Hologram generation by horizontal scanning of a high-speed spatial light modulator

Yasuhiro Takaki* and Naoya Okada

Institute of Symbiotic Science and Technology, Tokyo University of Agriculture and Technology, 2–24–16, Naka-cho, Koganei, Tokyo 184–8588, Japan

*Corresponding author: ytakaki@cc.tuat.ac.jp

Received 3 April 2009; accepted 8 May 2009; posted 27 May 2009 (Doc. ID 109281); published 8 June 2009

In order to increase the image size and the viewing zone angle of a hologram, a high-speed spatial light modulator (SLM) is imaged as a vertically long image by an anamorphic imaging system, and this image is scanned horizontally by a galvano scanner. The reduction in horizontal pixel pitch of the SLM provides a wide viewing zone angle. The increased image height and horizontal scanning increased the image size. We demonstrated the generation of a hologram having a 15° horizontal viewing zone angle and an image size of 3.4 inches with a frame rate of 60 Hz using a digital micromirror device with a frame rate of 13.333 kHz as a high-speed SLM. © 2009 Optical Society of America

OCIS codes: 090.2870, 090.1760, 070.6120, 090.1970, 100.2000.

1. Introduction

Recently, the development of three-dimensional displays has accelerated. In many of these displays, rays emitted from an object are reconstructed. In contrast, holography reconstructs the wavefront emitted from an object and so is considered to be an ideal three-dimensional display technique. However, an extremely high-resolution spatial light modulator (SLM) is required to display practical three-dimensional images. When a SLM has a pixel pitch of p and a resolution of $N_x \times N_y$ and the wavelength of light is denoted by λ, $2\sin^{-1}(\lambda/2p)$ gives the diffraction angle, which determines the viewing zone angle, and $N_x p \times N_y p$ gives the display screen size. A very fine pixel pitch is required for a wide viewing zone angle, and a large pixel count is required for a large screen size. For example, in order to obtain a three-dimensional image with a screen size of 20 in. and a viewing angle of 30°, the pixel pitch should be $0.97\,\mu$m and the resolution should be approximately $420,000 \times 316,000$, when the wavelength of light is $0.5\,\mu$m.

0003-6935/09/173255-06$15.00/0

One of the most effective techniques for reducing the resolution required for an SLM is horizontal-parallax-only (HPO) holography. The HPO holography technique limits the parallax of a three-dimensional image only in the horizontal direction because horizontal parallax is dominant in human three-dimensional perception. The HPO hologram consists of horizontal scan lines, which are one-dimensional holograms. Thus, the vertical pixel pitch and the vertical pixel count are comparable to those of conventional two-dimensional televisions. However, a very fine pixel pitch and a large pixel count in the horizontal direction are still required in order to generate one-dimensional holograms.

Several techniques by which to increase both the viewing zone angle and the screen size have been proposed. In the HPO hologram display system developed at MIT [1], a high-resolution one-dimensional hologram distribution generated by an acousto-optic modulator (AOM) is scanned two-dimensionally by a mechanical scanner. A hologram having an image size of 150 mm × 75 mm (6.6 in.) and a viewing zone angle of 30° was generated using 18 AOMs and six mechanical scanners. Slinger *et al.* [2] proposed the active tiling technique whereby demagnified images generated by a high-speed SLM are tiled onto an optically addressed SLM. A hologram having an image size of 136 mm×34 mm (5.5 in.) and a pixel pitch of 6.6 μm with a frame rate of 30 Hz was demonstrated using four tiling systems. Several techniques by which to increase the viewing zone angle have also been proposed. Maeno *et al.* [3] proposed the use of multiple SLMs. Mishina *et al.* [4,5] proposed a time-multiplexing technique, and Takaki *et al.* [6] proposed the use of a resolution redistribution system.

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

2. Proposed Technique

A. Quasi-Coherent Holography

The technique proposed in the present study uses spatial scanning of a small elementary hologram.

As shown in Fig. 1, light diffracted from an elementary hologram converges to generate points that constitute a three-dimensional image and then enters the viewer's pupil. Thus, the coherence of light should be maintained only in the elementary hologram and not in the complete hologram. Ignoring the diffraction effect, the width of an elementary hologram should be larger than approximately $|dz/(l-z)|$, where d is the pupil diameter, z is the distance between the display screen and a three-dimensional point, and l is the distance between the screen and the viewer. For example, the width of the elementary hologram should be at least 2.5 mm when $d = 5$ mm (average pupil diameter), $z = 200$ mm, and $l = 600$ mm.

The reconstructed image is generated by spatially scanning the elementary hologram. However, the light diffracted from an elementary hologram does not always cover the entire pupil of the eye when an elementary hologram moves spatially. The diffraction light partially covers the pupil, when the diffraction light enters the pupil and leaves the pupil. Therefore, the spatially scanning holography described herein generates a quasi-coherent hologram. The image quality of the quasi-coherent holography is worse than that of fully coherent holography and depends on the width of the elementary hologram. However, the condition given in the previous paragraph describes the critical width for the elementary hologram.

The concept of scanning a small hologram was previously proposed by Haussler *et al.* [7].

B. Horizontally Scanning Holography System

The holographic display system proposed in the present study is illustrated in Fig. 2. The proposed system incorporates a high-speed SLM, an anamorphic imaging system, and a horizontally scanning system.

The high-speed SLM modulates light two-dimensionally with a high frame rate. The frame rate is denoted by f_{slm}. The pixel pitch of the high-speed SLM is denoted by p, and the resolution is denoted by $N_x \times N_y$.

A two-dimensional light distribution generated by the high-speed SLM is squeezed in the horizontal direction and expanded in the vertical direction by an anamorphic imaging system. The vertically long image generated by this process is an elementary hologram. The anamorphic imaging system consists of two orthogonal cylindrical lenses, and has different magnifications in the horizontal and the vertical directions. Horizontal magnification is performed by cylindrical lens 1, the centerline of which is aligned vertically, and the vertical magnification is performed by the other cylindrical lens 2, the centerline of which is aligned horizontally. The absolute magnification in the horizontal direction is denoted by $M_x(<1)$, and that in the vertical directions is denoted by $M_y(>1)$. The horizontal pixel pitch is reduced to $M_x p$ so that the diffraction angle is increased to $2\sin^{-1}(\lambda/2M_x p)$. The width and height of an elementary hologram are given by $M_x N_x p$ and $M_y N_y p$, respectively.

The elementary hologram generated by the anamorphic imaging system is scanned horizontally by a horizontal scanner. The high-speed SLM displays a series of elementary images in synchronization with the horizontal scanner. The horizontal scan pitch is denoted by q, and the scan frequency is denoted by f_{scan}. A complete hologram consists of $f_{\mathrm{slm}}/f_{\mathrm{scan}}$ elementary holograms. The horizontal scan pitch should be equal to or less than the horizontal width of the elemental hologram, i.e., $q \le M_x N_x p$.

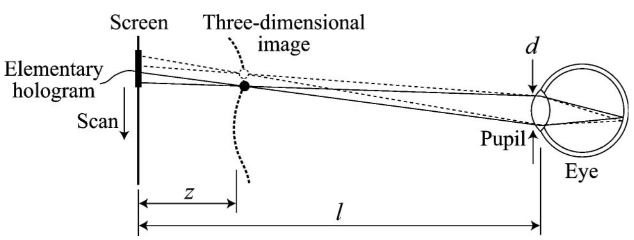


Fig. 1. Hologram generation by scanning an elementary hologram.

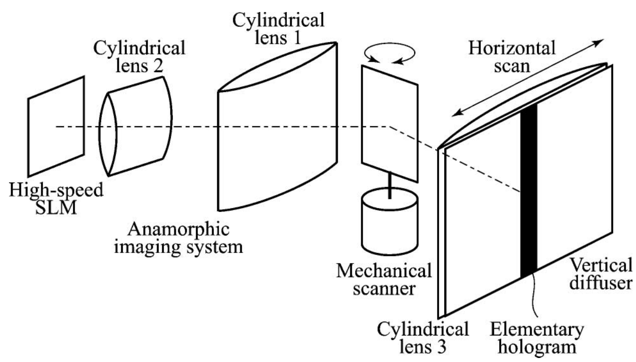


Fig. 2. Hologram generation by horizontal scanning of an elementary hologram generated by a high-speed SLM.

The width of a complete hologram is given by $qf_{\text{slm}}/f_{\text{scan}} + M_x N_x p$.

Cylindrical lens 3 is placed on the display screen to redirect the light proceeding direction toward the viewers. A vertical diffuser is also placed over the display screen to increase the vertical viewing zone.

The vertical image enlargement by the anamorphic imaging system and the horizontal scanning increase the size of the complete hologram. The width and height of the complete hologram are $qf_{\text{slm}}/f_{\text{scan}} + M_x N_x p$ and $M_y N_y p$, respectively.

The proposed holography display system generates all of the horizontal scan lines of a HPO hologram simultaneously. The horizontal scan frequency f_{scan} should be higher than 60 Hz in order to achieve flicker-free image generation.

3. Experimental System

Figure 3 shows the experimental system used to demonstrate the hologram display system proposed in the present study.

A digital micromirror device (DMD) was used as a high-speed SLM. An ALP-3 (ViALUX GmbH) was combined with a Discovery 3000 (Texas Instruments, Inc.) to enable high-frame-rate operation. The resolution was $1,024 \times 768$, and the pixel pitch was $p = 13.68\,\mu\text{m}$. The frame rate depends on the number of gray levels, because the ratio on time of the mirror device determines the gray level (binary pulse-width modulation). The maximum frame rate is 13.333 kHz when the number of gray levels is two (binary gray level). In the experimental system, the DMD was driven with the maximum frame rate, i.e., $f_{\text{slm}} = 13.333\,\text{kHz}$.

A laser diode with a wavelength of 635 nm was used as an illumination light source. The laser light was collimated and set to illuminate the DMD at the angle specified by the tilt angle of the micromirror. For the sake of simplicity, the illumination optics is not shown in Fig. 3. The use of the laser diode enables not only the compact system size, but also the pulse modulation of an illumination light to reduce image blurring, as described below.

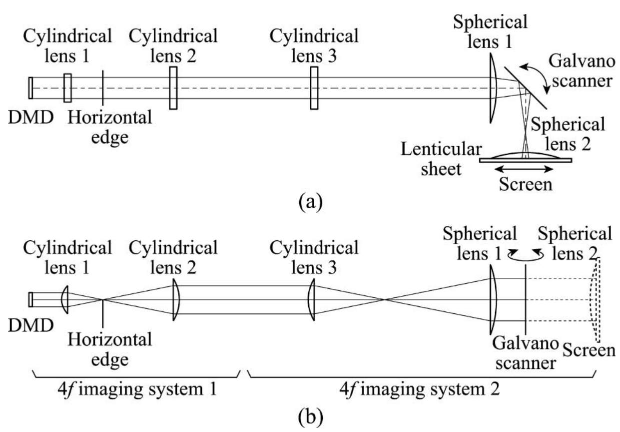


Fig. 3. Experimental system: (a) horizontal cross section and (b) vertical cross section.

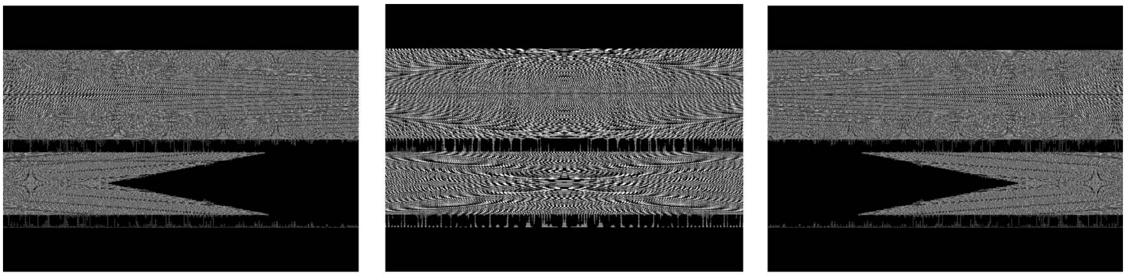
The anamorphic imaging system consisted of one spherical lens and three cylindrical lenses with their axes aligned horizontally, instead of two orthogonally aligned cylindrical lenses. The cylindrical lens 1 in Fig. 2 must be large in order to reduce the horizontal pixel size several times to obtain a small pixel pitch. Unfortunately, such a large cylindrical lens was not available. Therefore, instead of a cylindrical lens, a large spherical lens was used for the horizontal magnification. The horizontal magnification was $M_x = 0.183$. In the vertical direction, two $4f$ imaging systems were constructed by adding three cylindrical lenses to the spherical lens to obtain the vertical magnification. The vertical magnifications of the two $4f$ imaging systems were 1.67 and 3.00 so that the total vertical image magnification was $M_y = 5.00$. The horizontal pixel pitch was reduced to $2.50\,\mu\text{m}$ to increase the horizontal viewing zone angle to 14.5°. The size of the elementary hologram was 2.56 mm×52.5 mm. The quasi-coherent holography condition requires that a three-dimensional image be displayed within a distance of $0.339l$ from the screen.

A galvano mirror was used for the horizontal scan. In order to obtain a flicker-free reconstructed image, a complete hologram was constructed from 222 elementary holograms, and the horizontal scan frequency f_{scan} of the galvano mirror was set to 60.045 Hz. The hologram was displayed with both clockwise and counterclockwise rotating directions, and so the vibration frequency of the mirror was set to 30.023 Hz. The rotation angle of the mirror was ±5°, so that the horizontal scan angle of the elementary hologram was ±10°. The distance between the rotating mirror and the display screen was 200 mm. Therefore, the horizontal scan width was 70.6 mm, and the elementary holograms were displayed with a horizontal pitch of 0.32 mm on the display screen. There were substantial overlaps among the elementary holograms. The size of the complete hologram was 73.1 mm×52.5 mm. The size of the galvano mirror was determined to reflect the whole light bundle in the anamorphic imaging system.

Instead of a cylindrical lens 3 placed on the display screen shown in Fig. 2, a spherical lens was used, because a cylindrical lens whose size is larger than the complete hologram was not available. The focal length of the spherical lens was 200 mm, which was equal to the distance between the rotating mirror and the display screen. A lenticular sheet was used as a vertical diffuser.

Table 1. Specifications of the Proposed Holographic Display System[a]

Screen size	73.1 mm×52.5 mm (3.5 in.)
Horizontal viewing zone angle	14.6°
Frame rate	60.045 Hz
Dimensions of E.H.	2.56 mm×52.5 mm
Number of E.H.	222
Horizontal pitch of E.H.	0.32 mm



(a) (b) (c)

Fig. 4. Examples of elementary holograms: (a) 66th hologram, (b) 111th hologram, and (c) 156th hologram.

The laser was driven by a pulse signal that was synthesized from an image update signal from a DMD driver. The pulse width was $37.5\,\mu$s, which is half of the pulse period, in order to reduce the horizontal image blurring caused by the horizontal scan. The horizontal image blurring occurs because the image of the SLM does not change during a single frame time, whereas the image is scanned continuously. The horizontal image blurring width of the experimental system was 0.16 mm.

The conjugate image and the zeroth order diffraction light were removed using the single-sideband technique [8]. A horizontal edge was placed on the Fourier plane of one of the two vertical $4f$ imaging systems. Therefore, the vertical resolution of elementary holograms became half that of the SLM so that a reconstructed image consisted of 384 horizontal scan lines.

The specifications of the constructed hologram display system are listed in Table 1.

4. Experimental Results

The elementary hologram patterns were calculated as Fresnel holograms. The phase distribution of the lens on the screen was included in the hologram calculations. Some of elementary holograms with binary gray level are shown in Fig. 4.

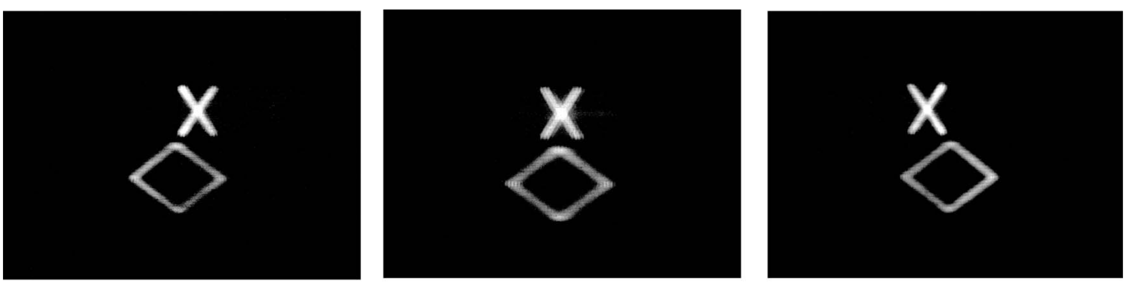
Photographs of the reconstructed image captured from different horizontal viewpoints are shown in Fig. 5. The circle and the cross, respectively, appeared at 100 mm and 150 mm in front of the screen. The measured viewing zone angle was 15°, and the measured screen size was 70 mm×52 mm (3.4 in.). The reconstructed image was visible to both eyes because the viewing zone angle was increased. The motion parallax was very smooth, and flicker was not observed. Additional examples of reconstructed images are shown in Fig. 6.

5. Discussion

The proposed system enabled the viewing zone angle to be increased to 15°. In addition, the viewing zone angle could be increased by further reducing the pixel pitch. In this case, a larger numerical aperture (N.A.) is required for the horizontal imaging system. A larger N.A. requires a larger galvano mirror. The diameter of the spherical lens 1 in the current experimental system is 145 mm in order to obtain N.A. ≥ 0.26.

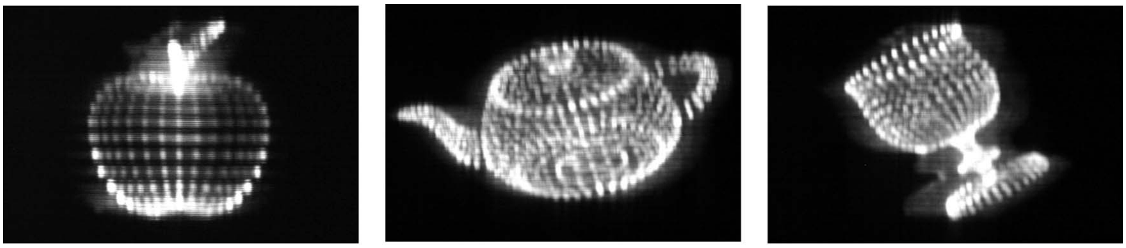
There are substantial overlaps among the elementary holograms in the experimental system, and it is possible to increase the screen size. Increasing the screen size can be achieved by increasing the scan width and the vertical magnification of the anamorphic imaging system. The screen size of the experimental system was determined while considering the mirror size of the galvano mirror and the size of the screen lens. The scan angle can easily be increased to over $\pm 10°$. In order to increase the screen size, increasing the size of the galvano mirror and increasing the size of the screen lens are also required.

In this experimental system, all spherical lenses and cylindrical lens are plano–convex lenses. Therefore, the lens aberrations might have deteriorated the reconstructed images, and distortion of the elementary images was observed. Since precise



(a) (b) (c)

Fig. 5. Reconstructed three-dimensional image captured from (a) the left, (b) the center, and (c) the right.



(a) (b) (c)

Fig. 6. Reconstructed three-dimensional images: (a) apple, (b) teapot, and (c) wine glass.

alignment of the scanning system was difficult, the distance between the mirror and the screen lens was not clearly determined. This distance is required in order to calculate the elementary holograms. The reconstructed image might be improved by improving the optical system.

The proposed technique is compared to the HPO hologram technique developed at MIT [1]. The MIT system generates each scan line by horizontal scanning, and the scan lines are aligned vertically by the vertical scanner. Therefore, the horizontal scanner must have a very high-speed scanning frequency. In contrast, the technique proposed in the present study generates all scan lines simultaneously. Therefore, the vertical scanner is not required, and the horizontal scan frequency can be decreased to as low as the video frame rate ($\sim$60 Hz). Since the size of the scanning mirror should be large in order to achieve sufficient demagnification of the pixel pitch in the horizontal direction, a low horizontal scanning frequency is preferable for rotating a large mirror. The high-speed SLM used in the proposed technique can modulate only binary amplitude. The AOM used in the MIT display can modulate a continuous amplitude. The image quality of the reconstructed image of the binary amplitude hologram is generally lower than that of the continuous amplitude hologram. A number of studies have investigated the design of binary-amplitude holograms, and the results of these studies will be used for the hologram calculation in our system. As described in Section 3, horizontal image blurring occurs in the proposed system because the modulation pattern of the DMD does not change during a single frame time, whereas the image is moved continuously in the horizontal direction by the horizontal scanner. The horizontal image blurring might be decreased by reducing the pulse width of the illumination light. The pulse width of the laser diode can easily be reduced to $<\mu$s while maintaining sufficient optical energy. The characteristics of the MIT system and the proposed system are given in Table 2.

Table 2. Characteristics of the MIT System and the Proposed System

	MIT System	Proposed System
Spatial scan	Horizontal and vertical	Horizontal
Light modulation device	AOM	DMD
Horizontal scan	High speed	Low speed (60 Hz)
Vertical scan	Low speed (30 Hz)	None
Gray level of hologram	Continuous	Binary
Illumination laser	Continuous wave	Pulse wave

6. Conclusions

We proposed a new technique that enables both the screen size and the viewing zone angle of a hologram to be increased. The proposed technique uses a high-speed SLM, an anamorphic imaging system, and a horizontal scanner. The image generated by the high-speed SLM is converted to an elementary hologram by the anamorphic imaging system, and the elementary hologram is scanned horizontally by the horizontal scanner.

We demonstrated the proposed holographic display system using a DMD and a galvano mirror. The horizontal pixel pitch was reduced to 2.5 μm to achieve a horizontal viewing zone angle of 15°. The screen size was increased to 70 mm×50 mm (3.4 inches). The frame rate was 60.045 Hz.

The experimental system shown in this paper is a preliminary demonstration system. The screen size and viewing zone angle can be increased by using larger lenses and a larger galvano mirror. The reconstructed image can be improved through the use of aberration-corrected lenses. Precise alignment of the optical system would also improve the reconstructed image.

References

1. P. St. Hilaire, S. A. Benton, M. Lucente, M. L. Jepsen, J. Kollin, H. Yoshikawa, and J. Underkoffler, "Electronic display system for computational holography," Proc. SPIE **1212**, 174–182 (1990).
2. M. Stanley, R. W. Bannister, C. D. Cameron, S. D. Coomber, I. G. Cresswell, J. R. Hughes, V. Hui, P. O. Jackson, K. A. Milham, R. J. Miller, D. A. Payne, J. Quarrel, D. C. Scattergood, A. P. Smith, M. A. G. Smith, D. L. Tipton, P. J. Watson, P. J. Webber, and C. W. Slinger, "100-megapixel computer-generated holographic images from Active Tiling: a dynamic and scalable electro-optic modulator system," Proc. SPIE **5005**, 247–258 (2003).
3. K. Maeno, N. Fukaya, O. Nishikawa, K. Sato, and T. Honda, "Electro-holographic display using 15 mega pixels LCD," Proc. SPIE **2652**, 15–23 (1996).

4. T. Mishina, F. Okano, and I. Yuyama, “Time-alternating method based on single-sideband holography with half-zone-plate processing for the enlargement of viewing zones,” Appl. Opt. **38**, 3703–3713 (1999).
5. T. Mishina, M. Okui, and F. Okano, “Viewing-zone enlargement method for sampled hologram that uses high-order diffraction,” Appl. Opt. **41**, 1489–1499 (2002).
6. Y. Takaki and Y. Hayashi, “Increased horizontal viewing zone angle of a hologram by resolution redistribution of a spatial light modulator,” Appl. Opt. **47**, D6–D11 (2008).
7. R. Haussler, A. Schwerdtner, and N. Leister, “Large holographic displays as an alternative to stereoscopic displays,” Proc. SPIE **6803**, 68030M (2008).
8. O. Bryngdahl and A. Lohmann, “Single-sideband holography,” J. Opt. Soc. Am. **58**, 620–624 (1968).