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# SMOOTH SHADING OF SPECULAR SURFACES IN POLYGON-BASED HIGH-DEFINITION CGH

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## ABSTRACT

High-definition computer-generated holograms (CGH) created by the polygon-based method feature reconstruction of very fine 3D image accompanied with strong sensation of depth. However, rendering technique for specular surfaces has not been established. We propose a novel technique for smooth shading of specular surfaces in the polygon-based method. This technique divides the surface function of polygons into some segments and controls the spectral envelopes.

**Index Terms**— Holography, Computer graphics, Optical imaging

## 1. INTRODUCTION

Today, we easily watch 3-D movies in our home and cinemas because of the extraordinary development of display devices such as LCD or DMD. However, 3-D images reconstructed by these conventional displays are not a true 3-D image, i.e. they are made by only use of binocular disparity. This sometimes leads to eyestrain caused by seeing it for several hours. Therefore, holography that reconstructs true 3-D images accompanied with all depth cues is expected to be the next generation of 3-D displays.

The computer-generated holograms (CGH) are a kind of holography. The CGH can reconstruct a true 3-D image of virtual objects unlike classical holography, but have been suffering from two serious problems. First, CGHs require a long computation time to create it. The most common method for CGH computation has been the point source method for a long time. In this method, an object is assumed to be covered up with many point sources of light, and spherical waves emitted from the point sources is computed at every sampling point in the hologram plane. However, this method needs too many point sources to represent the 3-D surface of objects. As a result, this method cannot create high-definition full-parallax CGHs. Therefore, a field-oriented polygon-based method has been proposed to overcome the limits of the point sources method [1,2]. In this method, an object is composed of surface sources of light with polygonal shapes, and the wave-fields emitted

from the polygonal surface sources are calculated and superposed in the hologram plane. This method remarkably reduces computation time of CGHs, because the number of polygons necessary for forming object surfaces is much smaller than that of point sources. In addition, there is one more advantage that the technique is similar to conventional CG.

The second issue of recent CGHs is the difficulty reconstructing a variety of realistic surfaces as much as modern CG. Only diffusive surfaces are calculated and reconstructed even in the polygon-based method [2]. As a result, viewers of the hologram do not have any hint to feel materials of the surfaces in the optical reconstruction. To improve rendering techniques in CGHs, a few methods, for example microfacets of the bidirectional reflectance distribution function (BRDF) [3], have been attempted for realistic rendering in polygon-modeled CGHs. However, the proposed methods require too many sampling points in object surfaces to produce high-definition full-parallax CGHs. Furthermore, there is no method to create CGHs that reconstruct smooth surfaces of objects. Here, the smooth surfaces mean the surfaces in that any patches or seams are not perceived by reviewers' eyes.

We present a novel technique for smooth shading of specular surfaces. Since the proposed technique drastically reduces the computation time as compared with another method, high-definition CGHs with more than billion pixels can be calculated in practice. We demonstrate a CGH created by this technique to verify the validity of the technique.

## 2. SPECTRAL ENVELOPE IN PHONG MODEL

The surface source of light is expressed by a complex function referred to as a surface function. Figure 1 shows an example of the surface function. The amplitude distribution of the surface functions expresses the shape, texture, and brightness of a polygon, while the phase distribution gives diffusiveness of light. To render diffusive surfaces, a pseudorandom phase pattern with a wideband spectrum is used for the phase distribution [1,2], because wider spectrum of the surface function leads to more diffusiveness

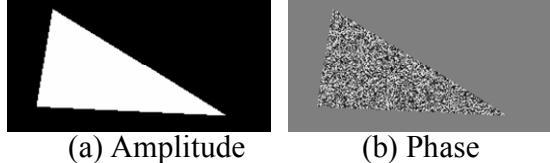


Fig. 1. An example of surface function.

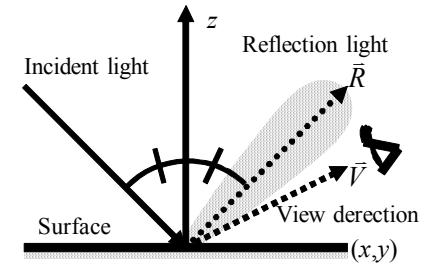


Fig. 2. The Phong model for specular reflection

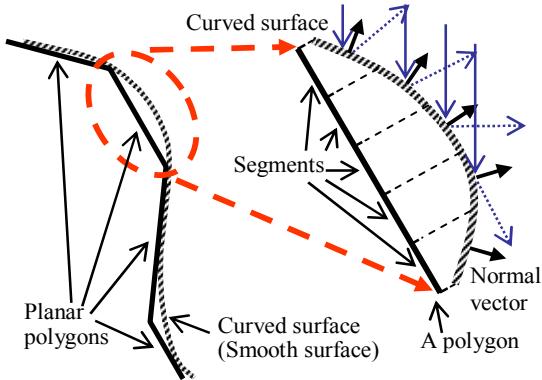


Fig. 3. Imitation of curved surfaces by planar polygons.

of the reconstructed polygon. The form of the surface function is commonly given as:

$$h(x, y) = a(x, y) \exp[i\phi(x, y)], \quad (1)$$

where  $a(x, y)$  and  $\phi(x, y)$  are the amplitude and phase distribution, respectively.

In the contrast with the diffusive surface, a specular surface obviously has a limited diffusiveness. This means the spectrum of the surface function must be band-limited in specular surfaces. We make use of Phong model to determine the shape of spectrum of phase distribution  $\phi(x, y)$ . The Phong model illustrated in Fig. 2 is the most popular model for rendering a specular surface in CG. In the Phong model, the brightness observed in the view direction  $\bar{V}$  is given as:

$$I(\bar{V}, \bar{R}) = k_s (\bar{R} \cdot \bar{V})^\alpha, \quad (2)$$

where  $k_s$  and  $\alpha$  are a specular reflection and shininess constant, respectively. The vector  $\bar{R} = (R_x, R_y, R_z)$  gives the direction of regular reflection. Supposing that the view direction  $\bar{V}$  can be interpreted as the unit wave vector of

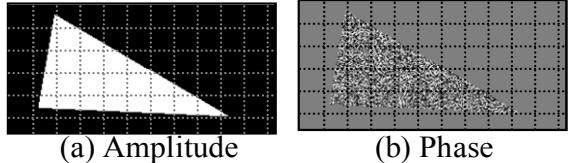


Fig. 4. Segmentation of a surface function.

the plane wave traveling in the  $\bar{V}$  direction, the vector is written as:

$$\bar{V} = \lambda(u, v, (\lambda^2 - u^2 - v^2)^{1/2}), \quad (3)$$

where  $u$  and  $v$  are Fourier frequencies with respect to  $x$  and  $y$  direction. Substituting Eq. (3) into (2), the envelope of spectrum of the phase distribution is given as:

$$\begin{aligned} A_s(u, v, \bar{R}) &= I(\bar{V}, \bar{R})^{1/2} \\ &= k_s^{1/2} \left[ \lambda(R_x u + R_y v + R_z (\lambda^2 - u^2 - v^2)) \right]^{\alpha/2} \end{aligned} \quad (4)$$

Therefore, the phase distribution  $\phi(x, y)$  must be modified in the Phong model of specular surfaces so that the envelope of the spectrum is fitted to  $A_s(u, v, \bar{R})$ . In this study, iterative Fourier-transform algorithm (IFTA) [5] is used for modification of the spectral envelope of the diffusive phase.

### 3. SMOOTH SHADING OF SPECULAR SURFACES

In the polygon-based method, the polygonal facets approximates to a curved surface, as shown in Fig. 3. The method described in the previous section creates a specular polygon. This polygon mainly reflects light in the direction of  $\bar{R}$ . However, the object surface composed of the specular polygon does not resemble the curved surface, because individual polygon is planar and reflects the incident light in a given direction [4]. To create smooth surface, polygons must be subdivided into smaller polygons and the sub-polygons must be processed by the method in section 2. However, we do not adopt this tessellation approach, because this is most likely time consuming.

Instead of the tessellation approach, the surface function is segmented in our method. This segmentation is illustrated in Fig. 4. At the beginning, the whole surface function is generated by the same method as that in section 2. Here, the reflection direction is set to  $\bar{R} = (0, 0, 1)$ , i.e. the polygon created by the surface function emits its light in the direction almost perpendicular to the polygon. Then, as in Fig. 4, the created surface function is divided into many rectangular segments as follows:

$$\begin{aligned} h(x, y) &= \sum_i \sum_j h_{ij}(x, y), \\ h_{ij}(x, y) &= a_{ij}(x, y) \exp[i\phi_{ij}(x, y)], \end{aligned} \quad (5)$$

where  $i$  and  $j$  are indices of the segment, and  $h(x, y)$  and  $h_{ij}(x, y)$  give the full- and sub-surface function, respectively.

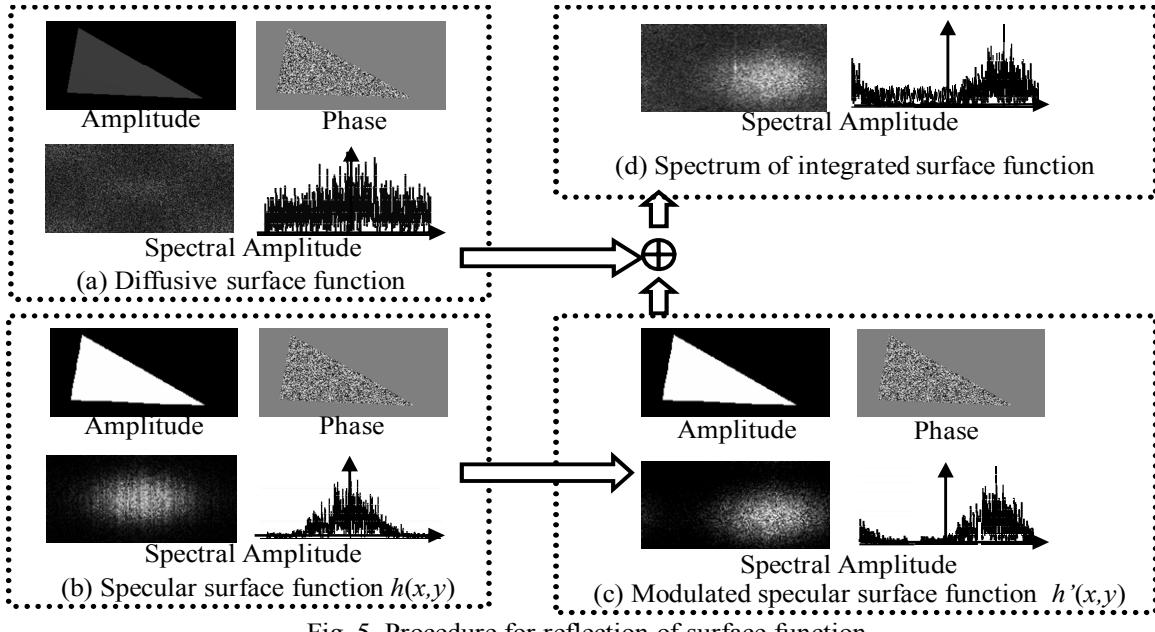


Fig. 5. Procedure for reflection of surface function

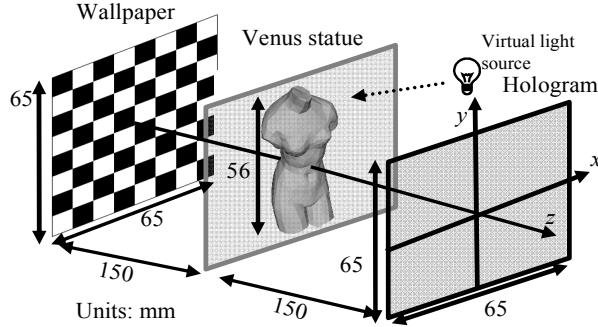


Fig. 6. The 3-D scene of the smooth metal venus

For creating a smooth surface, each sub-function should reflects the incident light in different directions determined by the normal vector of the original curved surface, as shown in Fig. 3. Therefore, the sub-functions are individually modulated as follows:

$$h'_{ij}(x, y) = a_{ij}(x, y) \exp[i\{\varphi_{ij}(x, y) + k\bar{R}_{ij} \cdot \vec{r}\}], \quad (6)$$

where the factor  $\exp[ik\bar{R}_{ij} \cdot \vec{r}]$  is a plane wave traveling in the direction of  $\bar{R}_{ij}$  that is the reflection vector of the segment  $(i, j)$ . This reflection vector should be determined by the direction of incident light and the normal vector of the original curved surface. In practice, the normal vector of a segment is given by the same technique as the Phong shading of CG, i.e. by linear interpolation of the normal vector in vertices of the polygon. Finally, the full-surface function is given by superposition of the sub-functions as follows:

$$h(x, y) = \sum_i \sum_j h'_{ij}(x, y). \quad (7)$$

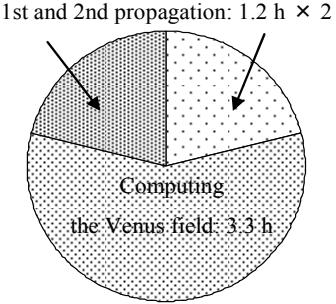


Fig. 7. Computation time for computing the CGH

Figure 5 shows an example of the procedure of the proposed smooth shading for specular surfaces. The diffusive light, whose surface function is shown in (a), must be mixed with the light produced from the specular surface function in (b) for realistic rendering, because the specular-only surfaces lead to a narrow viewing-zone. The specular surface function is modulated by using Eq. (6) as in (c) before this integration. The spectrum of the full-surface function is shown in (d).

#### 4. CREATION OF A HIGH-DEFINITION CGH “THE METAL VENUS II”

##### 4.1. The 3-D scene and computation time

We compute a CGH named “The Metal Venus II”. The 3-D scene of the CGH is illustrated in Fig. 6. Here, the statue of the Venus is 5.6 cm in height and composed of 1396 polygons. Some parameters used for computing the CGH are summarized in Table 1.

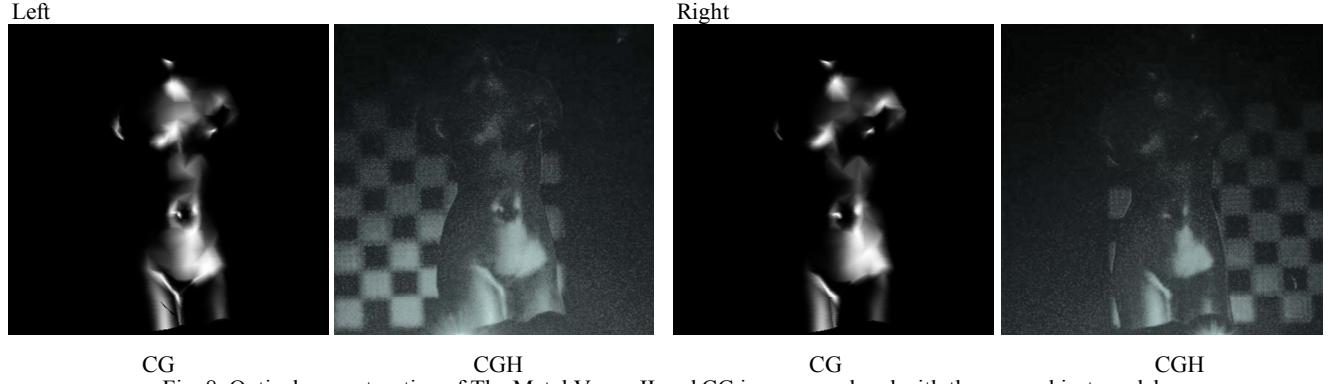


Fig. 8. Optical reconstruction of The Metal Venus II and CG images rendered with the same object model.

Table 1 Parameters used for creation of “The Metal Venus II”.

Hologram	
Pixel sizes	65,536 × 65,536
Pixel pitches	1.0 μm × 1.0 μm
Wavelength	632.8 nm
The Venus statue	
Number of polygons (front-face only)	718
Dimension of Venus (W × H × D)	25.6 × 56.0 × 21.0 mm <sup>3</sup>
Specular surfaces shininess const. ( $\alpha$ )	10

Computation of the CGH was executed by using a PC with four CPUs of the XEON E7540 (2.0 GHz) and main memory of 256 G bytes. The total computation time was approximately 5.7 h. The itemized computation time is shown in Fig. 7. The longest time was consumed by computing the Venus field. This is two or three times longer than the Venus rendered only with diffusive surface. The increase of computation time is most likely attributed to separate computation of the specular and diffusive field, i.e. two surface functions are independently computed in the proposed method.

#### 4.2. Fabrication and optical reconstruction

The computed object field of The Metal Venus II is numerically interfered with a spherical reference wave and the fringe pattern is printed by using a laser lithography system [2]. Figure 8 shows photographs of optical reconstruction of The Metal Venus II by using He-Ne laser. Here, the photographs are taken from different view-points. CG images rendered with the same model are also shown in Fig. 8. The view-points of the CG images are also changed for comparison. It is verified that the seams of the polygons are not detected in the optical reconstruction and the specular light is in excellent agreement with that of the CG.

## 5. CONCLUSION

A novel technique for smooth shading of specular surfaces is proposed for creating polygon-based high-definition CGHs. The technique controls the spectral envelope of the diffuser phase by iterative Fourier-transform algorithm and makes it possible to smooth shading by using segmented surface functions. The optical reconstruction shows that the CGH created by the proposed technique reconstructs an excellent 3-D image; the seams of polygons disappear and the specular light changes as the view-points changes.

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