Shape Recovery of Specular Objects from Multiple Lights

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SUMMARY

This paper describes the method of shape recovery of specular objects illuminated by multiple light sources by pattern recognition. In this method, a three-dimensional shape is recovered from an epipolar plane image (EPI) of a rotating image. The highlight reflected from an object has a traveling characteristic corresponding to the surface profile of the object. The highlight appears in EPI as image speed. Therefore, the three-dimensional shape can be quantitatively recovered by tracing the locus of the highlight on EPI if the relationship among the shape of the object, light source, direction of view, and highlight is equated. In this study, the relationship among the object shape under illumination from multiple light sources, direction of view, and highlight is equated in order to quantitatively recover the cross-sectional view of a columnar object. In addition, three-dimensional shape recovery of a general object is accomplished by introducing the light source model of a cone-shaped illumination plane. Finally, in order to show the validity of this method, the experimental result on the recovery of specular objects and its evaluation will be described. © 1998 Scripta Technica. Syst Comp Jpn, 28(14): 11–20, 1997

Key words: Specular reflection; highlight; EPI; cross-sectional view; three-dimensional shape recovery.

1. Introduction

Recently, noncontact measurement using pattern recognition has been in demand in the fabrication industries.

In addition, since computer graphics has been widely used in introducing commercial goods and video conferencing, three-dimensional (3D) shape recovery technology is in high demand.

In order to accomplish noncontact 3D shape recovery, the laser projection methods such as range finder and the image method (shape from Xs, where X represents contour [1, 2, 4] or motion [3, 8]) have been proposed. However, they have limits in the environment and the shape of objects and often cannot be used to recover images with highly reflecting surfaces.

On the other hand, many objects have highly reflecting surfaces in the real world. When a person visually recognizes an object with highly reflecting 3D (specular) objects, eye motion and change in highlight of the object play roles in estimating the shape of the object in addition to stereographic procedure using the parallax of two eyes. However, the majority of studies on image recognition based on highlight change employ the extraction method to remove the highlight and the condition in the pattern recognition [5–7]. Few studies have been proposed for shape recognition by highlight motion.

The authors have proposed a method for 3D shape recovery of a specular object based on highlight motion under a single light source [9, 10, 12]. In our work, we first described the relationship among the light source; object, and visual point using a first-order differential equation. It was shown that the cross-sectional shape could be quantitatively estimated by tracking the locus of the highlight extracted from the epipolar plane image (EPI). In addition, a 3D shape model was quantitatively recovered by solving the first-order differential equation. However, since the derived equation contained cumulative integration (error was included), the recovered shape contained error.
This paper proposes a method for 3D shape recovery of a highly specular object under illumination from multiple light sources [13]. When multiple light sources are present, the relationship among the highlights due to each light source, cross section, and view point is used to describe an object with a complex shape using a simple linear equation. As a result, accurate and stable shape recovery can be expected.

First, the methods used to create EPI and to extract highlight from EPI will be described. Second, the geometrical relationship among light source, cross section of an object, and view point are described under, for example, illumination from two light sources, and an equation for shape recovery of a columnar object will be derived. Third, in order to apply the derived equation for general 3D shape recovery, the light source model for a cone-shaped illumination plane will be introduced. Finally, the validity of this method will be described using the experimental result.

2. Principle

This section describes the methods used to create EPI and to extract highlight.

2.1. Imaging environment and EPI creation

Figure 1 illustrates the method of EPI creation. An object is placed on a turntable and planar images (x, y) of the object are obtained while the object is rotating. Then, the images are accumulated on the time axis (θ). In order to realize orthogonal projection, the camera and object are far apart and a zoom camera is used to obtain images. The image data (x, y, θ) provide a 3D spatial image. However, the cross section parallel to the rotational plane is taken into account in this study. For each cross section, the image data for one line are accumulated with respect to θ to create a spatial cross-sectional image (x, θ) EPI.

2.2. Extraction of highlight

The highlight which is the specular component of the reflected light has the highest intensity when the incident angle normal to the surface is the same as the reflection angle. In this case, the density difference between the diffused reflected light and highlight becomes distinctive on the EPI [5, 6]. The section where the density drastically changes in the horizontal axis direction is processed by a roof-edge operation to extract the peak of the density profile as a highlight characteristic point from the EPI. The extracted point has continuities at the rotational angle θ in the time axis. However, when it does not behave like a series of loci because of extraction error and the noise component, it is treated as a group of loci of highlights from a light source, using the linear approximation and fine wire treatment. Since multiple light sources are used, multiple observation points of highlights are extracted. Therefore, they are treated as a group. The surface points, such as angle and texture, form sinusoidal curves on the EPI [3] and the locus of the highlight crosses the sinusoidal curve.

3. Recovery of 3D Shape—Columnar Object

This section describes the method of 3D shape recovery of a columnar object in the direction of nρ = 0.

3.1. Cross section of object and light source

Figure 2 shows the relationship between the cross section of an object parallel to the rotating plane and light source, where L is the light source direction, n the normal direction, and v the visual line direction. When the object is illuminated as shown in Fig. 2, highlight is observed if the incident angle ∠LPn is the same as the reflection angle ∠vPn. Then, the highlight is projected at point x(θ) on the projection plane. Therefore, the direction from the center to point x(θ) is given by x = (cos θ, sin θ). The magnitude of x(θ) is given by

\[ x(θ) = X \cos θ + Z \sin θ \] (1)

Then, (X, Z) on the right-hand side is the coordinate of the cross section of the object.
3.2. Derivation of cross section

Figure 3 shows the relationship between the highlight due to rotation and the shape of cross section. Light source 1 illuminates the object at angle $\phi_1$ (center coordinate system of the camera) and the light source illuminates the object at angle $\phi_2$ (center coordinate system of the camera). When the light from light source 1 incides to the surface point with normal ($\phi_1$)/2 and the light from light source 2 incides to the point in the direction of normal $\phi_2$/2, highlights are observed. Therefore, when the object is rotated by ($\phi_2 + \phi_1$)/2 from the angle at which highlight is observed, highlight from $P(X, Z)$ is observed again by light source 2.

If the points at which the highlight is observed due to light source 1 and light source 2 are $x_1(\theta)$ and $x_2(\theta + \Delta \phi/2)$, respectively, then

$$x_1(\theta) = X \cos \theta + Z \sin \theta$$
$$x_2(\theta + \Delta \phi/2) = X \cos \left(\theta + \frac{\Delta \phi}{2}\right) + Z \sin \left(\theta + \frac{\Delta \phi}{2}\right)$$

(3)

where $\Delta \phi$ is $\phi_2 - \phi_1$ and is assumed to be known.

$(X, Z)$ on the right-hand side in Eqs. (2) and (3) is the boundary point in the cross section of the object. This indicates that one point on an object is twice observed due to two light sources and that two visual lines cross at the point in the 3D space. $(X, Z)$ can be given using Eqs. (2) and (3) as follows:

$$X = \frac{1}{\sin \left(\frac{\Delta \phi}{2}\right)} \begin{pmatrix} \sin(\theta + \frac{\Delta \phi}{2}) & -\sin \theta \\ -\cos(\theta + \frac{\Delta \phi}{2}) & \cos \theta \end{pmatrix} \begin{pmatrix} x_1(\theta) \\ x_2(\theta + \frac{\Delta \phi}{2}) \end{pmatrix}$$

(4)

where $\theta$ is the rotation angle, the left-hand side of the coordinate of the object and $x_1$ and $x_2$ on the right-hand side are the values obtained from the image locus.

3.3. Derivation of 3D shape—columnar object

When a columnar object is illuminated under the condition of orthogonal projection, the $y$-axis component of the normal is zero at every cross section. Therefore, the shape of the cross section can be calculated using only the position of highlight $\Delta \phi$, which is always the same at every boundary point. Therefore, in case of a columnar object, the equations derived in the previous section are applied at the cross section at each height. The 3D shape can be obtained by accumulating the cross-sectional shapes.

The concept of this method is basically to determine the crossing point of two visual lines and is close to the principle of moving stereo or that of shape from motion [3, 8]. In this method, the corresponding point on the surface is not the edge point but is determined by the highlight caused by the relationship between light source and observation point. Since the highlight on the EPI has a continuity in the time axis direction at a rotational angle $\theta$, it can be easily identified by treating a group of loci. Therefore, this method can be referred to as the specular moving stereo...
method and is advantageous in calculating numerous 3D positions on the specular surface which do not have fixed points such as edges.

4. 3D Shape Recovery—General Shape

In this section, the equation derived for recovery of columnar shapes in the previous section will be applied for recovery of general shapes using the light source model.

4.1. Light source model

The equations derived in the previous section were based on the cross-sectional shape on the visual plane (X, Z) parallel to the rotational plane. The change of shape in the height direction was not taken into account. In case of a columnar object where the y-axis component of the normal is zero, the calculation is based only on the position of the object and the equations can be applied to every cross section. However, in an object with a general shape, the y-axis component of the normal is not always zero and the highlight may not be projected on the EPI. In order to apply this method to recover a general shape, the light source model must be applied, where each surface point becomes a highlight. In a one-light-source model, extension of illumination can be adopted. In order to easily carry out calculation, the angle between the light sources must be given by $\Delta \phi 1/2$ and $\Delta \varphi 2/2$, regardless of $n_z$. In this study, a light source model satisfying the above condition will be introduced.

4.2. Assumption of light source

Figure 4 shows the relationship among the normal on a Gaussian sphere, light source, and visual point, where $v$ is the image projection direction, $n$ the normal direction, $L$ the light source direction, and $n'$ the projection vector of $n$ on the rotational plane. At the point on the normal $n$, light is generated when $\angle von = \angle Lon$. When the normal is $n'$, the light source direction in which the point $O$ is observed as highlight is $L'$. This situation corresponds to that of a columnar object described in section 3. In order to apply this method to recovery of general shape, the angle between light sources must be given by $\Delta \phi 1/2$ and $\Delta \varphi 1/2$, regardless of the change of $n$. Now, it is assumed that even when the direction of $n$ changes, the rotational plane component of the normal $n$ is constant and $\angle von$ is always equal to $\angle Lon$.

The visual direction $v$, normal direction $n$, and light source direction $L$ are shown below. It is assumed that $\angle von$ and $\angle Lon$ are $\Phi /2$ and $\angle von$ is $\varphi$.

$$v = (0, 0, 1)$$

$$n = (n_x, n_y, n_z)$$

$$L = (l_x, l_y, l_z)$$

Because of the optical characteristic of reflection, $v$, $n$, and $L$ are present on the same plane. Therefore, the following relationship holds:

$$L \times n = n \times v$$ (5)

Equation (5) expresses the condition of highlight observation by the product of the light source direction and normal direction and the product of the visual direction and normal direction. The components of $n$ are as follows:

$$n_x = \cos \varphi \cos \Phi /2$$

$$n_y = \sin \varphi$$

$$n_z = \cos \varphi \sin \Phi /2$$

Therefore,

$$L \times n = (l_y \cdot n_z - l_z \cdot n_y)i$$

$$+ (l_x \cdot n_y - l_y \cdot n_x)j + (l_x \cdot n_y - l_y \cdot n_x)k$$ (6)

$$n \times v = (n_y \cdot 1 - n_z \cdot 0)i$$

$$+ (n_z \cdot 0 - n_x \cdot 1)j + (n_x \cdot 0 - n_y \cdot 0)k$$ (7)

From Eqs. (6) and (7),

$$l_x n_z - l_z n_x = n_y$$

$$l_x n_x - l_y n_y = n_z$$

$$l_y n_z - l_z n_y = -n_z$$

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Using the above assumption, shape recovery of an object will be carried out, using two circular light sources. From Eq. (9), the coordinate of the light source on the Z-axis is \( Z = \tan \Phi / 2 \). When \( \Phi = \pi / 2 \), \( Z = 1 \). The angle between two pairs of fluorescent tubes is set to be \( \pi / 2 \) and the center line of the fluorescent tubes meet on the Z-axis. Then, the distances between the edges of the fluorescent tubes and the center axis are the same. As a result, the object is illuminated by cone-like illumination. In this study, the light source condition is as follows.

[Condition 1] The sizes of the light sources are sufficiently large compared with the size of the object.
[Condition 2] The light beam is cone-shaped and passes through the center axis.
[Condition 3] The angle between the light sources is known \( (\Delta \Phi) \).
[Condition 4] The angle between the highlights and normal is \( \Delta \Phi / 2 \).

5. Experiment and Consideration

5.1. Experimental result

In this study, an object is set on a turntable rotating clockwise, the light source is circular and its diameter is 300 mm, and image data of 512 pixels per line are provided. To generate EPI, the data are generated every 360/400 degrees and the number of data is 400. The EPI contains 512 pixels in the x-axis direction and 400 pixels in the \( \theta \)-axis direction. For one object, 40 stages of EPI with 10 pixels of separation between stages are sampled. Ideally, the stage-to-stage separation in EPI generation should be 1 pixel wide. However, it takes too long to form a model and the load on a computer is too high. Therefore, in this study, the stage-to-stage separation is chosen to be 10 pixels wide. For the final

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Fig. 5. Estimation of the light shape.

Fig. 6. Sphere: original shape (diameter 45 mm).
3D model, the cross-sectional shape for each stage is accumulated (surface model [9]).

The shape recoveries for two highly specular objects with different sizes and a nongeometrical object with low reflection were attempted as shown in Figs. 6 to 16.

Figure 6 shows a small highly specular object and Fig. 7 the EPI and highlight trace. Figure 8 shows the recovered cross-sectional shape obtained from the highlight and Fig. 9 the recovered 3D model.

Figure 11 shows a highly specular object and Fig. 12 the recovered 3D model.

Figure 13 shows a nongeometrical object with weak reflection, Fig. 14 the EPI and highlight trace, Fig. 15 the matching cross section, and Fig. 16 the recovered 3D model.

The unrecovered sections are shown as holes.

5.2. Consideration

The entire shape was recovered when the object was highly specular. However, the object shown in Fig. 11 was relatively large compared with the circular light source, causing error. The sections with holes shown in Fig. 16 were caused by missing highlight or failure of recovery despite the presence of highlight.

Missing highlight may have occurred because the reflection was much lower than that from the object shown in Fig. 6 or the circular light source was not sufficiently large compared with the size of the object. Under the required condition, the light source must be sufficiently large with respect to the size of an object. In this study, the diameter of the light source was 300 mm and highlight from the object was sometimes hidden by a section of the object. In the result shown in Fig. 13, the chin of the doll is the trouble spot. In order to avoid the problem as described above, the size of the light source should be increased or the direction of illumination should be changed.
Examples of nonrecoverable shapes are corners, fine surface structures such as a fine carved section, and wrinkles. Since highlight from such an area drastically oscillates in the EPI, it is impossible to trace the highlight. In the doll shown in Fig. 13, the arm and back are the trouble spots. In order to accurately recover a shape, resolution must be increased.

When the equations proposed in this study are used, the accuracy in locating the 3D coordinate is strongly influenced by the angle between the light sources. That is, since the angle between two light sources is $\phi_2 - \phi_1$, the accuracy is maximized when $\phi_2 - \phi_1 = 2\pi$ at which $\sin(\phi_2 - \phi_1)/2$ is maximum. In this method, it is not necessary to switch the light source as done in the photometric stereo method.

Figure 17 shows a comparison between the results obtained by a previously proposed method using a single light source [10] and the present method, where the object was columnar shaped and the cross section was bottle gourd-shaped with a vertical length of 160 mm and a
horizontal length of 70 mm. In both cases, the conditions were the same except for the number of light sources. The result on the left was obtained using a single light source and the result on the right was obtained using the present method. The solid line represents the cross section of the actual object and the dotted line, the recovered result. The errors caused in the previous and present methods are 3.1 and 1.5%, respectively.

Since a long focus lens was used in this study, the error with respect to orthogonal projection is small. The error calculation is the same as that used in the stereo method. Therefore, the error observed in the left figure is believed to have occurred because the size of the light source was too small. In the conventional method, the cross-sectional shape was derived by using differential equations. However, in this method, a simple linear equation was used, which contributes to the reduction of error.

Fig. 16. Recovered surface model of object 2.

Fig. 17. Recovered cross section 160 \times 70 \text{ mm}. Left: under unity light; right: under multiple lights.

By comparing the two results, it is concluded that the present method is more effective.

6. Conclusions

In this study, the relationship among the light from an object projected on the time-space cross-sectional image under multiple light sources, light sources, and object and view points was established to recover the cross-sectional shape. Using this method in experiments, its effectiveness was demonstrated.

In addition, the method was effective in shape recovery of specular objects that could not be accomplished by the conventional laser projection method. However, when the size of the light source was not sufficiently large compared with the size of the object, the highlight was hidden by the object and accurate shape recovery could not be accomplished. In addition, fine surface structure such as a fine carved section and surface wrinkles could not be recovered because the highlight could not be observed. In order to avoid these problems, the combination of this method and the conventional “shape from Xs” method should be used.

REFERENCES


**APPENDIX**

Extension to Multiple Light Sources

When multiple light sources are used, multiple observed points for highlights due to light sources are obtained. Then, multiple equations are established:

\[
x_1(\theta) = X \cos \theta + Z \sin \theta \quad (A.1)
\]

\[
x_1(\theta + \Delta \phi_1) = X \cos(\theta + \Delta \phi_1) + Z \sin(\theta + \Delta \phi_1) \quad (A.2)
\]

\[
x_2(\theta + \Delta \phi_2) = X \cos(\theta + \Delta \phi_2) + Z \sin(\theta + \Delta \phi_2) \quad (A.3)
\]

where \(\Delta \phi_i = (\phi_i + \phi)/2\) and \(\Delta \phi_i\) is known. Since \(X, Z\) on the right-hand sides of the equations represent the same point, the following equation is obtained from the minimum square method:

\[
\begin{bmatrix}
  X \\
  Z 
\end{bmatrix} = \frac{1}{n^2 - \frac{1}{2} \sum_{k<j} \cos(\phi_k - \phi_k)} \times \left( \begin{array}{c}
  -\sum_{i=1}^{n} \sin(2A) \\
  \cos(2A) \\
  \sin(2A) \\
  \cos(2A) \\
  -\sum_{i=1}^{n} \cos(2A) \\
  \sin(2A) \\
  \cos(2A) \\
  \sin(2A) \\
  \end{array} \right) \begin{bmatrix}
  x_1(A) \\
  x_2(A) \\
  \end{bmatrix} \quad (A.4)
\]

where \(A = \theta + \Delta \phi_2, B = \theta + \Delta \phi_1,\) and \(C = \theta + \Delta \phi_e.\)
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