PATTERN-RECOGNITION ENABLED DRILLING AND GEOTECHNICAL SCIENCE SUPPORT.

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Introduction: This paper will examine methods, data structures and *laboratory experience* that could support real-time science operations during crewed Artemis mission elements that involve drilling, subsurface sensor emplacement, sample collection and other classes of mechanical interaction between instrumented EVA tools and lunar soil and rock.

Digital Toolkit: The exponential growth of artificial intelligence and machine learning (AI-ML) tools is driving revolutionary advancement in the field of academic and commercial geoscience, creating onramps for industry experience and offering tools that can enhance the scientific return of NASA planetary surface missions including robotic and human operations. Tools are being developed that streamline data collection and processing, demonstrating unprecedented sensitivity in the discernment of geological and geotechnical information.

Lunar Geotechnical Data Support: Numerous unknowns associated with lunar polar missions include geologic and geotechnical uncertainty. Instrumented drilling and other mechanical interactions with lunar soil can help reveal the mission and program-critical geotechnical information that is needed for assessment of soil stability, erosion rates, landing pad stabilization requirements and the ease or difficulty of future ISRU operations. Raw data will be generated by a diverse set of onsite tools in real time, with the most-likely consequence of consuming scarce bandwidth. An early data management strategy is recommended. Tools are now in development that can combine laboratory testing, calibration and edge computing in order to sharply reduce the anticipated communication system bandwidth requirements to manageable levels. These systems, combined with the live interaction and feedback of geoscientists in the mission control center, can dramatically enhance the pace of scientific discovery for Artemis human lunar missions.

Early Stage Innovation at CSM: Under the NASA Early Stage Innovation (ESI) grant, the Earth Mechanics Institute (EMI) at Colorado School of Mines (CSM) was tasked with developing pattern-recognition algorithms to characterize lunar subsurface properties using real-time, high-frequency drilling data. Such algorithms allow for an in-situ analysis of drilling data on the Moon, negating the need for large data storage systems.

Test Rig and Data Collection: A rotary, auger drill unit was developed at EMI to replicate the drilling process as expected on the extraterrestrial conditions. Figure 1 shows the test drilling unit with the sensors. A high-frequency data acquisition system was installed to store drilling measurements such as Weight on Bit (WOB), rotary speed, drilling depth, and time at upto 1000 Hz frequency and parameters such as mechanical specific energy (MSE), penetration rate (ROP), and N-FPI (Normalized Field Penetration Index) were calculated. These parameters allowed for a more holistic understanding of the effect of various subsurface properties on the drilling measurements.

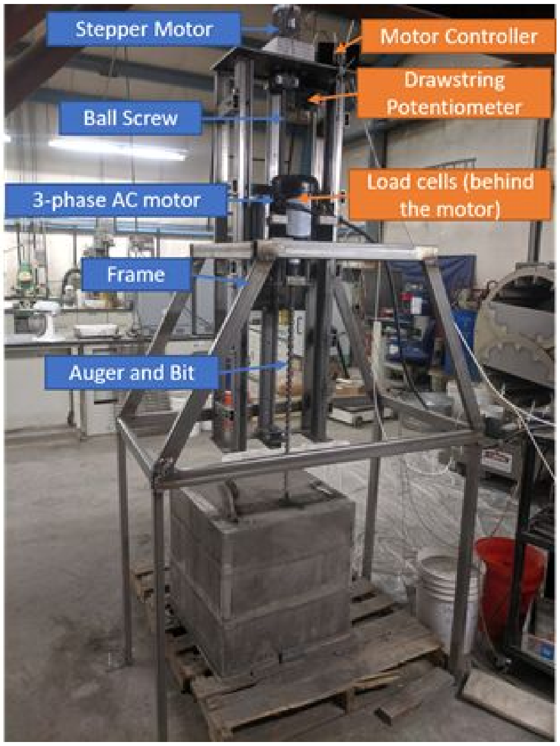

Figure 1: Test drilling unit with all embedded sensors[1].

Extensive testing was conducted at both atmospheric and cryogenic conditions to acquire drilling data from a variety of subsurface conditions. This data was then used to train and validate a comprehensive pattern-recognition algorithm capable of identifying strata, differentiate between different forms of water-bearing lunar regolith simulant, and estimate Uniaxial Compressive Strength (UCS).

However, the raw drilling data was extremely noisy. This made it impossible to correctly label the dataset and use it to train the algorithm. A scheme was developed to clean the dataset without losing significant information. First, an in-line electro-magnetic interference filter was installed. Algorithmically, a bandpass filter was used to remove electrical noise and then the data was re-sampled at 10 Hz to deliver a cleaner data.

Algorithms Utilized for Data Reduction and Feature Extraction: Figure 2 shows the architecture of the final algorithm developed. It includes three classification modules and two regression modules. First the raw data is cleaned using the methodology described above, then a drilling-state classification algorithm identifies non-drilling data and separates it out from the drilling data. A regression model calculates torque and MSE using the drilling data and the entire dataset is now used to identify the layer boundaries, detect drilling dysfunctions such as auger choking, and qualitatively describe the porosity type (high-porosity vs low-porosity). All of the data from here can be used in a regression module to estimate UCS of the sample and in a classification module to predict the form of the water-bearing lunar regolith.

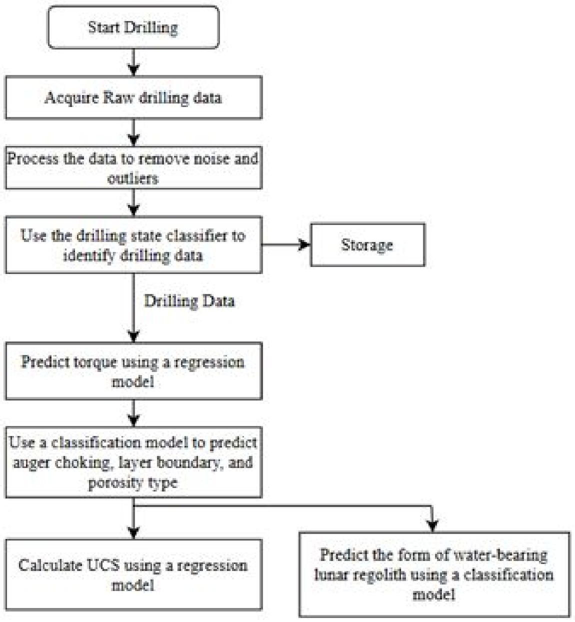

Figure 2: Final architecture of the lunar material characterization algorithm[1].

The algorithms were tested both using a blind dataset and using a simulated dataset. Figure 3 shows the predicted UCS vs actual UCS of a layered cryogenic sample with depth. As shown, the algorithm correctly adjusts for changing strata and accurately calculates the UCS.

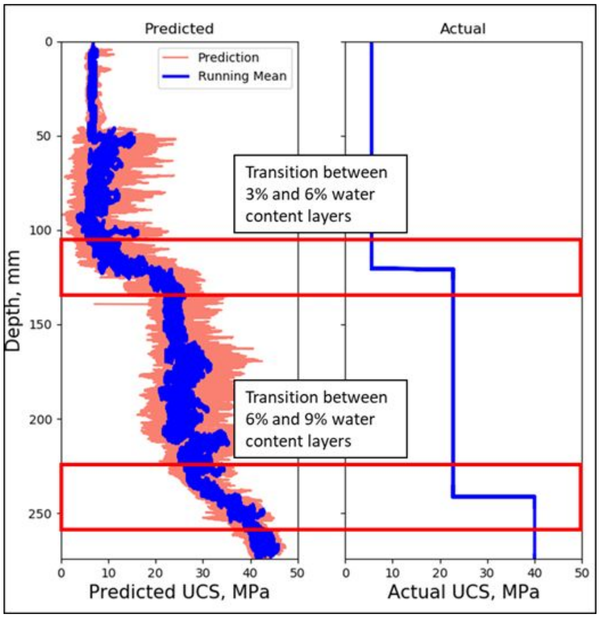

Figure 3: Predicted UCS vs Actual UCS for layered cryogenic sample [2].

Application to Crewed missions: The algorithms developed here can play a vital role in the upcoming Artemis crewed missions by assisting the crews in getting more data from the existing mission objectives of sampling and subsurface sensor emplacement. Data captured while drilling for subsurface mineral samples, as accomplished during the Apollo missions through the Apollo Lunar Surface Drill (ALSD), can be analyzed in real-time using the algorithms as described above to better understand subsurface strata and geotechnical properties on the Moon. This eliminates the need to have a large data storage and transmission systems for the analysis of the drilling data on Earth by conducting in-situ analysis. They also help streamline the data management process to be used for the crewed missions.

Conclusions: Academic and industrial research is being conducted in order to continuously improve the performances of the machine learning methods for the geoscience community. These innovations, combined with direct human mission support by scientists in the control center, could play a significant role in future human space exploration by providing real-time measurement of key geological and geotechnical features in order to reduce data transfer needs while significantly expanding the scientific return of crewed missions in exploring the Moon compared to the Apollo baseline.

References: [1] Joshi D. R. et al. (2021) SPE Drilling Conference and Exhibition, *SPE-204108-MS.* [2] Joshi D. R. et al. (2020) AIAA ASCEND 2020.