SIMULATION OF LUNAR TERRAIN FOR HAZARD DETECTION AND RELATIVE NAVIGATION DEVELOPMENT AND TESTING

M. Ebrahim Mohammadi, Tyler Stephans, Zachary Mattis, Russell Schwartz, Bikalpa Khatiwada, Louis Moon, Theodore Lincoln, Richard Chen, Patrick Ribas, Amanda Horacio, Brian Podobnik, Adam Begley, Chris Owens, and Andrew Horchler; Astrobotic Technology, Inc. 1016 N. Lincoln Ave., Pittsburgh, PA 15233 (andrew.horchler@astrobotic.com)

Abstract. *Hazard detection and avoidance (HDA) and hazard relative navigation (HRN) are critical technologies for ensuring spacecraft land safely at target sites and for accurate rover mission planning and operation. Consequently, highly detailed and high-resolution map products are essential for supporting the development and testing of these systems. This paper explores key modeling capabilities of Astrobotic's DEMkit software tools for HDA and HRN, demonstrating features to realistically generate rocks, craters, and boulders at scales not captured in high-resolution orbital images and discusses HDA and HRN approaches to detect hazards and safe landing site locations. The paper also highlights LunaRay's new sensor data generation capabilities. This includes accommodating varying illumination conditions, sensor-specific properties, altitudes, positions, and orientations, as well as simulating LiDAR scan dynamics. Additionally, a lunar analog test site for evaluating HDA and HRN system performance is presented. These data products support the development and testing of hazard detection sensor systems and machine learning-based algorithms.*

Introduction. Currently, available orbital data of the lunar surface does not capture the level of detail that is required for HDA, HRN, or rover mission planning. For example, images captured with the Narrow Angle Camera instrument on the Lunar Reconnaissance Orbiter have a resolution of 0.5 meters per pixel (mpp) under nominal conditions and roughly two times lower resolution at locations with low sun angle (e.g., at the South Pole). Such images allow the reconstruction of a three-dimensional scene with a resolution of 1–3 mpp at best [1,2]. More recently collected data, including images from the Korean Pathfinder Lunar Orbiter, provide high-resolution imagery, but still do not achieve the required centimeter-scale detail [3]. Methods for creating high-detail terrains and maps are essential for supporting the development and testing of landing sensors. These datasets must feature surface properties and characteristics that quantitatively and qualitatively align with our understanding of the lunar surface, derived from high-resolution orbital data. Generally, there are two approaches to creating these datasets: generating synthetic datasets based on high-resolution terrain data and lunar geology or collecting data from regions on Earth that mimic lunar terrain features, whether naturally found or constructed. Astrobotic's DEMkit and LunaRay software are designed to generate synthetic hazard terrains and simulated sensor datasets. In addition, the HDA algorithm presented utilizes synthetic hazards to identify a safe landing site through a series of integrated computational steps.

Scientifically modeled high resolution lunar terrain. One solution to the lack of high-resolution data required for HDA workflow is to create synthetic lunar terrain that may be generated at higher resolutions. Astrobotic's DEMkit terrain modeling software tools [4] support adding different hazardous features including craters, roughness, rocks, and boulders to existing lunar terrain using physically derived generative geometric functions. The same generative functions are also used to improve the level of detail of real hazard features. This process of improving the level of detail of existing terrain enables full control over hazard geometry and distribution and may be targeted to match conditions at specific landing sites (see Figs. 1 and 2). Additionally, because the location of every synthetic hazard is known, ground truth hazard maps can be tailored to specific mission requirements, providing a crucial feature for curating datasets. As a result, terrain features can be added in various configurations, ranging from nominal to edge cases, across a landing site or rover operating area to generate large datasets for testing and the training of machine learning algorithms.

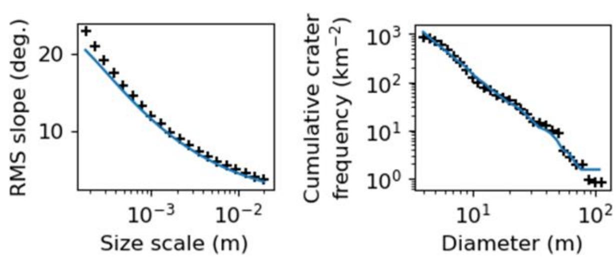

Figure 1. Synthetic crater and roughness hazards targeted to match specific sites on the Moon. Measured crater size frequency near Shackleton Crater (black crosses, [5]) and empirically derived size frequency distribution (blue line, left). Root mean square (RMS) slope derived from fractal properties at cm- to mm-scale measured from Apollo 11 data (black crosses, [6]) and RMS slope of generated synthetic terrain (blue line, right).

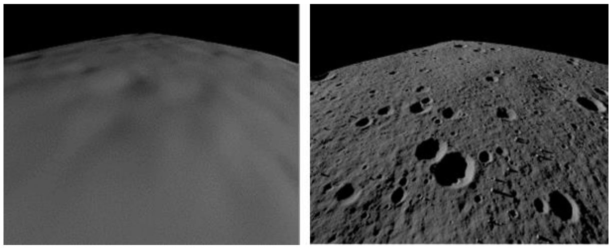

Figure 2. Synthetic hazard features added to elevation models based on real lunar terrain: original lunar terrain (left) and with added craters, roughness, rocks, and boulders (right).

Lunar Surface Proving Ground. Another common approach is to collect data from lunar-like terrains. Astrobotic's Lunar Surface Proving Ground (LSPG) in Mojave, CA is a lunar analog test site. The terrain geometry was designed using DEMkit and high-resolution orbital data and lunar geology-informed generative functions. The three-dimensional 100-by-100 meter test site replicates the surface properties and topography at the South Pole of the Moon, including craters of varying diameters, sloped areas, rough and smooth terrains, and rocks and boulders ranging in size from meters to centimeters. Additionally, the site includes features common to equatorial regions, such as rills (Fig. 3). This realistic environment enables the data collection with actual sensors, incorporating genuine sensor errors and noise patterns in the development of HDA and HRN techniques.

Figure 3. Astrobotic's Lunar Surface Proving Ground.

Physics-based simulation software. The Moon, especially its south pole region, presents numerous challenges for terrain relative navigation (TRN) and image-based HDA and HRN due to low sun elevation and a wide range of sun azimuth angles. This complicates the creation of hazard maps with identified hazards in advance. As a result, LiDAR sensors are also considered for this task. Astrobotic's LunaRay can simulate real camera and LiDAR sensors [4, 7]. This software can render multiple instances of a synthetic or real-world terrain sampled under varying illumination conditions, sensor-dependent properties (e.g., exposure, LiDAR scan patterns), position, and orientation. It can also simulate camera and LiDAR noise, motion blur induced by vehicle motion during data collection, and LiDAR scan dynamics resulting in skewed point clouds. These capabilities support the development and testing of image and LiDAR-based TRN, HDA, and HRN algorithms as well as real-time point cloud de-skewing solutions, TRN map generation, Monte Carlo testing, and generation of mission-relevant datasets for machine learning applications (Fig. 4).

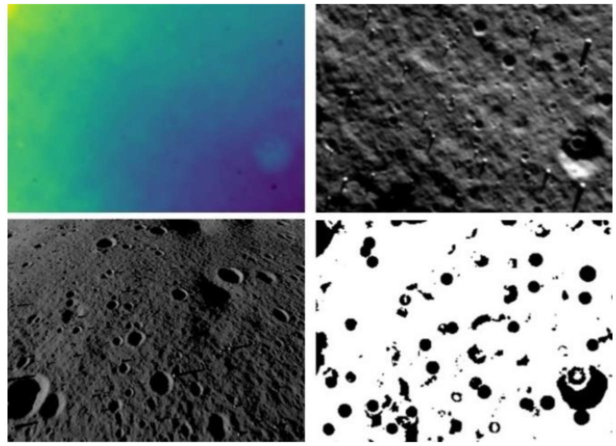

Figure 4. Example of data products (clockwise from top left): synthetic depth image, corresponding grayscale image, segmented hazard ground-truth data (in black and white), and example simulated image.

Hazard Detection Algorithm. An HDA algorithm can be decomposed into multiple steps: surface-reconstruction, terrain-analysis, contact-modeling, hazard-evaluation, and safe site selection. In the first step, surface-reconstruction processes a collected LiDAR scan into a representation of the lunar surface that can be efficiently queried. Then, the terrain-analysis functions compute slope and roughness metrics of the full region of interest. Contact-modeling simulates the interaction between the lander geometry and the lunar surface independently for every candidate landing location and orientation (Fig. 5). Finally, hazard-evaluation and safe site selection use all these intermediate products along with probabilistic models to produce an ultimate landing site recommendation. Figures 6 and 7 depict HDA segmentation results along with the selected landing site for a synthetic test case. An evaluation of an HDA algorithm with various simulated cases is presented in Table 1. In each case, a binary map is created by thresholding the probabilistic output of the hazard map. False hazards and missed hazards are evaluated by comparing the results with the true outcomes. The results are intentionally conservative, as the threshold is selected to minimize false positives (missed hazards).

Table 1. HDA test results.

Test ID	False hazard%	Missed Hazard%
Run 1	34.69	0.69
Run 2	34.62	0.74
Run 3	34.17	0.84
Run 4	35.14	0.52

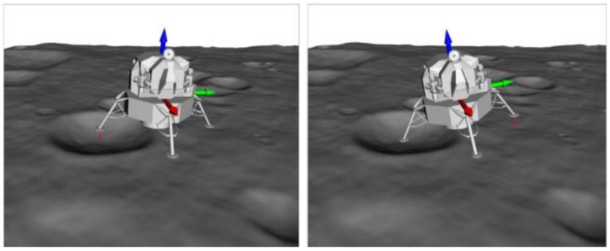

Figure 5. Example of contact-modeling simulation for a particular landing candidate, revealing a potential lander "rocking" hazard.

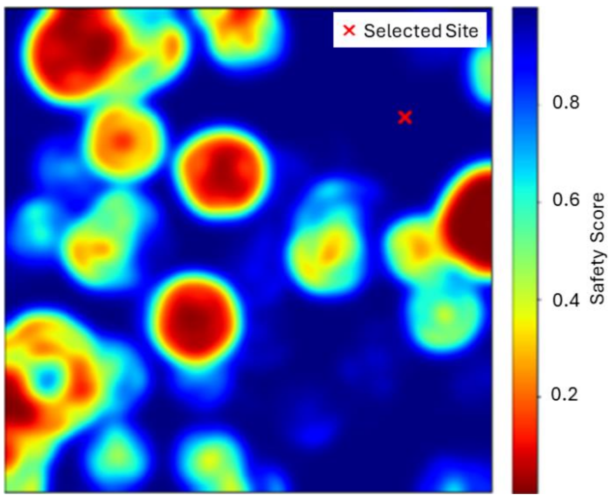

Figure 6. Example hazard map and site selection. The scale bar indicates safety score where higher values correspond to safer areas.

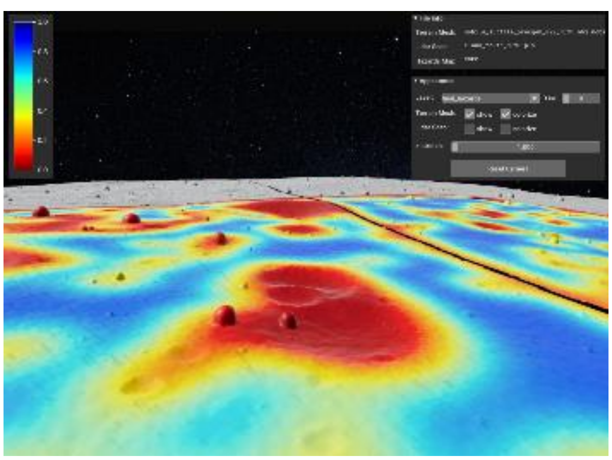

Figure 7. HD visualization software: a hazard map superimposed on synthetic lunar terrain. Regions classified as hazardous are colored in red.

Conclusions. Current lunar terrain products are not available at the level of detail needed for planning future lunar missions around hazardous locations. Instead, synthetic high-detail terrain may be either modeled in simulation or through analogous sites on Earth for the purpose of HDA and HRN system development and evaluation. Astrobotic's DEMkit software enables the addition of high-detail, physically derived, and region-specific hazardous features to existing terrain for any location of interest on the Moon. These terrain maps are then used in LunaRay to generate simulated sensor data. The benefits of using synthetic data include full control over the type, geometry, dimension, and spatial distribution of features, enabling the simulation of both nominal and edge cases. To acquire real-world sensor data, the LSPG provides an environment with geometric features and hazards common to the Moon. By developing these capabilities, sensors, rovers, and algorithms can be evaluated in more realistic and demanding scenarios, leading to improved performance and reliability of HDA and HRN algorithms, particularly in handling realistic sensor errors and noise distributions. The systematic application of surface reconstruction, terrain analysis, contact modeling, hazard evaluation, and site selection enables the HDA algorithm to provide a detailed and real-time assessment of potential lunar landing sites. This effectiveness is demonstrated by the results and the selected site presented in Figure 6.

References.

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