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Three-Dimensional Shape Measurement of a Transparent Object Using a Rangefinding Approach

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Abstract – ***This paper describes a non-contact optical measuring approach by which to measure the three-dimensional (3D) shape of a transparent object such as a glass panel or an acrylic plate. In conventional approaches to obtain the 3D shape of a transparent object, contact-type sensors have been widely used. However, the measurement accuracy of contact-type sensors is susceptible to the influence of various factors . In this paper, we propose a novel triangulation-based rangefinding approach that can be applied to the 3D shape of a transparent object or to an opaque object. The rangefinder is based on the fact that the light projected onto the surface of a transparent object is in part reflected by the surface, though the majority of the projected light is transmitted through the surface. From the experimental results, the proposed rangefinding approach has the advantage that it can easily measure the 3D-shape of an object even if the object reflects or transmits light, depending on its location. As a result, we conclude that the proposed approach has great potential for a wide range of industrial applications.***

I. INTRODUCTION

Many practical tasks in industry, such as automatic inspection or robot vision, often require the determination of three-dimensional (3D) shapes by use of non-contact optical techniques. Among the various optical techniques, the triangulation-based laser rangefinding technique is one of the widely used methods in industrial applications from the viewpoint of speed, accuracy, and reliability. However, the triangulation-based rangefinder has some drawbacks. The most severe is that the range of measurable objects is limited. It is difficult to apply the technique to 3-D shapes of both specular objects that has a specular reflection and transparent objects that allows the light to pass through.

This paper describes a non-contact optical measuring approach by which to measure the three-dimensional (3D) shape of a transparent object such as a glass panel or an acrylic plate. In conventional approaches to obtain the 3D shape of a transparent object, contact-type sensors have been widely used. However, the measurement accuracy of contact-type sensors is susceptible to the influence of various factors [1].

Recently, non-contact 3D shape measuring approaches for a transparent object have been proposed. However, because the principle of these approaches strongly depends on the transparent properties, the measurable objects are limited to transparent objects [2].

If a rangefinding approach, which has been previously used for an opaque object, can be applied to a transparent object as well, the rangefinding approach could be effectively applied for a number of industrial 3D shape measurement applications. However, to our knowledge, such a rangefinding approach does not yet exist.

In this paper, we propose a novel triangulation-based rangefinding approach that can be applied to the 3D shape of a transparent object or to an opaque object. The rangefinder is based on the fact that the light projected onto the surface of a transparent object is in part reflected by the surface, though the majority of the projected light is transmitted through the surface [3]. Since it is known that the reflected light from a transparent object is a specular reflection, we attempted to apply our previously proposed rangefinding approach [4], which can be applied to specular and Lambertian objects, to measure the 3D shape of a transparent object. The objective of the present investigation was to experimentally examine the feasibility of this approach. This paper describes the principle of the rangefinding approach, the system configuration embodying that principle, and the experimental results.

II. CHARACTERISTICS OF TRANSMISSION AND REFLECTION OF A TRANSPARENT OBJECT

Fig.1 shows a physical situation in which a light is projected onto the surface of a transparent object. In this figure, the front surface of the object is defined as A and the rear surface is defined as B. In this situation, unless transmittance of an object is 100%, the projected light 1 is in small part reflected by the outside of the surface A, and the bulk is transmitted through the surface A. The reflected light from outside of the surface A generates the light 2. The light 3, transmitted through the surface A, is in part

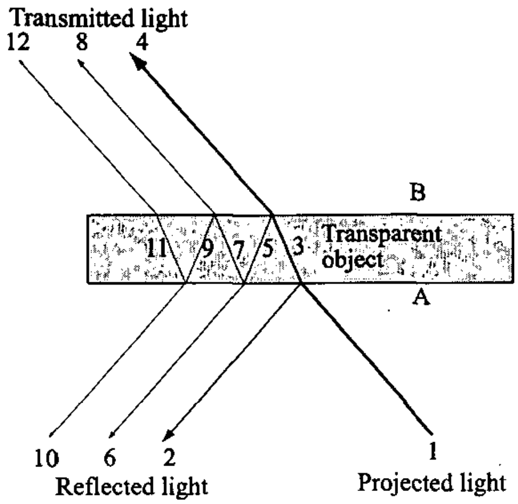


Fig.1 physical situation in which a light is projected onto the surface of a transparent object.

transmitted through the surface B, and generates the light 4. The light 3 is also in part reflected by the inside of the surface B, and generates the light 5. The light 5 is transmitted through the surface A, and generates the light 6.

Now we let the intensity of the projected light be a, and we let the transmittance and the reflectance of the object be t and r $(=1-t)$, respectively. In this way, the light transmitted through the surface A repeats transmission and reflection in the transparent object. Then, the intensity of each light is estimated as follows:

Projected : light 1 : a

Reflected : light 2 : ar , light 6 : $atrt = at^2r$,
light 10: at^2r^3

Transmitted : light 4 : $at^2 = a(1-r)^2$,
light 8 : at^2r^2 , light 12 : at^2r^4 .

Inside : light 3 : $at = a(1-r)$, light 5 : atr
light 7: atr^2 , light 9: atr^3 ,
light 11: atr^4

Given that the relation of $t >> r$ holds in the case of the transparent object with a high degree of transparency, the types of reflected light that can be in sight at once is at most two: light 2 and light 6. Given that it is known that the light reflected from the surface of the transparent object has specular reflectance, the 3D shape of the transparent object can be measured by applying the method for specular objects. Therefore, we applied the measuring method for specular objects to the 3D shape measurement of the transparent object.

III. 3-D SHAPE MEASURING PRINCIPLE FOR TRANSPARENT OBJECTS

Based on the above observation, we applied our previously proposed rangefinder, which is based on detecting the position and the incident angle of the light, to the 3D shape measurement of a transparent object.

In order to realize the 3-D shape measurement of transparent objects, we used the characteristics that the reflected light from the surface of transparent objects is the specular reflection. We will begin by considering the characteristics of specular reflection.

Fig.2 shows the characteristics of the specular reflectance. In Fig.2(a), the light projected onto Object 1

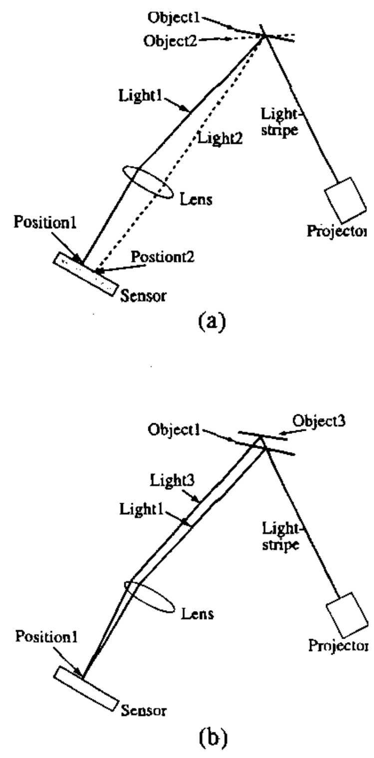


Fig.2 Reflection from the surface of transparent objects

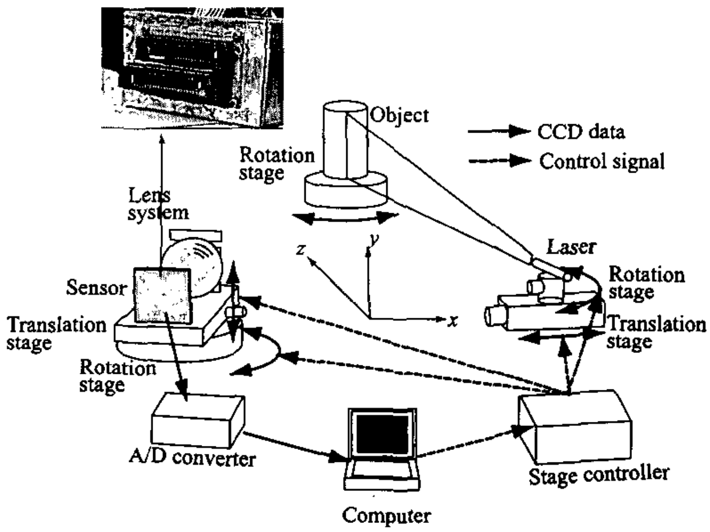


Fig.3 Configuration of the rangefinder used for the experiment.

reaches the received position 1 via the path of Light 1. In the case of Object 2, which is in the same position as Object 1 but in a different in orientation, the light is received at Position 2 on the image sensor via the path of Light 2. In spite of Object 1 and Object 2 located at the same position, each reflected light from Object 1 and Object 2 is received at the different pixel position on the image sensor. On the other hand, in Fig.2(b), although Object 1 and Object 3 are located at different positions, the received position on the image sensor is the same. Under these conditions, it is difficult that we easily compute the 3-D shapes of specular objects based on the triangulation principle. We thus applied the previously developed rangefinder for specular objects to measuring the 3-D shapes of transparent objects.

Fig.3 shows the configuration of the rangefinder used for the experiment. The rangefinder consisted of a semiconductor laser diode, a measured object, a lens system, and an image sensor. The image sensor, which is the core of the rangefinder, has the ability to simultaneously detect the position and the incident angle of a light [5]. As shown in Fig.2, the image sensor consists of two array-type sensors whose depth positions are slightly different. The image sensor detects the pixel position of the light stripe using the deeper-sided sensor array. The image sensor also detects the incident angle of the light stripe in terms of the difference between the two peak positions of the light stripe that their two sensor arrays detect.

When the coordinate system is used, as shown in Fig.4, the 3D position of a projected point onto the object is calculated as follows:

$$x = z\tan(\alpha_x + \alpha) - s_1 \cos\alpha\{\tan(\alpha_x + \alpha) - \tan\alpha\} \quad (1)$$

$$z = \frac{d + s_1 \cos\alpha\{\tan(\alpha_x + \alpha) - \tan\alpha)\}}{\cot\gamma + \tan(\alpha_x + \alpha)} \quad (2)$$

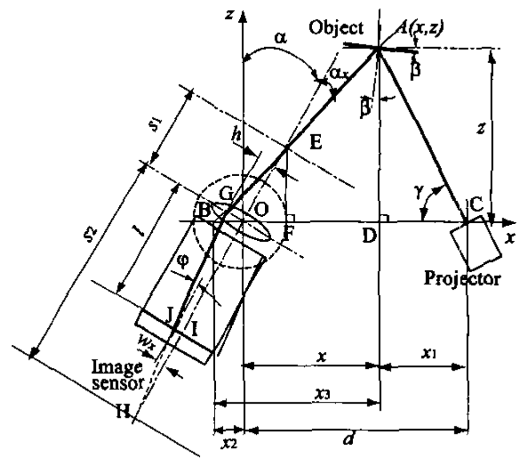


Fig.4 Coordinate system

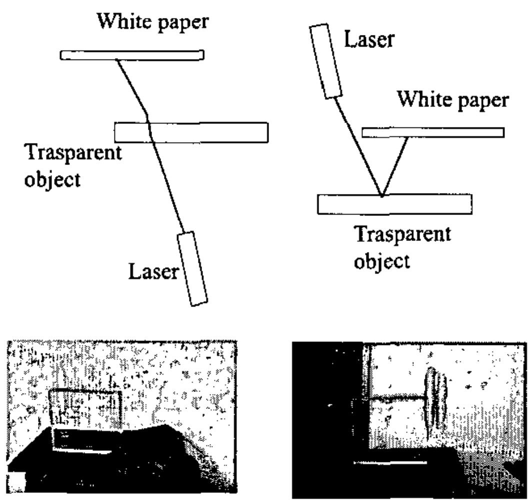
$$s_1 = \frac{f \cdot (w_x + l \tan\varphi)}{w_x + (l - f)\tan\varphi} \tag{3}$$

$$\alpha_x = \tan^{-1}\left(\frac{h}{s_1}\right) \tag{4}$$

The deatailed development of the equation is published in reference 4 and 5. The variable φ in the equation is the incident angle of the light-stripe onto the image sensor. To allow the rangefinder to measure the incident angle is one of the most striking characteristic. The above equation can apply to specular and Lambertian objects as well as to transparent objects.

IV. EXPERIMENTAL RESULTS

Fig.5 shows the observed results when a light-stripe generated by the semiconductor laser diode was projected onto a transparent acrylic plate. Fig.5 (a) shows the characteristics of transmission. The light-stripe transmitted thorough the acrylic plate was projected onto a white sheet of paper, which was located over the acrylic plate as shown in Fig.5 (a). From Fig.5 (a), it can be seen that one light-stripe is visible on the white paper. Fig.5 (b) shows the characteristics of reflection. The light-stripe reflected from the acrylic plate was projected onto a sheet of white



(a) (b)

Fig. 5 Observed results when a light-stripe was projected onto a transparent acrylic plate.

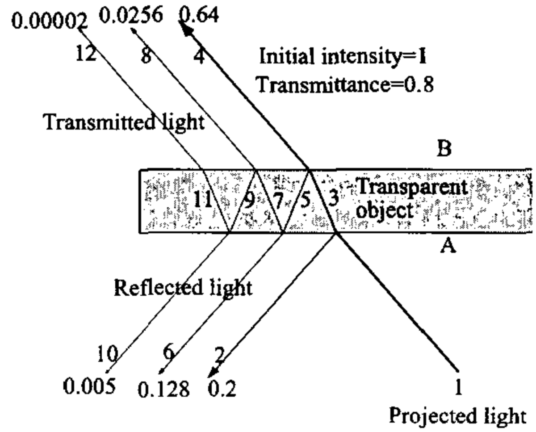
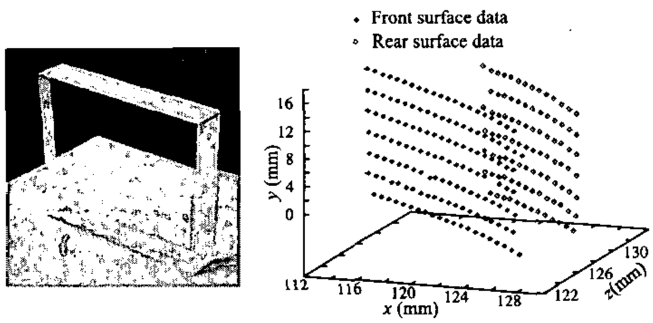


Fig.6 Calculated intensity of transmitted light and reflected light in a transparent object/

paper, which was located toward the light-stripe generator. From Fig.5 (b), it can be seen that in this case, two light-stripes were visible. The observed results could easily be predicted based on the following theoretical consideration.

Fig.6 shows the light intensity calculated by the consideration of section II. When we let the initial intensity of the light-stripe be 1, the transmittance of the acrylic plate be 0.8, and the reflectance of the acrylic plate be 0.2, then the intensities of all light-stripes shown in Fig.1 are calculated as follows: The intensities of light 4, light 8, and light 12 on the transmitted side are 0.64, 0.0256, and 0.0000205, respectively. The intensities of light 2, light 6, and light 10 on the reflected side are 0.2, 0.128, and 0.00512, respectively. In this way, the doubled reflection of the light by the surface of the transparent object greatly lowers the intensity of the light, and, as a result, one light-stripe was visible on the transmitted side, and two light-stripes were visible on the reflected side. Because two reflected light-stripes are observed even if only one light-stripe projects onto a transparent object, it is necessary for 3D shape measurement to determine whether the two respective reflected lights are a reflection from the front side or a reflection from the rear side of an object.

Fig.7 shows a 3-D shape measurement result for a transparent acrylic plate. The plate is 20mm in thickness, and the transmittance is about 0.8. In this case, although the two reflected light-stripe, which are the light reflected from both the front side and the rear side, was observed, it was difficult to distinguish between the light reflected from



(a) Masured object
(Transparent acylic plate)

(b) Masurement result
(3D display)

Fig.7 3-D shape measurement reslut (1)

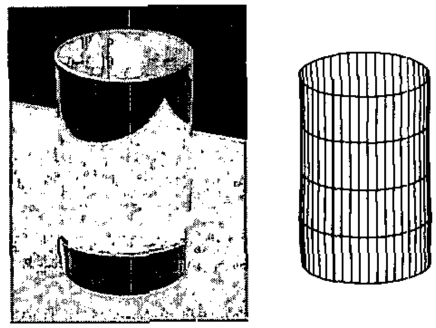
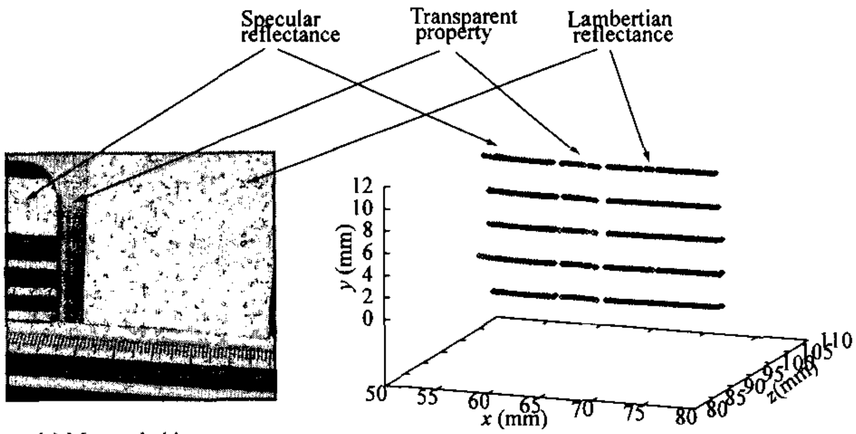


Fig.8 3-D shape measurement reslut (2)



(a) Masured object
(Transparent acylic plate)

(b) Masurement result
(3D display)

Fig.9 3D shape measurement result for an object that has a combination of transparent and opaque properties

the front side and the light reflected from the rear side by the light intensity in the present system. As shown in this figure, points on both the surface of the front side and on the rear side are plotted. The maximum relative error was about 1.1%.

Fig.8 shows the 3-D shape measurement result for a transparent cylinder. The diameter of the cylinder was 50mm, and the transmittance was about 0.8. The maximum relative error was about 1.5%.

Fig. 9 shows a 3D shape measurement result for an object that has a combination of transparent and opaque properties. Starting from the left of the object in the figure, surfaces with a specular, transparent, and Lambertian property are shown.

This figure demonstrates that the rangefinder is able to measure the 3D shape of such an object.

V. CONCLUSIONS

This paper described the 3-D shape measurement method of transparent objects using a previously developed rangefinder, which equipped with a new image sensor having the ablility to detect the incident angle of a light as well as its position. The basic concept is to use the specular reflected light from the surface of transparent objects. We built a prototype rangefinder for 3-D shape measurement of transparent objects. From the experimental results, the proposed rangefinding approach has the advantage that it can easily measure the 3D-shape of an object even if the object reflects or transmits light, depending on its location. As a result, we conclude that the proposed approach has great potential for a wide range of industrial applications.

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