National Aeronautics and Space Administration

FY24 Strategic University Research Partnership (SURP)

Modeling of Enceladus Landing Stability using Resistive Force Theory

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Objectives: This effort aims to model interactions between surface material and lander footpads during Enceladus landings. It informs safe landing on its unconsolidated ice surface and aids landing system design. The CRAB Lab at Georgia Tech, led by Professor Goldman, specializes in mechanical systems interacting with granular materials, utilizing Resistive Force Theory (RFT). Partnering with CRAB Lab enables JPL to model lander, sampler, and mobility system interactions with deformable terrain using RFT.

Significance/Benefits to JPL and NASA: This work introduces RFT, an emerging terramechanics modeling method, to JPL. The collaboration enhances research areas of mutual interest for CRAB Lab at Georgia Tech and JPL. It advances understanding of complex granular mechanical systems, improving terrain interaction, locomotion, and autonomy. This effort fuels strategic research in astrobiological and oceanographic exploration of Enceladus, fostering stronger ties between Georgia Tech and JPL communities.

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. This effort has direct and immediate implications for ongoing and future mission concepts in development. 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.

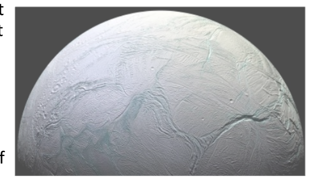

Photo credit: NASA

Approach and Results: This study aims to model how Enceladus terrain may interact with the footpad of a lander by conducting intrusion experiments into cornstarch powder, which is used to model the cohesive properties and particle size of Enceladus plume deposits. A custom test chamber with air-fluidization is used to reset the powder between trials. The vertical and horizontal stress per unit depth heatmaps for the test plate are illustrated in Fig 1. Both heatmaps α_z and α_x have qualitative agreements with the heatmaps derived for the non-cohesive substrate [1].

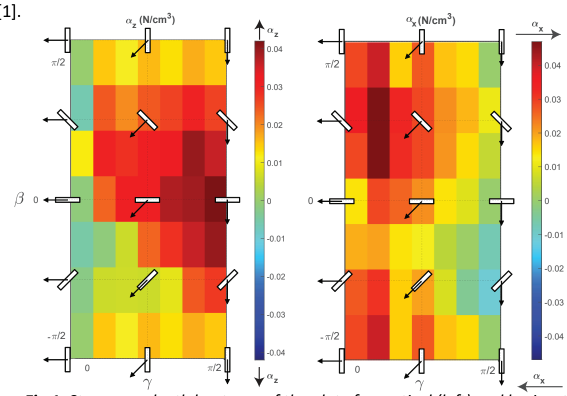

Fig 1: Stress-per-depth heatmap of the plate for vertical (left) and horizontal (right) axes.

We investigated whether the forces acting on a complex intruder moving through powder could be estimated by applying linear superposition to the forces acting on its individual elements. We first 3D printed a small-scale model footpad which has a curved shape, characterized by the ratio of its length to depth: 6 cm long, 1 cm deep, and 2 cm thick. We intruded the model footpad into the powder in two different configurations and measured vertical and horizontal forces (Fig 2). We compared the resulting force curves to the predictions from the RFT calculations, which accurately predicted the forces for both intrusion scenarios with minimal error.

Next, we aim to test our model's capabilities by testing various footpad shapes. We begin by generating random shapes of zero angle of attack (β), as shown in Fig 3A. We then calculate the RFT forces for each penetrating footpad. We hypothesize that the footpad shape producing the largest vertical force at a given depth will sink less, making it a safer option compared to shapes that generate smaller forces. Fig 3B shows the RFT force curves for the shapes in Fig 3A, while Fig 3C illustrates a sample footpad penetrating at 70° of angle of intrusion (γ).

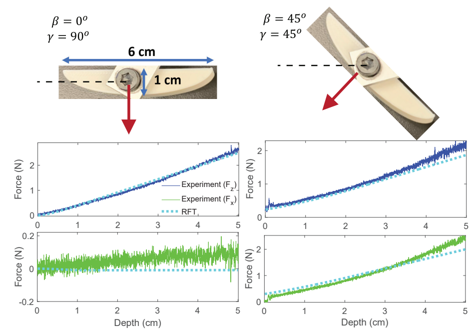

***Fig 2:** Comparison of force curves obtained from powder intrusion experiments and powder RFT calculations.*

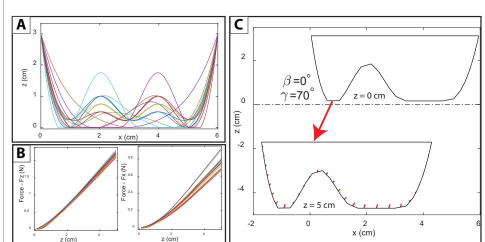

***Fig 3:** A) Footpad shape generation. B) RFT forces of the footpad shapes in vertical (left) and horizontal (right) axes. C) Illustration of penetration of a footpad shape to a 5 cm depth.*

We plot peak vertical RFT forces of all footpads penetrated to 5cm depth as a function of respective footpad surface area for γ = [10°,50°,90°] in Fig 4, identifying shapes that produced minimal and maximal vertical forces. Shapes with large wedge-like protrusions resulted in the lowest vertical forces across all γ values, while shapes with increased surface area and a wavy pattern led to the highest forces for γ = [10°, 90°], and a flat surface for γ = 50°.

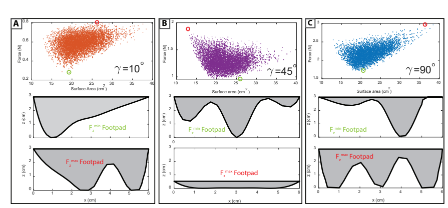

***Fig 4:** RFT force calculations for all the footpads generated for 3 different angle of attacks and . A) Almost horizontal touchdown (γ = 10º) B) Diagonal touchdown and (γ = 50º) vertical touchdown (γ = 90º).*

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Reference: [1] Li et al, *Science* **339**(6126):1408-12, 2013

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