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Measurement range expansion of a range image sensor using a multi-slit laser projector

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Abstract— **This paper proposes a method for expanding the measurement range of a range image sensor using a multi-slit laser projector. In the conventional method, the measurement range is 360–800 mm. In order to extend the measurement range, it is necessary to solve the correspondence problem. The measurement range is expanded using blur when the camera is not in focus. The effectiveness of the proposed sensor is verified through distance measurement experiments.**

I. Introduction

In recent years, rescue activities and investigations at disaster sites by autonomous mobile robots have become expected. For autonomous mobile robots to operate efficiently, it is necessary to understand the surrounding environment, and one of the sensors used there is a range image sensor. Among the range image sensors, the active stereo method can measure distances even in environments without textures. Because of their high practicality, many studies have been conducted [1], [2]. Moreover, several products have been commercialized such as Kinect.

We have been performing obstacle avoidance for humanoid robots [3] and texture mapping of range images [4] and 3D map generation by overlaying range images [5] with a range image sensor using a multi-slit laser projector. However, to avoid the correspondence problem, the measurement range had to be limited. In these papers, this problem was relaxed by rotating the CCD camera [6]. Aiming to further alleviate this problem, Feng et al. used two measurement methods, disparity and blur, to expand the measurement range [7]. They measured by using blur at short distance and disparity at long distance. However, the two methods had to be switched manually, and short distance and long distance simultaneously could not be obtained from the same image. So it was not practical.

In this paper, we expand the measurement range by mitigating the corresponding point problem by using blur as a supplement to the measurement method using disparity, and obtain the short distance and long distance from the same image. The accuracy and effectiveness are examined through experiments.

The remainder of this paper is as follows. Section II describes the range image sensor. Section III describes a method for measuring distance. Section IV presents our proposed method for expanding the measurement range. Section V shows the experiments we conducted. Finally. Section VI is the conclusion.

II. Constructed Sensor

In this section, we show the range image sensor that we constructed and used for experiments. The appearance of the range image sensor is shown in Fig. 1. This sensor consists of a monochrome CCD camera with a low pass filter attached to the tip of the lens and a laser projector that projects multi-slit lights. The camera is a Point Grey Research Blackfly S, whose number of pixels is 1280 × 1024. In addition, the Kenko R64 is used as a low pass filter, which blocks light with a wavelength of less than 640 nm. The laser projector is the COHERENT MINI-715L-690-35. The wavelength is 690 nm, and the output power is 35 mW. Fifteen slit lights are projected, and the angle between the slits is 2.3°. In addition, Fig. 2 shows acquired images of the monochrome camera at (a) a short distance (260 mm), and (b) a long distance (800 mm). In this sensor, the slit image is formed to the left as the distance is shorter and to the right as the distance is longer.

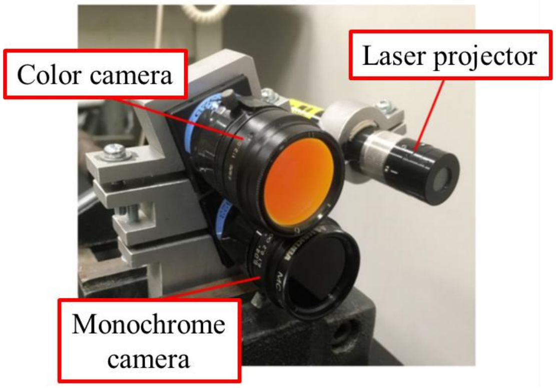
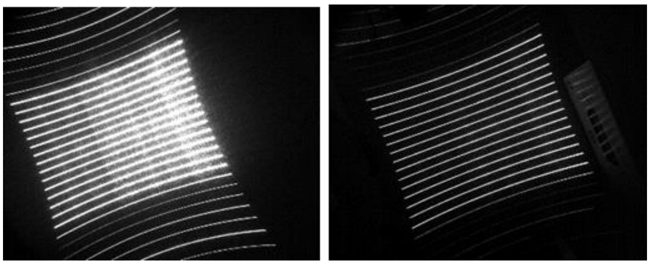


Figure 1. Constructed sensor.



(a) At a short distance. (b) At a long distance.

Figure 2. Acquired image.

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III. Distance Measurement Method

In this section, we describe a method for measuring distance using the sensor. This sensor calculates the distance between the position of the slit image formed on a monochrome camera image and the position assuming infinity and calculates the distance by the principle of triangulation. Fig. 3 shows a simple triangulation model. We define the baseline length as b mm, the lens focal length as f mm, the pixel width as p mm/pixel, the position of the slit image on the image plane as the u pixel, and the position to be imaged when reflected from infinity as the u_∞ pixel. The distance value Z mm to the object can be expressed as follows:

$$Z = \frac{b \cdot f}{p \cdot (u - u_\infty)} \equiv \frac{\alpha}{u - u_\infty} \qquad (1)$$

where α and u_∞ are determined in advance for each slit image using the least squares method from 55 known distances (10 mm intervals for 260–800 mm).

In this sensor, the correspondence problem occurs; as there are multiple slits, it is necessary to obtain the correspondence between projected slits and their observed images. Previous studies [3], [4], [5] took limiting measurement range so that the correspondences become unique. They rotated the CCD camera to increase the measurement range [6]. Fig. 4 (a) illustrates the image of slits without rotating the camera. In the image plane, each point on each slit moves along the epipolar line according to the distance. In order to achieve the uniqueness of the correspondence, movable ranges of slits in the image have to be restricted so that they have no overlap as shown in Fig. 4(a). This limit can be relaxed by rotating the CCD camera. Fig. 4(b) illustrates the image of slits with the rotation and shows that the movable ranges of slits become larger. Consequently, the measurable range of the sensor becomes larger. When the rotation angle is θ, the movable range of a slit becomes $1/\cos\theta$ times. In this paper, θ is about 70°.

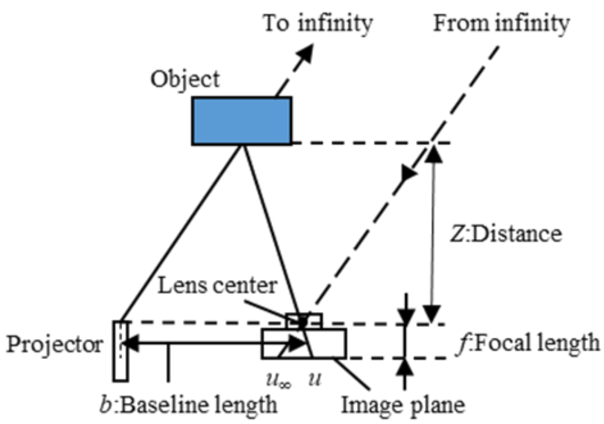
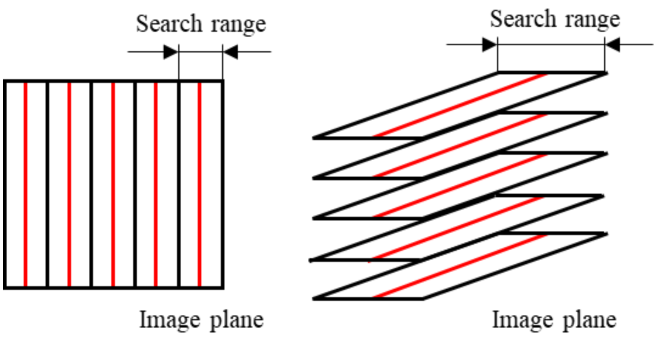


Figure 3. Simple triangulation model.



(a) Without rotation. (b) With rotation.

Figure 4. Restriction for epipolar line of each slit.

IV. Expansion of the Measurement Range

In this section, we propose a method for expanding the measurement range. In Section III, it was mentioned that the imaging position of the slit image is needed for measuring distance. In the previous method [3], [4], [5] using disparity, in order to obtain the imaging position, the position where the slit image is formed at the middle of the disparity is set as the reference position, and the imaging position of the slit image is obtained in the left and right search range from the reference position. If the intensity value is defined as D_i, and its u coordinate is u_i, the imaging position u_g can be calculated as follows:

$$u_g = \frac{\sum_{i=1}^{n}(u_i \cdot D_i)}{\sum_{i=1}^{n} D_i}. \qquad (2)$$

Fig. 5 shows the search range of two slits in the previous method. The correspondence problem is avoided by making one slit image exist in the search range. Therefore, the search range is limited, and in previous studies [3], [4], [5] the measurement range was set to 360–800 mm. In this paper, propose to relax the correspondence problem by using blur when the camera is not in focus. As a result, even if there are two slit images in the search range, the imaging position in one slit image can be calculated. With the proposed method, the measurement range can be expanded to 260–800 mm. Fig. 6 shows a blur of the image at different distances. Fig. 6 (a) shows that the image becomes larger if the distance is shorter than the focused distance. Fig. 6 (b) shows that the image is smallest if the distance is the focused distance. Fig. 6 (c)

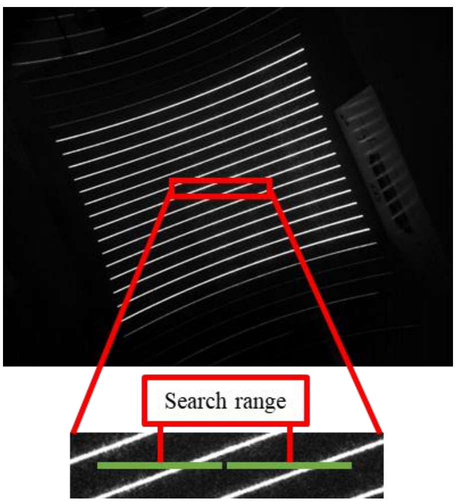
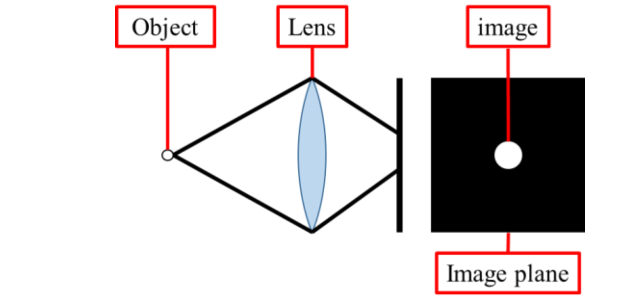
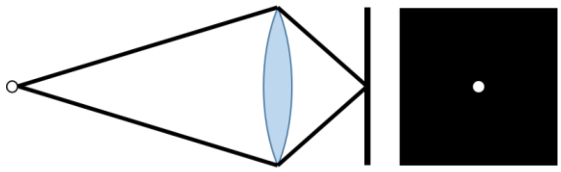


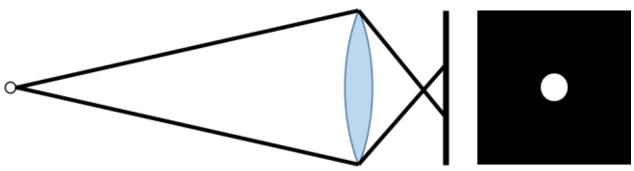
Figure 5. Search range of the conventional method.



(a) Shorter than the focused distance.



(b) Focused distance.



(c) Longer than the focused distance.

Figure 6. Relationship between distance and focusing.

shows that the image becomes larger if the distance is longer than the focused distance. Thus, as the distance becomes shorter or longer than the focused distance, the image becomes larger than the image of the focused distance [8].

In this paper, we demonstrate that the slit image becomes smaller as the distance increases by setting the focused distance to the maximum measurement range (800 mm). Fig. 7 shows the relationship between distance and the number of pixels exceeding the threshold of intensity (180) at a measurement point. It can be seen that the number of pixels exceeding the threshold decreases as the distance increases.

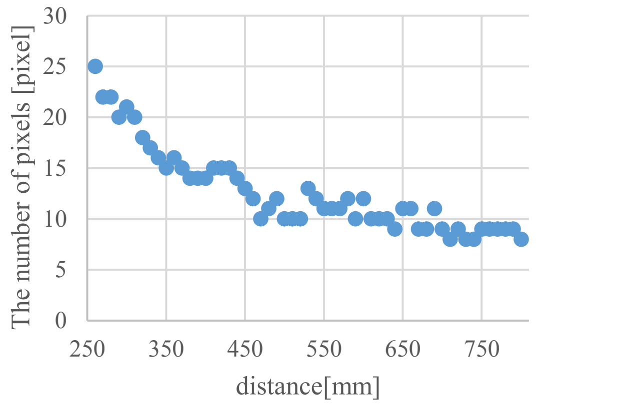


Figure 7. Relationship between distance and the number of pixels exceeding the threshold.

Using number of pixels that exceed the threshold, it is possible to discriminate between slit images when there are two slit images within the search range. Fig. 8 shows the flow of search range identification. The number of pixels exceeding the threshold at the reference position is acquired in advance. When calculating the imaging position, the number of pixels that are equal to or greater than the threshold of intensity in the left and right of the search range is found. If the number of pixels exceeding the threshold of intensity in the left search range is greater than the number at the reference position, the imaging position is calculated only in the left search range (case 1) because this sensor forms a slit image on the left and the number of pixels above the threshold of intensity becomes greater as the distance is shorter. Fig. 9(a) shows case 1. If case 1 is not satisfied and the number of pixels exceeding the threshold of intensity in the right search range smaller than the number at the reference position, the imaging position is calculated only in the right search range (case 2) because this sensor forms a slit image on the right and the number of pixels above the threshold of intensity becomes smaller as the distance is longer. Fig. 9(b) shows case 2. If neither case 1 nor 2 are satisfied, it is determined that there is no imaging position because of occlusion, etc. (case 3).

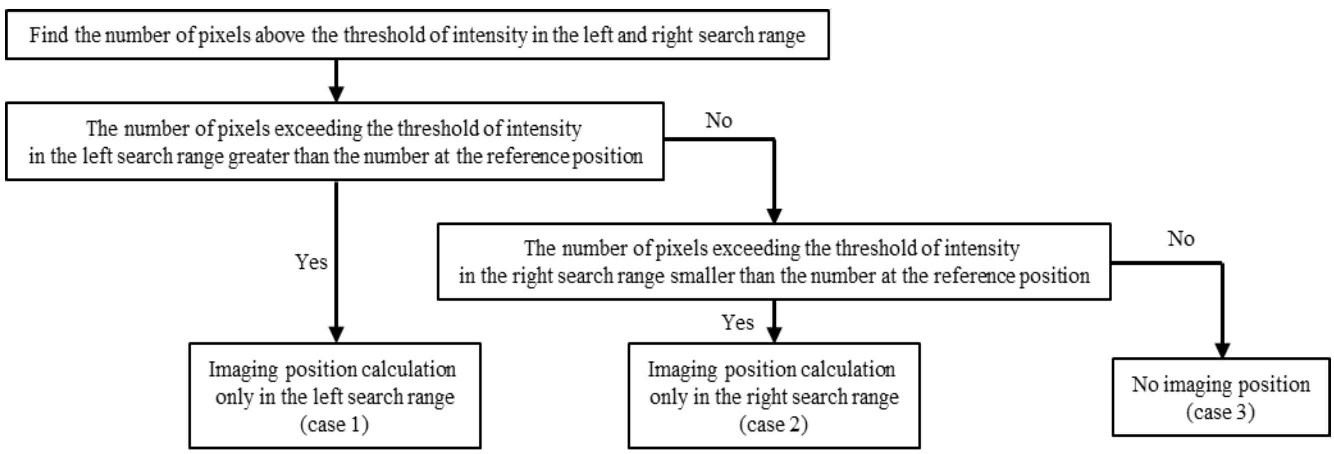
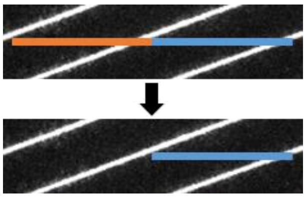


Figure 8. Flow of search range identification.

(a) case 1



(b) case 2

Figure 9. Search range of the proposed method discriminated by the number of pixels.

V. Experiments

In this section, we verify the proposed method by experiment.

A. Verification of distance measurement accuracy

To confirm the measurement accuracy of this method, we verified the accuracy of the distance measurement. A wooden board was used for measurement. The measurement was performed by changing the distance to the object to 260 mm and 300 mm and, thereafter, at 50 mm intervals up to 800 mm. Two points were used to obtain the distance value: the v-coordinate 509 pixel point (Point 1) of the 8th slit from the top at the center of the image, and the v-coordinate 123 pixel point (Point 2) of the 1st slit from the top in the periphery of the image. Fig. 10 shows the positions of Points 1 and 2. Measurements were taken five times at each distance. Table 1 shows the mean and standard deviation of five measurements at each distance at Points 1 and 2. Since

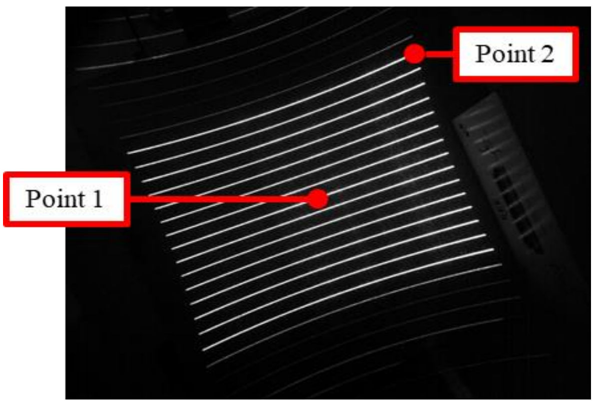


Figure 10. The positions of Points 1 and 2.

measurement results close to the true value were obtained and the standard deviation was small, it is considered that the measurement was highly accurate. At Point 1, the standard deviation increases after 700 mm. In the method using the principle of triangulation like this sensor, it is considered that the uncertainty of the measured distance increases in proportion to the square of the distance.

TABLE I. Measurement Results (unit: [mm])

True value	**Point 1**		**Point 2**	
	Mean	*Standard deviation*	*Mean*	*Standard deviation*
260	263.8	0.6647	262.4	0.1199
300	303.5	1.455	303.9	0.8889
350	351.9	0.02862	349.5	0.6890
400	392.2	1.784	397.5	1.101
450	451.9	0.8743	442.7	0.1417
500	502.0	0.2667	489.2	1.338
550	549.4	2.803	540.7	1.517
600	603.6	0.08515	596.1	0.1487
650	644.8	0.07863	645.8	0.03696
700	700.1	2.551	695.1	0.2611
750	755.0	2.038	753.5	2.960
800	802.7	2.748	808.8	0.2296

B. Measurement of objects with different distance values

In order to confirm the effectiveness of this method, we conducted measurement experiments on objects at different distances. Measurements were taken with wooden boards placed at a minimum distance of 260 mm and a maximum distance of 800 mm within the measurement range. Fig. 11 shows the experimental environment, Fig. 12 shows the acquired image, and Fig. 13 shows the range image. Although intensities are vastly different between short and long distances as shown in Fig.12, it can be seen that accurate measurement is possible at most points.

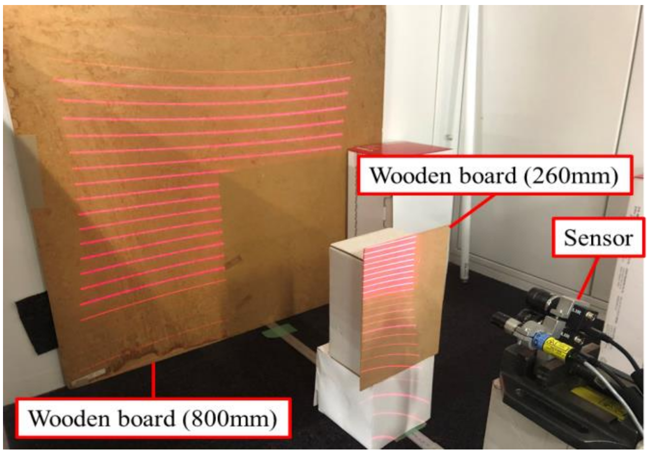


Figure 11. Experiment environment.

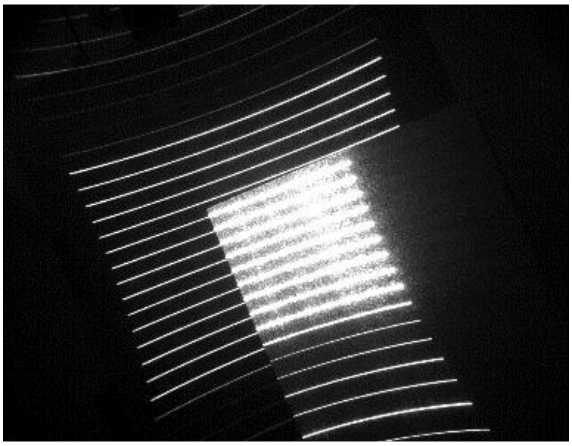
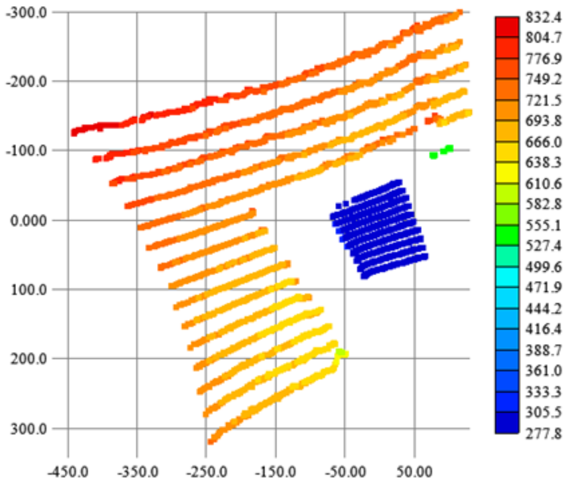
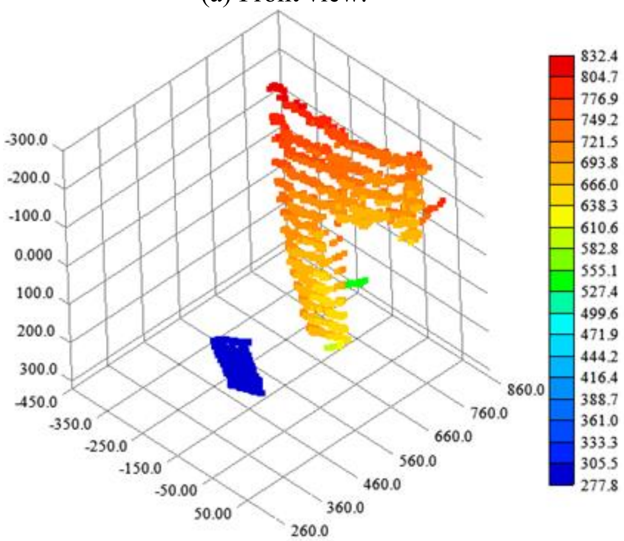


Figure 12. Acquired image.



(a) Front view.



(b) Side view.

Figure 13. Range image when measuring objects with different distance values.

VI. ONCLUSION

In the range image sensor using a multi-slit laser projector, the correspondence problem was solved by using blur when the camera is not in focus, and the measurement range of the sensor was expanded. The distance measurement experiment showed the measurement accuracy and effectiveness of the constructed range image sensor. As a future work, we will apply the proposed method to a smaller range image sensor and aim to construct a practical sensor for robot mounting.

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