PERFORMANCE ANALYSIS OF ROBOTIC EXCAVATORS IN THE 2025 NASA LUNABOTICS UNIVERSTY COMPETITION

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Introduction: The 2025 NASA Lunabotics competition provided a unique opportunity to assess the performance of more than fifty university-built lunar excavation and construction robot prototypes operating in high-fidelity basaltic lunar regolith simulant: Black Point 1 (BP-1). By evaluating both competition video and team-submitted technical questionnaires, this study identifies engineering patterns, terramechanics behaviors, and design features that most strongly influenced excavation productivity, mobility robustness, autonomy success, and berm-construction repeatability. The analysis builds on historical trend data from earlier competitions, which have cataloged hundreds of prototype excavators and their subsystem design choices

Methods: Video recordings of the full competition were reviewed frame-by-frame to extract measurable indicators of performance including:

• traverse time across obstacle fields,
• wheel/track slip ratios,
• digging implement fill factor and unloading efficiency,
• regolith flow behavior, adhesion, and dust projection patterns,
• berm construction rates normalized to robot mass and energy.

Team questionnaires were analyzed to correlate observed behaviors with design parameters such as mobility configuration, excavation mechanism selection, autonomy architecture, sensor payloads, structural layout, and dust-mitigation approaches.

A combined dataset was created to cross-evaluate design choices, control strategies, and environmental interactions within the BP-1 terramechanics envelope

Results and Discussion:

Mobility Performance. Robots employing larger diameter and wide-profile wheels, moderate ground clearance, and compliant or semi-suspended drivetrains showed higher mobility scores and fewer instances of entrapment, consistent with trends from earlier competitions. Slip onset was strongly linked to insufficient weight distribution and over-torqued drivetrains generating soil shearing and fluffing, leading to localized loss of shear strength.

Excavation and Terramechanics. Bucket-wheel and bucket-ladder systems remained the most common mechanisms, with auger-based designs showing improved performance in compacted BP-1 but reduced throughput in loosely raked top layers. Teams that integrated vibration or active dust-shedding surfaces showed improved soil flow during regolith simulant unloading. Video analysis confirmed that clogging events and material adhesion were often linked to geometry transitions inside hoppers or conveyors, where BP-1's cohesive properties became dominant.

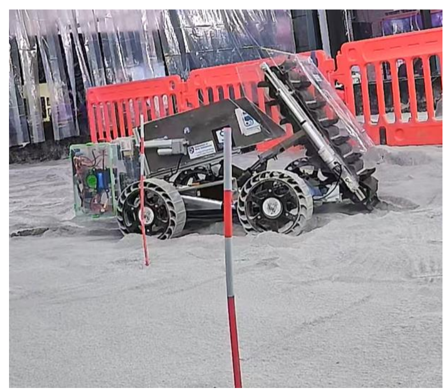

Fig. 1: Lunabotics excavator with stuck back wheel

Autonomy. Teams using fused localization (Inertial Measurement Unit (IMU) + odometry + fiducials) demonstrated smoother navigation trajectories and more consistent obstacle-avoidance performance, matching historical data on successful autonomy architecture. Convolutional-neural-network-based perception systems showed promise but struggled in low-contrast, dust-laden environments.

Construction Productivity. Performance varied widely, but the highest-scoring robots demonstrated:
• predictable excavation depth control,
• stable regolith transport without spillage,
• precise berm placement with minimal airborne dust.
Energy-normalized berm productivity strongly favored lightweight robots with efficient drivetrains and minimal material-handling losses.

Results and Discussion: The 2025 Lunabotics competition continues to serve as a large-scale, high fidelity lunar mare regolith simulant testbed for lunar excavation demonstrations and research. Analysis of video evidence combined with technical questionnaires shows clear convergence toward design practices that enhance mobility robustness, excavation efficiency, and autonomy reliability in lunar-analog soils. Terramechanics behavior in BP-1—particularly soil cohesion, flow resistance, and dust adhesion—remains the central driver of performance variability. These findings provide actionable engineering insights for future Lunabotics teams and inform NASA's development of off-world excavation and construction systems for Artemis-era missions.

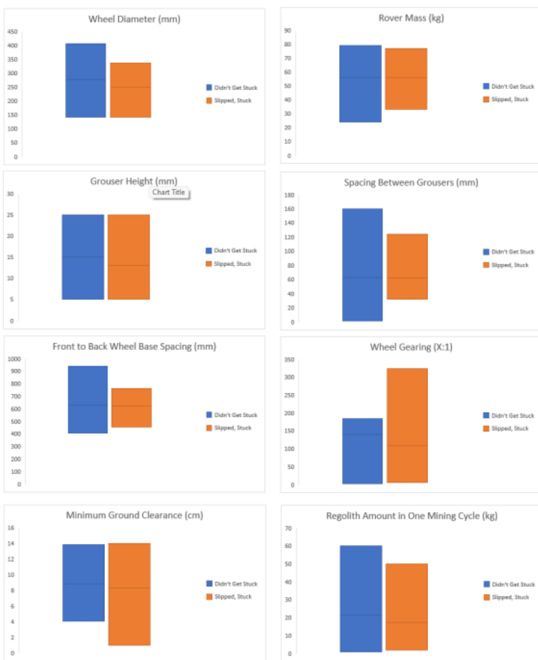

Fig. 2: Examples of Lunabotics robot metrics

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