# Three-Dimensional Measurement of Objects in Liquid with an Unknown Refractive Index Using Fisheye Stereo Camera

Kazuki Sakamoto, Alessandro Moro, Hiromitsu Fujii, Atsushi Yamashita, and Hajime Asama

***Abstract*—This paper proposes a method to estimate the refractive index of liquid using a stereo camera. Sensing in liquid environment is important to research liquid structures, aquatic lives and liquid resources. Methods using cameras are often performed. However, methods using cameras are affected by the refraction of light. Therefore, refractive index is needed to know to consider the refraction of light. The use of the refractive index of the liquid is a common approach described in literature, for most of the researches of three-dimensional (3-D) measurement in liquid based on a camera. Those approaches does not take in account that the refractive index of liquid may change by dissolved material, concentration of solute, temperature. Moreover, in the real environment, a precise refractive index in liquid is needed to get an accurate measurement. In this work, we propose a stereo camera based method to measure the refractive index. An object whose scales are known is attached in front of the transparent waterproof container as reference. The refractive index is estimated measuring the distances between key feature points on the object. Experimental results show the validity of the proposed method.**

## I. 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, when the robots are used instead of human, in which case, in order to determine the position and shape of the investigation objects, the acquisition of three-dimensional (3-D) information is required. Thus, 3-D measurement in water is important.

There are several studies about 3-D measurement in water using camera [1], [2], [3], [4]. 3-D measurement methods of objects in liquid with light projection equipment such as a laser range finder and a projector by considering the refraction effects are proposed [5], [6], [7], [8]. In this case, 3-D measurement is performed even if objects have no texture. The methods with a stereo camera are also proposed [4], [9]. Because those methods don't have to scanning the object's surface, those methods can measure the objects in a short time. A method by the use of motion stereo images obtained with a moving camera is also proposed [10]. Because this system consists of only one camera, whole device to measure 3-D information can be made smaller.

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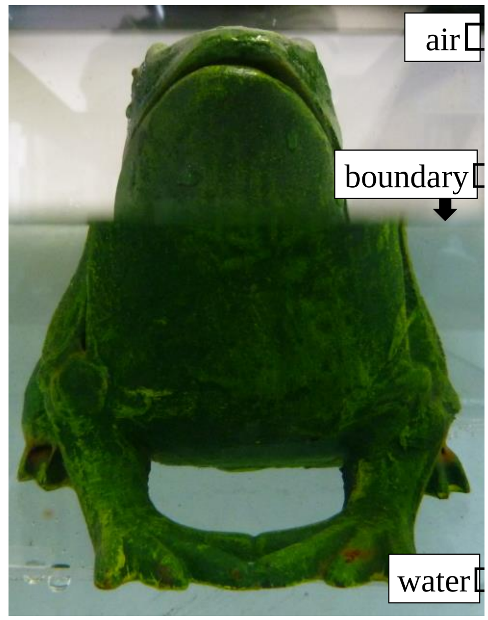


Fig. 1: Refraction of light

Because cameras are stored in transparent waterproof container in those cases, light passes through the materials having different refractive index, for example, water, transparent waterproof container and air. Therefore, investigation objects look distorted, and look at different positions. Figure 1 shows an example of refraction effect. It is an image of a frog 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.

Taking into account the refraction of light is required. However, in almost all the researched on 3-D measurement in liquid that use cameras, the refractive index value is equivalent of the value in literature. Those approaches does not take in account that the refractive index of liquid may change by dissolved material, concentration of solute, temperature. Moreover, in the real environment, a precise refractive index in liquid is needed to get an accurate measurement.

As a conventional study of refractive index estimation in liquid, there is a method to estimate the refractive index from the discontinuous of contour of an object between above and below the water surface (Fig. 1) [11]. However, because cameras must photograph the object above and below the water surface in this study, it is impossible to estimate the refractive index when cameras are completely in liquid.

In this paper, we propose a refractive index estimation method of liquid, in which cameras can be completely in liquid. A wide range fisheye camera lens which has 180 degrees of field of view is required. This is because not only 3-D measurement objects that exist near the center of the acquired image but also a known object that exists on the edge of the image are need to photographed.

## II. Estimation of Refractive Index

Figure 2 shows the measurement system to estimate refractive index of liquid and to measure the shape of measurement object using estimated refractive index. As a rectangular in liquid shown in Figure 2, object whose distance $L$ between two features points (point A, point B) are known is placed in liquid. Two parallel fisheye cameras are used to calculate 3-Dこ coordinates of two features points. These coordinates are calculated by changing the refractive index of the liquid ($n_3$) finely within the range that can be assumed as a real environment. That is, 3-D coordinates of the two features points corresponding to different refractive index ($n_3$) are obtained. Then, the distances $L(n_3)$ between two features points are calculated. Finally, refractive index are obtained, in which case the difference between the calculated distance $L(n_3)$ and the known distance $L$ is minimum. Details of the method are described in the following sections.

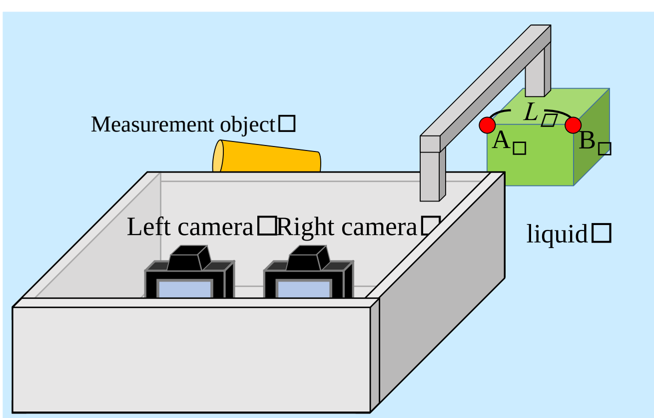


Fig. 2: Measurement system

### A. Ray tracing

In order to calculate 3-D coordinates of two features points (point A, point B), the rays from the cameras are traced. This process is performed for each value of the refractive index $\hat{n}_3$ of the liquid.

The ray from the camera is calculated using the acquired image and the value of the distortion of the lens. In the proposed method, the fisheye lens is used. The lens can get the wide range area even in liquid where field of view is narrow. The projection method of the fisheye lens is equidistance projection method. Figure 3 shows the model of

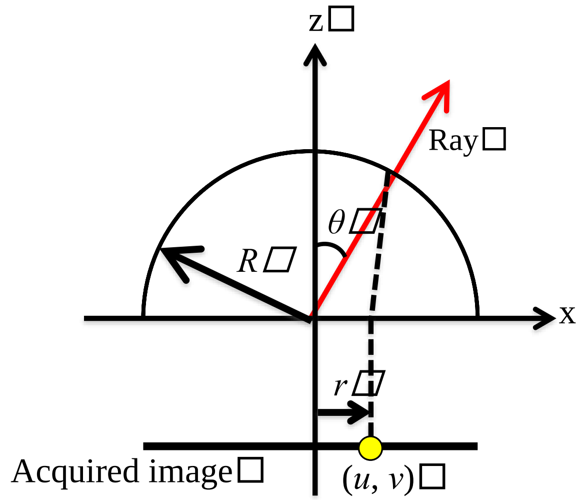


Fig. 3: Fisheye lens

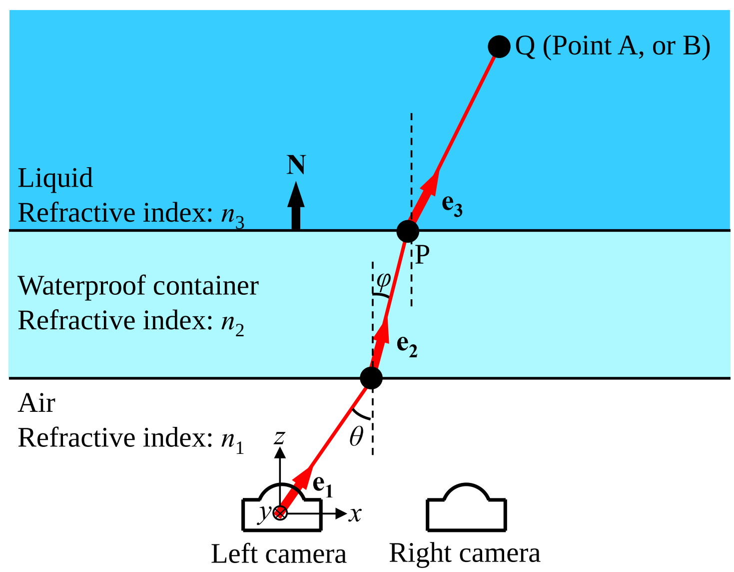


Fig. 4: Refraction of light

the lens. The value $u$ and $v$ are the coordinates of the image. The image height $r$ satisfies the following equation.

$$r = \sqrt{u^2 + v^2} \tag{1}$$

Let the angle between optical axis and the ray be $\theta$. Let the focal length of the lens be $f$. Projection equation of equidistant projection method is expressed as follows.

$$r = f\theta \tag{2}$$

That is, on the condition that the image height $R$ is the value of $r$ when $\theta$ is 90 degrees, the angle $\theta$ is expressed as follows.

$$\theta = \frac{\pi}{2} \cdot \frac{r}{R} \qquad (3)$$

In this way, the rays from the cameras to the features point are calculated.

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

Here, let refractive indexes of air and the container be $\hat{n}_1$ and $\hat{n}_2$, incident and refractive angles from air to the container be $\theta$ and $\varphi$, respectively. A unit vector of ray in the container $\mathbf{e}_2$ can be calculated by using a unit vector of ray from air $\mathbf{e}_1$ and a unit normal vector of the container $\mathbf{N}$ as follows.

$$\mathbf{e}_2 = \frac{n_1}{n_2}\mathbf{e}_1 + a \qquad (4)$$

where

$$a = \left[\sqrt{1 - \left(\frac{n_1}{n_2}\right)^2 \sin\theta} - \frac{n_1}{n_2}\cos\theta\right]\mathbf{N} \qquad (5)$$

A unit vector in water $\mathbf{e}_3$ is also calculated by the using refractive index of water $n_3$.

$$\mathbf{e}_3 = \frac{n_2}{n_3}\mathbf{e}_2 + b \qquad (6)$$

where

$$b = \left[\sqrt{1 - \left(\frac{n_2}{n_3}\right)^2 \sin\varphi} - \frac{n_2}{n_3}\cos\varphi\right]\mathbf{N} \qquad (7)$$

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

$$\varphi = \sin^{-1}\left(\frac{n_1}{n_2}\sin\theta\right) \qquad (8)$$

The ray from the camera finally reaches on the surface of the object in liquid at the point Q.

$$\mathbf{Q} = s\mathbf{e}_3 + \mathbf{P} \qquad (9)$$

where $s$ is a constant and P is the intersection point between the ray from the transparent waterproof container and the refraction boundary.

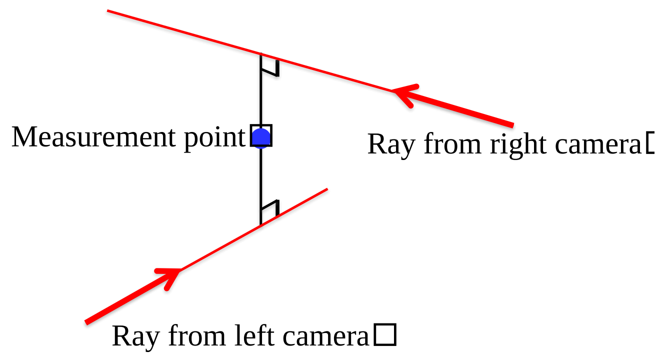


Fig. 5: Measurement point

### B. 3-D Measurement

Two rays are calculated by ray tracing [4] from the left and the right cameras, and the intersection of the two rays gives the 3-D coordinates of the target point in liquid. 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 liquid (Fig. 5).

### C. Estimation of Refractive Index

In the previous section, the coordinates of the point A and B are calculated, which correspond to various refractive indexes of liquid.

Then, the distances $L(n_3)$ between two points are calculated using the 3-D coordinates. The distances $L(n_3)$ take different values according to the refractive index $n_3$. Therefore, the evaluation function $J(n_3)$ is designed as follows.

$$J(n_3) = |L - l(n_3)| \qquad (10)$$

Refractive index $(n_3)$ on condition that $J(n_3)$ is minimum, is regarded as estimated value $(\hat{n}_3)$ of refractive index in liquid. In other words, $\hat{n}_3$ is a value that satisfies the following equation.

$$\hat{n}_3 = \underset{n_3}{\operatorname{argmin}}\{J(n_3)\} \qquad (11)$$

In this way, we can estimate refractive index liquid $n_3$, and measure objects in liquid by using $n_3$.

## III. Experiment

A virtual underwater environment was constructed using a water tank filled with unknown liquid (Fig. 6). It is an equivalent optical system to sinking the waterproof camera in underwater, because in the both systems, the light from an object in liquid passes in the order of liquid, transparent waterproof container and air. Figure 7 shows the digital fisheye cameras used in the experiments. The resolutions of the cameras were 1600×1200 pixels.

The refractive indices of the air and transparent waterproof container were 1.0 and 1.5, respectively. The thickness of the tank was 2.0mm. The optical axis was set vertical to the surface of the tank.

Two objects were put in unknown liquid. Object 1 (the cube on the right (fig. 8)) was a cube whose length of the side were known and Object 2 (the cube on the left (fig. 9)) was a cube whose angle of the two sides was 90 degrees.

Figure 10 shows the acquired image by the left camera. Firstly, the refractive index of unknown liquid was estimated using Object 1. Secondly, the 3-D shape of Object 2 was measured using the estimated refractive index. And finally, the evaluation was performed using the calculated angle of the two sides and the true value 90 degrees.

### *A. Estimation of Refractive Index*

The 3-D coordinates of the vertex points of Object 1 were estimated, whose values took different values according to the refractive index $n_3$. Then, the distances $L(n_3)$ between two points were calculated using the 3-D coordinates. The evaluation function $J(n_3)$ was calculated using the calculated value $L(n_3)$ and true value $L$. Figure 11 shows the evaluation function $J(n_3)$. From the above results, the refractive index of unknown liquid was estimated to be 1.345.

### *B. 3-D Measurement*

The intersections of the checkered pattern of Object 2 were extracted from left and right images as corresponding points. By using the estimated refractive index, the shape of Object 2 (cube) was measured quantitatively. When the refractive index was unknown ($n_3 = 1.00$) and the refraction effect was not considered, the vertex angle was measured as 96.28deg, while the ground truth was 90.0deg. On the other hand, the result was 86.4deg when the refraction effect was considered by using the estimated refractive index. Figure12 and 13 shows reconstructions of the intersection of the checkered pattern. From these results, it is verified that our method can measure accurate shape of underwater objects. Figure 11 shows the result of the 3-D measurement. These

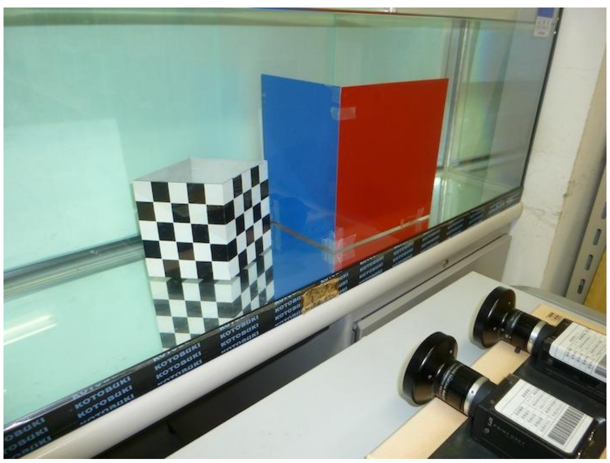

Fig. 6: Experiment environment

Fig. 7: Fisheye cameras

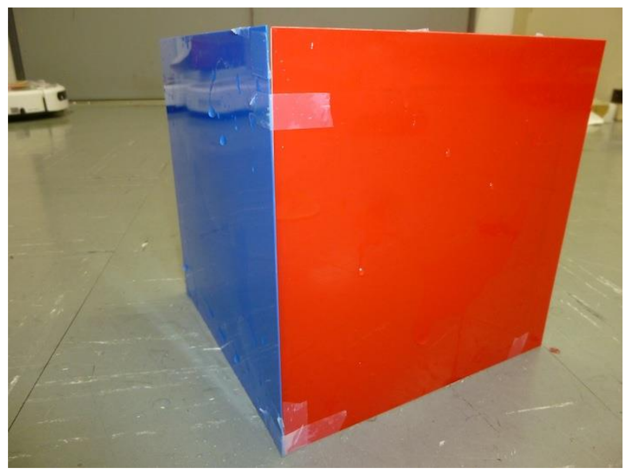

Fig. 8: Object 1

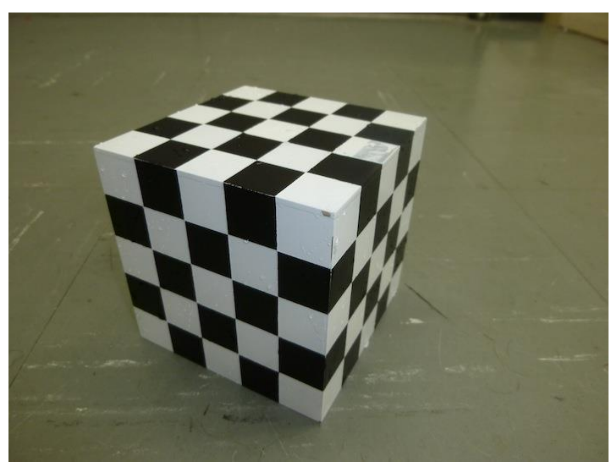

Fig. 9: Object 2

results show that our method can work well without failure regardless of the existence of unknown liquid by estimating the refractive index of liquid and considering the light refraction.

## IV. Conclusion and Future Works

### A. Conclusion

This paper proposed a method to estimate the refractive index of unknown liquid using fisheye stereo camera. The effectiveness of the proposed method is verified through experiments.

### B. Future Works

As future works, measurement with various liquids should be executed to confirm the effectiveness of the method. Measurement with a fisheye stereo camera accommodated in watertight container in real environment also should be executed to confirm the effectiveness.


## Acknowledgment

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Fig. 10: Acquired image

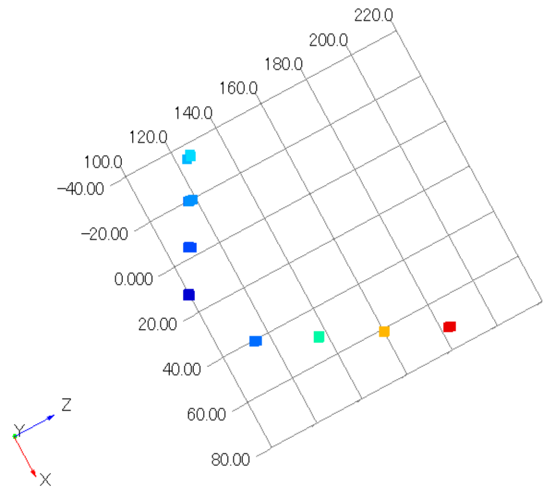


Fig. 12: View of reconstructed the intersections from the overhead

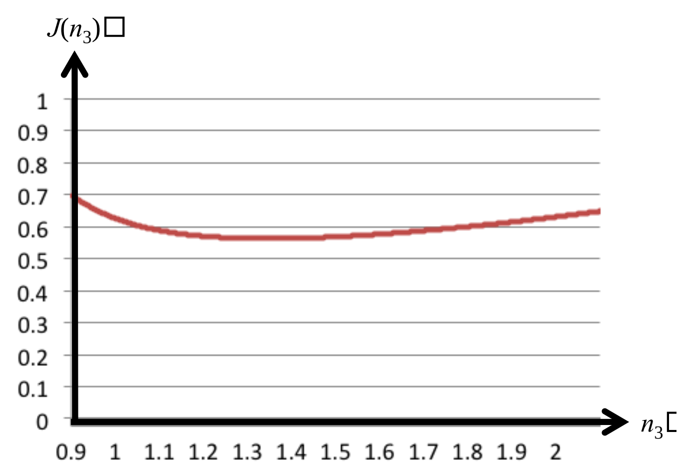


Fig. 11: Result of evaluation function $J(n_3)$

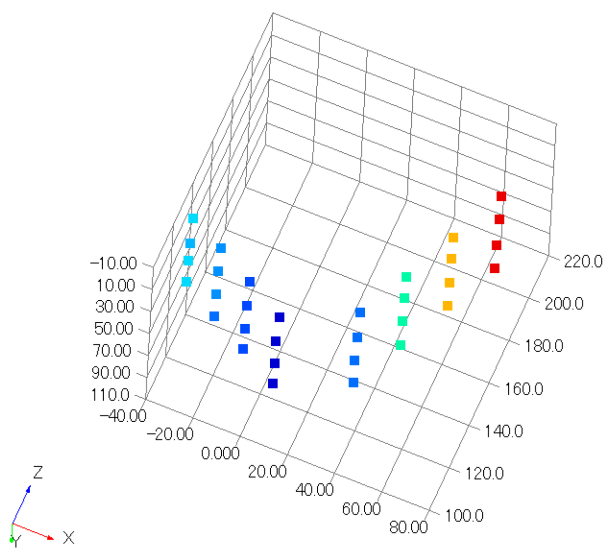


Fig. 13: View of reconstructed the intersections from the oblique

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