ROBOTIC LEGS AS NOVEL PLANETARY INSTRUMENTATION TO EXPLORE THE MECHANICAL PROPERTIES OF REGOLITH.

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Introduction: As we explore extraterrestrial bodies such as the Moon and Mars, there is a growing need for precise and spatially dense measurements of planetary regolith geotechnical properties. The ability to effectively examine regolith properties across a wide range of planetary-relevant gradients can provide invaluable insight into the geology and climate of extraterrestrial environments.

Our research proposes a novel solution: by enabling legged robots to sense regolith responses from their legs during every step, high-mobility robots could offer the unprecedented ability to traverse a variety of challenging planetary terrains while capturing spatially dense, high-precision data of regolith strength.

By characterizing and analyzing regolith properties in analogue environments, we can relate gradients in regolith properties to changes in the landscape. Spatial gradients in regolith properties across landscapes can signal the presence of biology, water, and ice, and inform the locations of landing sites and mining operations, furthering our goals of scientific exploration into deep space.

Background and Opportunities: Recent developments in robotics have enabled the creation of high-mobility legged robots, inspired by the agile movement capabilities of various animals in nature. Additionally, recent advances in motor technology have allowed for lower-gear ratio motors to be used in robotic joints while still achieving high performance. Quasi-direct-drive (with gear ratios lower than 10:1) and true-direct-drive (gearless) setups minimize gearing backlash within the joints of the robot, allowing for unrivaled transparency and proprioceptive capabilities. Within this paradigm of highly transparent robotic actuators, robots can effectively and precisely feel regolith force responses from their legs throughout the entire contact period with the surface.

For legged and wheel-legged robots moving through complex, deformable regolith on Earth and other planetary surfaces, substrate forces “felt” through locomotive appendages at each step can be more informative than visual or other exteroceptive inputs for inferring environment properties and gradients [1], particularly on anisotropic regolith with varying levels of surface crust or ice content. By combining the sensing and locomotion capabilities of the robot into every step, our legged platforms can provide regolith strength measurements with unprecedented spatial and temporal resolution, as well as use these measurements to avoid locomotion failures.

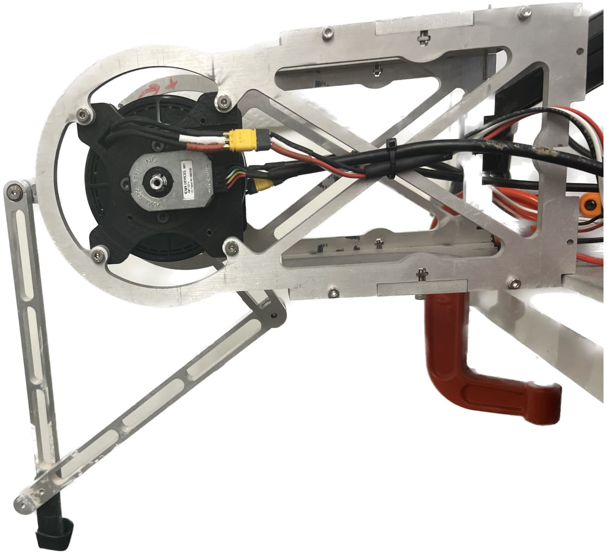

Figure 1: Traveler, a 2-degree-of-freedom (DoF) robotic leg actuated with direct-drive motors, is able to obtain accurate, continuous regolith force measurements through every step.

Direct-Drive Robotic Leg as Regolith Sensor: Our group integrated the proprioceptive signals from direct-drive motors with insights from the physics of granular and yielding substrates, and developed a novel 2-degree-of-freedom (DoF) direct-drive robotic leg [1] (Fig. 1) that can characterize regolith strength through penetration and shear tests.

The 2-degree-of-freedom (DoF) direct-drive robotic leg, Traveler, is comprised of two high-torque pancake-style brushless DC motors, whose positions are precisely controlled by a motor controller (ODrive, v3.6). Using the leg kinematics and the current draw of the two direct-drive motors, the Traveler leg can obtain an accurate, continuous estimate of the external forces in the sagittal plane of the leg at 100Hz sampling frequency. The measurements can be achieved with a diverse range of regolith-probing actions (*e.g.,* with varying penetration and shear velocities). The accurate force measurement and versatile probing protocols allow the leg to be used as a active and high-precision regolith sensor, to rapidly characterize the mechanical properties (*e.g.,* shear and penetration resistance) of the regolith *in-situ.*

Laboratory and Field Testing: One particular interest is to determine how the strength of regolith admix-

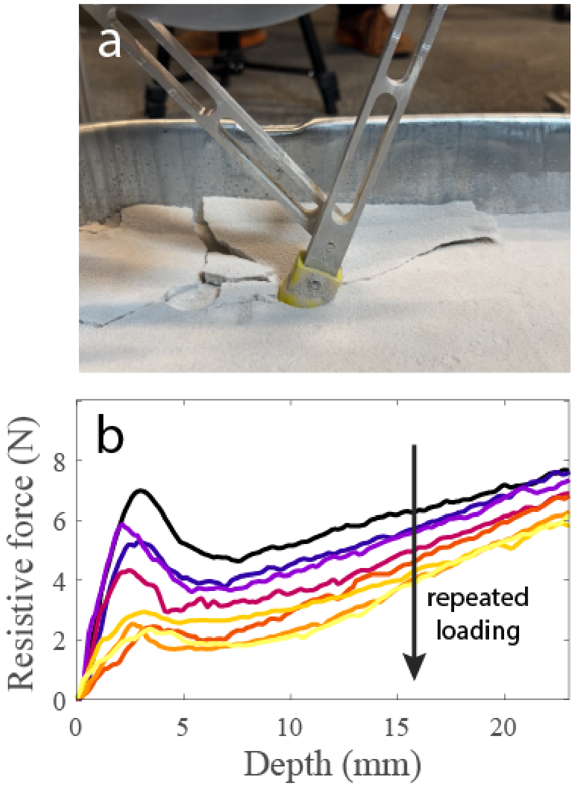

Figure 2: Laboratory characterization of crusted regolith. (a) The Traveler leg penetrating a laboratory-created salt crust during experimental trials. (b) Examples of the penetration resistive force measured from a crusted regolith sample with 1.25% salt concentration. Each color represents one penetration measurement, performed on the same crust sample and spaced a few centimeters from the last measurement.

tures is altered by gradients in surface crusts and lags. To understand this, we form crust samples in laboratory settings by spraying sodium chloride solution in a fine mist onto regolith samples, and drying with heat lamps. We then use the Traveler leg to characterize the force responses of these crust samples under mechanical penetration and shear. Our preliminary results suggested that the mechanical strength of the crust samples depended sensitively on crust properties such as salt concentration, whereas the rupture dynamics depend sensitively on the external forcing direction, velocity, and repetition.

Fig. 2b illustrates the mechanical response of a crust sample when subject to repeated vertical penetration. Under the initial penetration, the crust exhibited a “buckling” response, consisting of a yielding phase (Fig. 2b, penetration depth $<$ 3mm) up to the yield point of the crust (Fig. 2b, penetration depth around 3mm where the resistive force increased to a local maximum), followed by a sudden decrease in resistive force where the crust ruptured and underwent plastic deformation. The penetration resistive force subsequently increased again as the intruder engaged with the loose sediment beneath the surface crust (Fig. 2b, penetration depth $>$ 8mm).

We discovered that with an increased number of penetration on the same crust sample, the mechanical strength of the sample would decrease. The decreased strength reflected in both a reduced penetration resistance (Fig. 2b, the slope of resistive force per depth during the yielding phase), and a reduced yield strength (Fig. 2b, the peak resistive force around penetration depth of 3mm). We also found that increased salt concentration in the crust samples resulted in higher yield strength, but more brittle crusts, where the yield force occurred at a smaller penetration depth.

In collaboration with our team’s geoscientists and planetary scientists, we have deployed the robotic leg in a number of field campaigns [2, 1], please see the accompanying abstract by Kenton et al for more details on the field deployment of the robotic leg. The gearless actuators exhibit a high degree of transparency and the ability to rapidly transduce the substrate deformation forces of key scientific interest [3, 1]. We expect that the integration of laboratory and field data could inform how regolith physical properties are connected to geology and climate, and may help to anticipate regolith properties on planetary surfaces.

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References:

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