Horizontally scanning holography to enlarge both image size and viewing zone angle

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ABSTRACT

In order to enlarge the image size and viewing zone angle of a hologram, an image generated by a high-speed spatial light modulator (SLM) is converted into a vertically long image by an anamorphic imaging system, and this image is scanned horizontally by a galvano scanner. The reduction of the horizontal pixel pitch of the SLM provides a wide viewing zone angle. The increase of the image height and horizontal scan enlarge the image size. In this study, a digital micromirror device (DMD) with the resolution of 1,024×768 was used as a high-speed SLM. A laser diode with the wavelength of 635 nm was used as a light source. An anamorphic imaging system had the magnifications of 0.183 and 5.0 in the horizontal and vertical directions, respectively, to generate a vertically long image with the size of 2.56 mm×52.5 mm. The horizontal pixel pitch was reduced to 2.5 μm to provide the horizontal viewing zone angle of 15°. The horizontal scan width of the galvano scanner was 73.1 mm, so the resultant image size was 73.1 mm×52.5 mm. The scanning frequency of the galvano scanner was 60 Hz and the frame rate of the DMD was 13.333 kHz so that one hologram consisted of 222 vertically long images. The vertically long images were displayed with the horizontal pitch of 0.32 mm and there were substantial overlaps. We succeeded the generation of a hologram image having 15° horizontal viewing zone angle and 3.5" screen size with a 60 Hz frame rate.

Keywords: hologram, three-dimensional image, high-speed SLM, mechanical scanning, large screen, wide viewing angle

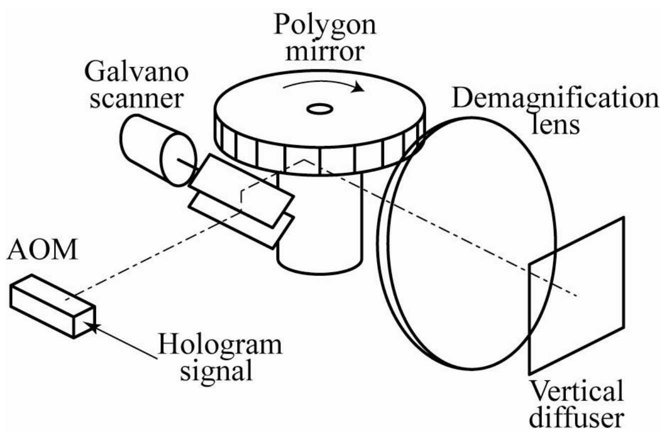
1. INTRODUCTION

Holography is an ideal three-dimensional display technique because it reconstructs the wavefront emitted from an object. However, an extremely high-resolution spatial light modulator (SLM) is required to display a practical three-dimensional image. When an SLM has pixel pitch p and resolution $N_x \times N_y$, $2\sin^{-1}(\lambda/2p)$ gives the diffraction angle that determines the viewing zone angle and $N_x\, p \times N_y\, p$ gives the display screen size. A very fine pixel pitch is necessary for a wide viewing zone angle, and a huge pixel count is necessary for a large screen size. Horizontal parallax only (HPO) holography offers a practical solution to relax the requirements for the SLM. Since an HPO hologram consists of horizontal scan lines which are one-dimensional holograms, the vertical pixel pitch and the vertical pixel count become comparable to those of conventional two-dimensional televisions. However, a very fine pixel pitch and a huge pixel count are still required in the horizontal direction to generate one-dimensional holograms.

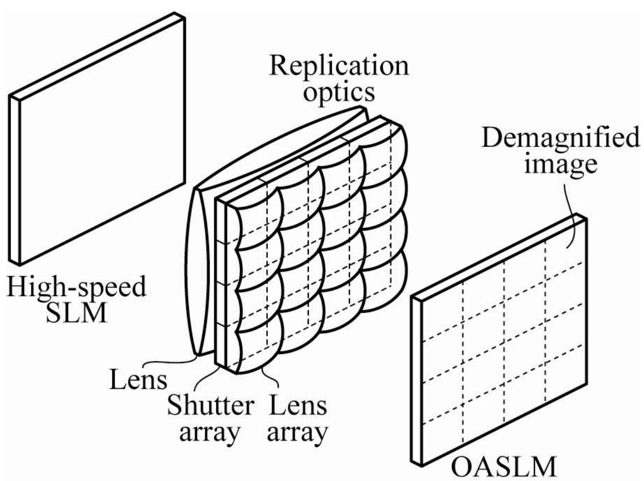
Practical Holography XXIII: Materials and Applications, edited by Hans I. Bjelkhagen, Raymond K. Kostuk,
Proc. of SPIE Vol. 7233, 723309 · © 2009 SPIE · CCC code: 0277-786X/09/$18 · doi: 10.1117/12.808831

Several techniques have been proposed to enlarge both the viewing zone angle and the screen size. Hilair et al.[1, 2] proposed an HPO hologram technique, in which a high-resolution one-dimensional hologram distribution generated by an acousto-optic modulator (AOM) is scanned two-dimensionally by a mechanical scanner. This technique is illustrated in Fig. 1(a). A hologram of 150 × 75 mm^2 image size and 30° viewing zone angle was generated using 18 AOMs and six mechanical scanners. Slinger et al.[3] proposed the active tiling technique, which tiles de-magnified images generated by a high-speed SLM onto an optically addressed SLM. The active tiling technique is depicted in Fig. 1(b). A hologram of 136 × 34 mm^2 image size and a pixel pitch of 6.6 µm with a 30 Hz frame rate was demonstrated using four tiling systems. Several techniques have also been proposed to increase the viewing zone angle. Maeno et al.[4] proposed the use of multiple SLMs, Mishina et al.[5, 6] proposed a time-multiplexing technique, and Takaki et al.[7, 8] proposed the use of a resolution redistribution system.

In the present study, we propose a new technique to enlarge both the viewing zone angle and the screen size of a hologram using a high-speed SLM, an anamorphic imaging system, and a horizontal scanner.



(a)



(b)

Fig. 1. Previous holographic display techniques for enlarging both image size and viewing zone angle: (a) MIT technique, and (b) active tiling technique.

2. PROPOSED SYSTEM

First, we consider the case when a hologram is generated by spatially scanning a small elementary hologram (see Fig. 2). Light diffracted from the elementary hologram converges and generates the points of a three-dimensional image that enters the viewer's pupil. From this figure, coherence should be maintained only in the elementary hologram, not in the whole display screen. The width of the elementary hologram should be larger than $|dz/(l-z)|$, where d is the pupil diameter, z is the distance between the display screen and three-dimensional points, and l is the distance between the screen and the viewer. For example, the width should be larger than 2.5 mm, when d = 5 mm (average pupil diameter), z = 200 mm, and l = 600 mm. When the elementary hologram is scanned spatially, a hologram reconstruction image can be observed by the viewer. In the human eye imaging system, this quasi-coherent holography has approximately the same effects as conventional fully coherent holography. The idea of scanning a small hologram was previously used in the MIT system[1, 2] shown in Fig. 1(a).

Figure 3 illustrates the holographic display system proposed in the present study. An image generated by a high-speed SLM is squeezed in the horizontal direction and enlarged in the vertical direction by an anamorphic imaging system consisting of two orthogonal cylindrical lenses. The generated vertically long image, which is an elementary hologram, is scanned horizontally by a mechanical scanner. The high-speed SLM displays a series of elementary images in synchronization with the horizontal scanning. The pixel pitch of the SLM is reduced in the horizontal direction to increase the horizontal viewing zone angle. The vertical image enlargement by the anamorphic imaging system and the horizontal scanning increase the hologram size. Because the vertical pixel pitch increases, the generated hologram becomes an HPO hologram. For flicker-free image generation, the horizontal scan frequency should be higher than 60 Hz.

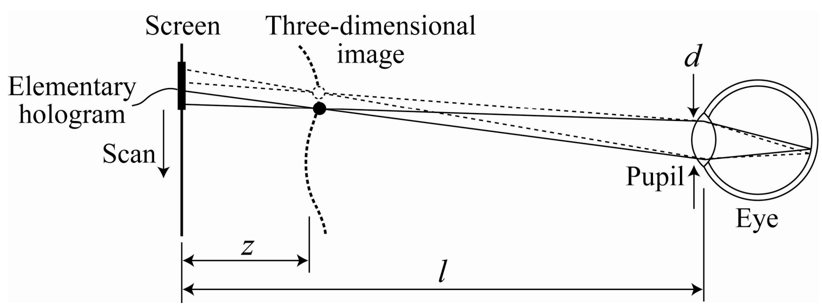


Fig. 2. Hologram generation by scanning an elementary hologram.

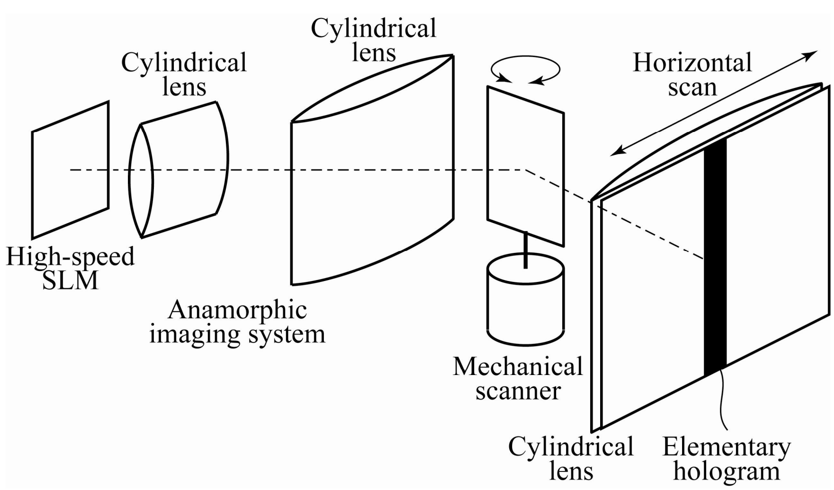


Fig. 3. Hologram generation by horizontally scanning of a high-speed SLM.

3. EXPERIMENTAL SYSTEM

The experimental system is shown in Fig. 4. As the high-speed display, a digital micromirror device (DMD) with the resolution of 1,024 × 768 and pixel pitch of 13.68 μm was used. A laser diode with a wavelength of 635 nm was used as the light source. Because of the difficulty of obtaining a large size cylindrical lens, the anamorphic imaging system consisted of one spherical lens and three cylindrical lenses with horizontally aligned axes. In the horizontal direction, the spherical lens squeezed an image with a magnification of 0.183. In the vertical direction, the spherical lens and the three cylindrical lenses constituted two 4*f* imaging systems with magnifications of 3.00 and 1.67, so that the total vertical image magnification was 5.00. The size of the elementary hologram was 2.56 × 52.5 mm^2. The quasi-coherent holography condition requires that a three-dimensional image be displayed within a distance of 0.339l from the screen. The horizontal pixel pitch was reduced to 2.50 μm to enlarge the horizontal viewing zone angle to 14.6°.

A galvano scanner was used for the horizontal scan, the vibration frequency of the mirror was 30 Hz, and the rotation angle was ±5º. The hologram was displayed with both clockwise and counter-clockwise rotating directions, and the frame rate for displaying the holograms was 60 Hz. The horizontal scan angle of the elementary hologram was ±10º and the distance between the rotating mirror and the display screen was 200 mm. Therefore, the display screen size was 73.1 × 52.5 mm^2. A spherical lens with the focal length of 200 mm was placed on the display screen to redirect the light proceeding direction. A lenticular sheet was also placed on the display screen as a vertical diffuser to enlarge the vertical viewing zone.

The frame rate of the DMD was 13.333 kHz and the whole hologram consisted of 222 elementary holograms. The elementary holograms were displayed with a horizontal pitch of ~0.32 mm on the display screen, so there were substantial overlaps among the elementary holograms. Since the DMD has a trade-off between frame rate and number of gray levels, the number of gray levels was set to one bit for the high frame rate operation. The laser was driven by the pulse signal synthesized from the image update signal from the DMD driver. The pulse width was 37.5 μs, which is half of the pulse period, in order to reduce the horizontal image blurring caused by the horizontal scan.

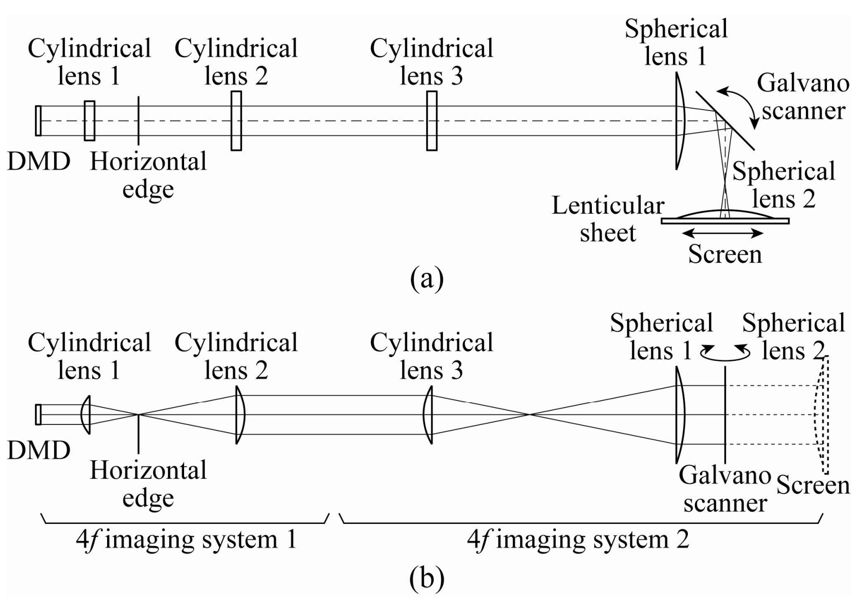


Fig. 4. Experimental system: (a) horizontal cross-section, and (b) vertical cross-section.

The conjugate image and the zero-th order image were removed by placing a horizontal edge on the Fourier plane of one of the two vertical 4*f* imaging systems [9]. Therefore, the vertical resolution of the elementary holograms became half of that of the SLM, and so the reconstructed image consisted of 384 horizontal scan lines. The elementary hologram patterns were calculated as Fresnel holograms. Some of elementary holograms with binary gray levels are shown in Fig. 5.

The specifications of the constructed holographic display system are listed in Table 1. The photograph of the experimental system around the DMD device is shown in Fig. 6.

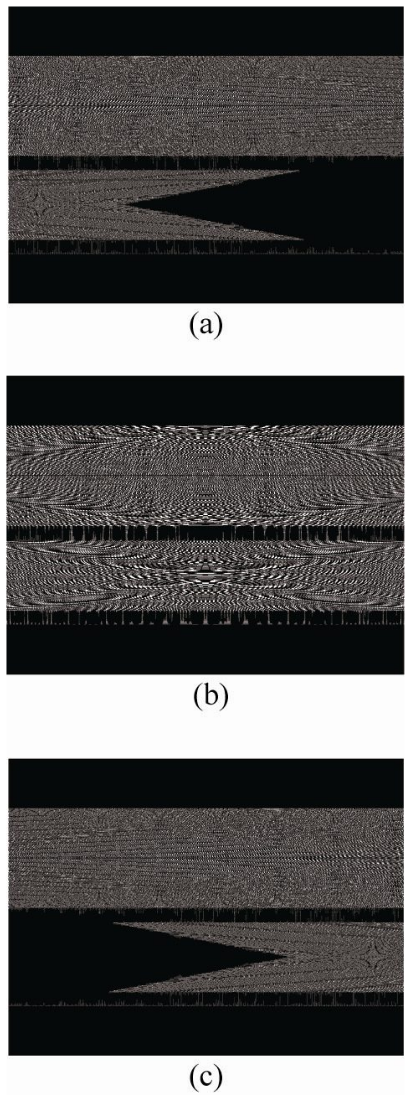


Fig. 5. Examples of elementary holograms: (a) 66th hologram, (b) 111th hologram, and (c) 156th hologram.

Table 1 Specifications of constructed hologram display system; E.H.: Elementary Hologram.

Screen size	73.1×52.5 mm^2 (3.5'')
Horizontal viewing zone angle	14.6°
Frame rate	60 Hz
Dimensions of E.H.	2.56×52.5 mm^2
Number of E.H.	222
Horizontal pitch of E.H.	0.32 mm

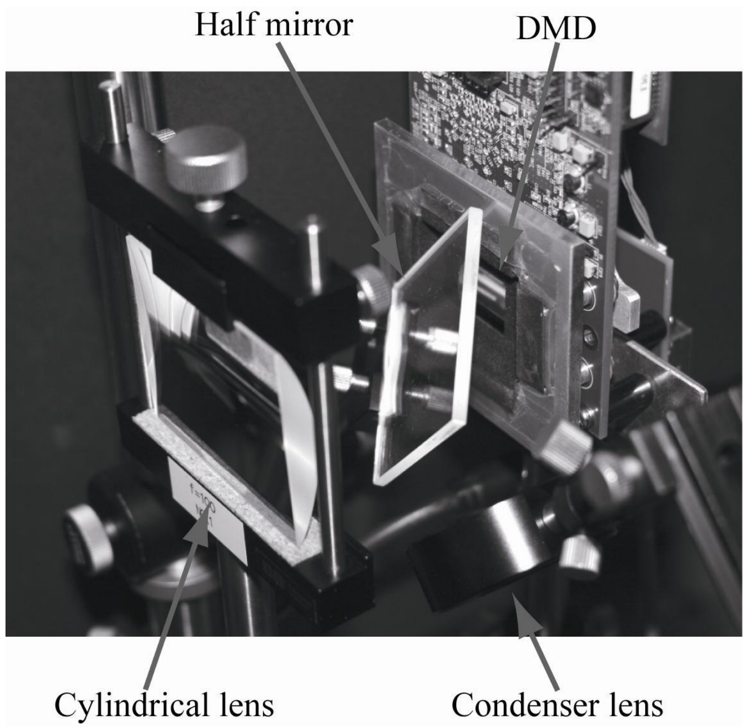


Fig. 6. Photograph of the experimental system around the DMD device.

4. EXPERIMENTAL RESULT

The reconstructed images are shown in Fig. 7. The images are photographs of the reconstructed image captured from different horizontal viewpoints. The cross and the rhombus were displayed at 100 mm and 150 mm, respectively, in front of the screen. The measured viewing zone angle was 15º and the measured screen size was 70×52 mm^2. Other reconstructed images are shown in Fig. 8. No ficker was observed.

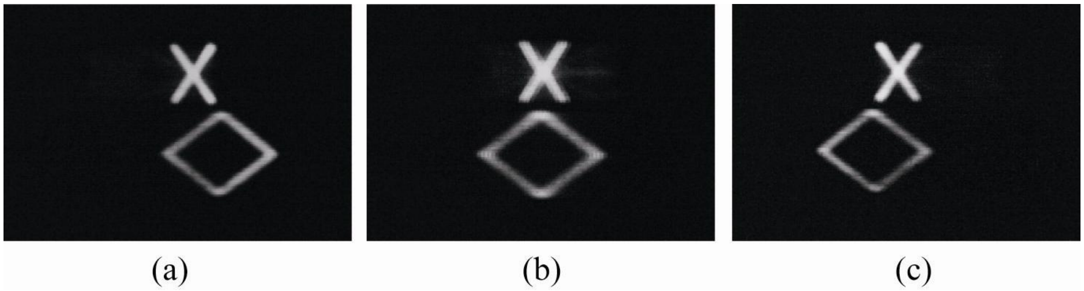


Fig. 7. Reconstructed three-dimensional image captured from (a) left, (b) center, and (c) right viewpoints.

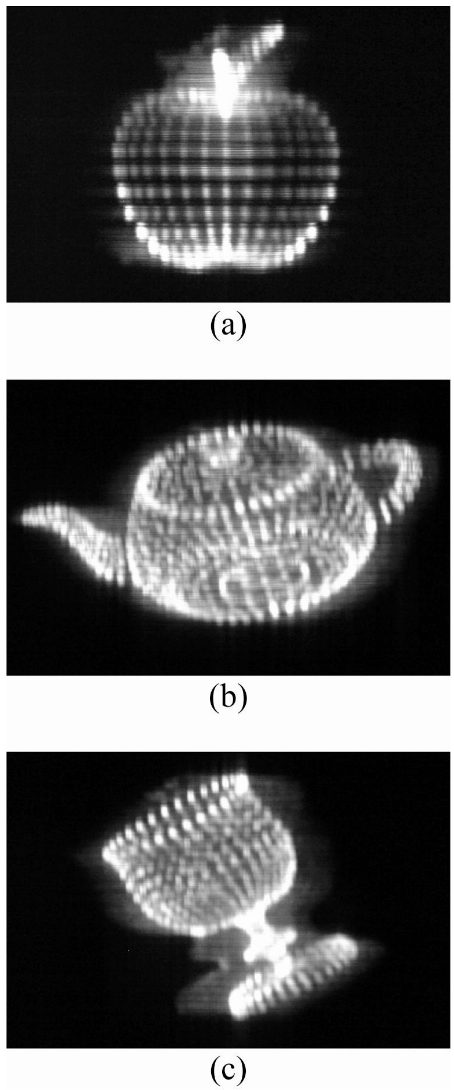


Fig. 8. Photographs of three-dimensional images: (a) apple, (b) teapot, and (c) wine glass.

5. CONCLUSION

In this paper, we propose a new technique to increase both the screen size and the viewing zone angle of a hologram by using a high-speed SLM, an anamorphic imaging system, and a horizontal scanner. We demonstrated hologram reconstruction using the holographic display system based on the proposed technique.

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