APEX - An In-Situ Resource Utilization Excavation Research Tool. P. B. Abel,[1] S. W. Bauman,[2], and K. A. Johnson[3], [1] NASA Glenn Research Center, 21000 Brookpark Rd., Cleveland, OH 44135, phillip.abel@nasa.gov, [2] NASA Glenn Research Center, 21000 Brookpark Rd., Cleveland, OH 44135, steven.w.bauman@nasa.gov, [3] NASA Glenn Research Center, 21000 Brookpark Rd., Cleveland, OH 44135, kyle.a.johnson@nasa.gov.

Introduction: Space Policy Directive 1 calls for returning "astronauts to the Moon... for long-term exploration and use." For an extended human presence on the Moon, significant amounts of lunar regolith will need to be moved, likely for processing but also potentially for landing area berms and habitat radiation shielding. Depending on mission cadence, multiple tons per year of oxygen could need to be extracted from the local minerals, whether autonomously or with guidance from Earth or a nearby human outpost. While extraction processing efficiency will then dictate the regolith feedstock mass requirements per year, minimizing the excavation system mass lofted from Earth as one design goal is a given. In the reduced lunar gravity however, an excavating vehicle can only generate about one-sixth the traction as compared to Earth, so reacting the forces needed for routine excavation will be more difficult. One approach to In-Situ Resource Utilization (ISRU) resource gathering then is to minimize the reaction forces required for excavation by various means, which depends upon actually measuring those forces. Described here is one such tool for quantifying the forces and energy needed for excavating regolith, which was designed, built, and installed for testing at the NASA Glenn Research Center.

Hardware Description: Technology demonstrations at varying levels of fidelity can illustrate how an approach might actually work in a given non-terrestrial environment, or at least suggest the direction additional development should take. The Advanced Planetary Excavator (APEX) robotic positioning prototype functions similarly to a traditional terrestrial backhoe, but with specific adaptations for lunar analog operations. APEX was designed for mounting on and interfacing with the Centaur 2 mobility platform [1] designed and constructed at the NASA Johnson Space Center (JSC), and was demonstrated on Centaur 2 sporting a Kennedy Space Center percussive bucket in the JSC rockyard in August of 2014 (Fig. 1).

The APEX design represents a strictly terrestrial robot arm implementation, however, which was not built to be light weighted for launch. The same basic elements as a conventional backhoe are present, comprising a two-segment arm, with end-effector ("wrist") rotation. Rotation of the entire arm about a vertical axis at the base of the arm gives four degrees of freedom with a "reach" radius of over two meters horizontally, and the ability to access at least one meter below grade when mounted on top of Centaur 2.

Fig. 1: Combination of JSC Centaur 2, GRC APEX, and Kennedy Space Center percussive bucket.

Design features illustrated by APEX include all-electric actuation, using powerful linear actuators inside each arm segment. The actuators internally provide high resolution motion control, provide mechanically stiff positioning of each arm segment, and are protected from external environmental dust by their respective arm segments. With the actuators protected within the arm segments, only sealed rotary joints are presented to a dusty environment.

With modularity in mind, and similar to the conventional backhoe ability to exchange end-effectors (bucket, pick, rake, even drills or jack-hammer), the APEX wrist plate has both power and full ethernet wiring routed, to be available to potential instruments mounted there. While APEX power circuitry matches what is available from Centaur 2, which is high voltage nominally 320V DC, for a dusty environment both proximity communication and power transfer conceivably could be wireless to an end effector, with nearly off-the-shelf transceiver design options to choose from.

Current Research: With a rigid, position adjustable mounting point having four degrees of freedom, both the forces at that robotic arm end and the energy to move it can be measured. A six-axis load cell is currently mounted on the APEX wrist plate, with an excavation bucket mounted to the load cell. Precisely executed bucket trajectories can be repeated through lunar simulant as a function of soil condition, and without soil for baseline comparison. Initially a lunar mechanical simulant, GRC-3b [2], has been selected for testing, in part to validate excavation models such as classic Balovnev [3]. Future work can then measure reaction force reduction techniques as well as explore additional simulant and analog materials.

Summary: An existing terrestrial robotic platform for excavation research has been applied to validating our model understanding of lunar excavation forces and energy expended. For future long-duration, unattended excavation operations, repair or some type of return-to-service capability will be required, for example an entirely modular robotic architecture. With both power and an ethernet data channel routed internally and available at the end effector, APEX is a ready platform for exploring how to minimize the "interface penalty" of a physically robust, smart quick-disconnect. The challenges of modularity on the lunar surface include dust tolerance, temperature extremes, vacuum and radiation. Particularly for a power constrained mission, efficient energy transfer between modules could become an issue if direct connections are challenging due to dust.

As originally envisioned and to take advantage of the possible modular interface, an APEX type configuration could create a prospecting trench using a bucket, bucket-drum, or bucket wheel, and then exchange the end effector for a measuring device, such as a mass spectrometer, hyper-spectral camera, or x-ray fluorescence spectrometer. In addition to enabling robust long-duration excavation, modularity could extend the science and prospectig capabilities of lunar rovers also.

Future mission design decisions can well be based on the capabilities demonstrated and measurements made by the current research community terrestrially.

References: [1] https://er.jsc.nasa.gov/er4/ Curator, Mike Red; Media Contact, Dan Huot; Last Updated 05-25-2017. [2] He, C., Zeng, X., and A. Wilkinson, “Geotechnical Properties of GRC-3 Lunar Simulant,” ASCE Journal of Aerospace Engineering, Vol.26, No.3, 528-534, 2013. [3] Balovnev, V.I. (1983) "New Methods for Calculating Resistance to Cutting of Soil" ISBN 978-0862493004.