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A rendering method of background reflections on a specular surface for CGH

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Abstract. Computer-generated holograms (CGHs) are remarked as ideal three-dimensional displays. There are a lot of problems have to be overcome, and we focused on the rendering techniques to reconstruct realistic images. In particular, there is almost no calculation method that correctly expresses depth information. Reflected images are necessary to express complex realistic scenes. In this paper, we introduce a calculation method that generates reconstructed images with background reflections. Proposed method calculates intersections between virtual objects and rays by the ray tracing method. Then intersections are assumed as a point light source group, and light waves on a hologram plane are calculated. In the ray tracing process, when a ray hits the specular object, a ray is additionally casted to the specular direction from the intersection. If the ray hits other diffuse objects or background, the length of light path from a viewpoint to the diffuse object is calculated. By calculating light waves from a point light source on the diffuse surface distant from the light path, reflected images are expressed in the CGH. To express the quality of materials, we adopted the Cook-Torrance reflection model. In the experiment, we conducted the computer simulation to confirm that the depth of reflected images is correctly calculated. And results of optical reconstructions show that our proposed method is able to make CGHs of various qualities of material.

1. Introduction

A computer-generated hologram (CGH) is remarked as an ideal three-dimensional technology that fills human's visual features to perceive 3D images. Interference pattern on a hologram plane is calculated by simulating light propagation from virtual objects that is made in computer. In CGH, holograms are made by developing the interference pattern to the film or displaying on a spacial light modulator (SLM).

However there are some problems before CGHs will be put to practical use. First of all, the calculation of a CGH takes enormous computation time. Furthermore, rendering techniques to express realistic images like one in the field of computer graphics (CG) are scarce. To speeding up the calculation of CGH, a number of studies have been proposed already. For example, there are methods of hardware acceleration using a graphic processing unit (GPU) and special-purpose computer[1, 2, 3]. Besides, fast calculation algorithms have been proposed. In order to make the point wise method run faster, there is a method using a look-up table recording pre-calculated light wave on a hologram plane from a point light source[4]. And a technique using three-dimensional affine transforms of basic object light recording pre-calculated light waves from a basic plane has been also reported[5]. Thanks to these methods, CGH calculations can nearly work in real time.

On the other hand, studies that improve the appearance of the reconstructed images are inadequate. Rendering techniques include some kinds of problems. To improve each problem, some studies have been proposed. For example, various researchers have proposed methods that express the hidden surface removal[6, 7, 8, 9]. Moreover some methods have attempted to implement reflectance distributions that signify how an object's material affects its appearance[10, 11, 12]. However the above methods did not take into consideration the background reflection which renders reflected images mapped on metallic object's or mirror surfaces. Reflected images are necessary to express complex realistic scenes. A study [13] proposed a calculation method that expresses reflectance distributions and reflected images by modulating the phase differences on a object's surface. But this method can only apply polygon-based models and takes enormous calculation time. Some methods by using only amplitude information are existed, the depth of reflected images are not calculated correctly.

Thus we propose a calculation method of CGH which generates reconstructed images with background reflections using the ray tracing method. In the field of CG, the ray tracing method is used to express realistic images including the hidden surface removal, refraction, multi reflection and so on[14, 15] In this paper, we show the way to apply the ray tracing method to CGHs that generate reconstructed image having reflected images. In addition, accelerations of the calculation using GPU were implemented. By computer simulations and optical reconstructions, we confirmed that the reflected image with highlight was performed by proposed method.

2. Proposed method

2.1. Calculation method of CGH

We have proposed a method that calculates CGH expressing the hidden surface removal by using the ray tracing method[16]. The ray tracing method calculates intersections with objects by casting rays from a viewpoint. Our method make CGHs by treating these intersections as a point light source group. The view of this method is close to the holographic stereogram. By the ray tracing method from one viewpoint, overlapping of images with movement of a viewpoint is shown up because motion parallax is necessary in CGH. So that a hologram plane is divided into elementary holograms, and the ray tracing processes are conducted every an elementary hologram in the study [16].

First of all, a hologram plane is divided into elementary holograms (Fig. 1). Continuous parallax depends on division width of elementary holograms. The parallax between elementary holograms becomes big as the size of an elementary hologram becomes large. In this study, the size of elementary hologram is 1.216 [mm](128 [pixels]). Because it has been said that if the size is about 1[mm], there is no problem in continuous parallax by a research of CGH using multi-view images [17]. The θ in Fig. 1 signifies the angle of frequency limit. Rays are casted within the angle. Here the interval $\Delta\theta$ between rays is 1/60 degrees. Because a resolution of the human is assumed 1/60 degrees. Therefore gaps between rays is not visible by the observer.

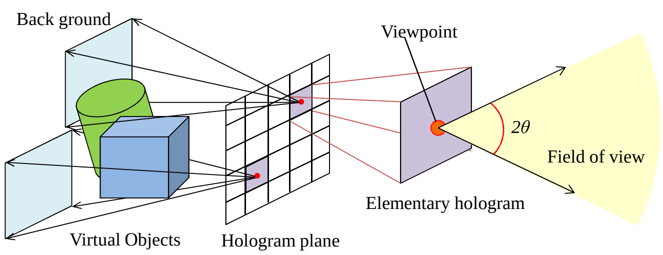


Figure 1. Division of a Hologram plane

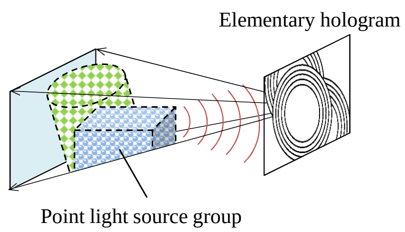


Figure 2. Light propagation

Next, every an elementary hologram, the determination of intersections is conducted with the ray tracing method. Rays are casted from the center of the elementary hologram. Each ray conducts intersection determinations with all objects (polygons) in the virtual scene. A ray obtains information of the brightness and the coordinate of the nearest intersection. Therefore, it is considered that intersections is a point light source group. The detailed computational algorithm of the ray tracing method is omitted here.

Finally, we calculate light waves on an elementary hologram. We use the point wise method that assumes virtual objects as an assemblage having three-dimensional coordinate. Here we focus on one elementary hologram (Fig. 2). This time, the calculation uses the intensities and depth information of each point light source. In the holographic stereogram, a hologram is made by combining the multi view images having only information of the intensity. On the other hand, our method is able to express depth perception in one viewpoint by using depths of the virtual objects in addition to the intensity. Complex amplitude distribution on a hologram plane $h_m(x, y)$ is calculated by

$$h_m(x,y) = \sum_{i=1}^{N_m} \frac{A_i}{r_i(x,y)} \cdot \exp\left(j\frac{2\pi}{\lambda} r_i(x,y)\right) \cdot \exp(j\phi_i)\,, \tag{1}$$

$$r_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + z_i^2}\,, \tag{2}$$

where parameters x, y and z represent the horizontal, vertical and depth components, while indices m and i respectively indicate the each elementary hologram and point light source. λ is the wavelength, and ϕ_i is the initial phase of each point light source. N_m is the number of point light sources that compose 3D objects at each elementary hologram. The intensity of the point light source A_i are added various reflectance distributions by using the normal vector of objects, position of the point light source and direction of the ray. The detailed flow of calculating the intensities is described by following paragraphs. Finally, whole light waves on a hologram plane are obtained by lining up every light waves of elementary holograms.

2.2. Representation of reflected images

Here the representation method of specular surface in CGH is described. Before I proposed a calculation method of CGH to express transparent object [18]. In a study [18], refraction on a transparent object was expressed by considering the length of light path and light attenuation in the medium. Then reflection on a surface of transparent objects is ignored. However reflected images in addition reflection on a surface are necessary to calculate the multiple reflection.

A simple graphic explanation of proposed method is shown in Fig. 3. At first, a ray (Ray_1) is casted from a center of an elementary hologram. When a ray hits the specular objects, the intensity and length $r_1 = t_1$ of a intersection P_1 is stored into a buffer of a point light

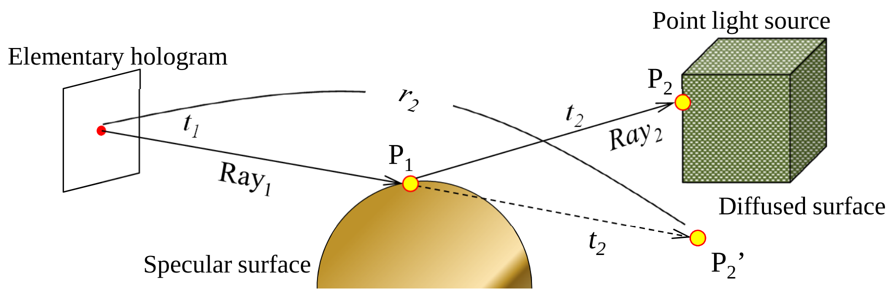


Figure 3. Expression of specular surface.

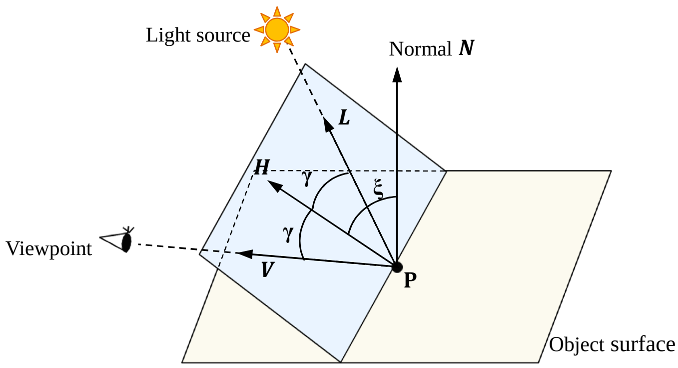


Figure 4. Cook-Torrance reflection model

source group. And more, a ray (Ray_2) is additionally casted to the specular direction from the intersection. If the ray hits other diffuse objects or background in the scene, the length of light path r_2 from a viewpoint to the diffuse object is calculated. If the ray hits the specular surface again, same process is repeated until an additional ray hits the diffuse surface or a reflection number of times reaches a setup maximum reflection number of times. So when a ray reflects I times, a length of light path is calculated by

$$r_I = \sum_{i=1}^{I} t_i \, . \tag{3}$$

In the example of Fig. 3, a intersection P_2 is the same as being arranged in the position of P'_2. By calculating light wave from a point light source on the diffuse surface distant from the light path r_2 along with a point light source on a specular surface using Eq. (1), reflected images are expressed. Furthermore the reflectance is set up on a specular surface, and the brightness of the intersection determined after a ray reflected is calculated by multiplying the reflectance. A calculation of the intersection is described by following paragraph.

2.3. Cook-Torrance reflection model

The brightness of intersections is determined with the normal vector of the surface, the viewpoint and so on. By being the brightness I_r as the intensity of the point light source in Eq. (1), various reflectance distributions are expressed. In this paper, we use a following equation to calculate the intensity of the reflected light

$$I_r = I_a\rho_a + (\mathbf{N} \cdot \mathbf{L})k_d\rho_d + (\mathbf{N} \cdot \mathbf{L})k_s\rho_s \, , \tag{4}$$

here, I_a is intensity of ambient light. k_d and k_s are respectively the ratio of Lambert light and specular light ($k_d + k_s = 1$). ρ_a, ρ_d and ρ_s are reflectance of ambient light, Lambert light and specular light. Vectors $\mathbf{N}$ and $\mathbf{L}$ are a normal unit vector and an unit vector to the light source. In proposed method, we used the Cook-Torrance model [19] to calculate the reflectance of the specular light. The Cook-Torrance reflection model is suitable for expressing metallic objects. In Cook-Torrance model, a object surface is assumed as an aggregate of minute surfaces, and it is granted that the direction of the minute surface is distributed centering on the normal direction of a surface. The Cook-Torrance model considers that reflectance distributions depend on the wavelength and incident angle of light, and the reflectance turned on materials is calculated by the Fresnel equation. These functions are composed of a half vector $\mathbf{H}$ and normal vector $\mathbf{N}$ in

Fig. 4. The reflectance by the Cook-Torrance model ρ_s is described with following equation

$$\rho_s = \frac{F}{\pi} \frac{D\,G}{(\mathbf{N} \cdot \mathbf{V})(\mathbf{N} \cdot \mathbf{L})} \,. \tag{5}$$

The Fresnel term F describes how light is reflected from each smooth micro facet and is given by Fresnel equations. The geometrical attenuation factor G accounts for the shadowing and masking of one facet by another. D stands for a distribution function, and is defined by Beckmann distribution with

$$D = \frac{1}{4m^2 \cos^4 \xi} \exp\Big(\frac{\tan \xi}{m}\Big)^2 \,. \tag{6}$$

Here, m is the coefficient which adjusts the roughness of a surface. As m becomes small, the surface is smooth and becomes specular. Light intensities of a intersections on a specular surface are obtained by above equations. As for diffuse surfaces, the intensity calculation is performed by the Phong model as with a study [16].

3. Experiment

3.1. Calculation system

We conducted some experiments to confirm the adequacy of the proposed method. At first, this section describes about our calculation system. The ray tracing method is avoided ever in CGH having a very high resolution because of enormous calculation cost. Then accelerations of the ray tracing algorithm and calculation of light waves by parallel computing with GPU were implemented in this study. In a calculation process of light waves, each pixel on a hologram plane can be calculated independently apparent to Eq. (1). So the calculation is suitable for a parallel calculation with GPU.

For the parallel computing of light propagation, we used the CUDA programming environment (NVIDIA). To accelerate the ray tracing algorithm, we used OptiX application acceleration engine. OptiX is real time ray tracing engine for CUDA-based video cards. A GPU that we used is an NVIDIA GeForce GTX 580, and a CPU is Intel Core i7-2600K. Tab. 1 shows detail specifications of our system.

3.2. Computer simulations

We conducted computer simulations that the reflected images are expressed in CGH. Computational reconstructed images were made by simulating the light propagation with a virtual lens from light distributions on a hologram plane. Experimental parameters in this experiment are shown in Tab. 2. At first, we verified whether the image reflected by the mirror would be reconstructed by the right position. Fig. 5 signifies the arrangement of virtual objects

Table 1. The spec sheet of our system.

Specification of Geforce GTX 580	
Number of streaming processors	512
Clock frequency	1544 [MHz]
Memory capacity	3GByte GDDR5
Specification of the host computer	
Core Clock	3.4 [GHz]
Memory capacity	8.0GByte
Operating system	Windows 7 64bit

Table 2. Setup parameters for experiment.

Number of elementary holograms	32(H) × 16(V)
Size of elementary holograms	1.216[mm] × 1.216[mm]
Number of rays of each elementary hologram	161 × 161
Number of pixels	4096 × 2048 [pixels]
Sampling pitch	9.5 × 9.5 [μm]
Wavelength	632 [nm]

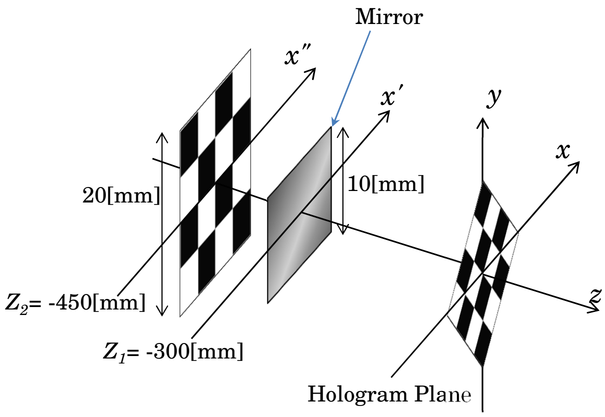
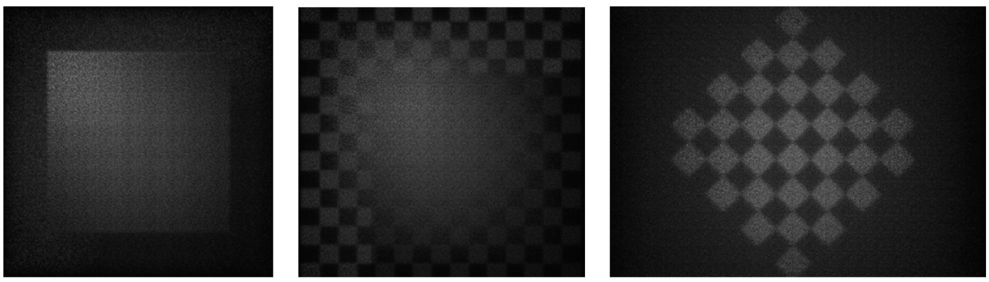


Figure 5. Geometry of the computer simulation.

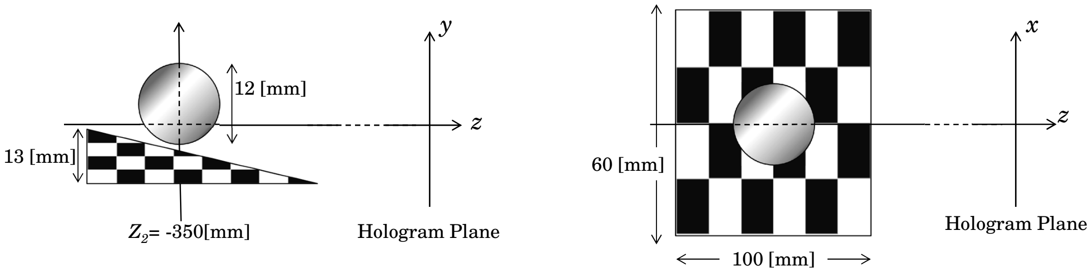


(a) $f = 30$cm. (b) $f = 45$cm. (c) $f = 60$cm.

Figure 6. Computational reconstructed images.

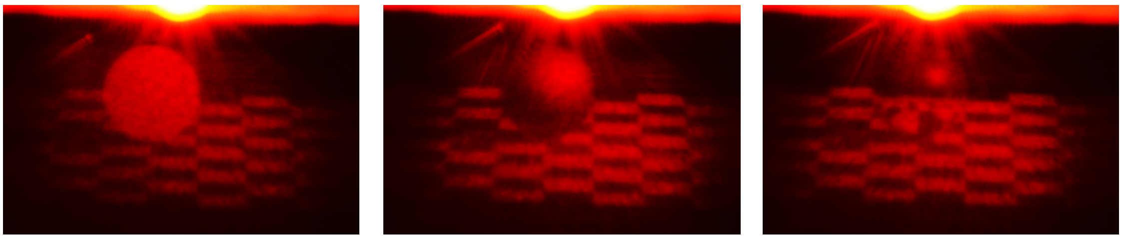
in the scene. The board of check pattern were made of diffuse surfaces, and a mirror had a specular surface. These objects were illuminated by a point light source. The ray tracing method was performed noting that the viewpoint was in a hologram plane ($z = 0mm$), and the hologram was calculated.

Fig. 6 show computational reconstructed images at each distance. Fig. 6 (a) was focused on the virtual mirror. Upper left part of a mirror surface seem gleaming because illuminated light hit to the surface light at an angle. Fig. 6 (b) and (c) were focused on each checker board. A reflected image by a mirror in addition to a checker board behind a mirror. It turns out that the image reflected in the mirror is also reconstructed by the right position as Fig. 5 in addition to the checkerboard in the back of a mirror. Therefore it was confirmed that the proposed method succeeded in expressing reflected images with correct depth.



(a) y-z plane (b) x-z plane.

Figure 7. Geometry of the optical reconstruction.



(a) Ambient light. (b) Phong model. (c) Cook-Torrance model.

Figure 8. Reconstructed images by three viewpoints.

3.3. Optical reconstructions

We conducted optical reconstruction to express the complex scene in CGH. Fig. 7 signifies the geometry of the optical reconstruction: Fig. 7 (a) is a view of y-z plane and Fig. 7 (b) is a view of x-z plane. The check pattern under the sphere was diffuse surface. The sphere was added some reflectance distributions. These objects were illuminated by a point light source in the top-right. The interference patterns were displayed on a spatial light modulator.

Results of the optical reconstructions are shown in Fig. 8. In Fig. 8 (a), the sphere was expressed with only ambient light. So the whole of a sphere is seen with the same luminance. A sphere in Fig. 8 (b) has reflectance distributions by the Phong reflection model. The sphere seems like being made out of plastic. Fig. 8 (c) was obtained by the proposed method. The sphere had specular surfaces, and the reflectance distributions by Cook-Torrance model were added. Therefore the reflected image of check pattern on a sphere is shown. Moreover the highlight by the Cook-Torrance model like a metal object appears. So this experiment shows that the proposed method can calculate CGH of various qualities of material. These results of the computational and optical reconstructed images show that the proposed method correctly expresses reflected images.

4. Discussion and Conclusion

Whole calculation of the proposed method were parallelized with GPU. Calculation times of experiments in sec. 3 are shown in Tab. 3. According to Tab. 3, it turns out that the calculation time of the wave propagation is by far longer than the ray tracing process. Our calculation algorithm of wave propagation and coding is still crude compared to the Optix ray tracing engine. So optimization and tuning the code is necessary. In the future, we aspire to becoming the real time calculation.

Table 3. Calculation times [ms].

	Setting	Ray tracing	Wave propagation	Total
sec. 3.2	2,137	2,531	16,773	21,660
sec. 3.3	2,169	2,593	17,491	22,459

In this paper, we propose a calculation method of a CGH that generates reconstructed images with background reflections using the ray tracing method. Background reflections are expressed by calculating the light path to reflected objects. And we adopted the Cook-Torrance reflection model to express metallic objects. As results of experiments, it was confirmed that the reflected image with highlight was performed by proposed method.

5. Acknowledge

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