PRELIMINARY EXPERIMENTS ON POINT CLOUD ACQUISITION TOWARD A GROUNDBREAKING SURVEYING FOR LUNAR BASE CONSTRUCTION

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ABSTRACT: Space development has become very active in recent years, and various approaches for construction work for lunar bases are being considered. However, many technical issues still exist. Groundbreaking surveying would be required for lunar base construction, and we propose an unmanned surveying approach in the lunar environment. Two preliminary experiments were conducted; the first experiment was a comparison of point cloud acquisition methodologies, such as structure from motion (SfM) and multiview stereo (MVS), light detection and ranging (LiDAR)-based simultaneous localization and mapping (LiDAR-SLAM), and visual odometry (VO), without global navigation satellite system positioning in environments consisting of few geometrical features. The second experiment consisted of simultaneous data acquisition of surface point clouds and underground at simulated lunar surfaces. First, through SfM/MVS experiments, it was confirmed that a short image acquisition interval with a high-resolution camera can achieve stable point clouds. Second, it was confirmed through LiDAR-SLAM experiments that the SLAM process failed. Finally, through VO experiments, it was confirmed that scale reduction and nonclosed events occurred. This study confirmed that visual SLAM has advantages of stability and accuracy in point cloud acquisition and trajectory estimation on simulated lunar surfaces. In future work, we plan to develop a rover platform.

1. INTRODUCTION

In recent years, space development has very become active, and approaches for construction work of lunar bases are considered. However, there are numerous challenges in construction work in the lunar environment. These include positioning outside the global navigation satellite system (non-GNSS) environment, few geometrical features of ground surfaces covered with sand (lunar regolith), extreme temperature differences, strong cosmic rays, no air, and gravity at one-sixth the magnitude of gravity on Earth. Thus, in three-dimensional (3-D) measurement and groundbreaking surveying on the lunar surface, there are many technical issues, such as positioning problems, point cloud matching problems, and image matching problems due to the few feature points. Previous research in lunar-like environments includes research related to NASA's Mars Exploration Rover (MER) mission, such as the verification of a spacecraft's self-position estimation on Mars (Cheng et al., 2005). Cheng et al. used several methods, including visual odometry (VO), to acquire trajectories to move to a set target. Their experiments showed that VO presented high accuracy under constraints. However, this technique was also shown to take a long time to process due to the low performance of the onboard computer. In this study, we propose an unmanned surveying method in the lunar environment with two experiments.

2. PRELIMINARY EXPERIMENT (EXPERIMENT 1)

In the preliminary experiment, point cloud acquisition was performed by terrestrial structure from motion (SfM) and multiview stereo (MVS), light detection and ranging (LiDAR)-based simultaneous localization and mapping (LiDAR-SLAM), and VO, in a non-GNSS environment with few feature points. We prepared a 3-D measurement system consisting of a multidirectional camera, an inertial measurement unit (IMU) camera, and a LiDAR system.

2.1 Methodology

2.1.1 Terrestrial SfM/MVS: SfM/MVS is a triangulation-based technique to generate point clouds with images taken from various viewpoints. Although the SfM/MVS technique can be applied to aerial photogrammetry using unmanned aerial vehicles, we focused on terrestrial image acquisition for SfM/MVS because there is no air on the lunar surface. In the preliminary experiment, we used a multidirectional camera mounted at a height of 2.0 m above ground level to acquire multidirectional images while moving. The acquired images were used as input data for SfM/MVS processing to obtain point clouds.

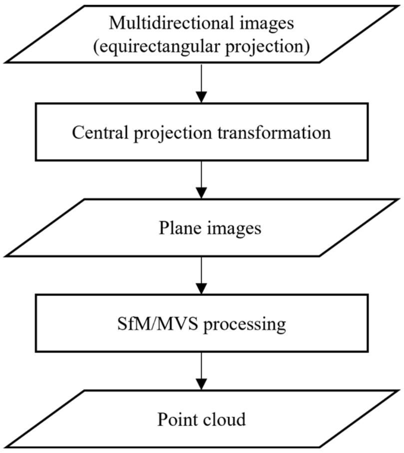

Figure 1. SfM/MVS processing flow using multidirectional images

The images acquired by the multidirectional camera were converted from spherical equirectangular cylindrical images to central projection images to use the general SfM/MVS software as shown in Figure 1. In the preliminary experiment, we used VisualSfM for SfM/MVS processing.

2.1.2 VO: VO is a method that uses a stream of images to estimate the relative position (Aqel et al., 2016). Another method of obtaining the relative position is wheel odometry, but wheel odometry often drifts on rocky terrain and is less accurate (Maimone et al., 2007). We used an IMU stereo camera mounted at a height of 0.20 m above ground level to estimate the trajectory data of the 3-D measurement system. In VO, relocalization and other processing were applied using the Standard SDK and library for an IMU stereo camera (see Table1), to improve the trajectory estimation.

Table 1. Used libraries

Name	Version
pyrealsense2	2.39.0.2342
OpenCV-Python	4.2.0.34

2.1.3 LiDAR-SLAM: LiDAR-SLAM is a methodology that uses point clouds acquired by a LiDAR scanner to estimate position and generate a map. We used a LiDAR scanner mounted at a height of 0.67 m above ground level to estimate movement trajectories and point clouds by SLAM postprocessing. For SLAM processing, we first performed general preprocessing of the point clouds obtained by the LiDAR scanner, such as frame thinning and read ranges. Next, in the experimental environment of the preliminary experiment, features such as trees and buildings that do not exist on the lunar surface were included in the point clouds, so scanning lines were set up that include features other than the ground surface and scanning lines that include only ground surface. Finally, all point clouds were inputted into the SLAM process. The Navigation Toolbox in MATLAB was used for processing without an error adjustment based on the loop closer.

2.2 Measurement System

In the preliminary experiment, we selected a square near the Toyosu campus of the Shibaura Institute of Technology in Tokyo as a test field with few geometrical features. The experiments were conducted using carts equipped with sensors as shown in Figure 2. The concave line in Figure 3 indicates the path of the experiment. The red circles in Figure 3 show target markers made of spherical foamed styrol wrapped with red duct tape as feature points. Four target markers were placed in the square at 4 m intervals. The IMU stereo camera (RealSense T265, Intel) was used to estimate cart direction and translation. An IMU stereo camera is a sensor for acquiring relative positions and has two cameras and an IMU. The RealSense T265 incorporates two cameras, an inexpensive IMU sensor and Visual Processing Unit, and outputs trajectories. A LiDAR system (VLP-32C, Velodyne) was used to acquire point clouds for SLAM processing. The sampling rates and the resolution of VO and LiDAR-SLAM are shown in Table 2. A multidirectional camera (THETA V, RICOH) was used to acquire images for SfM/MVS processing. Data acquisition was conducted at approximately 2 km/h to avoid vibration during moving. The cart was moved in parallel without azimuth angle changes.

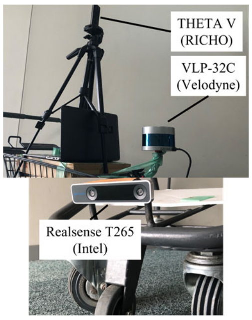

Figure 2. Experimental equipment

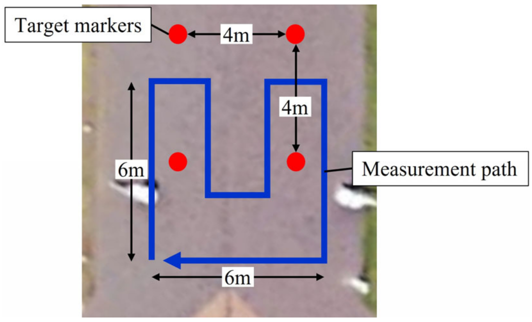

Figure 3. Experimental path diagram

Table 2. Sensor specifications

multidirectional camera: THETA V (RICOH, Japan)	
Sensor type	CMOS (×2)
Sensor size	1/2.3 (×2)
Image size	5376×2688
Valid pixels	12 megapixels (×2)
F-number	2.0
IMU stereo camera: RealSense T265 (Intel, U.S.)	
Base line	64 mm
FOV	173 deg
Valid pixels	848×800 pixels
Frame rate(image)	30 fps
Sampling rates (pose)	200 Hz
LiDAR scanner: VLP-32C (Velodyne, U.S.)	
Distance measurement accuracy	3cm
Angle resolution (Horizontal axis)	0.1 deg to 0.4deg
Angle resolution (Vertical axis)	0.33 deg
Measurement range (Horizontal axis)	360 deg
Measurement range (Vertical axis)	40 deg (-25 deg to + 15 deg)
Sampling rates	10Hz

2.3 Results

2.3.1 Results of SfM/MVS

The relationship between the center projection transformation method and the output results in the SfM/MVS preprocessing is shown in Table 3. Increasing the number of divisions decreases computation time and increases the number of point clouds (Table 3). In addition, as the number of pixels increases, processing time increases, and the number of point clouds increases. In preliminary experiments, we chose 20 equally spaced divisions of 600 × 600 pixels.

Table 3. Experimental results of projection transformation in SfM/MVS preprocessing

Number of pixels	number of divisions (Equidistant)	Total number of projected images	Number of point cloud	processing time [minute]
800×800	10	640	422702	1304
800×800	15	960	894183	1044
600×600	10	640	272769	950
600×600	15	960	514723	763
600×600	20	1280	639880	497

The relationship between the interval of image acquisition and the output results is shown in Table 4. The length of the experimental path was 32 m, and the number of images obtained is the path length divided by the interval of image acquisition. The total number of projected images obtained was also the number of images acquired multiplied by 20 because the image is divided into 20 segments. The number of point clouds and the processing time increase as the image acquisition interval becomes shorter (Table 4).

Table 4. Summary of terrestrial SfM/MVS processing results

interval of image acquisition [meter]	Number of image acquisition	Total number of projected images	Number of point cloud	processing time [minute]
2	16	320	203321	168
1	32	640	422912	443
0.5	64	1280	639880	497

Figures 4, 5, and 6 show that the smaller the interval between acquisitions, the more clearly the point clouds are generated. Figure 6 also shows that there are defects in the point cloud in the shadowed area.

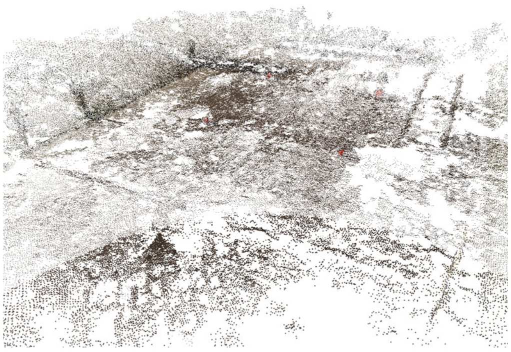

Figure 4. Processing result (the image acquisition interval was 2 m)

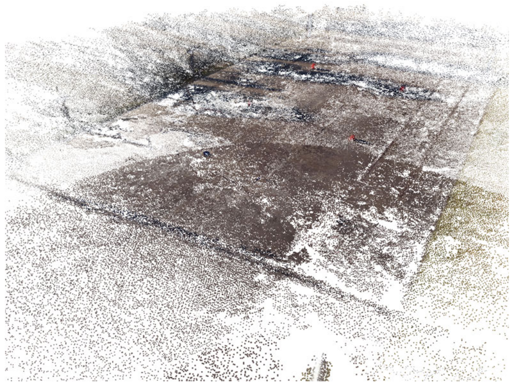

Figure 5. Processing result (the image acquisition interval was 1 m)

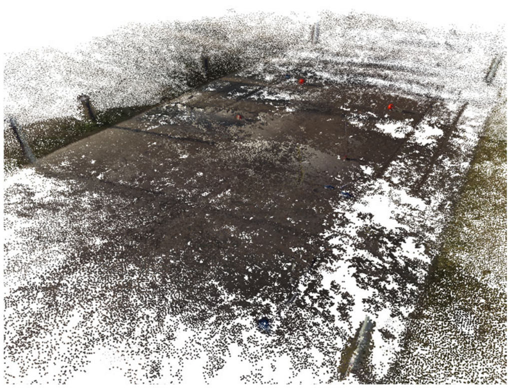

Figure 6. Processing result (the image acquisition interval was 0.5 m)

2.3.2 Results of VO

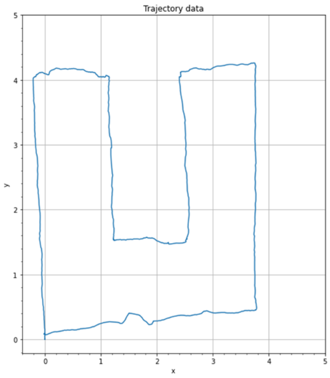

Figure 7. Measurement results (close to the actual path)

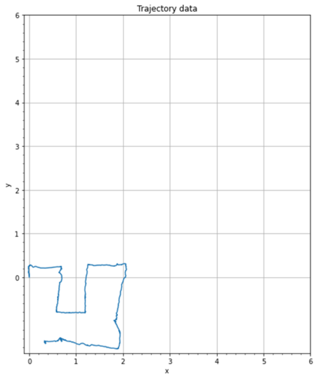

Figure 8. Measurement results (failed case)

The results are relatively close to the actual path, although there are some errors, and the closing difference was 0.089 m (Figure 7). Results such as Figure 7 were obtained in one out of five times. The trajectory estimation was failed at the start point of the measurement (Figure 8). Moreover, the scale factor was smaller than the actual experimental path.

2.3.3 Results of LiDAR-SLAM

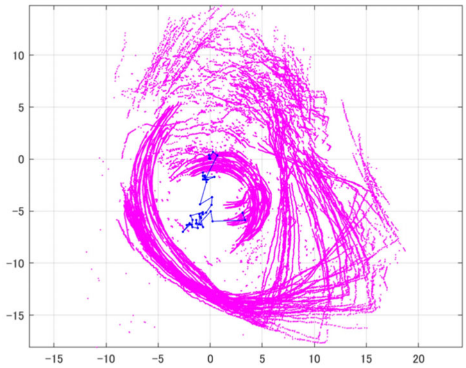

Figure 9. Processing result
(input: all point clouds)

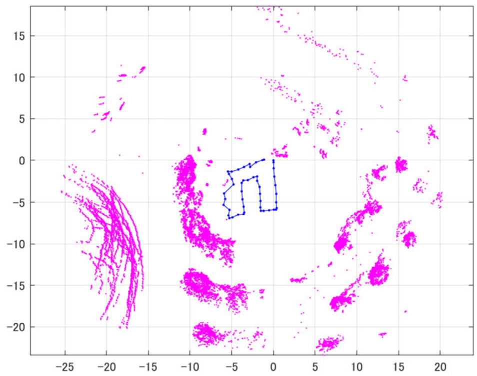

Figure 10. Processing result
(input: filtered point clouds)

The pink dots indicate the point cloud integration result, and the blue line indicates the trajectory estimated by the SLAM processing. SLAM processing has failed because the point clouds of horizontal features were included in the input (Figure 9). By contrast, although errors remained, the SLAM processing estimated the trajectory successfully (Figure 10).

3. FIELD EXPERIMENT (EXPERIMENT 2)

In the field experiment, simultaneous acquisition of ground surface point clouds and ground data in the simulated lunar environment was performed. We mainly describe SfM/MVS in this paper.

3.1 Experiment

In the field experiment, the equipment and configuration differed from the preliminary experiment. First, we used a multidirectional camera mounted at a height of approximately 1.7 m above ground level. Second, we used high-resolution cameras with two directions such as front and left. The equipment shown in Figure 11 was pushed by hand to move around an area of approximately 4.1 m × 7.5 m in Figure 12. A total of 19 target markers were placed in the experimental environment as features for cameras and LiDAR (Figure 13).

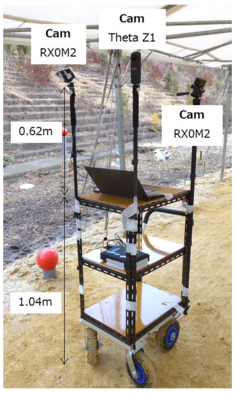

Figure 11. Experimental equipment

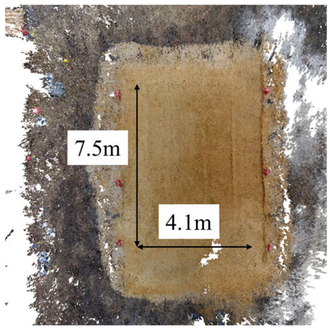

Figure 12. Experimental environment

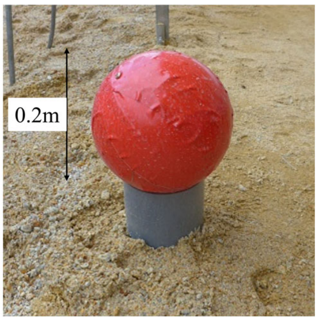

Figure 13. One of the target markers (sphere type)

Table 5. Sensor specifications

multidirectional camera: THETA Z1 (RICOH, Japan)	
Sensor type	CMOS (×2)
Sensor size	1.0(×2)
Image size	67203360
Valid pixels	20 megapixels (×2)
F-number	2.1,3.5,5.6
High resolution camera: DSC-RX0M2 (SONY, Japan)	
Sensor type	CMOS
Sensor size	1.0
Valid pixels	15 megapixels
F-number	4.0

3.2 Results

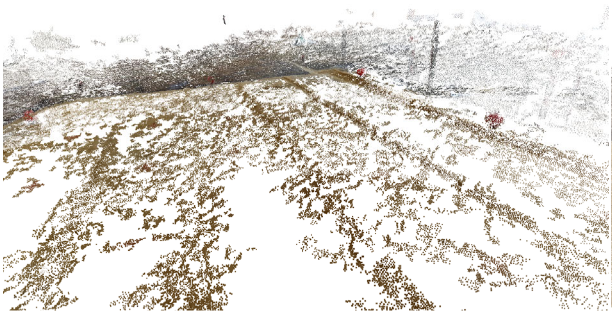

Figure 14. Generated point clouds using multidirectional images

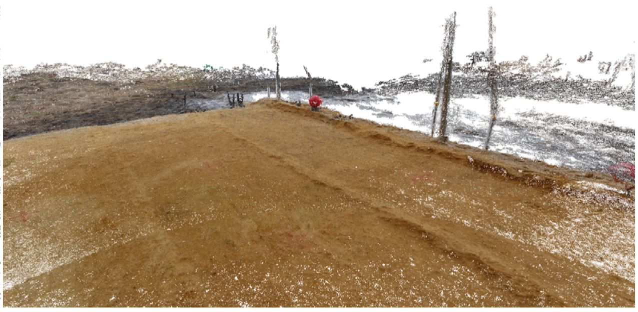

Figure 15. Generated point clouds using high-resolution images

The point cloud density was poor because the soil surfaces had few image features (Figure 14). The high-resolution camera successfully produced point clouds on soil surfaces with few image features (Figure 15).

4. COMPREHENSIVE DISCUSSION

There are many technical issues in 3-D measurement and surveying on the moon. First, we had a few suggestions for the issue of image matching due to fewer feature points by adjusting the projection transformation method and shortening the image acquisition interval in the preliminary experiment and using a high-resolution camera in the field experiment. The number of point clouds and processing time varied significantly by changing the segmentation method of the multidirectional image (see Table 3). It was confirmed that parameter tuning is important for the multidirectional camera. It was also confirmed that the SfM/MVS processing time increased significantly as the number of inputted images increased (see Table 4). The maximum processing time was approximately 8 h in this study because the measurement area was small, but it can be expected that measurements over a larger area would take longer. By contrast, we consider that the processing time could be reduced by improving the efficiency of image matching in the SfM process. In our qualitative evaluation, it was confirmed that a short image acquisition interval is effective in acquiring dense point cloud data in an environment with few feature points. In the field experiment, it was confirmed that the quality of the point cloud has improved by using a general high-resolution still camera instead of a multidirectional camera (Figures 14 and 15). It can also be considered that high-resolution cameras have the problem of lower measurement efficiency and higher costs compared with multidirectional cameras that can acquire images of all directions with a single unit. Although there are issues with high-resolution cameras, it was confirmed that even in environments with fewer feature points, point cloud data of homogeneity can be acquired, and that could be considered suitable for matching with ground information. Next, for positioning challenges such as non-GNSS environments, we proposed localization using LiDAR-SLAM and trajectory estimation using VO. In our qualitative evaluation, it was confirmed that the SLAM processing failed as expected only in the case of microtopography and fewer feature ground surfaces available (Figure 9), but it succeeded when trees and buildings or features other than the ground surface were obtained (Figure 10). Because the lunar environment is similar to that in Figure 9, we consider that applying LiDAR-SLAM to lunar surveying is difficult as it is. In our qualitative evaluation, it was confirmed that although the accuracy was not immediately applicable to surveying, trajectories can be estimated by VO even in environments with fewer features. However, because of the VO methodology, the longer the path, the more errors accumulate (Nister et al., 2004), so performance evaluation is required for longer paths. Nevertheless, previous studies have shown that VO has smaller errors than in this study (Cheng et al., 2005). Therefore, we performed a simple additional experiment, (Figures 16 and 17 below).

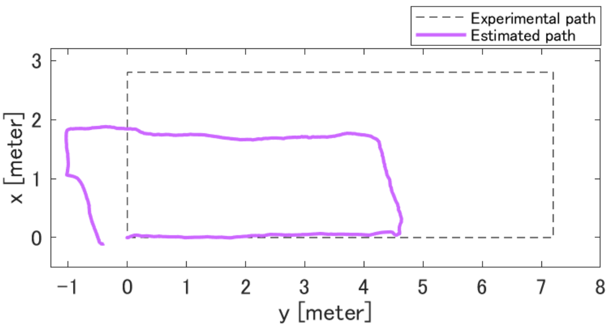

Figure 16. Trajectory estimation result (failed case)

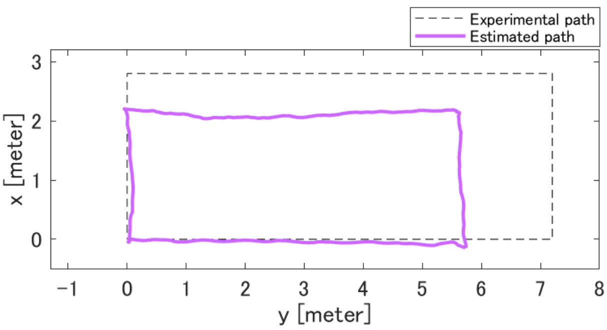

Figure 17. Trajectory estimation result (close to the actual path)

The experiment was conducted with the IMU stereo camera held by hand. Figure 16 shows the results of the experiment for the case in which the IMU stereo camera was intentionally shaken, and Figure 17 shows the results in the case where the IMU stereo camera was kept as still as possible. The estimated results deviate significantly from the actual experimental path (Figure 16), but in Figure 17, although the scale is reduced, the estimated path is close to the actual experimental path. We consider that the vibration of the IMU stereo camera caused blurring in the image, and as a result, the trajectory estimation failed. It was confirmed that the IMU stereo camera was sensitive to vibrations. Therefore, to apply VO to surveying the lunar surface, we believe that equipment should be developed that does not shake the camera, an algorithm should be developed that is not affected by shaking, and the movement speed needs to be slowed. The superiority of VO over LiDAR-SLAM was conclusively confirmed. In addition, LiDAR has excellent ranging accuracy, and the effectiveness of LiDAR in ranging between markers was also confirmed.

5. COMPREHENSIVE CONCLUSION

In this study, we aimed to propose a surveying method based on 3-D point cloud acquisition for groundbreaking surveying in the construction of a lunar base, and we conducted a preliminary experiment and field experiment. To acquire and survey a 3-D point cloud in a non-GNSS environment with few feature points, we conducted experiments on point cloud acquisition by SfM/MVS, point cloud acquisition and position estimation by LiDAR-SLAM, and trajectory estimation by VO. Through these experiments, we confirmed first that overall, 3-D measurement and surveying under the constraints of the lunar surface are difficult. Next, through the SfM/MVS experiment, we confirmed that point clouds of homogeneity can be obtained using a general high-resolution camera or by shortening the image acquisition interval. Finally, through the VO and LiDAR-SLAM experiments, it was confirmed that there are data acquisition challenges in these techniques. However, we consider that VO can be applied to surveying through system improvements. By contrast, we confirmed that LiDAR-SLAM failed in the environment with fewer features, but the LiDAR scanner has an advantage for measuring distances between markers. In future work, we will conduct the development of a rover platform that can be remotely operated and can acquire stable images. A study on marker location methodology is also needed.

ACKNOWLEDGMENTS

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