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

A. Schepelmann[1], E.T. Rezich[2], K.A. Johnson[3] , M.P. Proctor[4]. [1]NASA Glenn Research Center, 21000 Brookpark Rd., Cleveland, OH 44135, alexander.schepelmann@nasa.gov; [2]Ibid., erin.t.rezich@nasa.gov; [3]Ibid., kyle.a.johnson@nasa.gov; [4]Ibid., margaret.p.proctor@nasa.gov.

Introduction: Novel robotic and excavation technologies are needed to perform in-situ resource utilization (ISRU) tasks at levels required to sustain a long-term human 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. Such models can leverage modern computational tools like Discrete Element Method (DEM) simulations and can be coupled with automated design approaches like topology optimization to create preliminary excavation tool geometries, reducing the amount of prototyping and physical testing needed to realize useful tools. The proposed approach has the potential to automate and speed up tool development and to realize functional path-to-flight hardware more quickly than current excavation tool development approaches. This work describes ongoing development for a simulation of the Advanced Planetary Excavator (APEX), a robotic manipulator at NASA Glenn Research Center that is used to characterize the performance of ultrasonic excavation tools for ISRU tasks [2].

APEX Robotic Testbed: APEX is a four degree of freedom robotic manipulator located at NASA Glenn Research Center's Excavation Lab within the mTRAX Planetary Exploration Labs group (Fig. 1 a.)). The robot provides a modular platform to measure forces and power needed to excavate granular lunar regolith simulants using multiple tools at various compaction levels, rake angles, and tool trajectories. A 6-axis load cell located between the manipulator output and tool end effector measures excavation forces and torques, while a real-time data acquisition system simultaneously logs the full state of the robot.

High-Fidelity System Simulation: Data collected through preliminary experiments are used to create a high-fidelity system simulation of APEX using a multi-body physics engine (Simulink Simscape Multibody, Mathworks, Inc.), with rigid bodies defined at the individual component level (Fig. 1 b.)). The engine allows gravitational acceleration to be specified as a user input, enabling the simulation to model terrestrial and lunar environments. The simulation is composed of interacting subsystems executing both continuously and at various frequencies that match control-, sampling-, and data acquisition-loop frequencies found on the APEX hardware (Fig. 2). These parameters can be varied depending on the desired model fidelity and simulation run-time. Electrodynamic models in conjunction with simulated rigid-body assemblies of the system's actuators drive each degree of freedom, with optional discrete-time control loops that match hardware frequencies providing system feedback. Logged data and stochastic optimization are used to create lumped parameter friction models at the robot's joints to accurately capture static and viscous friction behavior at each degree of freedom.

Robot-Environment Interaction: Interaction forces between the robot and a simulated environment can be applied to any of the model's rigid bodies as

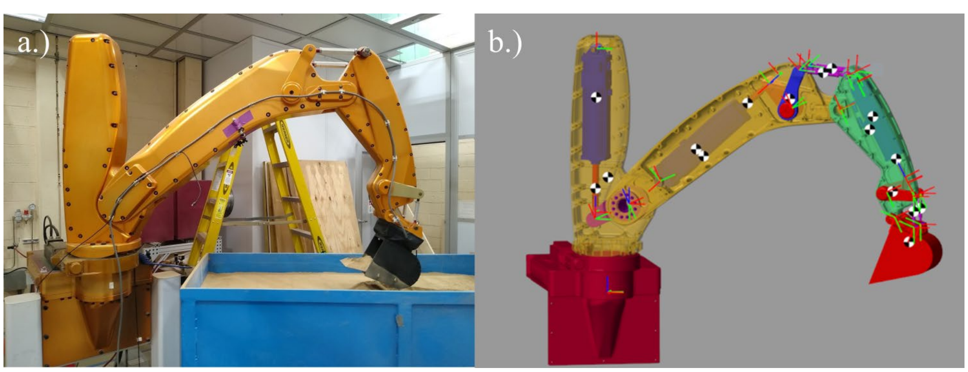

Figure 1. Advanced Planetary Excavator (APEX). a.) Hardware. b.) Simulation Model.

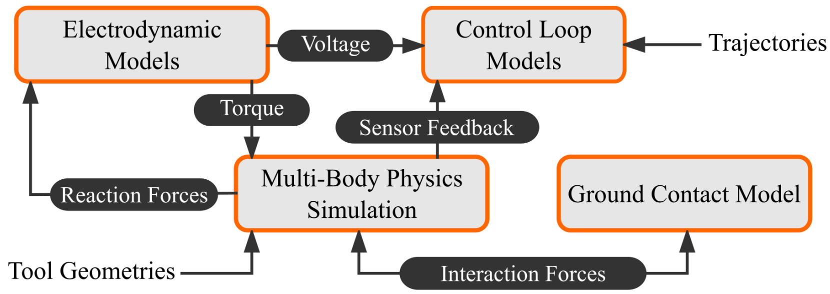

Figure 2. Simulation Architecture.

either equivalent force-moment pairs or as simultaneous discrete forces and moments, depending on desired model fidelity and simulation run-time. Discrete force contact points on rigid bodies of interest are calculated using a point-cloud library that approximates contact surfaces from input rigid body geometries. This enables forces generated by external solvers like the open-source Yade DEM framework [3] to interact with the APEX model and accurately simulate robot and control loop behaviors for a variety of excavation tools located at the manipulator output.

Optimization-Based Excavation Tool Design: The ultimate goal of this work is to couple the described physics-based robot model and DEM simulation with generative design and topology optimization frameworks to automate the design of excavation tools for a variety of ISRU tasks. Multiple approaches to optimization-based design exist [4-6] and will be explored during model development.

Potentials and Limitations: The proposed approach could significantly reduce the amount of required early-stage hardware prototyping and speed up initial design phases, which could ultimately result in more highly optimized tools for ISRU tasks. Furthermore, it could simulate a variety of soil types and different gravity environments, allowing for the creation of optimized tools that would be difficult to evaluate through physical testing on Earth.

While the amount of required hardware testing could be reduced by adopting this approach, DEM simulations, generative design, and topology optimization are each computationally intensive and require significant resources to create fully optimized end effectors. To speed up design iterations, alternative approaches such as lookup table interpolation or machine-learning based ground contact models could be adopted to generate environment forces depending on the required model fidelity. Constraining parameters for desired ISRU tools would also allow an optimization to converge on tool designs more quickly.

Current Progress: A rigid-body model of APEX has been completed and data collection to tune the model is ongoing. DEM and other granular media simulation tools, as well as generative design and topology optimization tools, are currently being investigated. The developed model will be validated with experiments that explore excavation force reduction using tools with an ultrasonic leading edge. Data from these experiments will be used to further characterize APEX and tune its simulation model.

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