Image Processing Technique for the Reproduction of Deep 3-D Images By Holoprinter

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A holographic 3-D printer (holoprinter) is being developed for the hardcopy output of 3-D image processing systems. In this paper, an image processing technique is proposed for the reproduction of deep 3-D images by the holoprinter. The sampling scheme of parallax information in the one-step and two-step holographic stereograms are compared, and it is shown that the image near the hologram plane has good parallax information in the one-step holographic stereogram, but the image far from the hologram plane is blurred. To suppress the image blur in the far image, a method to produce the image equivalent to two-step recording is developed. By this method, the image far from the hologram plane is displayed as a stereoscopic image hologram, resulting in the suppression of blur. But the image near the hologram plane is reproduced with fine sampling, and natural 3-D image can be displayed. Experimental results show the effectiveness of the proposed method.

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Introduction

Three-dimensional images are currently used in various kinds of multimedia information systems, and the output devices for 3-D images are demanded. Holographic 3-D printers (holoprinters) are being developed as a computer peripheral for the hardcopy of 3-D images[1-5]. Using the technique of holographic stereogram, high-quality 3-D images are produced from the 3-D data generated by the computers or 3-D image processing systems. The multidot recording method[1–3] of holographic stereogram was developed for the holoprinter to enable the automatic recording of distortion-free 3-D images. By the multidot method, full-parallax 3-D image can be recorded as a Lippmann-type holographic stereogram, which can be viewed under white-light illumination. The prototype of the holoprinter has been constructed and the feasibility has been demonstrated.[3]

Although high-quality images are reconstructed by the holoprinter especially in the subject near the hologram plane, the image far from the hologram plane is affected by image blur and discontinuity. The image blur in the reconstructed image is mainly caused by the chromatic dispersion of the Lippmann hologram, and the amount of blur is almost proportional to the distance of the image from the hologram plane. The discontinuity in the image is owing to the sampling of the parallax information. As a method to suppress image blur in the Lippmann hologram, the use of a holographic stereogram was proposed.[6] In the method, the viewing window is set to the presumed location of the viewer, so that the stereoscopic images without blur are reconstructed by the image hologram. The two-step recording method for holographic stereograms is used in Ref. 6, and the properties of the reconstructed image are different from that of the multidot recording method based on one-step recording.

In this work, an image processing technique for the holoprinter to display deep 3-D images with high-quality is proposed. The image located far from the hologram plane can be displayed without image blur, by application of a similar technique of Ref. 6 for the one-step holographic stereogram. But the image near the hologram plane can be displayed with high quality by the multidot recording based on Ref. 1, independent of the location of the observer. Therefore, we propose a hybrid technique in which the method of Ref. 1 is used for the image near the hologram plane and the method based on the concept of Ref. 6 is applied to the image far from the hologram plane. To obtain a reconstructed image like a two-step holographic stereogram, the method to generate the image for exposure is modified.

After brief review of the multidot recording method, we illustrate the differences between the sampling schemes of one-step and two-step holographic stereograms. Then, a new image processing method for the holoprinter is described. The experimental results are demonstrated in which the 3-D image comprising foreground and background objects is displayed without image blur using the proposed method.

Review of Multidot Recording

To explore the properties of light-ray reconstruction by holographic stereograms, the geometry of multidot recording,[1] used in the full-parallax holoprinter,[1–3] is briefly reviewed in this section.

Figure 1 shows the optical system for multidot recording of holographic stereograms. An image calculated from 3-D object data is displayed on the SLM, such as an LCD panel, and exposed as a small dot-shaped elementary hologram. After the exposure of the elementary hologram,

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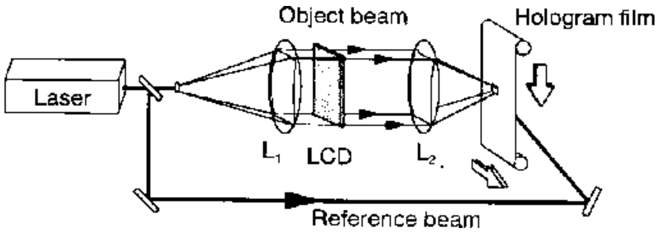


Figure 1. Optical setup for multidot recording. L1: collimator, L2: converging lens.

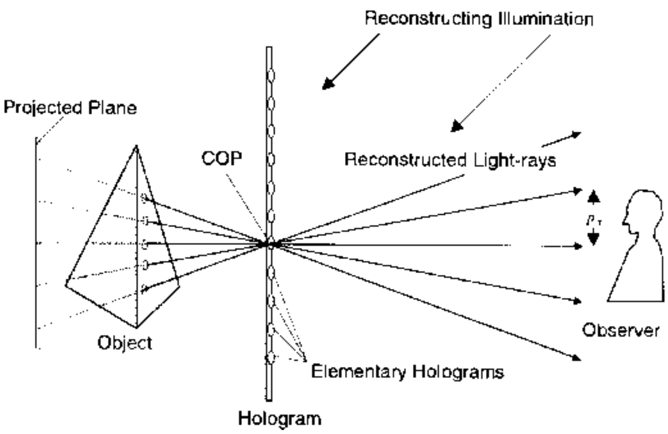


Figure 2. Geometry of multidot holographic stereograms. COP: Center of projection.

the hologram film is moved horizontally or vertically to expose next elementary hologram. 3-D image is synthesized by exposing whole surface of the hologram plane.

The image for exposure is calculated by the computer graphic technique such as ray tracing, as shown in Fig. 2. The projected image in Fig. 2 is displayed on the LCD panel and exposed in an elementary hologram. In the geometry of the ray tracing, the center of projection is positioned at the location of corresponding elementary hologram, while the hidden surface removal is based on the actual location of the observer, because the object may be located in front of the hologram plane. The image calculated by this geometry is exposed as an elementary hologram by the optical system of Fig. 1, so that the light rays traveling to all directions are recorded. With the Lippmann-type hologram, both horizontal and vertical parallax information can be reconstructed under white-light illumination, that is, full-parallax 3-D images can be displayed.

Light-Ray Sampling and Reconstruction in Holographic Stereograms

In the geometry of Fig. 2, the light rays are sampled at the hologram plane as well as the projected image. To display a smooth 3-D image, the sampling interval of the elementary holograms at the hologram plane should be smaller than the resolution of human vision.[1] But the sampling at the projected image determines the number of views in the stereogram, in other words, the parallax resolution. Because the projected image is displayed on the LCD plane at the time of exposure, the parallax resolution is limited by the resolution of the LCD panel.

In two-step recording of holographic stereograms, the parallax information is sampled at the presumed viewer's location, which is the location of the master hologram, as shown in Fig. 3. Considering that the hologram made from 3-D digital data, the image is calculated by the computer graphic technique based on the geometry in Fig. 3. The 3-D object is projected onto the plane of the final hologram, where the center of projection is located at the corresponding master hologram. In this case, the projected image is also sampled, which corresponds to the hologram plane sampling.

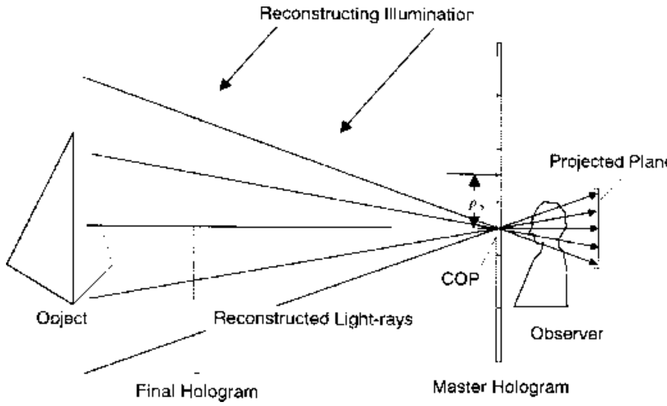


Figure 3. Light-ray sampling in a two-step holographic stereogram.

If the sampling intervals at the projected image and the parallax information are satisfactory small, the one-step and two-step holographic strereograms become equivalent. Comparing the sampling scheme in both types, the parallax information is sampled at the master hologram in two steps and at the infinity in one step. The image exposed onto the master hologram of the two-step holographic stereogram can be converted to the image for one-step recording by such technique described in Ref. 7. However, the properties of the 3-D images produced by one-step and two-step recording are different, because of the difference of the sampling scheme.

As an example, suppose that the sampling intervals at the viewer's location (p_1 and p_2 in Figs. 2 and 3) are almost equal to the size of an eye pupil; that is a practical case. In the case of two-step recording, the observer located at the master hologram can see a 2-D image by each eye, resulting that depth of image can be perceived by binocular parallax. The motion parallax can also be observed at the interval of the elementary master holograms. If the observer is not located at the position of the master hologram, however, several images of different views are mixed; block-like artifacts are sometimes observed. In the case of one-step recording, the influence of sampling is different from the two-step type. Let us consider a small object near the hologram plane as shown in Fig. 4. In this case, three light rays (fluxes) that travel different directions are incident into the observer's eye. When the focus of the observer's vision is adjusted to the actual location of the small object, the sharpness of the observed image becomes highest. Therefore it is possible that the observer perceives the depth of the image by the accommodation in addition to the binocular parallax. This phenomenon is especially effective in the full-parallax holographic stereogram, because the number of light rays incident to the eye pupil is large. Of course, evaluation by visual research is needed to obtain a conclusion, but we consider that this fact leads the natural 3-D images in the one-step holographic stereograms.

However, as easily understood, the density of light rays are sparse in the region far from the hologram plane re-

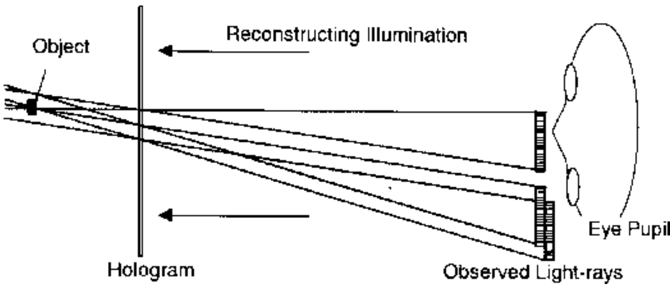


Figure 4. The reconstruction of light fluxes from a point object by a hologram recorded by the multidot method.

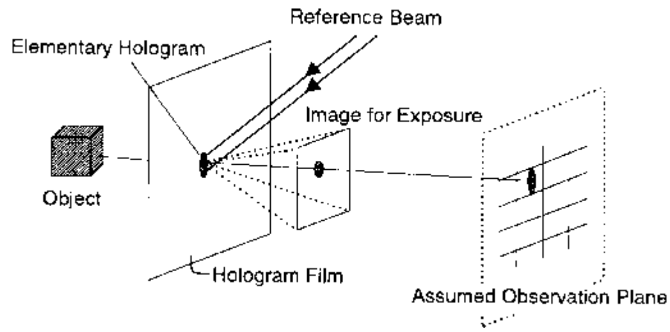


Figure 5. The geometry for the proposed ray-tracing scheme. The light rays are sampled at the assumed observation plane.

sulting in the limitation of the image resolution. Let the number of pixels in one-dimension of the image displayed on the LCD panel be N, the aperture size of the LCD be D, and the focal length of the lens system L_2 in Fig. 1 be f. Then the angular resolution limit due to the sampling at the LCD $\Delta\theta_s$ is given by

$$\Delta\theta_s = D / Nf . \tag{1}$$

Next, let us discuss the image blur. If the sampling intervals in the holographic stereograms are sufficiently small, the properties of the image blur appeared in the Lippmann-type holographic stereograms are almost equivalent to Lippmann holograms. If the size of illumination light source is not small enough, the reconstructed image is blurred. Even if a small light source is used for reconstruction, image blur appears because the diffracted light is not perfectly monochromatic. The size of image blur is proportional to the distance of the image from the hologram plane. The angular broadening of the light rays owing to the chromatic dispersion $\Delta\theta_c$ is given by differentiating the equation for Bragg condition[8]

$$\Delta\theta_c = (\Delta\lambda/\lambda)\,(\sin\theta_R - \sin\theta_O\,) / \cos\theta_O, \tag{2}$$

where θ_R and θ_O are the angle of the reference and object beams, respectively, and λ and $\Delta\lambda$ are the reconstructed wavelength and the width of the reconstructed spectrum, respectively.

In the two-step holographic stereogram, when the reconstructed image of the master hologram is blurred, the viewer observes images with different parallaxes mixed. However, if the pitch of the elementary holograms is larger than the amount of blur, the overlap of the blurred image of the master hologram does not dominant and the viewer see a 2-D image by each eye without blur, because the image is reconstructed by the image hologram. Then, a sharp and deep 3-D image is reproduced and the depth of the object can be perceived by binocular parallax .[6]

New Technique

From the above discussion, using the multidot technique and image generation described in Ref. 1, the image near the hologram plane can be displayed with high quality in parallax resolution, while the blur in the image far from the hologram can be veiled by the two-step holographic stereogram. Therefore, we consider to combine these two schemes for the display of deep 3-D images. For this purpose, we propose an image processing method to display 3-D images equivalent to the two-step stereogram using one-step multidot recording.

Figure 5 shows the geometry of the ray-tracing to calculate the image for exposure. In the ray-tracing technique described in Ref. 1, the light rays are sampled at the image for exposure and the rays passing through the location of the elementary hologram are traced. The objects near the hologram plane should be processed by this scheme. But in the proposed method to obtain an image equivalent to the two-step recording, the light rays are sampled at the assumed observation plane as shown in Fig. 5. This method is applied to the objects far from the hologram plane.

To determine the sampling interval at the observation plane, two factors should be considered: the sampling interval at the image for exposure and the blur due to the dispersion. From Eqs. 1 and 2, the amount of blur b and the spread of light-ray at the observation location w are given by

$$b = (\Delta\lambda/\lambda)\,(\sin\theta_R - \sin\theta_o)\; l/\cos\theta_o, \tag{3}$$

$$w = Dl/Nf.$$

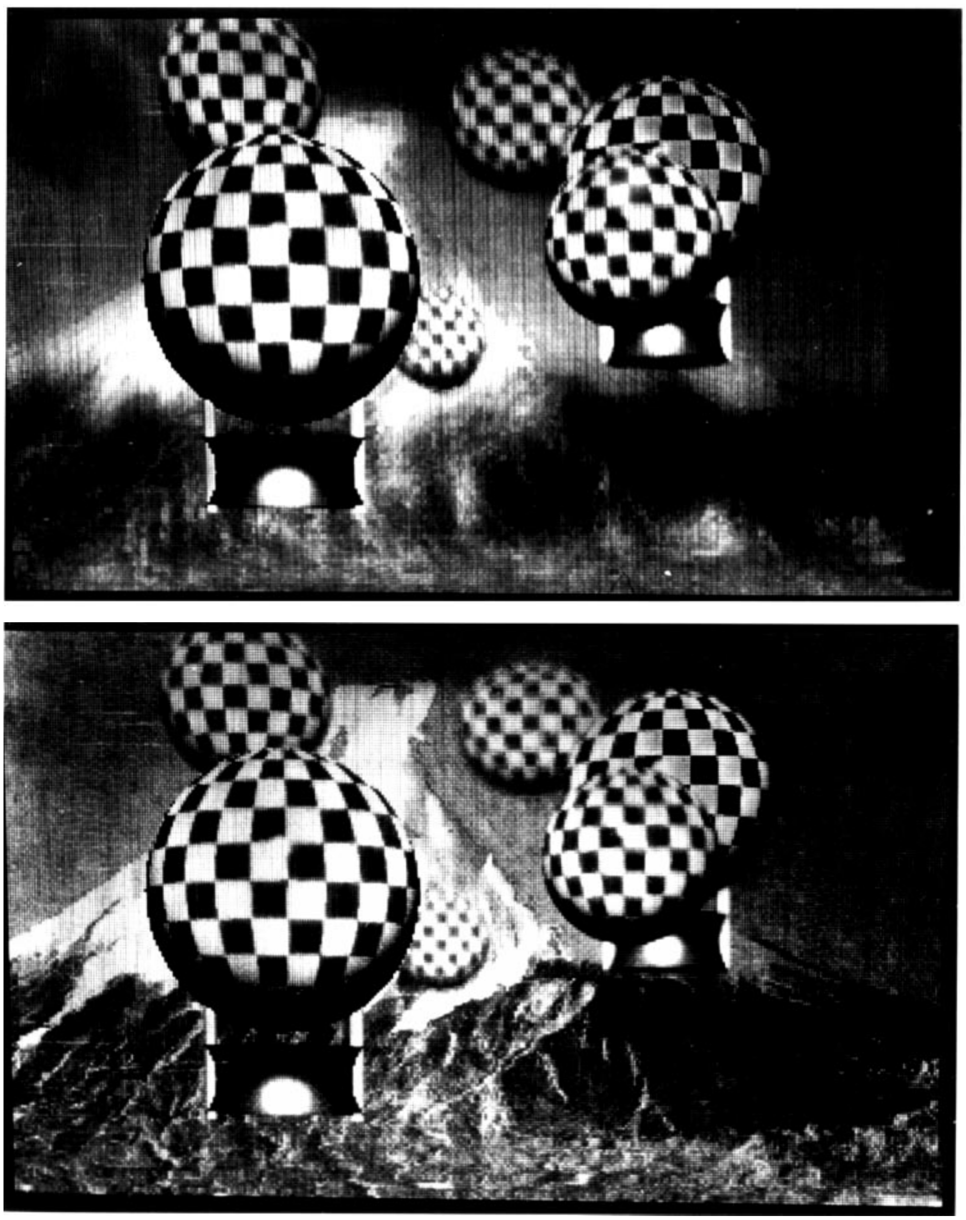
where l is the distance between the hologram and the observer. The sampling interval at the assumed observation plane should be larger than the limit of angular resolution b and w, so that the overlap of reconstructed light becomes small. Because the blur due to the chromatic dispersion depends on the angle of the object rays, the sampling interval at the observation plane should be adjusted depending on the direction of object rays, although it is invariant in the following experiment for simplicity. Usually, the reference beam illuminates the hologram vertically, thus $\theta_R = 0$ in the horizontal direction and $\theta_R \neq 0$ in the vertical direction. In this case the sampling interval in the vertical direction should be larger than the horizontal direction.

After the sampling intervals are determined, the light rays sampled at the assumed observation plane are traced and the results are applied to the image for exposure. When the 3-D image consists of foreground and background images, they should be processed separately. The foreground object is calculated by the technique described in Ref. 1, and the background image is calculated by the proposed scheme. Subsequent to these calculations, resultant images are synthesized to produce the image for exposure.

To determine the range of the background and foregound images, the resolution of the reconstructed image is considered. If the angular resolution of the reconstructed light-rays is $\Delta\theta$, then the resolution of the reconstructed image r_i is given by

$$r_i = |z|\,\Delta\theta, \tag{4}$$

Figure 6. An example of a synthesized image for exposure. A mosaic structure is observed because the background image is resampled.



(a)

(b)

Figure 7. Reconstructed images from the holograms recorded by the conventional technique (a) and the proposed method (b).

where z is the location of the image. On the other hand, the image resolution is limited by the sampling on the hologram plane, i.e., the interval of the elementary holograms. The resolution limit due to the hologram plane sampling r_s is obtained from geometric relation as,

$$r_s = (1 + z/l)p \tag{5}$$

where p is the interval of the elementary holograms. If $r_i \leq k\ r_s$, where k is not much larger than unity, then the resolution reduction by the spread of light-rays is not dominant. Then we have

$$-\frac{lkp}{l\Delta\theta + kp} \leq z \leq \frac{lkp}{l\Delta\theta - kp}. \tag{6}$$

Therefore, the foreground object should be located within the range given by Eq. 6, and the object at $z > lkp/(l\Delta\theta - kp)$ is dealt as the background object.

Experiment

In the experiment, 3-D data consisting of foreground and background objects are recorded by the prototype holoprinter.[3] Foreground objects are located within ± 30 mm of the hologram plane, and a background object is located 150 mm away from the hologram. For simplicity, a 2-D image is used as the background object in this experiment.

The images for exposure are calculated by two-steps; the sphere objects near the hologram plane are processed to generate the projected images by ray tracing, and the projected images are synthesized with the background image. The background image is resampled from the original 2-D scene before the synthesis as follows;

First, we assumed the observing distance from the hologram plane as l = 360 mm. Let us define the effective f/number as $F = f/D$, where f is the focal length of the lens L_1 in Fig. 1, and D is the horizontal or vertical width of the LCD panel, respectively. In this experiment, F = 1.17. Then, at the observation plane, the sampling interval of the image for exposure was $d_o = l/NF$ = 4.80 mm, where N = 64 is the number of pixels in horizontal or vertical direction, that is, the resolution of the image for exposure was 64 × 64 pixels. As for the horizontal direction, if $\theta_R = 0$, $-\tan^{-1}(1/2F) \leq \theta_o \leq \tan^{-1}(1/2F)$, $\Delta\lambda$ = 13.0 nm and λ = 633.0 nm, then the blur size and the resolution of reconstructed light-rays became $b \leq 6.32$ mm and w = 9.61 mm, respectively, and $b + w \leq 15.9$ mm. In vertical direction, similarly, $\theta_R = \pi/4$, $-\tan^{-1}(1/2F) \leq \theta_o \leq \tan^{-1}(1/2F)$, $\Delta\lambda$ = 13.0 nm, then we have $b \leq 17.7$ mm and w = 9.61 mm, respectively. The sampling interval at the observation plane should be larger than $b + w \leq 27.3$ mm. In order to satisfy these conditions, the sampling intervals in horizontal and vertical directions were 19.2 mm and 33.6 mm, respectively. As a result, the resolution of the background image at the image for exposure is 16 × 10 pixels, where the images of the near objects are sampled in 64 × 64 pixels. The synthesized images, eg., as shown in Fig. 6, are exposed by the optical system shown in Fig. 1.

The reconstructed images are shown in Fig. 7. Each hologram is composed of 340 × 200 elementary holograms, and the intervals of the elementary holograms are 0.3 mm in both the horizontal and vertical directions. The photograph was taken from 360 mm away from the hologram, which corresponds with the assumed observation location. It is obvious that the image far from the hologram plane can be clearly observed in the image synthesized by the proposed method.

However, if the hologram is observed from the improper distance, block-like artifacts appear in the far image. The only method to suppress this is to reduce $\Delta\theta_s$ and $\Delta\theta_c$ in Eqs. 1 and 2.

Conclusion

One-step and two-step recordings of holographic stereograms yield different types of 3-D images, because parallax is usually sampled at the location of the viewer in two-step recordings, while the light rays are sampled at the hologram plane in one-step methods. The one-step holographic stereogram can produce enough parallax information in the images near the hologram plane, but the image far from the hologram plane is affected by the image blur and the sampling of light rays. But the two-step holographic stereogram produces a pair of 2-D images without blur, which enables stereoscopic observation. This article presents a method to combine the both features in the one-step recording method, in which the foreground and background images are processed in a different manner. By the proposed method, deep 3-D images can be reproduced with suppression of image blur by the holoprinter.

Many of the 3-D images currently produced are composed of foreground and background objects, such as human portraits. The proposed technique is suitable for such 3-D images, because the foreground and background objects are processed separately and synthesized after the calculation of ray-tracing. In addition, if the background object is a 2-D image, the calculation is quite simple and only involves cutting out a rectangular region from the original background image and resampling the image. Therefore, it is easy to change the background with respect to the same foreground image after the ray-tracing calculation, like other multimedia applications for 2-D images.

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