3-D MEASUREMENT OF OBJECTS IN WATER USING FISH-EYE STEREO CAMERA

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ABSTRACT

In this paper, we propose a 3-D measurement method of underwater objects using a fish-eye stereo camera. Sensing in aquatic environments is important to maintain underwater structures and research aquatic lives. A 3-D measurement method of objects in water using a fish-eye stereo camera enables underwater robots to execute its task safely with a wide field of view. However, images taken by fish-eye camera have large distortion following projection model. Also, sensing in aquatic environments meets the difficulty that image distortion occurs by refraction of light due to the difference of refractive indices of air, watertight container and water. As to these problems, we introduce a method to correct fish-eye image and a ray tracing method to remove the effect of refraction. Experimental results show the effectiveness of the proposed method.

Index Terms— Fish-eye Camera, Stereo Measurement, Underwater Sensing

1. INTRODUCTION

In recent years, demands for underwater tasks, such as excavating of ocean bottom resources, exploration of aquatic environments, and inspection of underwater structures, have increased. However, it is dangerous to execute these tasks by human in many cases. Therefore, underwater sensing systems [1] that work instead of human become important.

There are several studies about 3-D measurement in water. Acoustical methods using sonar are often used especially for underwater robot sensors [2, 3]. These methods can measure a rough shape of the sea floor and detect the existence of a shoal of fish. However, they do not give high resolution due to relatively longer wavelength of ultrasonic waves than that of the light, and are not suitable for 3-D measurement of objects at a short distance with high accuracy.

Photographic 3-D measurement methods have the advantage that it is possible to measure objects at a short distance with high accuracy. However, measurement of objects in water by these methods have a problem of light refraction.

Figure 1 shows an example of refraction effect. It is an image of a dolphin model half dipped in water, seen from outside a water tank. The contour of the model looks discontinuous at the water surface, and the size and shape also look different between above and below the surface. The problem of refraction occurs not only when a vision sensor is set outside the water tank but also when it is used for underwater sensing, because in the latter case we usually make a discontinuity of refractive index by placing a protecting glass plate in front of a viewing lens. Strictly speaking, a ray is refracted at the boundary between air and glass and also at the boundary between glass and water. Therefore, it is essential for accurate 3-D measurement methods of objects in liquid to consider light refraction [4].

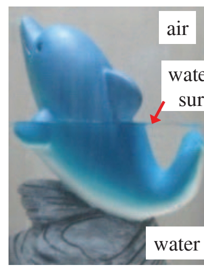

Fig. 1. Light refraction effect.

Fig. 2. Fish-eye stereo camera.

3-D measurement methods of objects in liquid based on light projection considering the refraction effects are proposed [5–7]. However, these methods take time because of repetition of light projection. Therefore, it is difficult to measure moving objects by these methods.

On the other hand, a stereo camera system is suitable for measuring moving objects [8]. However, a field which can be taken at a time is narrow because a camera has a narrow field of view. In case of measuring big objects, the number of photos becomes large. Therefore, methods using camera which has a wide field of view have been proposed.

There is a study about the 3-D measurement in water using an omni-directional stereo camera [9]. However, an omni-directional camera can not observe objects in front of the camera. Therefore, we propose a method using a fish-eye camera which can observe wide field in front of the camera (Fig. 2). When a fish-eye camera is used for stereo measurement, detecting the corresponding points of two images becomes difficult. This is because a fish-eye image has large distortion. Therefore, it is necessary to correct a fish-eye image.

In this paper, we propose a 3-D measurement method of objects in water using a fish-eye stereo camera.

2. MEASUREMENT METHOD

Fish-eye images have large distortion according to a projection model of fish-eye lens. In this work, we use fish-eye lens which has equidistant projection.

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(a) Acquired image (b) Corrected image

Fig. 3. Correction of distortion.

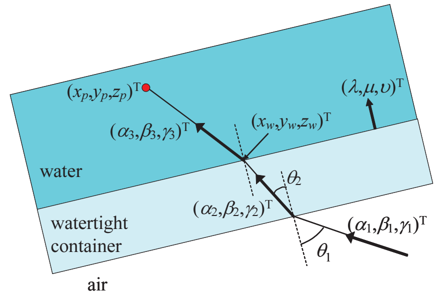


Fig. 4. Ray tracing.

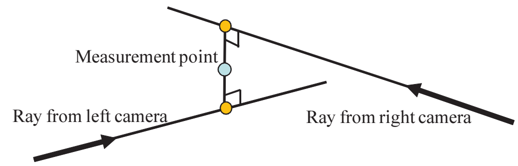


Fig. 5. Measurement point.

First, a stereo image pair is acquired by left and right fish-eye cameras. Next, fish-eye images are converted to perspective projection images. After detecting the corresponding points of the left and right images by template matching, 3-D points are calculated by ray tracing.

2.1. Correction of Fish-eye Image

It is difficult to detect corresponding points between fish-eye images by template matching because of their large distortion. To solve this problem, distortion of fish-eye images is corrected. An example of distortion correction is shown in Fig. 3. First, image coordinates on the fish-eye image corresponding to image coordinates on the corrective image are estimated. Next, the pixel value from image coordinates on the fish-eye image is transfered to the image coordinates on the corrective image. A correction way differs depending on projection model of fish-eye lens [10].

2.2. Ray Tracing

The ray from the image is refracted at the boundary of air and the watertight container, and then is refracted at the boundary of the watertight container and water. Finally, the ray is projected onto the object in water. This phenomenon can be analyzed by ray tracing [4]. Figure 4 shows light refraction effects from air to watertight container and from watertight container to water.

Here, let refractive indices of air and the container be n_1 and n_2, incident and refractive angles from air to the container be θ_1 and θ_2, respectively. A unit vector of ray in the container $(\alpha_2, \beta_2, \gamma_2)^{\mathrm{T}}$ can be calculated by using a unit vector of ray from air $(\alpha_1, \beta_1, \gamma_1)^{\mathrm{T}}$ and a unit normal vector of the container $(\lambda, \mu, \nu)^{\mathrm{T}}$ as follows.

$$\begin{pmatrix} \alpha_2 \\ \beta_2 \\ \gamma_2 \end{pmatrix} = \frac{n_1}{n_2} \begin{pmatrix} \alpha_1 \\ \beta_1 \\ \gamma_1 \end{pmatrix} + a, \tag{1}$$

where

$$a = \left[\sqrt{1 - \left(\frac{n_1}{n_2}\right)^2 \sin\theta_1} - \frac{n_1}{n_2}\cos\theta_1 \right] \begin{pmatrix} \lambda \\ \mu \\ \nu \end{pmatrix}. \tag{2}$$

A unit vector in water $(\alpha_3, \beta_3, \gamma_3)^{\mathrm{T}}$ is also calculated by using the refractive index of water n_3.

$$\begin{pmatrix} \alpha_3 \\ \beta_3 \\ \gamma_3 \end{pmatrix} = \frac{n_2}{n_3} \begin{pmatrix} \alpha_2 \\ \beta_2 \\ \gamma_2 \end{pmatrix} + b, \tag{3}$$

where

$$b = \left[\sqrt{1 - \left(\frac{n_2}{n_3}\right)^2 \sin\theta_2} - \frac{n_2}{n_3}\cos\theta_2 \right] \begin{pmatrix} \lambda \\ \mu \\ \nu \end{pmatrix}. \tag{4}$$

When Snell's law of refraction is applied, the following equation is obtained.

$$\theta_2 = \sin^{-1}\left(\frac{n_1}{n_2}\sin\theta_1\right). \tag{5}$$

The ray from the camera finally reaches on the surface of the underwater object at the point P $(x_p, y_p, z_p)^{\mathrm{T}}$.

$$\begin{pmatrix} x_p \\ y_p \\ z_p \end{pmatrix} = s \begin{pmatrix} \alpha_3 \\ \beta_3 \\ \gamma_3 \end{pmatrix} + \begin{pmatrix} x_w \\ y_w \\ z_w \end{pmatrix}. \tag{6}$$

where s is a constant and $(x_w, y_w, z_w)^{\mathrm{T}}$ is the intersection point between the ray from the container and the refraction boundary.

2.3. 3-D Measurement

Two rays are calculated by ray tracing from the left and the right images taken by the fish-eye stereo camera, and the 3-D coordinates of the measurement point in water are given by the intersection of the two rays. However, two rays do not cross because of noises. Consequently, the midpoint of the shortest line connecting two points each of which belongs to each ray is selected as the 3-D coordinates of the measurement point in water (Fig. 5). The relationship between corresponding points of the left and the right images is formulated with epipolar constraints. The epipolar lines are straight in aerial environments. However, the epipolar lines are not straight in aquatic environments because of the refraction of light (Fig. 6). Therefore, the epipolar lines are calculated by the ray tracing method.

Corresponding points on epipolar lines are searched for with template matching by using the sum of absolute differences (SAD) method. After corresponding points are acquired, the 3-D position of underwater object can be measured by ray tracing method.

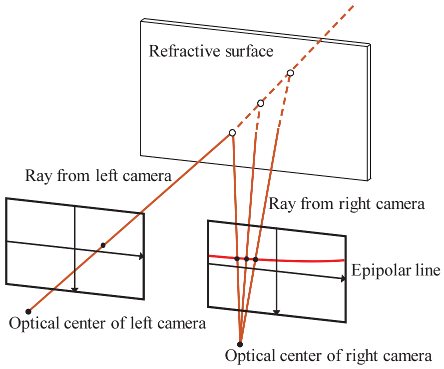


Fig. 6. Epipolar line.

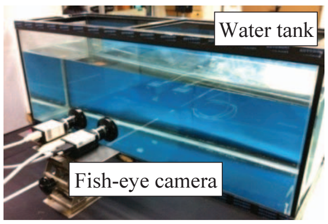
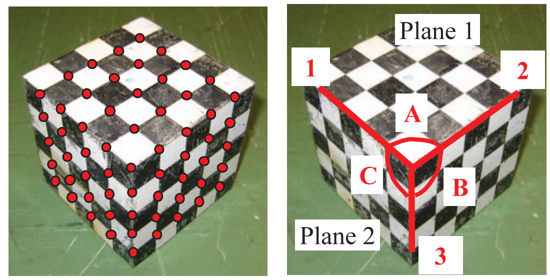


Fig. 7. Experiment environment.



(a) Corner point (b) Measurement points

Fig. 8. Measurement object 1.

Table 1. Measurement result of accuracy.

	length [mm]			angle [deg]	
	not considering refraction	considering refraction		not considering refraction	considering refraction
1	71.1	80.6	A	108.2	89.5
2	69.5	79.6	B	102.2	91.7
3	77.5	78.4	C	102.6	91.9
average	72.7	79.5	average	104.3	91.0

3. EXPERIMENTS

A virtual underwater environment was reconstructed using a water tank filled with water (Fig. 7). The resolution of images was 1600×1200 pixels. The refractive indices for the air, glass, and water were 1.0, 1.5, and 1.33, respectively. The thickness of the tank was 2.0mm. The optical axis was set vertical to the surface of the tank.

3.1. Evaluation of Accuracy

A measurement object was a cube which was in the tank filled with water. The cube is painted in a checkered pattern whose length of one square side is 20mm. Checkerboard corners shown in Fig. 8(a) were extracted from left and right images as corresponding points. Lengths 1, 2 and 3 and angles A, B and C which are shown in Fig. 8(b) were measured. The true value of length of 1, 2 and 3 is 80mm and the angle of A, B and C is 90deg.

Figure 9(a) and 9(b) show reconstructions of corner points on plane 1, and Fig. 9(c) and 9(d) show those on plane 2. The standard deviation of measurement points on each plane of cube from each least square plane are 0.54mm, 0.44mm and 0.44mm. The standard deviation is within 1mm while the object distance from the camera is about 200mm.

Table 1 shows measurement results with and without consideration of refraction effect. The average error of length and angle was 7.3mm and 14.3deg without consideration of refraction effect. On the other hand, by considering the refraction effect, the average error of length and angle is 0.5mm and 1.4deg. Therefore, error was reduced to about 1/10 by considering the refraction effect. These results show that measurement with considering the refraction effect is effective.

3.2. Evaluation of Range

To evaluate the viewing range of the fish-eye stereo camera, a moving object was measured and the field of view was calculated. The object was moved parallel to the surface of the tank in front of stereo camera.

Figure 10 shows the measurement result. Blue dots show measurement points, red dots show true values and two green dots show location of the fish-eye camera. In the measurement result, the farther the object is dislocated from the optical axis of the lens, the more the measurement points differ from the true positions. This is because there is residual distortion on the corrected image. The maximum error in the depth direction is 40mm. Also, from this result, the field of view of the fish-eye stereo camera was about 130deg.

From these results, it is verified that moving object can be measured accurately and widely by the proposed method.

3.3. 3-D Shape Measurement

A measurement object is shown in Fig. 11. To measure the shape of the object, edges were extracted from the left image, and points on the right image corresponding to edge points of the left image were searched for.

Figure 12 illustrates the experimental result showing the measurement points. Depth of a measurement point is represented by color. Blue is given to the near points to the camera, and according to the distance from the camera, color changes from blue to green, yellow and red. Although there are some uneven measurement points in the measurement result, scale and shape of the object is restored.

From this result, it is verified that shape of object in water can be measured by the proposed method.

(a) Plane 1 (not considering refraction)

(b) Plane 1 (considering refraction)

(c) Plane 2 (not considering refraction)

(d) Plane 2 (considering refraction)

Fig. 9. Reconstructed corner points.

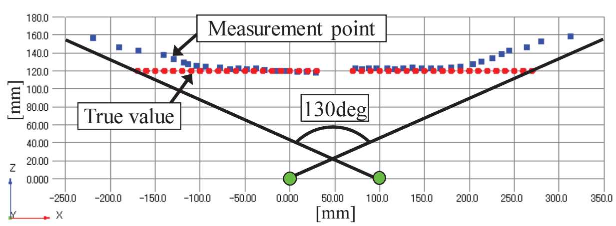


Fig. 10. Range measurement result.

4. CONCLUSION

This paper proposed a 3-D measurement method of objects in water using a fish-eye stereo camera. Two problems of light refraction effects and large distortion of fish-eye image are solved by the proposed method. The effectiveness of the proposed 3-D measurement method is verified through experiments.

As future works, measurement should be executed with a fish-eye stereo camera accommodated in watertight container in real environment. Measuring of objects with various shapes is needed to confirm the effectiveness of the method. To improve the measurement accuracy, reliable searching of corresponding points is required, especially for actual environment observation accompanied by noises.

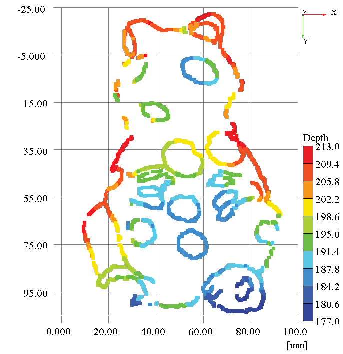


Fig. 11. Measurement object 2. **Fig. 12**. Shape measurement result.

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