HIGH-FIDELITY SIMULATION OF THE ADVANCED PLANETARY EXCAVATOR (APEX) MANIPULATOR FOR IN-SITU RESOURCE UTILIZATION TECHNOLOGY DEVELOPMENT

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ISRU REQUIRES NOVEL TOOLS. DEVELOPMENT IS CHALLENGING.

- Lengthy development time for TRL 7+
- Limited testing capabilities due to environment differences
- Unoptimized tools waste resources

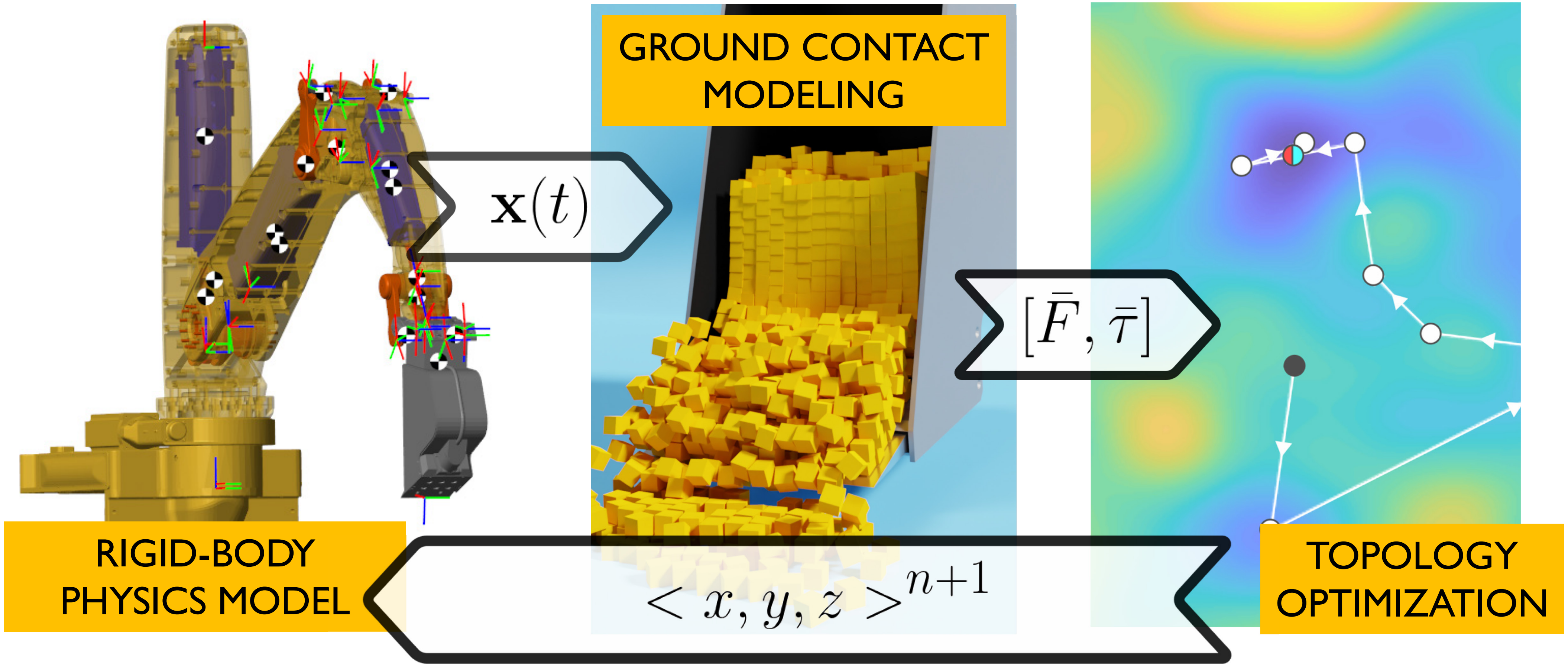
SIMULATION CAN SPEED UP THIS PROCESS

High-fidelity, physics-based simulation can reduce the time, effort, and cost required to develop and deploy robotic systems that are optimized for their operating environment.

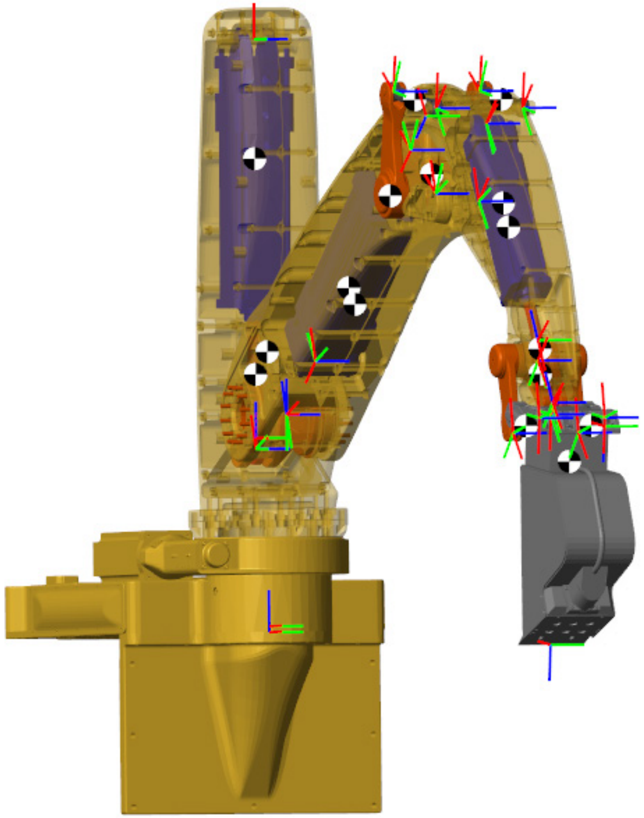
ADVANCED PLANETARY EXCAVATOR (APEX) ROBOTIC MANIPULATOR

- 4 degrees of freedom, fully electric
- Real-time, full-state logging
- Characterize excavation force/power

TOOL DEVELOPMENT APPROACH

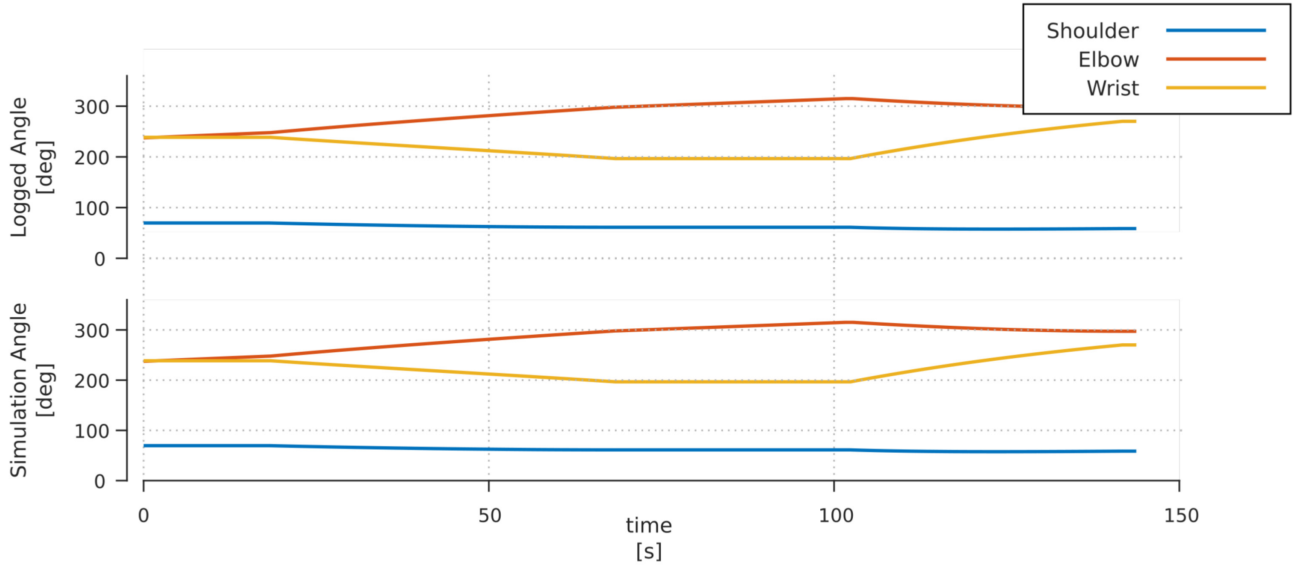


RIGID-BODY PHYSICS MODEL

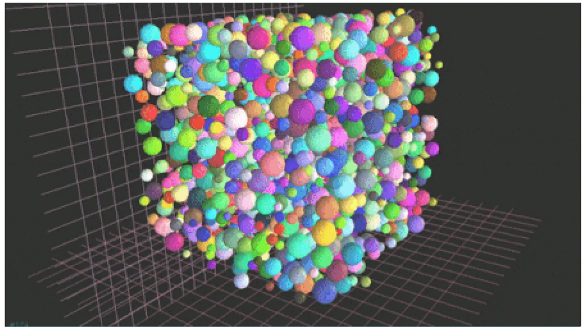


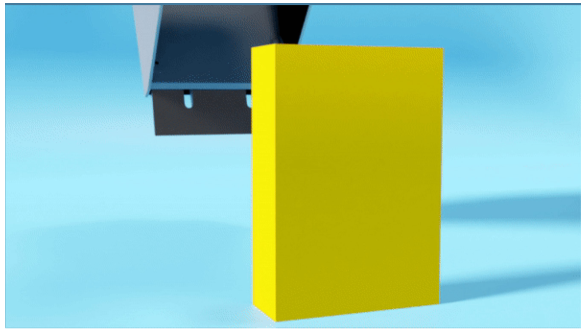
APEX Simscape Multibody Model

- Virtual reassembly with Inertia Tensors + CoMs
- Control loop + sensor simulations
- Data-driven friction models at relevant DoFs

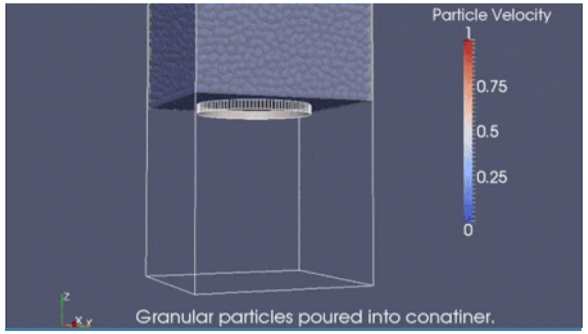


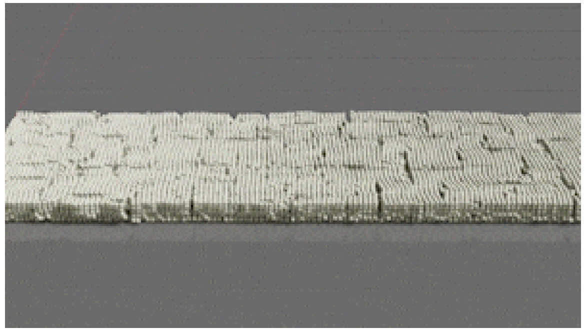
GROUND CONTACT MODELING

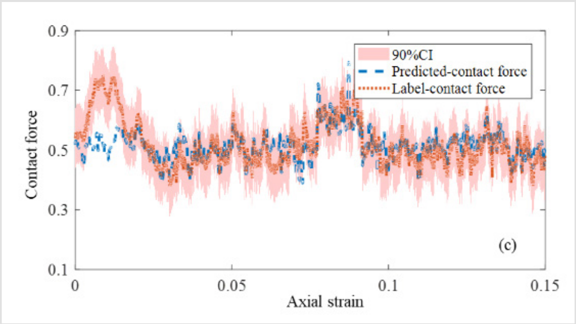




$$T = w\left[\left(0.5g\gamma t^2\{\tan^2(45+0.5\rho)\}d_1 + \frac{e^{2w'\tan\rho}-1}{4\tan\rho}r_0^2 g\gamma d_2 + gqt\{\tan^2(45+0.5\rho)\}d_4\right)d_3^{-1}\right] + w\left[\left(0.5(r_1^2 - r_0^2)\frac{c}{\tan\rho} + 2ct\{\tan(45+0.5\rho)\}d_4 + \frac{gqt}{\sin(45-0.5\rho)}d_5 + C_a l d_7\right)d_6^{-1}\right] \quad (1)$$







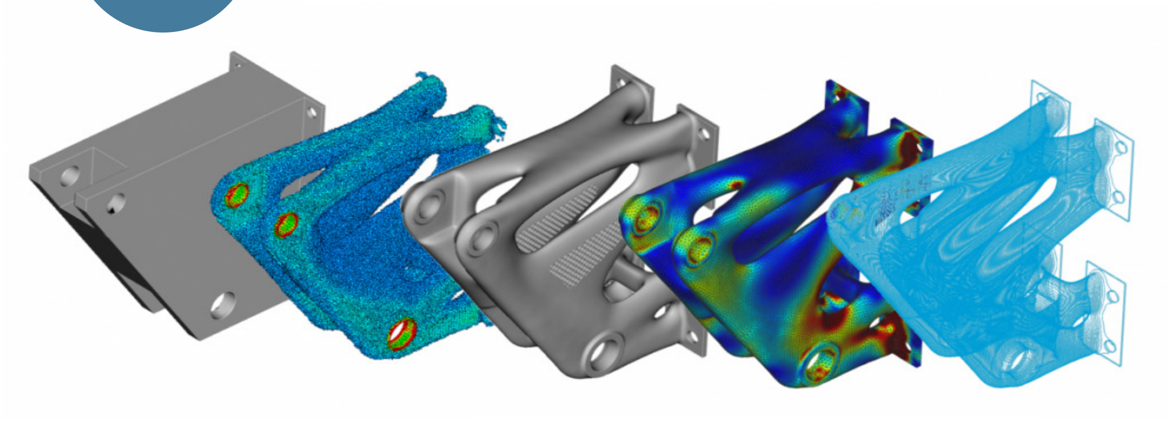
DEM Simulation
Top: Yade [1], *Bot:* LIGGGHTS [2]

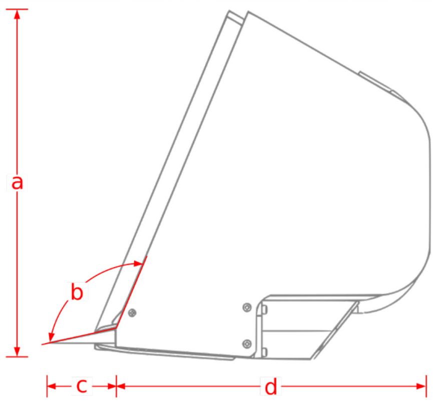
Rigid Body Physics Simulation
Top: Blender, *Bot:* NVIDIA Warp [3]

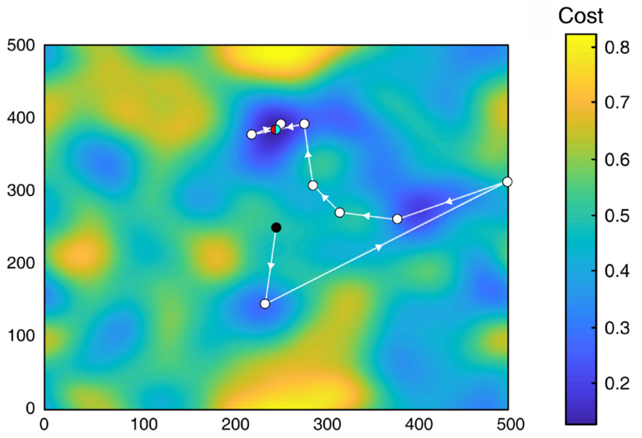
Other Methods
Top: LP Models [4], *Bot:* Data-Driven [5]

[1] V. Šmilauer *et al. Yade Documentation 3rd ed.* The Yade Project, 2021.
[2] C. Kloss *et al. Enhancing LAMMPS Capabilities.* 2nd LAMMPS Workshop, August 2011.
[3] M. Macklin. *Warp: A High-performance Python Framework for GPU Simulation and Graphics.* NVIDIA GTC, March 2022.
[4] A. Wilkinson and A. DeGennaro. *Digging and pushing lunar regolith: Classical soil mechanics and the forces needed for excavation and traction.* J. Terramechanics, November 2006.
[5] M. Wu and J. Wang. *Estimating Contact Force Chains Using Artificial Neural Networks.* Applied Sciences, July 2021.

TOOL OPTIMIZATION







Top: Topology Optimization [6]
Bot: Stochastic Parameter Optimization

- Truly optimal design
- Computationally intensive

- Optimal *a priori* design
- Faster convergence

[6] A. Chowdhury. *6 Main Benefits of Topology Optimization. Is It the Future of Engineering?* OpenBusinessCouncil.org, Accessed: 2022.

CONCLUSION

- Optimal designs require simulation
- Fidelity/computation trade-offs
- Investigating contact modeling

THANK YOU!