2024 to 2025 Moncrief Grand Challenge Award Final Report

Awardee **Krishna Kumar, Associate Professor, Civil, Architectural and Environmental Engineering**

Research Award Title **Digging on the Moon with Differentiable Simulations**

Research Summary

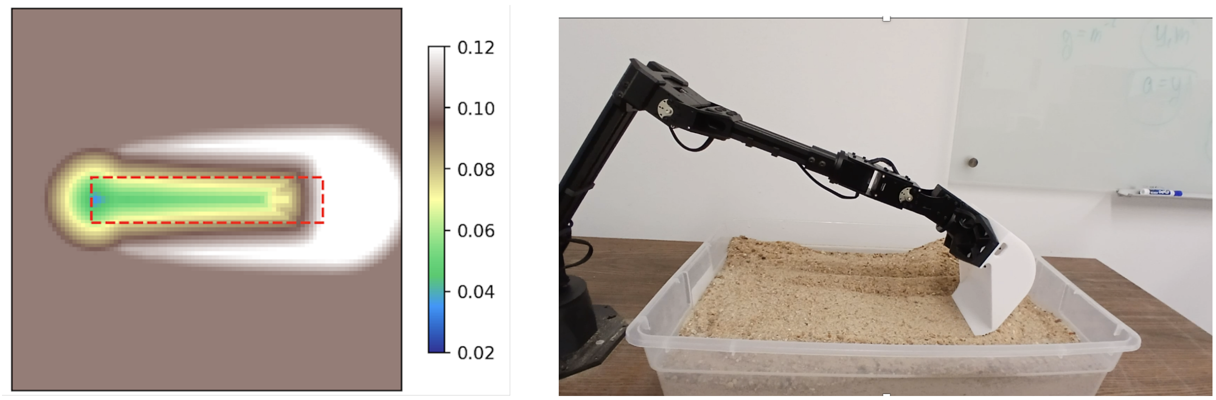
Autonomous excavation on the Moon requires knowledge of regolith properties, yet no test data exist at the excavation site. Apollo measurements indicate friction angles between 30 and 50 degrees depending on density and location. These values derive from a few samples in mare regions. Because standard geotechnical tests are impractical on the lunar surface, these properties must be derived from the excavation process itself.

This project developed differentiable simulations to estimate regolith properties from excavation data. These simulators compute the regolith motion and the gradient of that motion with respect to material parameters. Gradient-based optimization utilizes these gradients to fit the parameters to an observed excavation. The research team built two methods. The first method employs a graph network simulator (GNS) trained on material point method (MPM) data. This network replaces MPM as a fast surrogate model during inverse analysis. The second method reconstructs the terrain geometry from images and identifies the friction angle that minimizes the difference between simulated and observed images. Physical hardware experiments demonstrated a robot arm excavating sand. The system estimated the sand friction angle within 1.4 degrees of the direct shear value using only video of a single scoop. This work established an active collaboration with the Granular Mechanics group at NASA Kennedy Space Center through the SEVIS program.

Results of Aim 1. Robot excavation with differentiable graph network simulators

The material point method (MPM) resolves the large deformations, material separation, and tool-soil contact inherent to excavation. The MPM constitutive model uses a friction angle that direct shear tests can measure directly. Because inverse analysis requires many forward simulations, standard MPM execution is computationally prohibitive. The project trained a graph neural network simulator on MPM trajectories to serve as a fast surrogate. This GNS represents the soil as a graph of material points and learns the local interaction laws. Because these learned laws apply locally, the simulator successfully generalizes to excavation geometries and tool paths outside the initial training set. Figure 1(a) shows the simulated excavation depth for one scoop pass. The dashed box marks the excavation target.

The GNS is differentiable end to end. Applying reverse-mode automatic differentiation through the simulator (DiffGNS) fits the material parameters to an observed excavation. Hardware testing validated this approach. A robot arm equipped with a 3D-printed scoop excavated a bed of sand (Figure 1b). Direct shear tests previously established the sand friction angle at 30 degrees. Using only video of the excavation without force measurements, DiffGNS estimated a friction angle of 28.6 degrees. This result represents an error of 1.4 degrees. The simulator uses this identified friction angle to predict the soil response during the subsequent excavation pass.



(a) (b)

Figure 1: Robot excavation with differentiable simulation. (a) Simulated excavation depth field for a scoop pass. The dashed box marks the excavation target. (b) Robot arm excavating sand with a 3D-printed scoop. From video of this interaction, the differentiable graph network simulator inferred a friction angle of 28.6 degrees against a value of 30 degrees measured by direct shear test.

Results of Aim 2. From images to properties and vision-based parameter inversion

Because lunar rovers primarily carry cameras, the second aim estimates material properties exclusively from images. The developed framework couples Neural Radiance Fields (NeRF) with MPM. Multi-view images of the undisturbed terrain train a NeRF to reconstruct the three-dimensional surface. This reconstructed surface initializes the material points for an MPM simulation of the physical interaction. The experiments modeled this interaction as a plow dragged through sand. Fixed cameras record the resulting deformation over time. The system runs simulations with candidate friction angles and renders them from identical viewpoints for comparison against the recorded images. Bayesian optimization minimizes the image loss to identify the friction angle that best reproduces the physical observations. This parameter inversion requires no simulator gradients and accommodates any forward simulator, including closed-source engines.

Testing evaluated ground-truth friction angles of 25, 30, 35, and 45 degrees. Each case included ten optimization trials with ten simulations per trial. The mean absolute error ranged between 0.64 and 1.38 degrees, remaining within 2 degrees across all cases. Error magnitude increases alongside the friction angle because stiffer materials produce subtler deformation patterns in the visual data. These results appeared in the Powders and Grains 2025 conference proceedings (Hsiao and Kumar). This framework enables a rover to estimate regolith properties from images of a single soil interaction without physical sampling or laboratory testing.

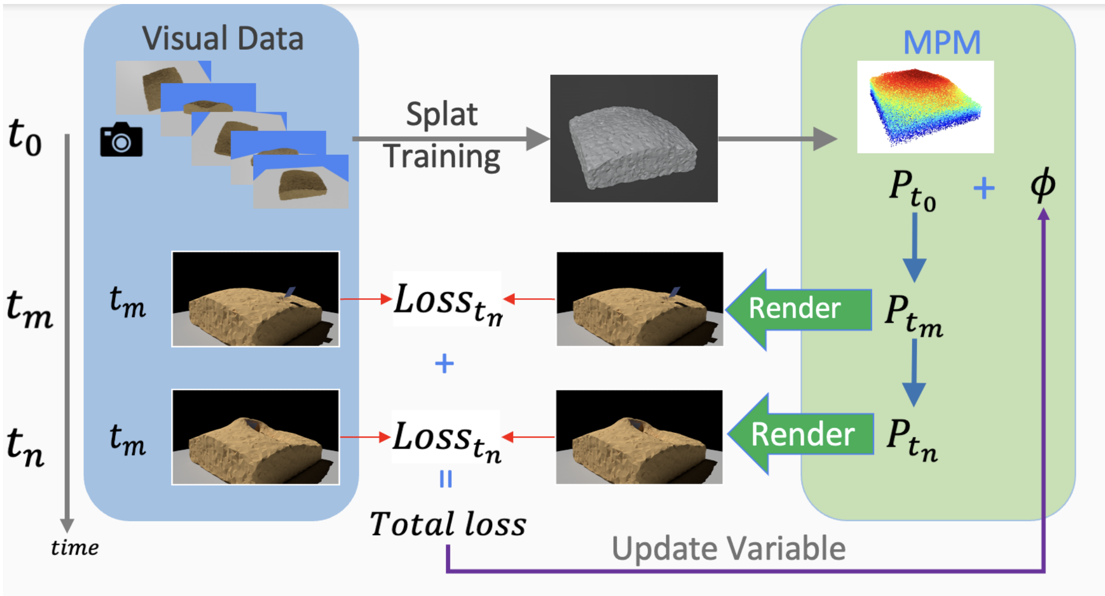


Figure 2: Images to properties pipeline. Multi-view images of the undisturbed terrain at t_0 are reconstructed into 3D geometry, which initializes the material points P_{t_0} of an MPM simulation with candidate friction angle ϕ. Simulated states at later times are rendered from the observation cameras and compared with the recorded images. The summed image loss updates ϕ until the simulation reproduces the observations, recovering the friction angle to within 2 degrees.

Broader outcomes and follow-on activities

The two methods integrate into a single workflow. Vision algorithms supply the terrain geometry, the differentiable simulator fits the material parameters to the observed interaction, and the identified model predicts the subsequent excavation. This work initiated a broader research program focused on physically viable world models. These learned representations of the physical world strictly produce physically admissible states and dynamically adapt to specific operational queries. The lunar construction collaboration with the Granular Mechanics group at NASA Kennedy Space Center continues beyond the award period through the SEVIS program.

Presentations

- Digging on the Moon with Differentiable Simulations, *17th U.S. National Congress on Computational Mechanics (USNCCM)*, Chicago, IL, July 2025. Speaker Krishna Kumar
- From Images to Properties A NeRF-Driven Framework for Granular Material Parameter Inversion, *Powders and Grains 2025*, Goa, India, 2025. Speaker Cheng-Hsi Hsiao
- Differentiable Programming and AI-accelerated Simulations, *SIAM Conference on Computational Science and Engineering (CSE25)*, Fort Worth, TX, March 2025. Speaker Krishna Kumar
- Interactive World Models, *Machine Learning in Geomechanics (MaGIC) 2025*, University of

Wisconsin Madison, 2025. Speaker Krishna Kumar

Publications

- Hsiao, C.-H., & Kumar, K. (2025). "From Images to Properties A NeRF-Driven Framework for Granular Material Parameter Inversion," *Powders and Grains 2025*. arXiv 2507.09005.

Recognitions received

- Active collaboration with the Granular Mechanics group, NASA Kennedy Space Center, through the SEVIS program
- Shimizu Visiting Professorship, Stanford University, 2026