National Aeronautics and Space Administration

Modeling of Enceladus Landing Stability using Resistive Force Theory

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Objectives The objective of this work is to develop a model of the interactions between surface material and lander footpads during a landing touchdown event on Enceladus. Such a tool can inform how to safely and reliably land on Enceladus' unconsolidated surface and provide valuable insights for the design, development, and testing of landing systems for a potential in-situ mission to Enceladus. The Complex Rheology and Biomechanics Laboratory (CRAB Lab) at Georgia Tech led by Professor Daniel Goldman focuses on interaction of mechanical systems with loose granular materials – an interaction that exhibits complex behaviors that remain poorly understood. To analyze these types of interactions, the CRAB Lab utilizes the resistive force theory (RFT) [1-4]. The partnership with Professor Daniel Goldman and the CRAB Lab provides JPL an ability to conduct modeling and analysis of landers, samplers, and mobility system interactions with deformable terrain utilizing the emerging RFT method.

Background Enceladus, Saturn's small yet active icy moon, remains one of the most scientifically compelling worlds in the solar system. There is great interest in sending an in-situ mission to Enceladus because Cassini's orbital exploration revealed it to be a complex Ocean World with astrobiological relevance. It is one of the very few places where materials originating from a potentially habitable ocean are deposited on the surface, giving a unique opportunity to assess the moon's habitability and potential for life right at the surface. The proposed effort has direct and immediate implications for ongoing and future mission concepts in development, such as the JPL-led study for a New Frontiers Enceladus lander concept. Future exploration of Enceladus by a lander will require a detailed understanding of Enceladus surface material and of the complex interactions during lander touchdown event.

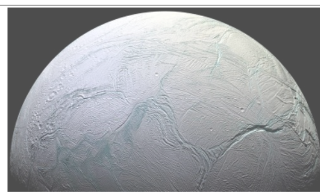


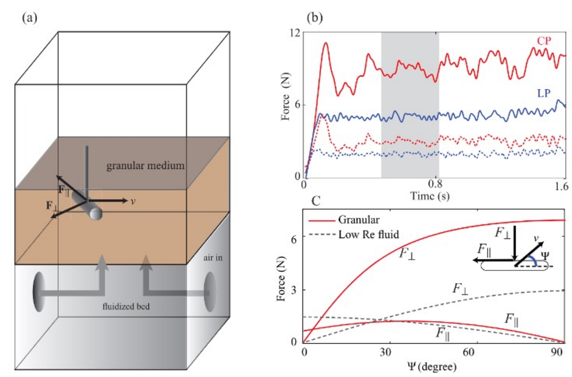
Photo credit: NASA

Significance/Benefits to JPL and NASA This work would have a significant impact on competitive mission proposals, such as the potential Enceladus lander New Frontiers 5 effort, for which JPL would need to perform engineering analysis to show that landing is safe on extremely weak, unconventional unconsolidated materials. Secondly, it brings RFT as a novel modeling capability to JPL as it is currently an emerging method for terramechanics modeling and has been percolating through the community over the last 5+ years but has not been yet adopted at JPL.

The collaboration advances research topics of particular interest to the CRAB Lab at Georgia Tech and to JPL. Specifically, advancements in understanding and modeling of complex granular mechanical systems enables more effective ways of interacting with the uncertain terrain, improve locomotion, and generally support the development and validation of system autonomy. This effort energizes the important strategic research area of astrobiological and oceanographic exploration of Enceladus and strengthens ties between the Georgia Tech and JPL communities.

References [1] Agarwal et al., *J. Terramechanics* **85**, 1-14, 2019; [2] Shrivastava et al., *Sci. Robot*. **5**(42), 2020; [3] Qian et al. *Bioinspir. Biomim*. **10**, 056014, 2015; [4] Zhang & Goldman, *Physics of Fluids* **26**, 101308; [5] Li, Zhang & Goldman, *Science* **339**, 6129, 2013; [6] Choukroun et al., *Geophysical Research Letters* **47**, 15, 2020;

Approach and Results To capture and model the reaction forces of Enceladus' surface of granular ice on a future lander's stabilizers, we require pressure per depth relations for arbitrary intruders in this class of media. Granular Resistive Force Theory (RFT) states that intruding surfaces will obey laws of superposition, so a set of penetration experiments into a representative media can provide empirical pressure per depth relations [5]. These experiments sweep a range of orientation and intrusion angles of an intruding plate to obtain the reaction forces under various kinematic configurations. The resultant forces are then used to calibrate the RFT parameters to make stress predictions of an arbitrary intruding body moving in granular media.



(a) Illustration of rod drag experiment used to determined RFT force relations (b) Example plot of measured drag force in glass particle assembly as a function of time (c) Example plot of average force on a cylinder wall as a function of the angle of attack. Figured adapted from Zhang, T. and Goldman, D. I. Physics of Fluids ***26****, 101308 (2014)*

The first requirement involves developing an experimentation platform that enables systematic intrusion tests to a suite of granular particles having different material properties such as particle shape, cohesion, volume fraction, etc. Then, rigid body intrusion experiments capture the resistive response of the material. The CRAB Lab developed an apparatus consisting of a structural frame supporting an acrylic tank, a particle filtering system, and an air blower. The tank is filled with Aluminum Oxide (40 microns diameter) powder which serves as an analog for Enceladus' loose granular ice. The air blowers reset the particles to a loosely-packed state via fluidization after each experiment. A particle filter is used to block out the hazardous particles dispersed into the air during testbed fluidization. A penetrometer cone used in JPL [6] is scaled via doubling in size in all dimensions and 3D printed for the powder testbed in the CRAB Lab.

The scaled penetrometer cone is vertically intruded into the test apparatus at a constant speed of 7.6 mm/s in an effort to capture the powder strength under quasi-static loading conditions. The penetration experiments revealed that the ground reaction force of the powdery media to the intruding cone scales linearly with intrusion depth. This linear intrusion response resembles the response of a unidirectional spring to an external input which the RFT model can already predict for granular media consisting of relatively large particles (1 mm of diameter). This preliminary finding suggests that the RFT model could be effectively extended to powder-like small grains without major theoretical modifications.

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