Efficacy and Wear of a Bucket Ladder for ISRU Regolith Excavation in Vacuum. Parker. S. Bradshaw[1], Paul van Susante[2], Kade R. Nielsen[3], and Marcello C Guadagno.
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Introduction: NASA's Artemis program calls for a sustainable human presence on the lunar surface. Utilizing resources already present in the lunar environment is a common strategy to lower the landed mass requirements for manned missions on the surface of other planets, a technique known as In-Situ Resource Utilization (ISRU). ISRU efforts have been studied for applications related to construction, propellant production, and refinement into useful commodities or products. [1] The excavation and collection of regolith is the necessary first step for many ISRU processes.

Lunar regolith is unlike earth materials due to its fine particle size, particle shape, high cohesion, and abrasive properties. These geotechnical properties lead to difficulties operating long duration excavation rovers. [2] Minimal non-pneumatic regolith excavation testing has been done in vacuum conditions using a regolith simulant. [3]

One commonly proposed method for excavating regolith in the low-gravity lunar environment is bucket ladders. [4] Bucket ladders consist of a continuous loop of roller chain onto which cutting teeth are mounted. These teeth are designed such that they retain material and make it available for collection and storage. Bucket ladders are favored due to their continuous operation, small excavation forces and relatively high excavation rates and efficiencies. [5] The first lunar prototype bucket ladder was built in 2005 [6] and many versions have been built and tested since for the Lunabotics Mining Competition [7,8]. A major concern of these excavators is the wear during long duration operation and excavation due the abrasive nature of lunar regolith. [1, 2]

Project History And Context: The PSTDL Lunar Trencher was based on 15 years of experience with bucket ladder prototypes and underwent several design iterations before testing in the vacuum chamber began. The first version of the modular bucket ladder was intended for use in atmospheric conditions and could excavate down to 1m depth (Figure 1). Testing of this prototype showed promise for the viability of bucket ladders excavating loose granular material efficiently. Further iterations of the bucket ladder included modifications for testing in lunar-like conditions. In order to enable testing in vacuum, the bucket ladder was integrated with an X-Z motorized gantry system which can be placed inside the PSTDLs vacuum chamber.

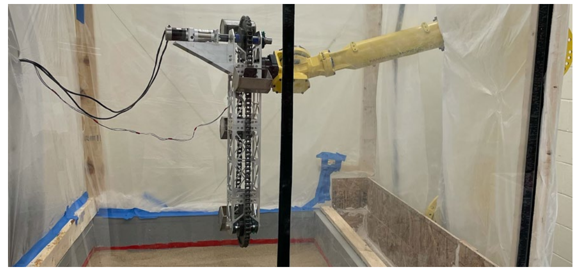

Figure 1: first iteration lunar trencher mounted in atmospheric testing configuration

A picture of the bucket ladder mounted on the gantry system can be seen in Figure 2. Results of this testing under vacuum showed lower than expected efficiency, partially due to the very high rake angle of the buckets and inefficiencies in the gantry system [9]

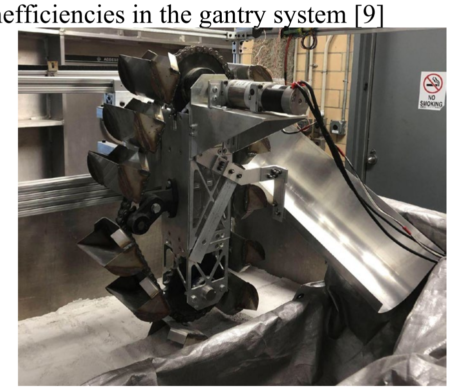

Figure 2: Vacuum configuration bucket ladder V1

The current version of the bucket ladder uses improved gantry systems and bucket geometry, with a rake angle reduced from over 45 degrees to less than 15 degrees. The body of the bucket ladder was angled at 15 degrees to lower material spillage from the regolith exiting the new buckets. Further vacuum testing of this version 2 PSTDL bucket ladder will be the focus of this paper. An annotated image of the current bucket ladder iteration is shown in Fig. 3.

Operating Conditions: Excavation rate, traversal speed, and power use are measured. These parameters are recorded for the PSTDL bucket ladder not only for earth ambient conditions but also at a vacuum level of 10E-6 torr. This will allow the comparison of the performance of bucket ladders in atmospheric operation and in vacuum operation. These correlations may be applicable to past work with bucket ladders and bucket wheels that have only been tested in atmospheric conditions.

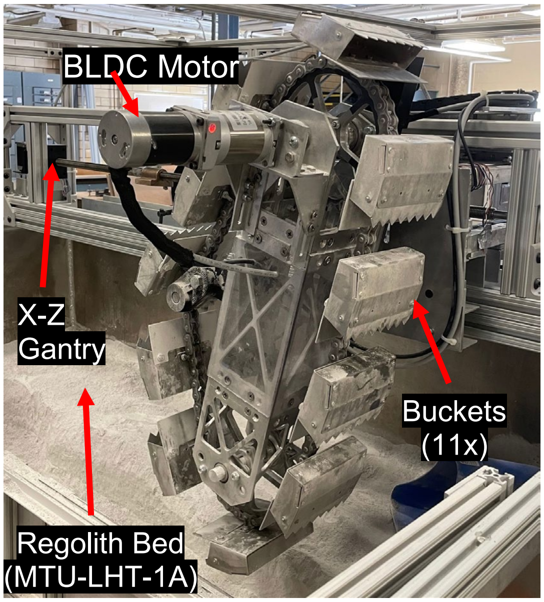

Figure 3: Vacuum configuration bucket ladder V2

To analyze wear and efficiency of bucket ladder systems in a lunar environment, testing will involve constant exposure to regolith simulant under vacuum. The regolith simulant used is MTU-LHT-1A [10] which is designed to match the particle size distribution and jagged shape of lunar highlands regolith. Wear indicators measured include component mass changes and surface roughness analysis performed before and after testing. The two-body wear of the excavation teeth is quantified using a laser profile scanner and mass change. Additionally, the three-body wear of select chain links is tracked over time using microscope visual analysis and mass change.

Experimental Design: The trencher testing hardware was designed to promote consistency in every aspect possible. The motor speed for the X-Z translating gantry is driven by a stepper motor and maintains a constant translation speed. The motor which drives the bucket ladder chain is controlled by a closed-loop control system and maintains a constant rotational speed. The speed of the bucket rotation and depth at which the Z-axis translation is to be set to was determined using a bucket motion computational model in order to achieve the desired per-bucket continuous excavation depth of cut and mass excavation rate.

The simulant in the regolith bin is compacted using a vibratory compactor to a consistent bulk density of 1.7 g/cm³. Excavation rate is to be determined by measuring the mass of excavated regolith which falls through the chute into a collection trough and recording the time over which excavation occurs.

The quantities of interest for this experiment are power draw of the excavation motor (BLDC), temperature of the translation motor and BLDC, and average mass excavation rate. The power draw of the BLDC is used in part as an indicator of system wear, as increases in motor power consumption to continue driving the motor at a constant speed indicates a decrease in performance of the bucket ladder system as a whole. The power use will be measured in a baseline test under vacuum conditions, and then again after the trencher has been used for a significant amount of time to excavate lunar regolith. For all tests described in the test matrix shown in Table 1, the horizontal translation rate of the trencher is a constant 8.5 mm/s.

Table 1: Test Matrix

Experiment Number	Per-Bucket Depth of Cut	Estimated Nominal Overall Excavation Rate	Test Conditions
1	10.5 [mm]	1971.13 [kg/hr]	Atmospheric
2	10.5 [mm]	1971.13 [kg/hr]	Vacuum
3	13.75 [mm]	3575.74 [kg/hr]	Atmospheric
4	13.75 [mm]	3575.74 [kg/hr]	Vacuum
5	17 [mm]	4462.13 [kg/hr]	Atmospheric
6	17 [mm]	4462.13 [kg/hr]	Vacuum

Timeline

The lunar trencher system has undergone a proof-of-life test in vacuum conditions and is now undergoing preparations for the tests described in Table 1. These tests are expected to be completed during the months of April and May of 2023.

References

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