LIDAR-BASED LUNAR CRATER DETECTION AND VOLUME ESTIMATION TRADE SPACE EXPLORATION

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Abstract. *Through use of Light Detection and Ranging (LiDAR), the volume of crater-like bodies can be found to aid in autonomous landing, navigation, and morphological studies. LiDAR scanning provides precise and high-resolution three-dimensional topographic point clouds. This study first simulates craters of differing shape and dimensions with ground truth volume, then obtains point clouds via simulated LiDAR scanning. Each point cloud is tested for crater detection and volume estimation to analyze how varying crater shapes and sizes, along with different LiDAR and flight parameters—such as speed, altitude, accuracy, scan frequency, and number of channels—affect the results. Beyond lunar bodies, this technology has broad applications including pothole evaluation, environmental monitoring, and urban planning.*

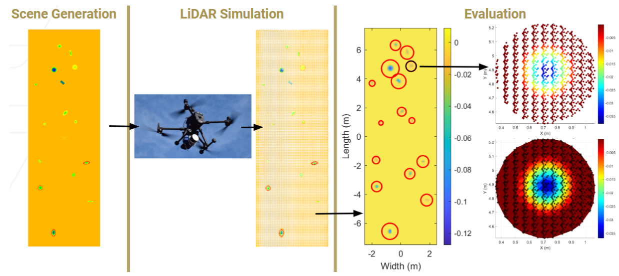

Figure 1. A high level top view of the simulation process. It begins with generating the scene then surveying it using virtual LiDAR to create a point cloud. The craters are then extracted from the point cloud for analysis.

Introduction. Light Detection and Ranging (LiDAR) technology has transformed how we gather and analyze topographical data, providing high-resolution three-dimensional point clouds for precise volume estimation of various surface features, including lunar craters.

Traditionally, crater volumes have been estimated using other remote sensing techniques such as photogrammetry, radar, and optical imaging, which can be limited by resolution and accuracy. LiDAR-based object detection and estimation offer higher resolution data to aid autonomous landing systems, morphological studies, and other 3D mapping applications.

This study leverages simulated LiDAR point cloud data to aid in a trade-space analysis comparing the accuracy of lunar crater volume estimation techniques. Herein, a variety of different shapes and sizes of craters are simulated in a Monte Carlo fashion with different LiDAR scan parameters and accuracies along with different flight parameters and volume estimation algorithms. The purpose of this study is to aid in optimal surveying parameters for crater detection and volume estimation to assist in autonomous landing and morphological studies.

Lunar Applications. Laser scanning for volume estimation has applications across various domains, including road safety through pothole volume estimation and construction through rubble volume estimation. In lunar applications, this technology facilitates safe exploration missions via autonomous landing and surface navigation while aiding scientific discovery through morphological studies.

Autonomous Landing. To land and navigate safely on planetary bodies like the Moon, avoiding hazards such as large rocks is crucial. Previous rovers, including NASA's Spirit and Opportunity and China's Yutu rover, used stereo imaging for obstacle detection.[1] In contrast, NASA's Navigation Doppler LiDAR (NDL), utilized on the Peregrine and Odysseus landers, provided object detection and velocity estimation for autonomous lunar landing.[2] This represented a significant advancement, as it was the first to employ coherent Frequency Modulated Continuous Wave (FMCW) LiDAR for accurate positional and velocity data. Given the high costs and risks of lunar missions, there is a growing push to test technologies through simulations alongside traditional field tests.[1] LiDAR is increasingly sought after in this context for its superior object detection capabilities compared to camera-based systems, enhancing safety and effectiveness during landing operations.

Morphological Studies. Craters on the Moon experience significant morphological changes due to geological processes like gravity, slope, and solar wind weathering. Accurately measuring crater volumes provides insights into these degradation processes.[3] Such measurements help distinguish between degradation classes, enhancing our understanding of lunar surface evolution across craters of different sizes and shapes.[4]

Volume Estimation Process. This study simulates LiDAR point cloud collection over a synthetic lunar surface to enable quick, iterative tuning of UAV and LiDAR parameters like pulse frequency, accuracy, channels, speed, and altitude—many of which aren't adjustable on commercial LiDAR hardware. By simulating both the LiDAR and the environment, we gain deeper insights for optimizing flight and LiDAR settings. A virtual cratered surface will be scanned using a Virtual Laser Scanner, and the resulting point cloud will be analyzed for crater detection and volume estimation. The process is illustrated in Figure 1.

The surface with craters is created by first randomly placing craters in a grid. Then, the craters are randomly modeled with various cross-sections, indentation shapes, and dimensions. At that point, the craters are then rotated in place, and the planetary surface is generated between the craters.

To simulate airborne laser scanning, this work will use HELIOS++, "an open-source framework for terrestrial, mobile, UAV-based, and airborne laser scanning."[5] It generates simulations based on inputs (scene, scanner, and platform) and produces outputs, including point clouds. The flight parameters (speed and altitude) and LiDAR parameters (pulse frequency, number of channels, and accuracy) will be varied to create different scans of lunar surfaces during flight.

To evaluate the impact of flight and scanner parameters, the point cloud is processed to detect craters and estimate their volumes through the following steps: First, the point cloud is organized into a grid and smoothed using a Gaussian filter. Potential craters are identified by applying an altitude-based threshold, and DBSCAN is used to cluster these points.[6] The original and surrounding points forming each cluster are then extracted for volume estimation. For the volume estimation process, a ground plane is fitted to each crater using RANSAC,[7] and the volumes above and below the plane are calculated using Delaunay Tetrahedralization.[8]

Preliminary Results. As a preliminary test, this study explores the impact of speed on crater detection using hemispherical craters with a radius of 0.1m. Platform speed and altitude specifications are provided in Table **??**,]. LiDAR parameters are in Table 1, in which the accuracy refers to the 1σ error value, optimized to 0.00m for baseline testing.

Table 1. LiDAR parameters for the survey. The accuracy represents the 1σ accuracy error of the scanner, set to 0.000m to determine optimal performance for a custom LiDAR with scan rate and channels based off of the Velodyne Puck 16.

LiDAR Parameters		
Accuracy (m)	**Channels**	**Scan Rate (Hz)**
0.000	16	20

Table 2. Platform parameters for the survey. The speed ranges from 1 to 40m/s to analyze performance at increasing speed.

Platform Parameters	
Speed (m/s)	**Altitude (m)**
[1,40]	10

As found in testing, as speed increases, the rate of crater detection decreases. Point density decreases at a proportional rate as speed increases. As the point density decreases, there is less data to detect craters, and thus the detection rate decreases. The results of the study for hemispherical craters are shown in Figure 2.

The dips in the graph are due to successive scan rotations aligning with previous channel scans, causing decrease in point cloud density along track. Those sudden

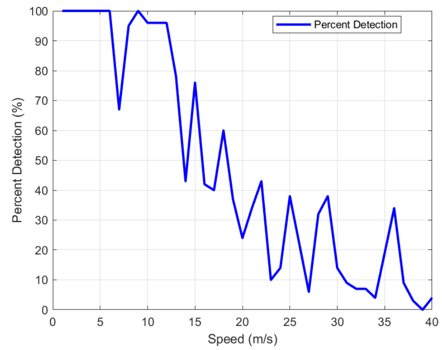

Figure 2. Crater detection percentage vs. speed. The dips in the graph are explained by the concentration of along-track point density, which occurs when the distance between successive rotations and channel spacing aligns.

decreases in point density are predictable through equating the distance between successive channel points on the ground and successive LiDAR head rotations. For the LiDAR (in Table 1) and platform specifications (in Table 2) of this survey, the first of those dips would occur at 7m/s, as exemplified in Figure 2.

Conclusions. This initial research demonstrates the effect of increasing platform speed on crater surveying. In the future, it will analyze detection and volume estimation rates at specific parameters for different crater shapes/sizes to determine optimal specifications.

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