Excavation and Driving Performance of the PRIMROSE Rover during the Break the Ice Lunar Challenge. M. C. Guadagno[1], A. J. Goddu[2], M. M. Decker[3], and P. J. van Susante[4]. [1-4]Dept. of Mechanical Engineering-Engineering Mechanics, Michigan Technological University 1400 Townsend Drive, Houghton, MI 49931 (contact: pjvansus@mtu.edu).

Introduction: To address the technological maturity gap in the ISRU value chain for cemented regolith excavation vehicles, NASA initiated the Break the Ice Lunar (BTIL) centennial challenge [1]. The final level of the competition called for creating complete rover-based architectures to excavate, transport, and deposit icy regolith simulant.

The excavation portion of the BTIL competition requires mining controlled low-strength material (CLSM), a weak concrete, while gravity offloaded to simulate lunar conditions. Gravity offloading poses a unique constraint as only ⅙ the weight would be available to react against excavation forces compared to a similar system on Earth. With relative ease, terrestrial systems can add more reaction mass or power to dig more material. Equivalent Lunar systems must limit mass and power use due to strict size, weight, and power, and cost requirements. Such realities are reflected in NASA's rubric for grading the BTIL challenge; most points are scored for architectures that maximize excavation and minimize total landed mass and energy use [2].

Thus, the Planetary Surface Technology Development Lab (PSTDL) [3] selected a single-rover solution to reduce the required total landed mass by combining regolith excavation and transportation duties into each vehicle. The hardware from each mission role also provided more reaction mass for excavation activities. This solution was named PRIMROSE: the Prototype Regolith In-Situ Mining Rover with Onboard Surface Excavator [4]. PRIMROSE uses conical point-attack picks set along a chain trencher's length to excavate icy regolith continuously. Four independently steered and actuated wheels are used for mobility and positioning the fixed excavation system (Figure 1). The resulting system has a 375kg dry mass with 1.55m wide, 1.95m long, and 1.35m tall dimensions.

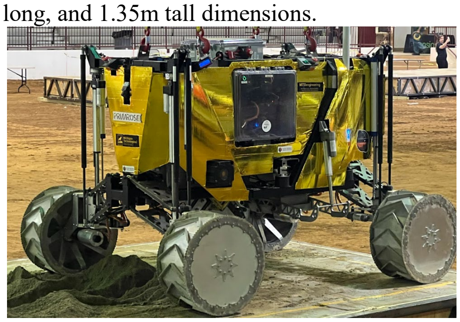

Figure 1: The PRIMROSE Rover.

In this abstract, the design decisions which lead to the current PRIMROSE configuration are discussed. The rover's excavation and mobility performance during the phase 2 level 3 of the BTIL level 3 competition are then quantified. Results from the competition are then extrapolated to a full lunar day mission, taking special note of long-term effects such as tool and growser wear.

Methods: The configuration for PRIMROSE was based on an internal optimization study which suggested that system SWAP could be minimized with a single-rover mission. A chain trencher was selected as the excavation system because of previous performance data in relevant environments demonstrating high excavation rates, compact packaging, easy configurability, and the ability for combined excavation and material transport.

The mobility system developed for PRIMROSE used four-independently steerable and actuatable toothed-growsers (Figure 1). The additional degrees of freedom of movement allowed the rover to quickly align itself for excavation passes and more easily avoid obstacles during the driving event. The unique grouser configuration was designed based on lessons learned from the Phase 2 level 2 competition [4] where chevrons supported mobility in loose granular media and the hard side-walls provided better traction on CLSM beds.

The excavation system was tested over three days: once for the competition and twice afterwards for data collection. For all three experiments, the rover was offloaded to its equivalent weight while at lunar gravity and excavated beds with approximately 2MPa of compressive strength (Figure 2).

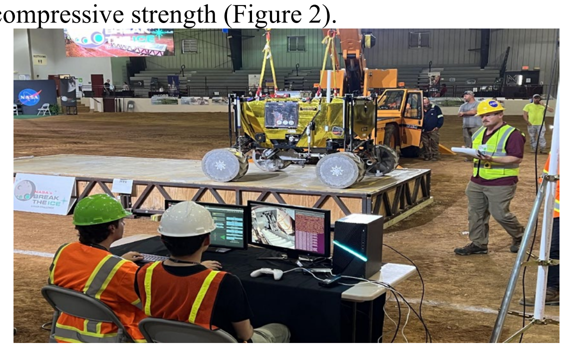

Figure 2: PRIMROSE rover excavating while gravity offloaded by crane to 1/6 Earth gravity.

Power consumption, excavation rate, wear, and material retention ratio data were collected by recording before and after conditions of the rover and excavation site.

Driving the rover was done at an outdoor arena on a bed of well graded granular material with obstacles including inline slopes, cross slopes, and boulder fields which could optionally be traversed as shortcuts. Competing rovers were required to drive up to 300 meters one way with a full hopper, dump its contents, and return unloaded. PRIMROSE completed two full driving cycles: one for the competition and another afterward for data collection (Figure 3).

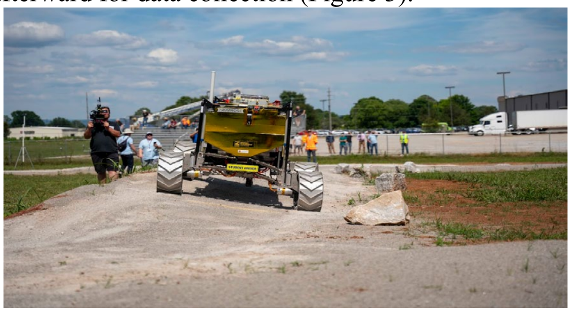

Figure 3: PRIMROSE traversing a sloped berm.

Mobility data was collected by timing how quickly PRIMROSE could complete all sections of the arena, including shortcuts and obstacles, while recording power usage, throttle, and general observations.

Results: Seven trenches were excavated across three excavation runs. Each excavation run lasted 25.35 mins on average totaling to 177.43 mins (Table 1). Excavation rate was on average 221.88 kg/hr with a max of 419.88 kg/hr recorded during the final run. Wear data from the excavation system, measured as Total Mass Loss (TML) revealed that after all excavation testing, cutting teeth lost on average 87 grams, or 0.55% of their total mass. With teeth on the edges of the chain experiencing a higher TML than those towards the center.

Table 1: Summary of all PRIMROSE excavation data taken at BTIL level 3.

For all runs:	Excavation time (min)	Collected material (kg)	Excavation Rate (kg/hr)	Energy Use (W-hr)	Retention Ratio (%)
Total:	177.43	493.26	N/A	1454.8	N/A
Avg:	25.35	70.47	221.88	207.84	70.94%

PRIMROSE was able to successfully navigate the obstacle course in 18 mins, clearing cross slope shortcut while carrying 270 kg of payload, and both the cross slope and a 30-degrees inline slope when emptied. Dumping a full hopper took 2 mins to complete. The average speed of the rover was 0.23 m/s.

Discussion: PRIMROSE was greatly improved between competition levels 2 [4] and 3, reducing the time to complete cycles by 200-300% and increasing excavation rate in uncut hardened material by as much as 570%. The excavation performance estimations were found to be highly operator dependent, with almost a doubling in excavation rate with improved control system tuning and operator experience. PRIMROSE likely could increase overall performance estimates with more time spent using it.

With further testing, PRIMROSE was able to traverse all obstacles unloaded, and all obstacles but a 30-degree inline slope while loaded, without using complex controllers to maintain the rover's orientation or traction. Between the competition runs and additional testing, PRIMROSE was found to be able to quickly traverse the simulated coarse lunar terrain while using minimal power. However, driving performance relied heavily on the operators, and more realistic operation will require greater degrees of autonomy.

Using the scenario described in earlier phases of the BTIL challenge [1], PRIMROSE would take 3.5 hours to complete a single cycle. Each cycle includes 1km of driving, excavating 270 kg of hardened icy regolith, dumping material, and recharging the rover. A single rover would deliver 25,920 kg of icy regolith with 4% water-ice to a refinery, extracting 1,037 kg of water over a period of lunar daytime (14 earth-days); surpassing the 10,000 kg minimum delivery mass requirement of ice in 1 year.

While the total excavation time was too short to notice wear effects on performance, it is expected to affect long term operations on a 14-day mission. Such effects can be mitigated with relative ease by replacing cutting teeth.

Conclusions: PRIMROSE is a novel configuration for an excavation and transportation rover which saw great success at the BTIL competition and was selected as one of three teams to be given the option to test in the large DTVAC facilities in MSFC at no cost. The PSTDL team continues adding incremental improvements to the electronics and control system. The excavation subsystem is soon to be independently tested on a novel force test stand being produced in-house.

References

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