Improvement in Accuracy of Flat-bed Scanning System for Spectral and Glossiness Recording

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Abstract

In this paper, we evaluate the accuracy of estimation for surface roughness and specular reflectance parameters in a flat-bed scanning system that we have proposed previously for recording the spectral and glossiness information of various sheets (Abe et al. 2006). The normal vector of an object is estimated using a shape from shading algorithm, and surface roughness and specular reflection parameters are estimated using the estimated normal vector. The estimated normal vector, roughness and specular reflectance parameters can be used to reproduce various appearances of target objects by using the computer graphics techniques. However, reproduction of objects is not accurate because of the low accuracy of estimation for the normal vector using a shape from shading algorithm. In this paper, we improve the accuracy of estimation for the normal vector by increasing the number of the light sources of scanning system. First, based on a computer simulation, we evaluated the accuracy of estimation for the normal vector, roughness and specular reflectance parameters in increasing the number of the light sources. Secondly, we performed experiments using a real object, and reproduced the object using the estimated parameters under arbitrary illuminant.

1 Introduction

With the wide spread of broad-band internet in the world, internet museum is come into practical use. On internet museum, objects such as art works are stored as digital data and a database of these data is made for digital archive. Across network, the digital data is delivered and we can browse various art works at any time and any place. For accurate reproduction of the original object, it is necessary to record the shape, color, and glossiness of the object accurately. In general, digital cameras are used for recording 3D-object, however in the case of sheet like object, it is easy to acquire images using image scanner. In a conventional image scanner system, the glossiness information is not recorded because an object is illuminated from only single direction. Gardner et al. [1] developed the linear light source apparatus to record reflectance parameters of sheet like object, by acquiring a series of images using a digital camera as a linear light source moves. However, the system takes a long time and high costs to use the digital camera. To record the spectral and glossiness information of various sheets easily and at low cost, we have proposed a flat-bed scanning system using two images taken under different light source directions.[2] In this system, however, it is not accurate to record glossiness of objects because of the low accuracy of estimation for the normal vector using a shape from shading algorithm. Therefore we need to improve the accuracy of estimation for the normal vector.

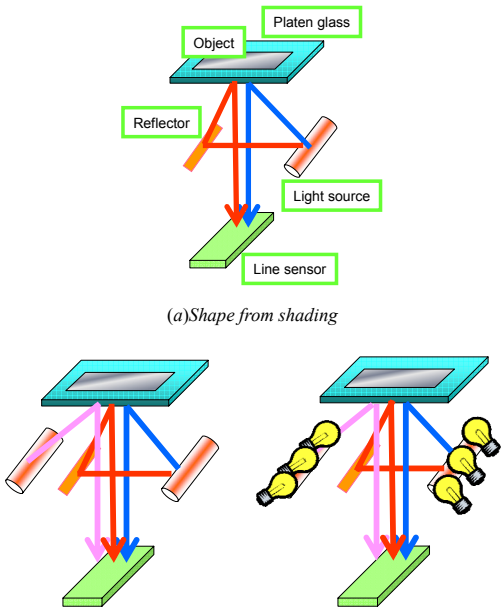
In this paper, we evaluate the accuracy of three types of methods for the normal vector estimation of objects, based on a computer simulation. First, a shape from

shading algorithm[3] used in previous scanning system is a technique to estimate the normal vector using a single diffuse reflection image. We use the Zheng and Chellappa approach[4] for the estimation of the normal vector. Second, photometric stereo method using two light sources[5] is a technique to estimate the normal vector using two diffuse reflection images taken under the geometry that the two light sources are placed symmetrically to the viewer direction. Last, photometric stereo method using three light sources[6] is a technique to estimate the normal vector using three diffuse reflection images taken under the different geometries of illuminants. In addition, we perform experiments using a real object and reproduce the object under arbitrary illuminant using the estimated parameters.

The paper is organized as follows. Section 2 describes the three types of geometry for scanning system. In Section 3, the scanning system proposed previously is explained. Section 4 introduces the three types of technique for estimation of the normal vector, used in our experiments. Based on a computer simulation, the evaluation of accuracy for estimating the normal vector, roughness parameter and specular reflectance parameter is explained in Section 5, and experiments using a real object are shown in Section 6. Finally, we conclude this work in Section 7.

2 Geometry of scanning system

In this section, we describe the three types of geometry of scanning system. Figure 1 (a) shows the geometry of the previously proposed scanning system[2]. The scanning system consists of the linear light source, the reflector, the line sensor, and the platen glass. The target object is put on the platen glass and illuminated by the linear light source or the reflector. The reflected light of the object is captured by the line sensor. For recording the glossiness information, we take two images of the object illuminated by the linear light source and the reflector respectively. The image of an object illuminated from the linear light source of 45 degrees including only the diffuse reflection component is used to estimate the normal vector. The image of an object illuminated from the reflector of 0-δ degrees including the diffuse reflection



(*a*)*Shape from shading*

(*b*) *Photometric stereo using two light sources.*

(*c*)*Photometric stereo using three light sources.*

Figure 1. Geometry of the scanning system.

component and specular reflection component is used to estimate roughness parameters and specular reflectance parameters of the object. The slight angle δ is effective to prevent the strong specular reflection from the platen glass.

To apply three different methods of estimation for the normal vector to the scanning system, a shape from shading algorithm is performed in the previously proposed geometry. Photometric stereo method using two light sources can be used in the system added by a linear light source to the previously proposed geometry as is shown in Figure 1 (b). Two images of the object illuminated from each linear light source include only the diffuse reflection component and they are used for estimating the normal vector. To use photometric stereo method using three light sources, complicated geometry is required such as a system using point light sources in place of a linear light source as is shown in Figure 1 (c). Three diffuse reflection images obtained by varying the position of the light source are used for estimating the normal vector. In all three methods, roughness parameters and specular reflectance parameters are estimated from the image of the object illuminated from the reflector.

3 Previously proposed glossiness scanning system

In this section, we describe the process of recording the glossiness information in the scanning system proposed previously[2]. As the first step of the process, the reflectance of the object is estimated from the image of the object illuminated from 45 degrees and the light source direction by using the histogram of the pixel values on the homogeneous reflectance area. As the second step, the normal vector is estimated from the image of the object illuminated from 45 degrees with the consideration of the light source direction. As the third step, the roughness and specular reflectance parameters of the object are estimated by using the above estimated normal vector and the image of the object illuminated from 0-δ degrees. Finally, the obtained normal vector and specular reflectance parameters and roughness parameters are used to reproduce the various appearance of the object under arbitrary illuminant. In this paper, we compare with the accuracy of estimation for the normal vector of the three types of method mentioned above.

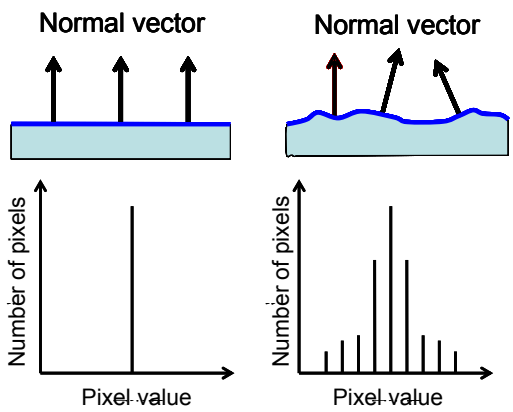
3.1 Reflectance estimation

The image of the object illuminated from 45 degrees includes the diffuse reflection component. Using this image, the reflectance can be estimated for the object. Figure 2 shows one example of flat and practical plane and their histogram for each pixel value. The histogram of the practical plane changes with variance of roughness because the practical plane has different normal vector at each pixel. The normal vector of the pixel at the peak of the histogram can be considered to be vertical to the object. Therefore, the reflectance of the object is estimated from the pixel value at the peak of the histogram.

3.2 Shape from shading

A shape from shading algorithm is a way to estimate the shape of the object from a shading image. In this paper, we use the Zheng and Chellappa approach[4] for the estimation of the normal vector. In the Zheng and Chellappa approach, the intensity gradient constraint is used for and their energy function E is as follows,

$$E = \iint F(p,q,Z)dxdy \qquad (1)$$



(*a*)*Flat plane.* (*b*)*Practical plane.*

Figure 2. One example of plane's image and histogram.

where

$$\begin{aligned} F(p,q,Z) = {} & \mu_1[R(p,q) - I(x,y)]^2 \\ & + \mu_2[R_p(p,q)p_x + R_q(p,q)q_x - I_x(x,y)]^2 \\ & + \mu_2[R_p(p,q)p_y + R_q(p,q)q_y - I_y(x,y)] \\ & + \mu_3[(p - Z_x)^2 + (q - Z_y)^2] \\ & + \mu_4 S(x,y)[(p - p_s)^2 + (q - q_s)^2]. \end{aligned} \qquad (2)$$

In the above equation, the parameters p and q are gradients and Z is a height of a pixel. The reflectance function is denoted as R and the intensity of a pixel of coordinate (x,y) is denoted as I. The first term of equation (2) comes from the perfect diffuse reflection. The second and third terms come from the smoothness constraint. The fourth term comes from the integrability constraint. The last term is a new term we added using specular reflection component. The specular reflection component of a pixel (x,y) is denoted as $S(x,y)$. The parameters p_s, q_s are gradients of the pixel which includes the specular reflection component. μ is a weighting factor.

3.3 Roughness from specular

The image of the object illuminated from 0-δ degrees includes the specular reflection component and diffuse reflection component of an object. Since we have already obtained the reflectance and the normal vector at each point as is described previously, the diffuse reflection component of the image of the object illuminated from 0-δ degrees is easily computed by Lambertian property of the diffuse reflectance component. Therefore, the specular reflection component can be extracted from the 0-δ degrees image by subtracting the calculated diffuse reflection component, based on Dichromatic reflection model[7]

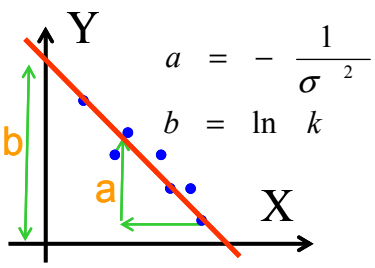


Figure 3. The least-square method.

The roughness and specular reflectance parameters of Torrance Sparrow reflection model[8] are estimated by using this specular reflection component. Equation (1) shows the simplified Torrance Sparrow reflection model[9] for specular reflection component.

$$I_s = k \frac{\exp\left(\frac{-\alpha^2}{2*\sigma^2}\right)}{\cos\theta} \tag{1}$$

where I_s denote the specular component, θ is the degree between the normal vector and the viewer vector, α is the degree between the normal vector and the halfway vector. The halfway vector is bisecting the angle between the light source vector and the viewer vector, σ is the surface roughness parameter and k is the specular reflectance parameter. Equation (1) can be linearized by taking the logarithmic operation as follows,

$$\ln k = \ln I_s + \ln\cos\theta + \frac{-\alpha^2}{2*\sigma^2}. \tag{2}$$

By defining the X, Y as:

$$X = -\alpha^2/2 \tag{3}$$

$$Y = \ln I_s + \ln\cos\theta \tag{4}$$

equation (4) can be re-written as follows,

$$Y = -\frac{1}{\sigma^2} X + \ln k \tag{5}$$

where the parameter σ and the parameter k are unknown parameter to be solved. The X and Y are obtained from the estimated normal vector and extracted specular reflection component at each pixel. The least-square method is used to solve the equation (5) for parameters σ and k from many pixels in the homogeneous area. The least-square method as is shown Figure 3 is used to fit the equation (5) into the plotted data, and the parameters σ and k are obtained from the fitted line.

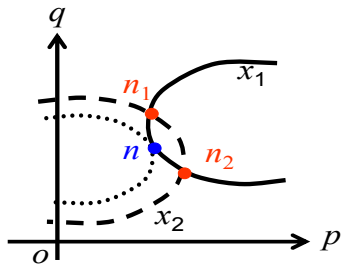


Figure 4. Reflectance map with two light sources.

4 Increasing the number of light source for estimating normal vector

In this section, we describe two methods of estimation for the normal vector. In section 4.1, photometric stereo method using two light sources[5], and in section 4.2, photometric stereo method using three light sources[6] are mentioned.

4.1 Photometric stereo method using two light sources

In the case that the reflectance of the object is known, there are several pixels that we could estimate the normal vector from two images[5]. Figure 4 shows a reflectance map with two light sources. The pixels that have the pixel value x_1=x_2 is the intersection points of two equal luminance curves and the normal vector of each pixel is $\boldsymbol{n}_1$, $\boldsymbol{n}_2$. In the case of the geometry that two light sources are placed symmetrically to the viewer direction, the only normal vector $\boldsymbol{n}$ can be estimated because two curves come in contact with each other. The point fills the multiple root condition of the irradiance equation. The multiple root condition is given by the equation as follows,

$$|\boldsymbol{s}_1 \times \boldsymbol{s}_2|^2 \rho^2 = |x_2\boldsymbol{s}_1 - x_1\boldsymbol{s}_2|^2 \tag{1}$$

where $\boldsymbol{s}_1$and $\boldsymbol{s}_2$ are the unit vector of the light source vector, ρ is the reflectance of the object, x_1 and x_2 are the pixel value of each image. We can estimate clearly the normal vector of a pixel filling equation (1) in the case that the reflectance of the object is known.

$$\rho\boldsymbol{n} = \frac{1}{|x_2\boldsymbol{s}_1 - x_1\boldsymbol{s}_2|} \cdot \left(\frac{x_1 - x_2(\boldsymbol{s}_1 \cdot \boldsymbol{s}_2)}{|\boldsymbol{s}_1 \times \boldsymbol{s}_2|}\boldsymbol{s}_1 + \frac{x_2 - x_1(\boldsymbol{s}_1 \times \boldsymbol{s}_2)}{|\boldsymbol{s}_1 \times \boldsymbol{s}_2|}\boldsymbol{s}_2 \right) \tag{2}$$

where $\boldsymbol{n}$ is the normal vector of the intersection points of two equal luminance curves and it is obtained from equation (2).

4.2 Photometric stereo method using three light sources

Photometric stereo method using three light sources[6] is a technique to estimate the normal vector using several images taken under the linearly independent geometries of the light sources. A pixel value $\boldsymbol{x}$ can be described using the unit of normal vector and the light source direction, $\boldsymbol{n}$' and $\boldsymbol{s}$', the intensity of the light l, and the reflectance of the object ρ, as follows,

$$\boldsymbol{x} = \rho l(\boldsymbol{n}'^T \cdot \boldsymbol{s}'^T). \tag{1}$$

Substituting $\rho\boldsymbol{n}'=\boldsymbol{n}$ and $l\boldsymbol{s}=\boldsymbol{s}'$, equation (1) can be re-written as follows,

$$\boldsymbol{x} = (\boldsymbol{n}^T \cdot \boldsymbol{s}) \tag{2}$$

where the reflectance of the object and the intensity of the light are $\rho=|\boldsymbol{n}|$ and $l=|\boldsymbol{s}|$ respectively because $\boldsymbol{n}$' and $\boldsymbol{s}$' are the unit of each vector. We estimate the normal vector using three images obtained by varying the position of the light source that is linearly independent. Each light source direction is $\mathbf{s}_1=[s_{1x},s_{1y},s_{1z}]^T$, $\mathbf{s}_2=[s_{2x},s_{2y},s_{2z}]^T$, $\mathbf{s}_3=[s_{3x},s_{3y},s_{3z}]^T$. Each pixel values x is described as follows,

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}^T = \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix}^T \begin{bmatrix} s_{1x} & s_{2x} & s_{3x} \\ s_{1y} & s_{2y} & s_{3y} \\ s_{1z} & s_{2z} & s_{3z} \end{bmatrix}. \tag{3}$$

This can be described as matrix as follows,

$$\boldsymbol{x} = \boldsymbol{n}^T \mathrm{S} \tag{4}$$

The normal vector is computed by multiplying equation (4) by inverse matrix of S.

5 Evaluation of accuracy in computer simulation

In this section, we perform the computer simulation for evaluation of estimating the normal vector. In the computer, we modeled shapes of target objects based on the Gaussian distribution which is shown in Figure 5. Table 1 shows the error of estimation for the normal vector using the objects modeled in computer. We take an average of error at each shape. Photometric stereo method using two light sources and photometric stereo method using three light sources have about 5 degrees error with true value and a shape from shading algorithm has about 10 degrees error with true value.

By using the estimated normal vector, roughness parameter σ and specular reflectance parameter k are estimated as is shown in Figure 6. The abscissa axis of the graph describes the variance of shape. The results are compared with the ground truth. In the ideal case, the estimation value is on the broken line. From Figure 6, we can see the accuracy of estimation for roughness parameter and specular reflectance parameter by using a shape from shading algorithm is the lowest and the accuracy of photometric stereo method using three light sources is the highest. Figure 7 shows the results of the estimation for specular reflectance parameters and roughness parameters in the case of changing each parameter 0.1～0.9 when we modeled objects in the computer. As mentioned above, in the ideal case, the estimation value is on the broken line. The accuracy of estimation for roughness parameters by using photometric stereo method using three light sources is the most accurate, and that is the lowest by using shape from shading. For the estimation of specular reflectance parameters, the accuracy is nearly accurate with all three types of methods. In computer simulation, it is high that the accuracy of estimation for the normal vector and roughness parameters with photometric stereo method using three light sources and photometric stereo method using two light sources.

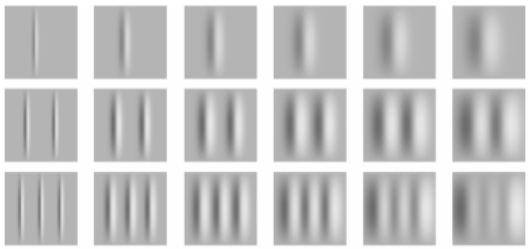
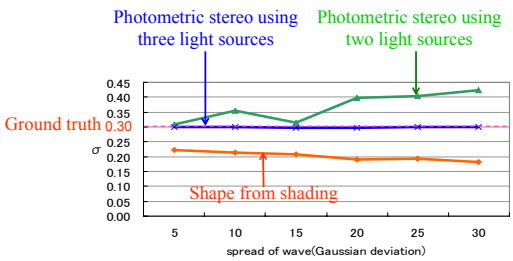


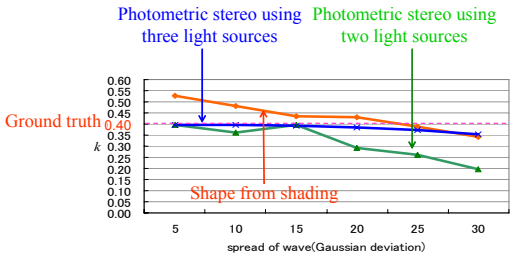
Figure 5. Shapes modeled in computer.

Table 1. Error of normal vector estimation.

	Number of using image	Average value of error(°)	Max value of error(°)
Shape from shading	1	11.4	33.3
Photometric stereo using two light sources	2	5.7	15.3
Photometric stereo using three light sources	3	4.5	13.0

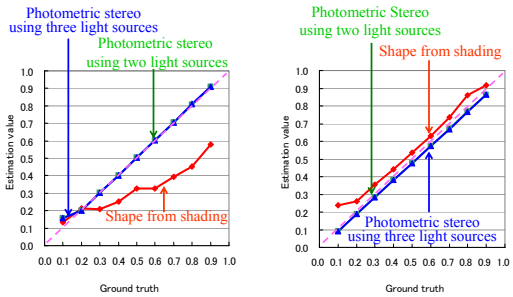


(*a*) *Roughness parameter σ.*



(*b*)*Specular parameter k.*

Figure 6. Results of parameter estimation.



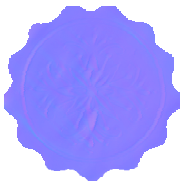
(*a*)*Roghness parameter σ.* (*b*)*Specular parameter k.*

Figure 7. Results of parameter estimation.

Figure 8. Gold sticker.

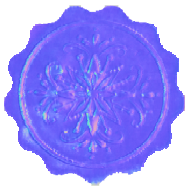
6 Experiment using real object

Figure 8 shows a gold sticker that we used for experiments. Using the above-mentioned the three types of method for estimating the normal vector, we performed the estimation for the normal vector of the real object. The obtained normal maps are shown in Figure 9. Normal maps are images that store normal vectors directly in the RGB values of an image. The real value of the roughness parameter of the object we used for experiments is 0.57 and that of the specular reflectance parameter is 0.41. These values are obtained by fitting the specular reflection components



(*a*)*Shape from shading.*

(*b*) *Photometric stereo using two light sources.*



(*c*)*Photometric stereo using three light sources.*

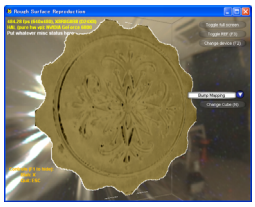
Figure 9. Estimated normal maps using three different methods.

Table 2. Results of parameter estimation.

	Roughness parameter	Specular reflectance parameter
Shape from shading	1.03	0.49
Photometric stereo using two light sources	0.53	0.69
Photometric stereo using three light sources	0.59	0.47
Ground truth	0.57	0.41

(*a*)*Shape from shading.*

(*b*)*Photometric stereo using two light sources.*



(*c*)*Photometric stereo using three light sources.*

Figure 10. Results of reproduced images.

of the multiple images to the simplified Torrance Sparrow reflection model[9] mentioned above. The multiple images are obtained by varying the position of the light source from -40 degrees to 40 degrees at 5 degrees intervals. Table 2 shows each result of specular reflectance parameters and roughness parameters obtained using the three types of method. We can see that the accuracy of estimation for the

specular reflectance parameter and roughness parameter with photometric stereo method using three light sources is the highest in the three methods.

Using the estimated normal vector and specular reflectance parameters and roughness parameters of the object, we reproduced the object under arbitrary illuminant on the computer graphics. Figure 10 shows the results of reproduced images.

7 Conclusion

We evaluated the accuracy of estimation for surface roughness and specular reflectance parameters in a flat-bed scanning system that we have proposed previously for recording the spectral and glossiness information of various sheets. A shape from shading algorithm is useful for a scanning system because only a single diffuse image is required, but the accuracy of estimation for the normal vector is the lowest in the three methods. In contrast, the accuracy of estimation for the normal vector with photometric stereo method using three light sources is the highest in the three methods, but it is not useful for a scanning system because the complicated geometry is required as mentioned previously. Therefore, photometric stereo method using two light sources that can be performed by adding a linear light source to the previously proposed scanning system is useful for a scanning system. In this paper, we don't make consideration for spectral information because we have used the object that has uniformity of color and material. Therefore, in the future work, we need to split the region of the object that have non-uniformity of color and material.

Acknowledgements

The authors are thankful to Dr. F. Nakaya, Dr. H. Ichikawa and Dr. Y. Minato of Fuji Xerox Corporation for several useful comments.

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