ISRU PILOT EXCAVATOR - DEVELOPMENT OF AUTONOMOUS EXCAVATION ALGORITHMS

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Introduction: The ISRU Pilot Excavator (IPEx) is a Space Technology Mission Directorate (STMD) Game Changing Development (GCD) project to develop a robotic excavator to demonstrate excavation of up to 10 metric tons of lunar regolith. IPEx is based on the Regolith Advanced Surface Systems Operations Robot (RASSOR) excavator developed at NASA Kennedy Space Center (KSC) [1] and utilizes a counter rotating bucket drum concept to balance excavation forces for use on reduced gravity planetary bodies. To take advantage of the counter rotating bucket drum mechanism, work is being done to develop new autonomous excavation strategies and algorithms. Referred to as "*Auto-dig*", these algorithms will allow IPEx to excavate, drive, and deliver its target mass of 10 metric tons of lunar regolith during an 11-day mission semi-autonomously. Due to bandwidth and latency constraints teleoperation will be kept to a minimum, with operators periodically confirming and verifying the excavator's high-level tasks and operations. While the work to develop optimized autodig solutions is ongoing at KSC, early tests have yielded interesting results that have led to the discovery of additional risks that need to be mitigated in autonomous excavation. Testing has also encouraged the development of new software and visualization tools that provide real-time insight into excavation loads during operation, allowing faster development and helping build better intuition to the excavation process. These tools will help in the pursuit to develop fully optimized digging algorithms that are robust enough to handle hazards such as rocks or irregular terrain.

Testing: Testing and development of autonomy for excavation is conducted on the RASSOR 2 prototype robotic excavator in the Granular Mechanics and Regolith Operations (GMRO) laboratory at KSC. Testing takes place in a large, enclosed bin of Black Point 1 (BP-1) lunar regolith simulant. The regolith testbed is over a meter deep and allows enough space to test complete auto-dig collection routines. RASSOR 2 makes use of the Robot Operating System 2 (ROS2) and its controls and automations are implemented as ROS2 nodes.

Auto-dig Control: A primary goal of the auto-dig algorithm is to equalize the torques on the front and rear drums while digging, so that the resultant horizontal forces cancel each other out. The torque on a drum while digging is directly related to the cut depth and the mass of regolith in the drums. While digging, IPEx will servo its front and rear arms up and down varying the depth of cut, and as a result, the torque loads on the drums. In this control system, the drum torque becomes the process variable (PV), while the arm position becomes the control variable (CV). Since the excavator does not have any direct torque or force sensors, actuator models are used to estimate torques on the joints at given currents and speeds. To balance the digging forces, the setpoint for both the front and rear drums are set to the same value. The setpoint across an auto-dig pass is varied to maintain consistent dig depth. Different algorithms and models are being tested to calculate the necessary setpoint and are typically functions of the mass excavated, the drum speed, and the cut depth. Other parameters such as terrain, hazards and pose must also be considered.

Mass Estimation: As regolith is collected in the drums, an increasing torque is observed on the rotating drum actuator as the mass inside the drum is forced to tumble. To account for this, the auto-dig setpoint models need frequent mass estimates of the regolith accumulated during the excavation process. One strategy is to use currents from the shoulder joints during intermittent upward motions that occur during the auto-dig process. This has been used with success to estimate the mass of regolith that has accumulated in the drum in real time while digging. With this capability, IPEx can be commanded a mass of regolith to collect and stop when it has reached its goal. The algorithms take advantage of models and trends to predict the necessary drive distance and collection time of the dig cycle to excavate the commanded mass and improve this prediction as more data is collected.

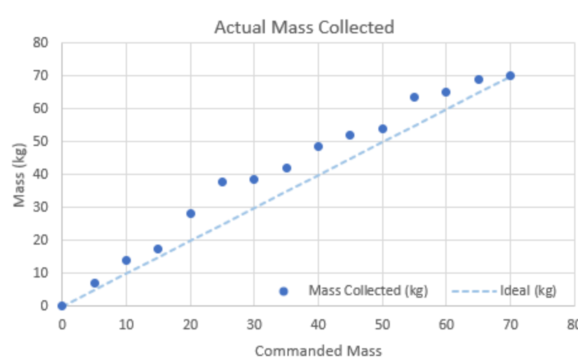

Figure 1. Autodig collection test results.

The results of an early test of the auto-dig algorithm are shown in **Figure 1**. A series of 14 auto-dig commands were conducted, each with an increasing target collection mass from 5 kg to 70 kg of BP-1 lunar regolith simulant. After each test the actual collected mass was recorded by weighing the excavator on a scale. **Figure 1** plots the actual collected mass for each test. Despite using very little data to fit the required models for mass estimation, the performance of the auto-dig commands were within acceptable margins. Note in **Figure 2** that the accuracy of mass predictions increases substantially as the commanded mass increases. This is likely due to the increased "signal to noise ratio" that is achieved when the recorded currents are larger at the shoulder joint lifting the arms. It is likely that these mass estimates can be greatly improved with the collection of larger data sets, and by improving the timing and conditions of the current measurement sequence that occur during auto-dig. Additionally, other techniques can be fused with this model to improve mass estimates.

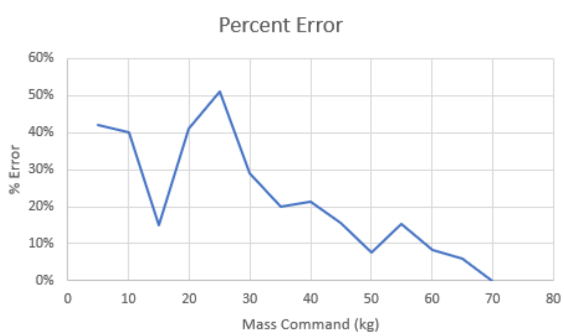

Figure 2. Autodig collection error.

Rock Detection: In addition to collecting regolith, the excavation process must be tolerant of encounters with rocks of varying sizes. Statistics of lunar rock sizes and distributions are used to determine the rock hazards that IPEx is likely to encounter during its mission. Preliminary testing of the auto-dig algorithm's encounters with rocks showed that larger rocks (10 cm or more) can pose a threat to the excavator's autonomy (**Figure 3**). While smaller rocks can be collected or passed over with little trouble, larger rocks can be problematic for algorithms tuned specifically for collecting dirt. Without explicit detection and handling of the larger rocks the digging algorithm can end up in a stalled state, where the excavator fails to advance past the rock and requires intervention. Further, in some cases the bucket drum scooping motion can grab the edges of a buried or submerged rock, lifting and pulling it out onto the surface, resulting in an even more challenging and problematic hazard to avoid. Because of these risks, it's important that the excavator's auto-dig system is capable of recognizing when it encounters larger rocks and be able to adjust its strategy and tuning to avoid potential damage to the excavator or disruption of excavation autonomy.

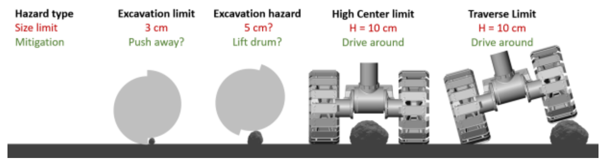

Figure 3. Rock hazards (credit JPL)

Visualization: Testing of autodig algorithms and strategies is done iteratively. A code, test, analyze cycle has been used to quickly improve the capabilities of the algorithms, and assess their performance. During this development cycle, tools and capabilities have been developed and integrated into the excavator's software stack to allow visualization and deeper understanding of the algorithms. Often observing the emergence of trends and patterns in actuator loads and states provides more insight into performance than measured performance metrics. Visualizing excavator state in real time allows on-the-fly tuning and adjustment that can save valuable development time. Included in the excavator's control user interface is a 3D model (**Figure 4**) that shows the excavator's state in real time. Joint positions and velocities are all rendered in real time, and actuator loads are represented by a green to red color scale on each joint. This visualization tool was created using OpenGL and integrated into the control UI. Monitoring this model during auto-dig processes provides valuable information and allows a deeper understanding of the algorithms' inner workings.

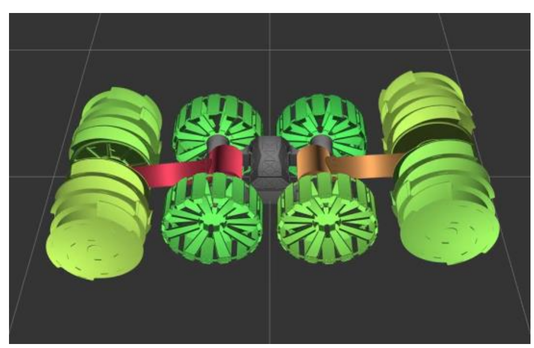

Figure 4. Visualization of loads during autodig.

References: [1] 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