ISRU Pilot Excavator: Bucket Drum Scaling Experimental Results

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ABSTRACT

NASA's Space Technology Mission Directorate (STMD) is funding the development of a robotic excavator called the "ISRU Pilot Excavator" (IPEx) which will be a technology demonstration of excavating and transporting 10 metric tons of lunar regolith on the surface of the Moon with a 30kg-class robotic excavator. IPEx will be the next generation of robotic excavators to use bucket drums as excavation tools. This is an evolution of the Regolith Advanced Surface Systems Operations Robot (RASSOR) developed at NASA's Kennedy Space Center (KSC).

Bucket drums are hollow cylinders with regularly spaced scoops around the perimeter. The drums rotate in one direction to collect regolith with the scoops. The regolith slides down an internal baffling system inside the drum which prevents the regolith from falling back out of the scoops. The captured regolith can then be transported while held in the drum and then deposited by rotating the drum in the opposite direction allowing the regolith to slide back down the baffling and out of the excavation scoops. Bucket drums were developed by Lockheed Martin in 2008 and used on multiple robotic excavator prototypes ever since. However, the forces on a bucket drum and considerations for scaling have not been measured in detail. Bucket drums are challenging to model using classical blade\bucket equations because of their unique geometry. Therefore, this experiment was performed to measure the forces on three bucket drums of the same geometry at different scales. Small: 9.4" (239mm) dia. x 8.1" (206mm) width, Medium: 11.6" (294mm) dia. x 10" (254mm) width, and Large: 17" (432mm) dia. x 14.1" (358mm) width.

The test stand consisted of an actuated gantry with controlled motion in the vertical (Z) and horizontal (X) axes and a single rotation axis (R). The bucket drums were individually mounted to the rotary axis of the test stand and translated across a prepared

bed of Black Point 1 (BP-1) lunar regolith simulant at a specified linear speed and cutting depth. The test stand was outfitted with a torque sensor in line with the rotation of the drum (R) and a 3 axis (X, Y, and Z) load cell. In addition to the three sizes of bucket drums the linear excavation speed and cutting depth were test variables.

The results of these experiments show the relationship between the three scales of bucket drums for factors such as: excavation force, torque due to regolith rotation inside the drum, excavation energy, time to fill, etc. and will be discussed in detail in this paper. This fundamental data will be used in the design of IPEx and can inform the design of future bucket drum excavators.

INTRODUCTION

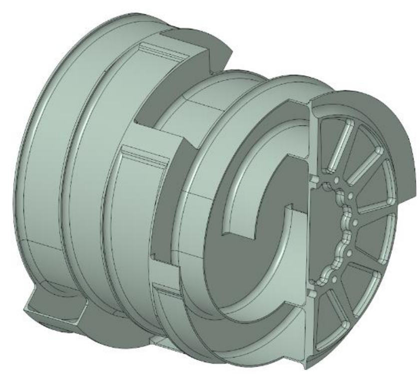

Figure 1. Bucket Drum partial section view showing internals

The In-Situ Resource Utilization (ISRU) Pilot Excavator (IPEx) Project will develop a 30 kg-class excavator to demonstrate robotic excavation of large amounts (10,000 kg) of lunar regolith. IPEx uses novel excavation tools, called bucket drums (Clark et al (2009)), which are hollow cylinders with scoops staggered around the outside. Regolith is collected with the scoops and flows into the drum where it is captured due to an internal baffle system. The excavator can then transport the regolith in the drum and reverse the direction of the drum rotation to dispense the regolith back out. IPEx uses sets of bucket drums that dig simultaneously in opposing directions (see Figure 2). This combination of bucket drum excavation tools and counter-acting excavation forces (Dickson et al (2016)) enables low mass robotic excavators to effectively dig in reduced gravity environments. This is a significant departure from terrestrial excavators that rely on high mass and weights to produce tractive forces to counteract the forces of excavation. To date, NASA has only excavated tens of kilograms of lunar regolith. Excavation has never been performed by a dedicated excavation technology machine/robot, rather only as a secondary function of an exploration rover or by an astronaut using scooping/sampling methods. IPEx will be NASA's first lunar surface robot specifically designed with the reliability and efficiency to excavate large quantities of regolith. This capability is critical to sustained lunar mission success. By the end of the decade, the excavation needs increase from sampling levels to tens or hundreds of tons of regolith per year. Full-scale sustained ISRU and construction of infrastructure will increase that amount to thousands of tons of regolith per year.

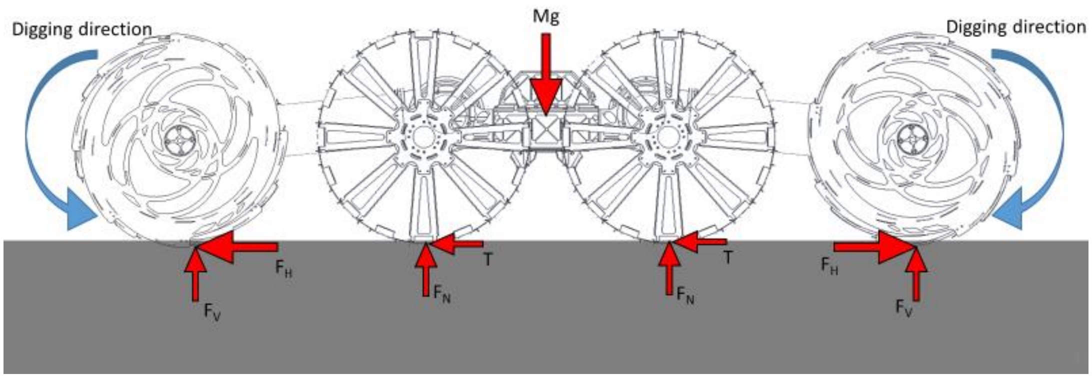

Figure 2. Counter-acting excavation forces

The IPEx leverages years of design refinement and testing of RASSOR (Mueller et al (2013)). The first generation of RASSOR was a proof-of-concept that demonstrated the ability to do excavation in low gravity with a low mass excavator by using counter-acting excavation tools. The second generation of RASSOR (known as RASSOR 2.0) (Mueller et al (2016)) was a breadboard system built with components that have proven paths to flight, which enabled the team to accurately estimate key metrics such as mass and energy usage for future flight versions of the excavator to inform architecture studies.

The IPEx dry mass target is 30kg which requires a reduction in scale from the current RASSOR 2.0 system which has a dry mass of 65kg. Volumetrically, IPEx will be scaled between 50% - 70% of RASSOR 2.0. The bucket drums of IPEx will therefore also be reduced scale, and a method of estimating the forces on the scaled bucket drums during excavation is needed.

An abundance of prior work and models exist for prediction of excavation forces (Gallo et al (2010), Wilkinson et al (2007), Zeng et al (2007), and Zelenin et al (1975)) however these models represent conventional excavation tools such as blades and buckets and do not address the unique configuration of a bucket drum.

The primary goal of this work is to inform the design of the IPEx by answering the following questions:

- What is the regolith capacity of the scaled bucket drum?
- What are the forces (X,Y,Z) and torque due to excavation?
- How do those forces and torque change with drum rotational speed, linear cutting speed, and cut depth?
- How much time is needed to fill at various cut depths and speeds?
- How much energy is used during excavation, and how does it vary with drum rotational speed, linear cutting speed, and cut depth?

EXPERIMENTAL SETUP

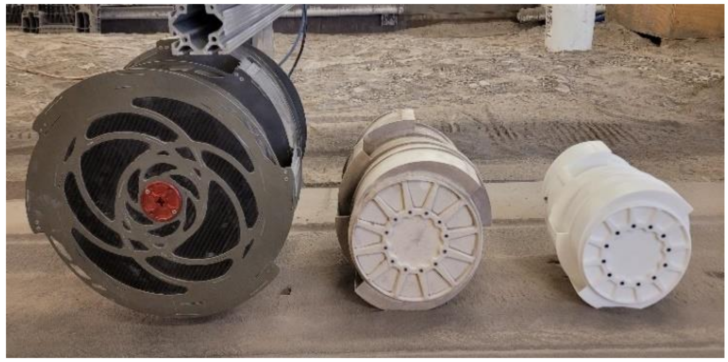

Figure 3. Bucket Drum Size Comparison

Three different bucket sizes have been selected for the test (see Figure 3). The range of sizes is to help determine a scaling relationship for different size bucket drums. The largest drum is the RASSOR 2.0 drum. The medium and small drums were scaled to meet the minimum and maximum required sizes for the ISRU Pilot Excavator. The overall dimensions for the bucket drums are as follows (see Figure 4 and Table 1):

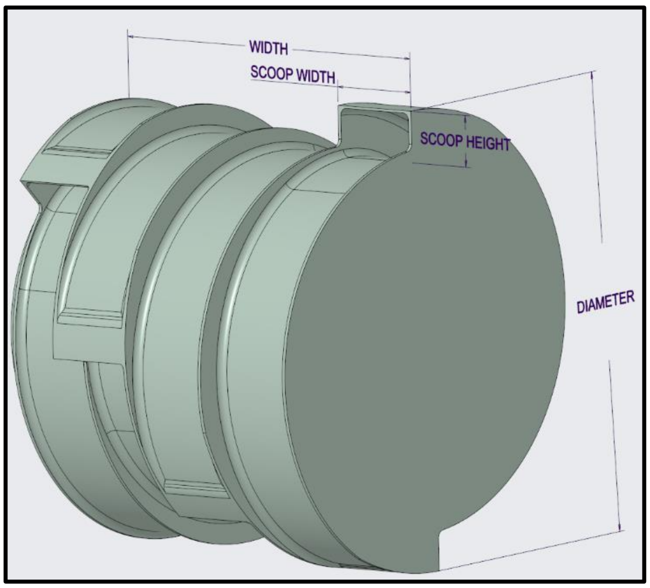

Figure 4. Bucket Drum Dimensions

Table 1. Bucket Drum Dimensions

	Width	Diameter	Scoop Width	Scoop Height
Small	7.83”	9.35”	2.03” (51.6mm)	1.04” (26.4mm)
Medium	9.69”	11.62”	2.5” (63.5mm)	1.36” (34.5mm)
Large	13.88”	17.21”	3.56” (90.4mm)	1.88” (47.8mm)

Bucket drums have many performance-dependent dimensions that effect their digging and collection. The scoop height and width determine the dig depth and flow rate into the drum. Special consideration needs to be made to mitigate bridging of the regolith as it enters the drum. Scoop height also determines the effective internal diameter, which determines the amount of total regolith collected. The baffle follows behind the scoop opening and is required to keep regolith from falling out of the scoop opening during digging and transportation. The baffle geometry can also affect bridging, and total regolith collected. The baffle channel width expands as it approaches the center to reduce bridging and ease the flow of regolith as it enters the drum. Each drum slice, which consists of two scoop openings, has closed section walls to separate the drums slices from one another. The intent of the closed slices is to reduce the amount of regolith that may fall out of a downward facing drum scoop by limiting the exposed volume to one slice instead of the entire bucket drum.

The bucket drums are made using two different construction techniques and materials. The large drum was made for RASSOR 2.0 and is a bonded assembly consisting of aluminum, carbon fiber, and stainless steel. The vertical side and section walls are aluminum. The top scoop and baffle sections are thin carbon fiber sheets which are glued to the vertical side and section walls. The cutting-edge teeth are made from stainless steel and are riveted to the carbon fiber sheets and vertical side and section walls. The small and medium bucket drums are a monolithic piece made from 3D printed Selective Laser Sintering (SLS) nylon. The general geometry of all bucket drums is intended to be identical except for the obvious scaling differences. The major differences between the large and small/medium buckets drums are the sharp corners of the baffle sections and the scoop teeth. The larger bucket drum has perpendicular corners in the baffle sections and the small/medium bucket drums have a radius. The radius is assumed to help reduce friction and aid in reducing bridging. The small/medium bucket drums were printed with a straight edge along the scoop cutting edge whereas the larger bucket drums have a jagged tooth profile.

Testing was performed in the KSC Regolith Test Bed (RTB). The RTB is an enclosure with 120 tons of BP-1 lunar simulant corresponding to a volume of 8m x 8m x 1.1m. BP-1, or Black Point 1, lunar simulant is an inexpensive geotechnical lunar regolith simulant sometimes used for excavation and mobility testing. BP-1 is derived from material in the Black Point basalt lava flow in northern Arizona. Because it is derived from basalt, BP-1 is more representative of mare lunar soils than highland lunar soils. The granular size distribution of BP-1 falls within the one standard deviation of actual lunar regolith particle distribution returned by Apollo lunar missions.

The bucket drum test stand consists of 2 linear axes, X and Z, and a rotary axis, R (see Figure 5). The linear axes are closed loop controlled and have linear absolute sensors measuring the position of the final stage. The X axis has a maximum speed of 246 mm/sec and a positioning accuracy of 0.25 mm. The Z axis has a maximum speed of 460 mm/sec and a positioning accuracy of 0.25 mm.

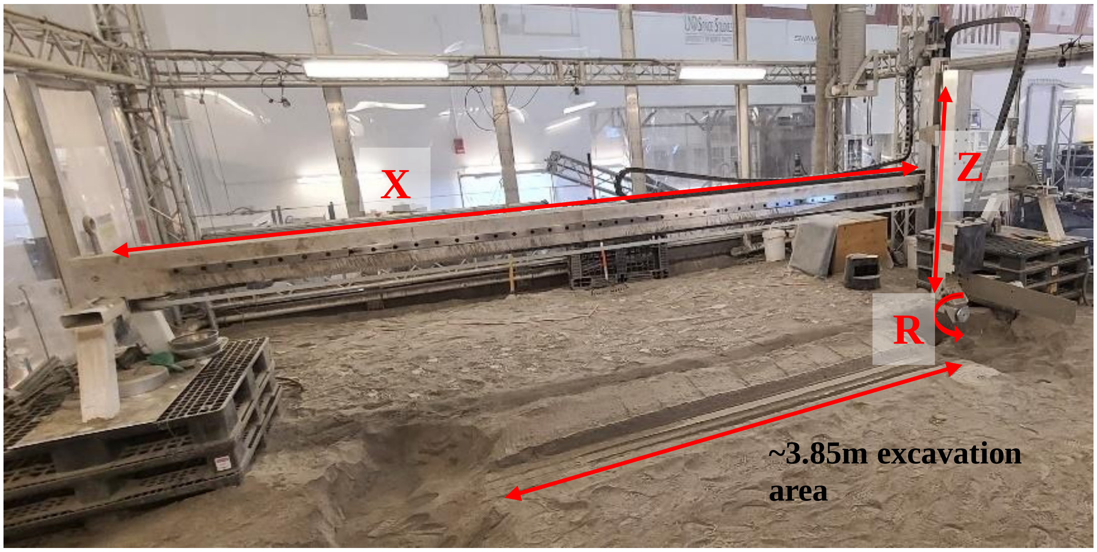

Figure 5. Bucket Drum Test Stand

To prepare the BP-1 simulant, leveling and compacting attachments were designed to attach to the bucket drum test stand. A beam was used to drag across the excavation area using the X axis to create a surface parallel with respect to the test stand (see Figure 8). Relief trenches were dug at the start and end of the excavation area to allow deposition of the surcharge of the regolith collected by the beam. The compacting attachment uses a handheld vibratory concrete compactor with a modified compacting plate (see Figure 9). The compacting plate is wider than the large bucket drum and has bent up edges to allow it to stay above the regolith during operation. The compacting attachment is driven using the X axis. The relief trenches also allow for the bucket drum to start and end excavation without engagement. The end relief trench was also used as the dump location for the bucket drum after excavation.

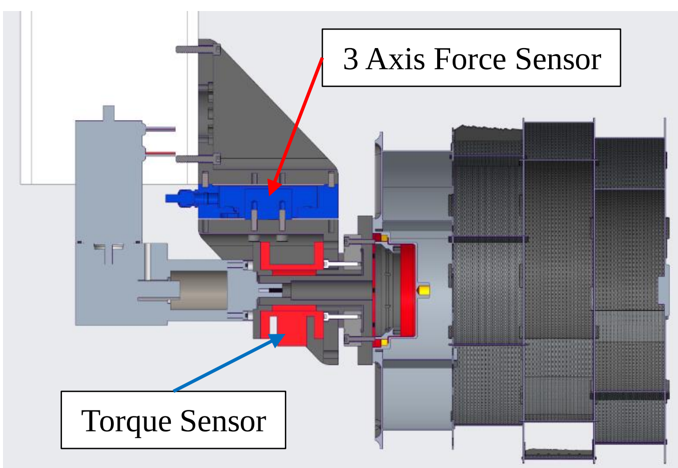

Figure 6: Sensor Layout

The test is outfitted with two feedback sensors: a torque sensor and a multi-axis force sensor (see Figure 6). The torque sensor is coaxial with the R axis. The torque sensor is an Interface Force sensor part number: 5330-600. This sensor has measuring range of ±600 in·lbf (68 N·m) and a nonlinearity of ±0.1% of full-scale output. The multi axis sensor is an Interface Force sensor part number: 3A120-1kN. This sensor has measuring range of ±225 lbf (±1 kN) and a nonlinearity of ±0.2% of full-scale output. National Institute of Standards and Technology (NIST) calibrations were used for both sensors. A calibrated weight was used to verify the sensors in their system configuration.

The Data Acquisition System (DAQ) is a National Instruments (NI) cRIO. The software allows for manual and scripted control of the test stand actuation. The scripted control allows for blocking and non-blocking position and velocity commands and time waits for each axis. This ensures repeatable test motion profiles for each experiment. The force and torque sensors are logged at 1 kHz, but the feedback from the motor controllers is logged at 10 Hz. This motor feedback is oversampled to properly align with the force/torque data. The slower rate of motor feedback is due to the limitations of the CAN bus interface used to control the motor controllers. The force/torque sensors are measured using a NI-9237 C Series Strain/Bridge Input Module, which has a 24-bit resolution and a ±25 mV/V input range. The software performs all the unit conversions real-time. The variables that are recorded are as follows: X (lbf), Y(lbf), Z (lbf), Torque (in*lbf), Z position (mm), Z Velocity (mm/sec), X Position (mm), X Velocity (mm/sec), R Position (revolutions), R Velocity (rpm), R (Motor Active Current, Amps), Sample Rate (Hz), Elapsed Time (minutes).

EXPERIMENTAL VARIABLES

Tests were performed varying the size of the bucket drum, linear speed during excavation, and cut depth. Table 2 lists the experimental variables and their ranges.

Table 2. Experimental variables and ranges

Test Variable	Range
Bucket Drum Size	Small, Medium, Large
Linear Cut Speed	10mm/s, 30mm/s
Cut Depth	10mm, 40% of scoop height

The combination of these variables resulted in 12 unique tests and each test case was repeated 4 times resulting in a total of 48 tests. The two values for cut depth were chosen to provide absolute (10mm) and relative (40% of scoop height) comparisons between the drum sizes. The cut depths were based on prior experience with the RASSOR 2.0 excavation robot. During the many hundreds of hours of testing with RASSOR 2.0, it was observed that when digging at the full depth of the bucket drum scoop the regolith could bridge across the opening and reduce the amount of regolith collected per rotation. The team found that limiting the cut depth to only utilize a maximum of 50% of the bucket drum scoop opening would collect more regolith per rotation.

The rotational speed of the bucket drums and the linear cut speeds were intentionally linked during testing to keep a constant cut pitch (the number of scoops per linear distance) across all bucket drum sizes. When the linear cut speed was increased or decreased the rotational speed was changed proportionally. The chosen ratio resulted in a bucket drum tangential velocity that was 8.5x the linear cut speed. This ratio was based upon previous experience and modeling and ensured a relatively smooth cut surface that would benefit subsequent cutting passes (see Figure 7). The linear cut speeds chosen are in the range needed for the IPEx concept of operations.

Figure 7. Bucket Drum Test Bed being precision leveled

TEST PROCEDURE

Prepare/Reset Test Bed:

The test bed was carefully prepared and characterized with hand geotechnical tools throughout the testing regimen to ensure consistency and repeatability. The BP-1 lunar regolith simulant requires special considerations when preparing or resetting the test bed. The geotechnical properties of the soil bed can vary wildly based on factors such as humidity, pouring method, compacting method, and surrounding soil densities, just to name a few.

To prepare the test bed or to reset it between test regimens, a team member first used a hand shovel to loosen the bed of simulant. This operation involved scooping up the BP-1 simulant to approximately 80cm of depth, and then gently pouring it back into the same location. This operation was performed on the entire width and length of the bucket drum test bed.

The team member then scooped excess material from previous tests to roughly fill in noticeable low spots. After the simulant had been adequately churned up and roughly evened, a wide flat rake was manually pulled across the surface to perform a rough level. Care was taken to not compact the soil during this process. Once the surface was roughly leveled by hand, the Bucket Drum Test Stand was outfitted with a leveling bar and was used to perform final precision leveling and smoothing (see Figure 8).

Next, the Bucket Drum Test Stand was outfitted with a vibratory compactor and was used to perform precise and repeatable soil compaction. The compactor was gently lowered onto the surface and dragged across the full length of the test bed for 4 separate passes while being lowered 2mm between each pass (see Figure 9).

Figure 8. Bucket Drum Test Bed being precision leveled

Figure 9. Bucket Drum Test Bed being precision compacted

The bucket drum under test was then spun up by the Bucket Drum Test Stand and gently lowered via manual control to find the exact Z-axis position where the bucket drum just barely touched the surface. This Z-axis position became the zero position for height and all subsequent Z-axis position commands were based off that number.

Once the bucket drum test bed was leveled and compacted, hand-held geotechnical tools were used to characterize the soil (see Figure 10). A Humboldt Pocket Shear Vane Tester was used for quick and efficient determinations of shear strength. A Humboldt Soil Penetrometer was used to determine compressive strength of the unconfined soil. Three measurements with each tool were taken in three separate locations along the length of the bucket drum test bed. These measurements were taken before and after each bucket drum test run to confirm consistency from test to test. During the course of testing the average measurement from the shear vane tester ranged from 27-32 kPa and the penetrometer from 206-226 kPa.

Figure 10. Team members taking geotechnical measurements of the Bucket Drum Test Bed following a test run

After the bucket drum test bed was precisely leveled and compacted, a 5mm skim cut was performed with the bucket drum under test. This skim cut removed the less compacted topmost layer of simulant and ensured each test began with a regolith bed under the same conditions. All these steps were taken to prepare the bucket drum test bed for the actual bucket drum testing.

Bucket Drum Testing:

The Bucket Drum Test Stand control software was configured for each test run by test personnel. Configurable parameters include bucket drum rotational speed in rpm, X-axis linear speed in mm per sec, Z-axis cut depth in mm, data log filename, load cell zeroing speed in rpm, X-axis start/end/dump positions in mm, and others.

Once all the control software parameters were configured per the current line in the test matrix, the operator simply pressed the START TEST button and the Bucket Drum Test Stand control software automatically performed the entire test run. Each automated test run included the following actions:

- start data logging
- temporarily spin the bucket drum under test in mid-air and monitor the values of all the load cells
- calculate each load cell value offset, zero the load cells, and stop drum rotation
- while still in mid-air, move the bucket drum under test to the configured starting X-axis position
- lower the drum via Z-axis to the configured cut depth inside the trench so it is still hanging in mid-air
- spin the bucket drum under test to the configured rotational speed
- translate the bucket drum under test along the X-axis at the configured linear speed
- once the bucket drum under test has reached the configured end X-axis position (or user hits the ABORT TEST button), raise the bucket drum in mid-air, allow the full drum to rotate a minimum of one rotation, halt the bucket drum spinning, move the bucket drum in X-axis to the dump location, and spin the bucket drum backwards to dump out the material (see Figure 11)
- halt data logging

Figure 11. Bucket drum dumping collected

After each test run, test personnel used the hand-held geotechnical tools to characterize the soil along the newly revealed surface layer. Then test personnel configured the control software parameters per the next line in the test matrix and another run was performed. As this sequence was repeated, the bucket drum under test dug a step deeper into the prepared regolith simulant during each test run. After several test runs, the Bucket Drum Test Stand reached a depth limit as the structure on the Z-axis approached the uncut top layer of regolith simulant. The test matrix was designed such that test runs were paused prior to this limit and the test bed was then reset per the earlier section before continuing.

RESULTS

Example Test Output Data

In order to properly design IPEx the forces and torques during excavation must be understood. Figure 12 below shows a typical plot of the forces and torques produced during a bucket drum excavation test. The force in the X direction is the primary force of excavation. This force was generally constant during an excavation test because the regolith bed was prepared and leveled, and the cutting depth and speed were constant. The force in the Y direction was negligible in all test data. The force in the Z direction starts from zero and linearly increases as the regolith is captured in the drum. The total torque about the R axis of the bucket drum is a combination of the torque due to the excavation X-force and the torque of the captured regolith recirculating inside the

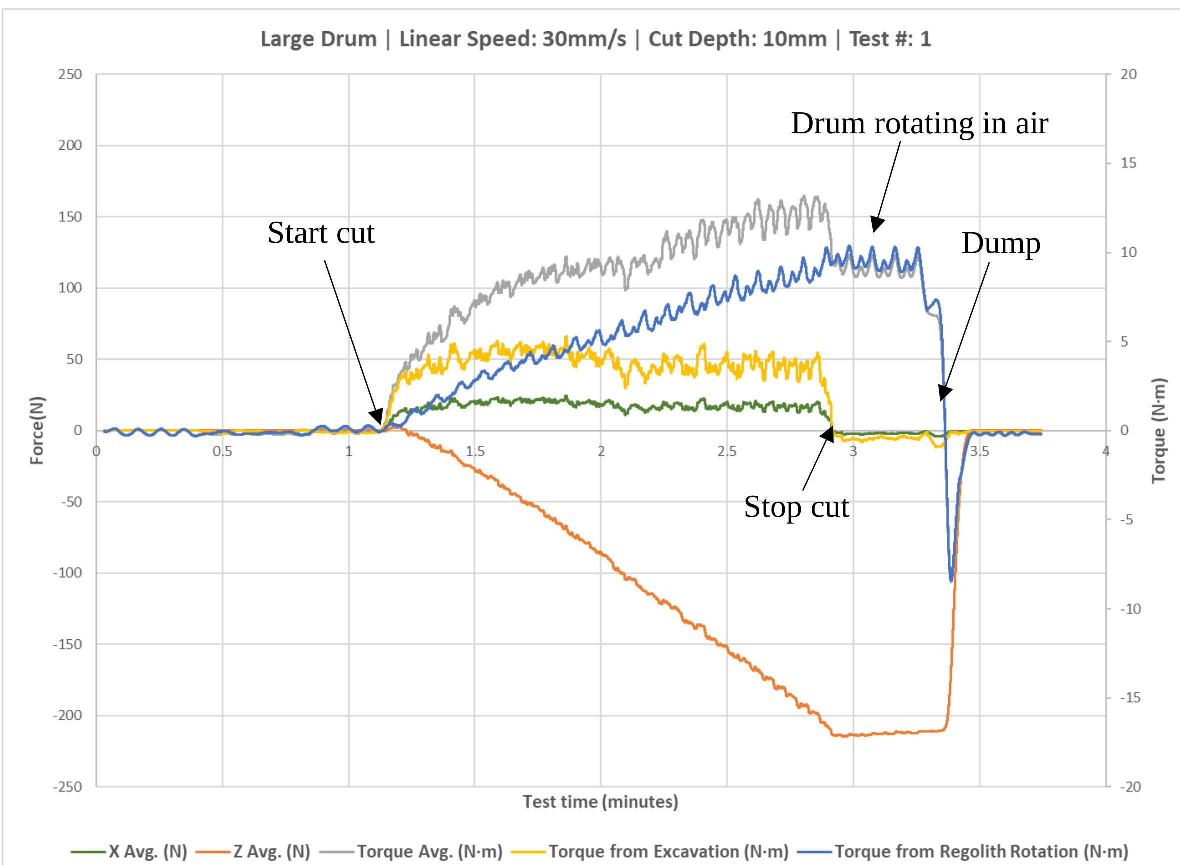

Figure 12. Example bucket drum test output data

drum. Following a test cut the bucket drum was lifted into the air and rotated multiple revolutions. The torque shown during that process is purely due to the recirculation of the captured regolith as the drum is no longer in contact with the test bed. Similarly, the Z force at that time is constant and equates to the weight of the regolith captured in the drum. Finally, the forces and torques can be seen returning to zero quickly upon reversing the rotation of the drum and dumping the regolith.

Excavation Force Sensitivity To Cut Depth and Speed

To aide with the design of bucket drums and their actuators a plot was generated that shows the horizontal excavation force per bucket drum width vs cut speed and depth (see Figure 13). This plot can be used to provide an estimated horizontal excavation force for various scales of bucket drums, cut depths, and cut speeds. The ranges of the variables in this work envelope the needs for the IPEx concept of operations, however future work could increase these ranges to increase fidelity. The shaded area in the plot shows the tested range of these variables and the resulting trend lines from the data.

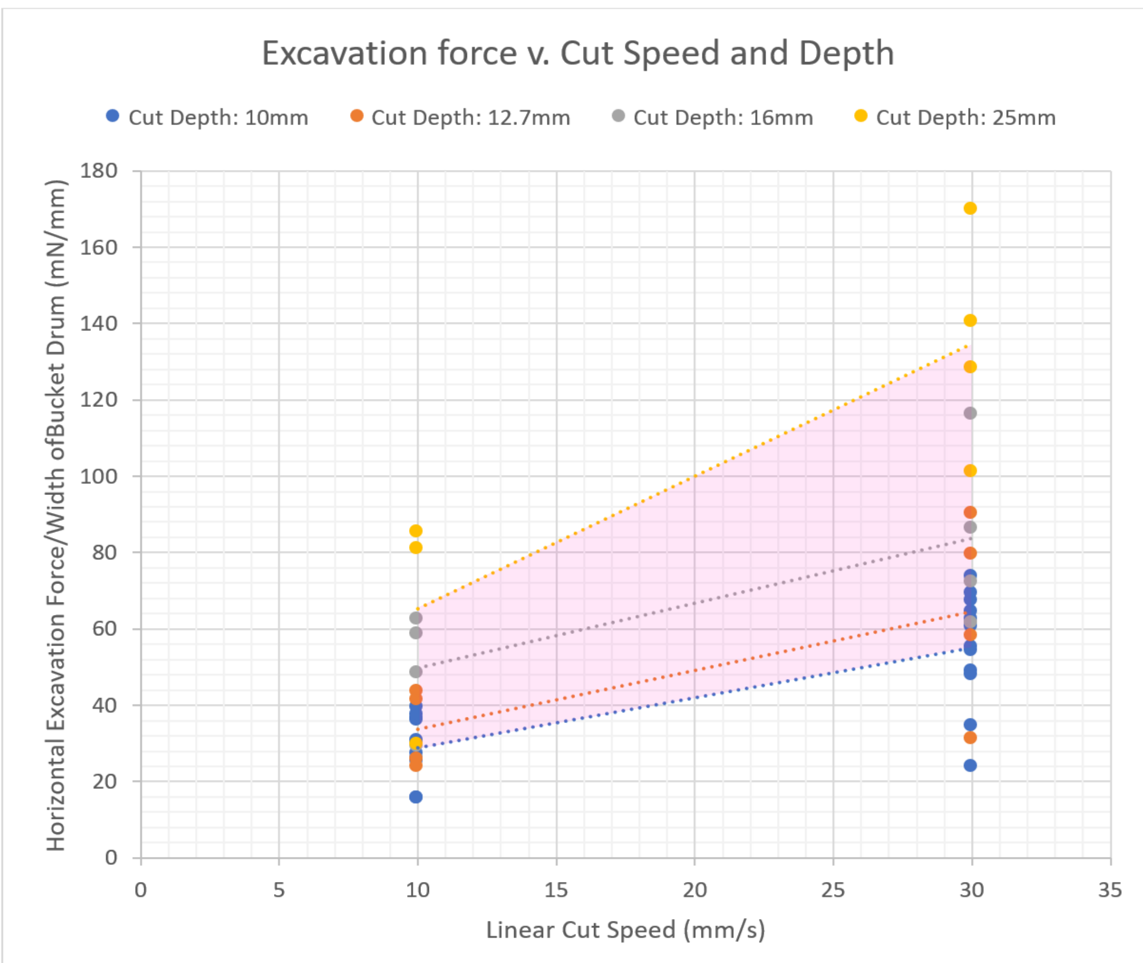

Figure 13. Example bucket drum test output data

Total Regolith Collected

The average mass of regolith collected by each bucket drum is an important metric to properly scale IPEx to meet the mission KPPs. Table 3 below lists the average mass of regolith collected for the three scales of bucket drums tested and corresponding total excavator capacity for a 4-bucket-drum system.

Table 3: Total regolith collected

Bucket Drum Size	Avg. Total Regolith Collected Per Drum (kg)	4- Bucket-Drum Excavator Capacity (kg)
Small	3.80	15.21
Medium	7.30	29.20
Large	24.98	99.94

Regolith Collection Rate

Similarly, the regolith collection rate of each bucket drum is an important metric to properly scale IPEx to meet the mission KPPs. Figure 14 below shows a plot of the collection rate of a single drum against the drum size, cut speed, and cut depth.

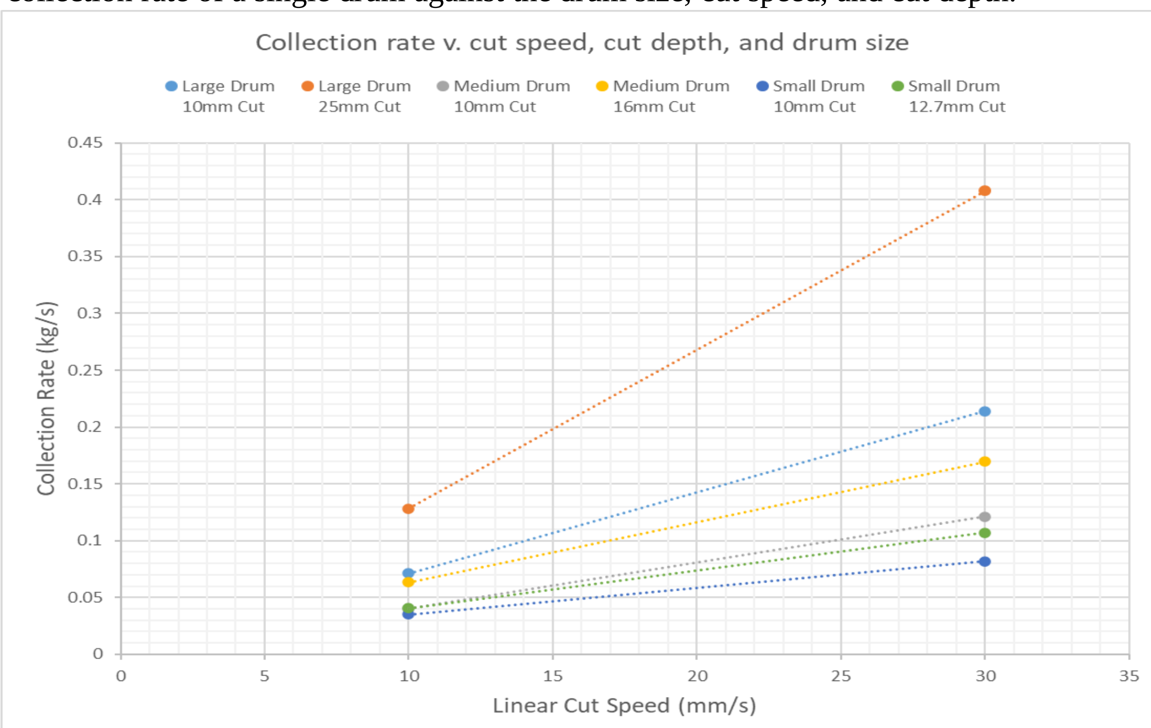

Figure 14. Example bucket drum test output data

Excavation Energy Per Mass Of Regolith Collected

The energy used to excavate the regolith is also a metric that will inform the IPEx design. Figure 15 below shows a plot of the mechanical energy (from torque and RPM at the bucket drum) per kilogram of collected regolith against the tested bucket drum sizes, cut speeds, and cut depths.

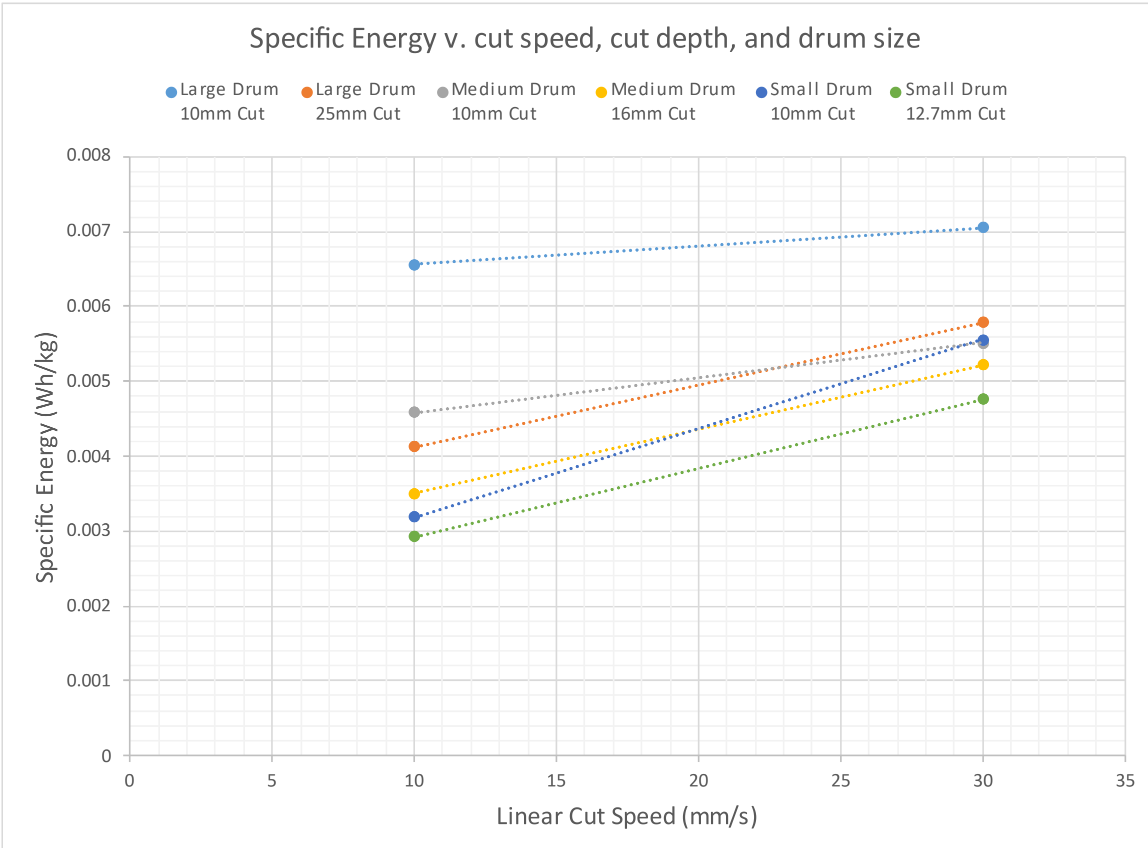

Figure 15. Example bucket drum test output data

CONCLUSION

The experimental data from the testing described above results in the following conclusions:

- The horizontal excavation force per unit width of bucket drum increases with increasing linear cut speed and cut depth. The plot of this data can be used to estimate the forces for various scale bucket drums, cut speeds, and cut depths.
- The medium and small-scale bucket drums tested can collect the necessary amount of regolith at the desired rate to support the IPEx concept of operations.
- Excavation energy per mass of regolith collected is reduced as cut speed decreases, drum size decreases, and cut depth increases.

These data and the corresponding trends will be used to inform the design of the IPEx bucket drum subsystem and can form a baseline for future bucket drum designs. Additional tests should be conducted to increase the data available and the fidelity of the predicted trends.

REFERENCES

Clark, D., R. Patterson, and D. Wurts. "A novel approach to planetary regolith collection: the bucket drum soil excavator." AIAA Space 2009 Conference & Exposition. 2009.

Dickson, D. C., Sibille, L., Galloway, G. M., Mueller, R. P., Smith, J. D., Mantovani, J. G., & Schreiner, S. (2016). Modeling Dynamics of Counter-Rotating Bucket Drum Excavation for In Situ Resource Utilization (ISRU) in Low-Gravity Environments. Earth and Space 2016.

Gallo, C.A., Wilkinson, R.A., Mueller, R.P., Schuler, J. M., & Nick, A.J. (2010). Comparison of ISRU Excavation System Model Blade Force Methodology and Experimental Results. NASA/TM- 2010-215591. Glenn Research Center, Cleveland, OH.

Mueller, R. P., Cox, R. E., Ebert, T., Smith, J. D., Schuler, J. M., & Nick, A. J. (2013, March). Regolith Advanced Surface Systems Operations Robot (RASSOR). In Aerospace Conference, 2013 IEEE (pp. 1-12). IEEE.

Mueller, R. P., Smith, J. D., Schuler, J. M., Nick, A. J., Gelino, N. J., Leucht, K. W., Townsend, I. I., & Dokos, A. G. (2016). Design of an Excavation Robot: Regolith Advanced Surface Systems Operations Robot (RASSOR) 2.0. Earth and Space 2016.

Suescun-Florez, E., Roslyakov, S., Iskander, M., and Baamer, M. (2014). Geotechnical Properties of BP-1 Lunar Regolith Simulant. American Society of Civil Engineers (ASCE), Reston, VA.

Wilkinson, A. & DeGenarro, A. (2007). “Digging and pushing lunar regolith: Classical soil mechanics and the forces needed for excavation and traction.” Journal of Terramechanics 44, 133–152.

Zelenin, A., Balovnev, V., & Kerov, I. (1975). Machines for Moving the Earth: Fundamentals of the Theory of Soil Loosening, Modeling of Work Processes and Forecasting Machine Parameters. Amerind Publishing Co. and Mashinostroenie, Moscow.

Zeng, X., Burnoski, L., Agui, J., & Wilkinson, A. (2007). Calculation of Excavation Force for ISRU on Lunar Surface. 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV.