Simulation of Soft Regolith Dynamic Anchors for Celestial Exploration

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Abstract—**Recent exploration missions to celestial bodies have shown an increasing demand for surface based landers and rovers designed to perform experiments on the ground, rather than relying purely on traditional orbiting observatories. Many of the scientifically interesting locations have proven hazardous and difficult to reach and traverse, driving the need for different methods of locomotion. Some of these locations lie in deep, permanently shadowed craters or in rocky, highly uneven landscapes. Various wheeled, flying, jumping, and legged rovers have been proposed. Those chosen for development have experienced both success and problems alike. Even stationary landers, such as the Philae lander which attempted to perform a controlled landing onto a comet surface, encountered unforgiving terrain causing it to bounce multiple times due to the ineffectiveness of its two on-board anchoring mechanisms. A new generation of legged rovers and landers is envisioned to utilize dynamic anchors on the feet of its legs to claw into the surface, engaging and disengaging with each step or landing. A method for simulating and evaluating the performance of these dynamic anchors is proposed to aid in-progress surface missions with relatively quick response to new target data. Discrete Element Method software is used to simulate a lunar-like regolith medium and the interaction of a dynamic anchor with this medium. The engagement, holding, and disengagement forces are recorded during this simulation. Physical testing was performed by using a robotic arm to engage a series of anchors with a lunar regolith simulant while measuring the same three forces as the simulation. The actual test data efficient anchor geometry as determined during testing is compared to predicted data to evaluate the simulation accuracy. Calibration testing to determine suitable simulation parameters is also presented. Results show the applicable forces can be predicted well within an order of magnitude, but improvements are possible to predict soil behavior more accurately.**

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1. INTRODUCTION

The exploration of other planets, moons, comets and asteroids is moving to surface based landers and vehicles, with the support of orbiting spacecraft that have previously been the main mission. Recent missions, such as Curiosity [1] and Rosetta [2], have shown that landing and maneuvering on a celestial body is challenging due to the extreme terrain features found at the scientifically interesting locations. The LCROSS impactor together with the Lunar Reconnaissance Orbiter, showed the likely presence of water ice at the bottom of permanently shadowed craters on the moon [3]. The steep slopes that cause these permanent shadows make it nearly impossible to navigate with traditional rovers.

The presented research relates to a new type of mobile surface explorer capable of traversing much more difficult terrain than conventional rovers. The anchor simulated within this resarch is envisioned to be used as a claw on each foot of four or more legged walking robot. These claws would grab the loose soil found on the moon and Mars to climb steep slopes, or hold on to the surface in low gravity environments such as asteroids. This research is an expansion of the dynamic anchor testing presented by Ebert and Larochelle [4], where actual test data was recorded during representative testing in a regolith simulant called BP-1. This simulant is a mining by-product found in Black Point, Arizona. It has been shown to have nearly identical physical properties to high fidelity lab created simulants [5].

Dynamic anchoring, in this research, refers to a method of anchoring that is much like clawing into soft soil or regolith, where the anchor or claw is engaged and disengaged repeatedly while a legged robot walks or runs along the surface. The anchor holding force is most important for this application. In this case the holding force is not the traditional pull-out force perpendicular to the surface, but rather the force parallel to the surface that would allow the robot to propel forward along the terrain. The engagement force is also evaluated as it dictates the required reaction force for driving the anchor into the regolith, which may be limited in low gravity environments. Disengagement force can be useful for keeping the robot in contact with the terrain in low gravity situations, as suggested by Parness [6]. Both engagement and disengagement forces are referred to as perpendicular forces in the scope of this paper, as they are pointed into or out of the surface of the regolith.

This paper proposes a method for predicting the holding and perpendicular forces involved with dynamic anchoring through the use of Discrete Element Method, or DEM, simulations. DEM is a type of particle method where granular material is modeled using representative particles that are

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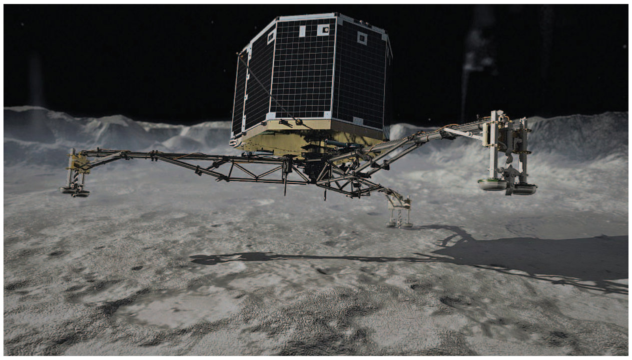

Figure 1. **Artist Render of Philae Lander**

assigned certain properties such as density, stiffness, and friction coefficient. The particles interact with neighboring particles or other features which dictates their motion and forces. If properly set, those simulated particles will have a bulk media behavior similar to that of the actual granular material being modeled. Lichtenheldt and Schaefer [7] present a comprehensive introduction to DEM.

The need for prediction of dynamic anchoring forces became apparent during the Rosetta mission to a comet. The Philae lander released by the Rosetta spacecraft was the first attempt at anchoring on the surface of a comet under microgravity. The Philae lander is shown in Figure 1 [8]. The lander included two separate mechanisms to anchor into the regolith, one based on three angled harpoons, the other on cork screw like augers. Both mechanisms failed to perform their intended function, and the lander bounced several times before coming to a rest at a location far from the targeted area [2]. If an effective and efficient method for simulating the anchors interaction with the regolith was available, Rosetta or future missions like it, may be able to tailor the behavior of its available anchoring tools and successfully perform their function. The DEM particle parameters could be calibrated using data from the orbiting spacecraft or even a sacrificial impactor, after which the simulation can be completed with a few days of computation.

2. RELATED RESEARCH

Several researchers have developed novel mobility platforms that could benefit planetary explorations. One such platform is AXEL [9], developed at NASA's Jet Propulsions Laboratory. It is a two wheeled rover that anchors a tether at the top of a slope to repel down and somewhat along slopes. It is capable of traversing very steep slopes, but is limited by the length of its tether in both distance up and down as well as along the slope. In addition, the tether is prone to snagging on larger surface irregularities.

Stanford University developed both SpinyBot [10] and StickyBot [11], both gecko-inspired legged robots capable of climbing up hard vertical walls. SpinyBot is a six legged robot that uses micro-spines, tiny flexible metal hooks to grab surface irregularities on stucco, brick, or concrete. StickyBot is a four legged robot that uses directional adhesives to grab onto very smooth surfaces like glass. Both of these robots are shown in Figure 2.

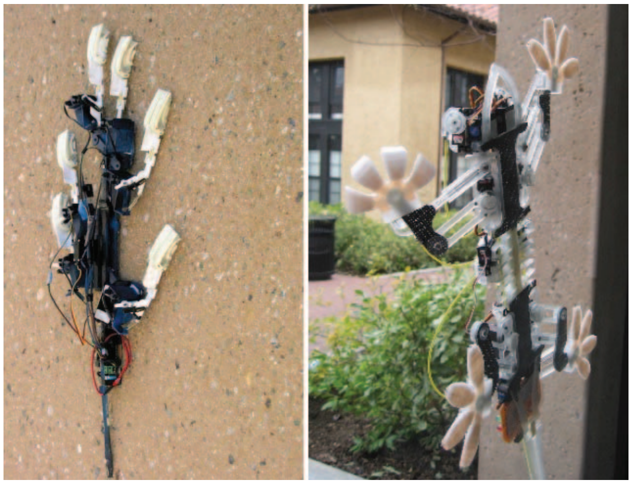

Figure 2. **SpinyBot (left) and StickyBot (right).**

Discrete Element Method has been successfully used in many wheeled locomotion simulations. Sane et al. [12] from Purdue University Indianapolis applied DEM to evaluate the forces and torques involved in bulldozing operations in soft soil. Cohesive soil modeling was applied to simulate mud or snow. No comparison was made to real test data, however, the soil deformations looked realistic.

Wasfy et al. [14], also from Purdue University Indianapolis, highlights an empirical approach to accurately model various types of soil through a series of simple tests that focus on one bulk media property at a time. These tests include soil flow from a hopper, compaction stiffness, shear strength, and angle of repose. The methods can be used to calibrate the DEM soil properties prior to simulating any actual interactions with the anchors or, in the case of their research, wheels.

Due to the high computational requirements for DEM, the applications have been limited. Smith and Peng [13] from the US Army Tank Automotive Research, Development and Engineering Center have developed a surrogate DEM model for soil-wheel interactions that once trained, can produce accurate results three orders of magnitude faster than regular DEM. This surrogate model may be useful for future evaluation of the dynamic anchors presented here, as it would allow near real time predictions of forces.

3. TEST SETUP

In order to establish the parameters for the simulation as well as gain a baseline for the forces associated with dynamic anchoring, physical testing was performed. The BP-1 simulant was contained within a 20 cm tall, 50 cm square container instrumented with two load-cells to measure both vertical (perpendicular) and horizontal (holding) forces independently.

A Fanuc M-410iC robot arm with 4 degrees of freedom was used to move various anchor geometries, mounted vertically to the end effector, through the BP-1. The motion profile programmed into the robot inserted each anchor 5 cm vertically down and at +/- 10 degree orientations, then dragged each anchor horizontally through the BP-1 over a distance of 20 cm, and finally extracted each anchor vertically out of the simulant.

A total of eight anchor geometries were used to perform 20 unique anchoring tests. An analysis of all data collected

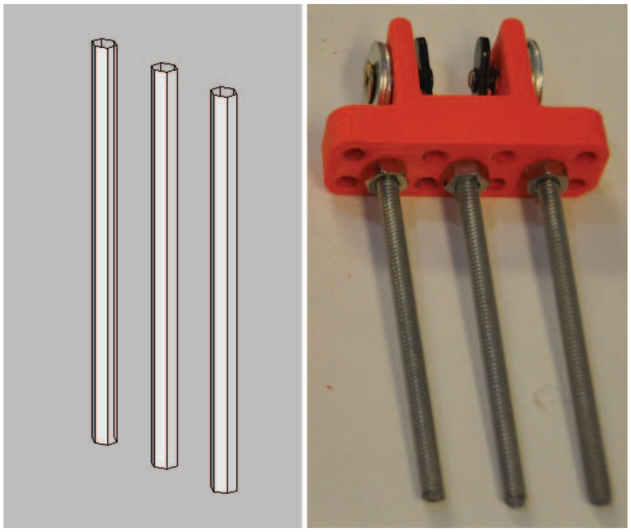

Figure 3. Three Rod Anchor: Simulated (left) and Physical (right).

showed that the three rod geometry exhibited the most beneficial combination of forces, as well as immunity to slightly off vertical insertion angles. The test setup, results and result analysis are presented in detail in a previous publication by Ebert and Larochelle [4]. Within the tested set of anchor configurations, the one exhibiting the best combination of characteristics is the three rod anchor. It generates a relatively large amount of holding force for the amount of material required and displaced. It also requires the least vertical force relative to the holding force and maintains almost all of its holding force in the event of an anchoring within a previous footprint. Lastly, the three rod anchor is one of the least sensitive to the engagement angle, meaning it can tolerate a bad approach angle of an anchor, which in turn simplifies the leg design and control. Because of these factore this anchor in a 0 degree configuration was selected for the simulation. The three rod anchor geometry used in the testing and simulation is shown in Figure 3.

In addition to gathering the baseline test data for comparison, calibration testing is performed to determine the DEM particle properties which provide a more accurate bulk media representation of the BP-1. This testing is based on the single property calibrations suggested by Wasfy et al. [14], combining the hopper flow test with the angle of repose test. The test setup consists of a square hopper with 60 degree sidewalls measured from horizontal, a top opening of 8 cm by 8 cm with a variable bottom opening mounted 16 cm above a flat surface. The bottom opening is initially set to 1.3 cm by 1.3 cm, at which point no BP-1 is flowing when the bottom surface of removed. The opening is gradually increased until the BP-1 begins to flow freely at an opening size of 3.2 cm by 3.2 cm. The flow of regolith simulant is captures on video, and the angle of repose of the resulting pile below the hopper is measured from the video frame. The flow video and angle of repose image are then used to compare to a simulation using the same physical constraints.

4. SIMULATION SETUP

The software used to perform the DEM simulations is PFC3D by Itasca [15], which allows for particle and geometry generation, as well as the extraction of forces on specific geometries.

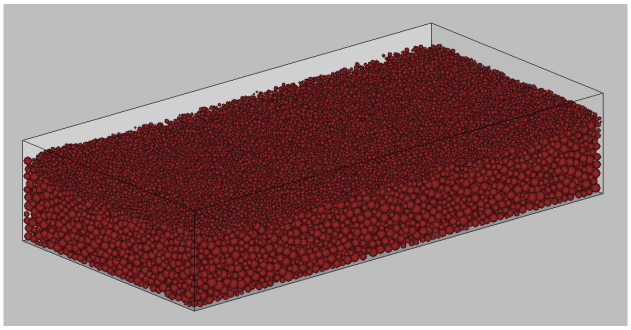

Figure 4. Simulated Test Bin with 100,000 Particles.

Using this software, the test bin is set up by forming the four flat walls and the bottom. The test bin dimensions were reduced to be 50 cm long, 25 cm wide, and 10 cm tall because observations during the physical testing showed no soil disturbance outside of those dimensions. Boundary reduction is important since DEM is computationally expensive and directly related to the number of particles.

The bin is filled with four layers of particles. Each layer is generated above the bin at a height of 10 cm to 30 cm, and allowed to fall under earth's gravity to come to rest on the previous layer before the next layer is generated. This produces a loose media with low compaction levels similar to the regolith used in testing. In an effort to reduce computation time yet still provide a realistic regolith representation, the first two layers are made up of 10,000 larger particle, ranging from 2.5 mm to 5 mm in diameter. This fills the bin approximately half way, such that the simulated anchor would just contact this layer at the tip, providing minimal impact on the forces. The remaining two layers consist of 40,000 particles, each ranging from 1 mm to 2.5 mm in diameter. The bin with all four layers of particles is shown in Figure 4. The top two layers contain the particles that generate the forces of interest on the anchor during its motion, requiring these particles to generate an accurate representation of the actual regolith. It is not feasible to generate particles of sizes equal to the actual regolith grains, so a guideline presented by Lichtenheldt and Schaefer [16] are used to size the particles. They proposed a scaling factor for the particles based on the dimensions of the interacting geometry as shown in the following equation.

$$\Gamma \leq L_{min}/2r_{max} \tag{1}$$

Where Γ is the resolution, L_{min} is the smallest dimension of the tool manipulating the soil, and r_{max} is the biggest particle diameter. The suggested range for the resolution where the particle size has shown little influence on simulation results is 1.25 to 5. In this research, the smallest dimension of the tool, or anchor, is the diameter of each rod at 6.5 mm, resulting to an r_{max} value of 2.6 mm using a resolution of 1.25. Hence the particle size selection of 1 mm to 2.5 mm.

Once the particle size is determined, further properties have to be assigned to make the mass of particles behave like the real bulk media. Density is assigned based on the measured weight of a known volume of BP-1 with a fill factor applied to account for the air voids between modeled particles. Friction coefficient, normal stiffness, and shear stiffness are assigned based on typical values for loose soil simulations [17]. Finally, the normal and shear bond strengths are determined and assigned based on the hopper and angle of repose test

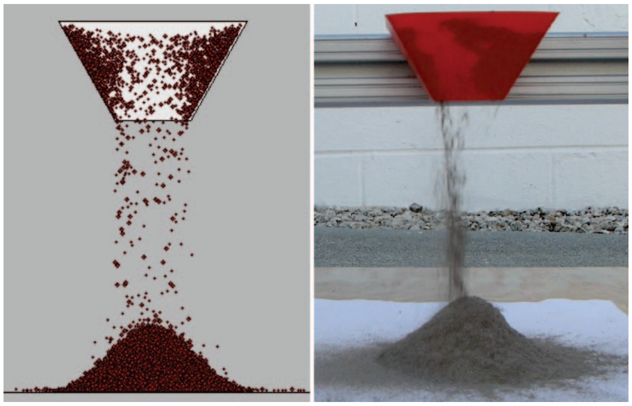

Figure 5. Hopper Test: Simulated (left) and Physical (right).

Table 1. Summary of Particle Properties

Parameter	Value
Particle Size (mm)	1 to 2.5
Density (kg/m^3)	1,000
Friction	0.5
Normal Stiffness (N/m^2)	1e+4
Shear Stiffness (N/m^2)	1e+4
Normal Bond Strength (N/m^2)	2e-4
Shear Bond Strength (N/m^2)	2e-4

results to give the soil its high level of cohesion. This is accomplished by modeling the hopper with the bottom opening of 3.2 cm by 3.2 cm described in Section 3, and filling it with the 1 mm to 2.5 mm particles. An initial guess of the bond strengths yielded no particle motion once the bottom of the hopper was removed. The bond strength value is reduced gradually until the particles begin to fall from the bottom of the hopper and form a pile below. The particles now behave as they should for the hopper flow test. The angle of repose of the formed pile is visually compared to the test pile to ensure that the particles behave properly. The comparison of the test and simulation is shown in Figure 5.

A summary of the particle properties used in the simulation is presented in Table 1.

After the particle properties are determined and assigned to the simulation, the anchor geometry is generated. The version of PFC3D utilized in this research requires all geometry to be represented by flat surfaces called walls that can be combined to make a convex shape. The three cylindrical rods of the selected anchor are each approximated by a hexagonal extrusion with a flat cap on the bottom end. This geometry can be seen in Figure 3. These convex shapes are then programmed to follow the same path as the actual testing, inserting 5 cm into the particles, moving across 20 cm, and retracting back out by 5 cm. Force histories for both holding and perpendicular directions are set up and recorded during this entire motion.

All of the PFC simulation runs were performed on a Windows 7 Workstation with an Intel Core i7 processor and 16 GB RAM.

Figure 8. Excavated Path created by 3 Rod Anchor.

5. RESULTS

As stated in Section 1, the forces of interest for dynamic anchoring are those in the directions parallel and perpendicular to the regolith surface. These forces are measured during both the actual testing and the DEM simulation. To collect the test data, the anchor is inserted into the regolith simulant a total of five times, the measurements of which are represented as solid lines in Figure 6 for the holding direction, and Figure 7 for the perpendicular direction. For the simulation, the anchor was only inserted into the representative particle mass once since the results are expected to be nearly identical each time the program is given the same particle and geometric properties. The predicted results output by PFC3D are shown as the dotted line in Figure 6 for the holding direction, and Figure 7 for the perpendicular direction. For the perpendicular force positive values are into the regolith.

A comparison of the holding forces shows that, in testing, the anchor provides about 80 percent more holding force than the simulation predicts. Furthermore, the shape of the force curve is significantly different as the tested force builds continually to the peak, whereas the simulation shows the force reach its plateau quickly and maintain a near constant holding force throughout. The above two differences can be explained by looking at the shape of the regolith or particle mass after the tool has passed through in each case. In testing, the anchor leaves a noticeable excavated area in its path, and also pushes a mound of simulant in front that increases in height, effectively increasing the area of anchor in contact with the regolith. In the simulation this effect is not observed. Here it behaves more closely to beach sand, where the particles effectively flow around the anchor and fill in the area behind it. The excavated path left during one of the test runs is shown in Figure 8, while the simulated bin looks like the one shown in Figure 4, prior to and after the anchor moves through.

Comparing the forces in the perpendicular direction shows the simulation over-predicts the actual insertion force determined during testing by a factor of about four. This could be caused by the flat wall approximation on the bottom of the simulated rods, which have a slightly higher surface area than the actual tool, as well as the relatively large size of the particles. The profile of the simulation force history, however, appears to match the testing profile closely, with a sharp peak upon initial insertion, and a sharp drop-off after the anchor is fully inserted to 5 cm. The simulated profile is missing the gradual increase of perpendicular force throughout the motion through the particles, which again is likely due to the

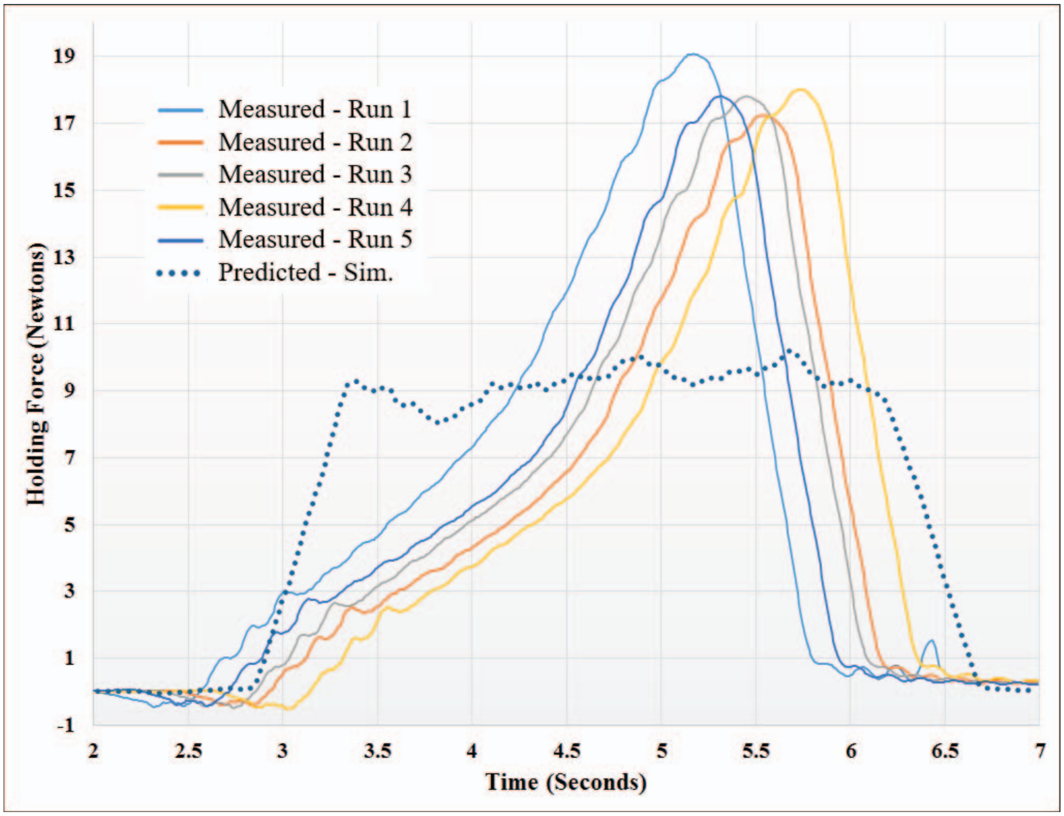

Figure 6. **Holding Force: Measured and Predicted**

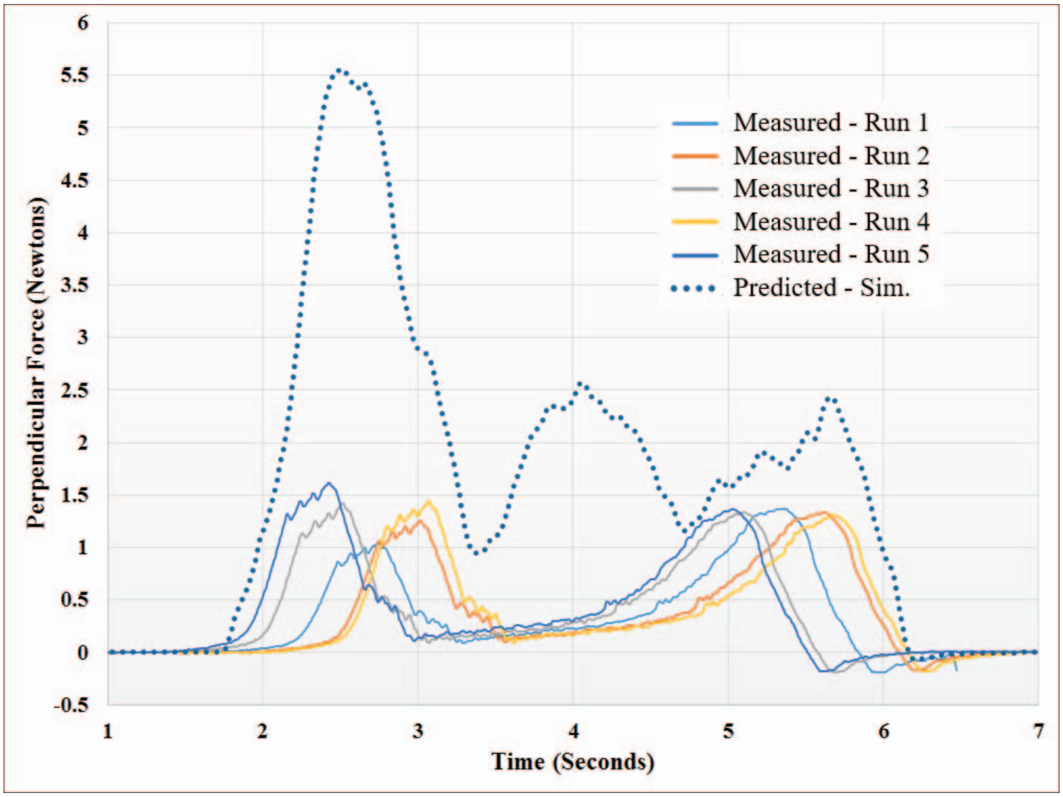

Figure 7. **Perpendicular Force: Measured and Predicted**

regolith buildup that occurs in front of the tool in testing, but not in simulation.

The simulation timing was also evaluated for this research to assess its usefulness for in-progress exploration missions. The initial setup of the simulated test bin, which included the loose filling with 100,000 particles, took approximately four days on the workstation described in Section 4. This step, however, can be performed well in advance and only needs to be done once per simulation set, as the properties of the particles can be adjusted after the bin is filled. The actual anchoring simulation, which totaled 3 seconds real time, required 36 hours to run on the same workstation.

6. CONCLUSION

The proposed application of using Discrete Element Methods to model the interaction of dynamic anchors with regolith is shown to enable an expedited means for anchoring tool selection. The results presented show predicted forces well within an order of magnitude with most accurate prediction in the holding direction which provides the primary anchoring force for locomotion along slopes.

The differences between the simulation results and the actual testing can be attributed to particle parameters that are not representing the actual regolith accurately. The lunar simulant regolith, and by extension actual lunar regolith, holds unique properties that cause it to behave in ways that are very different from typical dry granular material such as beach sand [5]. This includes the well-defined shape of the excavation left behind after the anchor traverses the test bin. For the application presented within this research, the DEM particle properties should be further refined to achieve a simulation that more closely resembles this profile.

It is promising that the hopper and angle of repose test alone provided sufficient data to get the results presented in this paper. This shows that even with minimal data from an orbiting satellite or impactor, one could tailor a simulation to provide order of magnitude predictions of available anchoring forces. Additionally, the time frame required for the simulations is short enough to provide valuable data to inform a future mission after it has already neared its target, but prior to attempting to land on or traverse the terrain.

Further research should be performed to attempt to refine the simulation parameters for the particular application presented here, as well as expand to different types of regolith expected on other celestial bodies. The research may also be expanded to evaluate the simulation method against the other types of anchors and anchor orientations presented by Ebert and Larochelle [4]. A case study canl be performed that shows how the developed anchoring forces may be used on a representative mission during which a four legged robot traverses up a slope under lunar gravity to determine the maximum slope capability.

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BIOGRAPHY

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