3D display with wide viewing zone using holograms with reduced information

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ABSTRACT

The superimposing method for information reduction in hologram is compared with the sampling method to clarify their features. 3D images with motion parallax are reproduced in the wide viewing zone from holograms with reduced information. The visual field is divided in several fields for displaying visual depth of the image under reduced information, and partial images in divided visual fields are separately recorded on several Fourier transform holograms (FTHs). A time-sharing display system is developed to reconstruct the 3D image in real time from several FTHs. Experiments are carried out for reconstruction of the practical 3D image from recorded holograms. Results show that resolution of the image is improved, and the speckle noise is suppressed by the superimposing method. Observer can perceive motion parallax of the image with wide viewing zone by viewing a pair of stereoscopic images from right-eye and left-eye positions. Observer can also perceive the correct visual depth of images through a parallax-fusing perceptual phenomenon.

Keywords: information reduction, superimposition, Fourier transform hologram, time-sharing system, holographic display, visual depth, motion parallax, depth perception

1. INTRODUCTION

Real-time holographic display systems have become significant interest in recent years, after remarkable progress of computers and development of micro optical devices. The Spatial Imaging Group at the MIT Laboratory has succeeded in reconstructing the 3-D moving image using acoustic optical modulator (AOM)1,2. Experiments using the liquid-crystal display (LCD) panel have been carried out to demonstrate reconstruction of a real time 3-D image3-5. There are problems that should be solved to realize practical holographic displays. A major problem is that massive information makes hard to record or to transmit hologram.

An ordinary hologram contains far more information than necessary for the purpose to reconstruct the 3D image. The information in hologram is too much for real-time electronic processing. Some methods of information reduction have been proposed previously6-9. Among of them, two similar methods presented by Burckhardt6 and by Lin9 are practically useful for the visual display of the 3D image. In these methods, only small areas of an ordinary Fourier transform hologram are sampled, and a periodic hologram for reconstruction of the image is produced by repeating the small holograms. The total area sampled is much smaller than the ordinary one. Resolution of the reconstructed images is limited by the sampling bandwidth of small hologram in the sampling method. When the sampling bandwidth is smaller than the diameter of pupil, resolution of the image decreases and the speckle noise increases due to discontinuity of the periodic hologram. The observer cannot perceive the depth of image through focal adjustment. For improving depth perception of the image, many small band holograms are required10.

We have three purposes of this paper. The first is to clarify features of the superimposing method for information reduction in hologram as comparing with the sampling method. The second is to propose a new method for displaying the 3D image with motion parallax in the wide viewing zone using holograms with reduced information. The third is to propose a time-sharing system for displaying visual depth of the image from several FTHs with reduced information.

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2. INFORMATION REDUCTION

2.1 Sampling method

In the sampling method proposed by Lin\(^9\), the second hologram is reproduced from a lens-less Fourier transform hologram. If a holographic image is on the Fourier-transform plane of the hologram, the position of the image is invariant with respect to the translation of the hologram on its plane. Because of this invariant relation, it is possible to reproduce a large hologram by repeating a small spatial frequency band without apparent motion of the image.

At first, only a small area of spatial frequency band is sampled with the sampling bandwidth \( T \) from an original hologram as shown in Figure 1(a). Bandwidth of the original hologram is reduced to the sampling bandwidth \( T \). Next, the periodic hologram is reproduced by repeating the sampled small spatial frequency band as shown in Figure 1(b). This method is effective to reduce information for holographic display. However, we have problems in this method. One is loss of resolution of the image due to information deduction. Resolution of the image reconstructed from the periodic hologram is estimated by

\[
\delta = \frac{L}{T} \lambda ,
\]

where \( L \) is distance from the hologram to the image and \( \lambda \) is the wavelength. Another is increase of the speckle noise. If the sampling width is taken to be smaller than the diameter of observer’s pupil, quality of the reconstructed image degrades. Resolution of the image decreases and the speckle noise increases as the sampling width becomes small. Degradation of the image is mainly due to discontinuity of the periodic hologram, which is produced by repetition of the identical small hologram in the sampling method.

![Figure 1](image-url)  
(a) A small hologram sampled from the original Fourier transform hologram (FTH) and (b) the periodic second hologram with reduced information produced by repeating the small hologram.

2.2 Superimposing method

In order to improve quality of the reconstructed image, we have proposed a method of information reduction by superimposing spatial frequency bands\(^10\). We describe procedures of this method as follows. At first, the original Fourier transform hologram is divided into a number of small holograms, and a number of divided small holograms are superimposed in order to produce a small hologram as shown in Figure 2(b). Spatial frequency bands on divided holograms are integrated and recorded on the small hologram with bandwidth \( T \). The continuous periodic hologram is reproduced by repetition of the small hologram as shown in Figure 2(c).
Resolution of the image reconstructed from the continuous second hologram is estimated by

\[ \delta_s = \frac{L}{NT} \lambda, \]

where \( NT \) is width of the original hologram. Because of this, we can reduce information of a hologram without loss of resolution. Superimposition of many divided holograms also improved quality of the reconstructed image by suppressing the speckle noise. The speckle noise decreases as width \( NT \) of the original hologram increases \(^{11}\). As a result of information reduction by superimposing method, the image reconstructed on the Fourier-transform plane is sampled spatially. The width of the spatial sampling agrees with Eq. (2). Period \( T_s \) of the spatial sampling is given by

\[ T_s = \frac{L}{T} \lambda, \]

where \( T \) is the period of the continuous periodic hologram. Resolution of the image on the Fourier transform plane is improved and the speckle noise is suppressed by this method as compared with the sampling method at the same information reduction ratio.

![Figure 2.](image_url)

(a) The original Fourier transform hologram (FTH) divided into a number of small holograms, (b) the small hologram produced by superimposing the divided holograms, and (c) the continuous periodic second hologram with reduced information produced by repeating the small hologram.

### 3. DISPLAY OF IMAGE WITH MOTION PARALLAX

As a result of information reduction, motion parallax is lost from the image reconstructed from holograms. In order to display the image with motion parallax in the wide viewing zone, we propose a new method using holograms with reduced information. In this method, we first recorded holograms at different positions as shown in Figure 3. Information in holograms is reduced by applying the superimposing method. Small holograms with bandwidth \( T \) are produced from holograms recorded at different viewing positions by superimposing a number of divided small holograms. The hologram at a position between two recording positions is produced by superimposing small holograms so as to reconstruct overlapped two images which are recorded at different two positions. Light-intensity ratio of overlapped two images is determined from the distance ratio between the position and two recording positions.

Linear interpolation of the light-intensity ratio between overlapped two images in the present method is similar to that of the luminance ratio between overlapped two 2D images in the depth-fusing perceptual phenomenon \(^{12}\). As the result of the linear interpolation of light intensity, one can observe continuously changing stereoscopic images if his eye moves from a position to another position. When each eye sees the appropriate overlapped images of a pair of overlapped...
stereoscopic images, the observer perceives a parallax-fused image. The observer can perceive the correct visual depth of the image through the parallax-fusing perceptual phenomenon. The 3D image with motion parallax is reconstructed in the wide viewing zone from holograms produced by the present method.

![Diagram](image)

**Figure 3.** Production of a hologram from holograms recorded at different position. The hologram at a position between two recording positions is produced by superimposing small holograms so as to reconstruct overlapped two images.

### 4. DISPLAY OF VISUAL DEPTH

#### 4.1 Division of visual field in depth

When we view overlapped stereoscopic images from intermediate positions, there is a limitation of the visual depth for the parallax-fusing perception. We perceive an image far from the Fourier transform plane as an image which is double. In order to display the image with large visual depth under the reduced information, we separate the 3D image in the depth direction and record each separated images on several Fourier transport holograms.

The visual field is divided into several fields by the Fourier transform planes parallel to the hologram as shown in Figure 4. Partial images in the divided field are recorded on the corresponding Fourier transform hologram. Holograms with reduced information are reproduced. Since the partial image in the divided field is reconstructed on the corresponding Fourier transform plane, the observer can perceive visual depth of the whole 3D image with long depth by viewing several partial images reconstructed on different Fourier-transform planes.

There mainly are two methods to reconstruct a real-time moving image from several Fourier transform holograms with reduced information. One is the method to produce one Fresnel hologram for reconstruction of the image in the whole visual field by combining several Fourier transform holograms. Real-time display of the image by this method is difficult because high-speed numerical calculation is required for transforming Fourier transform holograms to the Fresnel holograms at frame rate.
Figure 4. Visual fields divided in the depth and Fourier-transform planes in the divided fields. The image in each field is recorded on and reconstructed from the Fourier transform hologram by illuminating with the reference light source located on the Fourier transform plane.

4.2 Time-sharing display of image with visual depth

Figure 5. Time-sharing display of visual depth from holograms with reduced information. Each point-light source is reconstructed from hologram H1 on the Fourier transform plane in order to illuminate hologram H2. Partial images in divided fields are reconstructed from hologram H2 rotationally.

In this paper, we propose another method to reconstruct the partial image in divided fields at high frame rate from Fourier transform holograms by adopting a time-sharing system. The image in the whole visual fields is displayed by reconstructing partial images rotationally. Since numerical calculation for transformation of the hologram is not required in this method, real-time display is possible. A point-light source on Fourier transform plane is necessary for reconstructing the image from the Fourier transform hologram. Then, several point-light sources corresponding to each field are necessary for reconstruction of the image in the whole visual field. We reproduce these point-light sources by displaying the hologram on the liquid crystal display (LCD) panel. Position of the point-light source can be easily moved at high frame rate by changing hologram displayed on the LCD panel.
Figure 5 shows time-sharing display of the image with visual depth from holograms with reduced information. Hologram H1 which reconstructs the point-light image is illuminated by the reference light, and hologram H2 which reconstructs the image is illuminated by this point-light source. Partial images in divided fields are rotationally displayed at high frame rate for reconstruction of the image in the whole visual fields by using time-sharing system.

Figure 6 shows optical setup for time-sharing display of visual depth from several holograms with reduced information. Hologram H1 is illuminated by collimated reference light for reconstructing the image of point-light sources, and H2 is illuminated by the light beam emitted from H1 for reconstruction of the image. When the image of point-light sources is reconstructed from the hologram H1, the direct beam and the conjugate beam are also emitted from H1. These needless light beams are eliminated by setting up lenses L1 and L2 and the aperture as shown in Figure 6. The observer can view the image reconstructed from the hologram H2 through the half mirror located in front of H2.

Figure 6. Optical setup for time-sharing display of visual depth from several holograms with reduced information. Hologram H1 is for reconstruction of point-light sources and H2 is for reconstruction of the image. Lenses L1 and L2 and the aperture are set up for eliminating the direct beam and the conjugate beam emitted from H1.

5. EXPERIMENTAL RESULTS

Experiments for reconstruction of the image have been carried out using holograms that are recorded for practical 3D images by CCD. A hologram data is displayed on a high-resolution reflective liquid-crystal display (LCD) panel which has 1920(H)x1080(V) square pixels with pixel pitch of 8.1µm. A red laser diode with wavelength of 650 nm, a green diode pumped solid-state laser with wavelength of 532 nm and a blue diode pumped solid-state laser with wavelength of 473 nm are adopted as reference-light sources.

5.1 Reconstruction of image from hologram with reduced information

We first reconstruct the image from holograms recorded by CCD in order to demonstrate improvement of quality of the image by the superimposing method under information reduction. Figure 7 shows photographs of the real image of the 3D object reconstructed in the vicinity of the Fourier transform plane. A die with the size of about 1 cm is located at the position 72 cm apart from CCD. Fresnel hologram is recorded by CCD using the phase-shifting interferometry, and is numerically translated to the Fourier transform hologram for application of information-reduction methods. The Image with the same size is reconstructed at the same position apart from holograms. Figure 7(a) is the real 3D image reconstructed from the original hologram, and Figs. 7(b) and 7(c) are images from holograms with T= 3.0 mm and with T= 1.0 mm produced by the sampling method respectively. Figures 7(d) and 7(e) are images from holograms with N=3 and T= 3.0 mm and with N=9 and T= 1.0 mm produced by the superimposing method respectively. Hologram data for images in Figs. 7(c) and 7(d) are reduced to about 0.5 % of that in Fig. 7(a). Quality of the image in Fig. 7(d) or 7(e) is higher than that of images in Figs. 7(b) or 7(c). High-resolution image with low speckle noise is reconstructed on the Fourier transform plane from the hologram produced by the superimposing method.
Figure 7. 3D images of a die reconstructed (a) from the Fourier transform hologram recorded by the CCD, (b) from the hologram with bandwidth $T=3.0$ mm and (c) with $T=1.0$ mm produced by the sampling method, and (d) from the hologram with $N=3$ and $T=3.0$ mm and (e) with $N=9$ and $T=1.0$ mm produced by the superimposing method.

5.2 Display of image with motion parallax

We reconstruct the 3D image in order to demonstrate display of the image with motion parallax. Holograms are recorded by CCD at three viewing positions 6cm apart from each other as shown in Figure 8. A sphere with radius of 1.2cm is located on the Fourier transform plane at $z=99$cm, a cone with radius of 1.2cm is located at $z=96.5$cm, and a cube with size of 1.2cm is located at $z=101.5$cm. Information in recorded holograms is reduced by superimposing a number of divided small holograms with bandwidth $T=3.0$mm.

Figure 9 shows images reconstructed from holograms recorded at positions (a) of $x=-6$cm, (b) of $x=0$cm, (c) of $x=6$cm, and overlapped images viewed from positions (d) of $x=-3$cm and (b) of $x=3$cm between recording positions. The 3D image with motion parallax is displayed by overlapping two images with different light intensity. As the result of the linear interpolation of light intensity, overlapped images continuously change if viewing position moves from a position to another position. When we view overlapped stereoscopic images from right-eye and left-eye positions, we perceive a parallax-fused image with correct visual depth through the parallax-fusing perceptual phenomenon. The present method is applicable to realize a holographic display which reproduces the image with motion parallax in the wide viewing zone from holograms with reduced information.
Figure 8. 3D objects located near the Fourier transform plane at $z=99\text{cm}$ and three recording positions.

![Diagram of 3D objects and hologram positions](image)

Figure 8. 3D objects located near the Fourier transform plane at $z=99\text{cm}$ and three recording positions.

Figure 9. Images reconstructed from holograms recorded (a) at $x=-6\text{cm}$, (b) at $x=0\text{cm}$, (c) at $x=6\text{cm}$, and overlapped images viewed from positions (d) of $x=-3\text{cm}$ and (b) of $x=3\text{cm}$, where the bandwidth $T$ of holograms is taken to be $3.0\text{mm}$ for information reduction.

![Reconstructed images](image)

Figure 9. Images reconstructed from holograms recorded (a) at $x=-6\text{cm}$, (b) at $x=0\text{cm}$, (c) at $x=6\text{cm}$, and overlapped images viewed from positions (d) of $x=-3\text{cm}$ and (b) of $x=3\text{cm}$, where the bandwidth $T$ of holograms is taken to be $3.0\text{mm}$ for information reduction.

We carried out subjective tests to confirm the depth perception of 3D image. Figure 10 shows a schematic diagram of experimental apparatus, and Figure 11 shows a photograph of the reconstructed image together with the movable reference plane. Position of the movable reference plane is adjusted so that the depth of the reference plane can be perceived to be the same depth of the reconstructed image.

Figure 12 shows the perceived depth of the image versus the real distance of the object from the Fourier transform plane (FTP). The FTP is located at $z=82.5\text{cm}$ in this experiment. The observer views the image with both eyes from the position where holograms were recorded (Position 1), from the middle position between recording positions (Position 2), and from some position between Position 1 and Position 2 (Position 3). The observer can perceive one 3D image with visual depth through a parallax-fusing perceptual phenomenon by viewing two overlapped stereoscopic images with both eyes. The deviations between three curves in Fig. 12 are within 10%. This indicates that the observer can perceive the correct visual depth of images by viewing superimposed stereoscopic images reconstructed on Fourier transform planes.
5.3 Display of 3D image with wide viewing zone and wide visual field

We reconstructed the 3D image from recorded holograms with reduced information in order to demonstrate display of the image with wide viewing zone and wide visual field. Holograms were recorded by CCD at three viewing positions 6.5cm apart from each other as shown in Figure 13. Triangle, circular and square cylinders with length of 4cm are located at z=72cm, 82cm, and 92cm, respectively.

The image is reconstructed from three Fourier transform holograms with reduced information, where the bandwidth $T$ of small holograms is taken to be 3.0 mm. Three separated images are rotationally reconstructed on three Fourier transform planes at $z=72$, 82 and 92cm following the manner as described in Chapter 3.
Figure 14 shows images reconstructed from holograms recorded at positions (a) of $x=-6.5\text{cm}$, (b) of $x=0\text{cm}$, (c) of $x=-6.5\text{cm}$, and overlapped images viewed from positions (d) of $x=-3.3\text{cm}$ and (b) of $x=3.3\text{cm}$ between recording positions. 3D images with motion parallax are displayed over wide viewing zone by superimposing two stereoscopic images with different viewing positions. The light-intensity ratio of two images is determined by the linear interpolation. The observer can perceive full parallax and the visual depth of the image with wide viewing zone and wide visual field by viewing stereoscopic images reconstructed on three Fourier transform planes with both eyes.

Figure 13. 3D color objects with depth of 4 cm located at $z=72\text{cm}$, $z=82\text{cm}$ and $z=92\text{cm}$.

Figure 14. Images with wide viewing zone and wide visual field reconstructed from holograms recorded (a) at $x=-6.5\text{cm}$, (b) at $x=0\text{cm}$, (c) at $x=6.5\text{cm}$, and images viewed from intermediate positions (d) of $x=-3.3\text{cm}$ and (b) of $x=3.3\text{cm}$, where the bandwidth $T$ of holograms is taken to be 3.0 mm for information reduction. The images at intermediate positions are displayed by superimposing two images with different recording positions.
6. CONCLUSION

The superimposing method for information reduction in hologram has been compared with the sampling method in order to clarify their features. A new method has been proposed to display the 3D image with motion parallax in the wide viewing zone. A time-sharing system has also been proposed for real-time display of the image with visual depth from several Fourier transform holograms with reduced information. Experiments for reconstruction of the practical image have shown that high-resolution images with low speckle noise are reconstructed from the hologram produced by the superimposing method. Observer can perceive motion parallax of the image by viewing a pair of overlapped stereoscopic images with both eyes. The visual depth of the image can be perceived by viewing stereoscopic partial images reconstructed on Fourier transform planes.

Drastic information reduction by the present method is useful for electronic processing of the practical electro-holography. We are now working to apply the present methods to the holographic display in order to experimentally demonstrate a parallax-fusing perception phenomenon of the 3-D image and in order to develop a real-time display with wide viewing zone and wide visual field.

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