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Dense 3D mapping based on SfM-MVS using phosphorescent materials in extremely dark environments

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Abstract: This paper describes a novel approach to build a dense three-dimensional (3D) map based on Structure from Motion (SfM) and Multi-View Stereo (MVS) using a general optical camera in extremely dark environments such as the lunar surface and planetary environments. The challenge is to generate a highly visible map that accurately reproduces the geometric structure and color information in a dark environment.To achieve this, we propose a method to generate a geometrically accurate 3D map using the light emitted from a phosphorescent material as a feature point, and then generate a 3D map with improved visibility by pasting a texture image with brightness correction. Experimental results in dark environments demonstrate that our SfM and MVS framework using phosphorescent materials can build a geometrically accurate dense 3D map that includes natural texture information.

Keywords: SfM, MVS, 3D mapping, phosphorescent material

1. INTRODUCTION

In recent years, with the progress of international space exploration programs such as the Artemis program, research and development into the practical application of autonomous mobile robots in harsh space environments has become active. In particular, for long-term manned stays on the moon or Mars, it is necessary to establish exploration techniques in dark environments such as caves and permanent shadows in order to determine the presence of water resources and select habitats [1]. In such harsh environments, it is important for autonomous mobile robots to perform reliable localization and optimal motion planning. To achieve this, it is essential to build a highly accurate three-dimensional (3D) map. LiDAR-based 3D mapping is one of the popular schemes. However, due to its high-power consumption, optical cameras are more widely used in environments such as the moon and planets [2]. Structure from Motion (SfM) and Multi-View Stereo (MVS) are widely used to generate 3D maps from images acquired by optical cameras. SfM is a method that extracts relevant features from multiple images and simultaneously estimates the camera pose and 3D point cloud from their geometric relationships. MVS is a technique that estimates the depth between each image using disparity information based on the camera pose obtained by SfM to estimate a denser 3D point cloud. These techniques can generate high-resolution 3D maps that include color texture information. Including texture information makes it easier to identify rocks and terrain, improving the accuracy of the robot's understanding of the surrounding environment and situation. However, in pitch-black environments, it is difficult to acquire images with high visibility, making it impossible to build maps using SfM or MVS. To improve visibility in such dark environments, robots equipped with artificial light sources to capture high-brightness images can be considered. However, since the lighting angle changes as the robot moves, the target objects become overexposed or underexposed; thus, the reliability of features for matching is reduced [3]. Furthermore, in environments with poor texture and few feature points, such as lunar surfaces and planetary environments, feature extraction and matching become even more difficult due to lighting bias.

In this respect, we focus on phosphorescent materials that are excited by ultraviolet light and spontaneously emit light for a certain period of time, as shown in Fig. 1. Because they do not require complex wiring, they can be easily used as feature points even in environments where it is difficult to supply electricity. Similar research that uses light sources as feature points has used indoor lighting, but as they require complex wiring and a power supply, they are not suitable for the space environment where people cannot directly intervene [4]. To overcome aforementioned issues, this study proposes a framework for constructing a geometrically consistent, highly accurate 3D map by using the emission of phosphorescent materials as feature points. By attaching a texture image with brightness correction, it is possible to accurately reproduce even texture information.

The remainder of this paper is organized as follows.

(a) (b)

Fig. 1: Powder-based phosphorescent materials: (a) phosphorescent materials before emitting light and (b) phosphorescent materials when emitting light.

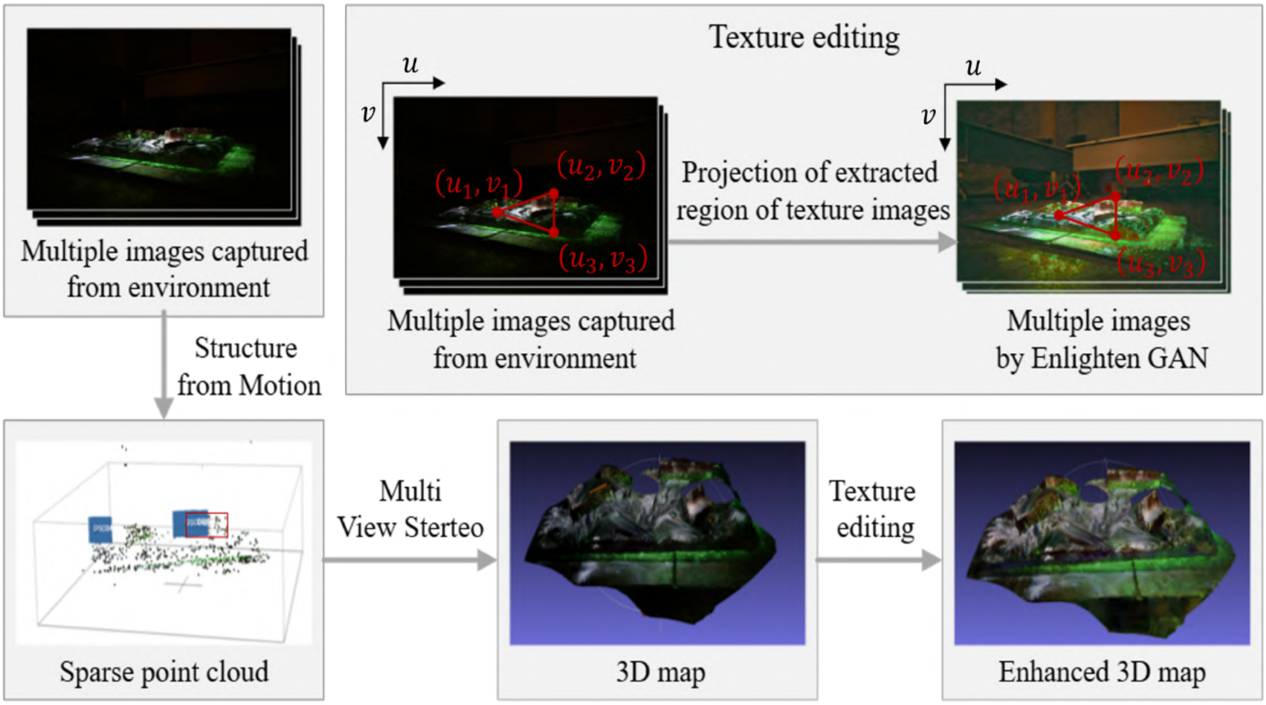


Fig. 2: Overview of proposed dense 3D mapping framework in extremely dark environment.

Section II describes the phosphorescent material utilized in this study to illuminate the environment. Section III introduces the proposed dense 3D mapping framework based on SfM and MVS in dark environments. In Section IV, we evaluate the effectiveness of the proposed framework using experimental results. Finally, Section V presents the conclusions of this paper and future Works.

2. PHOSPHORESCENT MATERIALS

In this study, the phosphorescent material, as shown in Fig. 1, is selected from two aspects: the luminous color of the material and the particle shape. In terms of color, phosphorescent material that emits white light is used as the main material in order to reproduce natural colors when generating the map. In addition, a small amount of green phosphorescent material is mixed in to express differences in brightness and color and improve the accuracy of matching feature points. On the other hand, in terms of particle shape, we choose powdered phosphorescent material to ensure that it would adhere closely to the complex topography, such as unevenness, and slope of the cave.

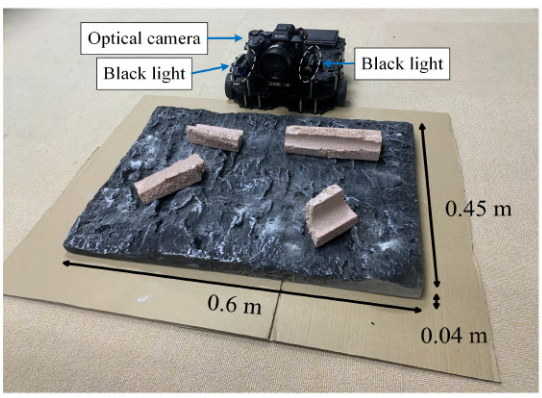
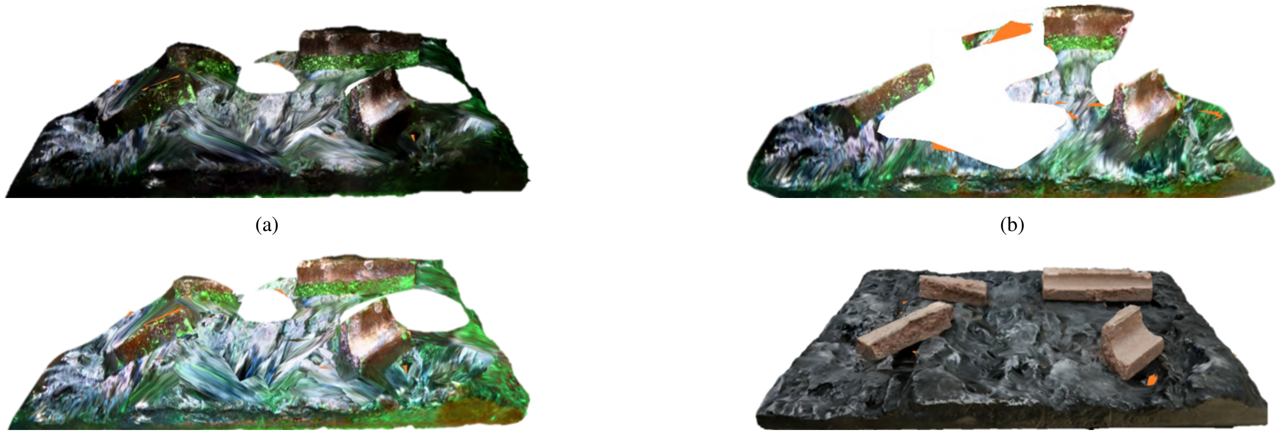


Fig. 3: Experimental environment constructed by cave floor and rocks.

3. DENSE 3D MAPPING

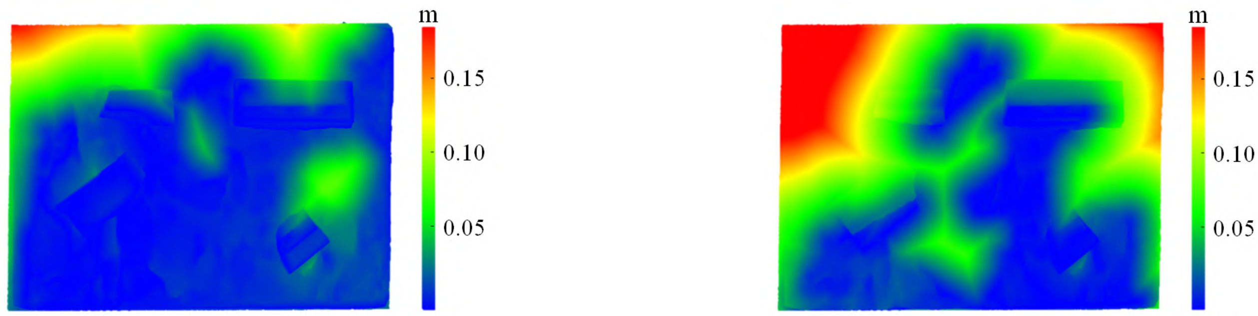
Figure 2 shows an overview of the framework proposed in this study. In a dark environment, phosphors emit light with high localized brightness, making them effective as visual features. However, because the background is dark, it is difficult to see the surface texture or color information of the object. Generally, brightness correction can be used to improve visibility of the entire image; however, if there is a large difference in brightness between the emitting area and the background, or if the image contains very dark areas, the correction process may introduce noise into the image, reducing the ability to extract features [5].

In this study, we propose a novel method to use phosphorescent materials as visual features to build a 3D map using SfM and MVS, pasting a texture image with improved visibility. The 3D map consists of a mesh and a texture image to be pasted on it. The vertices that make up each surface of the mesh correspond to the (u, v) coordinates that indicate the position of the texture image in the original image, which allows the corresponding area in the image to be accurately pasted onto the mesh surface. In the proposed method, Enlighten GAN [6] is used to correct the brightness of the original image, and the corresponding area is extracted from the corrected image based on the (u, v) coordinates that correspond to each



(a) (b) (c) (d)

Fig. 4: Comparison of generated 3D maps: (a) 3D map generated without any special processing, (b) 3D map using conventional method, (c) 3D map using proposed method, and (d) ground truth.



(a) (b)

Fig. 5: Visualization of distance errors on 3D maps: (a) distance error between map generated by the conventional method and the ground truth and (b) distance error between the map generated by the proposed method and the ground truth.

vertex that makes up the mesh, replacing the conventional texture. Enlighten GAN is a deep learning-based image enhancement method that does not rely on paired images and can obtain images with less noise and higher visibility. The corrected texture is accurately pasted onto the corresponding mesh surface since the resolution of the original image and the brightness-corrected image are exactly the same. This makes it possible to build a 3D map with high visibility in low-light environments without changing the 3D shape. In this study, colmap [7] and OpenMVS [8] are used for SfM processing and MVS processing based on SIFT (Scale-Invariant Feature Transform) features [9] since it can achieve stable feature point matching between different viewpoints due to scale and rotation invariance.

4. EXPERIMENT

To verify our 3D mapping framework based on SfM and MVS using phosphorescent materials, an experiment was conducted using the ROBOTIS TURTLEBOT3 mobile robot as shown in Fig. 3. The robot was equipped with an optical camera SONY α7S and Creer black lights. The experiment was conducted in a darkroom, with the windows covered with light-shielding sheets and the lights turned off. Diorama as the environment was built to reproduce the shape of rocks and the terrain to simulate the surface of the moon and a cave on a planet. The size of the ground was $0.45\,\mathrm{m} \times 0.6\,\mathrm{m} \times 0.04\,\mathrm{m}$. The phosphorescent material shown in Fig. 1 was scattered on the environment. Figures 1(a) and (b) respectively show the phosphorescent material before and after emitting light when exposed to ultraviolet light. During the experiment, the robot was moved to each of the viewpoints, and the phosphorescent material was irradiated with ultraviolet light to sufficiently excite it and emit light. After that, the irradiation was stopped so that the ultraviolet light would not interfere with the optical camera, and images were captured. A total of 23 images were captured from various viewpoints under the following conditions: 5 s shutter speed, 1000 ISO sensitivity, and 2.4 aperture value.

3D maps were generated from the captured images under the following four conditions and compared for evaluation. In the first condition, the map was generated by SfM and MVS without any special processing. In the second condition, a map was generated using a conventional method that directly applies image correction by Enlighten GAN to each captured image taken with an optical camera. The Enlighten GAN model was trained on a dataset of about 2,000 unpaired images, including the LOL (LOw-Light) dataset [10] and HDR images. In the third condition, the map was generated using the proposed method of pasting a texture image with brightness correction onto the map generated under the first condition. In the fourth condition, a map was generated from high-quality images taken in a bright environment as an ground truth data. All the generated maps are scaled to match the actual scale of the diorama. Figure 4 shows the maps generated under the four conditions. Compared to the map generated without any special processing shown in Fig. 4(a), the maps generated by the conventional method and the proposed method in Figs. 4(b) and (c) appear greenish overall due to the influence of the phosphorescent material, but the brightness has been improved, and the colors of the rocks have been accurately reproduced. Figure 5 shows the results of calculating the shortest Euclidean distance to the mesh surface generated by the proposed method and the conventional method for each vertex of the ground truth, and visualizing the distance distribution as a color map. The color maps represent the magnitude of the distance error, with areas with small errors displayed in blue to green and areas with large errors displayed in yellow to red. Figures 5(a) and (b) demonstrate that the proposed method suppresses missing areas compared to the conventional method. We also calculated the RMS (Root Mean Square), which is an average index of distance error. While the conventional method has an RMS value of 5.8 mm, the proposed method has an RMS value of 6.6 mm, both indicating low error values. This shows that both methods can generate maps that accurately reproduce geometric structures in the reconstructed regions. Consequently, the proposed method can generate highly visible maps that accurately reproduce the geometric structure and color information with few missing areas even in very dark environments.

5. CONCLUSIONS

In this study, we focused on the difficult task of building a highly accurate 3D map that precisely reproduces geometric structures and color information at the same time in an extremely dark environment. To solve this problem, we proposed a new SfM and MVS framework using phosphorescent materials. The proposed method generated a highly visible map that accurately reproduces not only the shape of the object but also its color information.

However, since it does not completely restore the entire structure, it will be necessary to design a new feature descriptor specialized for the luminescence characteristics of phosphorescent materials in the future. In addition, phosphorescent materials need to be irradiated with ultraviolet light every time a photograph is taken in our approach. Therefore, we aim to realize SfM and MVS that can generate highly accurate 3D maps with low power consumption by designing features that are not dependent on the attenuation of the luminescence intensity of phosphorescent materials as the future work.

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