Three-Dimensional Measurement of Objects in Water by Using Space Encoding Method

Ryohei Kawai, Atsushi Yamashita and Toru Kaneko

***Abstract*—In this paper, a new method for 3-D measurement of objects in water is proposed. When observing objects in water through a camera contained in a waterproof housing or observing objects in an aquarium tank filled with preserving liquid, we should solve a problem of light refraction at the boundary surfaces of refractive index discontinuity which gives image distortion. The proposed method uses a space encoding method which does not have a problem of corresponding point detection as a stereo vision system has, and is faster than spot light projection or slit light projection methods. A ray tracing technique solves the problem of image distortion caused by refractive index discontinuity. It should be noted that monochromatic light projection onto objects gives more accurate measurement than white light projection because the refractive index depends on the wavelength of the light. Then, in order to measure colored objects, we should project red, green and blue light patterns onto them separately. Experimental results show the validity of the proposed method.**

I. Introduction

Underwater imagery is essential to marine environment investigation, and three-dimensional measurement of objects in water gives important information [1][2]. This technique is also available when measuring the shape of specimens in a transparent container filled with preserving liquid.

Photographic 3-D measurement methods have the advantage that it is possible to measure objects without contact, and they are well used in atmospheric environments. However, measurement of an object in water by these methods has a problem of light refraction [3][4].

Figure 1 shows that an object in a jar filled with air (Fig. 1(a)) and an object in a jar filled half with water (Fig. 1(b)) look different. Accurate results can not be obtained from the measurement using the distorted image without considering the influence of light refraction. This problem occurs not only when the object in a container filled with water is observed by using the camera outside of water but also when the camera is put into water with waterproof housing. This is because the housing case for waterproof is filled with air and light refraction occurs at the boundary of air and water.

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(a) Image without water. (b) Image with water.

Fig. 1 Influence of light refraction.

Ray tracing solves the problem of light refraction. Accurate results considering the influence of light refraction can be obtained by calculating the direction of rays from the camera before and after light refraction.

Methods for 3-D measurement of objects in water with camera are possible to measure objects which are relatively near to the camera more accurately than methods with supersonic waves [5][6] do, and there have been proposed a variety of methods such as using a stereo camera system [7]-[9], using a motion stereo system [10] and using spot light projection [11]-[13] or slit light projection [14].

However, the methods using a stereo camera system have a problem that it is difficult to detect the corresponding points when the object does not have a texture nor a feature point, and the methods using a motion stereo system have a problem that the relationship between the camera and the surface of the water is difficult to estimate accurately because the camera moves. The methods using spot light projection or slit light projection also have a problem that it takes time to measure a wide range because the coordinates of only one point or one line can be obtained by one image.

To solve these problems, we propose a method for 3-D measurement of objects in water by using the space encoding method that considers the influence of the light refraction.

The space encoding method is a 3-D measurement method which projects the binary pattern light onto the object and takes pictures [15]. This method is widely used for the 3-D measurement because it does not have the problem to detect the corresponding points and it is possible to measure by fewer images than the methods using spot light projection or slit light projection.

In this paper, an object in water is measured by the space encoding method using the camera and the light source in air (Fig. 2).

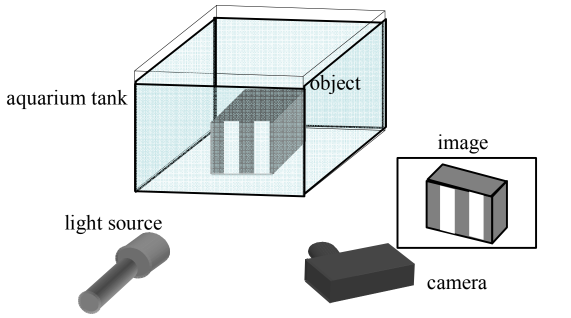


Fig.2 Measurement of an underwater object by space encoding method.

II. Pattern Light Projection

The proposed method uses monochromatic light as the projection light instead of white light. White light is composed of light components of various wavelengths, and each component is refracted in its own direction because the refractive index of light depends on its wavelength and its difference is considerably large in water (Fig. 3). This causes a problem that the edge of each pattern becomes obscure when the pattern light is projected onto objects in water from outside. Therefore, by using monochromatic light, an underwater object is illuminated more clearly.

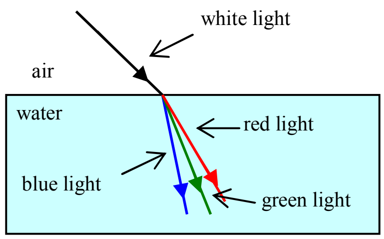


Fig. 3 Refraction of white light.

When the object is white, it is possible to project the pattern with one monochromatic light. However, when colored object is measured, the effective wavelength of the projection light depends on the color of the object. For example, when green light is used, it is difficult to measure red parts of the object. Therefore, colored object is measured by projecting red, green and blue light individually (Fig. 4).

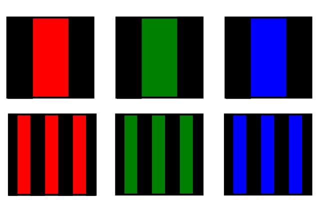


Fig. 4 Example of monochromatic projection pattern.

III. 3-D Coordinates Calculation

A. Prerequisite condition

Figure 5 shows the measurement model of the proposed method. The origin of the world coordinate system is the center of the camera lens. The Z-axis is set in the same direction of the optical axis of the camera. The X-axis is set in the direction which is perpendicular to the Z-axis and parallel to the horizontal plane. The Y-axis is set in the direction which is perpendicular to the Z-axis and the horizontal plane.

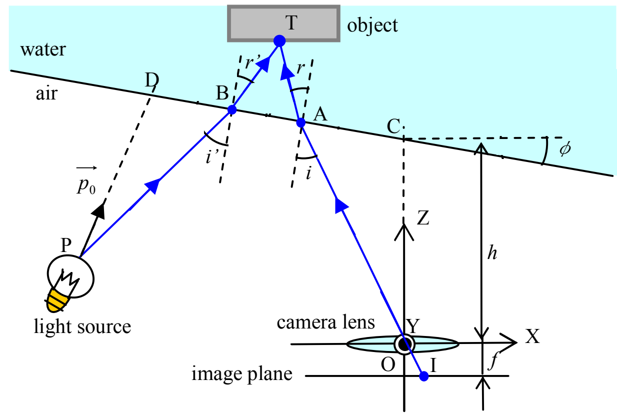


Fig. 5 3-D measurement model.

The prerequisite conditions in this paper are as follows.

- The boundary of air and water (the surface of the aquarium tank) is perpendicular to the horizontal plane.
- The patterns of the projection light in air are perpendicular to the horizontal plane.

The explanation of parameters in Fig. 5 is shown below.

O (0, 0, 0) : the center point of the camera lens

T (X_T, Y_T, Z_T) : the point on the object surface

P (X_P, Y_P, Z_P) : the light source

I (X_I, Y_I, Z_I) : the point in the image plane of point T

A (X_A, Y_A, Z_A) : the intersection point of the ray from the camera with the boundary of air and water

B (X_B, Y_B, Z_B) : the intersection point of the ray from the light source with the boundary of air and water

C (X_C, Y_C, Z_C) : the intersection point of the Z-axis with the boundary of air and water

i : the angle of incidence of the ray from the camera at A

r : the angle of refraction of the ray from the camera at A

i': the angle of incidence of the ray from the light source at B

r': the angle of refraction of the ray from the light source at B

f : the image distance (the distance from the center point of the camera lens to the image plane)

h : the distance from the center point of the camera lens to the boundary of air and water ($=\overline{OC}$)

ϕ: the angle of the boundary of air and water to the X-axis

$\overrightarrow{p_0} = (X_{p0}, Y_{p0}, Z_{p0})^T$: the unit vector along the optical axis of the light source

In order to obtain the coordinate of T, it is necessary to calibrate the internal parameters of the camera, the relationship between the camera and the boundary of air and water, and the relationship between the camera and the light source. Concretely, f, h, ϕ, X_P, Y_P, Z_P, X_{p0} and Z_{p0} should be calibrated in advance.

A sheet that has circle marks drawn in square frame is used for calibration. First, by taking pictures of the calibration sheet at various positions and poses, the internal parameters of the camera are calibrated by the relationship of each circle mark in images. Then, the relationship between the camera and the boundary of air and water is calibrated by taking a picture of the calibration sheet put on the aquarium surface.

Next, the relationship between the camera and the light source is calibrated. The calibration sheet is placed at random positions, several spot lights are irradiated to it from the light source, and take a picture of it. This process is repeated several times, and the relationship between the camera and the light source is calibrated.

B. Ray tracing from the light source

The rays from the light source are refracted at the boundary of air and water to project onto the object in water, and then the rays reflected by the object are refracted again at the boundary of air and water to project onto the image plane of the camera. This phenomenon can be analyzed by ray tracing [7].

First, the ray from the light source is traced.

A set of light planes is projected onto the object. The individual light planes are indexed by an encoding scheme for the light patterns. Each light plane is decomposed into rays projecting light spots (Fig. 6).

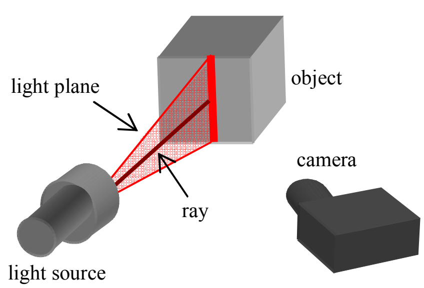


Fig. 6 Light plane.

$\overrightarrow{OB} = (X_{OB}, Y_{OB}, Z_{OB})^T$ is expressed as Eq. (1) by using constant a and $\vec{p} = (X_p, Y_p, Z_p)^T$, where $\vec{p}$ is the unit vector of $\overrightarrow{PB}$. The X-component and the Z-component of $\vec{p}$ are determined. However, the Y-component of $\vec{p}$ is still unknown here.

$$\overrightarrow{OB} = \overrightarrow{OP} + \overrightarrow{PB} = \overrightarrow{OP} + a\vec{p} \tag{1}$$

Here, Eq. (2) holds for $\overrightarrow{OB}$, too.

$$Z_{OB} = h + X_{OB}\tan(\pi + \phi) \tag{2}$$

Then, a and $\overrightarrow{OB}$ are obtained from Eqs. (1) and (2).

$$a = \frac{Z_{OP} - h - X_{OP}\tan(\pi + \phi)}{X_p \tan(\pi + \phi) - Z_p} \tag{3}$$

$$\overrightarrow{OB} = \overrightarrow{OP} + \frac{Z_{OP} - h - X_{OP}\tan(\pi + \phi)}{X_p \tan(\pi + \phi) - Z_p}\overrightarrow{pb} \tag{4}$$

If we denote the unit vector of $\overrightarrow{BT}$ by $\vec{p}' = (X_{p'}, Y_{p'}, Z_{p'})^T$ and the unit normal vector to the boundary of air and water by $\vec{v} = (\cos(\phi + \pi/2), 0, \sin(\phi + \pi/2))^T$, the inner product of $\vec{p}$ and $\vec{v}$ and the inner product of $\vec{p}'$ and $\vec{v}$ have the following relations.

$$\vec{p} \cdot \vec{v} = \cos i' \tag{5}$$

$$\vec{p}' \cdot \vec{v} = \cos r' \tag{6}$$

Equations (7) and (8) holds by using constants b and c, because $\vec{p}$, $\vec{p}'$ and $\vec{v}$ are on the same plane.

$$\vec{p}' = b\vec{p} + c\vec{v} \tag{7}$$

$$\vec{p}' \cdot \vec{v} = b\vec{p} \cdot \vec{v} + c = \cos r' \tag{8}$$

The magnitude of the outer product of $\vec{p}$ and $\vec{v}$ and the magnitude of the outer product of $\vec{p}'$ and $\vec{v}$ are calculated as follows.

$$|\vec{p}' \times \vec{v}| = |b\vec{p} \times \vec{v}| = \sin r' \tag{9}$$

$$|\vec{p} \times \vec{v}| = \sin i' \tag{10}$$

Equation (11) shows Snell's law, where the refractive index is known.

$$\frac{\sin i}{\sin r} = \frac{\sin i'}{\sin r'} = n \tag{11}$$

Constants b and c are obtained from Eqs. (8), (9), (10) and (11).

$$b = \frac{\sin r'}{\sin i'} = \frac{1}{n} \tag{12}$$

$$c = \cos r' - e\vec{p}\cdot\vec{v} = \cos r' - \frac{1}{n}\cos i' \quad (13)$$

$\vec{p}'$ is obtained from Eqs. (7), (12) and (13).

$$\vec{p}' = \frac{1}{n}\vec{p} + \left\{\cos r' - \frac{1}{n}\cos i'\right\}\vec{v} \quad (14)$$

cos*i'* and cos*r'* are expressed as Eqs. (15) and (16), where cos*r'* is positive since $-\pi/2 < r' < \pi/2$.

$$\cos i' = \vec{p}\cdot\vec{v} \quad (15)$$

$$\cos r' = \sqrt{1 - \frac{1}{n^2}(1-\cos^2 i')} \quad (16)$$

C. Ray tracing from the camera

The ray from the camera is traced.

$\overrightarrow{IO} = (X_{IO}, Y_{IO}, Z_{IO})^T$ is obtained by images and the image distance, then $\overrightarrow{OA}$ is expressed as Eq. (17) by using constant *d* because $\overrightarrow{OA}$ and $\overrightarrow{IO}$ are on the same line.

$$\overrightarrow{OA} = d\,\overrightarrow{IO} = (X_{OA}, Y_{OA}, Z_{OA})^T \quad (17)$$

Here, Eq. (17) holds for $\overrightarrow{OA}$, too.

$$Z_{OA} = h + X_{OA}\tan(\pi + \phi) \quad (18)$$

Then, *d* and $\overrightarrow{OA}$ are obtained from Eqs. (17) and (18).

$$d = \frac{h}{Z_{IO} - X_{IO}\tan(\pi+\phi)} \quad (19)$$

$$\overrightarrow{OA} = \frac{h}{Z_{IO} - X_{IO}\tan(\pi+\phi)}\overrightarrow{IO} \quad (20)$$

If we denote the unit vector of $\overrightarrow{OA}$ by $\vec{q}$, we obtain their inner product.

$$\vec{q}\cdot\vec{v} = \cos i \quad (21)$$

The inner product of $\vec{q}' = (X_{q'}, Y_{q'}, Z_{q'})^T$ and $\vec{v}$ is calculated next, where $\vec{q}'$ is the unit vector of $\overrightarrow{AT}$.

$$\vec{q}'\cdot\vec{v} = \cos r \quad (22)$$

Equations (23) and (24) hold by using constants *e* and *f* because $\vec{q}$, $\vec{q}'$ and $\vec{v}$ are on the same plane.

$$\vec{q}' = e\vec{q} + f\vec{v} \quad (23)$$

$$\vec{q}'\cdot\vec{v} = e\vec{q}\cdot\vec{v} + f = \cos r \quad (24)$$

The magnitude of the outer product of $\vec{q}'$ and $\vec{v}$ and the magnitude of the outer product of $\vec{q}$ and $\vec{v}$ are calculated.

$$|\vec{q}'\times\vec{v}| = |e\vec{q}\times\vec{v}| = \sin r \quad (25)$$

$$|\vec{q}\times\vec{v}| = \sin i \quad (26)$$

Constants *e* and *f* are obtained from Eqs. (24), (25), (26) and (11).

$$e = \frac{\sin r}{\sin i} = \frac{1}{n} \quad (27)$$

$$f = \cos r - b\vec{q}\cdot\vec{v} = \cos r - \frac{1}{n}\cos i \quad (28)$$

$\vec{q}'$ is obtained from Eqs. (23), (27) and (28).

$$\vec{q}' = \frac{1}{n}\vec{q} + \left\{\cos r - \frac{1}{n}\cos i\right\}\vec{v} \quad (29)$$

cos*i* and cos*r* are expressed as Eqs. (30) and (31).

$$\cos i = \vec{q}\cdot\vec{v} \quad (30)$$

$$\cos r = \sqrt{1 - \frac{1}{n^2}(1-\cos^2 i)} \quad (31)$$

D. Calculation of 3-D coordinates

The coordinates of the object are calculated by tracing the rays from the camera and the light source. The rays from the camera and the rays from the light source intersect at the point of the object surface.

$\overrightarrow{OT} = (X_{OT}, Y_{OT}, Z_{OT})^T$ is expressed as Eq. (32) by using constants *g* and *k*.

$$\overrightarrow{OT} = \overrightarrow{OA} + g\vec{q}' = \overrightarrow{OB} + k\vec{p}' \quad (32)$$

Each component of Eq. (32) is shown as follows.

$$X_{OT} = X_{OA} + gX_{q'} = X_{OB} + kX_{p'} \quad (33)$$

$$Y_{OT} = Y_{OA} + gY_{q'} = Y_{OB} + kY_{p'} \quad (34)$$

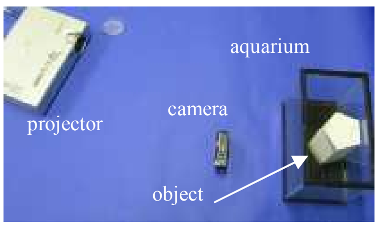
$$Z_{OT} = Z_{OA} + gZ_{q'} = Z_{OB} + kZ_{p'} \quad (35)$$

In Eq. (33), (34) and (35), X_{OA}, Y_{OA}, Z_{OA}, $X_{q'}$, $Y_{q'}$, $Z_{q'}$ are given for each point in the image. Here, Y_p is unknown, and if we determine Y_p, them X_{OB}, Y_{OB}, Z_{OB}, $X_{p'}$, $Y_{p'}$, $Z_{p'}$ are determined. Therefore, by changing the value of Y_p iteratively, we can find the solutions for Y_p, g and k which satisfy the three equations.

All the measurements are given by the above calculation.

IV. Experiments

Figure 7 shows the overview of the experiments. A projector is used as the light source. The resolution of the camera is 3072×2304 pixels and the resolution of the projector is 1024×768 pixels. In the first experiment, the object was a white pentagonal prism (Fig. 8) and it was set in the distance of 300mm from the camera.



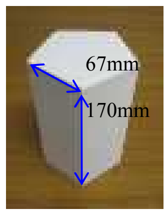


Fig. 7 Overview of experiments. Fig. 8 White pentagonal prism.

The projection light was green light. The number of projection patterns was ten. Fig. 9 shows captured image examples, Fig. 10 shows the encoded images and Fig. 11 shows the result of 3-D measurement.

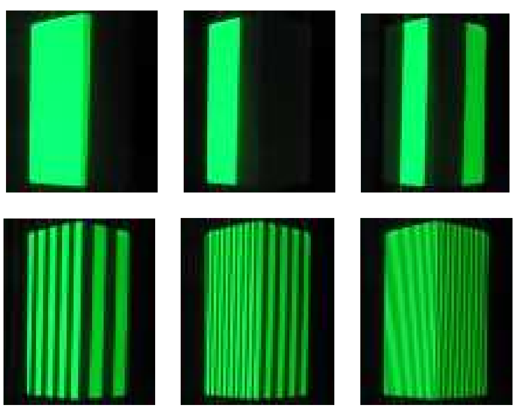


Fig. 9 Captured image examples (white pentagonal prism).

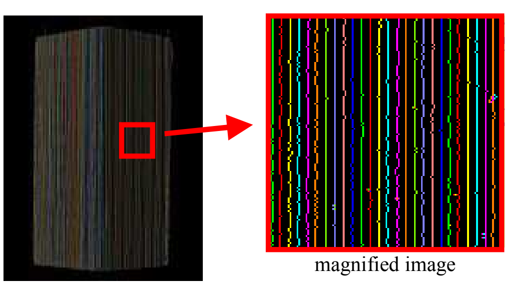


Fig. 10 Encoded image (white pentagonal prism).

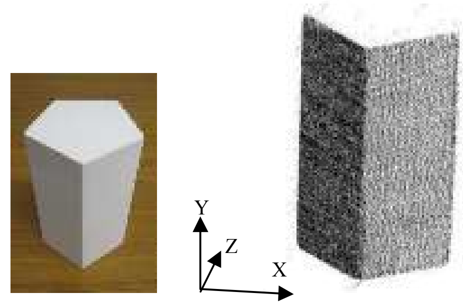


Fig. 11 Result of 3-D measurement (white pentagonal prism).

The green light made it possible to obtain the codes about twice the number compared with the white light because the boundaries of light and shade of the projection light became clear by using monochromatic light.

Table 1 shows the accuracy evaluation of the measurement result for the white pentagonal prism. The least square error planes are calculated by the measured coordinates, and the accuracy is evaluated by the angle between these planes and the standard deviation of measured points from these planes.

Table 1 Accuracy evaluation (white pentagonal prism).

	measurement value	actual value
Angle between two least square error planes [deg]	105.8	108.0
Standard deviation in the least square error planes [mm]	1.2	—

Table 2 shows the comparison of the measurement results with and without consideration of light refraction. In the case without consideration of refraction, much erroneous measurement was given.

Table 2 The measurement results with and without consideration of light refraction.

	considering refraction	not considering refraction	actual value
Angle [deg]	105.8	127.8	108.0
Standard deviation [mm]	1.2	1.6	—

Next, a color object (Fig. 12) was measured. In this case, the red, green and blue lights were projected respectively. Each number of projection patterns was ten.

Fig. 12 Color object.

Figure 13 shows captured image examples, and Fig. 14 shows the result of 3-D measurement. Measurement of color objects is given by integrating each result for individual color component projection.

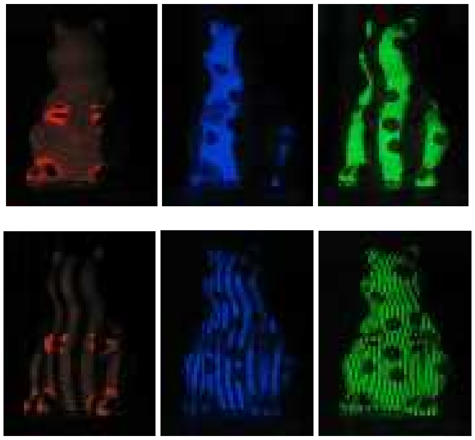


Fig. 13 Captured image examples (color object).

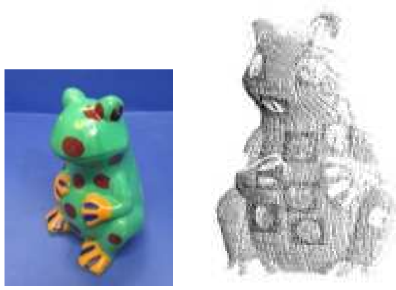


Fig. 14 Result of 3-D measurement (color object).

V. Conclusions

A method for 3-D measurement of objects in water is proposed. When observing objects in water through a camera contained in a waterproof housing or observing objects in an aquarium tank filled with preserving liquid, we should solve a problem of light refraction at the boundary surfaces of refractive index discontinuity which gives image distortion.

The proposed method uses a space encoding method which does not have a problem of corresponding point detection as a stereo vision system has, and is faster than spot light projection or slit light projection methods. A ray tracing technique solves the problem of image distortion caused by refractive index discontinuity. It should be noted that monochromatic light projection onto objects gives more accurate measurement than white light projection because the refractive index depends on the wavelength of the light. Then, in order to measure colored objects, we should project red, green and blue light patterns onto them individually. Experimental results showed the validity of the proposed method.

As future works, the accuracy of the method should be improved, observing conditions should be clarified, and more complicated cases should be studied, e.g., for a curved aquarium tank, and for liquids of unknown refractive indices.

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