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A New Method of Measuring the 3-D Shape and Surface Reflectance of an Object Using a Laser Rangefinder

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Abstract *– The present paper describes a newly proposed method for simultaneously measuring 3-D shape and surface reflectance of an object using a laser rangefinder. The original work of this method lies in the advantage that the proposed method measures the surface reflectance using the object itself that is used for the 3D shape measurement. Experimental results show that the proposed method was applicable to a noncontact industrial inspections, robot vision in automatic assembly, and reverse engineering*

Keywords *– Laser rangefinder, 3-D shape, Surface reflectance*

I. INTRODUCTION

Being able to measure the 3-D shape and surface reflectance properties of objects is an important issue in such industry applications as noncontact industrial inspections, robot vision in automatic assembly, and reverse engineering [1]. This paper describes a new method for measuring 3-D shapes and surface reflectance using a novel triangulation-based laser rangefinder designed to simultaneously provide both range data and the reflectance properties. The currently available laser rangefinders, which are based on active triangulation, usually operate by projecting on the scene, and observing the reflected light from a point that differs from that of emission [2]. The position of the reflected light from the illuminated surface is measured using a photosensitive device, and the Cartesian coordinates of the illuminated surface points are then computed. By introducing the scanning system of a light, we can acquire the 3-D shape information of objects.

Surface reflectances have traditionally been made with purpose-built devices known as gonioreflectometers [3], which are rare and expensive. Because, unlike when measuring the 3-D shape of an object, it is not easy to measure the surface reflectance of an object using a conventional rangefinder because of the complexity of the surface reflectance. Surface reflectance is roughly categorized into Lambertian and specular reflectance properties. Conventional rangefinders can easily measure the Lambertian reflectance components by exclusively detecting the intensity of a reflected light with the image sensor. However, since specular reflectance components are determined not only by the intensity of light, but also by the orientation of an object, because of the strong dependence of the object's orientation on the specular component, it is difficult to measure the surface reflectance using conventional rangefinders[4].

Researchers at the National Research Council of Canada [5] have attempted to determine the surface reflectance. However, their method has been limited to measured objects, because it was assumed the surface reflectance model, which means that the method cannot be applied to objects which are not suitable for the reflectance model they used.

We here propose a new laser rangefinder equipped with an image sensor which has the ability of simultaneously detecting the position of a light and the incident angle onto the sensor[6]. When the incident angle onto the sensor is determined, the orientation of an object can be mathematically estimated. As a result, this rangefinder can determine both the 3D shape and surface reflectance of an object.

This paper is organized as follows: an overview of surface reflectance is given in Section II, and a description of the principle and the configuration of the proposed rangefinder in Section III. In Section IV, a triangulation equation for the proposed rangefinder is derived. Section V presents the experimental results.

II. SURFACE REFLECTANCE

This section summarizes the various mechanisms of surface reflection. It is known that surface radiance may be decomposed into three primary reflection components: the diffuse lobe, the specular lobe, and the specular spike [4]. This reflectance framework covers the reflection of monochromatic light from surfaces ranging from smooth to rough. Fig. 1 shows the polar plots of these three components. The reflection components of this figure are plotted as functions of the sensor direction from a fixed source. The radiance detected on the sensor is the sum of the radiance from these three components. The diffuse lobe represents both an internal scattering mechanism and multiple and

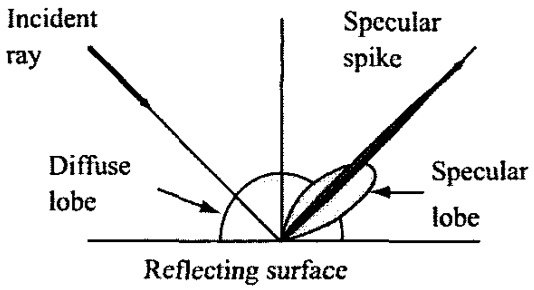


Fig. 1. Polar plots of the primary reflection components as functions of the sensor angle for a given source angle.

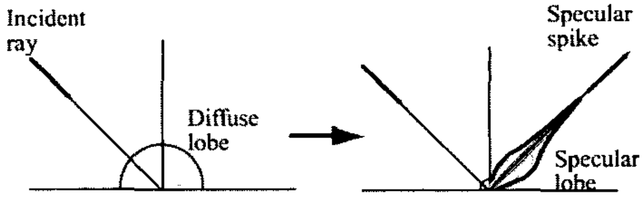
random reflections on the surface. As a result, the light reflected from the surface of the object diffuses hemispherically in all directions. The specular lobe spreads at a certain range around the specular direction, which is the angle at which the incident angle equals the reflected angled source. The specular spike represents a mirror-like reflection; it is nearly zero in all directions, except for a very narrow range around the specular direction. For a very smooth surface, the specular spike component is dominant. However, as the roughness of an object's surface increases, the specular spike component shrinks rapidly, and the specular lobe begins to dominate.

Many real-world applications involve various reflectance characteristics that exist in isolation. When a surface is quite rough, the diffuse lobe component is dominant and the other two components are nearly zero, which is called a Lambertian object, as shown in Fig. 2(a). When the the degree of the surface roughness is small, both the specular spike component and the specular lobe component rise, and the reflectance component is a combination of a mixture of the specular spike, specular lobe, and diffuse lobe reflectance components, which are called a hybrid object, as shown in Fig. 2(b) When the surface is not very rough, the reflectance component consists exclusively of a specular spike component, which is called a specular object, as shown in Fig. 2(c).

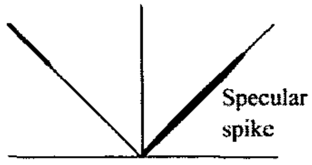
In this way, it is necessary to consider the characteristics of these three reflectance components in order to develop a rangefinder that can measure both the 3D shape and the surface reflectance of an object with various reflectance types.

III. PRINCIPLE OF THE PROPOSED RANGEFINDER

Fig. 3 presents a typical example of the light pattern of the reflected light for a hybrid object. In this figure, the specular spike component is larger than the other two components, and the angle of the peak in the reflected distribution is equal to



(a) Lambertian (b) Hybrid



(c) Specular

Fig. 2. Typical surface reflectance of a object.

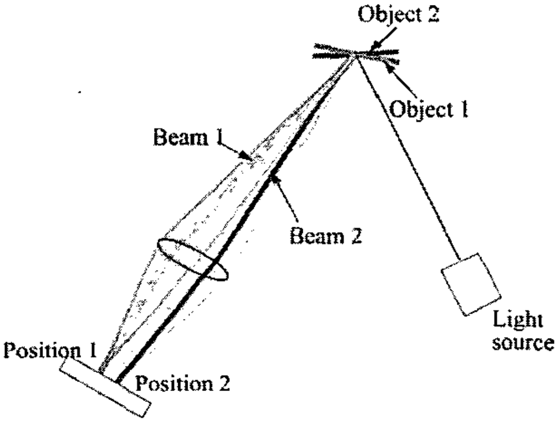


Fig. 3. The optical path of the reflected light from a hybrid object.

the angle of the specular reflection. Therefore, the reflected light in specular objects does not always pass through the center of the lens when objects are out-of-focus, as shown in Fig. 3. As a result, even if the light stripe is projected at the same angle, the reflected light may be received at a different pixel position of the image sensor by the interrelation of the projection angle and the orientation of the object surfaces. For example, in Fig. 3, the light projected onto Object 1 reaches the received position 1 via the path of beam 1. In the case of Object 2, which is in the same position as Object 1 but in a different orientation, the light is received at Position 2 on the image sensor via the path of beam 2. In spite of the fact that Objects 1 and 2 are located at the same position, the reflected light from Objects 1 and 2 are each received at a different pixel position on the image sensor.

Therefore, to realize a rangefinder that can be used for measuring both the 3-D shape and the reflectance of an object, it is necessary to acquire knowledge of both the incident positions and the incident angles of the light on the image sensor. To meet this requirement, we devised a new image sensor which has the ability of simultaneously detecting the position of a light and the incident angle onto the sensor [7].

IV. TRIANGULATION EQUATION OF THE PROPOSED RANGEFINDER

In this section, the triangulation equations for application to the proposed rangefinder, which uses the incident position and the angle of the light onto the sensor, are derived. Fig. 4 illustrates the geometry of this rangefinder and the parameters employed. The y-coordinate of the figure coincides with the vertical direction to the surface of this paper. In this figure, γ is a projected light-stripe angle, β is the surface's orientation, α is the optical axis of a lens and z co-ordinate, and α_x is the angle between the reflected light and the optical axis of a lens. φ is the incident angle to the sensor. The detailed development of the equations is published in references 8.

In the proposed rangefinder, the points of the object surface x and z are calculated as follows in equations (1) - (4).

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

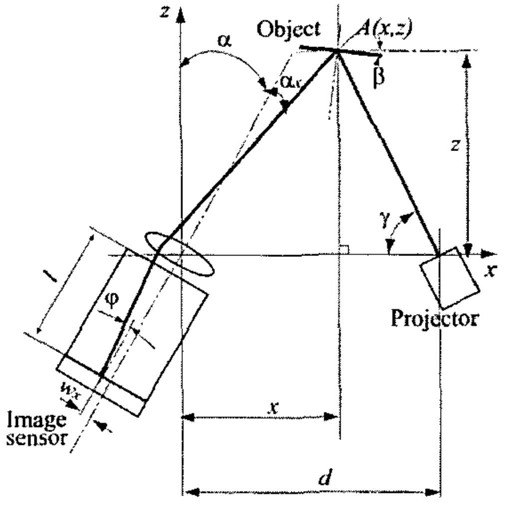


Fig. 4. Coordinate system of the rangefinder.

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

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

$$\alpha_x = \tan^{-1}\frac{w_x + (l - f)\cdot\tan\varphi}{f} \quad (4)$$

The orientation, β of an object is calculated by equation (5)

$$\beta = \frac{\alpha_x + \alpha + \gamma - \pi/2}{2} \quad (5)$$

We measured the surface reflectance as follows. Fig. 5 shows the geometry of surface reflection. The surface reflectance is expressed by the bidirectional reflectance distribution function (BRDF) [4]. The BRDF, f, completely describes the reflectance of an opaque surface at a single point. The BRDF is defined as

$$f(\theta_i, \phi_i, \theta_e, \phi_e) = \frac{dL(\theta_e, \phi_e)}{dI(\theta_i, \phi_i)} \quad (6)$$

where L is the reflected radiance in some outgoing direction, and I is the irradiance of the reflected surface form a small light source in some incoming direction.

Thus, when we measure two light intensities $L(\theta_e, \phi_e)$ and $I(\theta_i, \phi_i)$ at a given θ_e, ϕ_e, θ_i and ϕ_i, we can acquire the surface reflectance of an object.

The original work of this method is as follows: although the conventional surface reflectance method uses a sample that is made of the same material as the object being

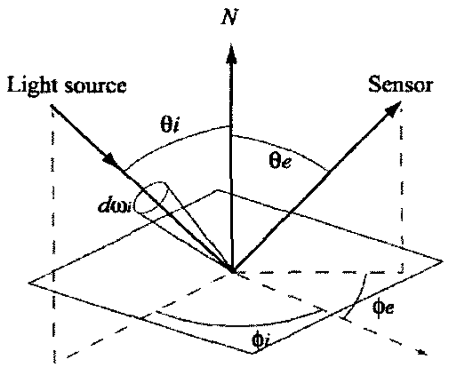


Fig. 5. Geometry of surface reflection.

measured, the proposed method measures the surface reflectance using the object itself that is used for the 3D shape measurement.

In calculating the BRDF with the measured values, information on the normal to the object's surface, that is, information on the surface orientation, is needed. Unlike with the conventional rangefinder, the proposed rangefinder can be used to measure the surface of the object using the above equation (5).

In this way, the proposed rangefinder can be applied to measure both the 3-D shape and the surface reflectance.

V. EXPERIMENT

A. Experimental setup and procedures

Fig. 6 shows the experimental setup. The setup consists of a laser, a laser scanning system, which are composed of a rotation stage and a translation stage, an object rotating system, and a sensor system that is mounted on the sensor moving system.

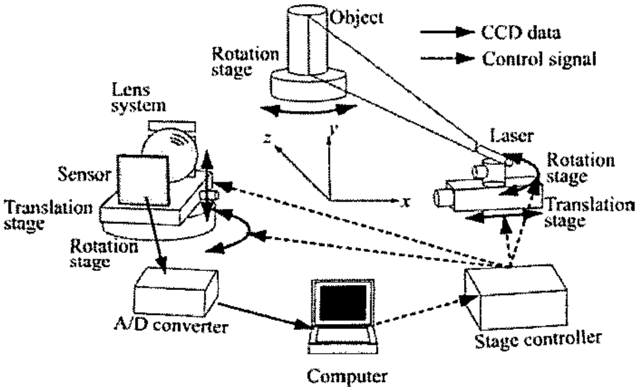


Fig. 6. Experimental setup.

A photograph of the experimental setup is in Fig. 7. The upper side of the figure is the image plane of the sensor. In this prototype sensor, two linear image sensors are arrayed step-wise, as shown in the figure. The lower side presents the general view of the experimental setup. The lens system is equipped with a field stop, which has several horizontal slits, in front of the lens. The proposed sensor, which can measure both the position and the incident angle of the light-stripe, is arranged behind the lens. It is necessary to be able to move the sensor's position in synchronization with the positions of the slits in the y-direction. We acquired the 3-D shape data by rotating the laser and by moving the sensor in the y-direction. In addition, we measured the surface reflectance by rotating the image sensor and laser at a fixed projected point on the measured object, as shown in Fig. 6, respectively.

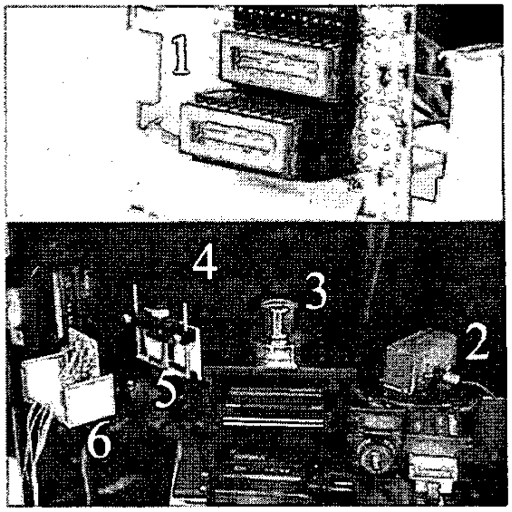


Fig. 7. A photograph of the experimental setup.

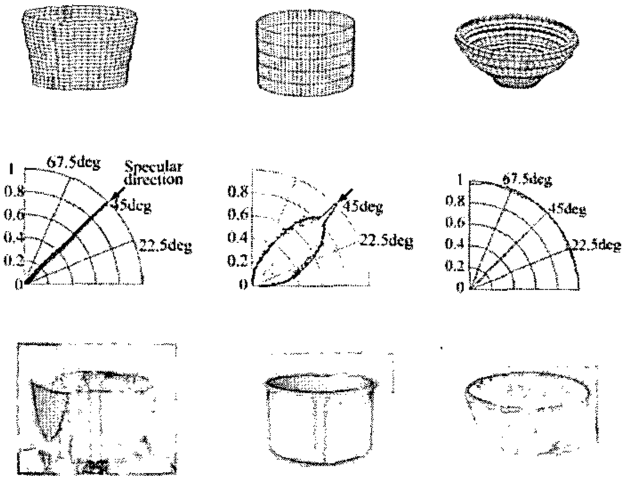
B. Experimental Results

We measured 3-D shapes and the surface reflectance of objects which had various levels of surface reflection. Contemporary Japanese sake cups were measured. The Japanese sake cups used for the experiment contained different kinds of reflectance. Such objects are therefore very suitable for confirming the usefulness of our rangefinder. Three types of sake cups, called Golden cup, Alumimum cup, and Igaoribe, were measured.

Fig. 8 shows the results obtained when measuring both surface reflectance and a 3-D shape. The upper side shows the 3-D shapes, the middle side shows surfeace reflectaces, and the lower side shows the photograph of the measured objects. From Fig. 8, we can find the surface reflectance of the measured objects as follows: (a) is an almost purely specular object, and is very shiny, (b) is a hybrid object, and (c) is a Lambertian This figure demonstrates that our rangefinder is able to measure the 3-D shapes and surface reflectance of various objects.

This rangefinder has the following two main advantages over ordinary rangefinders with regards to its ability to measure a wider range of reflectance:

1. The present rangefinder does not depend on a reflectance model. This demonstrates that the rangefinder can measure the 3D shape and surface reflectance of objects with any reflectance.



(a) Specular
(Golden cup)

(b) Hybrid
(Aluminum cup)

(c) Lambertian
(Igaoribe)

Fig. 8. Experimental results.

2. The present rangefinder enables us to realize the measuring principle by replacing the image sensor used or the ordinary rangefinder with our new image sensor. This rangefinder can use an ordinary light source and a scanning mechanism in their as-is form.

VI. CONCLUSIONS

In this paper, we have described a new method for simultaneously measuring 3-D shape and the surface reflectance of an object using a laser rangefinder. The laser rangefinder used for the method has the new image sensor, which was able to detect the incident position and the incident angle of a light. Using this laser rangefinder, we measured the incident positions and the incident angles for determining the 3-D shapes, and measured the light intensity and the incident angle for determining the surface reflectance of a measured objects. We experimentally demonstrated that the proposed method allows us to simultaneously measure the 3-D shape and the surface reflectance of three kinds of objects, which are specular, Lambertian, and hybrid objects.

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