Lunar Locomotion: Geotechnical Assessment of Trafficability On Regolith (GATOR)

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Introduction: Current U.S. Space Policy [1] states that NASA shall establish a permanent presence on the Moon. During the ~75 hour visit of Apollo 17 in December 1972, astronauts spent only ~22 hours outside the Lunar Module on the lunar surface. Future lunar operations will require surface activities of much longer duration. Earth-based terramechanics studies generally use regolith simulants in test bins to conduct analogue lunar tests. However, most trafficability (i.e., capacity of a soil to support and provide sufficient traction for vehicle movement) investigations typically focus on how to design and develop better wheels/rovers for planetary mobility. Considering the topic of lunar trafficability from a geological perspective, little attention has been dedicated to the topic of how the geomechanical properties of the near-surface regolith evolve due to prolonged interaction with lunar vehicles. This information will be fundamental for learning how to most efficiently undertake long duration vehicle excursions between lunar base camp and outlying sites (scientific assets, power stations, astronomical observatories, mining locations, PSRs, etc.), and will also inform future infrastructure development (e.g., launch/landing pad) and ISRU activities. Earth-based testing to prepare for these critical lunar surface activities often overlook an important aspect regarding the use of lunar simulant in large-scale engineering test beds; that is to understand how the regolith will withstand trafficability and construction activities, it will be critical to understand the geotechnical properties and density profile of the near-surface lunar regolith while performing large-scale engineering tests (i.e., pack simulant in layers of specific densities, rather than just dumping it into the test bed [2]). Here, we describe our experimental design for the Geotechnical Assessment of Trafficability On Regolith (GATOR) project, which will use three actual lunar rover vehicle wheels on a replicated lunar highland regolith stratigraphic column with the goal of measuring the effect that repeated traffic has on the geomechanical properties of the regolith column.

RIDER Test Facility: The GATOR project will be conducted using the Regolith Interactions for the Development of Extraterrestrial Rovers (RIDER) test rig, which is housed at Exolith Lab at the Center for Lunar and Asteroid Surface Science (CLASS) at the University of Central Florida (UCF) and has been developed in collaboration with the University of Notre Dame (UND). RIDER is designed to be a multi-purpose planetary rover wheel trafficability testing rig available to the science and engineering communities; capable of simulating full-scale rover locomotion on the Moon, Mars, and other bodies. The location at Exolith Lab provides easy accessibility to RIDER as well as on-site, cost-effective (no need to ship tons of simulant) access to large quantities of regolith simulants allowing for standard or custom simulants to be considered when planning terramechanics experiments. RIDER will have the ability to test a wide range of rover masses, wheel sizes, and wheel mounting configurations, with the ability to interchange a variety of motors to accommodate different motor speed and torque requirements [3]. A linear actuator serves as a gravity application and offload system suitable for simulation of vehicle wheel loads in variable gravity conditions depending on the target environment. Applied loads are controlled and measured by a microcontroller-based linear actuator and load cell that allows precise control and monitoring of simulated rover weight. The linear actuator system is connected to carriages rolling along guide rails at the top of the regolith bin, allowing the wheel to move freely back and forth along a single-axis within the test bin. RIDER is also equipped with a dehumidification unit to manage humidity and a dust containment and mitigation system for the safety of users and to prevent dust from negatively affecting mechanical and electronic systems.

Figure 1. The RIDER test rig is housed at UCF CLASS Exolith Lab and is a custom-built gravity offloading trafficability testing rig (3.8 m x 1 m x 1.7 m tall) designed to test wheel-regolith interactions. RIDER will be operational in early 2023.

Replicating Lunar Highlands Stratigraphic Profiles: Much of NASA's planned lunar exploration for the near-future is focused on highlands landing sites at or near the south pole [4]. Therefore, we will use Exolith Lab's LHS-1B Bulk Lunar Highlands Simulant to replicate highlands near-surface regolith stratigraphy to create a realistic lunar regolith column on which to perform experiments. LHS-1B is a "simplified" formulation of high-fidelity LHS-1 and is designed to be a lower-cost, simulant alternative applicable for large-scale engineering tests. Simplified LHS-1B is equivalent to high-fidelity LHS-1 with the exception that trace minerals are removed (e.g., ilmenite, olivine, & pyroxene). Recent geotechnical results show that density estimates obtained with cone penetrometer testing (CPT) for LHS-1B are essentially identical to high-fidelity LHS-1 [5], thus LHS-1B is suitable as a geomechanical lunar highlands analogue material. The density profile of lunar highlands regolith was found to vary on a local scale at the Apollo 16 landing site [6]. However, CPT results from Stations 4 & 10 display a general similarity in that a firm layer is encountered at ~5–10 cm below the surface, then resistance increases significantly at depths of ~20–40 cm below the surface. Therefore, we will use CPT results from Stations 4 & 10 [6,7] as a baseline to replicate a two-layer highlands stratigraphic column of ~35 cm depth within the RIDER test bin. This two-layer simulant column will consist of an upper ~20 cm layer with a bulk density of ~1.84 g/cm^3, with a lower 15 cm layer of ~1.88 g/cm^3, bulk densities which best mimic the density stratification measured during Apollo 16 [2].

Rover Wheels For Testing During GATOR Project: To accurately duplicate repeated rover traffic over the simulated highlands regolith column, we have obtained three prototype lunar rover vehicle wheels to be tested using RIDER (Table 1; Fig. 2). These wheels have been selected based on upcoming robotic (Astrobotic Polaris and VIPER-like prototypes) and human (LRV Replica as an analogue for a Lunar Terrain Vehicle wheel) exploration missions. Projected gross rover masses are used to define the load on each wheel in lunar gravity, which will be applied using the gravity offloading system on the RIDER test rig. We will perform ~900 total traverses for each wheel along the linear test bed at three different wheel speeds, which are based on ¼, ½, and 1 multiples of intended top speeds (Polaris; VIPER-like), while LRV replica experiments are based on speeds much slower than the Apollo LRV cruise speed of 6-7 km/h (speed limited by 3.8 m length of RIDER test bed).

Table 1. Rover prototype wheel parameters for GATOR project.

Wheel	Dia. (cm)	Width (cm)	Rover Gross Mass (kg)	Load/ Wheel Lunar (N)	Tested Speeds (cm/s)
Astrobotic Polaris	61.5	15.25	240	100	9,18,37
NASA VIPER-like	45	20	430	175	5,10,20
NASA Apollo LRV	81.8	22.9	800	325	14,28,56

Geotechnical Assessment of Trafficability on Regolith Simulant: Baseline geotechnical properties will be measured for the undisturbed simulated lunar highlands surface before performing wheel traverses. During the traverses for each wheel, we will pause the traverse every 100 passes to sample geotechnical properties of the LHS-1B simulant column (Table 2). Geotechnical properties include monitoring the simulant surface (within wheel tracks) for changes in particle size distribution (PSD), particle shape (e.g., grain diameter, aspect ratio, sphericity, roundness), and shear strength (vane shear). We will also test the full simulant column depth for changes in penetration stress vs. depth using CPT measurements, which will provide valuable information regarding potential changes in the density profile of near-surface lunar regolith due to repeated traffic.

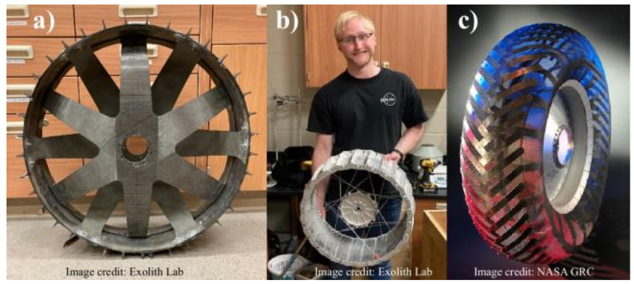

Figure 2. Three lunar rover vehicle wheels to be used for GATOR trafficability experiments. **(a)** Astrobotic Technology Polaris rover prototype, **(b)** NASA Glenn Research Center (GRC) VIPER-like (Resource Prospector) prototype (Jared Long-Fox for scale), **(c)** and the coolest of all three, GRC Apollo Lunar Roving Vehicle (LRV) replica tire.

Table 2. Geotechnical tests to be performed on LHS-1B highlands lunar regolith simulant for GATOR project.

Geotech Property	Standard Method	Samples per 100 passes	Total Samples per Wheel
Particle Size Dist. (PSD)	ASTM D2487	4	40
Particle Shapes	n/a	4	40
Shear Strength (Vane)	ASTM D8121	16	160
Bulk Density (CPT)	ASAE S313.3	12	120

Summary: Efficient movement over the lunar surface between base camp and outlying sites will require a thorough understanding of the effects of repeated traverses on the geotechnical properties of the near-surface lunar regolith column. These effects can be assessed using lunar regolith simulants in trafficability test beds on Earth.

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