A FRAMEWORK FOR OPTIMIZATION-BASED ISRU TOOL DESIGN USING DISCRETE ELEMENT MODELING

Alexander Schepelmann, Ph.D. and Erin T. Rezich, *NASA Glenn Research Center, Cleveland, Ohio*

2022 National Aeronautics and Space Administration Structures, Loads, and Mechanical Systems Early Career Forum

INTRODUCTION

Novel robotic excavation technologies are needed to perform in-situ resource utilization (ISRU) tasks at levels required to sustain a long-term presence on the lunar surface. Developing and testing multiple iterations of functional hardware is time and cost prohibitive, thus slowing down the pace of progress and delaying humanity's settlement of the Moon. High-fidelity, physics-based simulation can reduce the time and effort required to develop and deploy robotic systems [1]. We have adopted this approach to create high-fidelity models of robotic test hardware to enable rapid virtual design and optimization of excavation technologies [2]. Such models can leverage modern computational tools like Discrete Element Method (DEM) simulations that can be coupled with automated design approaches like topology optimization to reduce the amount of prototyping and physical testing needed to realize useful tools.

METHODS

Tool optimization is completed via the three-stage iterative process shown in Figure 1. A high-fidelity system model is first used to produce desired ISRU trajectories for a given tool geometry and a desired target task like drilling or shoveling. System trajectories can be generated using inverse kinematics based on variables such as a desired tool tip trajectory or other dynamic parameters such as maximum permissible system power draw. The generated trajectory is then imported into a DEM simulation that moves a mesh of the current iteration of the tool geometry through a simulated environment that applies ground contact forces to the surfaces of the tool. Relevant parameters are then exported from this simulation depending on the cost function used for tool optimization, which can include parameters such maximum permissible stress on the tool's leading edge and volume of regolith transported. Finally, stochastic optimization is used to generate a new tool geometry and the process repeats until convergence.

The optimization process is purposefully divided into three distinct, interacting modules – High-Fidelity System Simulation, Ground Contact Modeling, and Topology Optimization – to retain maximum flexibility in the choice of target application, desired ground contact modeling scheme, and available computational resources (Fig. 1). This modularity enables a variety of tool optimization approaches and DEM solvers to be used depending on various user-decided factors and enables the use of other simulation methods that may be developed in the future.

OBJECTIVE

We seek to create a computational design tool that couples high-fidelity, physics-based system simulations with DEM modeling approaches to generate ISRU tools optimized for the Moon, Mars, and other environments of interest. The tool specifically aims to minimize hardware prototyping, which is time consuming, expensive, and can be difficult to evaluate in an analog environment on Earth for relevant environmental factors such as reduced gravity, vacuum, and geotechnical soil properties. In this approach, ISRU tools will be optimized via multi-objective topology optimization, which automatically adjusts tool geometry depending on desired system variables such as tool mass, power, and ground reaction force limits generated during ISRU tasks.

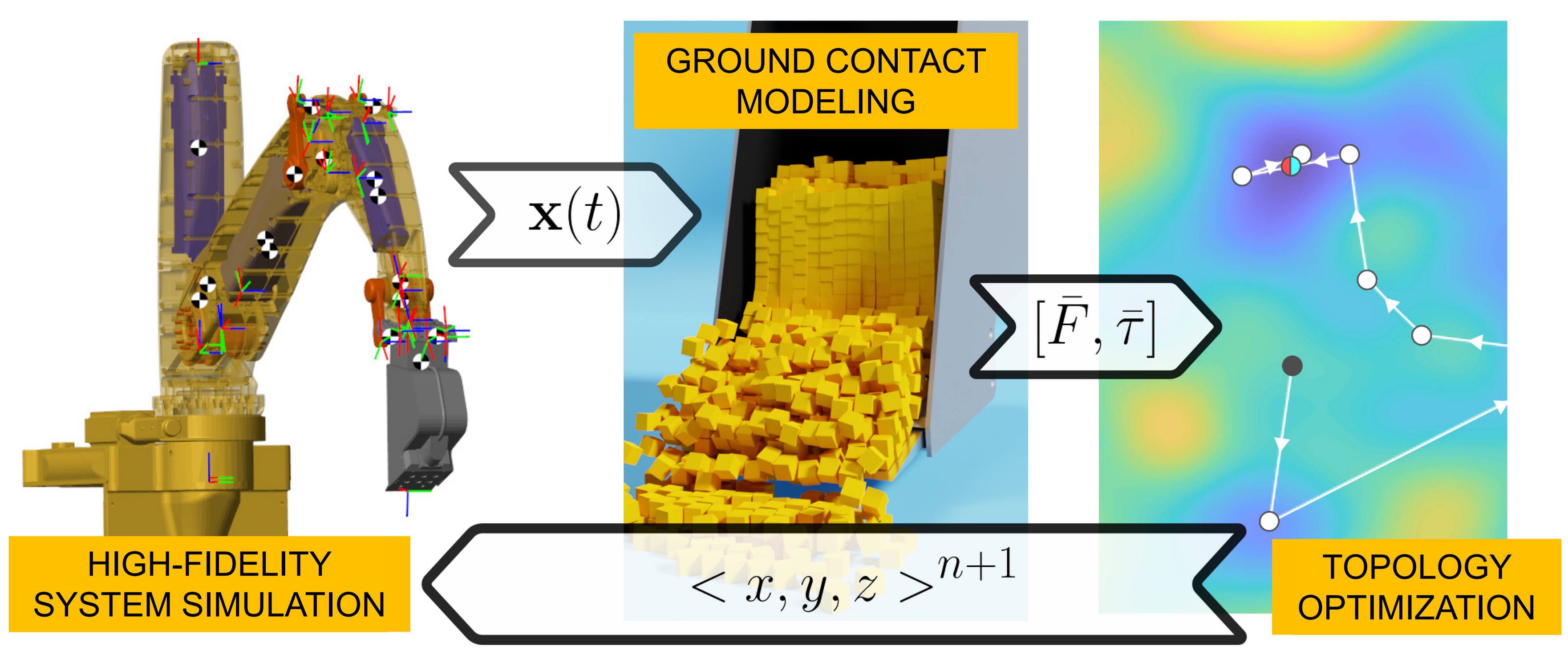

Figure 1: Proposed optimization loop for generative ISRU tool design.

RESULTS AND DISCUSSION

A high-fidelity rigid-body physics simulation of the APEX manipulator, a fully electric four degree-of-freedom excavator, was created in Simulink Simscape (Mathworks, Inc.), which models the system at the individual component level (Fig. 1). Masses, center of masses, and inertia tensors for each component in the simulation were calculated from CAD geometries using SOLIDWORKS (Dassault Systèmes SolidWorks Corp.). The simulation closely matches testbed kinematics and accurately replays joint angle log files collected during excavation experiments (Fig. 2). Work to implement control system, sensor, and friction models for future dynamic simulation applications is ongoing.

DEM simulations are being actively developed in YADE, an open-source framework for granular media numerical models [3] (Fig. 3). Development will proceed in three stages: geotechnical parameter optimization, tool geometry interaction, and tool geometry optimization. A methodology to tune virtual soil parameters, including Poisson ratios, shear moduli, and friction coefficients for relevant simulants of interest is currently being developed with 2023 NASA Center Innovation Grant funding. This approach will use stochastic optimization to adjust virtual soil parameters to match observed behavior during benchtop soil characterization experiments [4]. Mesh optimization studies will be conducted to determine required mesh parameters to accurately and efficiently simulate ground interactions between virtual ISRU tools and DEM simulations. Finally, various tool optimization methodologies will be investigated, which range from parametric optimizations to tune pre-defined tool parameters to topology optimizations that are able to arbitrarily optimize material layouts within a desired tool volume [5]. This will enable the tool to be used to create both optimal designs of existing tools, such as buckets, as well as novel end effectors for excavation.

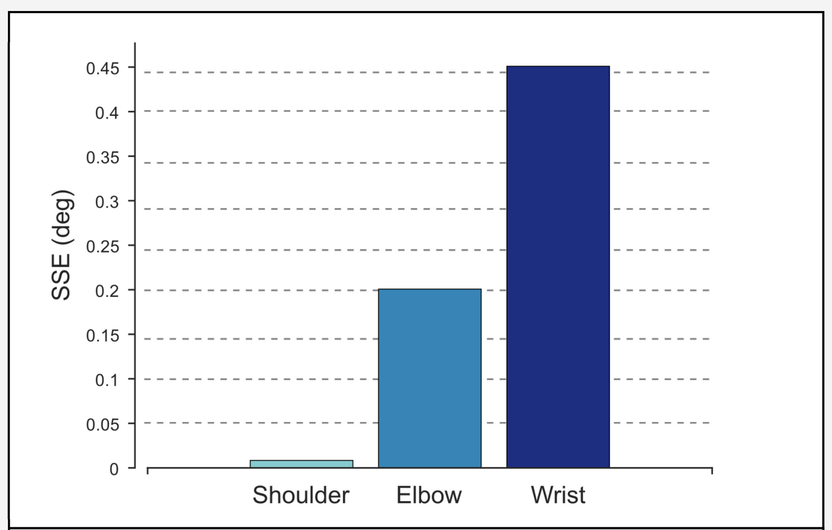

Figure 2: APEX simulation error.

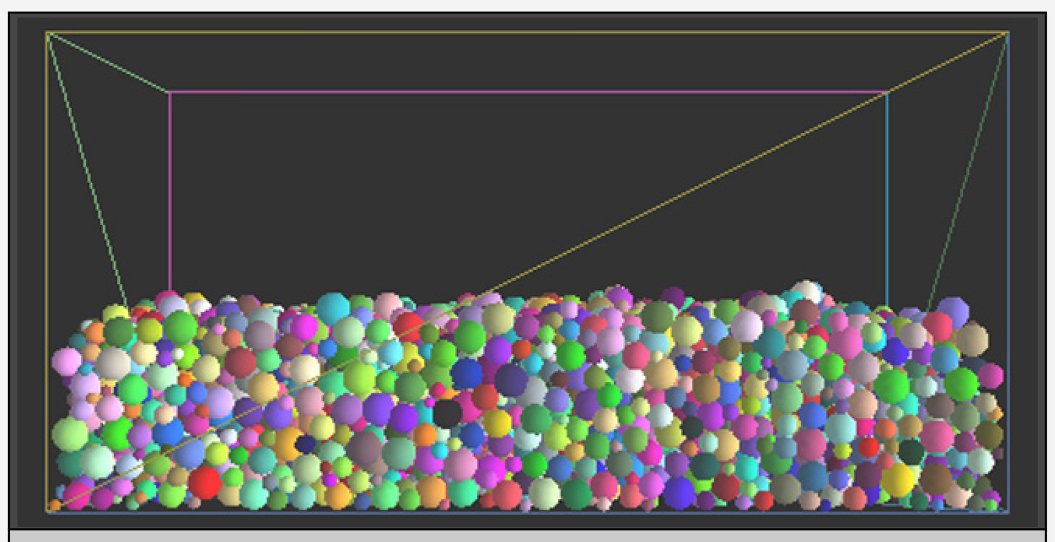

Figure 3: YADE simulation environment.

BROADER IMPACT AND BENEFIT

The proposed approach could significantly decrease the required amount of hardware prototyping needed to create optimized tools for various ISRU tasks. In addition to substantial cost and time savings, this approach would enable truly optimized tools to be created for desired resource harvesting and excavation tasks in a specific operating environment, which is currently difficult to accomplish due to limitations of analog testing on Earth.

While this method was originally developed with ISRU tool development in mind, it is not limited to this application and can be extended to optimize various other components and full-scale systems that interact with granular media, including rover wheels, anchoring and tether devices, and controllers for mobility systems, both for terrestrial and off-world applications.

Once a system model is implemented and tuned in the virtual environment, the simulation could also be used as a diagnostic tool to replay data logs collected *in-situ*. This could enable teams to more efficiently debug a system after deployment.

Finally, the simulation environment can be used as a testbed to develop more computationally efficient ground contact models for a given application, making it potentially useful for various development activities occurring throughout the agency.

REFERENCES

[1] A. Schepelmann *et al.* Experimental Evaluation of Robust Swing-Leg Placement Controls in Robotic Limb Testbeds, CMU-RI-TR-18-62, 2018.

[2] A. Schepelmann *et al.* High-Fidelity Simulation of the Advanced Planetary Excavator (APEX) Manipulator for In-Situ Resource Utilization Technology Development. Space Resources Roundtable XXII Meeting, Golden, CO, June 2022.

[3] V. Šmilauer *et al*. YADE Documentation 3rd ed. The YADE Project, 2021. (http://yade-dem.org/doc/).

[4] C. Igel *et al*. Covariance Matrix Adaptation for Multi-Objective Optimization. Evolutionary Computation 15(1), 1-28, 2007.

[5] O. Sigmund and K. Maute. Topology Optimization Approaches: A Comparative Review. Structural and Multidisciplinary Optimization 48, 1031-1055, 2013.

National Aeronautics and Space Administration
NASA Glenn Research Center,
21000 Brookpark Road, Cleveland, Ohio 44135