# Excavation and Driving Performance of the PRIMROSE Rover during the Break the Ice Lunar Challenge


Presented by: Marcello Guadagno

Ph.D. Candidate – Planetary Surface Technology Development Lab

*Authors: M.C. Guadagno, A.J. Goddu, M.M. Decker, & P.J. van Susante*


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SPACE RESOURCES ROUNDTABLE

# The Break the Ice Lunar Challenge

- **NASA Centennial Challenge from 2020 to 2024**
  - Compete for prize money - open to anyone
  - Down-selection to next level
- **Goal: Develop excavation and transport system for lunar water-ice ISRU architecture**
  - Deliver >10,000 kg water per year
  - Develop mobility and excavation system
  - Demonstrate functionality
- **Our team in the PSTDL competed over whole event**
  - Three iterations of our rover will be shown

**Phase 1**
- 11/20 – 6/21
- System architecture

→

**Phase 2, Level 1**
- Due 12/22
- Detailed engineering design

→

**Phase 2, Level 2**
- Due 10/23
- Full-scale prototype long duration testing

→

**Phase 2, Level 3**
- 1/24 - 6/24
- Gravity offload & difficult terrain testing

# Phase 1 Design

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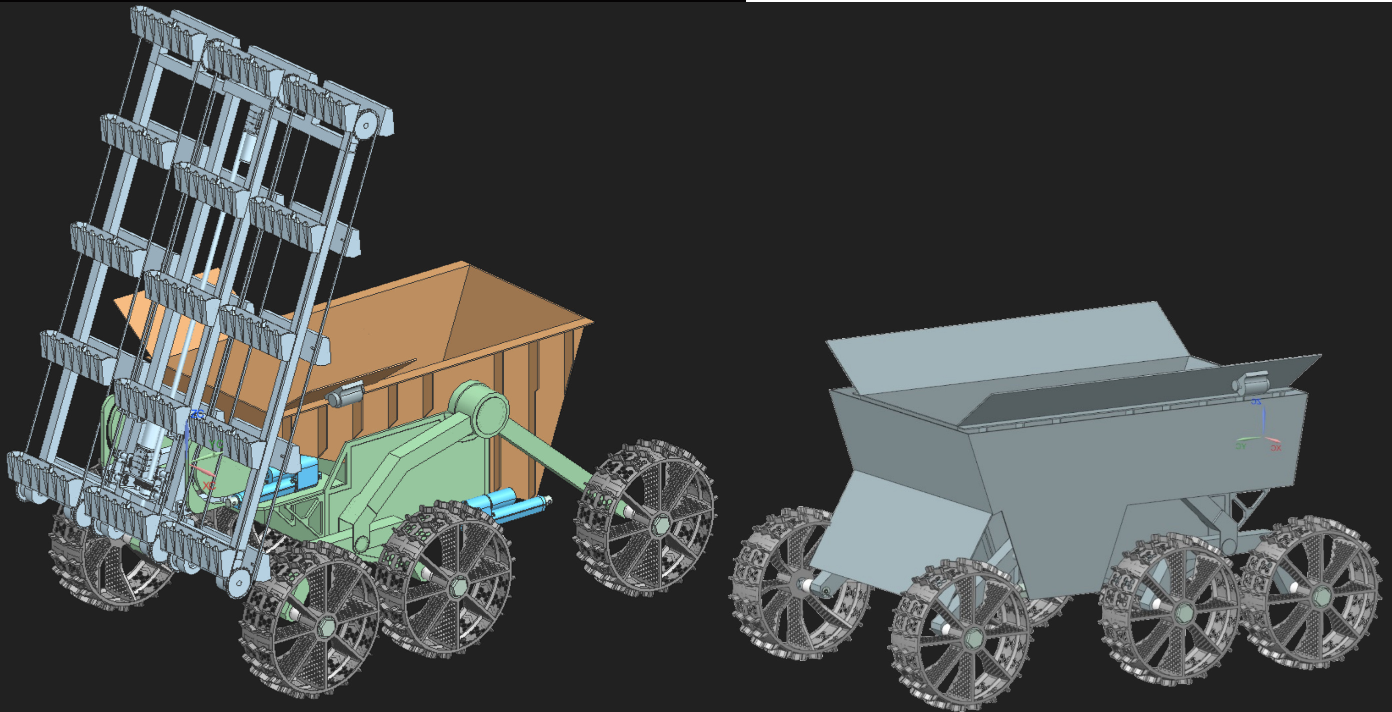
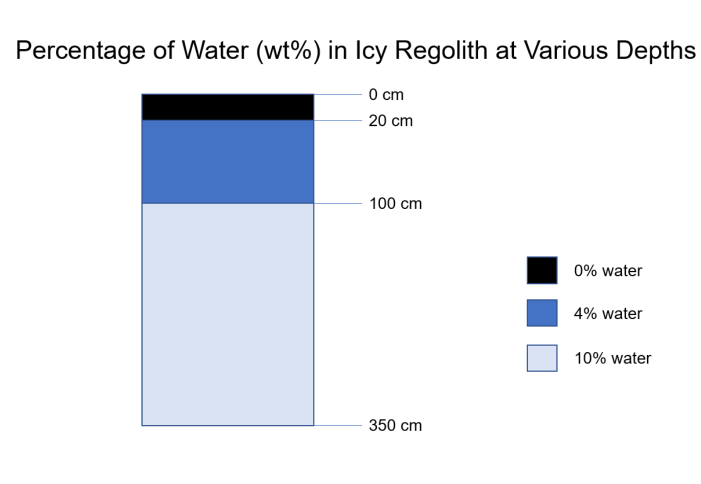
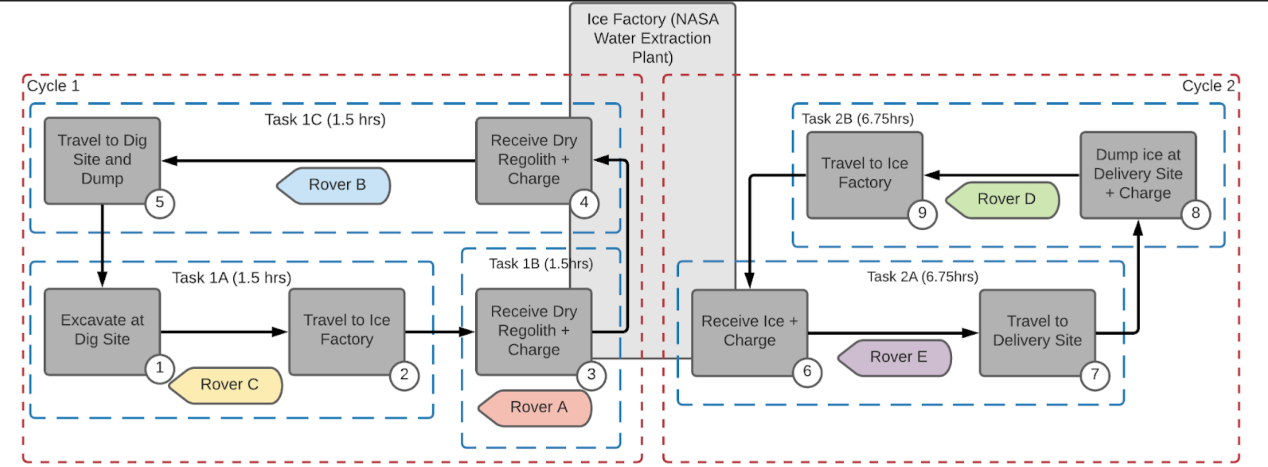
- **Our Initial Solution**
  - 2 Bucket ladder excavators
  - 3 Ice haulers
- **Performance Estimates**
  - 10,000 kg of water in 140 days
  - 1820 kg total landed mass
  - 1560 kW-hr to dig & transport
    250,000 kg of regolith to refinery
- **Won a runner-up prize**



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# Phase 2, Level 1 Design only

**New Requirements**

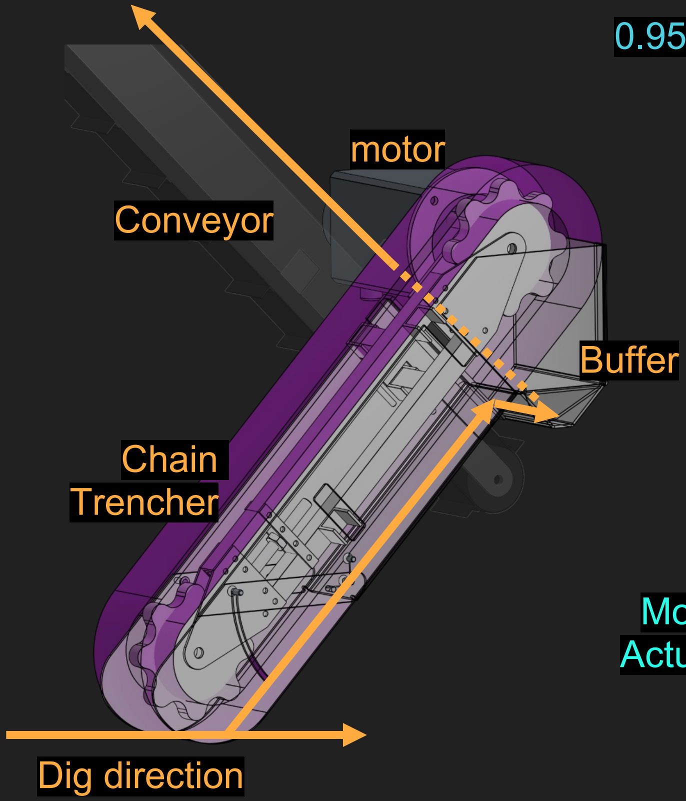
- Excavate CLSM with 2 MPa compressive strength & drive 0.5 km each way.
- 15-day demonstration @ 800 kg/day

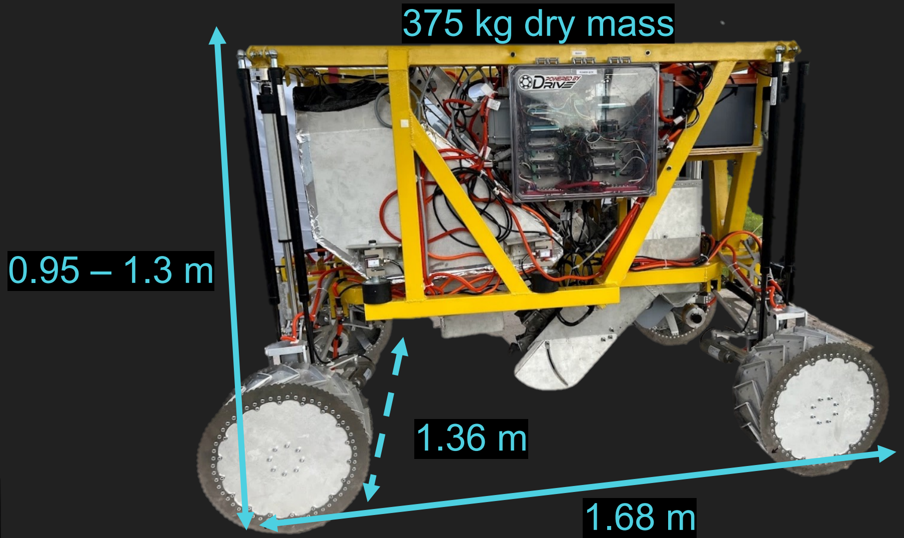
**A New Rover: PRIMROSE**

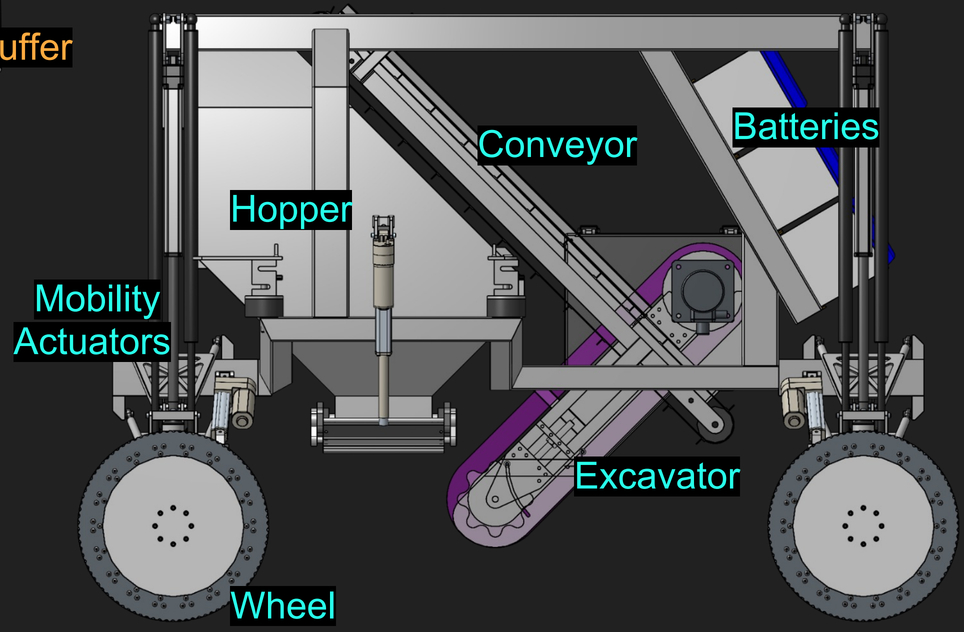
- *Prototype Regolith In-Situ Mining Rover with Onboard Surface Excavator.*
- All-in-one solution with chain trencher and hopper, and independently driven and actuatable wheels

**Why this configuration?**

- More reactive mass to counteract increased excavation forces
- Mobility configuration allows for better control for obstacle traverse & excavation
- Cheaper/easier to build




**Built and designed in 9 months!**

# Phase 2, Level 2 15-day Performance Durability Demonstration Test

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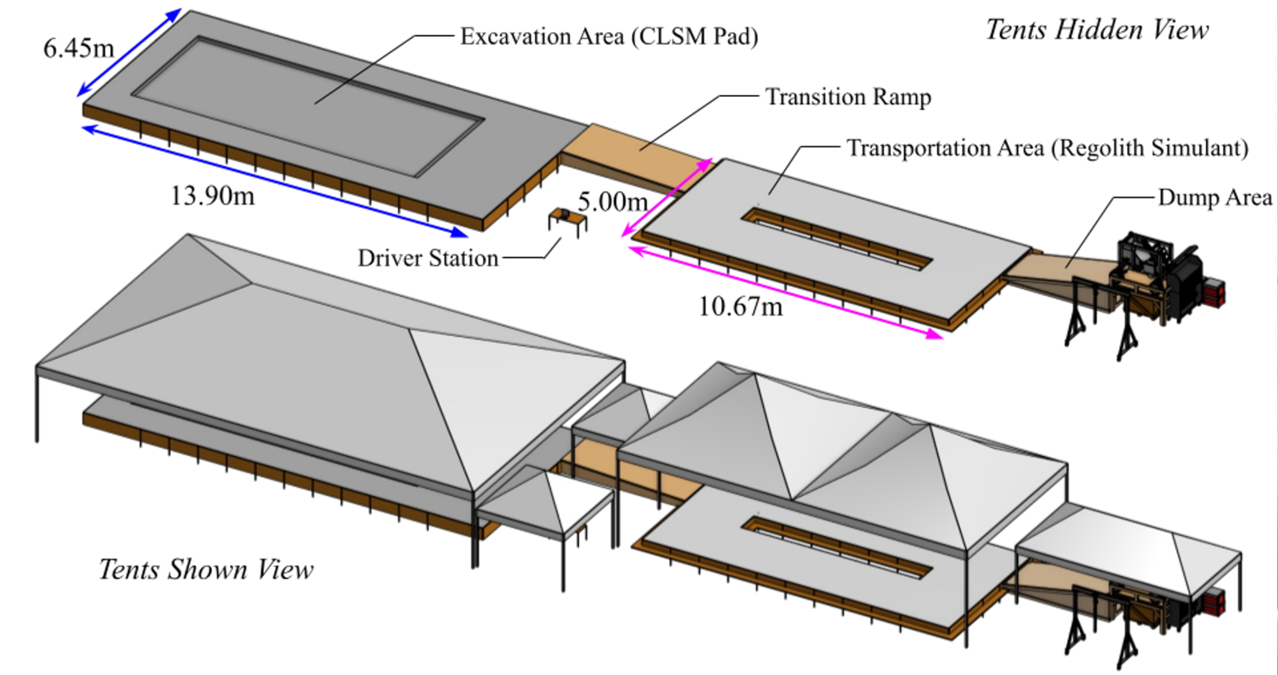
**Site Setup**

- Digging, travelling, and dumping for 15 days straight, 24/7 supervision.
- Setup a tent city, laid 50,000 kg bed of CLSM, prepared 16,000 kg track of lunar regolith simulant.

**Overall Performance**

- Collected 2990 kg of CLSM, using 61 kW-hr of energy, 256 hr run time, and 480kg total landed mass.

**Selected as one of 6 to go to Level 3, we were one of 3 runner ups**




# Phase 2, Level 2 15-day Performance

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**Performance Metrics:**

- 30-70 kg/hr excavation rate. Only 40% of dug up material made it to the hopper.
- Drove 30 km in lunar regolith simulant at up to 40 cm/s.
- Had to reduce hopper load from 270 to 100 kg due to degrading regolith road.

**Main Lessons Learned:**

- Mobility system needed to improve across the board.
- Rover could easily dig CLSM, but it was not retained.
- Comm system needed improvements
- Durability needed work


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# Phase 2, Level 3 Scenario & Refactor

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## The Level 3 Scenario:

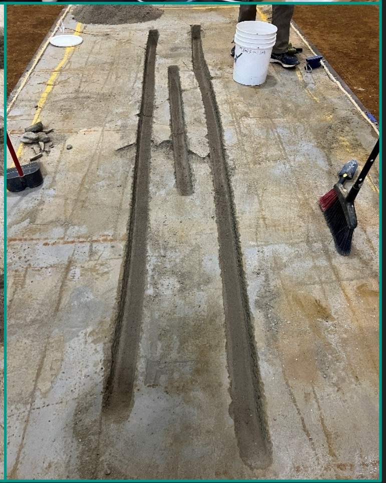
- Gravity offloaded CLSM excavation
- Large gravel track with obstacles
- Time available after competition to test rover

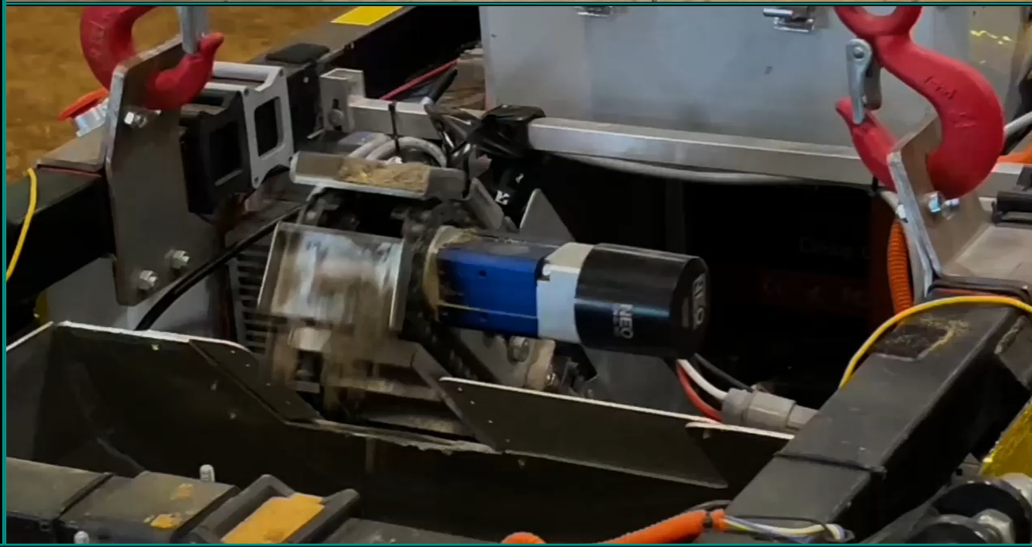
## Major Changes to PRIMROSE:

- 7 months to implement changes to design
- Focused on improving durability,
- complete redesign of drivetrain/mobility system,
- more robust control system
- New picks added to trencher train & belt conveyor replaced with a "cladded" bucket chain.
- Improved material retention

# Excavation Event & Post-comp. Testing



# Excavation Mishaps

- **Only two excavator mishaps during competition & subsequent testing:**
  - Rover sliding
  - Chain failure
- **Causes:**
  - Rover sliding from too quick of initial plunges with an empty rover
  - After Competition during additional system testing: Conveyor failure from pushing rover beyond normal excavation rate to limit of 400 kg/hr and getting a large CLSM rock jammed.

**Rover sliding**

**Conveyor chain failure**

# Excavation Results

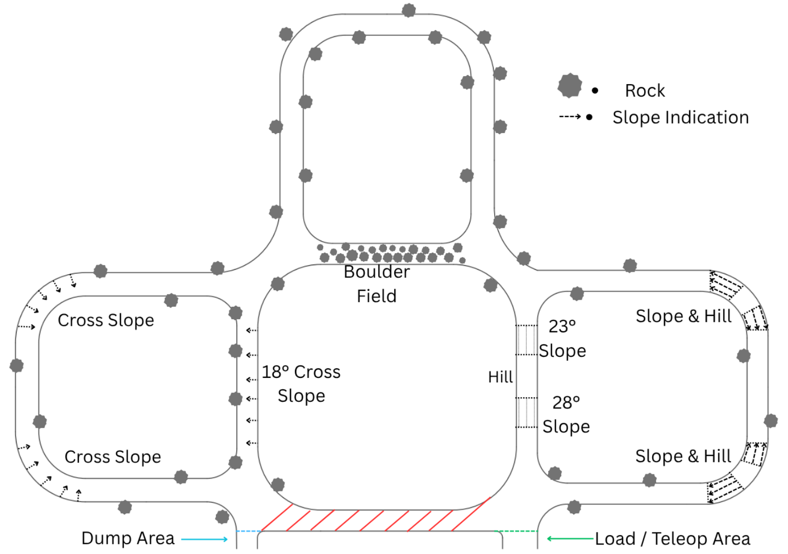
**Table**: Summary of PRIMROSE excavator performance during and after competition.

| Excavation Test # | Excavation time (min) | Collected material (kg) | Excavation Rate (kg/hr) | Energy Use (W-hr) | Specific Energy of Excavation (W-hr/kg) | Retention Ratio (%) |
|---|---|---|---|---|---|---|
| Sum for all Tests: | 177.43 | 493.26 | N/A | 1454.9 | N/A | N/A |
| Avg for All Tests: | 25.35 | 70.47 | 221.88 | 207.84 | 2.97 | 70.94% |

## Performance Notes

- Excavated at a rate of **173 kg/hr** in competition and maxed at **419 kg/hr** after competition.
- Dug 7 trenches in 3 CLSM beds with 10 x 15 x 300 cm dimensions.
- Performance is strongly dependent on operator experience & tuning control parameters.
- Only weighed material collected in hopper.
- Energy use includes total power use on PRIMROSE.
- All presented data was collected while gravity offloaded.

# Driving Event & Post-comp Testing




# Driving Results

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**Table**: PRIMROSE driving performance during competition.

| Travel Distance (m) | Travel time (min) | Energy Use (W-hr) | Dump Time (min) | Traverse Time (min) | Average Speed (m/s) |
|---|---|---|---|---|---|
| 230 | 18 | 150 | 1.6 | 16.4 | 0.23 |

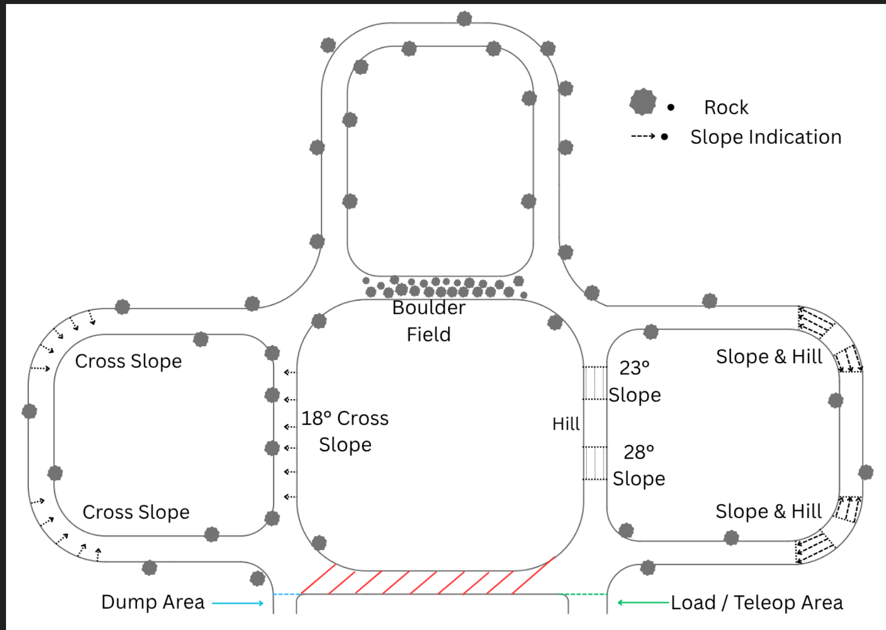
## Performance Notes

**During Competition:**

- Skipped every shortcut except 18° cross-slope

**After Competition:**

- Able to traverse every shortcut unloaded
- Unable to traverse 23/28° hill shortcut when fully loaded
- No difference in loaded vs. unloaded speed
- Traversing obstacles took double the power when loaded

# Extrapolated Performance

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## Performance Notes

- Using test data, PRIMROSE can collect 10,000 kg of $H_2O$ in 149 - 192 days.
- Performance is comparable to our Phase 1 estimations in 2021 which used 3 excavators.

| Scenario | | Time to completion (days) | Mass of ice delivered (kg) | Excavation & Refining Energy Use (kW-hr) | Total landed mass (kg)* | Landed mass to ice mass delivered Ratio (kg/kg) | Excavator Energy use to ice mass produced Ratio (kW-hr/kg) |
|---|---|---|---|---|---|---|---|
| Level 3 Comp. Data | To 10,000 kg | 192 | 10,000 | 1,268 | 1,855 | 5.39 | 0.13 |
| | To 1 year | 365 | 18,966 | 2,405 | | 10.22 | |
| Level 3 Best Case data** | To 10,000 kg | 149 | 10,000 | 1,156 | 1,855 | 5.39 | 0.12 |
| | To 1 year | 365 | 24,558 | 2,840 | | 13.24 | |
| Phase 1 Estimation | To 10,000 kg | 140 | 10,000 | 1,560 | 1,820 | 6.18 | 0.16 |
| | To 1 year | 365 | 28,869 | 4,067 | | 15.86 | |

** Total landed mass includes mass of excavator(s), NASA provided refinery and 2x of our 192kg hauling rovers from refinery to delivery location.*

*** "Best Case" data is if our excavator can maintain a 419 kg/s excavation rate and our hopper is able to be filled with 270kg of icy regolith.*

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# Conclusion & Moving Forward

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- Excavation testing is ongoing with beds of icy lunar regolith simulant. We build a new force test stand facility in a -40C freezer container for the campaign.
  - → See poster
- PRIMROSE chassis being used for several research grants, including testing lunar autonomy software with MTRI.



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# Acknowledgements

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## Michigan Tech Team, 2020-2024

Parker Bradshaw
Lucas Frank
Audrey Alexander
Mason Krause
Robin Austerberry
Hunter McGillivray
Collin Miller
Heather Goetz
Max Decker
Austin McDonald

Yamato Tajiri
Will Jennes V
Joe Primeau
Jay Sweeney
Mack Miller
Connor Dinkelmann
Matthew Oujiri
Faith Gartner
Ben Engle
Suhayb Zeqlam

Russell LaBeau
Austen Goddu
Greg Redlon
Kjia Moore
Dana Brouse
Brian Johnson
Will Galvin
Mohamed Salem
George Johnson
Paul van Susante

## Partners & Competition Sponsors

Vermeer

NASA's Break the Ice Lunar Challenge

NASA


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# BTIL Challenge Impact on Team

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| Michigan Tech Team, 2020-2024 | | |
|---|---|---|
| Parker Bradshaw | Yamato Tajiri | Russell LaBeau |
| Lucas Frank | Will Jennes V | Austen Goddu |
| Audrey Alexander | Joe Primeau | Greg Redlon |
| Mason Krause | Jay Sweeney | Kjia Moore |
| Robin Austerberry | Mack Miller | Dana Brouse |
| Hunter McGillivray | Connor Dinkelmann | Brian Johnson |
| Collin Miller | Matthew Oujiri | Will Galvin |
| Heather Goetz | Faith Gartner | Mohamed Salem |
| Max Decker | Ben Engle | George Johnson |
| Austin McDonald | Suhayb Zeqlam | Paul van Susante |

- Pursuing or completed MS/PhD in relevant field: **9**
- Internship or full-time job in relevant field: **7**
- Everyone else is still a student or got a job, outside of aerospace/robotics.
- Additionally, PRIMROSE is being used as a modular robotics test platform for various research grants & test contracts.

# Questions?


PC: *Greg Redlon*

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