Development of a Horizontally Rotating 3D LiDAR System for Control Point Surveying in Lunar Environments using a Rover

Amane H.[1*], Tomoki S.[1], Rikako S.[1], Masanori T.[2], Keitaro K.[2],

Takahiro H.[2], Tomowo O.[2], Hisatoshi S.[2], Taizo K.[3], Masafumi N.[1]

[1] Shibaura Institute of Technology, Japan

[2] Asia Air Survey Co., Ltd., Japan

[3] Ritsumeikan University, Japan

ah22074@shibaura-it.ac.jp

Abstract: *We developed a robust surveying a robust surveying methodology called LiDAR-SfM/MVS to support lunar development, which is challenged by extreme environments and high costs. This methodology overcomes the limitations of traditional image measurements on regolith-covered surfaces and LiDAR-SLAM in non-GNSS environments. Our system combines LiDAR-SLAM for control point surveying with structure from motion (SfM) and multiview stereo (MVS) to generate dense point clouds. Previous experiments with a horizontally mounted LiDAR on a rover showed that its limited vertical field of view hindered its ability to climb inclined surfaces because, there were no vertical objects to scan. To address this issue, we designed a new system that mounts a vertically scanning 3D-LiDAR on a horizontal turntable. We also developed a self-calibration methodology that uses the iterative closest point (ICP) algorithm to estimate and correct for internal structural misalignments. Experiments on a lunar-simulated terrain confirmed the effectiveness of our methodology. The system achieved a spherical marker fitting accuracy of less than 0.01 m. Registration errors averaged 0.0121 m when compared to total station surveys and 0.0271 m in sequential LiDAR point cloud registration, aligning with the LiDAR's 0.03m ranging accuracy. The system also generated dense point clouds with a density of less than 0.01 m, and achieved a registration accuracy of 0.03 m (RMSE) between LiDAR and SfM/MVS point clouds. These results confirm that our proposed methodology meets the required accuracy 0.10 m for unmanned construction. Future work will focus on designing a more robust sensor system for the lunar environment.*

*Keywords: lunar surveying, LiDAR, SLAM, SfM/MV*S

Introduction

In recent years, research on lunar development has increased, necessitating the development of technologies suited to the specific conditions of lunar environment. The lunar environment is characterized by extreme temperature variations and cosmic radiation, which makes manual work challenging. Moreover, the high cost of transportation requires efficient and precise construction. Consequently, detailed terrain data are essential for creating digital twins and simulations. However, the absence of GNSS hinders accurate localization for LiDAR-based SLAM, and traditional image-based measurements are difficult because the lunar surface is covered in regolith. To address these issues, we have developed a LiDAR-SfM/MVS methodology that integrates LiDAR-SLAM for control point surveying with markers and SfM/MVS processing for dense point cloud acquisition. This methodology uses a 3D-LiDAR mounted on a turntable and multiple asynchronous cameras. This research aims to verify the usability of a 3D-LiDAR system mounted on a lunar surveying rover for control point surveying.

As a related work, we focused a landmark-based navigation (Xu, et al. 2016) that uses landmarks to improve navigation accuracy to achieve pinpoint landing possible. This approach proposed a navigation scheme integrating measurement model of landmarks with known and unknown coordinates to perform state updates. The main target of this approach differs from ours in that it focuses on navigation during landing. However, the primary objective of this research is aerial position and attitude estimation. Due to its shared goal of using landmarks for surveying and improving positional accuracy. This paper can be cited as a relevant work emphasizing an alternative navigation methodology in extreme lunar environments. It focuses, specifically focusing on independence from lighting and securing an absolute position. The 5 m accuracy requirement, exceeds the 0.1m accuracy requirement of the present study and suggests potential for future enhancements.

Methodology

The LiDAR-SfM/MVS methodology was developed to address the challenges posed by lunar environments. It uses point clouds from a LiDAR and image data from cameras as input. The process involves acquiring LiDAR point clouds, extracting marker positions, performing SfM/MVS processing, and registering the SfM/MVS point clouds using the extracted marker positions. The system then outputs dense colored point clouds and positioning data.

Previous experiments at the JAXA Sagamihara Campus showed that a horizontally mounted LiDAR on a rover could not measure makers when the rover was tilted at large angles, as shown in Figure 1. This resulted in frequent omissions of control points. To address this issue, a new system and methodology are developed, as shown in Figure 2.

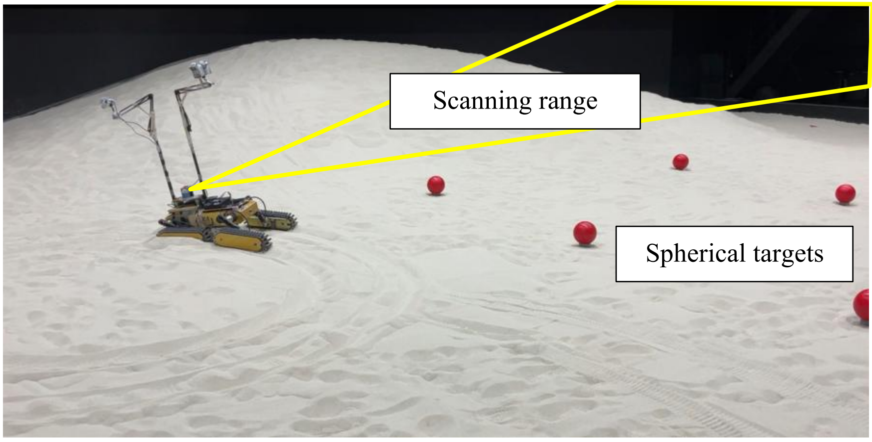


Figure 1: Previous experiments at the JAXA Sagamihara Campus.

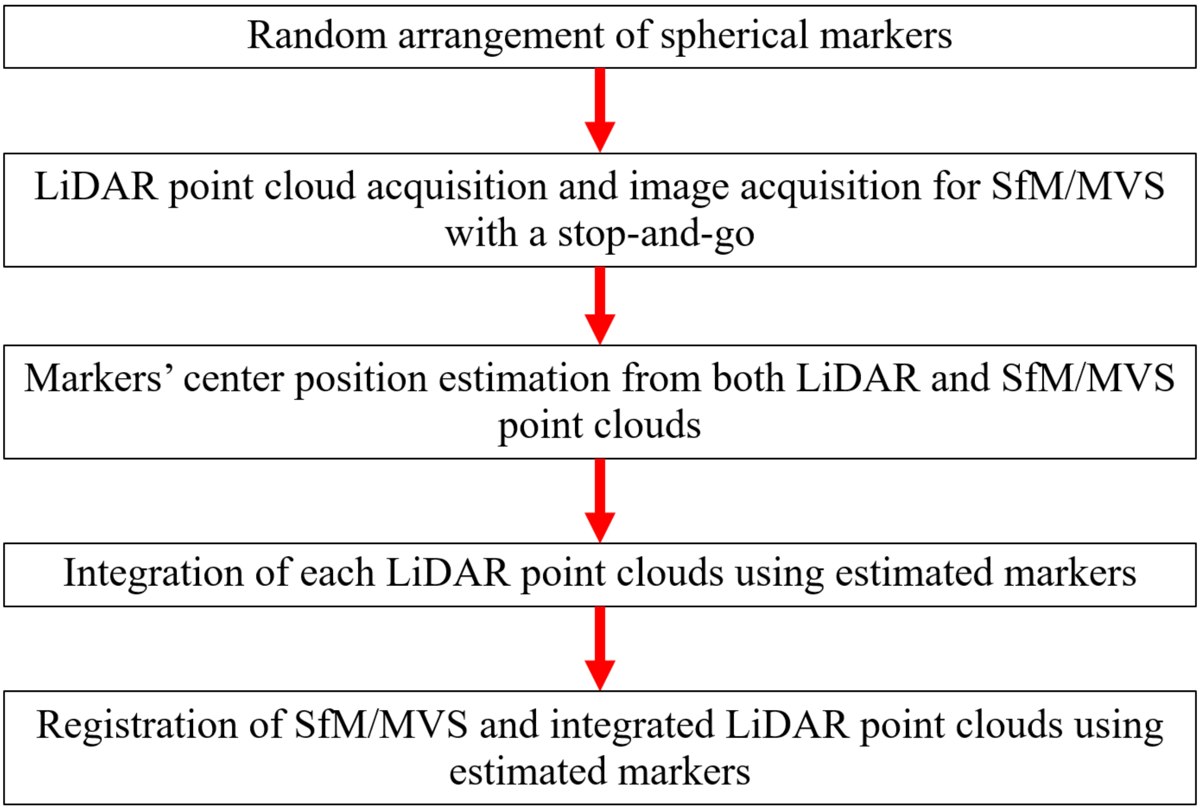


Figure 2: Proposed Methodology.

Similar to a terrestrial laser scanner, it mounts a vertically scanning 3D-LiDAR on a horizontal turntable. The system uses a self-calibration methodology based on the iterative closest point (ICP) algorithm to estimate and correct for structural misalignments. These misalignments include the line-of-sight offset angle, the L-frame distortion angle, and the rotation axis offset distance. Correcting these misalignments ensures a more stable point cloud acquisition.

Experiment

The experiment was conducted on a lunar-simulated terrain at Japan Metals & Chemicals Co., Ltd, as shown in Figure 3. It included a 3D-LiDAR mounted on a turntable and placed on top of an autonomous mobile robot, as shown in Figure 4. The robot was also equipped with high resolution cameras for SfM/MVS processing. Seven measurement locations were established within the field, and 11 spherical markers, each 0.20 meters in diameter, were placed in three or more directions visible from each location.

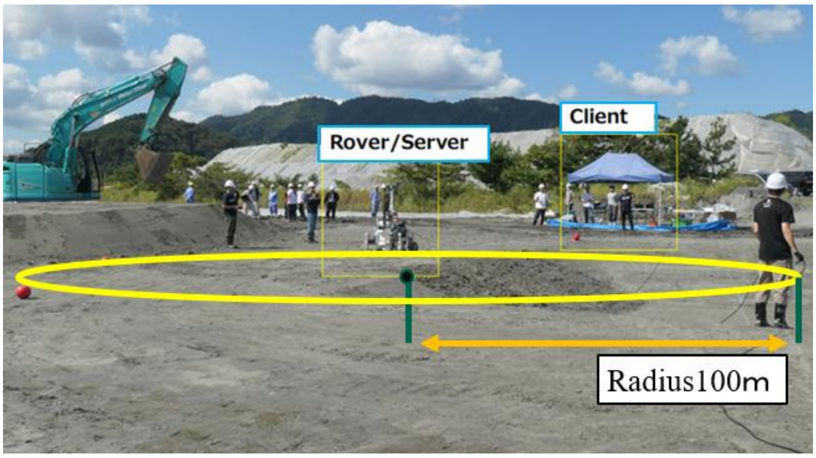
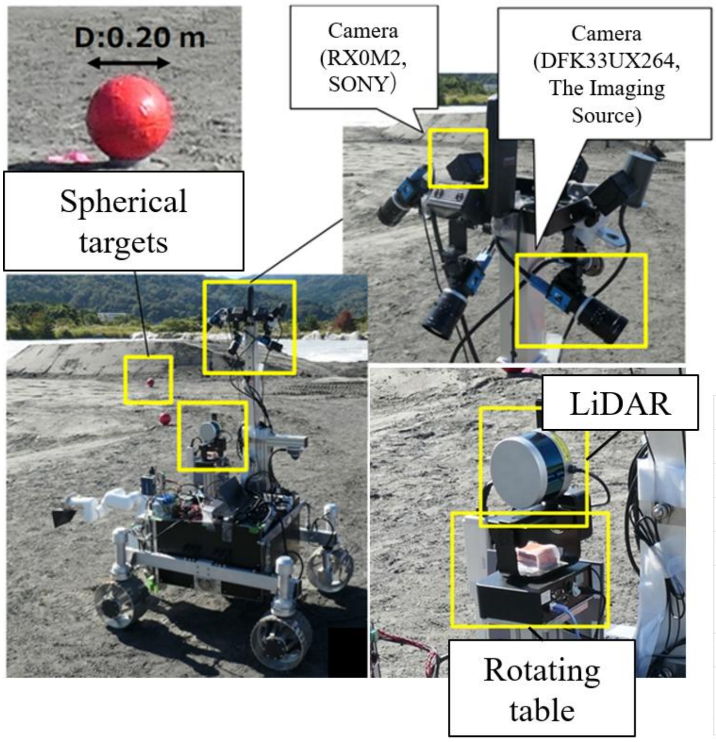


Figure 3: Measurement and Control Experiment.



LiDAR(VLP16,Velodyne)	
Number of lines	16
Range measurement range	100m
Range measurement accuracy	±3cm
Field of view (vertical)	30° (+15° ～-15°)
Field of view (horizontal)	360°
Angular resolution (vertical)	2°
Angular resolution (horizontal)	0.1° ～0.4°
Frame rate	5～20Hz
Wavelength	905nm
Weight	0.83kg
Size	103(D)×72(H)mm

Rotating table (PT-LAN50,Carina System)	
Pan rotation range	±170°
Tilt rotation Range	±174°
Pan rotation speed	0.4° ～50° Sec
Tilt rotation speed	0.4° ～50° Sec
External dimensions	161.0(W)×161.5(H)×121.0(D)mm
Weight	2.26kg
Maximum mountable equipment weight	1.5kg

Figure 4: Sensors Mounted on a Rover.

We evaluated the accuracy of the generated LiDAR point clouds by assessing the residuals during LiDAR point cloud registration with surveying results using total station (TS surveying results) and the residuals during sequential LiDAR point cloud registration.

Results

First in the evaluation using residuals from the TS surveying results, we confirmed that the spherical model fitting accuracy for estimating the center of the red spherical markers, as shown in Figure 5, was less than 0.01 m.

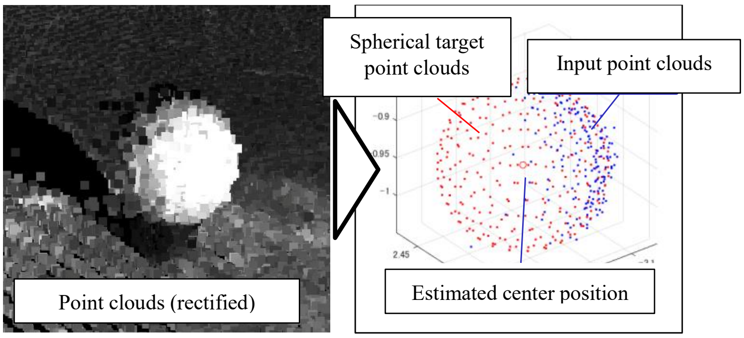


Figure 5: Center Position Estimation of Spherical Maker based on Spherical Model Fitting.

Next, we compared the total length of the sides of the triangle formed by three red spherical markers around the rover that were used for registration with the TS surveying results as shown in Figure 6. The average of these values was 0.0121 m.

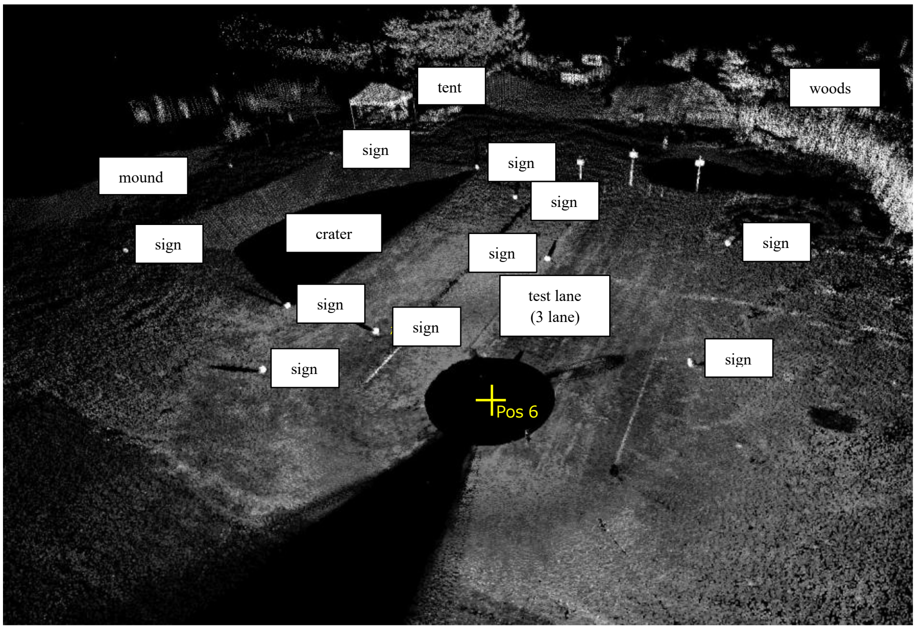


Figure 6: Example of LiDAR Single Scanning Data (Pos 6).

For the evaluation using residuals from sequential LiDAR point cloud registration, we registered the LiDAR point clouds in the following-order from Pos 1 to Pos 7, as shown in Figure 7. Then, we calculated the residuals, as shown in Table 1.

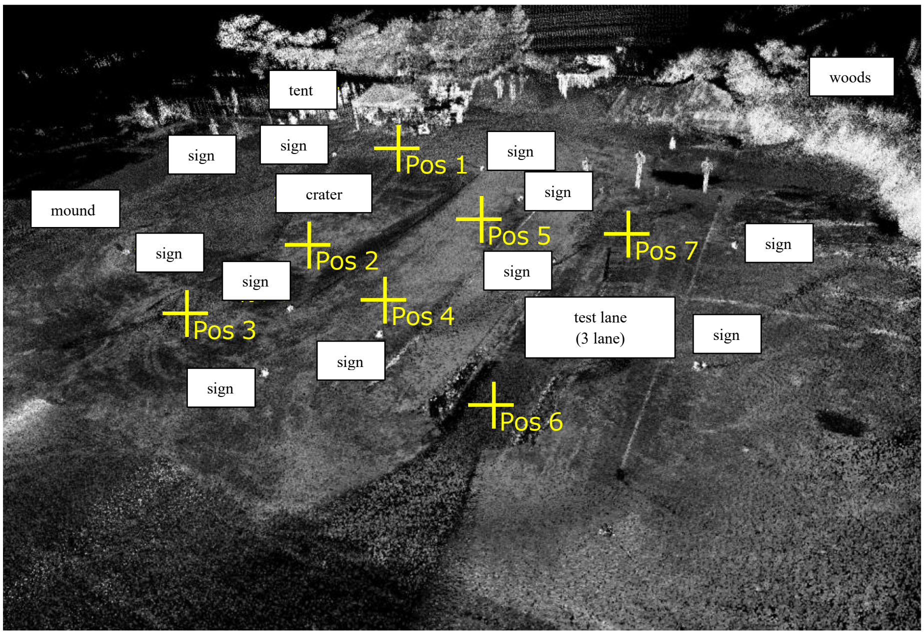


Figure 7: Results of LiDAR Point Clouds Measured at All Positions.

Table 1: Accuracy Verification Results using TS data.

Position ID	Pos 1	Pos 2	Pos 3	Pos 4	Pos 5	Pos 6	Pos 7
Registration error [m] (RMSE)	0.0051	0.0240	0.0298	0.0045	0.0112	0.0060	0.0044

With an average residual of 0.027 m, sequential LiDAR point cloud registration aligns closely with the specified ranging accuracy of 0.030 m, confirming the reliability of the proposed system.

The SfM/MVS point clouds acquired by the lunar ground surveying system equipped with LiDAR-SfM/MVS has a point density below 0.01 m, as shown in Figure 8. To scale the point clouds, LiDAR point clouds were used. The registration accuracy between two types of the point clouds using the red spherical markers was 0.03 m (RMSE), as shown in Table 2.

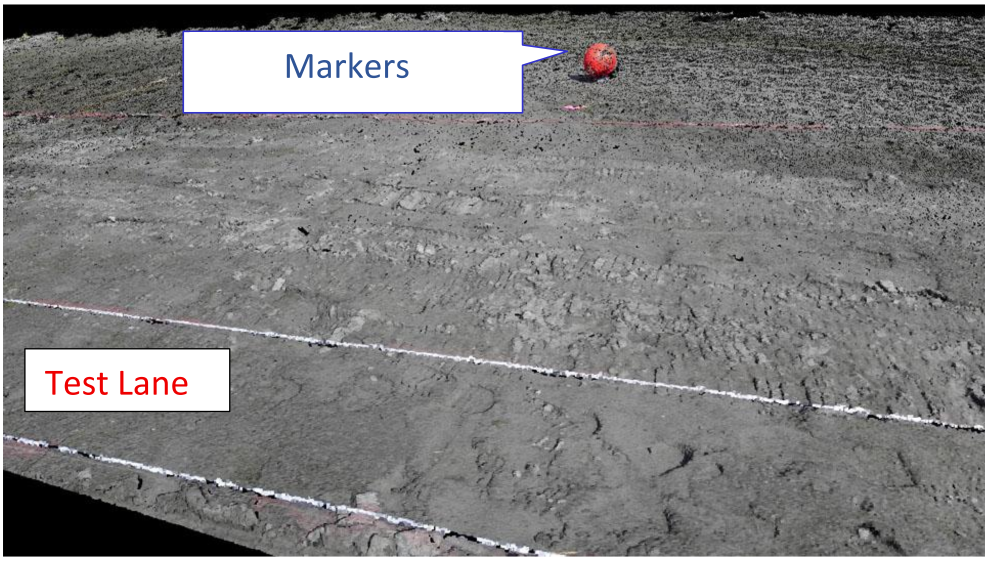


Figure 8: SfM/MVS Point Clouds

Table 2: Verification Results (Sequential Registration of LiDAR Point Clouds)

Base data	Pos 1	Pos 2	Pos 3	Pos 4	Pos 5	Pos 6
Reference data	Pos 2	Pos 3	Pos 4	Pos 5	Pos 6	Pos 7
Registration error [m] (RMSE)	0.0399	0.0293	0.0181	0.0203	0.0325	0.0223

We confirmed that the proposed methodology can achieve the required measurement accuracy of 0.10 m for unmanned construction.

Conclusion and Recommendation

This study verified the usability of a 3D-LiDAR system mounted on a lunar surveying rover for control point surveying. The results showed that the proposed methodology can achieve the required measurement accuracy of 0.10 m for unmanned construction on the Moon. Future work will focus on improving the durability for rocket launches and its resistance to extreme lunar conditions.

Acknowledgements

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