Low Mass Method for Lunar Regolith Surface Compaction

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Introduction

As human space exploration expands to include lunar bases, and resource collection, the development of infrastructure on the moon becomes imperative. Terrestrial construction vehicles are massive to leverage high reactive forces in moving large amounts of material, and often heavily utilize hydraulic actuation. Similar equipment would require replacement of these primary mechanisms to operate at vacuum and such large masses would be excessively costly to launch. These problems are especially true for compaction which typically uses large masses to compress and vibrate at the surface. To address these issues MTU has been investigating a novel alternative to better adapt to the planetary construction needs. Instead of massive surface loading, the design explored utilizes vibrated pins that are inserted into the regolith and vibrated at depth, greatly reducing the required mass and energy required to compact to desired depths. The system optimization is aimed to compact a simulated 10 m launch pad in accordance with NASA's 2021 LuSTR grant.

Figure 1: Single Pin Test Set-up

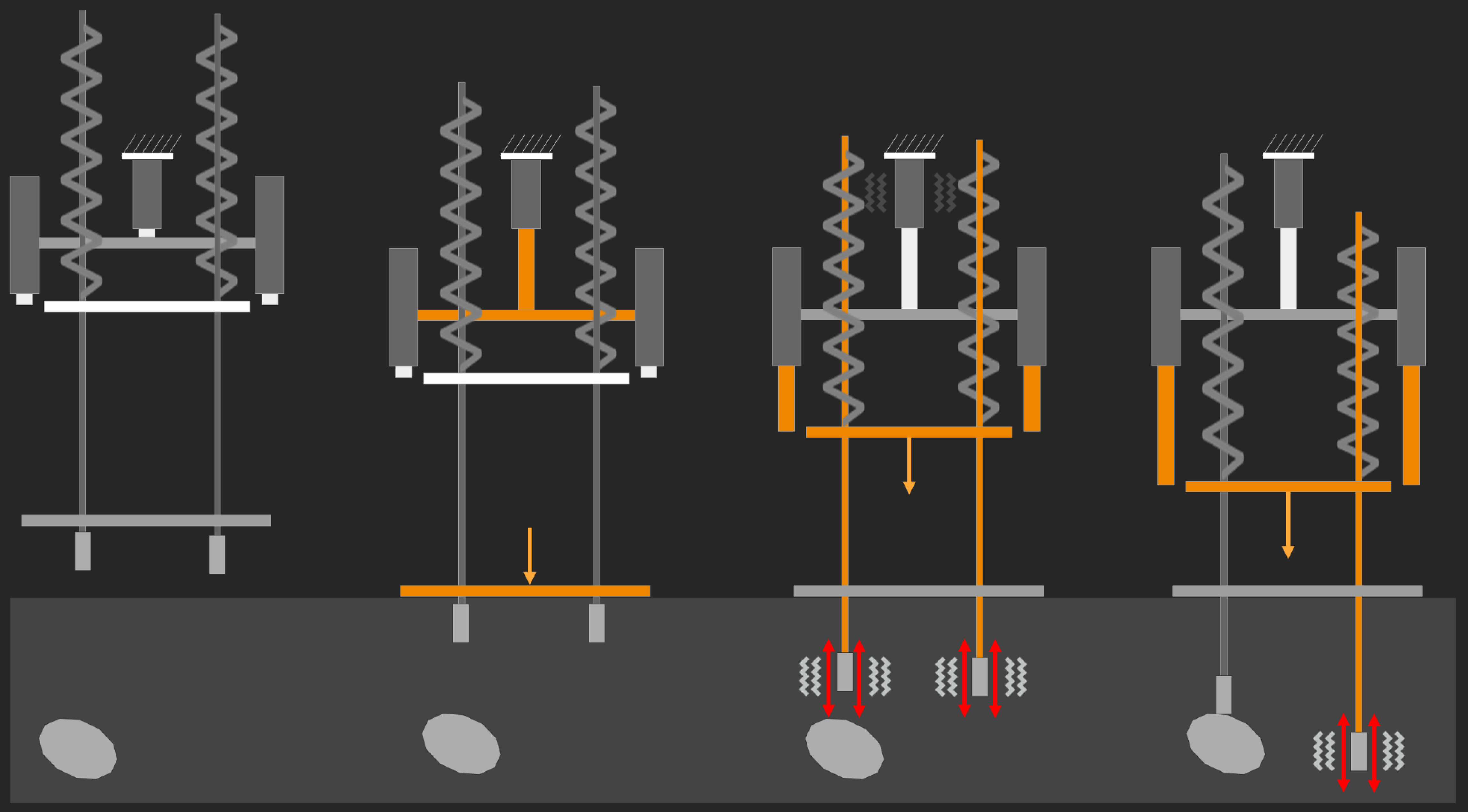

Figure 2: Overview design concept

Methods

The design explored uses long pins which are inserted while vibrating, reducing resistance in entering the regolith and provides necessary energy to reorganize particles to a more compact state. A surface plate applies the vehicles mass to prevent free movement of particles at the surface.

In a lunar environment we cannot assume uniformity in the pre-compacted bed and buried obstacles would hinder full compaction of a site. To address this the compactor's needles are each independent, attached via a spring to the main motion stage allowing the pins to deflect when the preload is met.

To optimize parameters, a prototype has been produced with a single pin as shown in figure 1.

This test setup enables optimization for pin spacing, vibration qualities, and duty cycle operation. Testing has started to investigate the duty cycle. The baseline operation for testing involves an initial plunge, followed by stepwise compaction, with a dwell period at the base of each compaction (shown by figure 3 telemetry data).

The dwell period has been the focus of the first optimization period: using constants for plunge and retract speed, step size, vibration frequency and amplitude. The surface pressure is not applied until halfway through the compaction reducing force to plunge. Testing is conducted on a pre-compacted 10 in regolith column. MTU-LHT-1A is used as the test material.

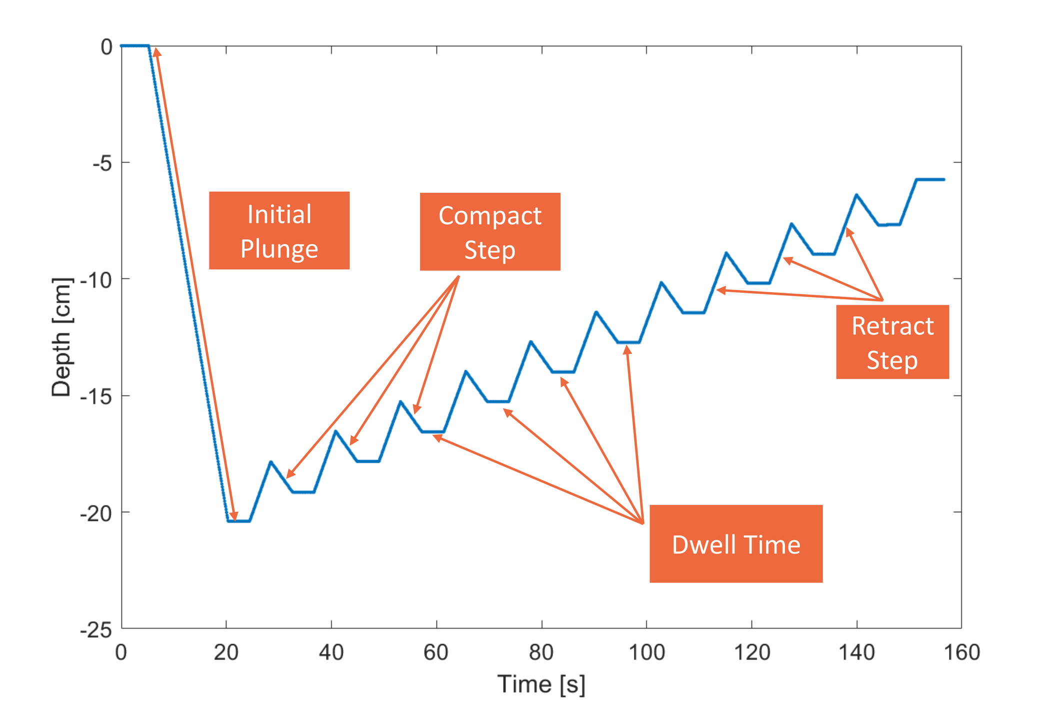

Figure 3: Annotated telemetry data showing duty cycle

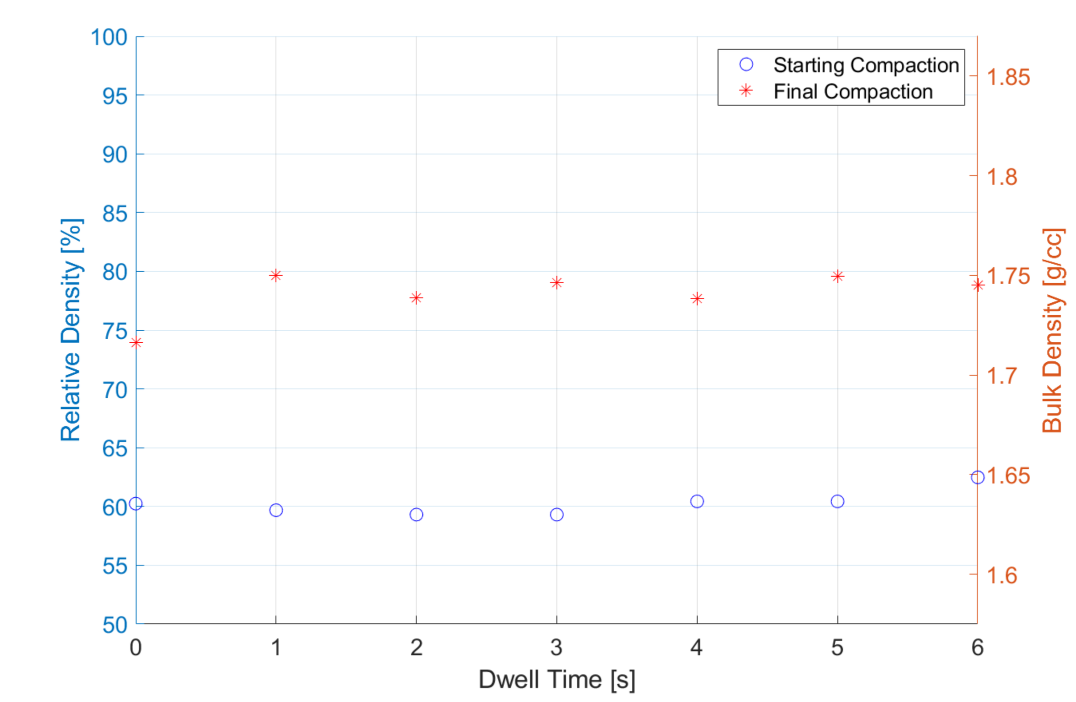

Figure 4: Comparison of dwell time to achieved compaction, starting at ~60% Compaction

Results / Discussion

Testing is complete for dwell times between 0 and 6 seconds on a 60% pre-compact. Figure 4 illustrates the results from a constant pre-compaction. At this pre-compaction there is not significant difference in the results for longer dwell periods, which may indicate loosening and re-compaction as time increases. More resolution will be needed in the 0-2 second region.

The compaction testing shows high levels of compaction 75-80% and indicates how to operate in order to maximize compaction at 60% starting compaction.

Conclusion

The compaction system has so far shown successful compaction, with minimal optimization currently complete. Lower initial compactions will be needed to complete operational reference, and additional features will be explored (driven frequency, magnitude of surface pressure etc.).

The test system is being altered to allow for more consistent testing and collection of more datapoints, including pin acceleration, axial force, and power use. Vibration will be the next test campaign, which should complete understanding needed to produce a final design. The final design will take two forms: a low mass compactor which does not have independent pins to meet needs of the final LuSTR demonstration requirements, and a full-scale model which would address concerns of buried obstacles or uneven pre-compaction.

The vibration settings will need to be reoptimized for the demonstration medium (not expected to be MTU-LHT-1A). The final design will be tested under vacuum at Planetary Surface Technology Development Lab's facilities. This re-optimization and vacuum testing will give insight into lunar operation, allowing in-situ flexibility for operation and understanding the differences in compaction without atmosphere.