Shape Measurement of Underwater Objects by Using Space Encoding Method

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We propose a new method for 3-D measurement of objects in water. 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 has no 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.

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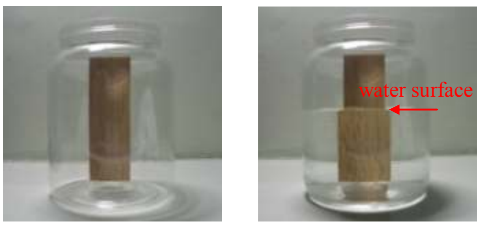
1. Introduction

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 container filled with air (Fig. 1(a)) and an object in a container 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 the case and at the boundary of the case and water.



(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 a camera are possible to measure objects which are near to the camera more accurately than methods with supersonic waves [5][6] do, and there have been proposed many methods such as methods 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 by projecting the binary pattern light onto the object and taking pictures of it [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).

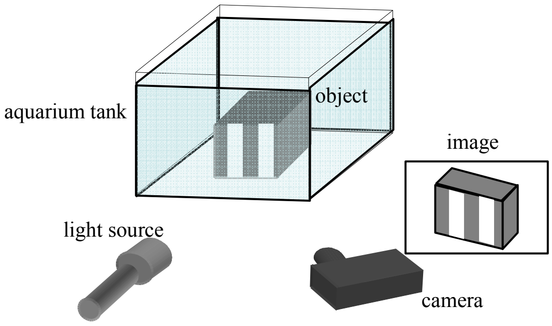


Fig. 2 Measurement of an underwater object by space encoding method

2. Pattern Light Projection

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

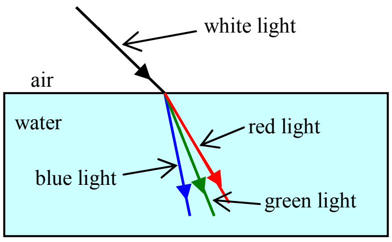


Fig. 3 Refraction of white light

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 separately (Fig. 4).

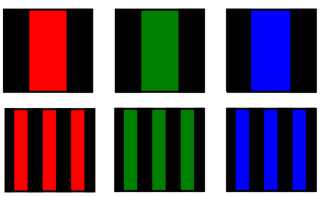


Fig. 4 Example of monochromatic projection pattern

3. Three-Dimensional Coordinates Calculation

3.1 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.

The prerequisite conditions in this paper are as follows.

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

In order to obtain the coordinate of the object surface (the point 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. Therefore, these should be calibrated in advance.

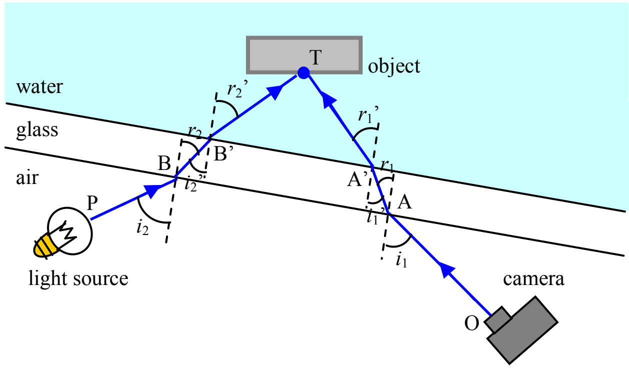


Fig. 5 3-D measurement model

3.2 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).

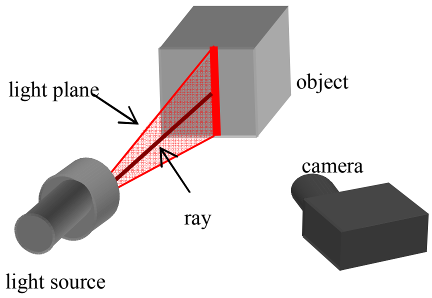


Fig. 6 Light plane

$\overrightarrow{OB}$ is expressed as Eq. (1) by using constant c_1, where $\vec{b}=(X_b,Y_b,Z_b)^T$ is the unit vector of $\overrightarrow{PB}$. The X-component and the Z-component of $\vec{b}$ are determined. However, the Y-component of $\vec{b}$ is still unknown here.

$$\overrightarrow{OB}=\overrightarrow{OP}+c_1\vec{b} \tag{1}$$

If we denote the boundary of air and glass by Eq. (2), c_1 is expressed as Eq. (3) because the point of B is on the boundary. Where $\vec{v}$ is the unit normal vector to the boundary of air and glass, and $\vec{v}$ and the constant d should be calibrated in advance.

$$\vec{v}\cdot(X,Y,Z)^T+d=0 \tag{2}$$

$$c_1=\left(-\vec{v}\cdot\overrightarrow{OP}-d\right)\Big/\left(\vec{v}\cdot\vec{b}\right) \tag{3}$$

Then, $\overrightarrow{OB}$ is obtained from Eqs. (1) and (3).

$$\overrightarrow{OB}=\overrightarrow{OP}+\left\{\left(-\vec{v}\cdot\overrightarrow{OP}-d\right)\Big/\left(\vec{v}\cdot\vec{b}\right)\right\}\vec{b} \tag{4}$$

If we denote the unit vector of $\overrightarrow{BB'}$ by $\vec{b'}$, $\vec{b'}$ is expressed as Eq. (5) by using constants c_2 and c_3 because $\vec{b}$, $\vec{b'}$ and $\vec{v}$ are on the same plane.

$$\vec{b}' = c_2\vec{b} + c_3\vec{v} \tag{5}$$

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

$$\vec{b}'\cdot\vec{v} = (c_2\vec{b} + c_3\vec{v})\cdot\vec{v} = c_2\cos i_2 + c_3 = \cos r_2 \tag{6}$$

$$|\vec{b}'\times\vec{v}| = |(c_2\vec{b} + c_3\vec{v})\times\vec{v}| = |c_2\sin i_2| = \sin r_2 \tag{7}$$

Equation (8) shows Snell's law, where n_a and n_g are the refractive indices of air and glass. And, these are known.

$$\sin i_2 / \sin r_2 = n_g / n_a \tag{8}$$

Constants c_2 and c_3 are obtained from Eqs. (6), (7) and (8).

$$c_2 = n_a / n_g \tag{9}$$

$$c_3 = \sqrt{1 - \left(n_a{}^2/n_g{}^2\right)\left\{1 - \left(\vec{b}\cdot\vec{v}\right)^2\right\}} - \left(n_a/n_g\right)\left(\vec{b}\cdot\vec{v}\right) \tag{10}$$

Then, $\vec{b}'$ is obtained from Eqs. (5), (9) and (10).

$$\vec{b}' = \left(n_a/n_g\right)\vec{b} + \left[\sqrt{1 - \left(n_a{}^2/n_g{}^2\right)\left\{1 - \left(\vec{b}\cdot\vec{v}\right)^2\right\}} - \left(n_a/n_g\right)\left(\vec{b}\cdot\vec{v}\right)\right]\vec{v} \tag{11}$$

Similarly, $\overrightarrow{OB'}$ and $\vec{t}_2$ are expressed as Eqs. (12) and (13), where $\vec{t}_2$ is the unit vector of $\overrightarrow{B'T}$, n_w is the refractive index of water, and the boundary of glass and water is expressed as $\vec{v}\cdot(X,Y,Z)^T + d' = 0$. However, Eqs. (12) and (13) include the unknown Y_b potentially.

$$\overrightarrow{OB'} = \overrightarrow{OB} + \left\{\left(-\vec{v}\cdot\overrightarrow{OB} - d'\right)/\left(\vec{v}\cdot\vec{b}'\right)\right\}\vec{b}' \tag{12}$$

$$\vec{t}_2 = \left(n_g/n_w\right)\vec{b}' + \left[\sqrt{1 - \left(n_g{}^2/n_w{}^2\right)\left\{1 - \left(\vec{b}'\cdot\vec{v}\right)^2\right\}} - \left(n_g/n_w\right)\left(\vec{b}'\cdot\vec{v}\right)\right]\vec{v} \tag{13}$$

3.3 Ray tracing from the camera

As ray tracing from the light source, Eqs. (14), (15), (16) and (17) about ray tracing from the camera are obtained, where $\vec{a}$, $\vec{a}'$ and $\vec{t}_1$ are the unit vector of $\overrightarrow{OA}$, $\overrightarrow{AA'}$ and $\overrightarrow{A'T}$.

$$\overrightarrow{OA} = \left\{(-d)/\left(\vec{v}\cdot\vec{a}\right)\right\}\vec{a} \tag{14}$$

$$\vec{a}' = \left(n_a/n_g\right)\vec{a} + \left[\sqrt{1 - \left(n_a{}^2/n_g{}^2\right)\left\{1 - \left(\vec{a}\cdot\vec{v}\right)^2\right\}} - \left(n_a/n_g\right)\left(\vec{a}\cdot\vec{v}\right)\right]\vec{v} \tag{15}$$

$$\overrightarrow{OA'} = \overrightarrow{OA} + \left\{\left(-\vec{v}\cdot\overrightarrow{OA} - d'\right)/\left(\vec{v}\cdot\vec{a}'\right)\right\}\vec{a}' \tag{16}$$

$$\vec{t}_1 = \left(n_g/n_w\right)\vec{a}' + \left[\sqrt{1 - \left(n_g{}^2/n_w{}^2\right)\left\{1 - \left(\vec{a}'\cdot\vec{v}\right)^2\right\}} - \left(n_g/n_w\right)\left(\vec{a}'\cdot\vec{v}\right)\right]\vec{v} \tag{17}$$

3.4 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.

$\overrightarrow{OT} = (X_T, Y_T, Z_T)^T$ is expressed as Eq. (18) by using constants c_4 and c_5.

$$\overrightarrow{OT} = \overrightarrow{OA'} + c_4\vec{t}_1 = \overrightarrow{OB'} + c_5\vec{t}_2 \tag{18}$$

In Eq. (18), $\overrightarrow{OA'}$ and $\vec{t}_1$ are given for each point in the image. Here, Y_b is unknown, and if we determine Y_b, them $\overrightarrow{OB'}$ and $\vec{t}_2$ are determined. Therefore, by changing the value of Y_b iteratively, we can find the solutions for Y_b, c_4 and c_5 which satisfy Eq. (18).

All the measurements are given by the above calculation.

4. 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.

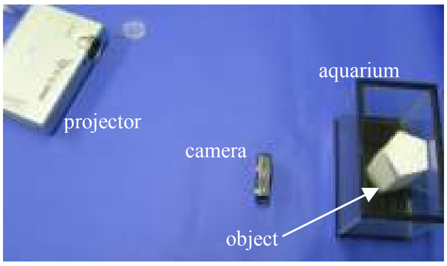


Fig. 7 Overview of experiments

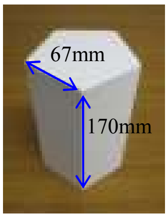


Fig. 8 White pentagonal prism

The projection light was green light. The number of projection patterns was ten. Figure 9 shows captured image examples, Fig. 10 shows the encoded images and Fig. 11 shows the result of 3-D measurement. In Fig. 11, red points are near to the camera and blue points are distant from the camera.

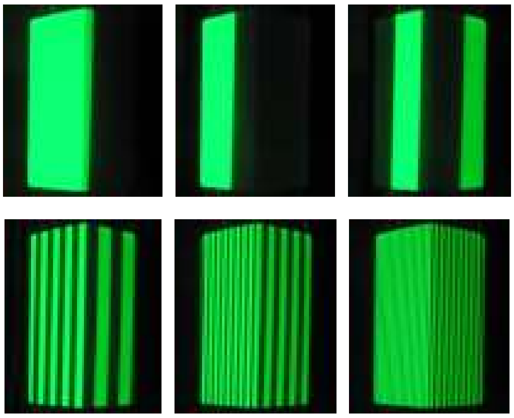


Fig. 9 Captured image examples (white pentagonal prism)

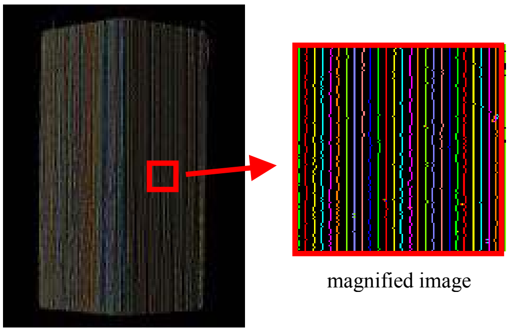


Fig. 10 Encoded image (white pentagonal prism)

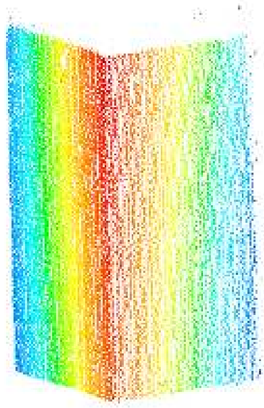


Fig. 11 Result of 3-D measurement (white pentagonal prism)

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 from 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 result 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	—

In the second experiment, we measured a complex shape coral replica (Fig. 12). The projection light was green light. The number of projection patterns was ten.

Fig. 12 Coral replica

Figure 13 shows captured image examples, and Fig. 14 shows the result of 3-D measurement. In Fig. 14, red points are near to the camera and blue points are distant from the camera. Figure 14 shows that each branch of coral replica is reconstructed

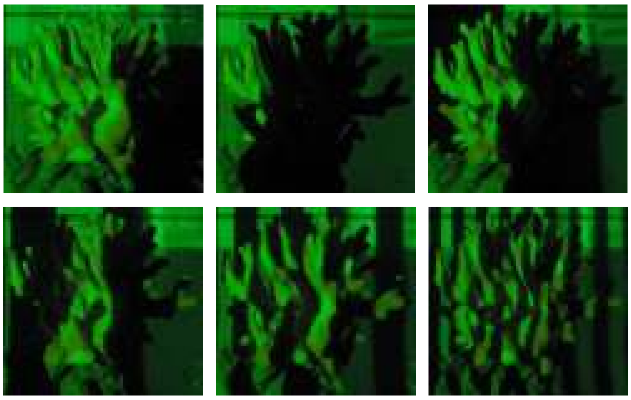


Fig. 13 Captured image examples (coral replica)

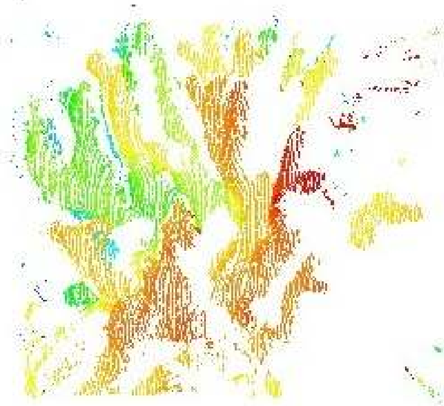


Fig. 14 Result of 3-D measurement (coral replica)

Next, a color object (Fig. 15) was measured. In this case, the red, green and blue lights were projected respectively. Each number of projection patterns was ten.

Fig. 15 Color object

Figure 16 shows captured image examples, and Fig. 17 shows the result of 3-D measurement. It is seen that the object is measured even if the object is color by Fig. 17. In Fig. 17, red points are near to the camera and blue points are distant from the camera. Figure 17 shows that the shape of the object and the details like arms and legs of the object are reconstructed.

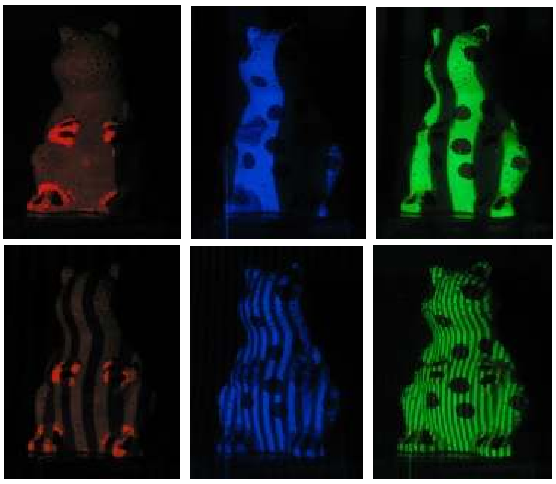


Fig. 16 Captured image examples (color object)

Fig. 17 Result of 3-D measurement (color object)

5. 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 has no 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 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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