TESTING LUNAR REGOLITH CHARACTERIZATION ALGORITHMS WITH SIMULATED SUBSURFACE SAMPLES AND DIGITAL TWIN DATA. D. R. Joshi[1], A. W. Eustes III[2], and J. Rostami[3], [1]Colorado School of Mines, 1600 Arapahoe St, Golden, CO. deepjoshi@mines.edu, [2]Colorado School of Mines, 1600 Arapahoe St, Golden, CO. aeustes@mines.edu, [3]Colorado School of Mines, 1600 Illinois St, Golden, CO. rostami@mines.edu

Introduction: In the next decade, the sustainable presence of humans on the Moon might get established. The success of the planned crewed missions depends heavily on using the water-ice resources available on the Moon. However, the form, quantity, composition, and distribution of the water-ice in the lunar permanently shadowed regions (PSRs) remain largely uncertain. Upcoming missions like VIPER and PRIME-1 will attempt to drill in the lunar PSRs to obtain ground-truth information and reduce this uncertainty.

This work was conducted under NASA's Early Stage Innovation (ESI) grant to develop algorithms to better understand lunar subsurface properties using the drilling data. This specific talk discusses the algorithm testing conducted in simulated lunar subsurface samples using drilling data from digital twin boreholes.

Experiment Setup: A rotary auger drill was designed and fabricated to conduct extensive analog and cryogenic drilling tests. The drill also contained a high-frequency drilling data acquisition system to record drilling responses which were then used to build the algorithms[1].

The drilling tests were conducted in analog samples (low porosity and high porosity) and cryogenic samples (low porosity aqueous icy, high porosity aqueous icy, unfused granular icy, and fused granular icy). Figure 1 shows different forms of cryogenic samples used for the drilling tests.

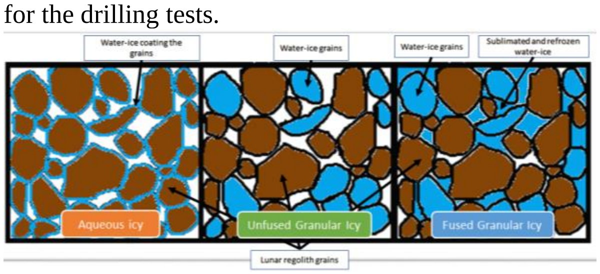

Figure 1: Different forms of cryogenic samples developed for drilling tests.

Algorithm Development: In total, 87 drilling tests were conducted. First, the drilling data was processed to minimize the noise and remove outliers. The processed drilling data was used to train a comprehensive pattern-recognition model consisting of three classification and two regression modules[2]. Table 1 summarizes the different modules used in the pattern-recognition algorithm.

Table 1: Description of different modules of the pattern-recognition algorithm.

Module	Purpose	Algorithm used
Drilling state classifier	Sort the data into drilling and non-drilling data	Random Forest
Torque estimator	Calculate torque and mechanical specific energy (MSE) using drilling data.	Random Forest
Batch classifier	Predict auger choking, identify layer boundary, and qualitative estimation	Random Forest
UCS estimator	Predict Uniaxial Compressive Strength (UCS) of the sample	Wide and Deep Neural Network
Form classifier	Identify the form of the water-bearing lunar regolith sample	Random Forest

Simulated Testing: The algorithms were tested using both the blind test data and the simulated sample. This work only describes the simulated testing of the lunar subsurface sample. The goal of testing the algorithm in a simulated sample was to evaluate the algorithm performance in complex subsurface conditions that might exist on the Moon. Based on the samples used for cryogenic testing, a simulated 3D complex lunar subsurface sample was designed. Figure 2 shows this sample. It contained nine layers with varying thicknesses and dip in the layers.

The raw drilling data collected during the cryogenic drilling tests was used to generate drilling data for five digital twin boreholes on the simulated samples (one in the center, four in each corner).

Results: The digital twin data was passed through the pattern-recognition algorithm to predict UCS and form at each borehole with depth in real-time. Figure 3 shows the predicted UCS for all five boreholes with depth. For each of the wellbores, the algorithm correctly identifies a change in the subsurface conditions and adjusts its predictions.

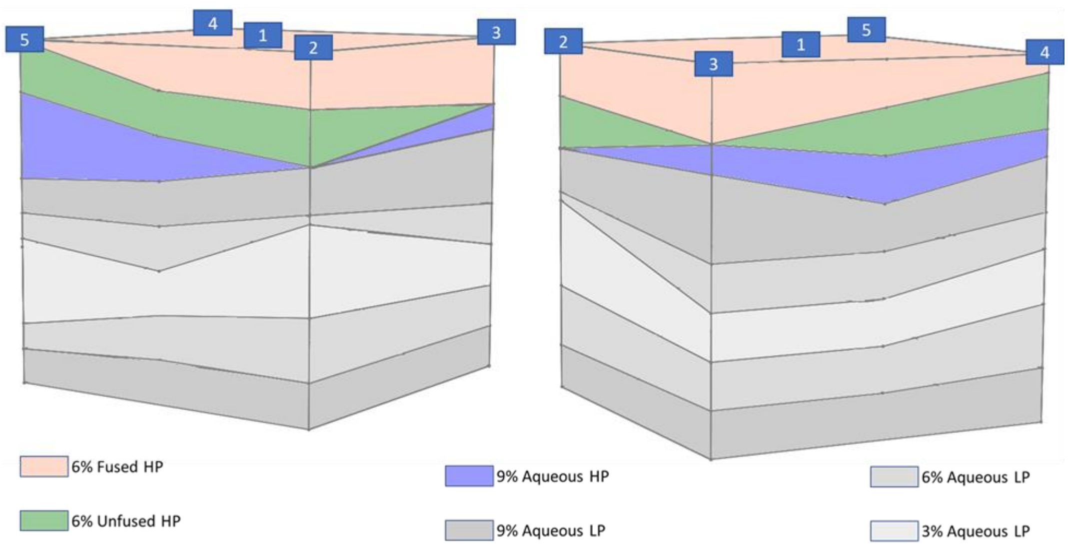

Figure 2: Simulated 3D complex lunar subsurface sample with different forms of water-bearing lunar soil (fused granular, unfused granular, and aqueous) with different water content and porosity type (high-porosity and low-porosity).

The algorithms also accurately adjust for the stratigraphy of the sample and adjust predictions based on it.

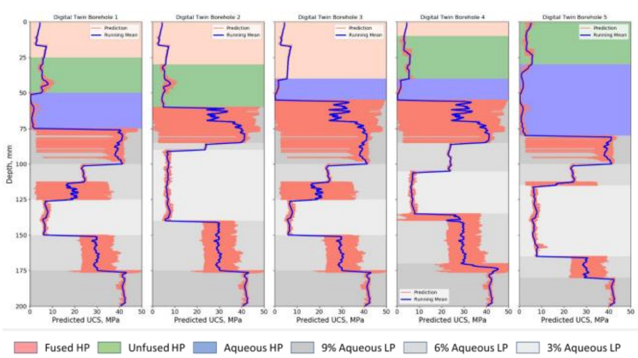

Figure 3: Real-time and 30 second running average of UCS for all five boreholes.

Additionally, the UCS and form predictions of the algorithms can be cross-correlated for the digital twin boreholes to estimate the stratigraphy of the sample. Figure 4 shows the stratigraphy between boreholes 1, 2, and 4 predicted using the estimations of the UCS and form of the water-bearing regolith.

Conclusions: This work proposes a testing methodology that can be used in tandem with the drilling tests for extraterrestrial drilling systems to test drilling control and characterization algorithms to ensure efficient algorithm performance in complex subsurface conditions, getting more value from the drilling missions and ensure the success of the operations.

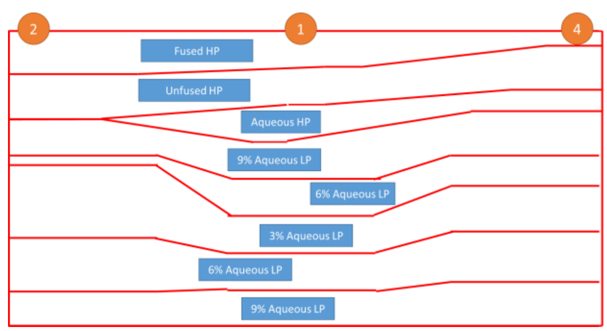

Figure 4: Sample stratigraphy between digital twins 1, 2, and 4 predicted using UCS estimation and estimation of the form of the water-bearing lunar regolith.

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References: [1] Joshi D. R. et al. (2020) SPE Drilling Conference and Exhibition, *SPE-196684-MS*. [2] Joshi D. R. et al. (2021) ASCE Earth & Space 2021.