USING THE TRIDENT DRILL TO ASSESS GEOTECHNICAL PROPERTIES OF PROBABLE ICY LUNAR REGOLITH ON UPCOMING SOUTH POLE MISSIONS. I. R. King[1,2], K. M. Cannon[2], V. T. Bickel[3], K. Zacny[1], D. Bergman[1], S. Goldman[1], R. Lin[1], P. Chu[1], P. Creekmore[1], P. Ng[1], and the TRIDENT team. [1]Honeybee Robotics (irking@honeybeerobotics.com), Altadena, CA 91001, [2]Space Resources Program, Colorado School of Mines, Golden, CO 80401, [3]CSH University of Bern, Switzerland

Introduction: Human and robotic visits to the Moon thus far have largely been motivated by science and exploration. However, engineering the technologies we will use in this new era of commercial space requires more sophisticated knowledge of the lunar surface than ever before. Specifically, more detailed knowledge of the geotechnical properties of regolith in permanently shadowed regions (PSRs) is of particular interest. PSRs are known to contain water ice [1], but the concentration and texture of the regolith-ice mixture is still unknown. Further, it has been postulated that the lack of thermal cycling in these locations might result in notably less compacted regolith [2]. Therefore, in-situ data collection in these locations is both of scientific and practical value to companies and agencies looking to characterize, recover, and utilize volatile resources in PSRs. In this abstract, we present an opportunity and plan to collect data for computation of geotechnical properties on upcoming missions.

Honeybee Robotics has developed The Regolith and Ice Drill for Exploring New Terrains (TRIDENT) to investigate the lunar subsurface at depths of up to 1 meter. In 2024, this drill will launch aboard both the IM-2 lander (as part of the PRIME-1 science suite) and VIPER rover to investigate the abundance of water ice near the lunar south pole. While the primary purpose of TRIDENT is to deliver volatile-rich samples to the surface for analysis by lander- and rover-based instruments, feedback from the drill can also be used to compute geotechnical properties [3]. Here, we describe recent experiments conducted with the TRIDENT Engineering Unit (EU), which is identical to flight units. Specifically, we focus on how the drill has been used to assess geotechnical properties of NU-LHT-2M regolith simulant in the lab, and how these experiments could be repeated on the lunar surface in order to generate novel data on the lunar south pole.

TRIDENT Mechanism: TRIDENT is a rotary percussive drill that uses a system of two linear stages to deploy the drill onto the lunar surface and advance the auger into the subsurface. Fig. 1 illustrates key subsystems in addition to the general deployment and drilling procedure. In summary, the drill head contains the actuators enabling auger rotation and percussion. The drill head and auger travel along the feed stage to advance the auger into the ground for drilling. This feed stage is mounted on the deploy stage, which presses the footpad down onto the ground.

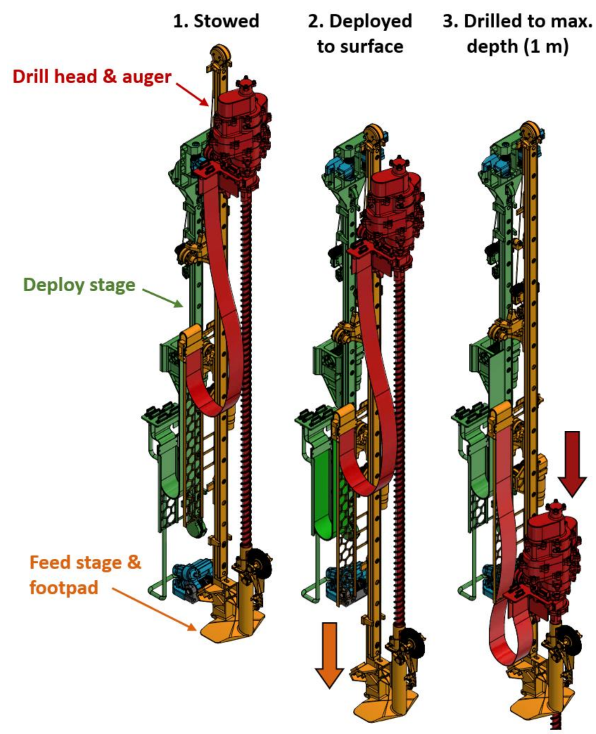

Fig. 1: Main TRIDENT subsystems and configurations

Key Geotechnical Properties: Thus far, methods for computation of three key geotechnical properties have been verified through EU testing. Note that all reported testing has taken place at ambient temperature and pressure with NU-LHT-2M regolith simulant vibratory compacted in a dedicated soil bin. This test setup is described in detail in [4].

Angle of Repose (θ): TRIDENT deposits cuttings to the surface after taking progressively deeper 10 cm "bites" of the subsurface. The cuttings are removed from auger flutes using a brush, which sweeps them down a chute where they are deposited in a cone. Analysis of camera images of the cuttings pile enable an estimation of the angle of repose. In the laboratory, measurements were also made with a handheld digital angle gauge. An example of one such test is shown in Fig. 2, for which the measured angle of repose is 39.8 degrees. For dry, unconsolidated material, the angle of repose represents a reasonable approximation of the internal friction angle, which is a fundamental soil property representative of how well the granular material is able to resist shear stress [5].

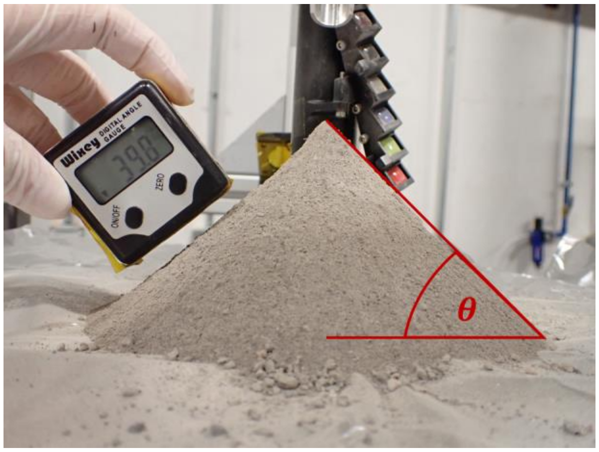

Fig. 2: TRIDENT cuttings pile from drilling to full 1 m depth in NU-LHT-2M. Angle of repose is measured with a digital angle gauge to be 39.8 degrees.

Modulus of Subgrade Reaction (k): Prior work described by [6] created a calibration curve and procedure for using the TRIDENT footpad as a modified plate load test, which is the standard for computing k terrestrially. Since that publication, further experiments have been performed, with results summarized in Table 1. Our average value of k is two to four times greater than the value computed for the actual lunar surface using images of Apollo bootprints [7]. This indicates that our simulant bin behaves two to four times “stiffer” than the surface of the Moon, which is known to be very fluffy in the top millimeters.

Table 1: Modulus of Subgrade Reaction (k) Experimentally Determined for NU-LHT-2M

Test ID	**d (mm)**	**k (kN/m^2/m)**
006B	4.55	2860.86
008B	4.23	3080.92
007	4.72	2762.21
008	3.09	4216.00
009	4.72	2762.21
010	4.39	2966.81
011	3.25	4005.20
012	3.58	3641.09
013	3.41	3814.48
014	4.06	3204.16
015	4.07	3204.16
017	4.88	2670.13
019	4.88	2670.13
020	4.39	2966.81
021	4.55	2860.86
022	3.74	3482.78
024	4.07	3204.16
Avg:	*4.15*	*3198.41*

Bearing Capacity (q): The bearing capacity of a soil represents the ability of that soil to resist a bearing pressure. The equation for this is simply $q = F/A$, where F is the applied force and A is the area over which the force is applied. Bearing capacity is not a fundamental soil property, and is only valid for the soil at the depth at which it was tested. Given that our footpad in the modified plate load test penetrates an average of 4.15 mm into the subsurface, we can calculate bearing capacity at this particular depth for our simulant. The footpad has a known area of 140 cm^2 and the footpad is deployed to a maximum preload of 183 N, and therefore q = 13.07 kPa. This is in family with measurements made on Apollo of the lunar surface, which was found to be roughly ~10 kPa [7].

Conclusions & Future Work: The TRIDENT EU test campaign is ongoing and future tests will investigate the use of a different simulant for drilling and geotechnical testing. While NU-LHT-2M is a good compositional analog of the lunar highlands, geotechnical properties of another simulant, LPS, may better replicate the elevated cohesion of real lunar regolith.

Future work will also seek to replicate work done by [8] to use images of the TRIDENT footpad print to estimate bulk density. An example of one such footpad print is show in Fig 3. Further, these results will be compared against the same measurements made with the VIPER rover wheels. Similar experiments investigating the use of wheel tracks to extrapolate geotechnical parameters such as *q* and *k* are ongoing [9]. Making footpad and rover wheel measurements in tandem on the VIPER mission could provide novel results useful in both engineering design and geological interpretation of the lunar south pole.

Fig. 3: TRIDENT footpad print after drilling in NU-LHT-2M regolith simulant

References: [1] Colaprete A. et al. (2010) *Science.* [2] Metzger P. T. et al. (2018) *Earth and Space.* [3] Zacny K. et al. (2010) *ASCE*, 166-181. [4] King I. R. et al. (2023) *SRR XXIII* [5] Sullivan R. et al. (2011) *JGR: Planets, vol 116 no. E2.* [6] King I. R. et al. (2024) *LPS 55* [7] Mitchell J. K. et al (1974) *NASA-CR-134306.* [8] Houston W. N. et al (1972) *LPS III*, 3255-3263. [9] Bickel V. et al. (2023) *Endurance Workshop.*