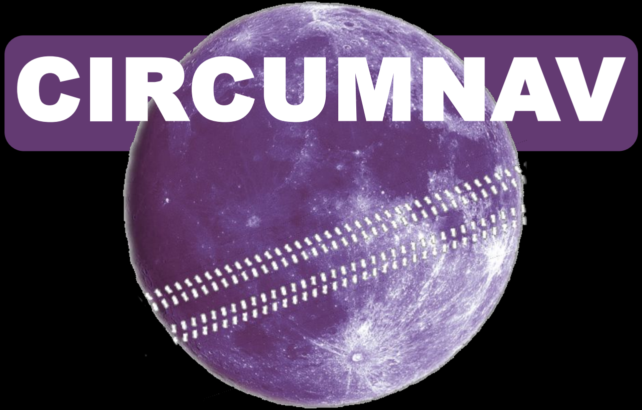
Simson D’Souza

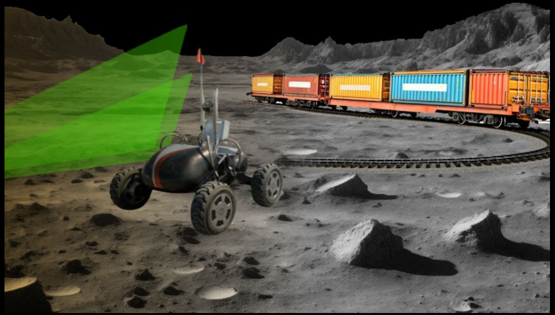
Boxiang (William) Fu

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?

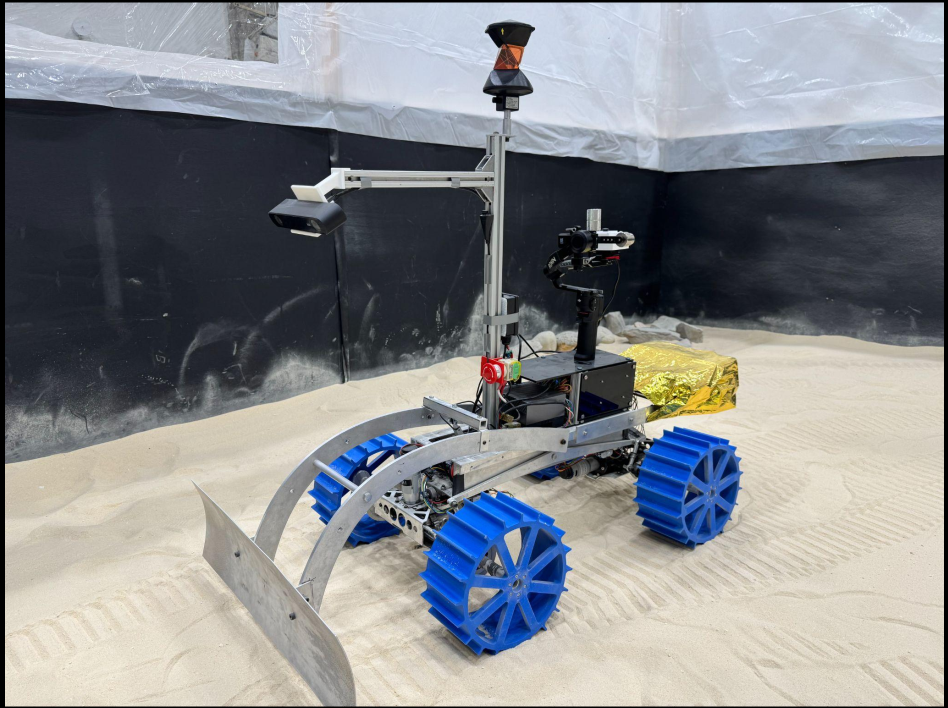
Motivation: The Lunar Polar Highway

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

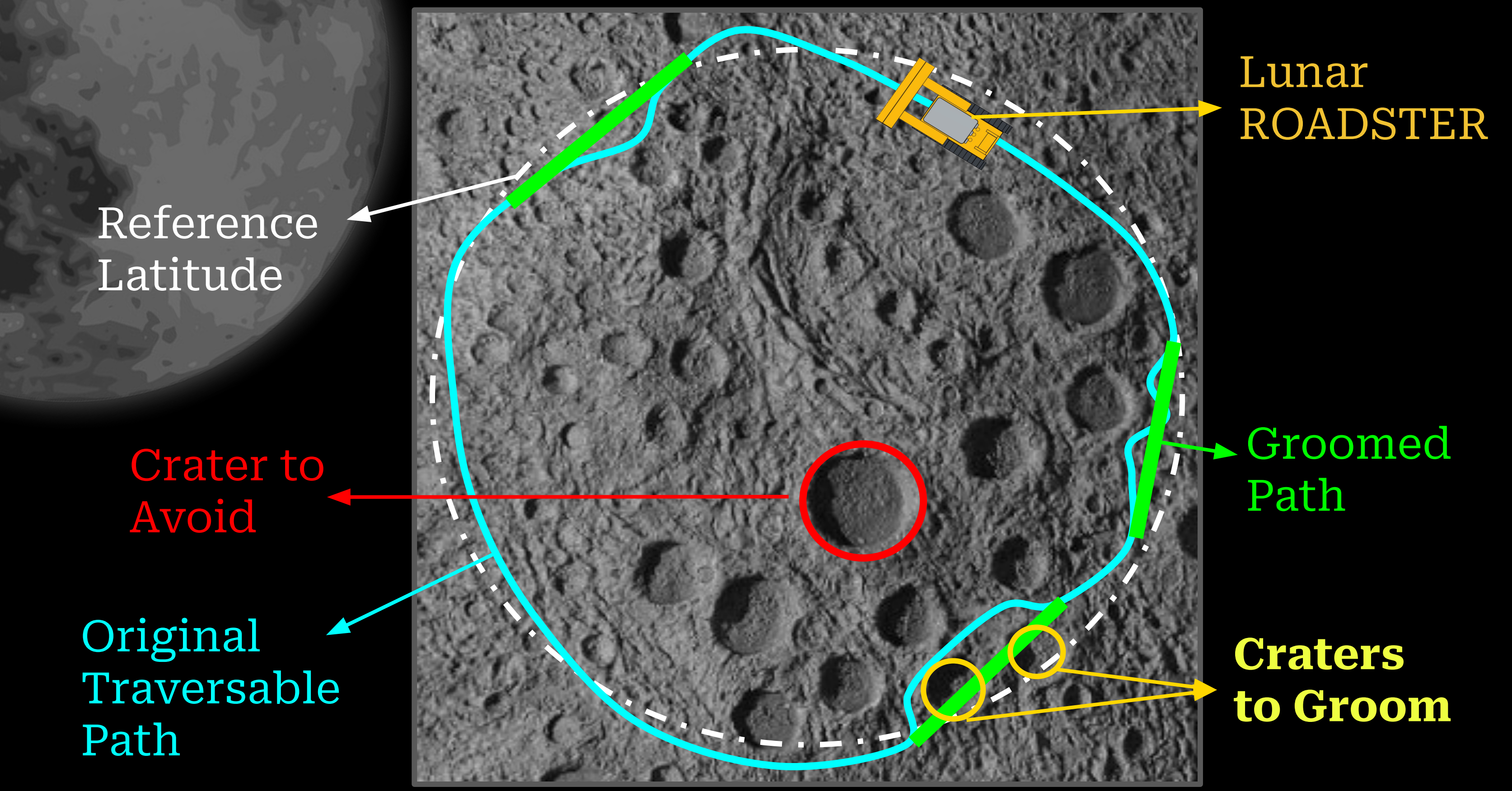
Jogging speed **IF** the route was flat, circular and traversable

The Project: Lunar ROADSTER

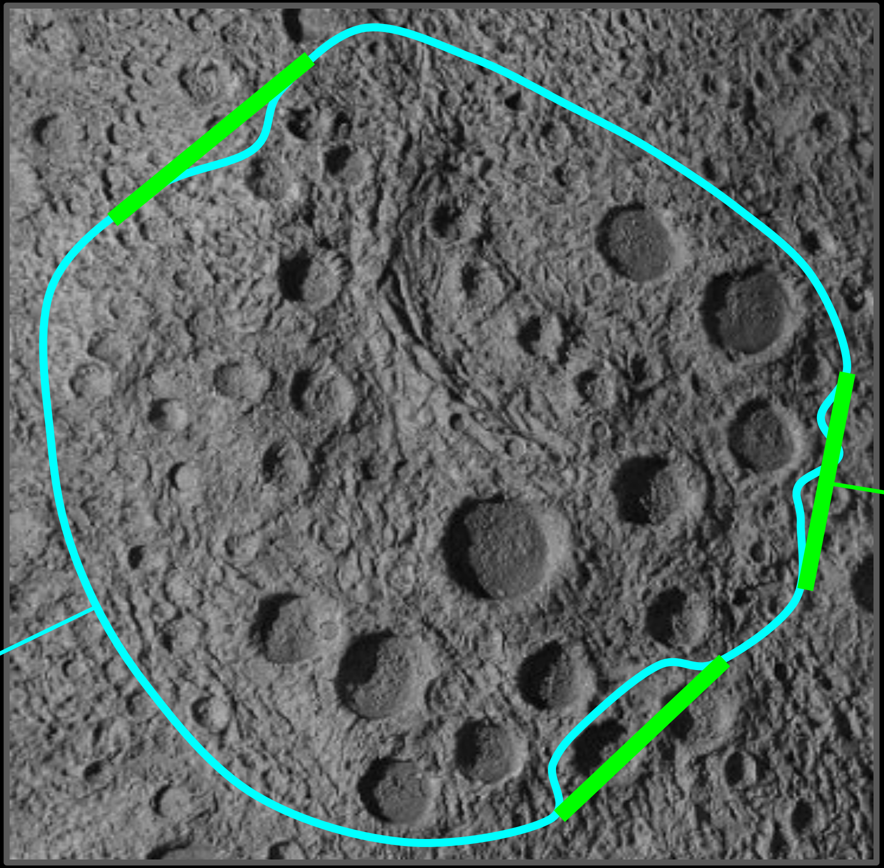


An autonomous moon-working rover capable of finding ideal exploration routes and creating traversable surface trails

Use Case


Lunar
ROADSTER
Reference
Latitude
Groomed
Path
Crater to
Avoid
Original
Traversable
Path
Craters
to Groom

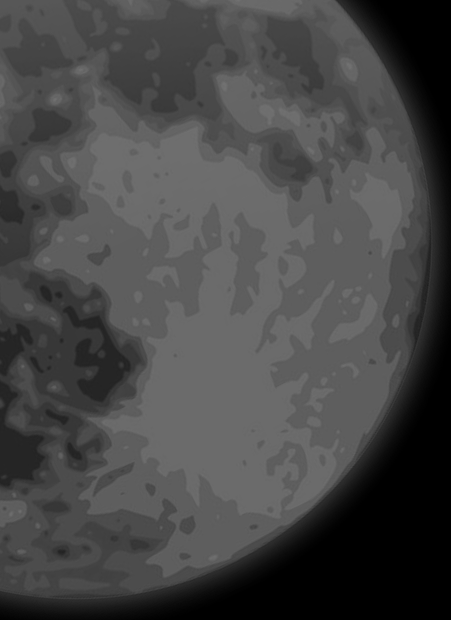
Use Case



ROADSTER

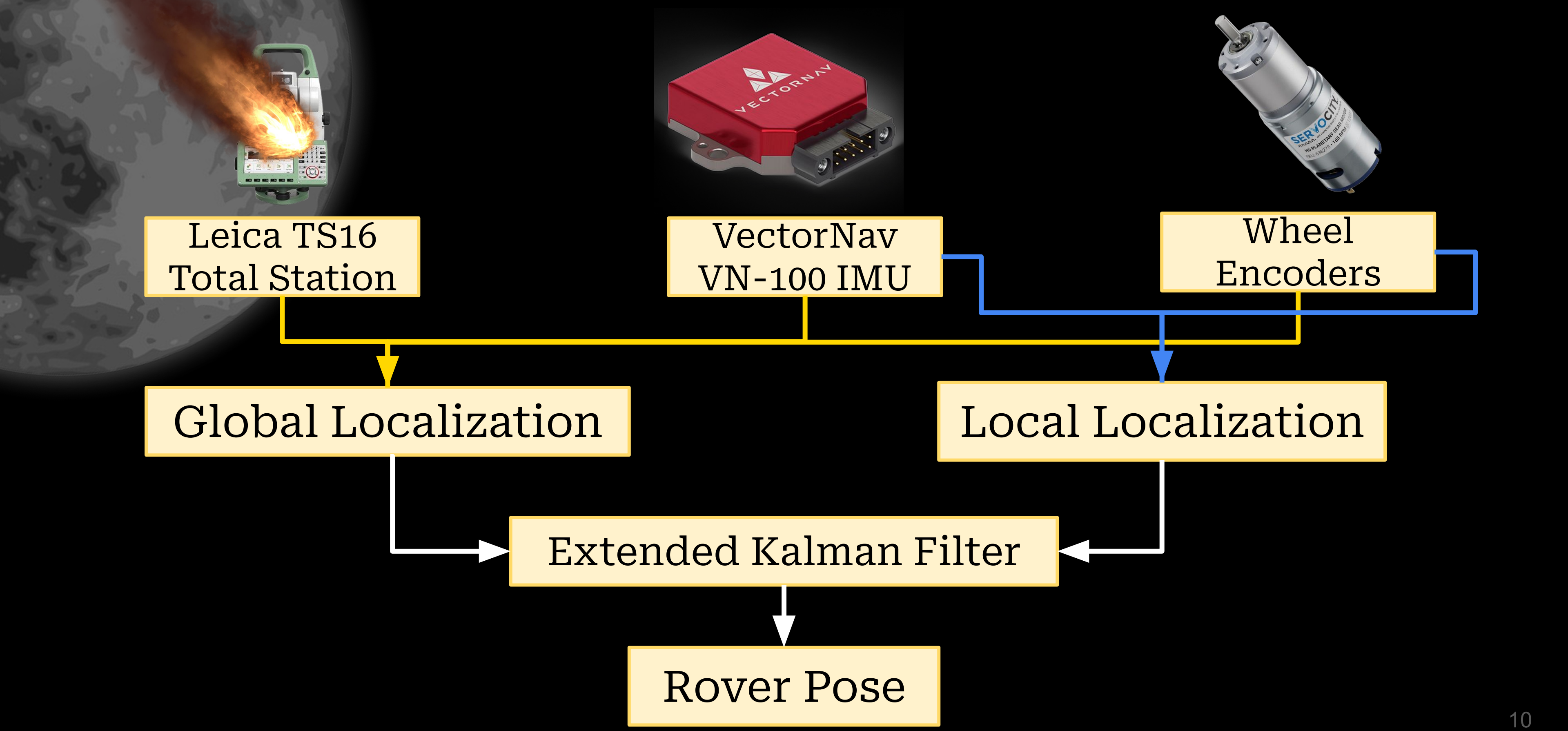
An autonomous mechatronic bulldozer for the Moon

- 60cm dozer width (3 times the predecessor)
- High tool actuation strength (can lift the whole ROADSTER)
- Custom wheels with high rimpull and maximised grip
- 135 kgf-cm drive actuators (2 times the predecessor)
- Superior pushing power (high drawbar pull)
- Reliable circuitry
- Efficient power distribution
- **An optimal, specialized machine for crater grooming**

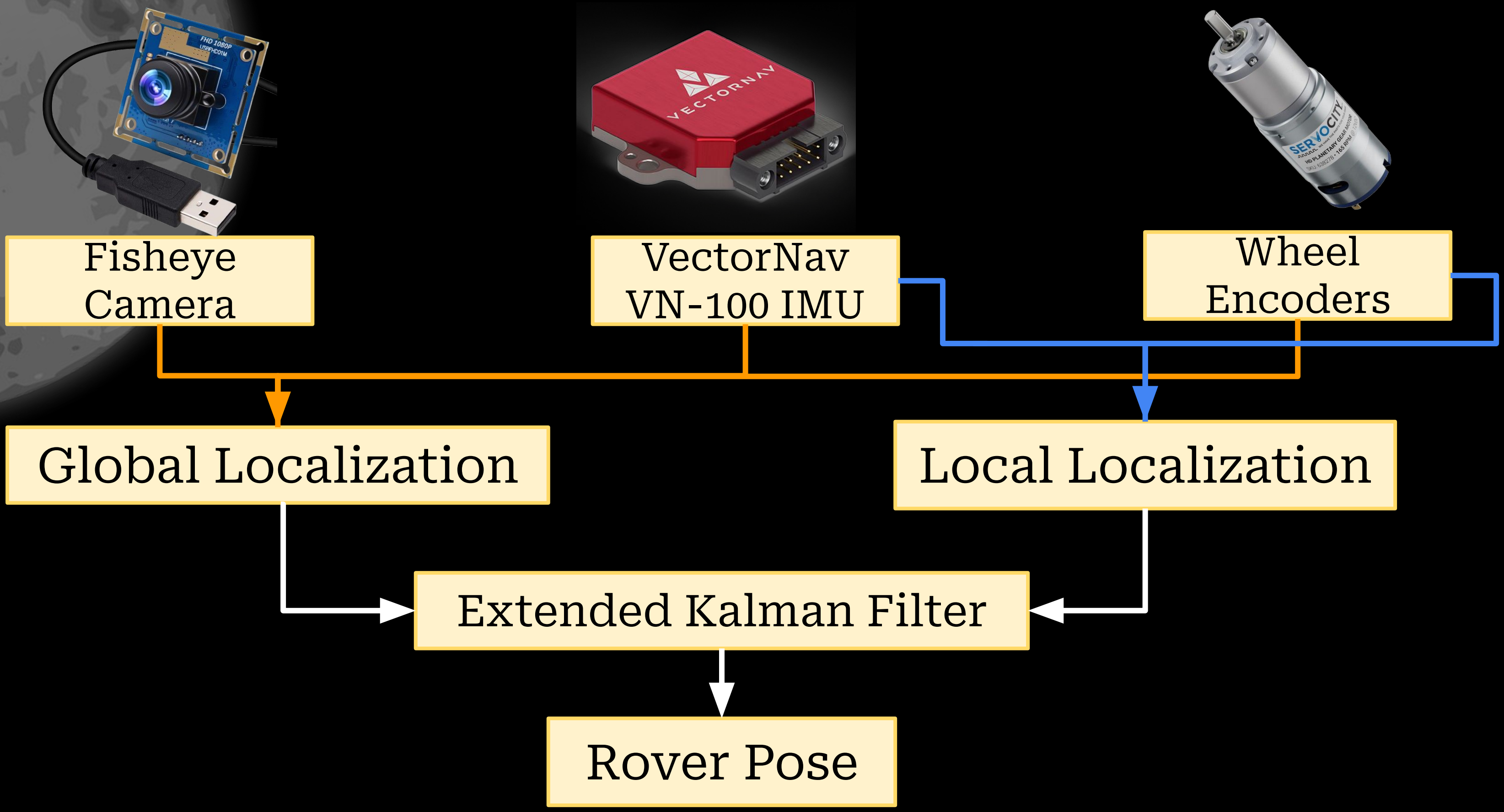


Demonstration

Localization



Localization (Encore)

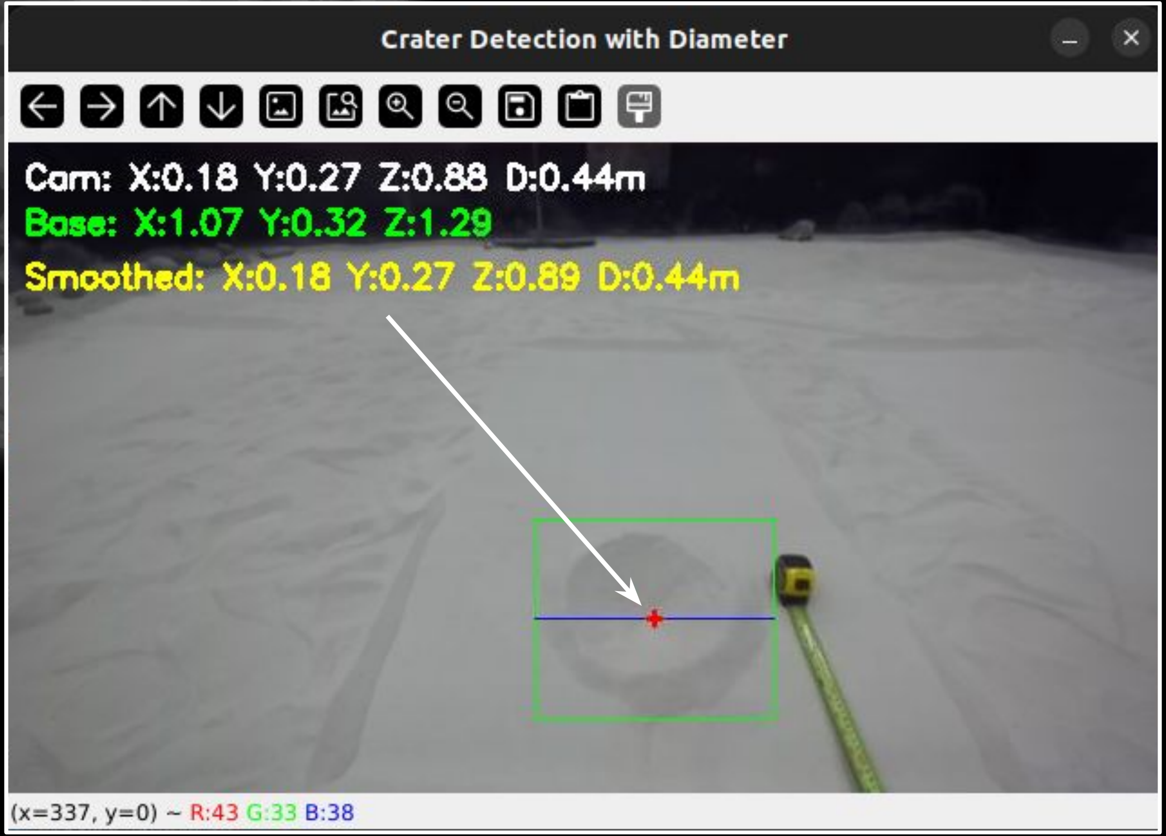


Demonstration

Mission Statement: The ROADSTER uses the excavator to groom multiple craters and create a traversable, circuitous path around the Moon Yard.

Procedure	
Pre-Demo Setup	**During Demo**
Prepare test environment - create craters	**Start Mission**
Obtain global map using laser scanner	**ROADSTER traverses to target crater**
Setup Operations Terminal	**ROADSTER perceives and manipulates**
Calibrate localization	**ROADSTER validates**
Setup GUI	**ROADSTER moves to next crater until end**
Send Start Mission command	**End Mission**

Perception



YOLO v8 model trained on custom dataset

RGBD frames from ZED 2i

↓

Crater Detection Model

↓

Geometry Extraction of the Crater

↓

Publish centroid coordinates and diameter

↓

Plan Sink and Source Poses using detected coordinates and current robot pose

Manipulation

Current Rover Pose

↓ Tool Up

Source Pose

↓ Tool Down (Grading)

Sink Pose

↓ Tool Up

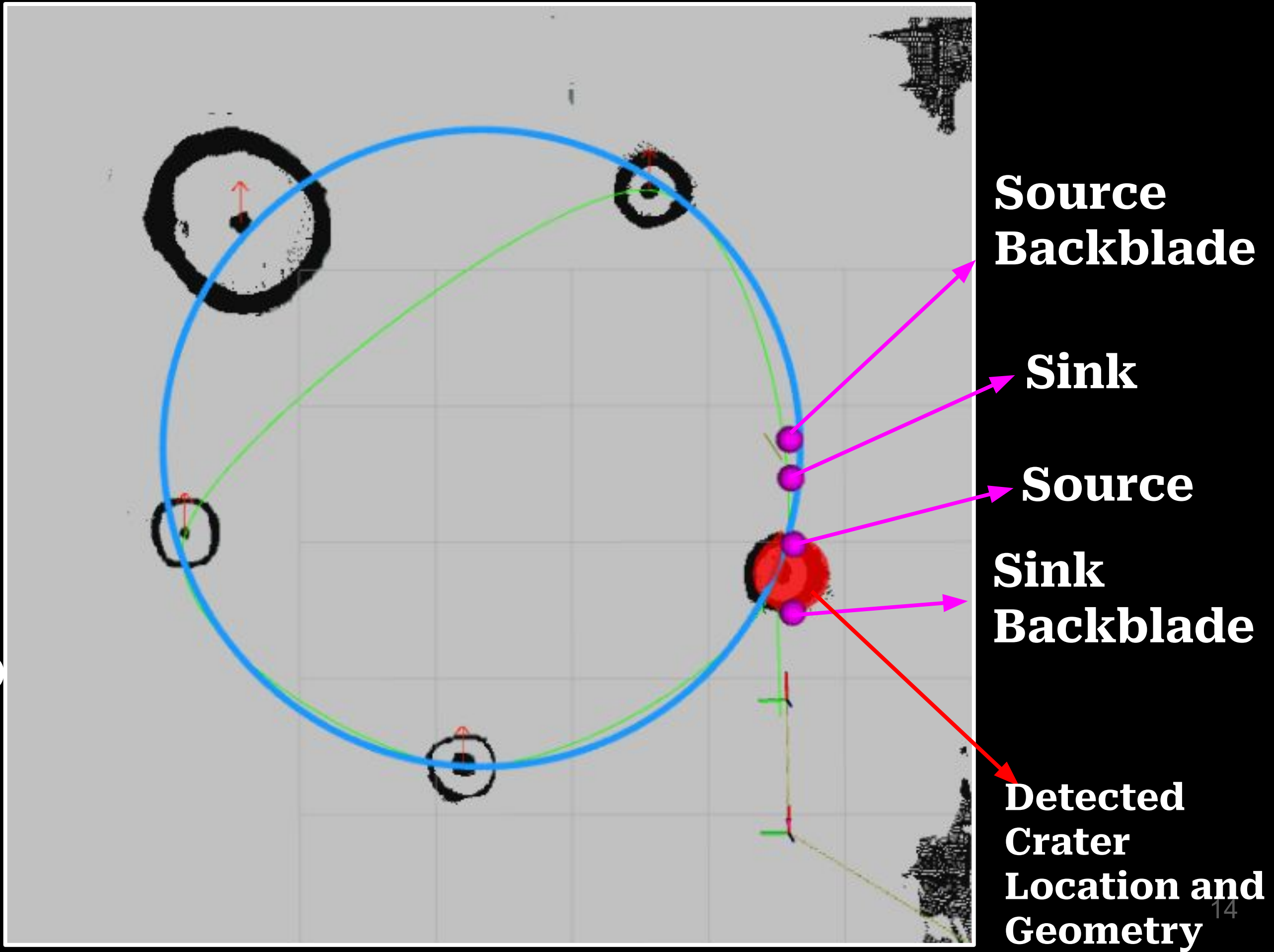
Source_Backblade Pose

↓ Tool Down (Backblading)

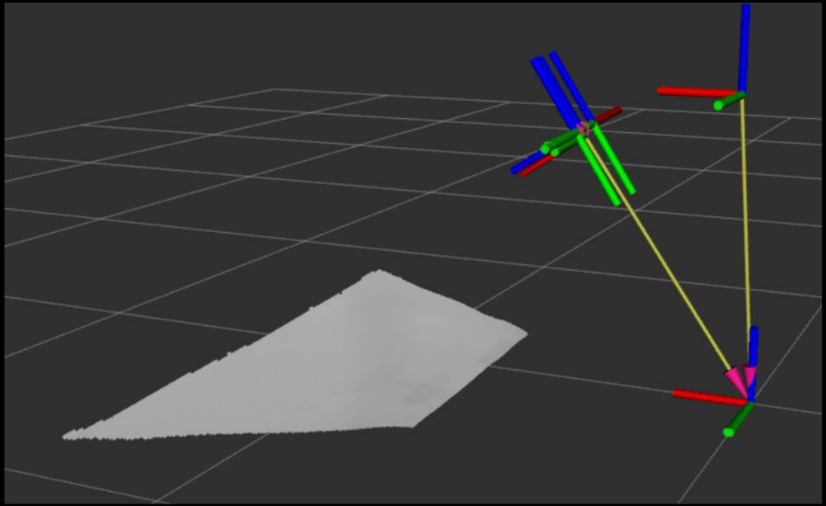
Sink_Backblade Pose

↓

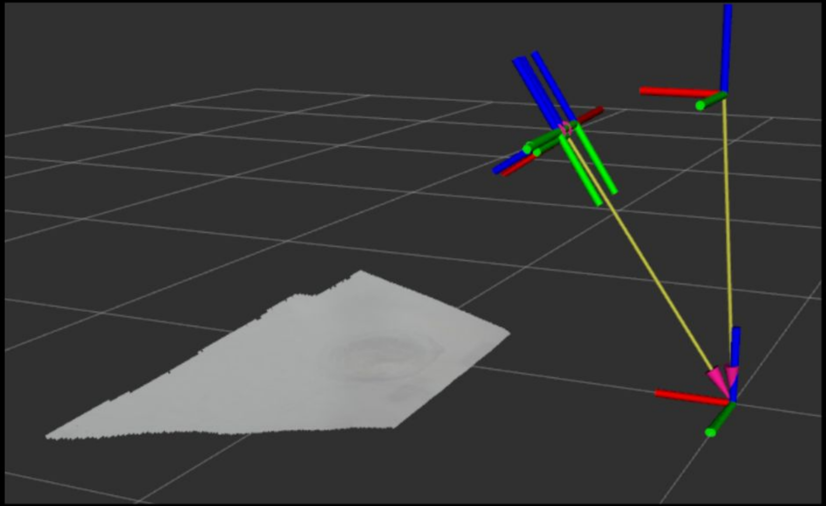
Next Crater



Validation



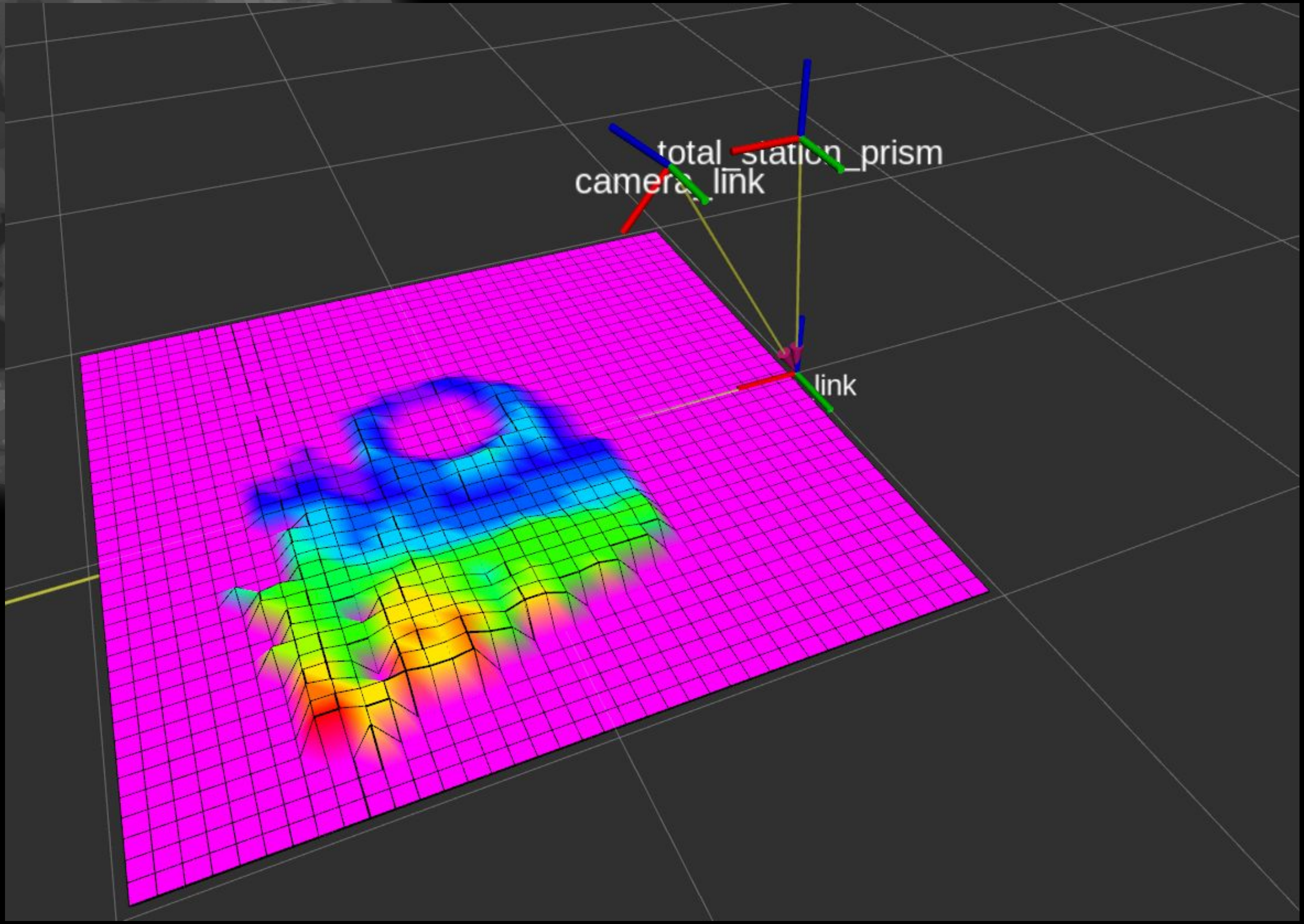
Validation on Flat Terrain
Grading Success = True, Slope = 1.44 deg



Validation on 15 Degree Crater
Grading Success = False, Slope = 14.78 deg

Get Point Cloud → **Voxel Downsample** → **Estimate Normals** → **Get Point Slopes** → **Mask Ghost Points** → **Compute Averages**

Tool Planner (Encore)



Get Point Cloud

↓

Crop Crater Region

↓

Find Max Elevation

↓

Map to Tool Offset

↓

Clamp to Tool Range

Localization (Encore)

Get Fisheye Image

↓

Find Bright Pixels

↓

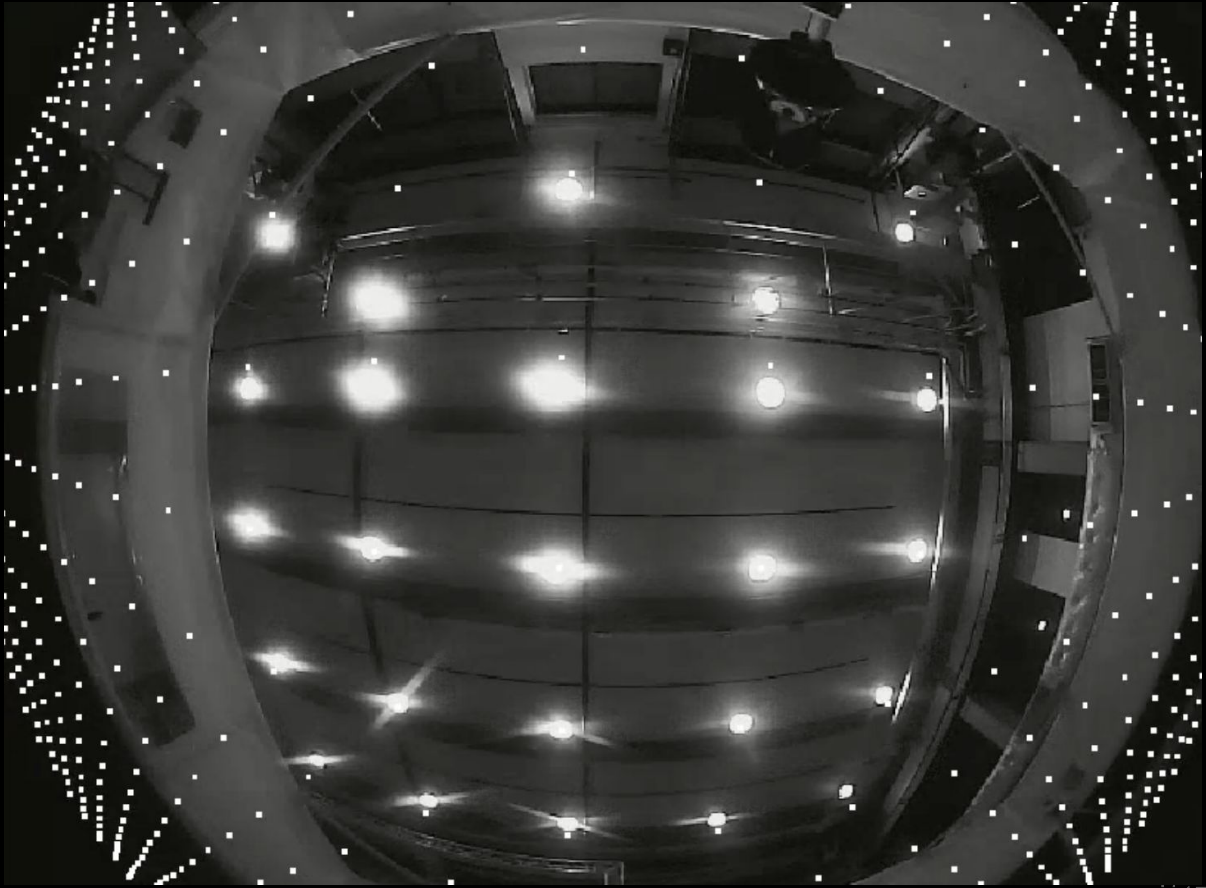
Regress to Sky Grid

↓

Calculate Pixel Offset

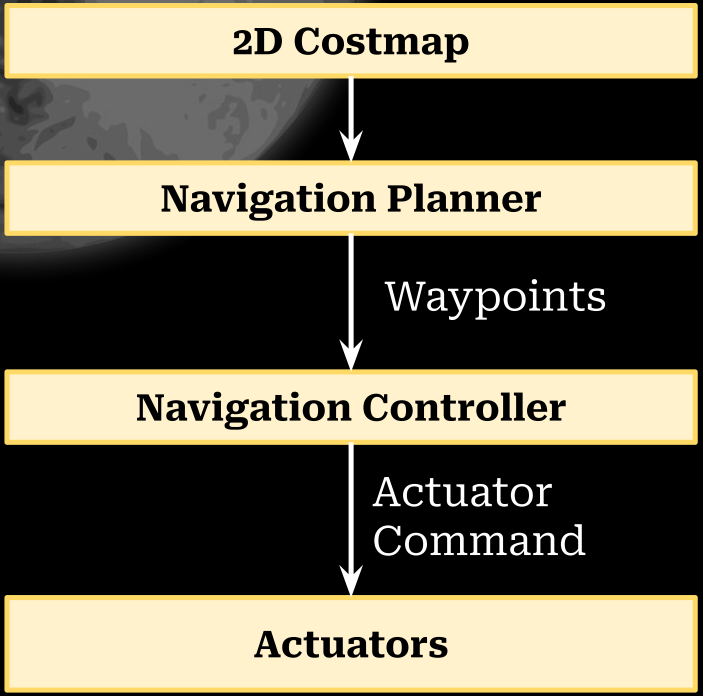
↓

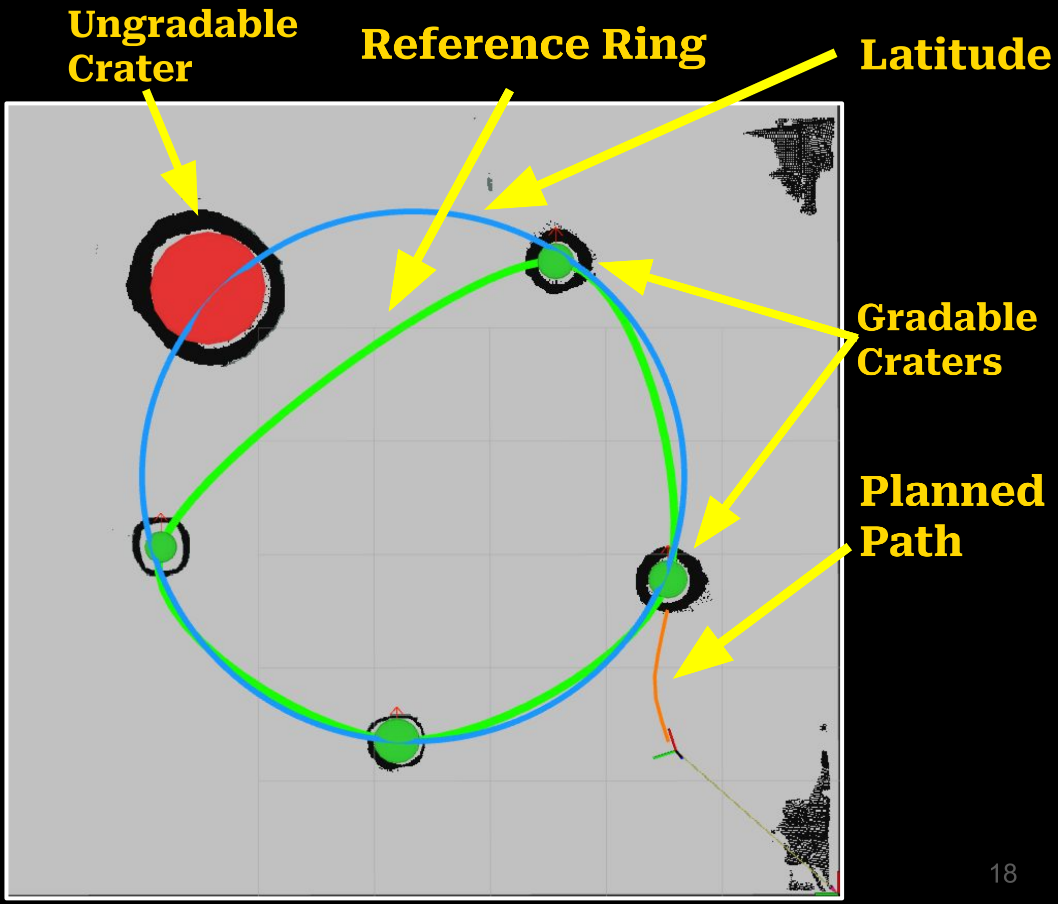
Reproject to 3D



Navigation

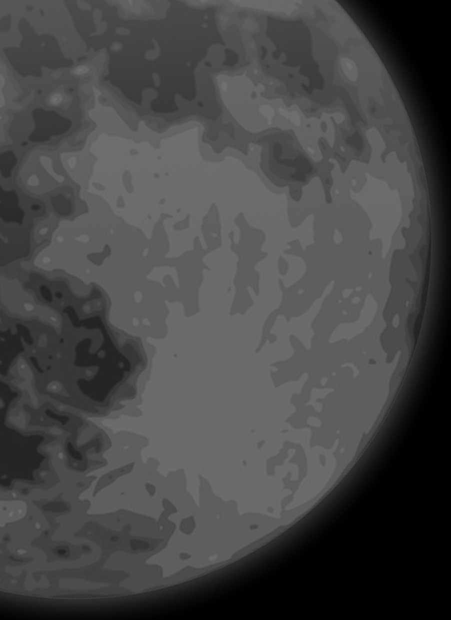
Navigation Planner: Lattice A* with Ackermann Primitives
Navigation Controller: Pure Pursuit





Behaviour Executive Node

Demonstration Video



Results

M.P.1: Plans a path with cumulative deviation of **<= 25%** from chosen latitude's length (due to untraversable terrain)

Radius of reference latitude = 2.33 m

Reference Latitude length = 14.66 m

Planned Path Length (m)	Deviation (m)	Deviation %
11.09	3.57	24.34%
11.51	3.15	21.47%
11.11	3.55	24.20%
11.51	3.15	21.47%
11.29	3.37	22.97%

Least: 21.47%

Max: 24.30%

Mean: 22.89%

Result: Satisfies requirement and rover plans path with average deviation of **22.89%** from reference latitude.

M.P.2: Follows planned path to a maximum deviation of 10% (due to localization/navigation error)

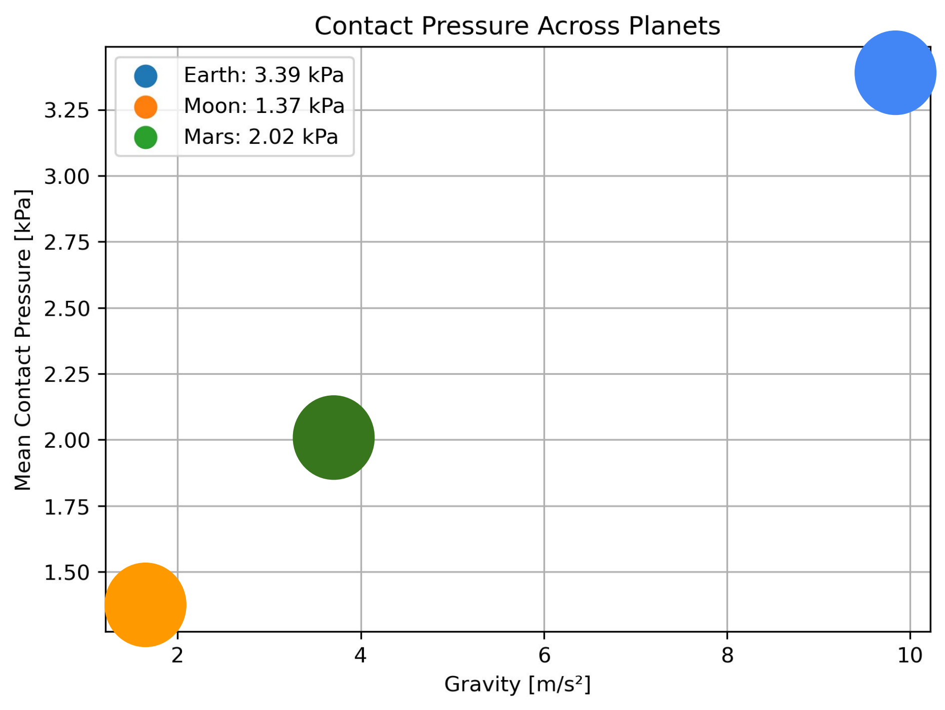
Radius of reference latitude = 2.33 m   Reference Latitude length = 14.66 m

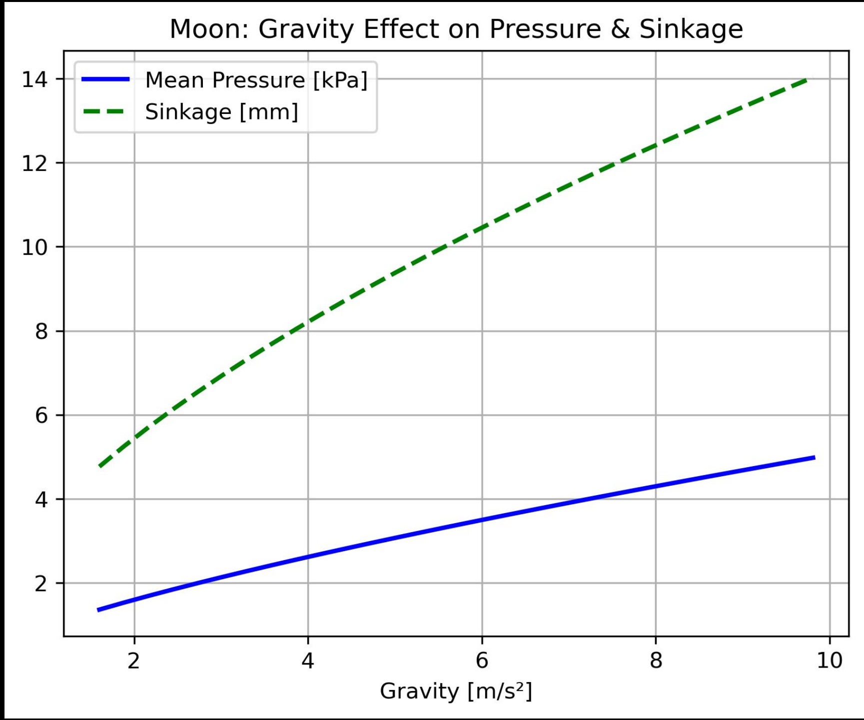
Planned Path Length (m)	Actual Traversed Path (m)	Deviation (m)	Deviation %
11.09	9.65	1.44	12.98 %
11.51	12.97	1.46	12.68 %
11.11	11.42	0.31	2.79 %
11.51	10.76	0.75	6.52 %
11.29	11.28	0.01	0.09 %

Least: 0.09 %   **Max: 12.98 %**   **Mean: 7.01 %**

Result: Satisfies verification criteria and rover follows planned path with average deviation of **7.01 %.**

M.P.3: Has a **contact pressure <= 1.5kPa**



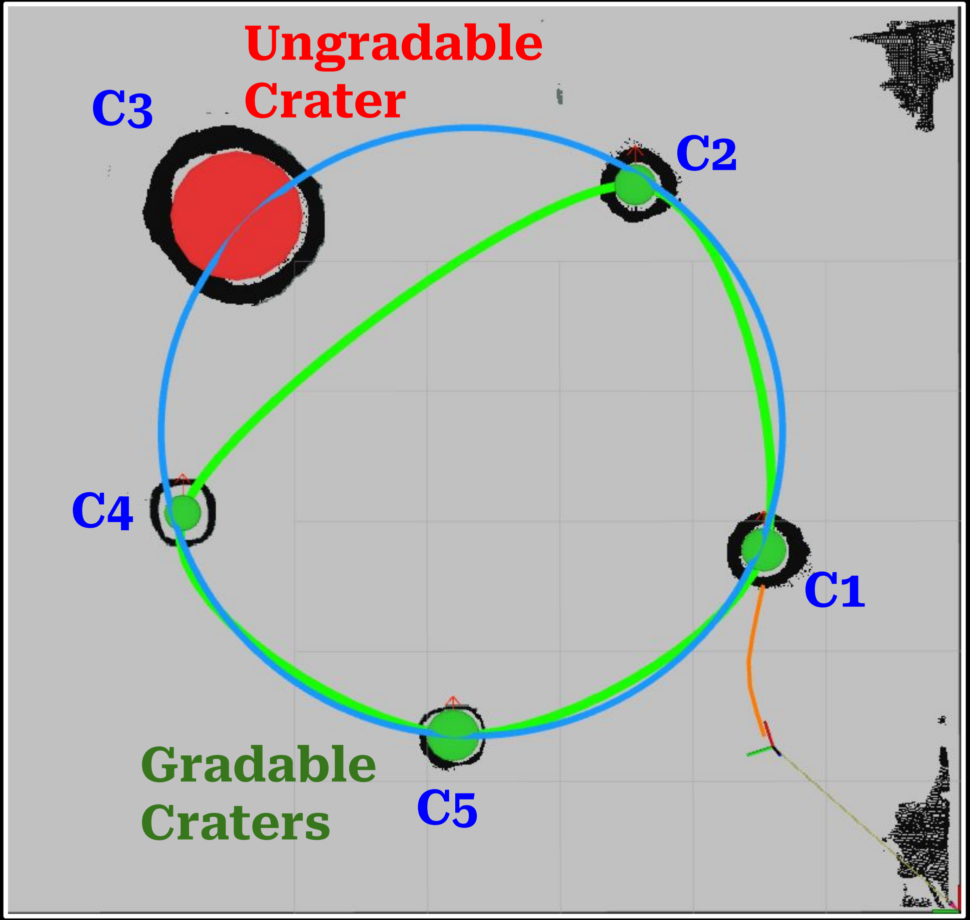


Contact Pressure of the ROADSTER on the Moon - 1.37kPa (0.199 psi)

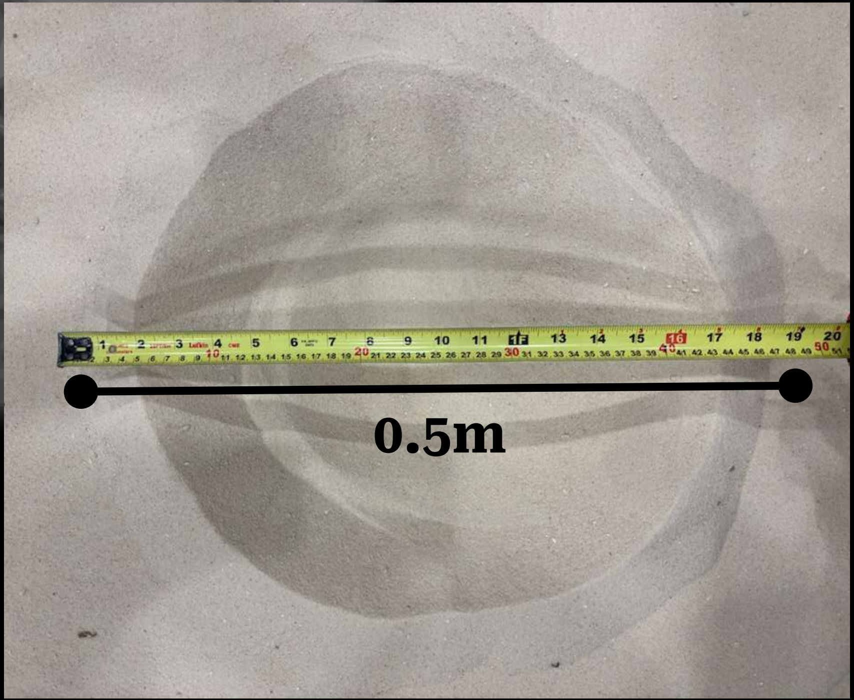
M.P.4: Avoids craters >= 0.5 meters

Gradable Craters Diameter and Location (Centroid):

- **Crater C1:**
  Diameter: 0.34 m
  Centroid: X=2.78 m, Y=1.466 m
- **Crater C2:**
  Diameter: 0.32 m
  Centroid: X=5.58 m, Y=2.431 m
- **Crater C4:**
  Diameter: 0.28 m
  Centroid: X=3.043 m, Y=6.126 m
- **Crater C5:**
  Diameter: 0.4 m
  Centroid: X=1.372 m, Y=3.803 m



M.P.5: Fills craters of up to 0.5 meters in diameter and 0.1 meters in depth



Grading craters with diameter <=0.5m and Depth <=0.1m

Functional Requirements

Sr. No.	Mandatory Functional Requirement	Result
M.F.1	Shall perform trail path planning	✅ Demonstrated
M.F.2	Shall operate autonomously	✅ Demonstrated
M.F.3	Shall localize itself in a GPS denied environment	✅ Demonstrated
M.F.4	Shall navigate the planned path	✅ Demonstrated
M.F.5	Shall traverse uneven terrain	✅ Demonstrated

Functional Requirements

Sr. No.	Mandatory Functional Requirement	Result
M.F.6	Shall choose craters to groom and avoid	✅ Demonstrated
M.F.7	Shall grade craters	✅ Demonstrated
M.F.8	Shall validate grading and trail path	✅ Demonstrated
M.F.9	Shall communicate with the user	✅ Demonstrated

Non-Functional Requirements (Mandatory)

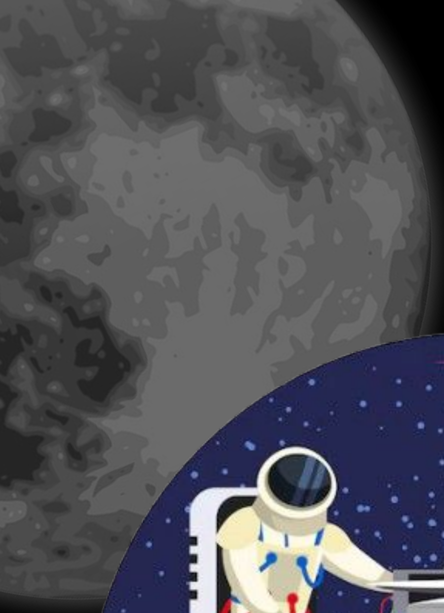
Sr. No.	Parameter	Description	Result
M.N.1	Weight	The rover must weigh under 50kg	✅ Achieved - 23.8 kg
M.N.2	Cost	The cost for the project must be under $5000	✅ Achieved - $4,995 (MRSD Budget)
M.N.3	Computing Capacity	The onboard computer should be able to run all required tasks	✅ Achieved (Shown in appendix)

Non-Functional Requirements (Desirable)

Sr. No.	Parameter	Description	Result
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 - Code comments and Notion page
D.N.2	Aesthetics	Requirement from sponsor, the rover must look presentable and lunar-ready	✅ Achieved - Verified with Sponsor
D.N.3	Modularity	To enable tool interchangeability, the tool assemblies must be modular	✅ Achieved - The tool assembly can be mounted and re-mounted easily
D.N.4	Repeatability	The system will complete multiple missions without the need of maintenance	✅ Achieved - Several test runs without maintenance

Colonize the Moon!

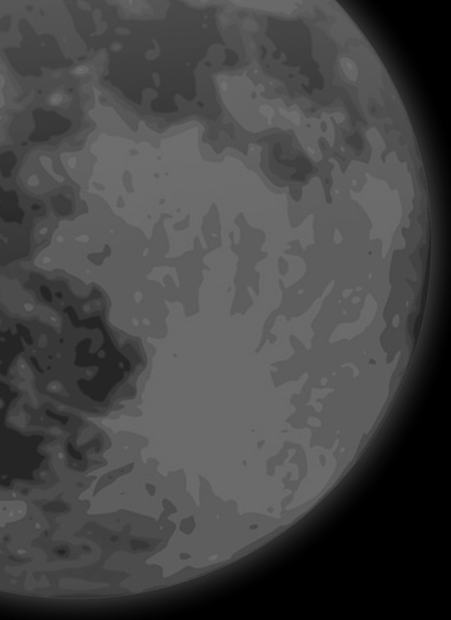
- *Team Lunar ROADSTER*



Acknowledgements

- Professor William 'Red' Whittaker - Project Advisor
- Dr. John Dolan and Dr. Dimitrios Apostolopoulos - Course Advisors
- Tim Angert - Workshop Supervisor
- Team CraterGrader
- Dr. Wennie Tabib
- Warren 'Chuck' Whittaker
- Dr. David Wettergreen

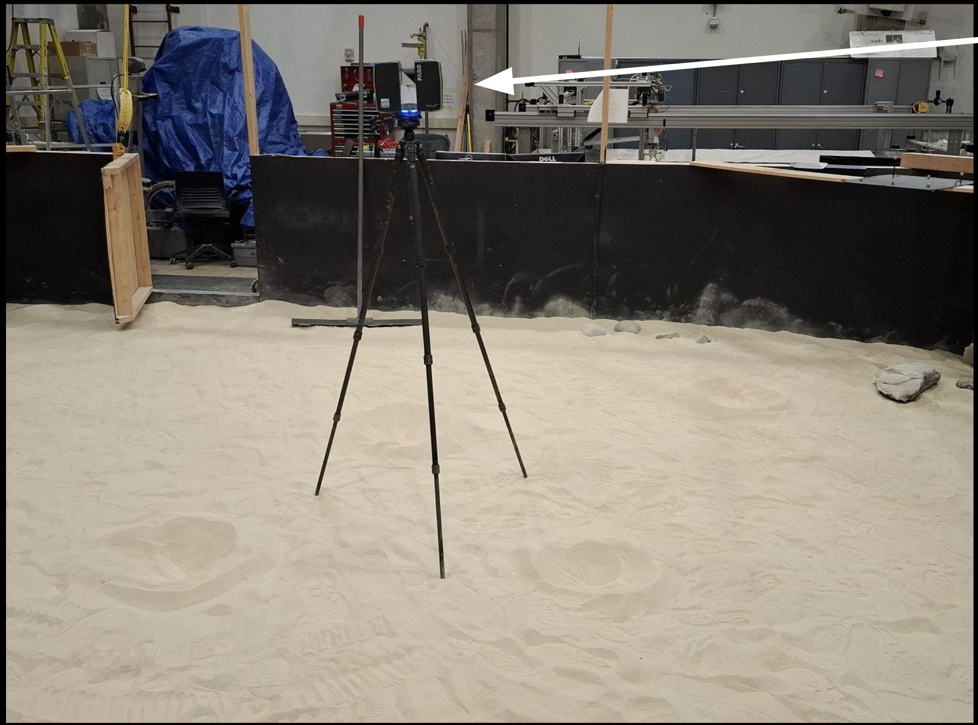
"Starting with a foothold on the Moon, we pave the way to the cosmos"

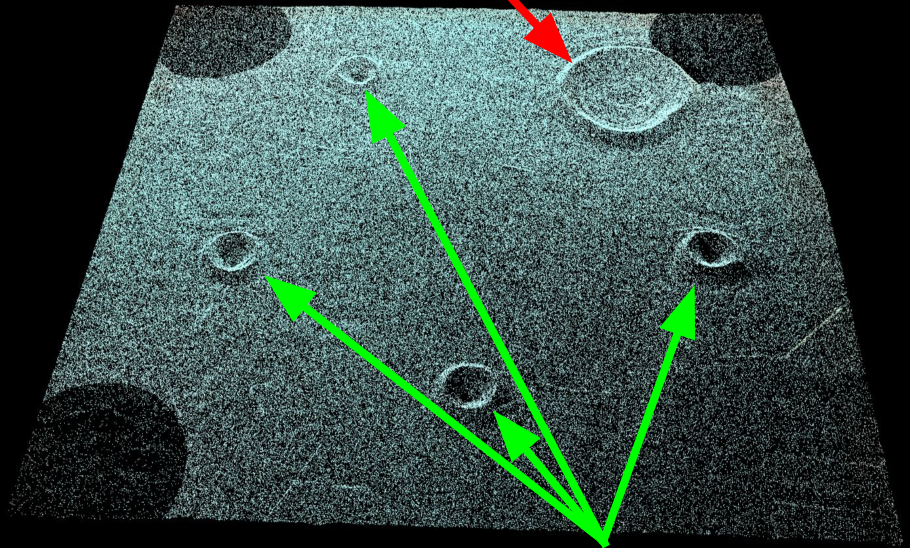


Appendix

Prepare test environment (Moonyard)

FARO Scanner

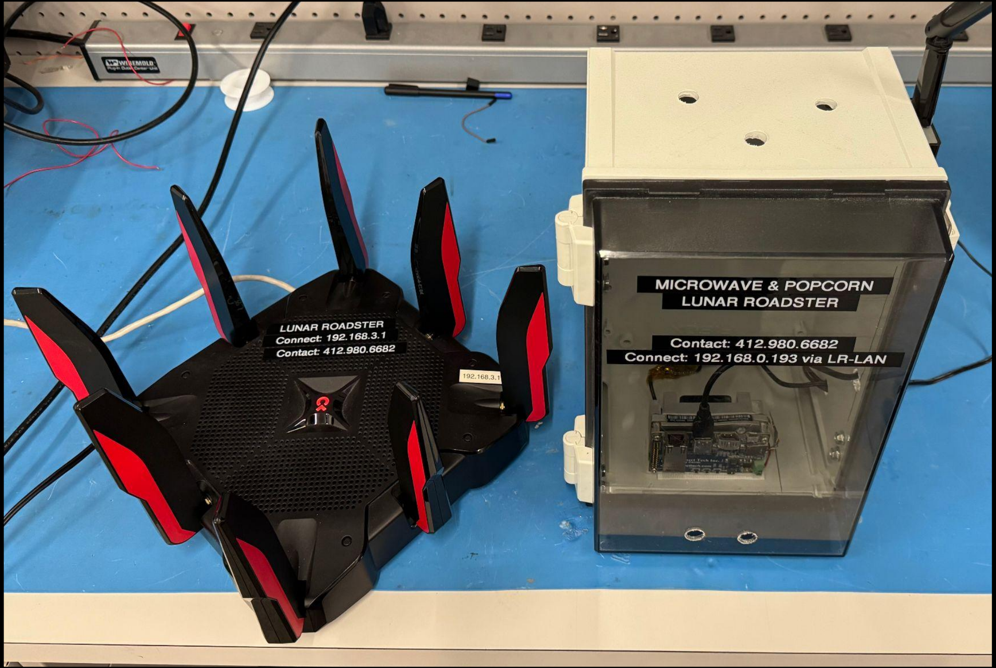




Obtain global map using FARO Scanner

Localization Setup

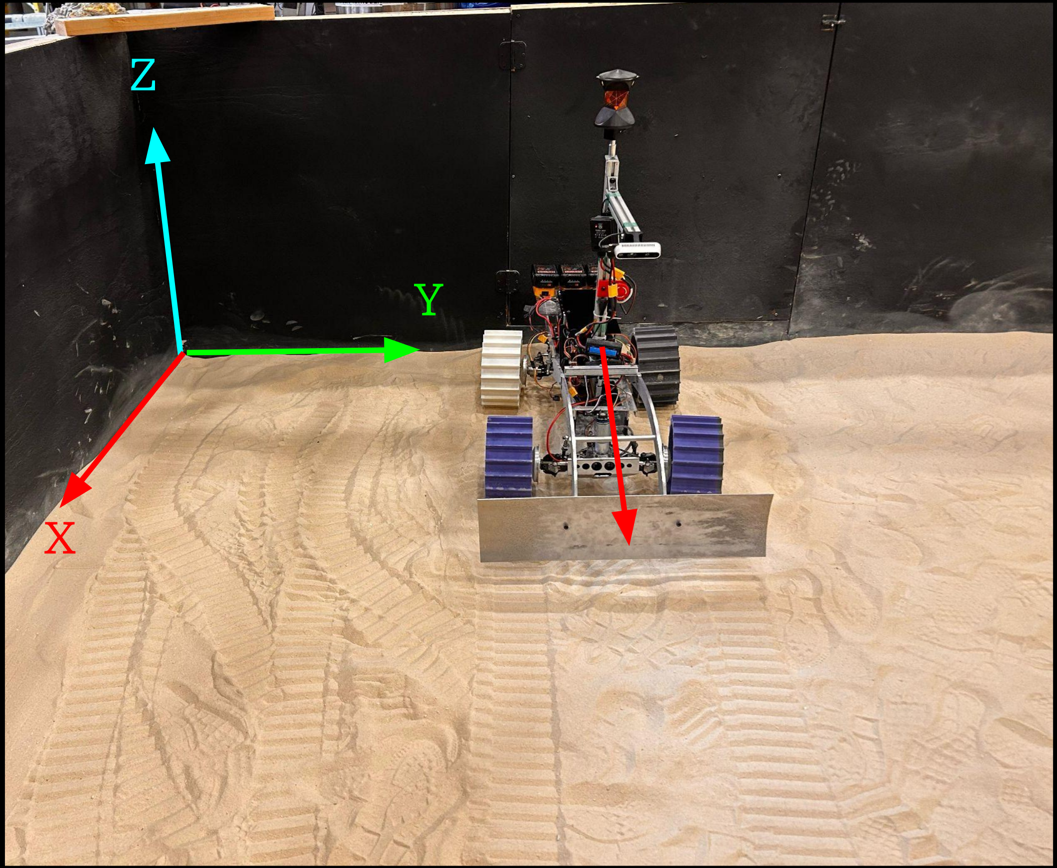
Leica TS16 Total Station



LAN Router & TX2 Relay

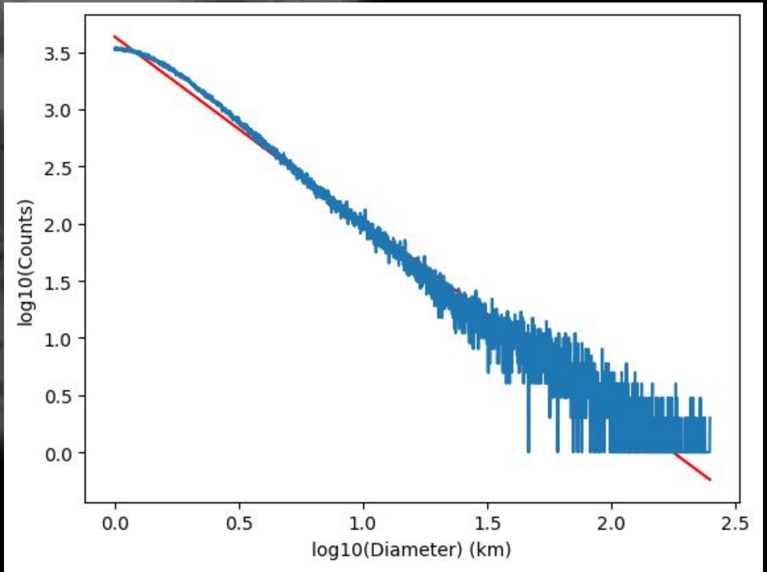
Set up external infrastructure

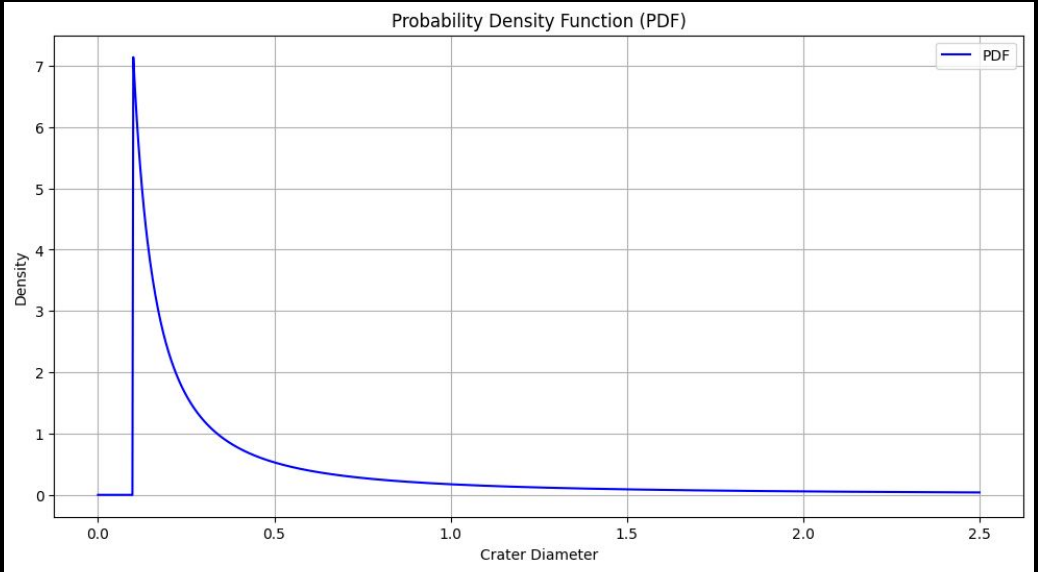
Yaw Calibration



Calibrating relative heading angle (yaw)

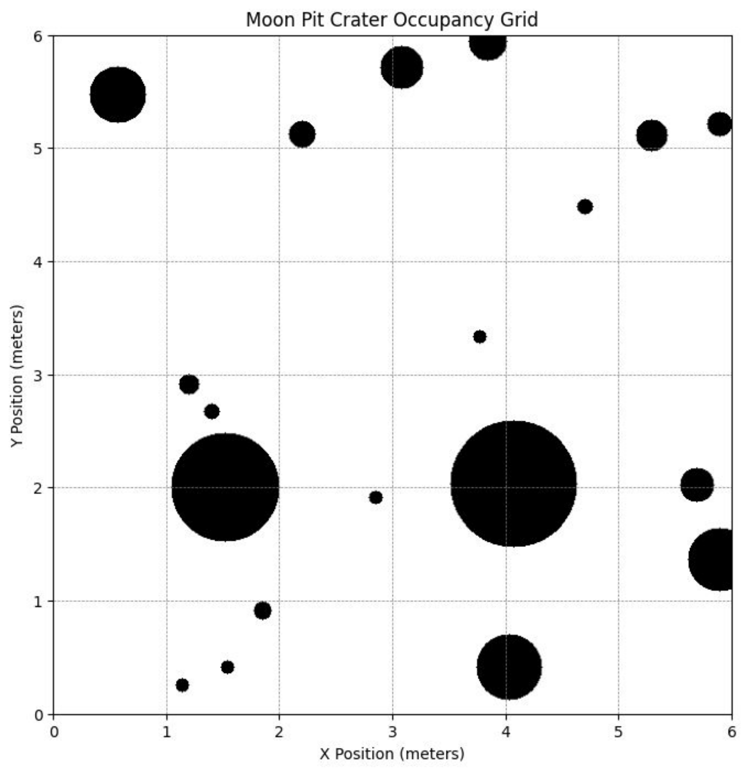
Moon Pit Crater Distribution

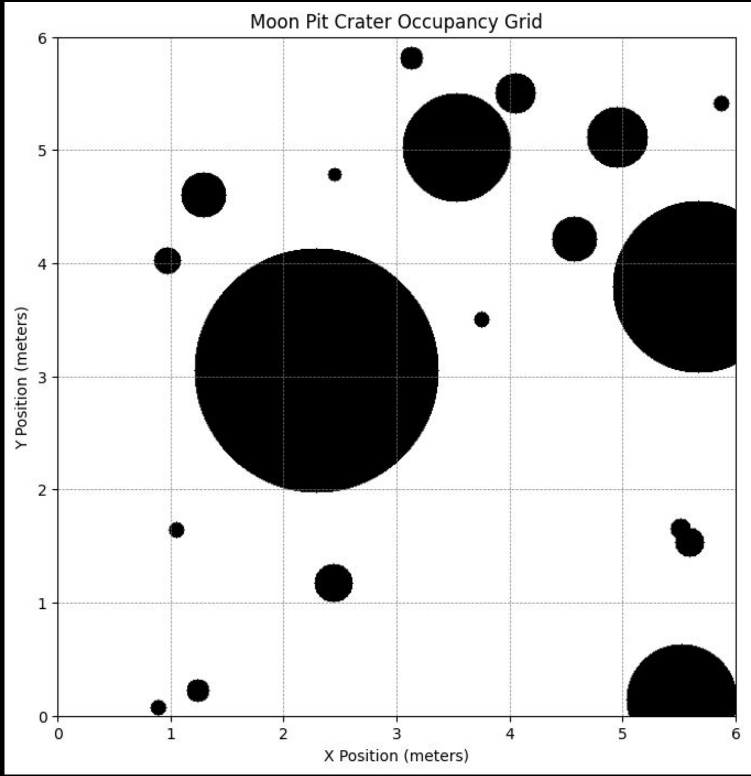




1. Raw data is read from the Lunar Crater Database (Robbins 2018)
2. A PDF and CDF is calculated based on a log-log fit linear regression model.
3. Then, we estimate the number and size of craters that would occur in a 6x6m area (assuming the size of craters to be restricted between 0.1 and 2.5m diameter).

Moon Pit Crater Size Distribution

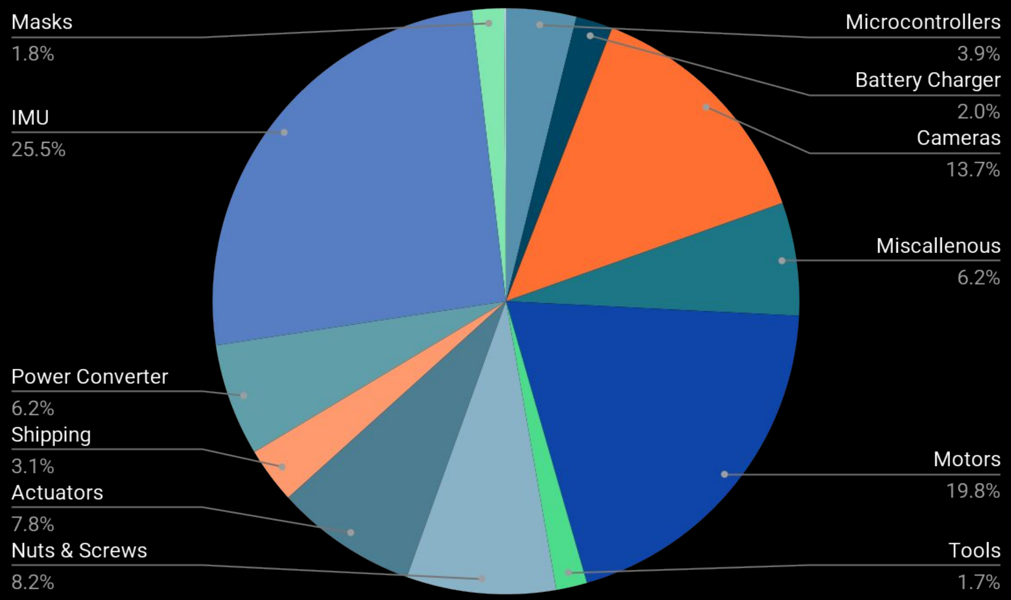




The majority of the data collection and processing is attributed to the Moonshot Circumnav Pathfinding team, and the crater generation code is attributed to Guo Ning (Andrew) Sue. William adapted it to fit the project scope.

Cost

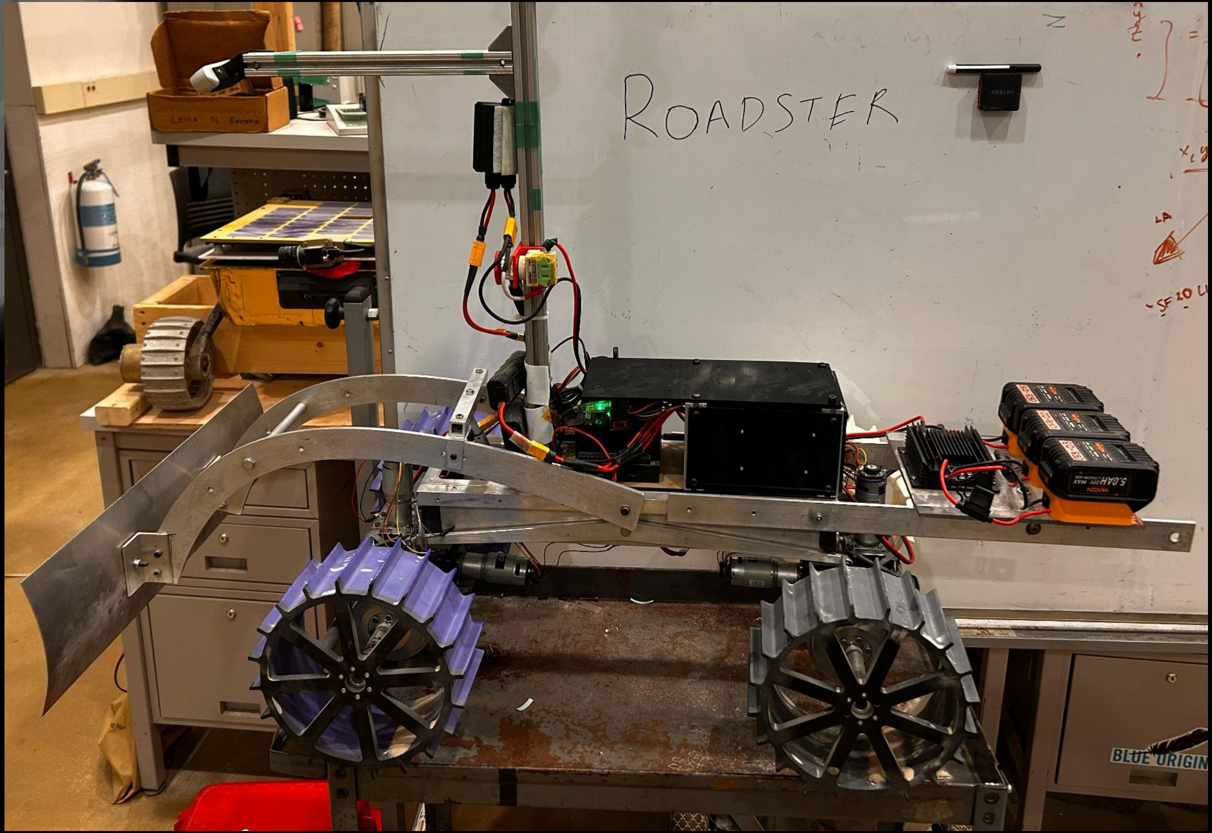
MRSD Budget	MRSD Budget Spent ($)	MRSD Budget Spent (%)	Total Budget Spent*	Remaining Balance
$5,000	$4,995.09	99.90%	$8,065.09	$4.91



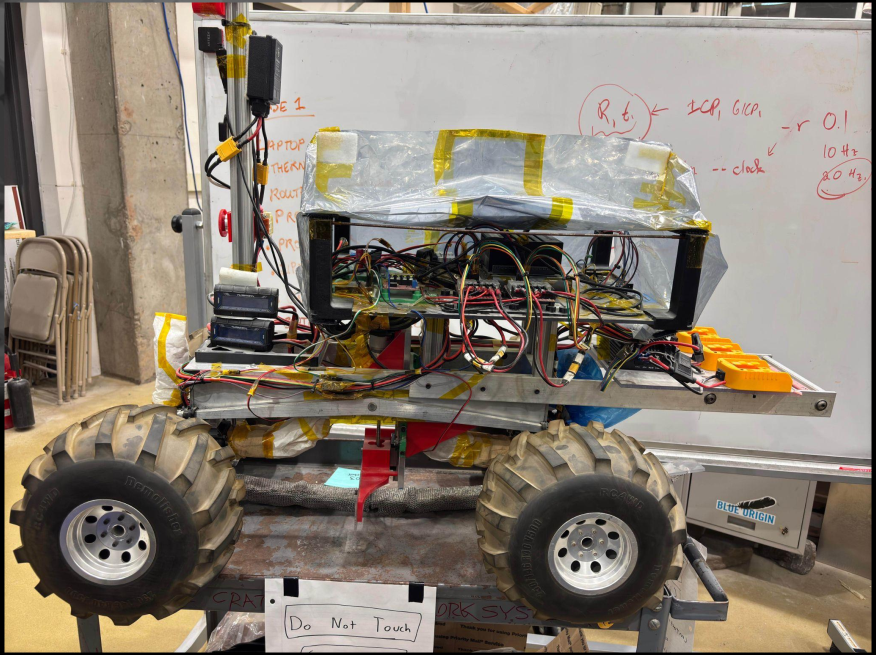
* Includes $3,070 worth of items inherited from Crater Grader and Supervisor

Out with the old...

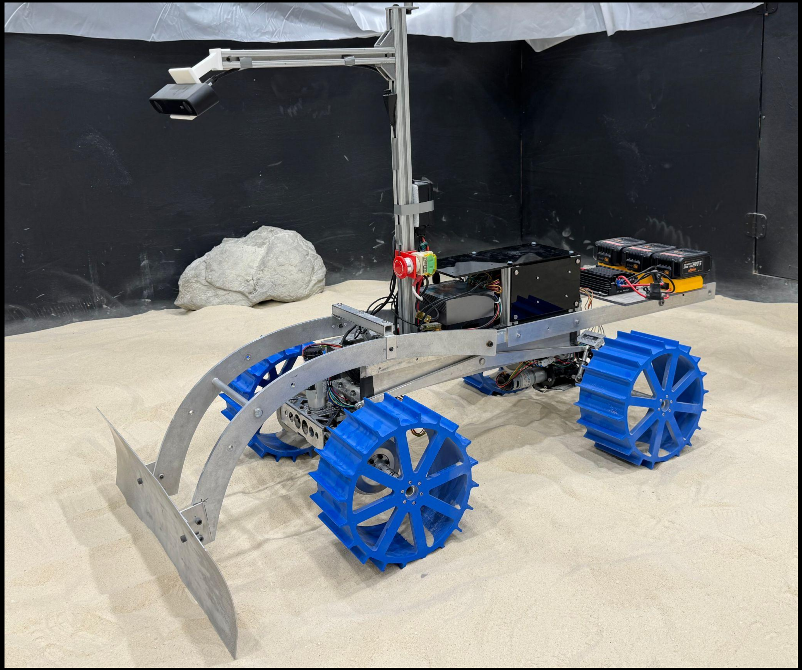
In with the new!



CraterGrader - - - - → Lunar ROADSTER



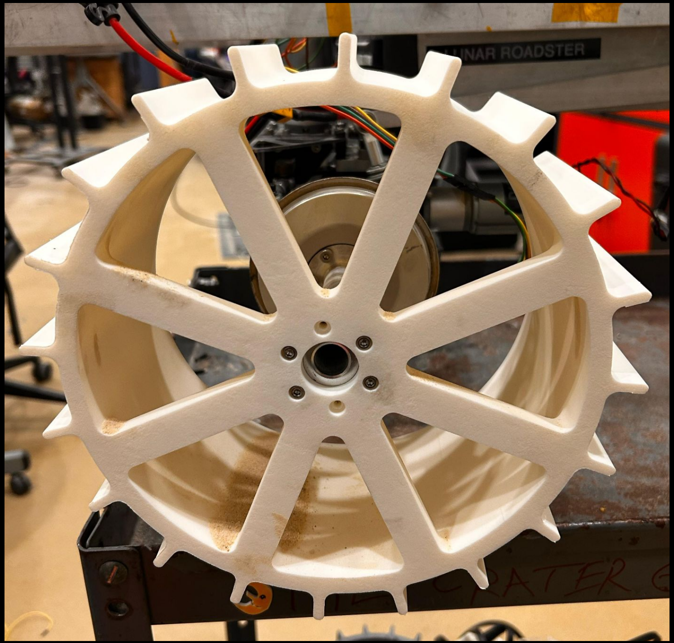
Before



After

Stock Wheels - - - - → Lunar Wheels

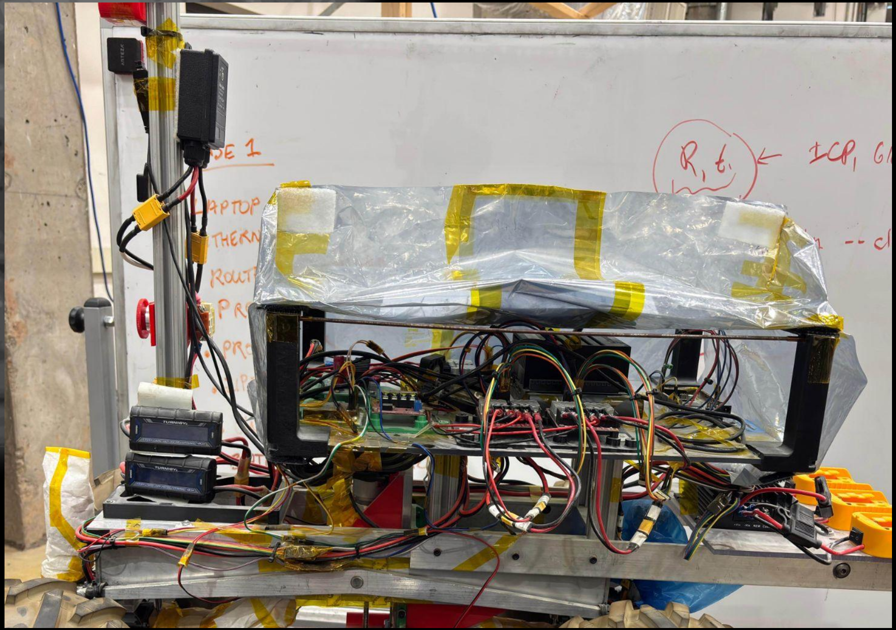
Before



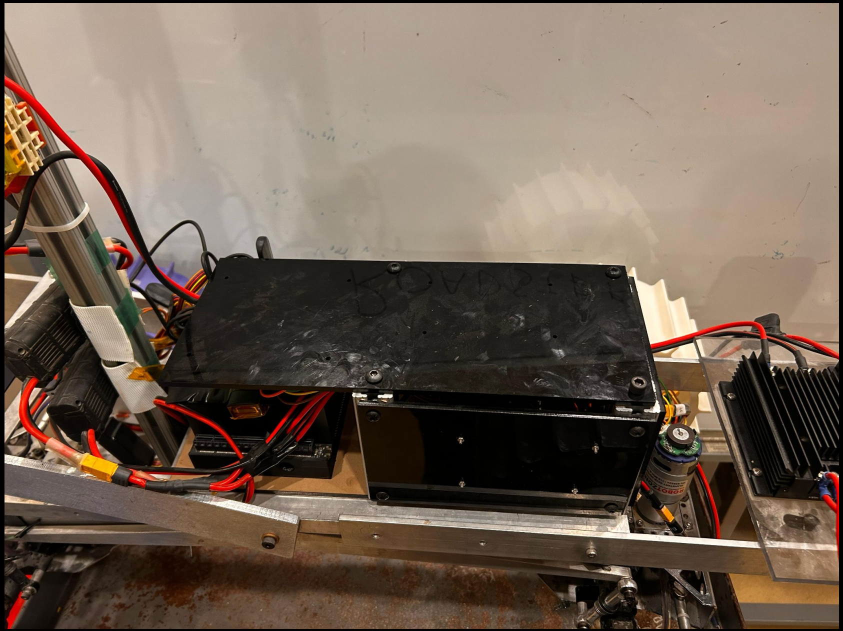
After

Wheel with more rimpull, coupled with higher torque motors results in higher traction generation

Cluttered Wiring - - - - → Compact E-Box



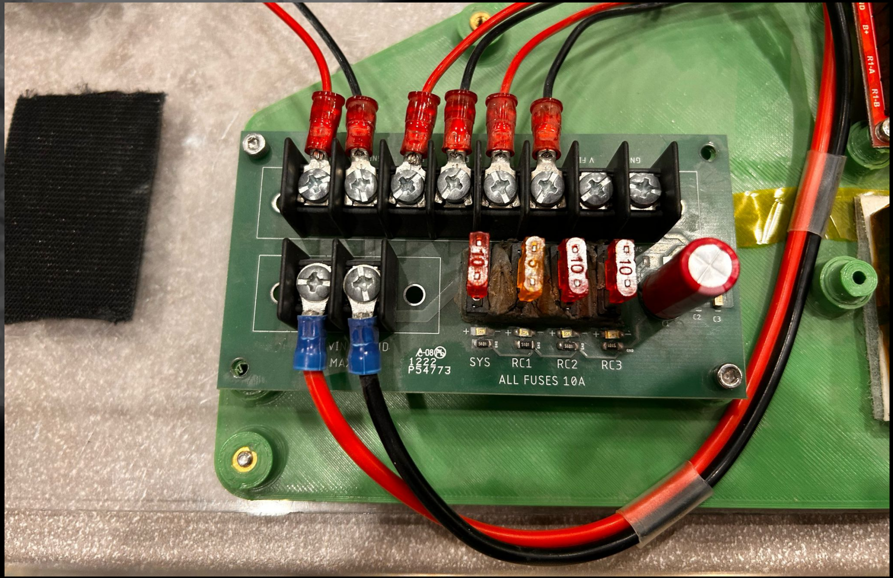
Before



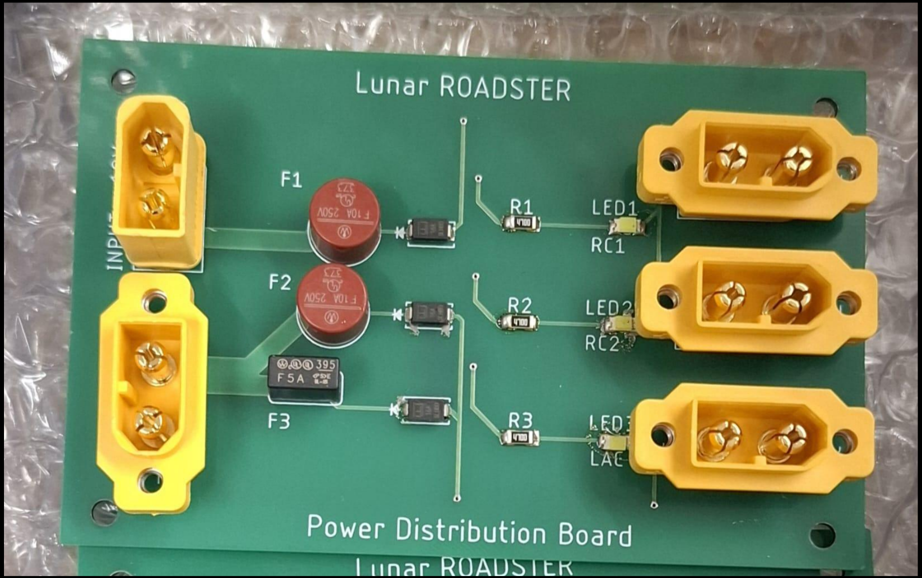
After

Custom PCB with an enclosed compact design creates more finished and reliable onboard circuitry

Improved Power Distribution Board



Before

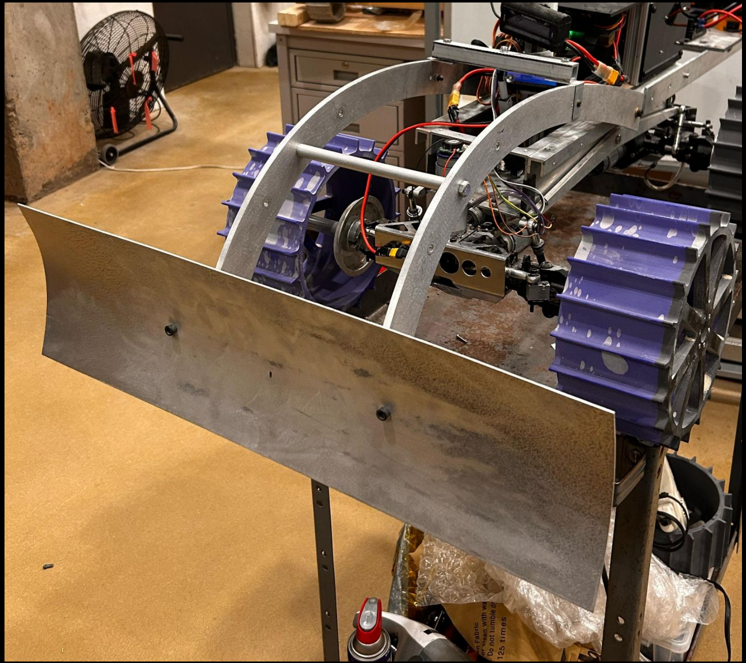


After

New design featuring OVP/RVP along with XT60 terminals for ease of assembly and reliability, has been fully integrated into the system.

Central Grader - - → Frontal Dozer

Before

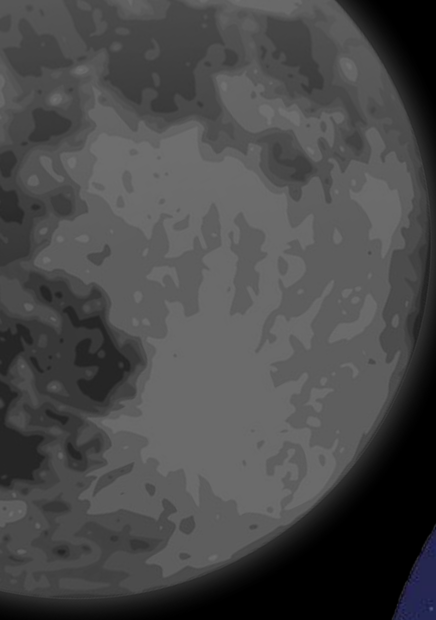


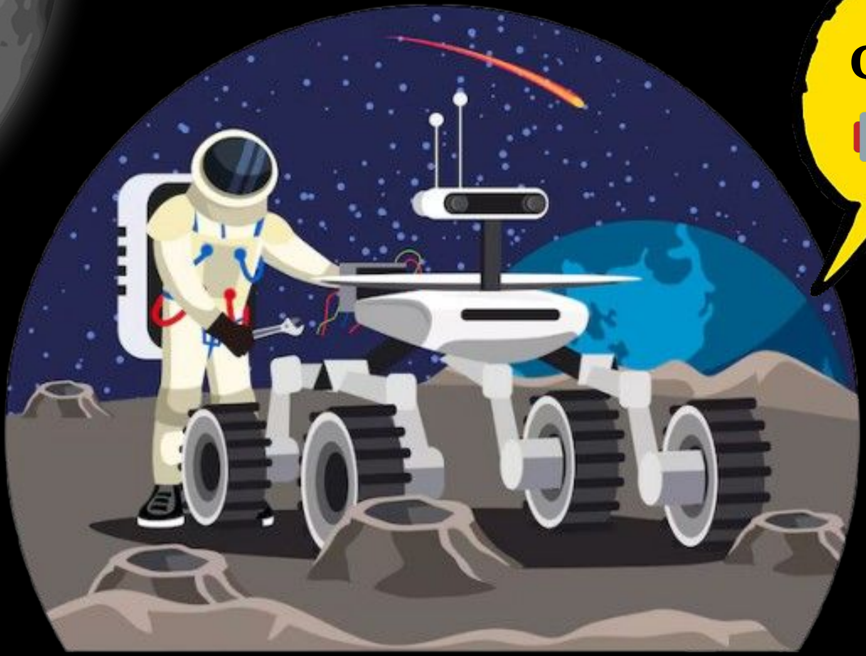
After

Frontal tool enables increased dozing area while maintaining stable wheel-ground contact

Colonize the Moon!

- *Team Lunar ROADSTER*





Questions?
🤖🦾🚀

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