Dynamic Anchoring in Soft Regolith for Celestial Exploration

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ABSTRACT

Recent science missions to celestial bodies have shown an increasing demand for surface based landers and robots to perform experiments on locations. The hazardous and difficult to traverse terrain found at many scientifically interesting locations drives the need for new methods of locomotion. A method for simulating and evaluating the performance of dynamic anchors that can engage and disengage repeatedly is developed. Dynamic anchors allow a mobile robot to claw into the surface of a low gravity body, or into the slope of a crater of a higher gravity body while traversing the terrain. Discrete element method (DEM) software is used to simulate a lunar-like regolith medium and the interaction of simplified anchors with this medium. Engagement, holding, and disengagement forces are recorded and compared to physical test data obtained to evaluate the model's accuracy.

Keywords: Anchoring, Regolith, Soft Soil, Discrete Element Method, Modeling and Simulation

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 and Rosetta, 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 Philae lander released from the Rosetta Spacecraft in particular was the first attempt at anchoring on the surface of a comet under micro-gravity. The ineffectiveness of the onboard anchoring mechanisms [6] shows a need for better methods to design and test anchors for different types of surfaces.

The presented work focuses on anchoring in loose regolith for the purpose of locomotion along the surface of a micro-gravity environment, or along the slope of crater walls in higher gravity environments. Dynamic anchoring in this paper refers to the ability to engage and disengage the anchor quickly and repeatedly. This is to allow a surface based exploration robot to âĂIJclawâĂİ into the regolith as it moves along quickly to take advantage of forward momentum. The vision is to have fast, legged robots with these anchoring mechanisms attached to the feet be able to literally run around the surface of other celestial bodies. An example of a robot that could be upgraded with the dynamic anchors is the Cheetah, developed by boston dynamics, shown in Fig. 1

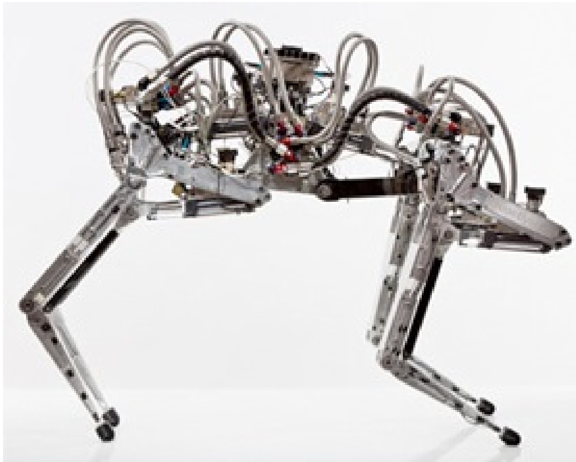

Figure 1. Cheetah, Boston Dynamics [4]

Dynamic anchoring has been studied in several previous research projects. Asbeck et al. at Stanford University developed SpinyBot [3], a six-legged gecko-like robot that uses micro spines, tiny bent hooks, on the bottom of its feet to engage surface roughness featured on stone, brick, or stucco walls. Asbeck also developed StickyBot [2], a similar gecko inspired robot that uses four legs and directional adhesives to climb up smooth surfaces such as glass. Both of these robots are mobility platforms capable of climbing vertical surfaces without a tether, but rely on hard surfaces to function properly. AXEL[1], developed at NASA's Jet Propulsion Laboratory is a two-wheeled tail dragging platform that can anchor at the top of a slope and repel down on a tether. The large wheels allow it to swing side-to-side while on near vertical slopes, but the tether limits its range and is susceptible to snagging. AXEL is capable of anchoring to soft soil, but the anchor is engaged and then used to hold the tether statically at the top of a slope.

The specific design of the anchoring mechanisms is left to future research. Instead, the presented research attempts to model and simulate a select set of simple anchors using discrete element methods, or DEM for short. DEM uses particle methods in which the grains of the regolith are modeled with spheres that are given specific properties in order to generate desired bulk properties. Each discrete particle is free to move based on inputs from neighboring particles without fixed constrains. Lichtenheldt and Schaefer[9] present a comprehensive introduction to DEM.

The anchor holding force is of primary interest since it affects the speed and slope at which the mobile robot can travel. In this case, holding force is not the traditional pull-out force, but rather the force parallel to the surface that is being traversed. Engagement and disengagement forces are of particular importance for the micro-gravity environments, as there is limited reaction force available to push against the surface. The simulation results are then compared to measurements taken during physical testing in order to validate the simulation results.

2. Simulation Setup

The DEM simulation was performed using the PFC3D 4.0 software package by Itasca[7] . This software allows for the modeling of the granular materials, such as regolith or soil, as well as the modeling of the anchors using multiple polygonal walls to make up the desired geometry. The finite simulation volume was chosen to be 20 cm tall bin with a 50 cm square footprint, large enough for a small scale anchor to be inserted without getting to close to the edges of the volume to avoid unrealistic boundary conditions.

This bin was filled with representative spherical particles of varying sizes by letting the particles fall while acted upon by 1g of acceleration. This produced a loosely cohesive simulated regolith, such as what would be expected under low gravity environments or undisturbed crater slopes. The size of the bin was chosen to be sufficiently large enough to avoid the walls affecting anchors performance, but small enough to limit the number of particles for computational efficiency. The granular material modeled and used in testing for this research is called BP-1[10], which is naturally occurring geotechnical bulk lunar regolith simulant. The particle size chosen for this particular simulation was significantly larger than actual grain size, since modeling the particles at their actual size is impractical due to the significant amount of contacts to be computed. Guidelines given by Lichtenheldt and Schaefer[8] regarding particle size were followed.

The PFC3D software allows the simulation to be resumed at designated save points, meaning once the bin was properly setup and the grains were settled, each anchoring simulation could be run using an identical regolith setup.

The initial simulations presented in this paper utilized simplified anchoring mechanisms that were reduced to only the portion that interacts with the regolith. Two different simple anchors were modeled and run through separate simulation. The first anchor is a single flat plate with a sharpened bottom edge, the second is a three pronged anchor with slender prongs sharpened at the bottom tip. Figure 2 shows the tool after which these anchors were modeled, and Fig. 3 shows how they are represented within the simulation environment.

Each of the two anchors is inserted into the regolith straight vertically to represent engagement, then pulled parallel to the regolith surface over a distance of 5 cm to represent the holding or anchoring stage, then pulled back out straight vertically to represent the disengagement. The pull distance of 5 cm was chosen as because it represents an allowable slip of the anchors that still renders it useful for forward locomotion.

Figure 2. Two Sided Anchoring Tool

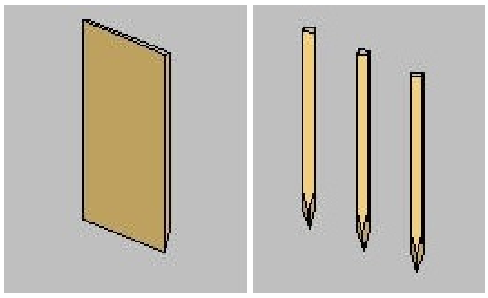

Figure 3. Simulation Representations of Anchors

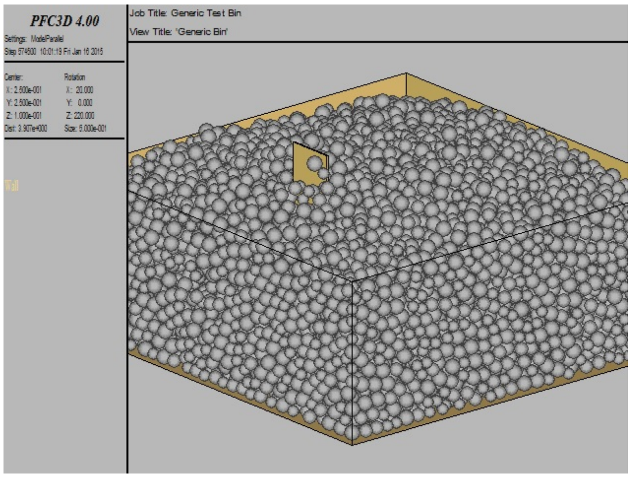

Figure 4. Simulation Screenshot

Within each simulation, measurements were set up to capture the time history of horizontal and vertical forces, which directly represent the engagement force, holding force, and disengagement force at the desired times. Figure 4 shows the simulation just prior to beginning the disengagement phase for the flat plate anchor.

3. Experimental Setup

In order to validate the proposed simulation methods, physical testing was performed. The goal was to closely match the test setup to the simulation model, so the test bin was sized at 50 cm long by 50 cm wide by 20 cm tall. Four ball bearing wheels were attached to the bottom of the bin to allow it to freely move in one axis parallel to the ground. A single axis load-cell was attached to the bin and a fixed base to measure the force in that same axis. The wheels are set on a plywood base to minimize rolling resistance. This

Figure 5. Test Bin with Load-Cell

Figure 6. Engaged Anchors

base was inclined by approximately 5 degrees towards the load-cell mount point in order to pre-load the load-cell and take up the slop in the load-path and increase the sensitivity of the measurement. The bin was filled with BP-1 lunar simulant by sifting it layer by layer from approximately 20 cm above the previous layer's surface in order to create a loosely packed medium. Figure 5 shows the bin and load-cell setup prior to the first test.

Each side of the anchor tool was fully inserted into the simulant by dropping it straight down into the center of the bin, keeping away from the walls to avoid unrealistic boundary conditions. Although the engagement and disengagement forces were recorded within the simulation, they were not measured in this experiment at this time. To determine the anchoring force, each tool was pulled by hand at a rate of approximately 2 cm per second parallel to the load-cell orientation for a total distance of 10 cm. This was to ensure the 5 cm distance used in the simulation was enveloped by the test. The test was repeated three times for each tool, and the simulant was reset after each test for consistency. Figure 6 shows the bin with the flat plate anchor on the left and the three pronged anchor on the right.

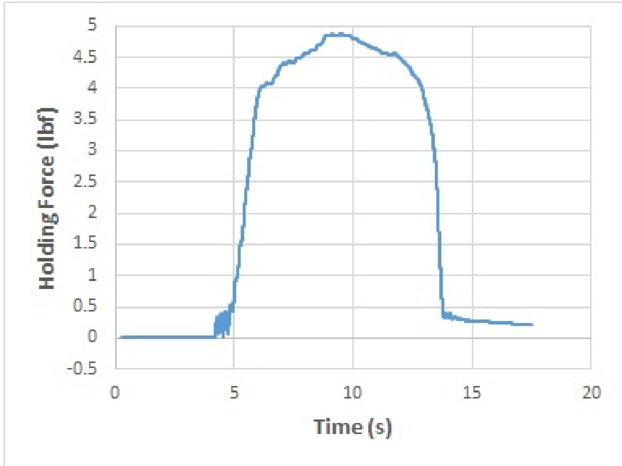

Figure 7. Holding Force History - Flat Plate Tool

4. Results

As previously stated, the outputs of the DEM simulation are the engagement, anchoring or holding force, and disengagement force. Those forces where determined by measuring the combined pressure on the surfaces of the wall that make up the moving tool. Due to the generation of one data point for each time step, along with the iterative nature of the simulation, the time histories for each of the three recorded forces is non-smooth, with data spikes multiple orders of magnitude higher than the neighboring points. The data was visually smoothed and the spikes removed by limiting the view scale to determine the maximum forces for each axis. The simulations shows the grains of the regolith simply flow around each anchor, and recombine behind it. This is likely due to the very low compaction level of the simulated regolith, as it was filled in multiple layers under 1g of acceleration, without any other forces to cause compaction.

The physical testing produced data more suitable for smoothing and interpretation. The holding force data was recorded at 1000 Hz, which enabled the use of a moving average function to produce a continuous history. The flat plate anchor produced a holding-force that seems intuitive with a sharp ramp-up as the anchor begins moving, a near constant force throughout the pull, and a sharp drop-off at disengagement. This profile shows that once the anchor begins to move, the loose regolith provides a resistance equivalent to a dynamic friction. As the anchor pulls through the regolith, the grains get pushed around it and refill the space behind the anchor, with only minor evidence that an object was dragged through. The three-prong tool, in contrast, produced a rounded force profile, with a ramp-up that slows as it gets closer to the peak. This may be due to the interaction of the three regolith grain flowpaths around the prongs, as they recombine behind the anchor to once again leave minimal evidence that and object was dragged through. Figure 7 and Fig. 8 show the history graphs for the flat plate and three-prong test, respectively.

Table 1 summarizes the simulation and test results for both types of anchors, along with percent difference of the test data from the simulation data. Engagement and Disengagement forces are omitted at this time as they were not measured in the physical tests and the simulation

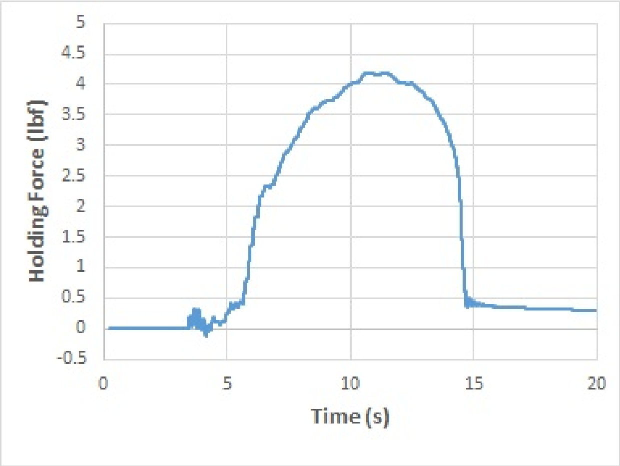

Figure 8. Holding Force History - Three Prong Tool

Table 1. Results Summary

	Holding Force (N)	Percent Diff.
Flat Plate - Sim	40	N/A
Flat Plate - Test 1	18.2	55%
Flat Plate - Test 2	21.8	46%
Flat Plate - Test 3	18.7	53%
Three Prong - Sim	20	N/A
Three Prong - Test 1	18.7	7%
Three Prong - Test 2	12.5	38%
Three Prong - Test 3	19.1	5%

results were very inconsistent in that axis. However, visual inspection of the force hstory data indicates an engagement and disengagement force of less 5 Newton for both simulations. This relatively low force is likely due to the behavior of the uncompacted soil making it suitable for penetration. This also indicates that an anchor that is inserted straight into the soil is not effectly for anchoring normal to the surface, and therefore likely not beneficial low gravity applications.

5. Conclusions

Close agreement between simulation and test data was observed for the three pronged anchor, while the flat plate anchor simulation resulted in a holding force roughly twice as high as that obtained during testing. The data is a promising starting point for simulation refinement, as there are further steps that can be taken to improve the accuracy for a multitude of anchoring mechanisms, some of which are outline in the Future Research section.

The results shows the proposed simulation method is viable for designing and evaluating dynamic anchors for use on future exploration missions. Furthermore, the holding force of 20N for each of the anchors tested in this research so far is on the correct order of magnitude to be useful for an extreme terrain mobility platform, using for or more legs with an anchoring mechanisms attached to each. With a running start to build up momentum, the provided force can be used to carry that momentum up a slope or along a surface.

Figure 9. Fanuc M-900iA Robot Arm [5]

6. Future Work

There are several expansions and improvements planned for the next phase of this research.

In an effort to more accurately model the behavior of the regolith used in testing, there is a series of calibration test that can be performed, as outlined by Wasfy et al.[11]. This calibration involves the testing a single property of the desired media, then adjusting the model parameters in the simulations software until the material behaves in a similar manner. Additionally, different regolith compaction levels should be tested to evalute simulation performance on a broader scale of loose surface parameters.

The engagement and disengagement forces are of importance for the function of the robot utilizing the anchors. Therefore the test setup will be expanded such that those forces can be measured and compared to the values already determined in the simulation.

Currently, the anchors are only inserted vertically for simplicity. There is a potential that the performance of the anchors can be improved by inserting them at angles not perpendicular to the surface, or inserting them using a non-linear motion. These variables should be added to the simulation to determine an optimized anchor configuration and motions. Prototype anchors that follows those motions can then be built to verify the accuracy of that simulation.

The experimental setup will be improved significantly to incorporate the above mentioned changes by the use of a 6 degree of freedom robot arm that can generate the simulated motion as well as measure the forces. Preparations are underway at NASA's Kennedy Space Center to utilize the Fanuc M-900iA robot arm, shown in Fig. 9, with a force-torque sensor and the prototype anchors attached as the end effector.

7. Acknowledgments

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References

[1] P. Abad-Manterola, J. W. Burdick, I. A. D. Nesnas, and J. Cecava. Wheel Design and Tension Analysis for the Tethered AXEL Rover on Extreme Terrain. *Proc. IEEE Aerospace Conference, Big Sky, MT*, 2009.

[2] A. T. Asbeck. *Compliant Directional Suspension for Climbing with Spines and Adhesives*. PhD Thesis, Stanford University, Stanford, CA, March 2010.

[3] A. T. Asbeck, S. Kim, A. McClung, A. Parness, and M. R. Cutkosky. Climbing Walls With Microspines. *Proc. IEEE International Conference on Robotics & Automation, Orlando, FL*, pages 4315–4317, 2006.

[4] Boston Dynamics. Cheetah. On the WWW, April 2015. URL `http://www.bostondynamics.com/robot_cheetah.html`.

[5] Fanuc Robotics. M-900iA. On the WWW, April 2015. URL `http://www.fanucamerica.com/cmsmedia/datasheets/M-900iA%20Series_22.pdf`.

[6] E. Hand. Philae Probe Makes Bumpy Touchdown On A Comet. *Science*, 346:900–901, 2014.

[7] ITASCA. PFC 3D. On the WWW, January 2015. URL `http://www.itascacg.com/software/pfc`.

[8] R. Lichtenheldt and B. Schäfer. Locomotion On Soft Granular Soils: A Discrete Element Based Approach For Simulations In Planetary Exploration. *Proc. 12th Symposium on Advanced Space Technologies in Robotics and Automation, ESA/ESTEC, Netherlands*, 2013.

[9] R. Lichtenheldt and B. Schäfer. Planetary Rover Locomotion on Soft Granular Soils - Efficient Adaptation of the Rolling Behavior of Nonspherical Grains for Discrete Element Simulations. *Proc. III International Conference on Particle-Based Methods - Fundamentals and Applications, Stuttgart, Germany*, 2013.

[10] D. Stoeser, D. Rickman, and S. Wilson. Preliminary Geological Findings on the BP-1 Simulant. *NASA/TM-2010-216444*, 2010.

[11] T. M. Wasfy, H. M. Wasfy, and J. M. Peters. Coupled Multibody Dynamics and Discrete Element Modeling of Vehicle Mobility on Cohesive Granular Terrains. *Proc. ASME 2014 International Design Engineering Technical Conferences And Computers and Information in Engineering Conference, Buffalo, NY*, pages 4188–4195, 2014.