Paper

On the Estimation of the Luminance Distribution by the Diffuse Reflection Component of an Object's Surface and Shape Measurement — Analysis by the Numerical Experiment —

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ABSTRACT

A method is described for estimating three-dimensional(3D) shapes from two-dimensional(2-D) shading information in gray-level images that uses the diffuse reflection components in a luminance distribution with diffuse and specular reflection components. It overcomes the problem of highlights caused by the specular reflection components that occurs when multiple fixed light sources are used, which is a drawback to the "photometric stereo" method proposed by Woodham. First, the bi-directional reflectance distribution function is estimated for the detected area of a gray-level image with highlights. Then, the luminance distribution caused by the diffuse reflection components in the detected area is estimated based on the luminance distribution in a gray-level image without highlights. Numerical shape-measurement experiments using mixed diffuse-specular objects with different characteristic reflectances and shapes showed that the proposed method can accurately measure the 3-D shape of mixed diffuse-specular objects.

KEYWORDS: bidirectional reflectance distribution function, reflection characteristic, photometric stereo, highlights, shape measurement, mixed diffuse-specular objects

1. Introduction

Non-contact measurement of the shapes of three-dimensional objects, especially applications of measurement technology by means of image recognition¹⁾⁻³⁾, has been greatly anticipated recently in various fields of industry. Three-D shape measuring methods are generally classified into multiple-eye vision and single-eye vision methods. The two-eye vision method can be cited as representative of the multiple-eye vision method, but how to correlate the two input images with each other is a problem. A method of illuminating a 3-D object with light projected through a slit has been proposed, but its difficulty exists in that the traditional method requires a large number of input images and consequently a lot of time for image input. The photometric stereo method⁴⁾⁵⁾ can be cited as representative of the single-eye vision method. The photometric stereo method is a way of determining the vectors normal to an object's surface based upon three images of the same scene taken with one camera set at the same position while the direction of the light source is varied. In this method, there is no visual difference because there is no change in the relationship between the camera and the object. This enables the determination of the normal vectors with high speed. However, this method has the drawback that, when the ratio of the specular reflection component of the reflective properties of the object's surface, or the reflection property itself, is

unknown, the relationship between the luminance and the slope of the surface is unobtainable and, accordingly, since information about the gray-scale of the image is used directly in the photometric stereo method, the normal vectors can not be obtained.

The purpose of this study is to measure the 3-D shapes of objects with unknown surface reflection properties by means of the photometric stereo method. When specular reflection components are included in the reflection properties of an object's surface, a highlight is generated in an image obtained by photographing the object. It has been reported that large errors are generated when measuring the 3-D shape is done by the photometric stereo method using images with highlights⁶⁾.

There are methods to cope with this problem, such as the method to assess the reflection properties of the surface from characteristic points and the method to calculate the inclination of the object points by means of selecting the gray-scale images with no highlights⁷⁾. However, these methods have weak points in that they need a lot of repetitive calculation treatment and also the number of the gray-scale images photographed should be increased. Also, the authors previously proposed a method for compensating gray-scale images⁸⁾ in which the luminance distribution of the highlights generated by the specular reflection components of the object's surface was structured to a Gauss distribution model. It was reported that the 3-D

shape measurement of a hemispherical object with unknown reflection properties (including the specular reflection component) of the surface can be done by means of the photometric stereo method, similar to the case of measuring an object with a uniformly diffuse surface. However, since the proposed method of compensation structured the model using the luminance distribution of a round highlight generated on a hemispherical object, its application is difficult when the shapes of the highlights are not round due to a different shape of the object.

Hence, as a compensation method that does not depend upon the shapes of the highlights, this paper will describe a method for eliminating the highlight from the gray-scale images by estimating the luminance distribution of the diffuse reflection component for the area where the highlight is generated, and then the validity of this compensation method will be verified through numerical experiments. Furthermore, with this compensation method applied, the measuring results of the shapes of objects with curved-surfaces (hemispherical object, semi-cylindrical object, and conical object) with specular reflection components included in the reflection properties of the surfaces will be shown. The results of the experimental verification will be reported in the next paper.

2. Photometric Stereo Method

Fig. 1 shows a schematic of the measurement of the shape of an object by the photometric stereo method. As shown in the figure, it is assumed that an object is put on the xy plane of the xyz rectangular coordinates system and it is illuminated by light from the light sources. Also, it is assumed that the light sources are point sources of light and that the surface of the object is an evenly diffuse surface. Then, the luminance L to be measured at an arbitrary point on the surface of the object can be expressed as follows⁸⁾.

$$L = \frac{I}{r_p^2 \pi} \rho \cos \theta = \frac{I}{r_p^2 \pi} \rho (\vec{N} \cdot \vec{S}) \quad (1)$$

Here,

$\vec{N}$: A vector normal at the point P on the object's surface (unit vector)

$\vec{S}$: A directional vector of a straight line connecting the point P and the light source (unit vector)

θ : Incident angle of the light (the included angle between $\vec{N}$ and $\vec{S}$)

$\vec{N} \cdot \vec{S}$: Inner product of $\vec{N}$ and $\vec{S}$

r_p : A distance from the light source to the point P

I : Luminous intensity of the light source

ρ : Reflectance of the surface

When the position of the light source is changed to i , j , and k , the luminance of the point P observed at the viewpoint becomes L_i , L_j , and L_k , which are levels corresponding to the positions of the light source. Therefore, when the vectors from the point P to the light sources are put as $\vec{S}_i$, $\vec{S}_j$, and $\vec{S}_k$, and the distance between the point P and the light source is put as r_{Pi} , r_{Pj} , and r_{Pk} , L_i , L_j , and L_k are expressed as follows.

$$\left. \begin{aligned} L_i &= \frac{I}{r_{Pi}^2 \pi} \rho (\vec{N} \cdot \vec{S}_i) \\ L_j &= \frac{I}{r_{Pj}^2 \pi} \rho (\vec{N} \cdot \vec{S}_j) \\ L_k &= \frac{I}{r_{Pk}^2 \pi} \rho (\vec{N} \cdot \vec{S}_k) \end{aligned} \right\} \quad (2)$$

The normal vector $\vec{N}$ at the point P on the object's surface can be obtained using equation (2). By implementing this process on all points on an object's surface, the normal vector distribution for an object's surface can be obtained.

Fig.1 The geometric relation between viewpoint and measurement object and light source.

3. Formation of Gray-Scale Images by the Phong Model

The reflection properties of the object's surface can be separated into the diffuse reflection light components and the specular reflection light components. It is assumed that the diffuse reflection light components are based upon the Lambertian cosine law and that the luminous intensity varies in proportion to the cosine of the angle of incidence relative to the normal of the reflecting surface. Regarding the models for handling the specular reflection light component, there are the Phong model⁹⁾, the Blinn model¹⁰⁾, the Torrance-Sparrow model¹¹⁾¹²⁾, and so on. Although the Phong model is used most frequently nowadays, it can not express the changes in the reflectance caused by the wavelength of the light, the perceived quality of a metal that is roughly polished, and so on, because it is a simple model. However, the Phong model can be acceptably applied to the surface of object that is a non-metal and that has a smooth surface¹³⁾. Accordingly, it is assumed that the object of this study is a non-metal with a smooth surface for which the Phong model is considered to be applicable and that the whole surface of the object has similar reflection properties.

Then, regarding the luminous intensity of the object's surface, it was decided to calculate the diffuse reflection light component based upon the Lambertian cosine law and to calculate the specular reflection light component using the Phong model. Also, it was decided to consider the direct light from the light source alone and not to consider the influence of the light in the environment and the surrounding light, as well as the indirect light due to mutual reflection. Furthermore, the light source was a point source of light.

Fig. 2 shows an example of the luminous intensity distribution of an object's surface that includes the specular reflection components calculated by the Phong model. The luminance L at a point P measured at the viewpoint is given by the following equation.

$$L = \frac{I}{r_s^2} (\vec{N} \cdot \vec{S}) \cdot \frac{\rho_d}{\pi} + \frac{I}{r_v^2} (\vec{N} \cdot \vec{S}) \cdot \frac{\rho_s(\theta) (\vec{V} \cdot \vec{R})^n}{\vec{V} \cdot \vec{N}} \quad (3)$$

Here,

$\vec{N}$: A normal vector at the point P on the object's surface (unit vector)

$\vec{S}$: A directional vector of a straight line connecting the point P and the light source (unit vector)

$\vec{V}$: A directional vector of a straight line connecting the point P and the viewpoint (unit vector)

r_P : A distance from the light source to the point P

I : Luminous intensity of the light source

ρ_d : Diffuse reflectance

$\rho_s(\theta)$: Function of the specular reflectance properties

n : Spread of the light of the specular reflection component

$\vec{R}$: Directional vector of reflection

(Positive direction against incident direction)

$$\vec{R} = -\vec{S} + 2\vec{N}(\vec{S} \cdot \vec{N})$$

Also, the function of the specular reflection properties $\rho_s(\theta)$ in equation (3) that expresses the changes in the specular reflectance against the incident angle is shown as follows¹⁴⁾, with $\rho_s(0)$ for the specular reflectance at an incidence angle of 0 radians and n_0 for the ratio of changes in the specular reflectance.

$$\rho_s(\theta) = \rho_s(0) + (1 - \rho_s(0)) \left(\frac{2\theta}{\pi} \right)^{n_0} \quad (4)$$

For the gray-scale images for the numerical experiment, the number of pixels was set as 1024 pixels along the vertical line and 1280 pixels along the horizontal line, and the luminance was set to be expressed by 1024 luminance gradations from 0 to 1023 (being in proportion to the luminance L). In other words, the gray-scale image was created by calculating the luminance of the assumed object to be measured based upon equation (3) and the quantization of the luminance at each pixel in a 1280×1024 two-dimensional array to one of 1024 steps.

Fig. 3 shows the relationship between the reflectance properties of the object's surface and the gray-scale images. Fig. 3 (a) shows the gray-scale image in a case in which the ratio of the specular reflection component included in the whole reflectance of the object's surface is large, and (b) shows the same in a case with a highly directional specular reflection component.

Fig.2 The luminous distribution curve of the Phong model.

(a) Case with a large specular reflection component

(b) Case with a highly directional specular reflection

Fig.3 The gray-level image by the reflection characteristic of object surface.

4. Numerical Experiment of Measurement of the 3-D Shape of an Object

The measurement environment assumed for the numerical experiment is shown in Fig. 4. An object was put on an xy plane (called the reference surface) in a rectangular coordinates system xyz with the origin O , of which the reflectance is 0% at $z = 0$. The object was illuminated by point sources, for which the distances from the origin O were r . The positions of each of three sources of light, which were required to obtain the three gray-scale images, were fixed at the distance r from the origin O and at the zenith angle θ of 30° . Furthermore, the three light source positions were set so that the azimuth angles ϕ were at 120° intervals, or 60° , 180° , and 300° relative to the x axis. The light sources with ϕ_1 of 60° , 180° , and 300° were called light source i , light source j , and light source k , respectively. The object was photographed from a viewpoint on the z axis, $0.5r$ distant from the origin O . Three kinds of objects, a hemispherical object, a semi-cylindrical object, and a conical object, as shown in Fig. 5, were used as the object. Also, in each case, the reflection properties of the whole object's surface were assumed to be even.

Fig.4 Measurement environment for the numerical experiment.

Fig.5 The shape of measurement object for the numerical.

4.1 Application of the Bidirection Reference Distribution Function

The proposed highlight compensation method is to extract the area of highlights of different shapes generated in the gray-scale images and then to assess the luminance distributions by the diffuse reflection component for the areas of highlights. In this paper, attention was paid to the Bidirectional Reflectance Distribution Function (BRDF)¹⁵⁾¹⁶⁾, which expresses the spatial distribution of reflectance properties, in order to extract the highlight area. In other words, the BRDF is calculated by means of approximation based upon the three images to be used for photometric stereo method, and the areas of highlight generated in the images are extracted based upon the BRDF.

When the specular reflection component is included in the reflection properties of an object, the BRDF becomes high in places where the highlights are generated because of the relationship between the light source and the normal vector of the object's surface. Therefore, the areas of highlights with different shapes generated in the gray-scale images can be extracted by the BRDF. The proposed compensation method is to remove the area of highlight from the image using the BRDF and to assess the luminance distribution by the diffuse reflection component for the removed area.

Fig. 6 shows the geometric relationship between an arbitrary point P on the object's surface versus a light source and the viewpoint. The illuminance E at the point P is expressed as follows.

$$E = \frac{I}{r_p^2} \cos \theta = \frac{I}{r_p^2} (\vec{N} \cdot \vec{S}) \quad (5)$$

Here,

$\vec{N}$: A normal vector at the point P on the object's surface (unit vector)

$\vec{S}$: A directional vector of a straight line connecting the point P and the light source (unit vector)

r_p : A distance from the light source to the point P

I : Luminous intensity of the light source

θ : Incident angle of the light

Also, since the luminance L of the point P as seen from the viewpoint can be obtained by the previously described equation (3), the BRDF $f(\vec{N}, \vec{S}, \vec{V})$ is given as the ratio of illuminance to luminance as follows.

$$f(\vec{N}, \vec{S}, \vec{V}) = \frac{L}{E} = \left\{ \frac{\rho_d}{\pi} + \frac{\rho_s(\theta)(\vec{V} \cdot \vec{R})^n}{\vec{V} \cdot \vec{N}} \right\} \quad (6)$$

Here,

$\vec{V}$: A directional vector of a straight line connecting the point P and the viewpoint (unit vector)

$\vec{R}$: Directional vector of reflection (Positive direction against incident direction)

As shown here, the BRDF $f(\vec{N}, \vec{S}, \vec{V})$ depends on the direction of the incident light, the direction of reflection, and the normal vector of the object's surface.

However, when the reflection properties of the object's surface have only a diffuse reflection light component, the BRDF becomes as follows, since $\rho_s(\theta) = 0$.

$$f(\vec{N}, \vec{S}, \vec{V}) = \frac{\rho_d}{\pi} \quad (7)$$

This is a value that does not depend upon the direction of the incident light, the direction of the reflection, and the normal vector of the object's surface. This enables the discrimination of the areas with the diffuse reflection light component alone from the areas containing a specular light reflection component that generates a highlight, both in the gray-scale images.

Next, the method for approximately calculating the BRDF based upon the three images used for the photometric stereo method will be described.

When the object is put on the xy plane of the xyz rectangular coordinates system and illuminated by the light from the light source as shown in Fig. 4, the luminance L_i , L_j , and L_k of the point P, which is observed from the viewpoint while the position of the light source is changed to i , j , and k , are expressed by BRDF $f(\vec{N}, \vec{S}, \vec{V})$ as follows.

$$\left. \begin{aligned} L_i &= E_i \cdot f(\vec{N}, \vec{S}_i, \vec{V}) = \frac{I}{r_{Pi}^2} (\vec{S}_i \cdot \vec{N}) \cdot f(\vec{N}, \vec{S}_i, \vec{V}) \\ L_j &= E_j \cdot f(\vec{N}, \vec{S}_j, \vec{V}) = \frac{I}{r_{Pj}^2} (\vec{S}_j \cdot \vec{N}) \cdot f(\vec{N}, \vec{S}_j, \vec{V}) \\ L_k &= E_k \cdot f(\vec{N}, \vec{S}_k, \vec{V}) = \frac{I}{r_{Pk}^2} (\vec{S}_k \cdot \vec{N}) \cdot f(\vec{N}, \vec{S}_k, \vec{V}) \end{aligned} \right\} \quad (8)$$

Here, the components of each vector are put as $\vec{N} = (N_x, N_y, N_z)$, $\vec{S}_i = (S_{ix}, S_{iy}, S_{iz})$, $\vec{S}_j = (S_{jx}, S_{jy}, S_{jz})$, and $\vec{S}_k = (S_{kx}, S_{ky}, S_{kz})$ to obtain the following equations.

$$\left. \begin{aligned} \frac{L_i r_{Pi}^2}{I \cdot f(\vec{N}, \vec{S}_i, \vec{V})} &= N_x S_{ix} + N_y S_{iy} + N_z S_{iz} \\ \frac{L_j r_{Pj}^2}{I \cdot f(\vec{N}, \vec{S}_j, \vec{V})} &= N_x S_{jx} + N_y S_{jy} + N_z S_{jz} \\ \frac{L_k r_{Pk}^2}{I \cdot f(\vec{N}, \vec{S}_k, \vec{V})} &= N_x S_{kx} + N_y S_{ky} + N_z S_{kz} \end{aligned} \right\} \quad (9)$$

Equation (9) can be expressed by a matrix equation as follows.

$$\frac{1}{I} \begin{bmatrix} \frac{L_i r_{Pi}^2}{f(\vec{N}, \vec{S}_i, \vec{V})} \\ \frac{L_j r_{Pj}^2}{f(\vec{N}, \vec{S}_j, \vec{V})} \\ \frac{L_k r_{Pk}^2}{f(\vec{N}, \vec{S}_k, \vec{V})} \end{bmatrix} = \begin{bmatrix} S_{ix} & S_{iy} & S_{iz} \\ S_{jx} & S_{jy} & S_{jz} \\ S_{kx} & S_{ky} & S_{kz} \end{bmatrix} \begin{bmatrix} N_x \\ N_y \\ N_z \end{bmatrix} \quad (10)$$

Here, in a manner similar to the case in which the reflection property of the object's surface was the diffuse reflection light component alone, the approximation of the BRDF is put as follows.

$$f_{app} = f(\vec{N}, \vec{S}_i, \vec{V}) = f(\vec{N}, \vec{S}_j, \vec{V}) = f(\vec{N}, \vec{S}_k, \vec{V}) \quad (11)$$

Equation (10) is solved for the BRDF f_{app} assuming that it approximately represents a normal vector to the object's surface to obtain the following equation.

$$f_{app} \begin{bmatrix} N_x \\ N_y \\ N_z \end{bmatrix} = \frac{1}{I} \begin{bmatrix} S_{ix} & S_{iy} & S_{iz} \\ S_{jx} & S_{jy} & S_{jz} \\ S_{kx} & S_{ky} & S_{kz} \end{bmatrix}^{-1} \begin{bmatrix} L_i r_{Pi}^2 \\ L_j r_{Pj}^2 \\ L_k r_{Pk}^2 \end{bmatrix} \quad (12)$$

When the solutions obtained by solving equation (12) are put as A_x , A_y , and A_z :

$$\left. \begin{aligned} f_{app} N_x &= A_x \\ f_{app} N_y &= A_y \\ f_{app} N_z &= A_z \end{aligned} \right\} \quad (13)$$

Furthermore, the approximate assessment of the BRDF f_{app} can be obtained by obtaining a square root of $(A_x^2 + A_y^2 + A_z^2)$ using the solutions of equation (12) A_x , A_y , and A_z as shown below:

$$\begin{aligned} &\sqrt{A_x^2 + A_y^2 + A_z^2} \\ &= \sqrt{(f_{app} N_x)^2 + (f_{app} N_y)^2 + (f_{app} N_z)^2} \\ &= f_{app} \sqrt{(N_x)^2 + (N_y)^2 + (N_z)^2} \end{aligned} \quad (14)$$

$$f_{app} = \sqrt{A_x^2 + A_y^2 + A_z^2} \quad (15)$$

In the areas where no highlight is generated in the image, equations (7) and (11) are valid, since there is no specular reflection light component included in the luminance L_i , L_j , and L_k that correspond to the illumination by each light source and, accordingly, the

following equation is valid.

$$f_{app} = \frac{\rho_d}{\pi} \quad (16)$$

Therefore, the diffuse reflectance ρ_d can be obtained by equation (17) as a value that does not depend upon the normal vector of the object's surface.

$$\rho_d = f_{app} \cdot \pi \quad (17)$$

Fig. 7 shows examples of the gray-scale images of a semi-cylindrical object photographed from the viewpoint while being illuminated by light from the light sources. Figures (a), (b), and (c) correspond to the cases of illumination by the light from light sources i, j, and k, respectively.

For the reflectance properties the following assumptions were made: the diffuse reflectance $\rho_d = 0.4$, the specular reflectance at the incident angle 0 radians $\rho_s(0) = 0.2$, the spread of the light of the specular reflection component $n = 40$, and the level of changes in the specular reflectance $n_0 = 10$. Also, the height of the semi-cylindrical object was assumed to be $0.01r$, the radius of the curvature to be $0.04r$, and the width to be $0.06r$. It is noted that there is no highlight generated in the gray-scale image shown in figure (b). However, there are highlights in the gray-scale images in figures (a) and (c), and it is noted that the areas where the highlights were generated are not round.

Fig. 8 shows the BRDF f_{app} obtained from the gray-scale images in Fig. 7. Figure (a) expresses the obtained BRDF f_{app} by the gray-scale image with 1024 gradations after normalization at the maximum value, and figure (b) shows the 3-D distribution of the BRDF.

In these figures, it is noted that the value of the BRDF is significantly high in two areas. Also, it is noted that the value is almost constant in other areas. Furthermore, in Figure (9) in which the gray-scale image and the BRDF f_{app} are compared on an arbitrary cross section of the object's surface A-A', it is noted that the area where the value of the BRDF is significantly high is consistent with the area of highlight generated in the gray-scale image. In other words, it is considered that the assumption for equation (11) is valid in the area where the value of the BRDF f_{app} is constant due to the lack of a specular reflection light component and that the highlight was generated in the area where the value of the BRDF f_{app} is significantly high due to the existence of a specular reflection light component.

Therefore, the area where the highlight is generated can be extracted by means of extracting the area where the value of the BRDF is not constant and instead is significantly high.

Fig. 10 shows the result of binary treatment with an appropriate threshold. From this figure, it is known

that the areas where the value of f_{app} is significantly high, that is to say, the areas where the highlights are generated, are extracted.

By the way, in cases with many highlight areas that overlap each other due to the reflection properties of the object, it is considered that treatment of images by judgment of the overlapped areas and their separation is necessary. However, the reflection properties of such objects is regarded as being outside the scope of this study.

The area where the highlight is generated depends upon n (the spread of the light of the specular reflection component) in equation (3). Accordingly, in this paper, the value of n was set above 40 so that the highlight areas generated on the object (Fig. 5) assumed for the numerical experiment do no overlap each other.

Fig.6 The geometric relation between viewpoint and light source.

(a) Case of illumination by light from source i (b) Case of illumination by light from source j (c) Case of illumination by light from source k

Fig.7 The gray-level images.

Fig.8 Bidirectional reflectance distribution function.

Fig.9 Comparison of luminance gray scale distribution and bidirectional reflectance distribution function on A-A' cross section.

Fig.10 Binary image.

4.2 Assessment of the Luminance Distribution by the Diffuse Reflection Light Component and a Highlight Compensation Method

The highlight compensation method is to extract the area where the highlight is generated by means of matching it to the area where the highlight is obtained by the BRDF f_{app} and then to assess the luminance distribution by the diffuse reflection light component of the extracted area.

Matching the area where the highlight obtained by the BRDF f_{app} to the area of the highlight generated by illumination from each light source i , j , and k in the gray-scale image is made by checking the conformity of the place with the maximum gray-scale distribution in the gray-scale image to the area where the highlight is generated in the BRDF f_{app} .

Fig. 11 shows the gray-scale images of cases with illumination from light sources i , j , and k respectively, and the white spot in each figure indicates the place where the luminance in each gray-scale image took the maximum value. The maximum luminance value in each gray-scale image was named L_{mi} , L_{mj} , and L_{mk} . Also, as shown in Fig. 12, the two areas of highlight obtained by the BRDF f_{app} were named area 1 and area 2. As shown in the figure, L_{mi} was included in area 1 and L_{mk} was included in area 2. Also, it is noted that L_{mj} was positioned outside the areas. Therefore, area 1 is the area of highlight generated in the gray-scale image when light source i is the illuminating source, and area 2 is the area of highlight generated in the gray-scale image when light source k is the illuminating source.

Fig. 13 shows the highlight areas realized on the gray-scale images. Figures (a), (b), and (c) are the gray-scale images corresponding to the cases of illumination by light from sources i , j , and k , respectively, and the area indicated by the white line is the area where the highlight was generated. Compensation of the highlight can be made by assessing the luminance distribution of the diffuse reflection light component in the area where the highlight was generated. Then, Fig. 14 shows the result of removing the areas where the highlights were generated in Fig. 13 from the gray-scale image.

Assessment of the luminance distribution for the removed area by the diffuse reflection light component is made as described below. Fig. 15 shows the luminance distribution of a cross section A-A' in the direction of u axis and a cross section B-B' in the direction of v axis, both containing an arbitrary point P in Fig. 14. By the way, the u and v axes are the coordinate axes for the gray-scale image, with the origin at upper left side of the gray-scale image. The luminance distribution expressed by the diffuse reflection light component for the area in each cross section, where highlight was generated, is assessed by the method of least squares using the luminance gray-

scale values by the diffuse reflection light component in the areas where the highlight was not generated.

Now, the luminance value by the diffuse reflection light component at the arbitrary point in Fig. 15(a), excluding the area where highlight in the direction of the v axis was generated, is put as $K(v)$. The luminance distribution by the diffuse reflection light component, including the area where highlight in the direction of the v axis was generated, is put as an approximation function $K_a(v)$ as shown below.

$$K_a(v) = C_0 + C_1 \cdot v + C_2 \cdot v^2 + \dots + C_m \cdot v^m = \sum_{i=0}^m C_i \cdot v^i \quad (18)$$

The unknown coefficient C_i in Fig. 18 is determined by the luminance values by the diffuse reflection light component $K(v)$. That is to say, the sum of the squares Q of the differentials (remaining differentials) between the approximation function $K_a(v)$ and the luminance values by the diffuse reflection light component $K(v)$ is obtained as shown below.

$$Q = \{ K_a(v) - K(v) \}^2 \quad (19)$$

The approximation function $K_a(v)$ expressed by the unknown coefficients C_i that make the sum of the squares Q the minimum is selected as the luminance distribution by the diffuse reflection light component.

The luminance distribution derived from the obtained approximation function is put as the luminance distribution by the diffuse reflection light component for the area where the highlight was generated.

Also, when the area where the highlight was generated is larger than the area of luminance distribution by the diffuse reflection light component as shown in Fig. 15, compensation is made by the luminance distribution by the diffuse reflection light component assessed based upon the other cross section. By implementing the above mentioned treatment on all areas where the highlight was generated, the luminance distribution for the diffuse reflection light component for the area where the highlight was generated can be assessed.

Fig. 16 shows the result of compensation of the highlight in the gray-scale image in Fig. 14 by assessing the luminance distribution by the diffuse reflection light component (Fig. 16(a)) and its isoluminance contour (Fig. 16(b)). Also, Fig. 16(c) shows, for reference, the isoluminance distribution of the gray-scale image in the case in which the reflectance properties of an object consisted of the diffuse reflection light component alone ($\rho_d = 0.4$). From this figure, it is known that the isoluminance distribution of the gray-scale image after highlight compensation conforms well with the isoluminance distribution in the case in which the reflectance

properties of an object consisted of the diffuse reflection component alone. Since the proposed compensation method is a method of assessing the luminance distribution by the diffuse reflection light component for the area where the highlight is generated based upon the luminance distribution in the area where the highlight is not generated, it can not be applied to cases in which the reflectance properties of an object consist of the specular reflection component alone ($\rho_d = 0$).

Fig.11 The gray-level images and a point of maximum luminance gray scale in gray-level image.

Fig.12 The area of highlight

Fig.13 Area of high-light in gray-level image.

Fig14. The Gray-level image of removed highlight.

Fig.15 The luminance gray scale distribution on each cross section.

Fig.16 The gray-level image of after the compensation and isoluminance gray scale contour.

4.3 Evaluation of Compensation Method for Highlight and Shape Measuring Results

In this section the results of shape measuring by the photometric stereo method, using highlight compensation and the gray-scale images after the compensation, on cases with changes in the shape of the object and in its reflection properties will be described in order to evaluate the usefulness of the proposed compensation method.

Fig. 17 shows gray-scale images for the case in which a hemispherical object was illuminated by light from source i. Figure (a) is the image before highlight compensation and figure (b) is the image after highlight compensation. The white line in figure (a) is the boundary between the area where highlight was generated and the area where it was not generated. By the way, the surface of this object was assumed to be as follows: the diffuse reflectance $\rho_d = 0.4$, the specular reflectance at the incident angle 0 radians $\rho_s(0) = 0.2$, the spread of the light of the specular reflection component $n = 40$, and the level of changes in the specular reflectance $n_0 = 10$.

The highlight that corresponds to a significantly high luminance value in the area of nearly a circle, as shown by a white line in figure (a), was changed to an approximation of the luminance value by the diffuse reflection light component in the area where the

highlight was not generated, as shown in figure (b), owing to the proposed highlight compensation. Thus, the highlight was removed.

Fig. 18(a) shows the isoluminance distribution of the gray-scale image on which the highlight compensation per Fig. 17 was made. By the way, Fig. 18(b) shows, for reference, the isoluminance distribution of the gray-scale image in the case of the object's reflection properties having only a diffuse reflection component ($\rho_d = 0.4$). From these figures, it is known that, although the line for the isoluminance value 384 is slightly different, for the other lines, the isoluminance distribution of the gray-scale image on which the highlight compensation was made conforms well with the case of the object with reflectance properties having only a diffuse reflection component.

Fig. 19 shows the gray-scale image for the case in which a conical object was illuminated by light from source i. Figure (a) is the image before highlight compensation and figure (b) is the image after highlight compensation. The white line in figure (a) is a boundary line between the area where highlight was generated and the area where highlight was not generated. By the way, the surface of the object was assumed to have the same reflection properties as previously described.

The highlight that corresponds to a significantly high luminance value in an approximately triangular area, as shown by the white line in figure (a), was changed to the approximation of the luminance value by the diffuse reflection light component in the area where highlight was not generated, as shown in figure (b), owing to the proposed highlight compensation. Thus, the highlight was removed.

Fig. 20(a) shows the isoluminance distribution of the gray-scale image on which the highlight compensation per Fig. 19 was made. By the way, Fig. 20(b) shows, for reference, the isoluminance distribution of the gray-scale image in the case of the object's reflection properties having only a diffuse reflection component ($\rho_d = 0.4$). From these figures, it is known that the isoluminance distribution of the gray-scale image on which the highlight compensation was made conforms well with the case of the object with reflectance properties having only a diffuse reflection light component.

From the results as mentioned above, it was made clear that the proposed highlight compensation method is sufficiently valid even in cases in which the shape of area where the highlight is generated is changed due to changes in the shape of the object.

Fig. 21 shows the normal vector distribution of the object calculated based upon the gray-scale image by the photometric stereo method. Figure (a) shows the case in which the image before highlight compensation was used, and figure (b) shows the case in which the image after highlight compensation was used. The

object was a semi-cylindrical object, and the reflection properties of the object's surface were assumed to be the same as previously described.

It is apparent that the distribution of the normal vectors calculated from the gray-scale image without highlight compensation shows conspicuous distortion in the areas where highlights were generated (Fig. 13(a) and (b)).

On the contrary, it is apparent that the distribution of the normal vectors calculated from the gray-scale image after highlight compensation shows information that is close to the normal vectors of the object.

Fig. 22 shows the results of reconstructing the shape of the object by means of calculating¹⁷⁾ the relative height of the object based upon the normal vector distribution in Fig. 21. Figure (a) is the case in which the image before highlight compensation was used, and figure (b) is the case in which the image after highlight compensation was used. The object was semi-cylindrical, and the reflection properties of the object's surface were assumed to be the same as previously described.

It is obvious that the reconstruction for the case without highlight compensation in figure (a) shows a convex portion that is different from the shape of the object. Meanwhile, the reconstruction for the case with highlight compensation in figure (b) shows that information very close to the shape of the object was extracted.

Also, the mean error of the height of the object from the reconstructions was calculated to obtain $0.00105r$ for the case using the gray-scale image without compensation and $0.00012r$ for the case of using the gray-scale image with compensation. Thus, it was shown that the mean error was reduced to around one-ninth by carrying out the compensation.

Fig. 23 shows the mean error of the normal vectors plotted against the reflection properties of the object, which is the ratio of the diffuse reflection light component to the specular reflection light component (the ratio of ρ_d to $\rho_s(0)$). The error of the normal vector was defined as the angle between the normal vector on the object calculated by the photometric stereo method and the true value for the normal vector at that same position on the object. Also, the ratio of the diffuse reflection light component to the specular reflection light component (the ratio of ρ_d to $\rho_s(0)$) is higher when the diffuse reflection light component is greater than the specular reflection light component in the reflected light from the object, and it is lower when the specular reflection light component is greater than the diffuse reflection light component. The plots of the black circles, the black triangles, and the black squares in the figure indicate the results of the cases using the gray-scale images without the highlight compensation, while the plots of the white circles, the white triangles, and the white squares indicate results

of the cases of using the gray-scale images after the highlight compensation. Also, the plots of black and white circles, the black and white triangles, and the black and white squares correspond to the semi-spherical object, the semi-cylindrical object, and the cone, respectively.

It is known from Fig. 23 that the mean error of the normal vector was reduced to less than one tenth, irrespective of the ratio of the diffuse reflection light component to the specular reflection light component (the ratio of ρ_d to $\rho_s(0)$), by performing the highlight compensation compared to the cases in which the highlight compensation was not performed. Furthermore, it is noted that the mean error of the normal vector in cases where the highlight compensation was performed is extremely small, even when the shapes of the objects were changed.

Fig. 24 shows the mean error of the normal vector against the coefficient n that expresses the spread of the light of the specular reflection component in the reflection properties of the object. The symbols and plots in this figure are the same as the ones for Fig. 23.

It is also known from Fig. 24 that in cases in which the coefficient n that expresses the spread of the light of the specular reflection component was changed, the mean error of the normal vector was reduced significantly by performing the highlight compensation compared to the cases in which the highlight compensation was not performed.

A factor to which the errors in the results in those cases in which the highlight compensation was performed can be attributed is the approximation of the 3-D coordinates for the object in the process of calculating the normal vectors by the photometric stereo method. In other words, the 3-D coordinates of an arbitrary point P on the object (P_x, P_y, P_z) is an approximation from the coordinate ($P_x, P_y, 0$) that is obtained from the gray-scale image observed at the viewpoint. Therefore, the errors due to approximation of the 3-D coordinates of the object are included in $\mathcal{S}$ (the directional vector on a straight line between the point P and the light source) and γ_P (the distance from the light source to point P), which are both in equation (1). However, this error can be reduced to a negligible level by making γ_P large compared to the height of the object (P_z).

As shown in the results described in above, it was clarified that the proposed method for highlight compensation is a sufficiently valid method, within the scope of this study, irrespective of the shapes and reflection properties of the object.

Fig.17 The gray-level image.

Fig.18 The isoluminance gray scale contour.

Fig.19 The gray-level image.

Fig.20 The isoluminance gray scale contour.

Fig.21 The normal vector distribution .

Fig.22 The three-dimensional reconstruction result.

Fig.23 The mean error of normal vector for reflection characteristic.

Fig.24 The mean error of normal vector for reflection characteristic.

5. Conclusion

This paper proposes, as a compensation method independent from the shapes of highlights, a method to remove highlights from gray-scale images by means of assessing the luminance distribution by the diffuse reflection component for the area where the highlights are generated. The validity of the proposed compensation method was examined by numerical experiments to obtain the following results.

(1) It was clarified that, after obtaining the BRDF from three images to be used for the photometric stereo method through approximate calculation, the areas of highlight with various shapes generated in the images can be extracted using the obtained BRDF.

(2) The luminance distributions by the diffuse reflection component for extracted areas of highlight were assessed by the least square method using the luminance values by the diffuse reflection light component for the areas where no highlight were generated. Then, the gray-scale images in which the highlights were generated

were compensated using the assessed luminance distributions. As a result, the compensated gray-scale images conformed well to the gray-scale images of the objects for which the reflection properties were the diffuse reflection component alone.

(3) The mean error of the normal vectors of the objects, which were calculated from the gray-scale images by the photometric stereo method, were found to be independent from the shapes and reflectance properties of the objects, and it was clarified that the mean errors decreased significantly with the implementation of the proposed highlight compensation compared to the cases in which no highlight compensation was used. Thus, the validity of the proposed compensation method was made clear.

Since it is considered difficult to apply the proposed highlight compensation method to cases in which multiple areas with generated highlights overlap each other due to the reflection properties of the object, we plan to study the judgment of areas with overlapped highlights and the treatment of images, such as the separation of images. Also, we plan to study the application of the highlight compensation method to metallic objects, to which the application of the Phong model is considered difficult.

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