Development of an Instrumented Percussive Cone Penetrometer for in-situ Characterization of Lunar Regolith Geotechnical Properties. M. C. Guadagno[1], B. D. Wiegand[2], P. J. van Susante[3], J. B. Primeau[4], C.J. Schaefer[5] [1]Michigan Technological University, 1400 Townsend Dr. Houghton, MI 49931, mcguadag@mtu.edu. [2]Michigan Technological University, 1400 Townsend Dr. Houghton, MI 49931, bdwiegan@mtu.edu. [3]Michigan Technological University, 1400 Townsend Dr. Houghton, MI 49931, pjvansus@mtu.edu.

Introduction: There is a renewed call to understand the distribution of resources under the lunar surface as the Artemins missions come closer to establishing a permanent human presence on the moon. Water-ice in particular has been identified as a target for extraction for use in propellent production. While remote sensing methods have been used to map polar regions where ice deposits are most prevalent, higher resolution data is required to enable viable excavation missions. A potential solution would be to use cone penetrometers.

Cone penetrometers have been used by various lunar surface missions during the Apollo era, to collect data for the estimation of regolith geotechnical properties. However, these preliminary in-situ static and shear vane penetration tests provided limited data on their own; Results were paired with later tests on collected lunar core samples at terrestrial locations.

A method to circumvent the logistical constraints of sample return would be to embed additional sensors into the penetrometer and conduct a more comprehensive geotechnical analysis in-situ. When coupled with percussive action, such a system would use significantly less power and impact mass compared to terrestrial dynamic cone penetrometers.

An Instrumented Percussive Cone Penetrometer (IPCP) is under development by the Planetary Surface Technology Development Lab (PSTDL) at Michigan Technological University for the 2020 LuSTR grant. An initial mathematical model for the in-situ determination of shear forces, friction angle, and apparent cohesion using embedded penetrometer sensors is presented. The mathematical model is then tested using a prototype IPCP in lunar regolith simulant. Preliminary results from testing are analyzed and a recommended path forward is proposed. The overarching goal of this development effort is to produce a set of science instruments which can map the spatial distribution and concentration of volatiles in the top layer of the lunar surface.

Penetrometer Designs: Penetrometers for lunar applications would require additional sensors because they lack the decades of data used by their terrestrial counterparts to empirically estimate in-situ bearing strength parameters. The prototype penetrometer shaft breaks out component forces by incorporating additional data streams from load cells in the cone head and the z-axis of the shaft, string potentiometers, and known impact energy from the driving mechanism. A custom housing was printed with sintered stainless steel with exterior geometry compliant to ASTM standards. The cone head measures 20mm in diameter with a half-angle of 30 degrees. Wiring for sensors is run through the hollow penetrometer shaft to NI data acquisition instrumentation. The penetrometer instrument assembly was designed to be independent of the driving mechanism and is moved between several penetrometer iterations during testing (Figure 1).

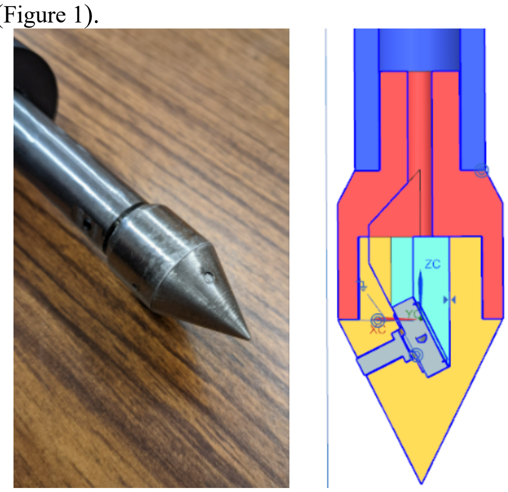


Figure 1: Penetrometer head CAD model (right) and fabricated cone head (left).

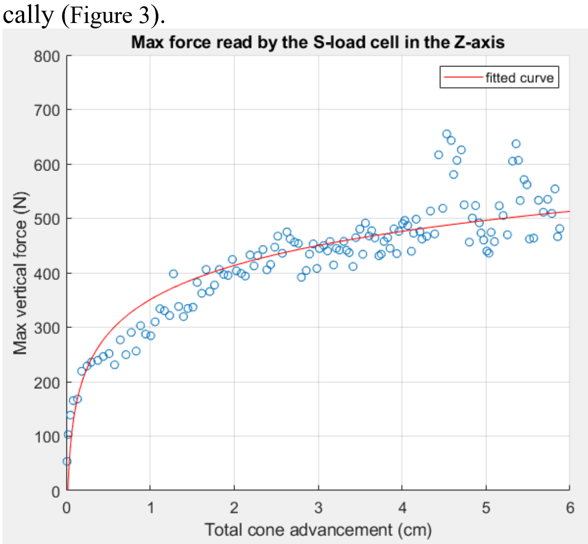
IDCP Penetration Testing: Tests were conducted initially with a modified standard ASTM dynamic cone penetrometer called the IDCP following the ASTM standard method for shallow pavement applications. Preliminary tests revealed that while the instrument could still be used to back out California bearing ratio and bearing capacity, measured load cell force accuracy suffered from the kilonewton shock created by a 4kg falling mass.

IPCP Penetration Testing: A percussive method for penetration was found to be desirable to increase the number of data points collected and reduce impact shock on sensors. Additional datapoints allow for higher layer resolution and the creation of more accurate trendlines as the cone advances through the non-uniform regolith. The current prototype penetrometer, put together by project partner Honeybee Robotics, uses a hammer drill which imparts approximately 600N of force at a 27Hz frequency to the top of the penetrometer shaft. Impact data is recorded by the load cells at 51kHz and displacement is measured by the string potentiometer at 1kHz (Figure 2).

Figure 2: Prototype IPCP test in shallow regolith bucket.

Testing is conducted in MTU-LHT-1A lunar regolith simulant which was compacted to maintain consistent layer bulk density. The IDCP was able to reach 6cm of depth in 6 seconds into a bucket of regolith with a bulk density of 1.78 g/cm^3. A total of 156 impacts were recorded over 6 seconds of operation. Data from this initial test is analyzed in the following section.

IPCP Data Analysis: Processing was conducted in MATLAB. Raw data output indicates that as the cumulative penetration increased, advancement per blow decreased and measured vertical forces scaled logarithmically (Figure 3).

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General model:
myfit(x) = a + b*log(x)
Coefficients (with 95% confidence bounds):
  a =       350.7  (340.3, 361)
  b =       90.47  (82.87, 98.07)
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Figure 3: Logarithmic fit for measured vertical force on penetrometer vs. total cone advancement

Relationships between measured normal and shear forces were estimated in addition to the example in Figure 3. Friction angle and apparent cohesion was calculated between blows by using the Mohr-Coulomb failure criterion with the estimated stresses. Testing is ongoing with the IPCP with a focus on sensor noise reduction and adding replication by testing in a large bin of lunar regolith simulant able to support up to 16 penetration tests before having to recompact the regolith (Figure 4).

Figure 4: IPCP on a 2D motion stage above a regolith test bin.

Upcoming Test Campaign: Test frequency is expected to increase now that larger support equipment is complete and operational (Figure 4). Future batches of regolith will be mixed with varying percentages of water-ice to understand the effect on changes to geotechnical properties. The culmination of several tests in the regolith bin will be used to build correlations to estimate bearing capacity in situ, similar to the process used for ASTM DCP testing.

Once the functionality of the instrumented IPCP for in-situ geotechnical property estimation is completed, other sensors will be integrated into the cone head for subsurface thermal profiling and volatile mapping. After this combined system is proven to work in atmospheric conditions, a vacuum-rated version will be built by Honeybee Robotics using a modified Z-stage from the lunar prospector TRIDENT drill. Testing will continue to raise the TRL of the combined system to TRL-6 via testing in a dusty thermal vacuum chamber facility.