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Lighting effects rendering in three-dimensional computer-generated holographic display

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ABSTRACT

We present a technique for generating three-dimensional (3-D) computer-generated holograms (CGHs) with realistic lighting effects based on a phase-only spatial light modulator (SLM). Phong reflection model is employed in the calculation of reflectance distribution for CGH synthesizing. Directional point-based algorithm produces realistic lighting effects of the 3-D scenes in processing the ambient, diffuse and specular reflections. A phase-only SLM is used to perform the optical experiments, and the results show that the proposed technique can perform quality reconstructions of the 3-D scenes with high optical efficiency and efficient utilization of the system space-bandwidth product.

1. Introduction

Holographic display can reconstruct the whole optical wavefront of the 3-D scene and hence has the potential to provide all the depth cues that human eyes can perceive [1]. With the developments of computer technology and spatial light modulators (SLMs), computer-generated holograms (CGHs) of various 3-D images can be displayed dynamically without the complicated interference recording systems [2–5]. Both existing and synthetic 3-D scenes can be encoded into the CGHs as long as their mathematical descriptions are provided. The algorithms for generating the CGHs are directly related with the image qualities of the reconstructed 3-D scenes.

Computer graphics rendering techniques can convert 3-D scenes into photorealistic two-dimensional (2-D) images, which have been used in the CGH algorithms to enhance fidelities of the reconstructed 3-D images [6–9]. Holographic stereograms can provide occlusion effects easily with the help of multi-viewpoint rendering process [6,7]. Physically based algorithms can generate CGHs with accurate geometric information by extracting coordinate information through the depth buffer [8,9]. In computer graphics, shading refers to the process of calculating the brightness of an object in the 3-D scene based on the relative positions between the light, object, and the viewer. It can depict the illumination and depth perception of the 3-D scene, which can benefit the visual effect of the rendered 2-D image. Shading process of computer graphics could be integrated with CGH calculation to produce realistic lighting effects for the improvements of the reconstruction quality of the 3-D CGH.

Lighting effects rendering in CGH calculation is crucial to the depth performance during optical reconstruction. Various algorithms have been proposed for simulating the wave reflection and propagation processes to render different lighting effects [10–15]. Spatial spectrum of the polygon-based algorithm was modified based on the Phong reflection model to imitate the specular reflection [10]. Zone plate based Phong reflection model was used to generate CGHs with characteristics of reflection [11,12]. Computer graphics rendering techniques were also used in the holographic stereogram computation to add lighting effects [13,14]. Recently, ray tracing method was introduced into the CGH calculation to simulate characteristic reflection effects [15]. However, the previous methods for generating CGHs are based on the amplitude modulation of the reconstruction wavefront, which would affect the optical efficiency and utilization rate of the system space-bandwidth product. Hence accurate and efficient lighting effects processing in CGH synthesizing needs to be further investigated.

In this study, directional point-based algorithm is used for generating phase CGHs with multiple lighting effects. The wavefront distribution of each object point is calculated directly according to the Phong reflection model with anti-aliasing technique. The proposed technique is more efficient in its utilization of the space-bandwidth product compared to the zone plate method since no conjugate image is reconstructed. A phase-only SLM is used to perform the optical reconstructions of the 3-D scenes, which can reconstruct quality 3-D images with realistic lighting effects and high optical efficiency.

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2. Phong reflection model

Phong reflection model is an empirical model for local illumination, which is widely used in 3-D computer graphics. During calculation, four unit vectors are used to compute the light intensity at an arbitrary point, as shown in Fig. 1(a). The light vector ***L*** denotes the direction vector from the point on the surface toward the light source. The normal vector ***N*** is perpendicular to the surface at the given point. The reflection vector ***R*** indicates the direction that a perfectly reflected ray of light would take from the point on the surface. According to the law of reflection, the angle of incidence equals the angle of reflection. The view vector ***V*** indicates the direction pointing towards the position of viewer or virtual camera.

Phong reflection model uses ambient, diffuse and specular components to characterize the lighting effects of an object surface. The ambient reflection term is presented in the entire 3-D scene, where all of the objects are brightened with a specified light intensity:

$$I_a = k_a I, \tag{1}$$

where k_a is the ambient reflection constant, and I denotes the illumination light intensity. The diffuse reflection is the reflection of the light from a surface such that an incident ray is reflected at many angles. An illuminated ideal diffuse reflecting surface will have equal luminance from all directions. According to the Lambert's cosine law, the diffuse reflection light intensity of the Phong reflection model is given by

$$I_d = k_d (\boldsymbol{L}\cdot\boldsymbol{N}) I, \tag{2}$$

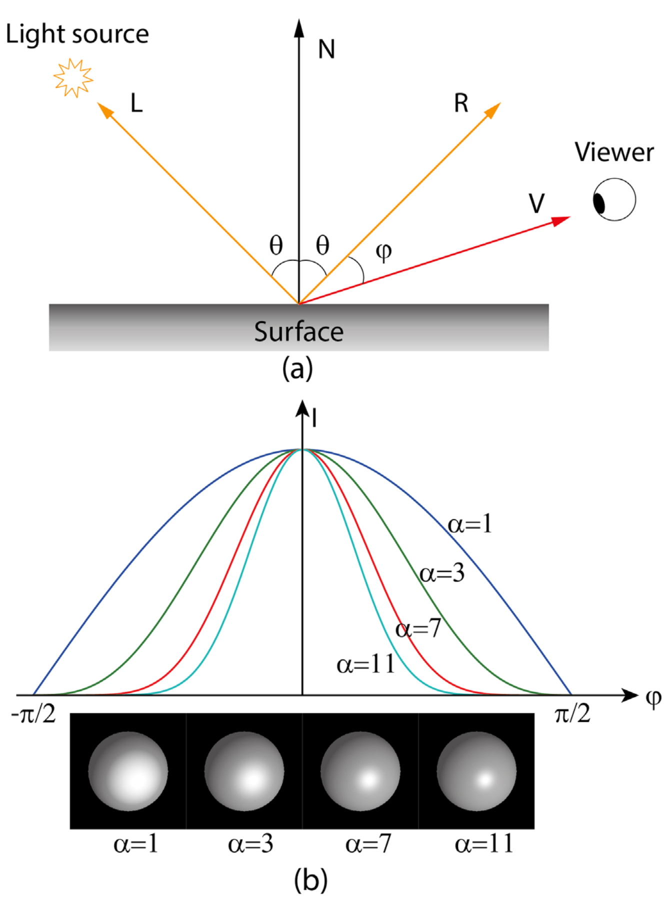

Fig. 1. (a) Vectors in Phong reflection model. (b) Specular reflections with different shininess constants.

where k_d is the diffuse reflection constant, and • denotes the dot product. The intensity of the diffuse reflection light depends on the angle of incidence, and has no relationship with the view vector. Hence the intensity of the diffuse reflection light would have the same value when viewed from any angle. The specular reflection is the bright spot of light that appears on shiny objects when illuminated, which can provide a strong visual cue for the shape of an object and its location with respect to the light source. The intensity of the specular reflection light depends on the angle between the reflection vector ***R*** and the view vector ***V***:

$$I_s = k_s (\boldsymbol{R}\cdot\boldsymbol{V})^{\alpha} I, \tag{3}$$

where k_s is the specular reflection constant, and α is a shininess constant of the surface. Specular reflection component has anisotropic distribution along different viewing directions, as shown in Fig. 1(b). ϕ denotes the angle between view vector and reflection vector. The specular reflection achieves its peak when ϕ is zero. As the shininess constant α increases, the specular spot becomes smaller, which would lead a smoother object surface.

We can deduce the equation of Phong reflection model by combining the three reflection components:

$$I_p = I_a + I_d + I_s = \left[k_a + k_d (\boldsymbol{L}\cdot\boldsymbol{N}) + k_s (\boldsymbol{R}\cdot\boldsymbol{V})^{\alpha}\right] I. \tag{4}$$

Fig. 2(a) schematically illustrates the ambient, diffuse and specular reflection components when the surface is illuminated by the light source. The ambient and diffuse reflection components have isotropic distributions over all viewing directions, while the specular lobe has the highest value along the reflection vector ***R***. Fig. 2(b) is the visual illustration of the Phong reflection model. Photorealistic lighting effects can be rendered by combining ambient, diffuse and specular reflection components.

3. CGH generation with Phong reflection model

In computer graphics, the Phong reflection model sets one viewpoint for each image during rendering process. Hence only one view vector is bundled with a specific object point. While for CGH computation, each hologram sample corresponds with one viewpoint, and multiple view vectors need to be considered in calculating a single object point. Fig. 3 illustrates the difference of the viewing parameters between computer graphics and CGH computation. A viewpoint array is formed in the hologram plane to fetch lighting information from the corresponding viewing directions.

In conventional point-based method, the complex amplitude distribution on the hologram plane can be calculated by superposing the optical wavefronts of all the point sources [16,17]:

$$H(x, y) = \sum_{j=1}^{n} \frac{A_j}{r_j} \exp\left[i\left(kr_j + \phi_j\right)\right], \tag{5}$$

where n is the number of object points, A_j is the amplitude of the jth point, $k=2\pi/\lambda$ is the wave number in free space, and ϕ_j is the initial phase. The distance between the jth object point and the sampling point $(x, y, 0)$ on the hologram plane is given by

$$r_j = \sqrt{(x - x_j)^2 + \left(y - y_j\right)^2 + z_j^2}. \tag{6}$$

With the proper choice of random initial phase, we may assume a uniform amplitude distribution in the hologram plane, and thus we could achieve quality reconstruction with the pure phase information [18,19].

Ambient and diffuse reflections can be reconstructed using Eq. (5) since the wave amplitude A_j of the jth point is uniformly distributed on the hologram plane, since these two reflection