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3D Shape Measurements Using Image Scanner with Multiple White Light Sources

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Abstract – *In this paper, we propose a 3D shape measurement method using an image scanner which has multiple white light sources. Since the reflectance intensity depends on the object shape and color (albedo), the object shape should be estimated with the albedo simultaneously. Here, we propose two algorithms to estimate the object shape and albedo, and discuss the effectiveness of these algorithms by the shape measurement experiments using the synthetic images. In result, the method which iterates the shape estimation using the formulations eliminating the albedo parameters and the albedo estimation by the photometric models can reconstruct the object shape accurately even if the albedo parameters are completely unknown.*

Keywords – *3D Shape Measurement, Image Scanner, Multiple White Light Sources, Photometric Stereo, Albedo Estimation*

I. INTRODUCTION

Measuring 3D shape of an object is an important technique for the structural and kinematic analysis, the object digital archiving, referencing over the network, and so on. Hence, many 3D shape measuring instruments have been developed such as arm-typed digitizers, laser range finders, stereo cameras and so on. But, these instruments are usually large scale and expensive, so everyone cannot use these instruments. In this paper, we propose a new shape measuring system using the image scanner to realize a low-cost and easy-operating shape measuring system.

We have proposed the object shape measuring method using the image scanner which has three color light sources, red, green and blue[1]. And we have also proposed the method using the stereo image scanner which has two CCD sensors[2]. But, there are some problems in these method. In [1], we assumed that the color of the object surface should be known. And in [2], it is difficult to estimate the adequate approximate shape previously, and using two CCD sensors has a problem in respect of cost.

To overcome these problems, we propose new shape measuring method using the image scanner which has three white light sources and one color CCD sensor. The 3D shape measuring method using multiple light sources is called "the photometric stereo" [3],[4]. This method usually assume the parallel light sources to simplify the photometric models. In this case, the surface normal vectors on the over all of the object surface are estimated as the shape data. On the other hand, the light sources used in the image scanner are the long fluorescent lights, and these light sources are close to the object surface. Hence, the illuminant intensity changes with the distance from the light source. Under such condition, we must estimate the surface normal vectors and the distance from the light sources as the object shape information. Moreover, the reflectance intensity also changes with the color of the object surface. Therefore, the surface normal vectors, the distance from the light source and the object surface color have the interdependence relations in the photometric models, and we must estimate these parameters to measure the object shape.

In this paper, we discuss the shape measuring algorithm under such complex interdependence relations. Here, we propose two shape measuring methods using the technique based on the alternating minimization method[5]. The one method is based on the previous method[1]. This method estimates approximate albedos (color) before the shape measuring. In a color scanned image under white light sources, the color on an object changes its brightness and saturation according to its shape. But its hue does not almost change, hence we will obtain approximate albedos from the color scanned image directly. The object shape is estimated by using approximate albedos.

The other method estimates the shape parameters first using the photometric models which is constructed to eliminate the color parameters from the multiple photometric models. Next, we estimate the color parameters using obtained shape parameters. And we iterate these estimations until the shape and color parameters are converged accurately.

In this paper, we also discuss the number of light sources. We apply each shape measuring method to the cases of two and three light sources, and compare the shape measuring results. Note that, since the image scanner equipped multiple light sources is not manufactured yet, we use the synthetic scanned images for experiments.

This paper is organized as follows. First, we show the structure of the image scanner and its photometric models, and next we propose the shape measuring method. And we show the experimental results and summarize this study.

II. IMAGE SCANNER AND PHOTOMETRIC MODELS

A. Structure of Image Scanner

Figure 1 shows the structure of the color image scanner we use. This scanner has three white light sources L_1, L_2 and L_3. The one dimensional color CCD sensor (D) moves with these light sources, mirror (M) and lens (C) under the scanning plane, and takes 1D image along the scanning line (S). The sequence of 1D images forms a 2D color image. We take three color images using each light source. Note that, while 1D images are acquired by the perspective projection, the projection along the y-axis is equivalent to the orthogonal projection.

The light sources in the scanner are long fluorescent tubes, hence they are modeled as linear light sources. The color CCD sensor takes three primary color images (red, green and blue). Therefore, the white linear light source is modeled as three color linear light sources which locate at the same position.

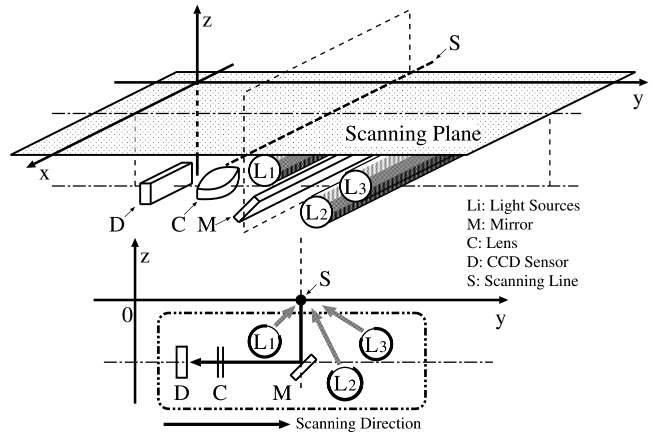


Fig. 1. Structure of image scanner with three light sources.

B. Photometric Models

In this paper, for the photometric property on the object surface, we assume that:

1. The object surface is Lambertian.
2. There are no interreflections on the surface.

In this case, the photometric models of the reflection on the object surface is modeled as follows. Here we show the red pixel intensity $P_{1r}(x, y)$ at (x, y) on the scanned image using the light source L_1:

$$P_{1r}(x, y) = a_r \cdot \rho_r(x, y) \cdot Is_{1r}(x, y) \cdot f_1(x, y) + \Delta_r, \quad (1)$$

where a_r and Δ_r the gain and the bias of the photoelectric transformation in the scanner respectively, $\rho_r(x, y)$ the albedo of the red color component on the object surface. $\rho_r(x, y)$ is the normalized value such as $0 \leq \rho_r(x, y) \leq 1.0$.

$Is_{1r}(x, y)$ is the illuminant intensity of the red component of the light source L_1 and described as follows:

$$Is_{1r}(x, y) = \frac{\alpha_{1r}}{\sqrt{d_{y1}^2 + (z(x, y) - d_{z1})^2}} + Ie_{1r}, \quad (2)$$

where (d_{y1}, d_{z1}) the position of the light source L_1 on $y - z$ plane, α_{1r} the parameter of the illuminant intensity, Ie_{1r} the environment light intensity, and $z(x, y)$ the height between the scanning plane and the object surface at (x, y).

$f_1(x, y)$ describes the Lambertian reflectance property. This is modeled as follows:

$$f_1(x, y) = \frac{n_y(x, y) \cdot d_{y1} - n_z(x, y) \cdot (z(x, y) - d_{z1})}{\sqrt{d_{y1}^2 + (z(x, y) - d_{z1})^2}}, \quad (3)$$

where $n_y(x, y)$, $n_z(x, y)$ the y and z components of the surface normal vector ($n_x(x, y)$, $n_y(x, y)$,$n_z(x, y)$) on the object surface. Note that $n_x(x, y)^2 + n_y(x, y)^2 + n_z(x, y)^2 = 1$.

The green and blue pixel intensities $P_{1g}(x, y)$, $P_{1b}(x, y)$ which are in case of the green and blue components of the light source L_1 are also modeled the same as $P_{1r}(x, y)$ except the following parameters:

- the gain and the bias (a_g, Δ_g and a_b, Δ_b)
- the albedo on the surface ($\rho_g(x, y)$ and $\rho_b(x, y)$)
- the parameter of the illuminant intensity (α_{1g} and α_{1b})
- the environment light intensity (Ie_{1g} and Ie_{1b})

but the light source position (d_{y1}, d_{z1}) is same coordinate.

Moreover, in case of the light sources L_2 and L_3, these photometric models are formulated the same as L_1 except the light source position, the parameter of the illuminant intensity and the environment light intensity.

III. SHAPE MEASUREMENT METHOD

In this paper, we propose two shape measurement methods. The performance of these methods are compared in experiments.

A. Method 1

First, we propose an shape measurement method based on the previous method[1]. The previous method used colored light sources, so it assumed that the albedo (color parameters) on the object surface is known. However, this method could not be applied to various objects. In this paper, we use white light sources, so if we assume that the maximum albedo value among red, green and blue is 1.0, we can estimate the approximated albedo values from the input color scanned images before applying the shape measurement method.

The following algorithm shows the proposed method. This shows the estimation of the height $z(x, y)$, the surface normal vector ($n_x(x, y)$, $n_y(x, y)$, $n_z(x, y)$) and the albedo ($\rho_r(x, y)$, $\rho_g(x, y)$, $\rho_b(x, y)$) at (x, y) on the scanned image. We call this method "Method 1".

1. In case of three light sources

Step 1. **Approximated albedo estimation**

Let P_{ir}^*, P_{ig}^* and P_{ib}^* ($i = 1 \sim 3$) the observed intensity of red, green and blue in the input image scanned under the light source L_i. Obtain the maximum value in the observed intensity and let the albedo value which corresponds to the color of maximum intensity 1.0. Other albedo values are obtained as the rate of observed intensity to the maximum intensity.

Step 2. **Initial shape estimation**

step 2-1. Let the initial values of the surface normal vector $(n_x, n_y, n_z) = (0, 0, -1)$.

step 2-2. Estimates the height z from photometric models using the observed intensity, estimated albedo values in Step 1 and the surface normal vector.

step 2-3. Estimate n_y and n_z again from photometric models using estimated z, albedo values and the observed intensity by linear least squares.

step 2-4. Iterate from step 2-2 until the height z is converged.

Step 3. **Optimal shape and albedos estimation**

Let estimated values of z, n_y, n_z and albedo values as the initial values, estimate these parameters by minimizing the following objective functional F using non-linear least squares:

$$\begin{aligned} & F(z, n_y, n_z, \rho_r, \rho_g, \rho_b) \\ &= \sum_{i=1}^{3} \Big[\{P_{ir}^* - P_{ir}(z, n_y, n_z, \rho_r)\}^2 \\ &\qquad + \left\{P_{ig}^* - P_{ig}(z, n_y, n_z, \rho_g)\right\}^2 \\ &\qquad + \{P_{ib}^* - P_{ib}(z, n_y, n_z, \rho_b)\}^2 \Big] \end{aligned} \quad (4)$$

Note that, after the applying the above method for all (x, y), $n_x(x, y)$ can be calculated from the equation $n_x(x, y)^2 + n_y(x, y)^2 + n_z(x, y)^2 = 1$ and its sign is determined by heights around $z(x, y)$.

2. In case of two light sources

In case of two light sources, the number of photometric models is reduced (using only the light sources L_1 and L_2). But, the algorithm and process of each step are not changed.

B. Method 2

As the second shape measurement method based on the alternating minimization, we obtain the optimal shape and color of the object by iterating the estimation of the albedo (color) and the shape (height and surface normal vector) parameters. Here we use the following formulations constructed by two photometric models of different light sources but same color components eliminating the albedo parameters:

$$\frac{P_{1r}(x, y) - \Delta_r}{P_{2r}(x, y) - \Delta_r} = \frac{Is_{1r}(x, y) \cdot f_1(x, y)}{Is_{2r}(x, y) \cdot f_2(x, y)}. \quad (5)$$

The following algorithm shows the shape and albedo estimation process. We call this method "Method 2".

1. In case of three light sources

Step 1. **Initial values**

Let the initial values $(n_x, n_y, n_z) = (0, 0, -1)$.

Step 2. **Height estimation**

By using the values of the surface normal vector, estimate the height z which minimize the following objective functional F' by non-linear least squares:

$$F'(z) = F_r(z) + F_g(z) + F_b(z), \quad (6)$$

where

$$\begin{aligned} F_r(z) = &\{(P_{1r}^* - \Delta_r) \cdot Is_{2r}(z) \cdot f_2(z) \\ &-(P_{2r}^* - \Delta_r) \cdot Is_{1r}(z) \cdot f_1(z)\}^2 \\ &+ \{(P_{2r}^* - \Delta_r) \cdot Is_{3r}(z) \cdot f_3(z) \\ &-(P_{3r}^* - \Delta_r) \cdot Is_{2r}(z) \cdot f_2(z)\}^2 \\ &+ \{(P_{3r}^* - \Delta_r) \cdot Is_{1r}(z) \cdot f_1(z) \\ &-(P_{1r}^* - \Delta_r) \cdot Is_{3r}(z) \cdot f_3(z)\}^2 \end{aligned} \quad (7)$$

and P_{1r}^*, P_{2r}^* and P_{3r}^* are pixel intensity of the red components in the scanned images. $F_g(z)$ and $F_b(z)$ are also same formulation.

Step 3. **Albedo estimation**

Estimate albedos ρ_r, ρ_g and ρ_b from obtained height z, surface normal vector and pixel intensity using the red, green and blue photometric models. Each albedo is estimated three values, so we calculate the average of each albedo.

Step 4. **Surface normal estimation**

Formulate nine equations of n_y and n_z using the height z and the albedos (ρ_r, ρ_g and ρ_b), and estimate n_y and n_z by linear least squares.

Step 5. **Iterate until converged.**

Iterate from Step 2 until the height z is converged.

Note that, $n_x(x, y)$ is calculated by the same method described in Method 1 after the applying the above method for all (x, y).

2. In case of two light sources

In case of two light sources, the number of photometric models is reduced (using only the light sources L1 and L2) similar to Method 1. The objective functional $F_r(z)$ (Eq.(7)) in Step 2 is formulated as follows:

$$\begin{aligned} F_r(z) = &\{(P_{1r}^* - \Delta_r) \cdot Is_{2r}(z) \cdot f_2(z) \\ &-(P_{2r}^* - \Delta_r) \cdot Is_{1r}(z) \cdot f_1(z)\}^2 \end{aligned} \quad (8)$$

$F_g(z)$ and $F_b(z)$ are also formulated similarly. But, the algorithm and process of each step are not changed.

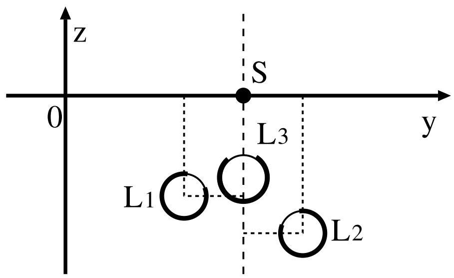


Fig. 2. Light source positions.

IV. EXPERIMENTS

A. Synthesized Images

In this study, we assume the use of the image scanner which has three white light sources. But such scanner has not been manufactured yet. So, we prepare the synthesized scanned images of the virtual objects by the photometric models and use them as the input scanned images.

In this experiment, The light source positions are set as shown in Fig.2 where,

- L_1: $d_{y1} = -60, d_{z1} = -120$ [dots]
- L_2: $d_{y2} = 60, d_{z2} = -150$ [dots]
- L_3: $d_{y3} = 0, d_{z3} = -40$ [dots]

And, we use the hemisphere with the radius of 100 [dots] as the virtual object in the synthesized images for the experiments. On the white surface of this object, there are three color regions. We set two kinds of albedos for these regions as follows:

- **Object 1:** For each color region, the maximum albedo value, which is one of the red, green and blue albedo is equal to 1.0.
- **Object 2:** For each color region, the maximum albedo value is less than 1.0.

Figure 3 shows the synthesized input images. (a), (b) and (c) are images of the Object 1 using the light sources L_1, L_2 and L_3. (d), (e) and (f) are images of the Object 2 using each light source. Table I shows the albedo values of the region from C1 to C7 in Fig.3 (c) and (f).

TABLE I

ALBEDO VALUES IN COLOR REGIONS.

region	ρ_r	ρ_g	ρ_b	region	ρ_r	ρ_g	ρ_b
C1	1.0	0.5	0.0	C5	0.8	0.5	0.0
C2	0.8	1.0	0.5	C6	0.0	0.6	0.5
C3	0.5	0.0	1.0	C7	0.0	0.6	0.8
C4	1.0	1.0	1.0				

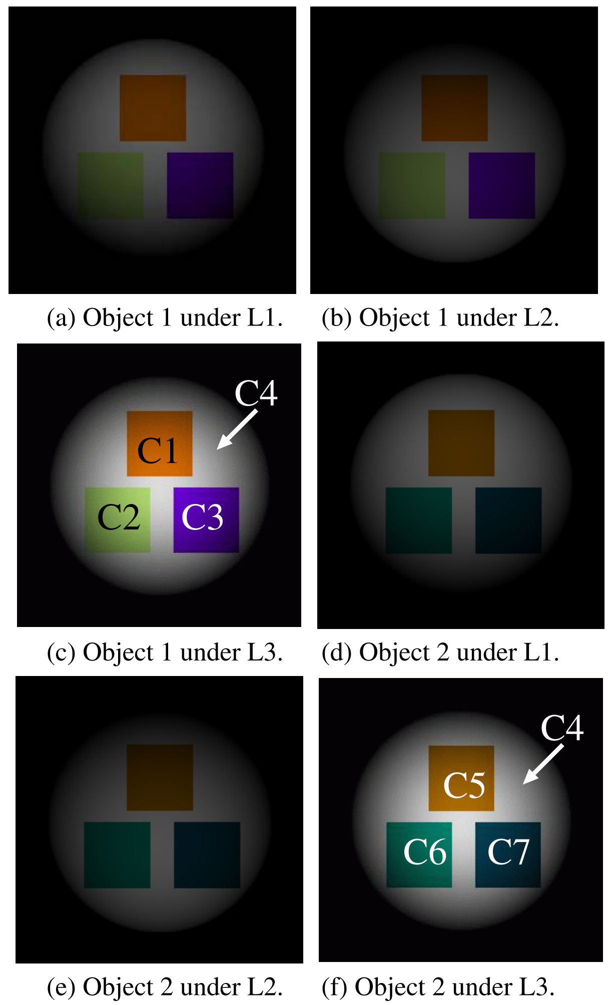


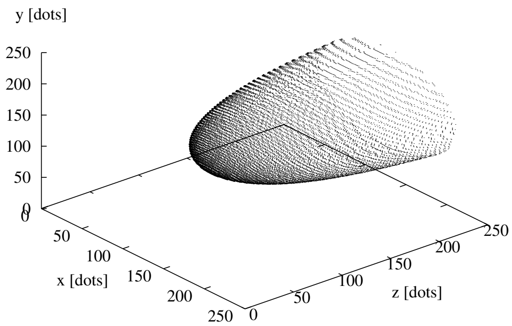
Fig. 3. Input synthesized images.

B. Experimental Results

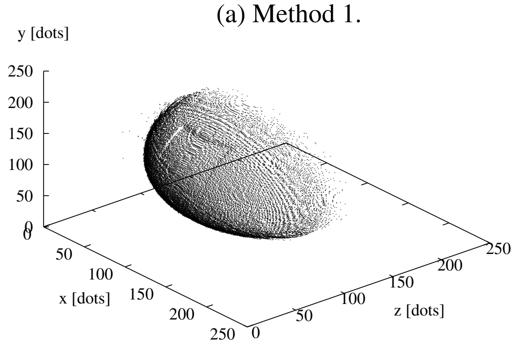
1. In case of three light sources

In this section, we show the experimental results of the shape measurements. Figure 4 shows the results of the shape measurements of the Object 1 using Method 1 and Method 2 in case of three light sources. These figures shows the distributions of the height z. From these figures, Method 1 and 2 can measure the shape of the hemisphere object, but Method 1 is not so accurate, especially, at the part of edges in the object. On the other hand, Method 2 can be estimate the object shape accurately. Figure 5 shows the distribution of the surface normal vectors. The result of Method 1 could not estimate them overall of the surface, and Method 2 could not estimate them at the part of edge.

Figure 6 shows the results of the height distributions of the Object 2. The Method 1 could not estimate the height z accurately especially at the regions whose approximated albedo values are different from the actual ones. On the contrary, the Method 2 can estimate accurate shape of the Object 2 similar to the Object 1. Note that, however, the accuracy of the surface normal vector is not so good.

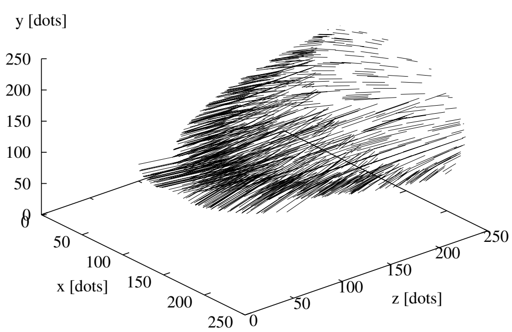


(a) Method 1.

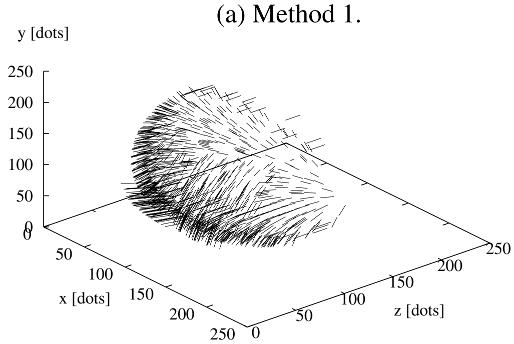


(b) Method 2.

Fig. 4. Estimated shapes of Object 1 (height z).

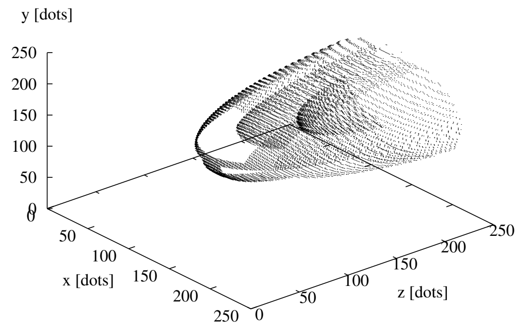


(a) Method 1.

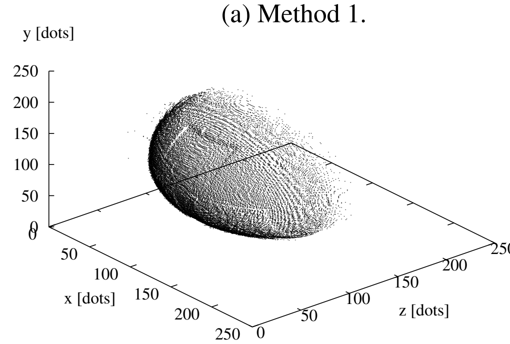


(b) Method 2.

Fig. 5. Estimated surface normal vectors.

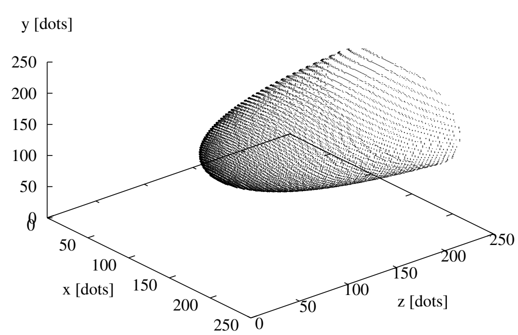


(a) Method 1.

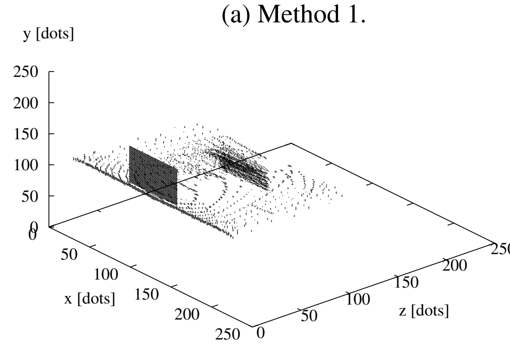


(b) Method 2.

Fig. 6. Estimated shapes of Object 2 (height z).

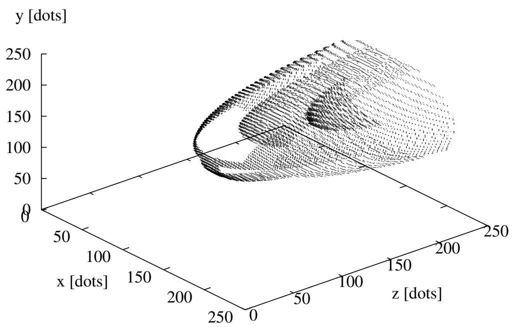


(a) Method 1.

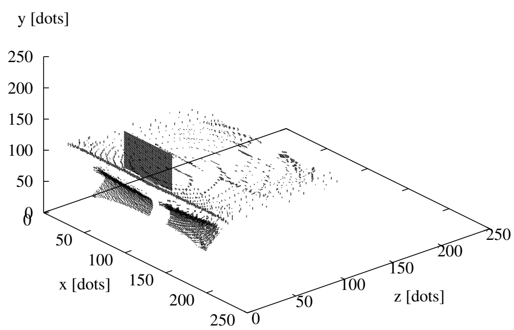


(b) Method 2.

Fig. 7. Estimated shapes of Object 1 under two light sources (height z).



(a) Method 1.



(b) Method 2.

Fig. 8. Estimated shapes of Object 2 under two light sources (height z).

2. In case of two light sources

Figure 7 shows the results of the shape measurements of the Object 1 using Method 1 and Method 2 in case of two light sources. Method 1 can obtain the object shape almost similar to the case of three light sources. But, Method 2 can not estimate the object shape.

Figure 8 shows the results of Object 2. In this case, the object shape can not be estimated by both methods.

C. Discussions

Table II (a) and (b) show the summaries of results of the shape measurement experiments. The signs express the qualitative evaluation of the shape measurement, e.g. ◯ is "good", △ is "not so bad", and × is "bad". From these results, Method 1 can measure the object shape under two or three light sources, but estimated shapes is not accuracy. Especially, when the albedos (color parameters) are approximated values, the object shape can not measure. This means that in Step 3 of Method 1, the optimal shape and albedos are not estimated effectively by non-linear least squares.

On the other hand, even if the albedo values are not known, Method 2 can measure the object shape, but it needs three light sources. In general, since the albedos (colors) on the object surface are not known, Method 2 is effective for the object shape measurement.

TABLE II

QUALITATIVE EVALUATION OF SHAPE MEASUREMENTS.

(a) Method 1

Light Sources	Object	Height	Vector	Albedo
3	1	△	×	—
	2	×	×	×
2	1	△	×	—
	2	×	×	×

(b) Method 2

Light Sources	Object	Height	Vector	Albedo
3	1	◯	△	△
	2	◯	△	△
2	1	×	×	×
	2	×	×	×

V. CONCLUSIONS

In this paper, we discussed the method to measure the 3D shape of the object using the image scanner which has multiple white light sources. Here, we proposed two methods to obtain the object shape: Method 1 obtains the object shape following the approximated albedos (colors) estimation, and Method 2 iterates the estimations of shape parameters and the albedo parameters alternately. And we show the experimental results using the synthesized scanned images of the hemisphere object. From the results of these experiments, we shown that Method 2 could estimate the object shape more accurate than Method 1 even if the object color is not known. The future work is to manufacture the image scanner with the multiple light sources and to verify the proposed method by using it.

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