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5—4 3D Shape Reconstruction using Three Light Sources in Image Scanner

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Abstract

We suggest the method to recover the 3D shape of the object by using the color image scanner which has three light sources.

The photometric stereo is traditional to recover the surface normal of the object using the multiple light sources. In this method, it usually assumes the distant light sources to make the model simple. But the light sources in the image scanner are so close to the object that the illuminant intensity varies with the distance from the light source, therefore these light sources should be modeled as the linear light sources. In this method, by using this models and two step algorithm; the initial estimation by the iterating computation and the optimization by the non-linear least square method, not only the surface normal but also the absolute distance from the light source to the surface are estimated. By this method, we can recover the 3D shape more precisely. In the experimental results, the reconstruction of the 3D shape of the real object is shown.

The proposed method changes the image scanner into the shape scanner. It makes the 3D data acquisition easily, so it will be very useful in the CAD/CAM and the virtual reality system.

1 Introduction

In this paper, we propose the method to recover the 3D shape of the object using the color image scanner which has three light sources. The method to recover the book surface shape using the image scanner has been proposed[1]. But this method assumes that the cross section shape of the book surface is constant, therefore only the 2D cross section shape can be recovered. Here, we show the method to recover the real 3D shape of the object which has no restriction about its shape.

The photometric stereo is familiar to recover the 3D shape using the multiple light sources[2],[3]. It estimates the normal vector and the albedo of the object surface. In this method, to simplify the photometric formulation, the light source is often assumed to be the parallel (distant) light source. But, the light source in the image scanner is very close to the object. The illuminance varies with respect to the distance from the light source. This property makes the formulation complex. But by assuming the constant albedo, we suggest the method to estimate not only the surface normal vector of the object but also the absolute distance from the linear light source to the object surface from such complex models.

2 Structure of Image Scanner

Figure 1 shows the color image scanner and the coordinate system. This scanner has one monochrome linear CCD sensor and three light sources which are red, green, and blue. Each light source can illuminate the object on the scanning plane independently. A color image is taken by scanning three times using each light source.

Three light sources are long and narrow fluorescent tubes. They are modeled as the linear light sources. When the scanning line S locates at $y = y_j$ as shown in figure 2, the illuminant intensity of the red light source $Is_r(x_i, y_j)$ is formulated as:

$$Is_r(x_i, y_j) = \frac{\alpha_r}{\sqrt{d_{yr}^2 + (z(x_i, y_j) - d_{zr})^2}} + Ie_r, \quad (1)$$

where $z(x_i, y_j)$ denotes the height from the point (x_i, y_j) on the scanning plane to the surface, (d_{yr}, d_{zr}) $(d_{zr} < 0)$ the location of the light source relative to the scanning line S on $y-z$ plane, α_r the parameter of the illuminant intensity, and Ie_r the environment light intensity. The green and blue light sources are modeled similarly. These models are expressed by changing the index 'r' in equation (1) to 'g' or 'b'.

3 Optical Model

First, to formulate the optical model, we use the following assumptions: 1) the object surface is the Lambertian, 2) the albedo on the surface is constant, 3) there are no interreflections. Let ρ be the albedo on the surface, and $(n_x(x_i, y_j), n_y(x_i, y_j), n_z(x_i, y_j))$

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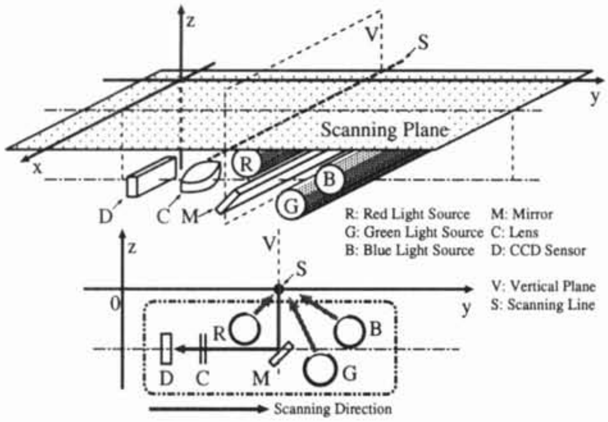


Figure 1: Structure of image scanner.

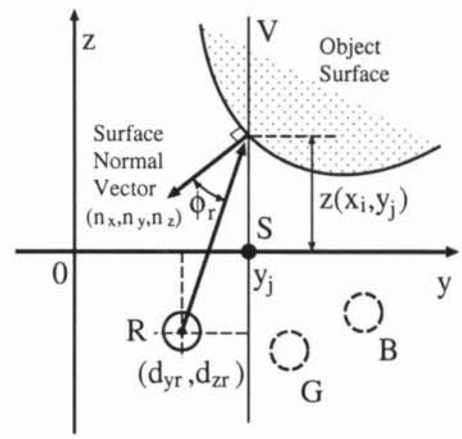


Figure 2: Direction and location of light sources.

$(n_x^2(x_i,y_j)+n_y^2(x_i,y_j)+n_z^2(x_i,y_j)=1)$ the surface normal vector at $(x_i,y_j,z(x_i,y_j))$. In case of the red light source, the image intensity $P_r(x_i,y_j)$ in the observed image is formulated as:

$$P_r(x_i,y_j)=a_r\cdot\rho\cdot Is_r(x_i,y_j)\cdot\cos(\phi_r(x_i,y_j))+\Delta_r, \quad (2)$$

where a_r and Δ_r denote the gain and the bias of the photo-electric transformation in the image scanner respectively. $\phi_r(x_i,y_j)$ is the angle between $(n_x(x_i,y_j),n_y(x_i,y_j),n_z(x_i,y_j))$ and the direction from $(x_i,y_j,z(x_i,y_j))$ to the red light source (figure 2) represented as:

$$\cos(\phi_r(x_i,y_j))=\frac{d_{yr}\cdot n_y(x_i,y_j)-n_z(x_i,y_j)\cdot(z(x_i,y_j)-d_{zr})}{\sqrt{d_{yr}^2+(z(x_i,y_j)-d_{zr})^2}}. \quad (3)$$

In case of the green and blue light sources, the image intensities $P_g(x_i,y_j)$ and $P_b(x_i,y_j)$ are formulated similarly.

4 Shape Reconstruction

In this section, we show the method to estimate the shape parameters; z, n_x, n_y, and n_z; at (x_i,y_j) from the observed image intensities; $Po_r(x_i,y_j)$, $Po_g(x_i,y_j)$, and $Po_b(x_i,y_j)$; by using the optical models; $P_r(x_i,y_j)$, $P_g(x_i,y_j)$, and $P_b(x_i,y_j)$. In this method, we assume that the parameters α_r, d_{yr}, d_{zr}, a_r, ρ, and Δ_r in equation (1) and equation (2) (including in case of the green and blue light sources) are known.

The basic idea to estimate z, n_x, n_y and n_z is to minimize the function F:

$$\begin{aligned} F &= \{Po_r(x_i,y_j)-P_r(x_i,y_j)\}^2 \\ &\quad+\{Po_g(x_i,y_j)-P_g(x_i,y_j)\}^2 \\ &\quad+\{Po_b(x_i,y_j)-P_b(x_i,y_j)\}^2, \end{aligned} \quad (4)$$

by the non-linear least square method. But when we use this method, the appropriate initial estimations are needed. If the initial estimations are not appropriate, then:

1. The finally estimated shape parameters are not the optimal estimations,
2. It costs much computation time to minimize F.

To avoid such problems, we use the following iterative algorithm to obtain the initial estimation and then the best parameters are estimated by the non-linear least square method:

STEP 0: Approximate the initial direction of the light sources.
Calculate $\cos(\phi_r)$, $\cos(\phi_g)$ and $\cos(\phi_b)$ from equation (3) under $(n_x,n_y,n_z)=(0,0,-1)$ and $z=0$.

STEP 1: Estimate the heights under the fixed normal vector.
Estimate the heights (z_r, z_g and z_b) under each light source by substituting $\cos(\phi_r)$, $\cos(\phi_g)$ and $\cos(\phi_b)$ for equation (2).

STEP 2: Estimate the normal vector under the fixed heights.
Formulate three linear equations about n_y and n_z by substituting z_r, z_g and z_b for equation (2) again. Estimate n_y and n_z by the linear least square method, and then obtain n_x^2.

STEP 3: Estimate the height and check convergence.
The values of z_r, z_g, and z_b will be equal ideally. But due to the influence of the noise and the approximated calculation from STEP 0 to STEP 2, they don't become same value. Therefore, we assign z to $(z_r+z_g+z_b)/3$ as the estimated height.
Calculate $\cos(\phi_r)$, $\cos(\phi_g)$ and $\cos(\phi_b)$ from equation (3) using z, n_y, and n_z and iterate

from STEP 1.
In the loop of this iteration, if z converge then go to STEP 4.

STEP 4: Final estimation.
Let the values of z, n_x^2, n_y and n_z obtained until STEP 3 be the initial estimations, estimate the optimal z, n_x^2, n_y and n_z from equation (4) by using the non-linear least square method.

After this process, $n_x(x_i, y_j)$ is calculated from $n_x^2(x_i, y_j)$, and its sign is determined by the hights around $(x_i, y_j, z(x_i, y_j))$.

5 Experimental Results

5.1 Estimation of Parameters in Optical Model

Before using the method described in section 4, we must obtain the parameters α_r, d_{yr}, d_{zr}, a_r, ρ and Δ_r in equation (1) and equation (2) (including in case of the green and blue light sources). To estimate these parameters, we use the following process.

First, we take the scanner images of the slope model which plane is put to the white paper approximated to the Lambertian surface by varying the slant angle (θ) and the rotation angle (ψ) as shown in figure 3. In this experiment, we set ψ from 0 to 330 step 30[deg.], and $\theta = 15, 30, 45, 60$[deg.] at each ψ. So, total 48 images are taken.

Next, the image intensities to θ, ψ and z are extracted at the region of the slope in the scanner images for the red, green and blue light sources. Figure 4 shows the distributions of the image intensities to ψ and z ($\theta = 30$[deg.]). Using these distributions, the parameters are estimated by the combination of the linear least square and the non-linear least square methods.

Note that, to avoid the influence of the external illumination, the image scanner and the slope model are covered with the black box. This black box is used in the next shape reconstruction experiment.

5.2 Shape Reconstruction

Here, we show the result of the shape reconstruction. Figure 5 shows the scanner images of the surface of the mouse device which reflectance property is approximated to the white Lambertian surface. Because of the difference of the light source location, the image intensities are different at the same point on the surface, so the white surface is colored. Figure 6 show the reconstructed shape (the distribution of the height z) by the proposed method. The shape can be recovered precisely all over the object but a part of the surface at the wheel button and the printed letters are not recovered because of the difference of the reflectance property.

We also examine the shape reconstruction by using only the non-linear least square method (initial

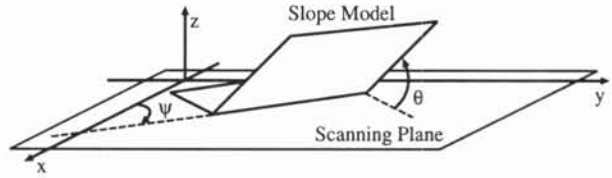
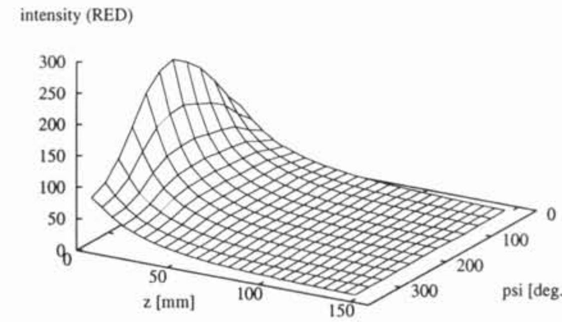
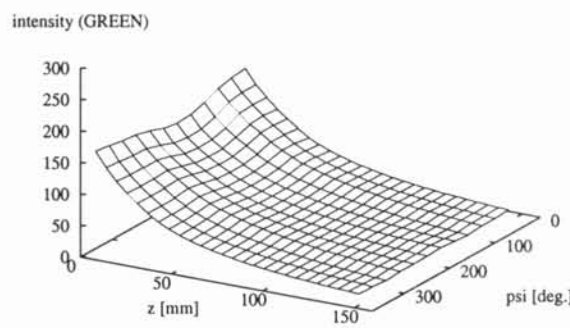


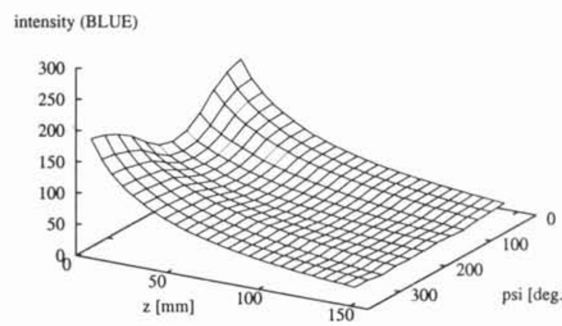
Figure 3: Slope model on scanning plane.



(a) Red light source.

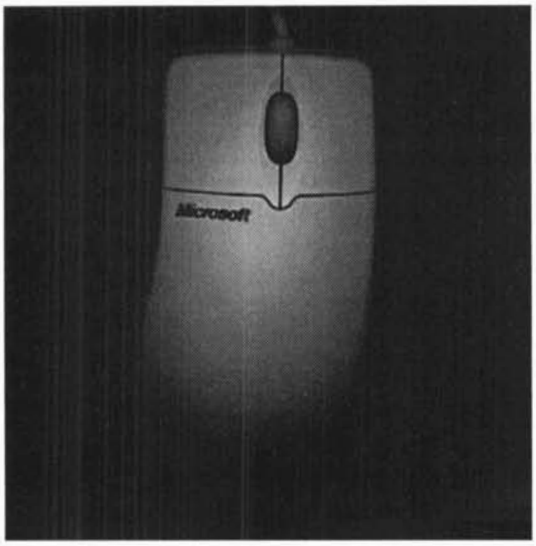


(b) Green light source.

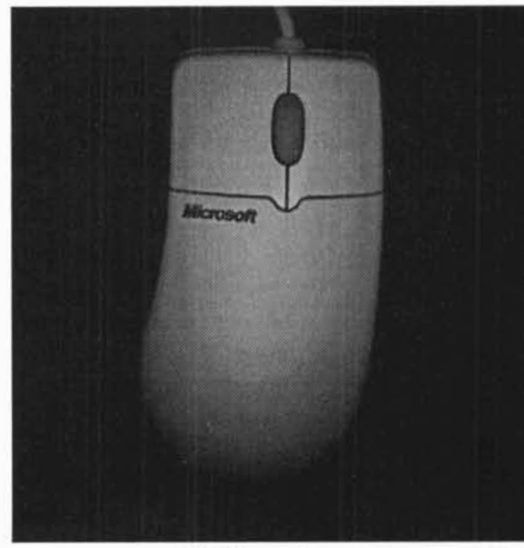


(c) Blue light source.

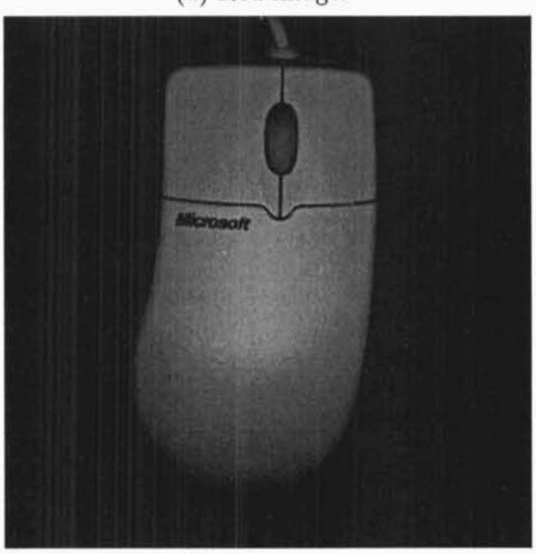
Figure 4: Distribution of slope image intensity ($\theta =$ 30 [deg.]).



(a) Red image.



(b) Green image.



(c) Blue image.

Figure 5: Observed image.

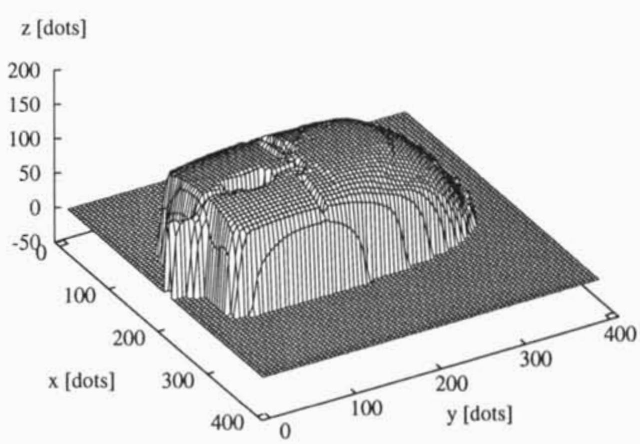


Figure 6: Estimated shape.

values: $(n_x, n_y, n_z) = (0, 0, -1)$, $z = 0$). But in this method, the computation time is needed more than three times as much as the proposed method and the shape parameters are not estimated exactly. Therefore, the proposed algorithm is effective to the shape reconstruction in this problem.

6 Conclusion

In this paper, we discussed the method to recover the 3D shape by using the color image scanner which has three light sources. Here, we showed the optical model under the linear light sources and the Lambertian surface, and proposed the two step shape reconstruction algorithm; estimating the initial values by the iterate computation and optimizing the parameters by the non-linear least square method. Feature works are to recover the object which has the different reflectance properties and to integrate the partial 3D shapes.

References

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