3-D Shape Reconstruction of Objects in Water by a Laser Range Finder Held on a Manipulator

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ABSTRACT

Three-dimensional shape reconstruction of objects in water by observing from outside requires a geometrical analysis which takes the refraction effect into account. In the analysis, it is indispensable to know the shape of a vessel whose surface has discontinuity of the refractive index. This paper proposes a method for three-dimensional measurement which determines the vessel shape at first and then reconstructs the object shape, by employing a laser-range finder which gives measurement points on the object and the vessel surface simultaneously. Experimental results have shown the effectiveness of the proposed method.

KEY WORDS: 3D measurement, Refraction, Laser Range Finder, Manipulator

INTRODUCTION

Shape reconstruction of three-dimensional objects is a very important issue in computer vision., and triangulation is a very effective technique which have been so often employed. Here it should be noted that, in most cases, triangulation systems are designed under the condition that environments around imaging equipment and around target objects have the same refractive index. Therefore, such systems are invalid when we measure objects in a vessel containing water from outside because of image distortions caused by the refraction effect (Fig.1). This problem also occurs when we make underwater observation with equipment protected in a waterproof housing.

Fig.1. Refraction effect.

To solve the above problem, Li *et al* proposed a method for quantitative photogrammetric analysis of underwater images using ray tracing[1]. Based on their analysis, Nakayama *et al* reported on a stereo vision calibration method for observation of objects in a cuboid glass water tank[2]. Yamashita *et al* proposed a light stripe projection method for shape reconstruction of objects in a cuboid glass water tank [3], and also proposed a method for measuring objects in a cylindrical glass vessel by using a range finder with a laser beam[4]. Quantitative analysis by ray tracing requires the location of boundaries where two media of different refractive indices meet. 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.

In this paper, we propose a method for 3-dimensional measurement which 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 (LRF) held on a manipulator. The method takes advantage of the fact that a weak but detectable reflection of a laser beam is observed on the vessel surface which is not perfectly transparent in general. The method determines the vessel surface locations first by ordinary triangulation, and then reconstructs the object surface coordinates by ray tracing[1]. In the following, the principle of measurement and experimental results are given.

PRINCIPLE OF MEASUREMENT

Procedure Outline

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

1) Set a LRF at a 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.

Figure 2 shows the relation among the LRF, the object, and the vessel. The LRF 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 vessel material (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 point *P*. A diffused reflection at point *P* is observed by the camera, point *P* is projected onto point *P’* on the image plane. The optical path from point *P* to point *P’* is determined by considering the refraction effect at the vessel surface point.

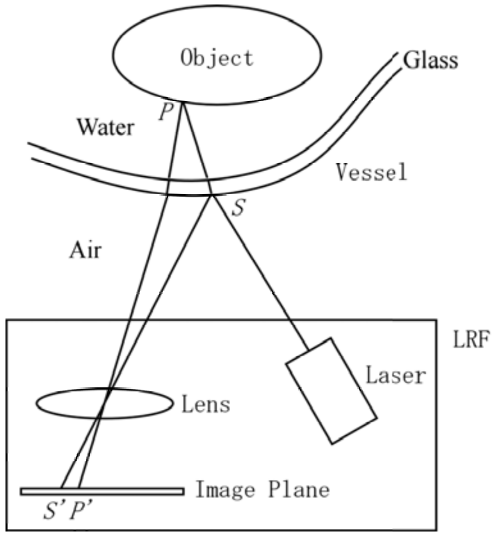

Fig.2. System geometry.

Image acquisition

In the method, a pair of images are 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 the two images in a pair.

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 which has no geometrical distortion owing to a lens abbreviation. 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.

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

1. 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 trajectory (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).

By applying the above rules, the laser point on the vessel surface is extracted as the left-most (or right-most) point along the trajectory line in the image. 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 relation between the manipulator coordinate system and the world coordinate system is known beforehand, then the vessel surface coordinates are converted into the world coordinates by LRF-manipulator transformation.

3-D measurement of object surface points

Using the vessel surface information obtained above, the 3-D coordinates of a point on the object surface is calculated by applying ray tracing. In Fig.3, 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 water, 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 LRF 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 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, n_1, n_2, and n_3 are the refractive indices of the air, glass, and water, respectively. A symbol "×" denotes a vector product.

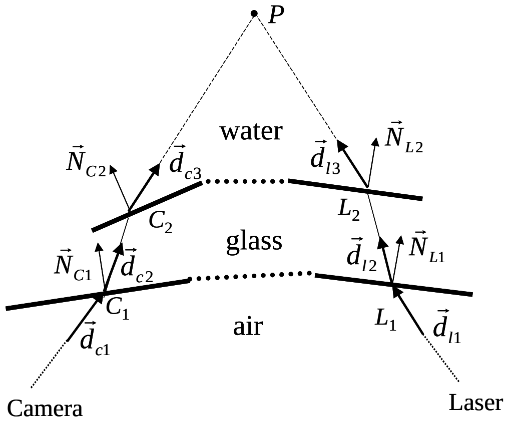

Fig.3. Ray tracing.

$$\left|\vec{d}_{l1} \times \vec{N}_{L1}\right| / \left|\vec{d}_{l2} \times \vec{N}_{L1}\right| = \left|\vec{d}_{c1} \times \vec{N}_{C1}\right| / \left|\vec{d}_{c2} \times \vec{N}_{C1}\right| = n_2 / n_1 \qquad (1)$$

$$\left|\vec{d}_{l2} \times \vec{N}_{L2}\right| / \left|\vec{d}_{l3} \times \vec{N}_{L2}\right| = \left|\vec{d}_{c2} \times \vec{N}_{C2}\right| / \left|\vec{d}_{c3} \times \vec{N}_{C2}\right| = n_3 / n_2 \qquad (2)$$

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 noise and quantization artifact in image processing. So, we select the midpoint of the shortest line connecting two points each of which belongs to each ray. The reliability of the point location is estimated by the distance between these two rays, and by checking whether this distance is small enough within an error tolerance or not, misselection of false laser points can be avoided, if there exist multiple laser points in the image except the point corresponding to the vessel surface.

EXPERIMENT

A preliminary experiment was made with a cuboid glass water tank shown in Fig.4. The refractive indices for the air, glass, and water were regarded as n_1=1.0, n_2=1.5,and n_3=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 5cm. In three cases the laser irradiated the under water portion of the object, while in the rest two it irradiated the above water portion.

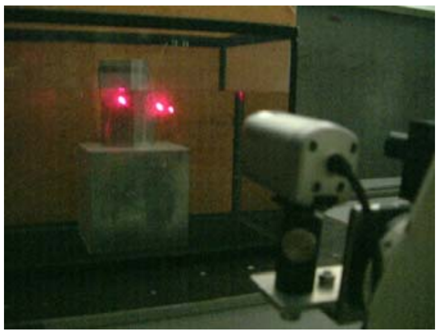

Fig.4. Experimental Setup.

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 object surface. In the experiment, the tank surface is a plane, then the normal vectors are of a same constant.

Figure 5 illustrates the experimental result showing the measurement points as a bird view. Five sets

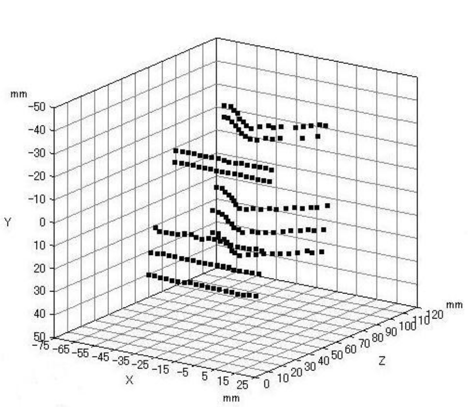

Fig.5. Experimental result (a bird’s eye view).

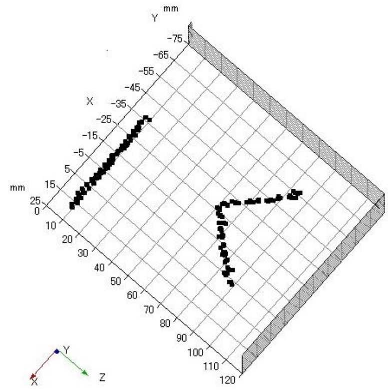

Fig.6. Experimental result (a plan view).

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 6 is a plan view of the vessel and object surfaces, and it shows that the points belonging to the same surface overlap well toghther. The angle between the two adjacent surface planes of the object was calculated by constructing two planes from the detected lines belonging to each object surface, and we obtained the angle of about 92 degrees, which shows the validity of the method.

CONCLUSION

This paper proposed a method for 3-D shape reconstruction of objects in water. 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. A preliminary experiment was made with a cuboid glass water tank and validity of the method was shown. To confirm the effectiveness of the method, we need a further study using vessels and objects of various shape.

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