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6-DoF SLAM in extremely dark environments considering the luminescent properties of phosphorescent materials

Shunsei Takarabe[1] and Yonghoon Ji[1]

Abstract— **This paper deals with 6-DOF (six-degrees of freedom) SLAM (simultaneous localization and mapping) using general optical cameras in extremely dark environments, assuming lunar and planetary environments. One of the challenging points is to obtain traceable features in dark environments. To cope with such problems, we propose a new landmark design using phosphorescent materials that emit light without using any power source and its recognition method. We demonstrated that the performance of 6-DOF SLAM can be improved by our new SLAM framework with new landmark information in an uneven terrain where the odometry of a mobile robot is inaccurate.**

I. INTRODUCTION

It is impossible for humans to directly explore harsh environments such as the moon and planets, where radiation levels are high and temperature differences are large. Therefore, introducing unmanned mobile robots is important to identify habitable areas and the presence of water in extremely dark environments such as shadows and caves [1]. In general, accurate localization and map building processes are essential for autonomous unmanned mobile robots in such environments. To this end, it is necessary to observe the surrounding environment with sensors mounted on the robot and obtain enough feature points that can be tracked. LiDAR sensor, which directly acquires dense 3D point clouds, is not generally used in environments where available power is limited, such as lunar and planetary environments [2]. The image data obtained from a thermal camera has low resolution, and it is difficult to effectively track image features in environments without thermal texture [3]. Therefore, image data acquired from an optical camera are mainly used in space environments. Gamma correction and generative adversarial network (GAN) can be used as techniques to convert images acquired by an optical camera to brighter images [4]. However, the absence of light sources in dark environments makes it difficult to acquire images with high visibility and limits the tracking of feature points in image data. For these reasons, robots equipped with headlights can be utilized [5]. However, although the use of headlights makes it possible to acquire feature points even in extremely dark environments, there are several problems. First, because the illumination range is limited, a portion of the field of view is not sufficiently illuminated, reducing the number of feature points that can be tracked. Also, depending on the position of the robot, the amount of light around it may be uneven, resulting in images with low visibility. One solution to this problem is to place LED lights around the robot to provide bright, even illumination [6]. This approach not only acquires feature points from highly visible image information from an optical camera but also recognizes the LED lighting itself as a landmark, which is a feature point, making it possible to estimate robot pose with high accuracy. However, challenges remain, as available electricity is limited and installation is difficult. In this respect, we focus on phosphorescent materials that emit light without using any power source. Phosphorescent materials are materials that absorb ultraviolet rays and emit light for a certain period. They are used to guide evacuations during power outages because they ensure visibility and serve as landmarks to indicate the direction of evacuation routes [7]. To the best of our knowledge, there is no precedent for applying phosphorescent materials to the operation of autonomous mobile robots so far. Therefore, in this study, we propose a novel landmark-based SLAM framework that uses phosphorescent materials as light emitters to estimate the 6-DOF robot pose with high accuracy. Landmark-based SLAM is known as a methodology that can estimate robot pose by recognizing landmark information which is easy to distinguish from others. To realize the Landmark-based SLAM, new landmarks that use phosphorescent materials are designed to recognize them even in dark environments. However, although phosphors emit light for a certain period, the intensity of the emitted light decreases over time. Moreover, we need to address the limitation of recognition difficulties due to image noise. Thus, we also propose a novel image recognition scheme that takes into account the luminescent properties of phosphorescent materials.

The remainder of this paper is organized as follows. Section II presents the overall structure of the proposed framework for 6-DoF SLAM in extremely dark environments with graph optimization. Section III describes our new design of the landmark using phosphorescent materials. Section IV introduces an image processing scheme to recognize the landmark, even though the images have a lot of noise due to the dark environment. The effectiveness of the proposed framework is evaluated with the experimental results in Section V. Finally, Section VI presents the conclusions of this paper and future work.

II. SYSTEM OVERVIEW

Figure 1 shows an overview of the framework proposed in this study. Conventional approaches usually estimate the robot trajectory based on an extended Kalman filter (EKF) by integrating wheel odometry and IMU information [8].

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[1] Graduate School for Advanced Science and Technology, Japan Advanced Institute of Science and Technology, 1-1 Asahidai, Nomi, Ishikawa, Japan (e-mail: {s2310091, ji-y}@jaist.ac.jp).

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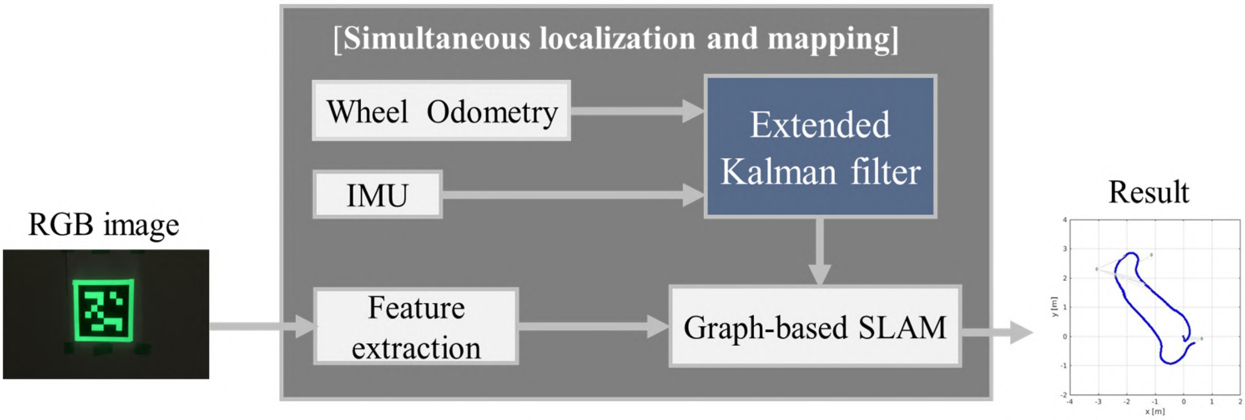

Fig. 1: System overview.

However, such approaches are prone to accumulating posture errors. To correct such errors in this study, landmarks made by phosphorescent materials are recognized from RGB images captured by an optical camera, and the distance and direction between the camera and the landmark are measured as features. All the information described above are applied to Graph-based SLAM [9] to estimate the trajectory with high accuracy.

III. LANDMARK DESIGN USING PHOSPHORESCENT MATERIALS

AprilTag [10] is widely used to measure relative position and distance; however, it is difficult to recognize in environments with poor lighting. In this study, we propose a new landmark design that enables AprilTag recognition even in dark environments. As shown in Fig. 2, the AprilTag has a design in which phosphorescent tape is pasted on the white part and a black pattern is placed around it. The phosphorescent tape suppresses unnecessary light reflection when emitting light and achieves clear contrast. LED lighting or sunlight is commonly used to make phosphorescent materials emit light. On the other hand, this study uses a special type of lighting called black light that emits 365 nm ultraviolet light, as shown in Fig. 3. This is because the excitation wavelength of the phosphorescent material matches the wavelength emitted by black light, allowing it to emit a longer and brighter light. Additionally, the light emitted from the black light does not overlap with the 400 nm to 700 nm perceptual range captured by optical cameras based on visible light, minimizing interference with image acquisition. This prevents overexposure and underexposure caused by the lighting installed on the robot, making it possible to obtain stable images. this study uses a phosphorescent material that emits green light given that optical cameras are generally more sensitive to green. Thus, landmarks can be recognized with high accuracy even when the light emitted from phosphorescent materials is attenuated.

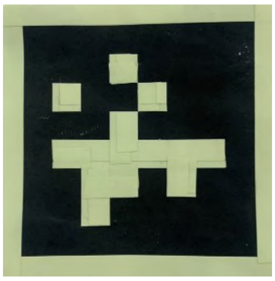

Fig. 2: Landmark design using phosphorescent materials.

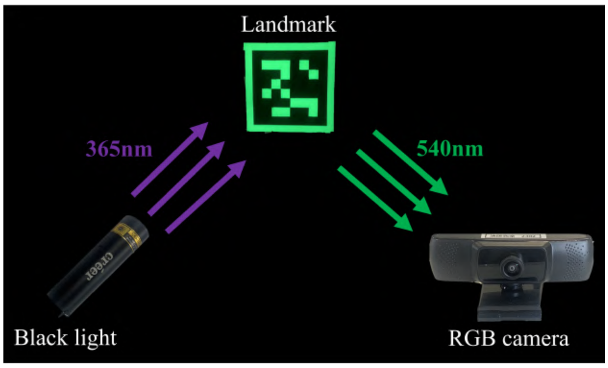

Fig. 3: Landmark illumination using ultraviolet light.

IV. LANDMARK RECOGNITION

Landmarks made of phosphorescent materials can be recognized by irradiating them with ultraviolet light; however, after irradiation, the landmarks may become unrecognizable for a certain period. This is because differences in the amount of light absorbed occur due to the uneven distribution of the phosphorescent material and unevenness in the intensity of ultraviolet irradiation, resulting in roughness due to differences in brightness values when the luminous intensity is attenuated. Adaptive Thresholding during binarization can reduce such noises to improve tag recognition accuracy [11]. However, it is not possible to completely eliminate noise caused by the emission characteristics of phosphors. There-

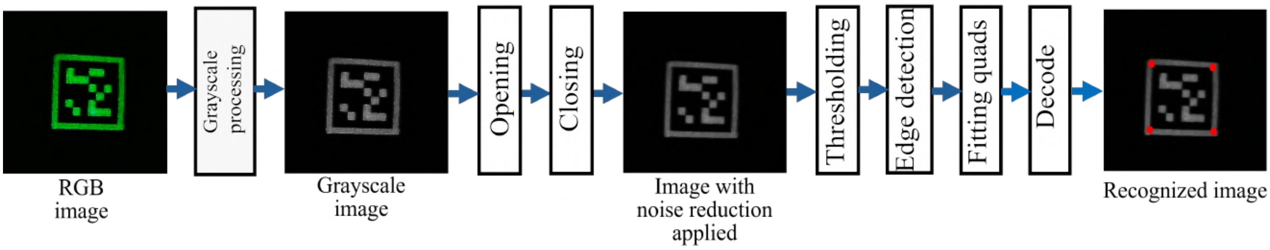

Fig. 4: Procedures for recognizing landmarks using phosphorescent materials.

fore, we suggest another approach that applies the opening and closing process as shown in Fig. 4. First, an RGB image is converted to a grayscale image. Then, we apply the opening process to remove fine noise with high brightness values and emphasize the contours of landmarks. Next, by performing a closing process to remove black roughness, a smooth image can be obtained without distorting the landmark's unique pattern. After binarization is performed, edge detection is carried out to extract the rectangular contours of the landmarks. Finally, homography transformation is performed using the four corners of the detected landmark to correct the distortion of the tag. The distance and direction from the camera to the landmark can be estimated using the corrected coordinates of the four corners of the tag, the known tag size, and the intrinsic parameters of the camera lens. Each ID information is acquired by tag identification.

V. EXPERIMENT

A. *Landmark Recognition*

In order to verify the recognition performance for the landmarks made by phosphorescent materials, we conducted an experiment using Sanwa Supply CMS-V43BK shown in Fig. 5 as an optical camera In a dark room environment with the windows covered with light-shielding sheets and the lights turned off. As shown in Fig. 6, we conducted experiments by changing the orientation relationship between the landmark and the camera from 0 deg to 45 deg, and the distance from 0.5 m to 1 m. After irradiation with light, we captured continuous 300 images at 0.5 fps. Table I shows comparison results of the landmark recognition rate. When the distance between the camera and the landmark is close, the recognition rate is dramatically improved compared with a conventional approach without any image processing.

Fig. 5: Optical camera, Sanwa Supply CMS-V43BK.

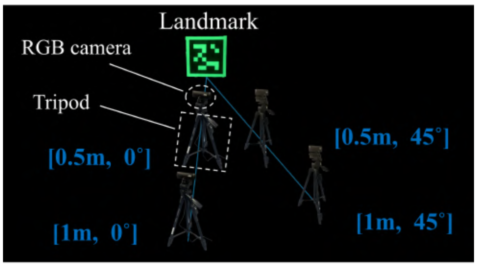

Fig. 6: Experimental conditions for landmark recognition.

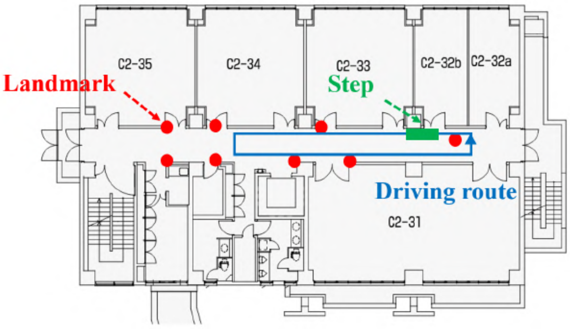

Fig. 7: Blueprint of experimental environment.

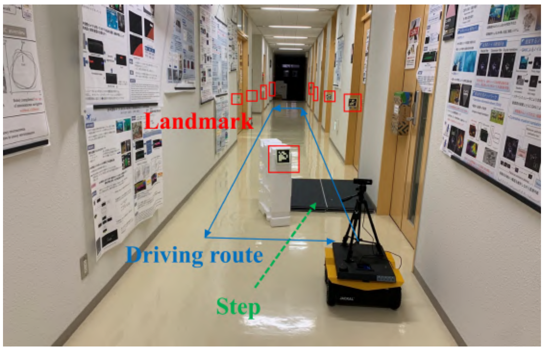

Fig. 8: Experimental environment with lights on. The actual experiment was conducted with all lights off to reproduce an extremely dark environment.

TABLE I: Landmark recognition rate.

(Distance, Angle)	Proposed approach	Conventional approach
(0.5m, 0°)	82%	72%
(0.5m, 45°)	68%	55%
(1m, 0°)	12%	13%
(1m, 45°)	4%	4%

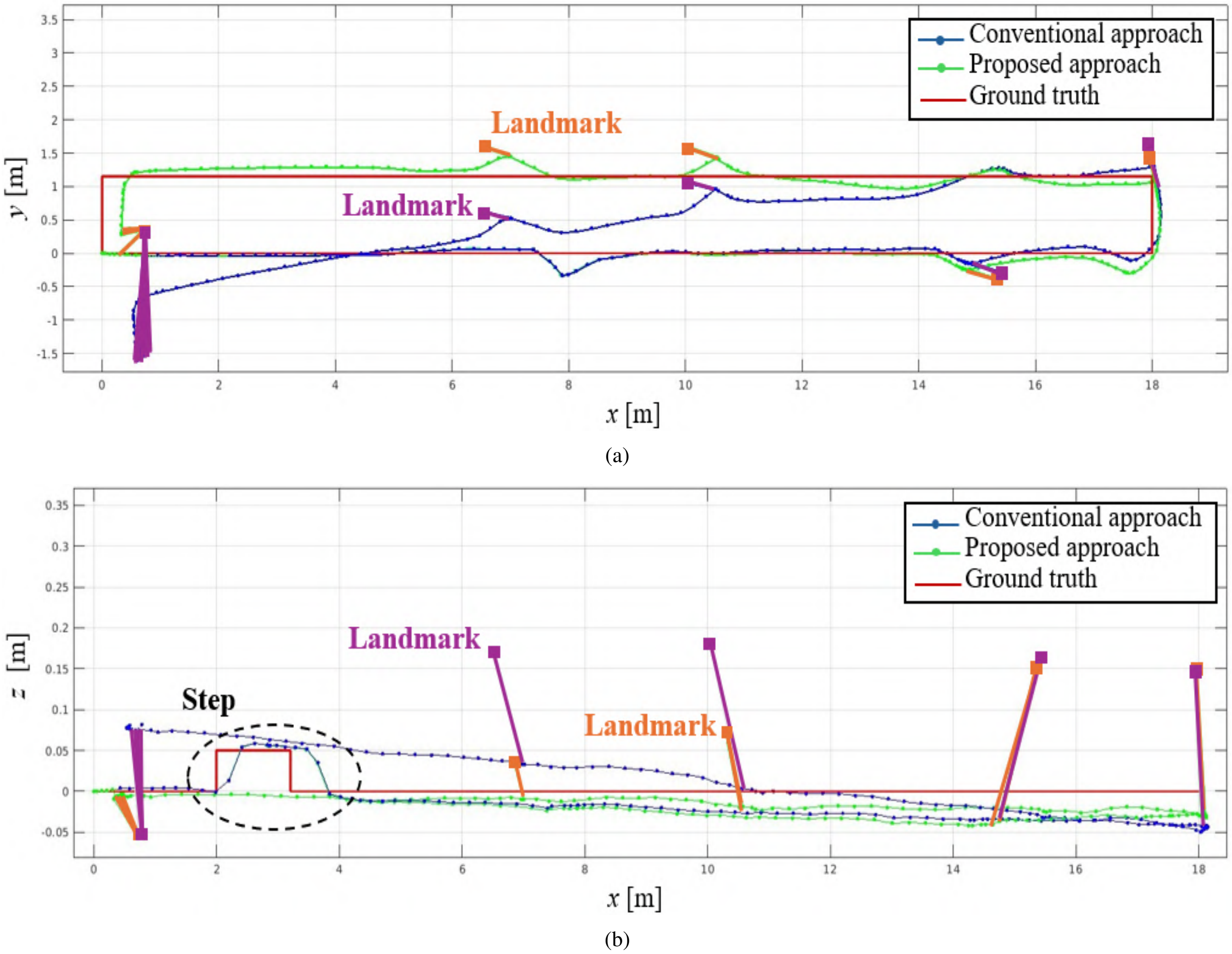

Fig. 9: Comparison of estimated trajectories: (a) trajectory on *x*-*y* axis and (b) trajectory on *x*-*z* axis.

B. 6-DoF SLAM

To verify our landmark-based SLAM using phosphorescent materials, we conducted an experiment using the CLEARPATH mobile robot JACKAL equipped with the optical camera shown in Fig. 5. Figures 7 and 8 show the blueprint and condition with the lights of the experimental environment, respectively. An experiment was conducted at night with the lights dimmed, and a step 90 cm wide, 120 cm long, and 6 cm high was installed to reproduce unevenness. The size of the landmark used is 11 cm in width and height. Before the robot moves, all landmarks are illuminated with ultraviolet light, making them glow. After that, the robot was navigated at a speed of approximately 0.5 m/s. Odometry and IMU information was acquired in every 500 ms. The camera frame rate was 2 fps. The proposed landmark recognition approach was applied to the acquired images. In the experiment, two conditions were set and compared. In the first condition, The robot trajectory was estimated using a conventional approach that uses an EKF to integrate wheel odometry and IMU information. In the second condition, the robot trajectory was estimated using the proposed approach, which applies graph-based SLAM to the trajectory and landmark measurement information obtained by the conventional approach. The trajectory and ground truth under these conditions are shown in Fig. 9. Here, the initial orientation of the robot was set according to the driving direction by the early odometry. As shown in Fig. 9(a), the proposed approach follows a trajectory close to the ground truth. On the other hand, the trajectory obtained by the conventional approach has a discrepancy between the start and end points, does not form a closed path, and has a large error. As shown in Fig. 9(b), the conventional approach draws an upward trajectory excluding the step, even though the passage is flat. However, with the proposed approach, the start point and the end point are almost the same, and the estimated height (*z* axis) remains almost 0 m. This shows that our proposed approach which uses phosphorescent materials as landmarks can estimate a more accurate trajectory compared to the conventional approach.

VI. CONCLUSIONS

In this study, to deal with a dark environment where it is difficult to track features in image data, we proposed a novel landmark-based SLAM framework that uses phosphorescent materials as emitters. The proposed method improved the landmark recognition rate and accurately estimated the 6-DOF pose of the robot. In the future, it will be necessary to improve the performance of image processing because the recognition accuracy decreases significantly as the distance from the camera to the landmark increases. Furthermore, since the luminous intensity and luminescence time of phosphorescent materials can be controlled depending on the chemical design of the material, we will define a new evaluation function for SLAM taking such physical characteristics into account to improve the accuracy of 6-DoF pose estimation even in more extreme environments.

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