3-D Measurement of Objects in Unknown Aquatic Environments with a Laser Range Finder*

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***Abstract*— In this paper, we propose a three-dimensional (3-D) measurement method of objects in aquatic environments whose refractive indices or boundary shape of the refraction are unknown with a laser range finder.**

When applying vision sensors to measuring objects in liquid, we meet the problem of an image distortion. It is caused by the refraction of the light on the boundary between the air and the liquid, and the distorted image brings errors in a triangulation for the range measurement. Therefore, 3-D measurement of objects in liquid requires a geometrical analysis that takes refraction effects into account.

In the analysis, it is indispensable to know the boundary shapes that have discontinuity of refractive indices, and refractive index of liquid. Our proposed method takes refraction effects into account and estimates these unknown parameters to measure accurate 3-D shapes of objects in liquid.

Experimental results have shown the effectiveness of the proposed method.

***Index Terms*— 3-D measurement, Aquatic environment, Unknown environment, Refraction, Laser range finder**

I. Introduction

In this paper, we propose a three-dimensional (3-D) measurement method of objects in aquatic environments whose refractive indices or boundary shape of the refraction are unknown with a laser range finder.

3-D measurement of objects' shapes is a very important technique in several applications. Autonomous robots must work in various spaces now and in the near future, and it is necessary to measure objects not only in the air but also in various environments. Therefore, 3-D measurement of objects in liquid is also essential technique. For example, important samples like creatures that are pickled in formalin must be measured with care without contacting (Fig. 1(a)). The underwater observation such as the generation of sea floor maps and the examination of the ecology of underwater creatures by underwater robots is important, too.

As to 3-D measurement of objects, triangulation is a very effective method that has been so often employed. Here it should be noted that, in most cases, triangulation systems are designed under the condition that environments around imaging equipments and around target objects have the same refractive index. Therefore, such systems are invalid when we measure objects in liquid because of image distortions caused by refraction effects.

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(a) Sample pickled in formalin. (b) Refraction effects.

Fig. 1. Examples of objects in liquid.

Figure 1(b) shows an example of the distorted image that single rectangular object is in a cylindrical glass water tank. The edge of the object on the boundary between the air and the liquid looks discontinuous and it appears to that two objects exist.

This problem occurs not only when a vision sensor is set outside the liquid but also when it is set inside such as underwater observation with equipment protected in a waterproof housing.

Therefore, it becomes difficult to measure precise positions and shapes of objects when liquid exists because of the image distortion by the refraction of the light.

About the 3-D measurement in liquid, there are several studies. Acoustical methods using sonars are often used [1], [2], especially for underwater robot sensors [3], [4]. These methods can measure the rough shape of the sea floor and detect the existence of a shoal of fish. However, they don't 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. Therefore, the photogrammetric images acquired by cameras are effective for the precise 3-D measurement [5]–[7].

For this reason, 3-D measurement methods by using cameras are proposed. For example, stereo measurement method for quantitative photogrammetric analysis of underwater images using ray tracing is proposed [7]. However, the methods by using a stereo camera system have the problem that the corresponding points are difficult to detect when the texture of the object's surface is simple in particular when there is the refraction on the boundary between the air and the liquid. The method by the use of motion stereo images obtained with a moving camera [8] also has the problem that the relationship between the camera and the object is difficult to estimate with high accuracy because the camera moves. The surface shape reconstruction method of objects by using an optical flow [9] is not suitable for the accurate measurement, too.

Therefore, 3-D measurement methods of objects in liquid with a laser range finder are proposed [10]–[13]. In these methods, spot lights (*e.g.*, [10], [11]) or slit lights (*e.g.*, [12], [13]) from a laser are projected on objects' surfaces for the easy detection of the corresponding points.

When the positional relationship among a camera, a protecting glass, and a laser never changes, and the refractive index of liquid is constant, we can make a calibration table of relations between distances and pixel positions in advance and utilize this table for 3-D measurement [10], [13]. However, the calibration table is useless when they changes, *e.g.*, 3-D measurement of objects in water tank from outside of it. The latter case is more difficult than the former case, and is a general problem. Therefore, we propose 3-D measurement methods of objects in a cylindrical glass vessel [11] and in a cuboid glass water tank [12].

These previous works that can measure objects in liquid from outside of a vessel assume the following conditions [11], [12].

1) A vessel in which an object exists can be moved. For example, a vessel can be located on a rotational table.
2) The shape of boundaries where two media of different refractive indices meet is known.
3) Refractive index of each region is known.

As to the assumption 1), we cannot move a vessel if it is heavy or fixed, *e.g.*, observation of creatures from outside of water tanks in aquariums. To treat this problem, a laser range finder is mounted on a manipulator in our method (Fig. 2). The positions and the directions of the laser range finder can be changed freely by using the 6DOF manipulator, and irradiated points of laser on objects in liquid can be also controlled. Our method can measure irremovable objects or objects in an irremovable vessel by changing the view with the manipulator.

As to the assumption 2), quantitative analysis by ray tracing requires the locations and the shapes of boundaries where two media of different refractive indices meet. Therefore, we have to estimate the boundary shapes when they are unknown. It is rather easy to locate the boundaries when they are geometrically simple as planar or cylindrical, but the shape of vessel is not always geometrically simple, then the problem will become difficult to solve. The method takes advantage of the fact that a weak but detectable reflection of a laser beam is observed on the vessel surface that is not perfectly transparent in general. In this paper, we propose a method for 3-D measurement that reconstructs the shapes of a vessel and objects inside at the same time from a data set acquired by scanning of a laser range finder held on the manipulator. The method determines the vessel surface locations first by the ordinary triangulation, and then reconstructs the object surface coordinates by ray tracing [11].

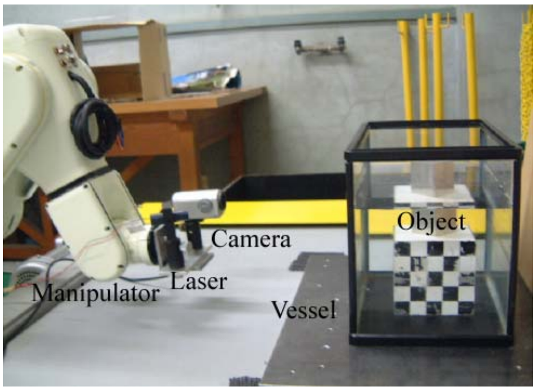


Fig. 2. Laser range finder equipped with manipulator.

As to the assumption 3), quantitative analysis also needs refraction index of each region. We decide the value of the refractive index in the case that the most consistent 3-D measurement result of objects in liquid can be obtained.

The composition of this paper is detailed below. In Section 2, the principle of the 3-D measurement and the process of the 3-D measurement of objects are explained. In Section 3, we verify our method with experiments and Section 4 describes conclusions.

II. Principle of Measurement

A. Procedure Outline

The proposed method reconstructs the shape of objects in a glass vessel filled with liquid by the procedure as shown below:

1) Set a laser range finder at a certain viewpoint by moving a manipulator.
2) Acquire an image of reflecting laser points.
3) Repeat 1) and 2) to cover the object surface of interest.
4) Extract laser point coordinates in each image.
5) Determine the shape of the vessel by triangulation.
6) Reconstruct the shape of the object by ray tracing while taking refraction effects into account.

Figure 3 shows the relation among the laser range finder, the object, and the vessel. The laser range finder consists of a laser and a camera whose components are a lens and an image plane usually made by CCD. A laser beam irradiates a vessel surface point S, and since the material of the vessel (*e.g.*, glass) cannot be perfectly transparent, a slight diffused reflection is observed by the camera, say point S is projected onto point S' on the image plane. At point S, the main portion of the laser beam transmits through the vessel surface while changing its direction by refraction at the surface. The refracted beam irradiates an object surface

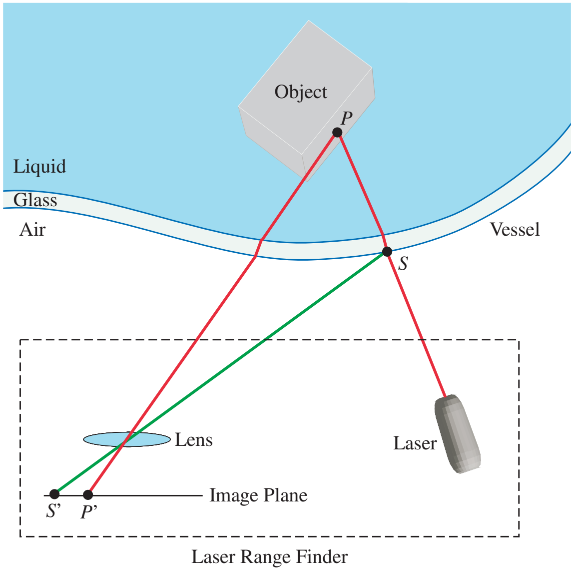


Fig. 3. Overview of 3-D measurement with a laser range finder.

point P. A diffused reflection at point P is observed by the camera, and point P is projected onto point P' on the image plane. The optical path from point P to point P' is determined by considering refraction effects at the vessel surface point.

In the method, a pair of images is taken for each viewpoint, one image is taken with laser irradiation (on-laser image), and the other without it (off-laser image). This is because laser points are easy to detect by finding differences between these two images.

B. Extraction of Laser Point Coordinates

A difference image is obtained by subtracting the off-laser image from the on-laser image both of which are taken from a same viewpoint. The difference image is converted into an image that has no geometrical distortion owing to a lens abbreviation [14]. From the distortion-free difference image, laser points are extracted by employing image processing techniques such as binarization, noise reduction, and region segmentation. The laser point coordinates are given as the coordinates of the centroid of each segmented region.

C. 3-D Measurement of Vessel Surface Points

The extracted laser points are mixture of those that are reflected on the vessel surface, reflected on the object surface, and also reflected on some other surface because of multiple reflections (Fig. 4).

In order to measure the shape of the vessel, the laser points caused by the vessel surface reflection should be selected from the mixture. Here, we have the following rules in general.

1) Epipolar geometry is utilized. The trajectory of a laser beam in the air is given definitely in the image when the camera and the laser are calibrated beforehand. Therefore, the selection of the laser point reflected on the vessel surface is realized by checking whether the point lies on the epipolar line (a straight line).
2) If the laser is set to the left (or right) of the camera, the laser beam flies across the image from left to right (or right to left).

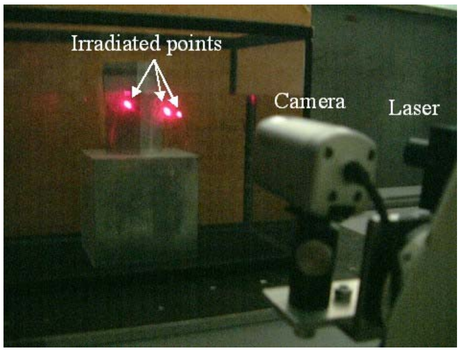
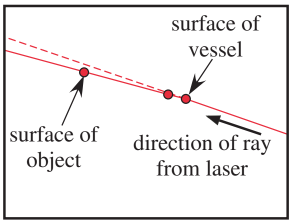
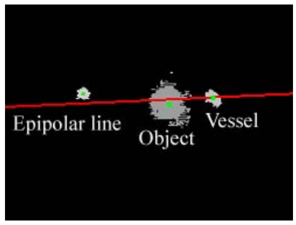


Fig. 4. Irradiated points.



(a) Epipolar constraints.



(b) Enlarged image around irradiated area.

Fig. 5. Extraction of irradiated points.

By applying the above rules, the laser point on the vessel surface is extracted as the left-most (or right-most) point along the epipolar line in the image (Fig. 5). The 3-D coordinates of the laser points on the vessel surface are calculated by triangulation from the image coordinates of the extracted laser points. The relations between the manipulator coordinate system and the world coordinate system, and between the manipulator coordinate system and the laser range finder coordinate system are known beforehand, then the vessel surface coordinates can be converted into the world coordinates.

D. 3-D Measurement of Object Surface Points

Using the vessel surface information obtained above, the 3-D coordinate of a point on the object surface is calculated by applying ray tracing. In Fig. 6, L_1 and L_2 are the intersections of the laser beam and the boundary between the air and glass, and the boundary between the glass and liquid, respectively. C_1 and C_2 are the intersections of the line of sight from the camera and the boundaries. Since the geometry of the laser range finder and the 3-D description of the surface are known, the coordinates of L_1 and C_1 are determined, and then by Snell's law, ray vectors can be traced definitely. Among ray vectors, the following equations are given, where $\vec{d}_{l1}$, $\vec{d}_{l2}$, and $\vec{d}_{l3}$ are unit ray

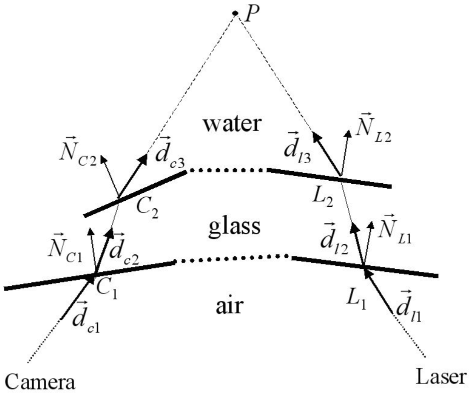


Fig. 6. Ray tracing.

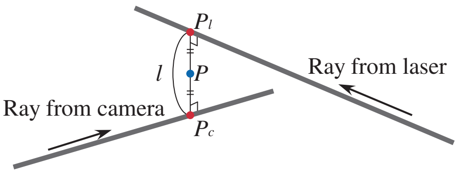
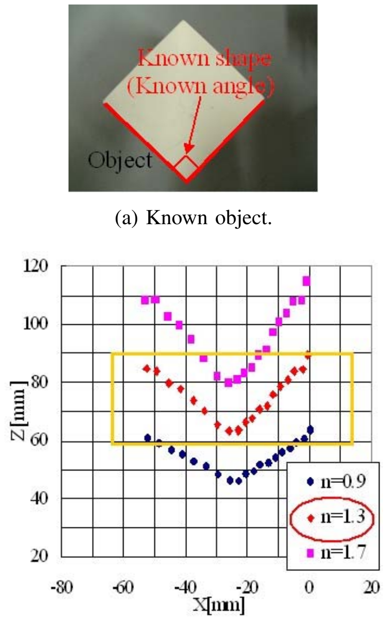


Fig. 7. Determination of object's surface.



(a) Known object.

(b) Shape reconstruction.

Fig. 8. Estimation of refractive index from known object's shape.

vectors of the laser, $\vec{d}_{c1}$, $\vec{d}_{c2}$, and $\vec{d}_{c3}$ are unit ray vectors of the line of sight from the camera, $\vec{N}_{L1}$, $\vec{N}_{L2}$, $\vec{N}_{C1}$, and $\vec{N}_{C2}$ are unit normal vectors at individual vessel surface points, and n_1, n_2, and n_3 are the refractive indices of the air, glass, and liquid, respectively. A symbol "$\times$" denotes a vector product.

$$\frac{|\vec{d}_{l1} \times \vec{N}_{L1}|}{|\vec{d}_{l2} \times \vec{N}_{L1}|} = \frac{|\vec{d}_{c1} \times \vec{N}_{C1}|}{|\vec{d}_{c2} \times \vec{N}_{C1}|} = \frac{n_2}{n_1}, \tag{1}$$

$$\frac{|\vec{d}_{l2} \times \vec{N}_{L2}|}{|\vec{d}_{l3} \times \vec{N}_{L2}|} = \frac{|\vec{d}_{c2} \times \vec{N}_{C2}|}{|\vec{d}_{c3} \times \vec{N}_{C2}|} = \frac{n_3}{n_2}. \tag{2}$$

Theoretically, intersection P of the two rays, $\vec{d}_{l3}$ and $\vec{d}_{c3}$, is the point on the object surface, but practically it is not always true because of noises and quantization artifacts in the image processing. Consequently, we select the midpoint of the shortest line connecting two points each of which belongs to each ray (Fig. 7). The reliability of the point location is estimated by the distance between these two rays (l). Miss-selection of false laser points can be avoided by checking whether the distance l is small enough within an error tolerance or not, if there exist multiple laser points in the image except the point corresponding to the vessel surface.

The detail of 3-D measurement method by using ray tracing and the detail of formulation are explained in [11].

E. Estimation of Refractive Index

We must measure objects in several situations with the inclusion of under unknown refractive index of liquid (n_{liq}). In these cases, unknown refractive index n_{liq} is estimated with the exploratory search.

In concrete terms, we decide the value of the refractive index in the case that the most consistent 3-D measurement result of an object in liquid is obtained, while the value of the refractive index is changed gradually.

When there is no object whose shape is already known in the field of view, we can use the distance between the ray from the camera and that from the laser (l in Fig. 7). It can be said that the value of the refractive index in case that the distance between two rays becomes the smallest is a correct one. Therefore, n_{liq} can be estimated by using following optimization.

$$n_{liq} = \arg\min_{n} \sum_{i} l_i(n), \tag{3}$$

where $l_i(n)$ is the calculated distance between two rays at i-th measurement point when the refractive index is presumed as n.

This estimation method needs no assumption and can be used in all situations. However, the accuracy of estimated value strongly depends on the accuracy of the camera calibration. In other words, this method is not robust against the calibration errors.

When there is a known object in the field of view, we can estimate the value of the refractive index from known object shape. Figure 8 (a) shows an example of known shape (known angle). The angle between two planes is 90 deg in this case, and Fig. 8 (b) shows the reconstruction results of the object shape when we assume the refractive index is 0.9, 1.3, 1.7, respectively. The angle is the closest to 90 deg when the refractive index is 1.3, and this value can be adopted as the refractive index of liquid.

Of course, the length of known edge, flatness of known plane, and curvature of known surface can be utilized for estimating the refractive index while the angle between two

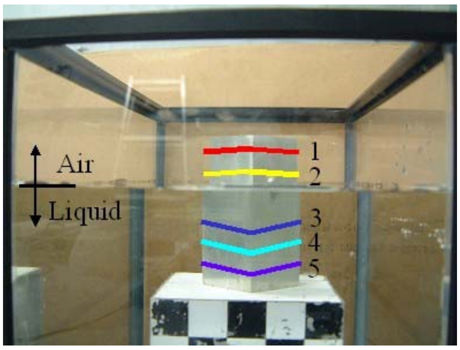


Fig. 9. Overview of measured object.

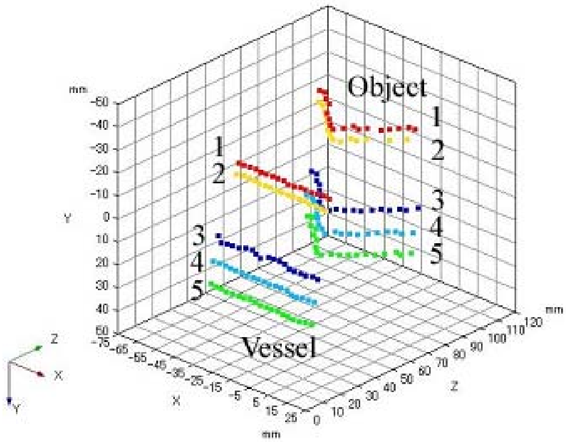


Fig. 10. Experimental result (bird's eye view).

planes is used in Fig. 8. In this case, n_{liq} can be estimated by using following optimization in the same way of the unknown case.

$$n_{liq} = \arg\min_{n} \sum_{j} \alpha_j (K_j - M_j(n))^2, \tag{4}$$

where K_j is a known parameter such as edge length and angle between two planes, j is the number of known parameters, $M_j(n)$ is the measurement results of known parameters when the refractive index is presumed as n, and α_j is a coefficient, respectively.

III. Experiments

The measurement equipment consists of a CCD camera, a laser diode device, and a 6DOF manipulator. They are fixed with each other rigidly.

At first, camera parameters were calibrated by using the planner pattern on which surface checked patterns are drawn in an aerial environment. In this step, the image distortion derived from the lens distortion was removed [14]. In the next step, the relationship among the camera, the laser, and the manipulator was calibrated by observing the planner pattern with the camera while changing the position and the direction of the manipulator.

A. 3-D Measurement of Unknown Object in Unknown Vessel

A preliminary experiment was made with a cuboid glass water tank shown in Fig. 9. The water tank is filled with water.

The refractive indices for the air, glass, and water were regarded as 1.0, 1.5, and 1.33, respectively. The thickness of the tank was 2.1mm. The manipulator was scanned five times almost horizontally along the front surface of the tank with the elevation interval of 50mm. In three cases the laser irradiated the under water portion of the object (3–5 in Fig. 9), while in the rest two it irradiated the above water portion (1–2 in Fig. 9).

First, the coordinates of a tank surface were obtained by detecting the laser points on the surface for each scan. The planar equation of the surface was calculated by a least mean square error method.

Next, the coordinates of the object in water were obtained by ray tracing of the laser points of the object surface. In the experiment, the tank surface is a plane, then the normal vectors are constant.

Figure 10 illustrates the experimental result showing the measurement points as a bird view. Five sets of points in front are the points on the tank surface, and five L-shape point sets are points on the object surfaces. Since the world coordinate system had a little slant to the tank, the tank surface is shown a little inclined.

Figure 11 is a top view of the vessel and object surfaces. Figure 11 (a) shows 3-D measurement result with consideration of refraction effects, and it shows that the points belonging to the same surface overlap well together, while Fig. 11 (b) shows the result without consideration of refraction effects.

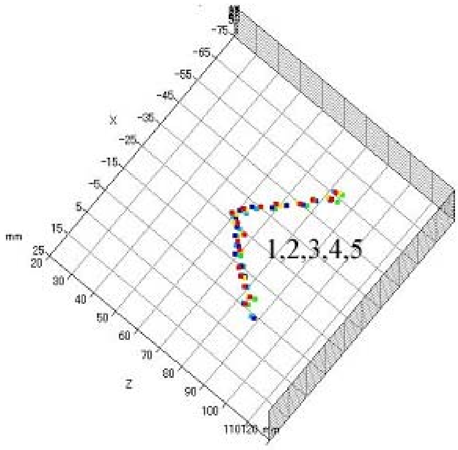
Therefore, it is found out that the consideration of the refraction of the light is very important and effective when objects in liquid are measured.

B. 3-D Measurement under Unknown Refractive Index

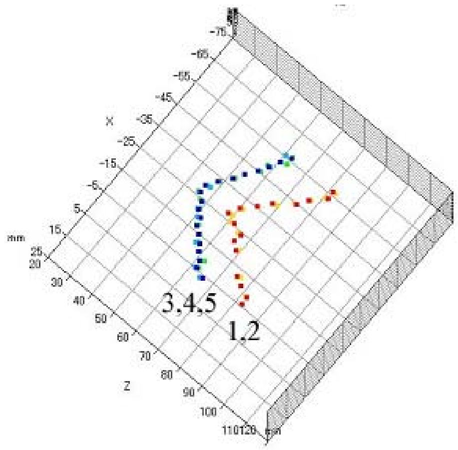
Unknown refractive index was estimated when there is an object whose shape is known in the field of view. If we can set a known object in the tank, this method can be applied. In addition, if we cannot set it in the tank, this method can be applied by setting the known object opposite side of the water tank in air.

Figure 12 shows the relationship between the angle between two plane of known object and the refractive index of unknown liquid. The horizontal axis indicates the refractive index, and the vertical one indicates the angle between two surfaces of the object. An approximated curve shows that the refractive index is 1.36, because the angle is 90 deg, while the true value is 1.33 (water). In this case, calibration error triggered little estimation error of refractive index. However, this result shows that unknown refractive index can be estimated quite correctly with our method.

If there is no known object in the field of view, we can estimate it by using the distance between the ray from the camera and that from the laser (Fig. 7).



(a) With consideration of refraction effects.



(b) Without consideration of refraction effects.

Fig. 11. Experimental result (top view).

From these results, it is verified that our proposed method can measure the accurate 3-D shapes of objects in liquid with ray tracing technique by estimating the boundary shapes where the light is refracted and the value of refractive index.

IV. Conclusions

This paper proposed a method for 3-D shape measurement of objects in liquid. The method employs a laser range finder held on a manipulator to obtain laser points on the object surface and the vessel surface simultaneously.

At first, from images taken with the movement of the manipulator, the method extracts laser points on a surface of the vessel, and obtains the locations and normal vectors of points on the surface. Then, the method extracts points on the object surface and calculates their 3-D coordinates by ray tracing using the vessel surface information. The refractive index can be also estimated from advanced known information. Experiments were made with a cuboid glass water tank and validity of the method was shown.

As the future works, we need a further study using vessels and objects of various shapes to confirm the effectiveness of the method.

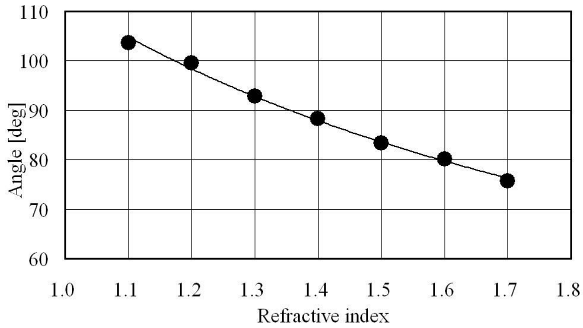


Fig. 12. Estimation of refractive index.

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