Viewing-angle enlargement in holographic augmented reality using time division and spatial tiling

Yuan-Zhi Liu,¹ Xiao-Ning Pang,¹ Shaoji Jiang,¹,² and Jian-Wen Dong¹,*

¹State Key Laboratory of Opto-electronic Materials and Technologies, Sun Yat-sen University, Guangzhou 510275, China
²stsj3@mail.sysu.edu.cn
*dongjwen@mail.sysu.edu.cn

Abstract: Viewing angle enlargement is essential for SLM-based 3D holographic display. An idea of constructing equivalent-curved-SLM-array (ECSA) is proposed by linear phase factor superimposition. Employing the time division and spatial tiling (TDST) techniques, an ECSA-based horizontal 4f optical system is designed and built. The horizontal viewing angle of a single SLM is increased to 3.6 times when retaining the same hologram area. An interlaced holographic display technique is developed to remove the flicker effect. Holographic augmented reality is performed using the TDST system. Floating holographic 3D image with parallax and accommodation effects is achieved. Both TDST and interlaced technique may extend to multiple SLMs system to achieve larger viewing angle.

©2013 Optical Society of America

#186911 - $15.00 USD Received 13 Mar 2013; revised 29 Apr 2013; accepted 2 May 2013; published 10 May 2013
(C) 2013 OSA 20 May 2013 | Vol. 21, No. 10 | DOI:10.1364/OE.21.012068 | OPTICS EXPRESS 12068
Viewing-angle enlargement in holographic augmented reality using time division and spatial tiling

Yuan-Zhi Liu,1 Xiao-Ning Pang,1 Shaoji Jiang,1,2 and Jian-Wen Dong1,*

1State Key Laboratory of Optoelectronic Materials and Technologies, Sun Yat-sen University, Guangzhou 510275, China
2stsjsj@mail.sysu.edu.cn
*dongjwen@mail.sysu.edu.cn

Abstract: Viewing angle enlargement is essential for SLM-based 3D holographic display. An idea of constructing equivalent-curved-SLM-array (ECSA) is proposed by linear phase factor superimposition. Employing the time division and spatial tiling (TDST) techniques, an ECSA-based horizontal 4f optical system is designed and built. The horizontal viewing angle of a single SLM is increased to 3.6 times when retaining the same hologram area. An interlaced holographic display technique is developed to remove the flicker effect. Holographic augmented reality is performed using the TDST system. Floating holographic 3D image with parallax and accommodation effects is achieved. Both TDST and interlaced technique may extend to multiple SLMs system to achieve larger viewing angle.

©2013 Optical Society of America

OCIS codes: (090.0090) Holography; (090.1760) Computer holography; (090.2870) Holographic display.

References and links
1. Introduction

Three-dimensional (3D) display has aroused increasing attention [1–4]. Viewing 3D objects floating in the real space without wearing stereoscopic glasses is the prospect of 3D display [5]. With the ability of producing the accurate depth cues for 3D objects that exist or never exist in the real world, computer-generated hologram (CGH) is a promising technique for true 3D display [6]. For the flexibility of controlling optical wave fronts, spatial light modulator (SLM) has been widely used in CGH display [7]. Recently, liquid crystal SLM becomes the most feasible device for dynamic holographic display because of the growth of display industry. Since Kinoform CGH has a high diffraction efficiency [8], phase-only SLM plays an important role in the SLM holographic display. Despite these advantages, one of the problems in commercial SLM is narrow viewing angle (VA), which limits the observing experience of SLM-based holographic display.

To increase the VA of SLM-based holographic display, several attempts have been performed. Mishina et al. used high-order diffraction to enlarge the viewing zone [9]. Ohmura et al. [10] and Chen et al. [11] placed mirror pairs to tile the sub-holograms into a spatial plane by using spatial segmentation of SLM and oblique incident light scanning, respectively. Yaraş et al. proposed a multi-SLM display system with planar configuration [12]. Slinger et al. employed a high speed electrically addressed SLM to drive optically addressed SLMs to tile a big planar hologram [13]. Takaki et al. adopted cylindrical lens to suppress the horizontal pixel pitch and to amplify the vertical pitch of the SLM. A galvano scanner was used for horizontal scanning to increase the hologram size [14]. Takaki et al. also proposed a resolution redistribution system to transfer the pixels of vertical direction to the horizontal direction [15]. Besides the planar display, recently researchers found that a curved configuration can further enlarge the VA. Hahn et al. arranged 12 SLMs as a curved array and divided the vertical information of each SLM into three parts in the horizontal direction. They tiled 36 sub-holograms in different angle and achieved 22.8° VA [16]. Yaraş et al. employed 9 phase-only SLMs and a beam-splitter to obtain 24° VA without any gap [17]. Kozacki et al. proposed a circular configuration with 6 tilted SLMs to extend the VA [18, 19].

In this paper, we propose an idea of equivalent-curved-SLM-array (ECSA) by superimposing linear phase factor. By utilizing ECSA method and 4f cylindrical lens system, the horizontal VA of a SLM can increase 3.6 times to the case without the ECSA method, while the hologram area maintains the same. An optical system has been designed and built to realize ECSA by time division and spatial tiling (TDST) techniques. Interlaced holographic
display technique is developed to remove the flicker effect. Augmented reality effect of floating holographic 3D image is obtained.

2. Equivalent curved SLM array (ECSA)

The viewing angle of a single SLM $\theta$ is defined by the maximum diffraction angle $\theta_{\text{diff_max}}$ when light illuminates the SLM normally [Fig. 1(a)], yielding

$$\theta = 2\theta_{\text{diff_max}} = 2\arcsin\left(\frac{\lambda}{2p}\right), \quad (1)$$

where $\lambda$ is the wavelength of the incident light, and $p$ is the pixel pitch of the SLM. The typical pixel pitch of commercial SLM is several microns, e.g. 8 microns for Holoeye phase-only SLM (Pluto). If a 532nm green light is used to illuminate the SLM with 8 microns pixel pitch, the VA is only 3.8°, which limits the range of observation. For a fixed wavelength, larger VA requires smaller pixel pitch, which depends on the SLM development. Multi-SLM can increase the display information; however, the planar configuration of SLM array cannot enlarge the VA because the maximum bandwidth depends on the pixel size only [18].

Curved SLM array has been demonstrated to be capable of enlarging the VA [14–16]. If there are $N$ SLMs to construct a circular array and they are tilted by $\alpha (< \theta)$ to each other, the total VA can be increased to

$$\theta + (N - 1)\alpha, \quad (2)$$

which indicates that the total VA is affected by the intrinsic diffraction angle ($\theta$), the amount of SLM ($N$), and the tilling angle ($\alpha$). However, maintaining normal illumination of each SLM requires accurate curved configurations of SLMs and light beams. This increases the difficulty of system construction. Actually, the essence of curved SLM array is to make the emergent light from each SLM slant to each other. If the SLMs are configured in the same plane but the diffractions are directed in an inclined way [Fig. 1(c)], the enlarging VA effect is equivalent to the curved SLM array [Fig. 1(b)]. Hence, we call it equivalent-curved-SLM-array (ECSA).

To simplify the explanation of the idea, oblique illumination of a one-dimensional grating is considered, as shown in Fig. 2. According to the grating equation, we have

$$\lambda/2p = \sin\theta_{\text{out}} - \sin\theta_{\text{in}}, \quad (3)$$

Fig. 1. Viewing angle of (a) single SLM, (b) curved SLM array, and (c) equivalent curved SLM array.

Fig. 2. Grating diffraction with inclined illumination.
where $\lambda$ is the wavelength, $2p$ is the grating period. $\theta_i$ and $\theta_o$ are the incident and outgoing angle. For the practical case, e.g. $\lambda = 532$ nm, $2p = 16 \mu$m, the small angle approximation (e.g. $\theta_i < 10^\circ$) is satisfied. So $\sin \theta = \theta$ and $\lambda/2p = \theta_{\text{diff,max}}$, which is the same as the diffraction angle for normal illumination [see Eq. (1)]. As a result, the viewing angles of SLM in both cases are the same. However, the image location for inclined illumination will have an additional rotating angle $\theta_i$, and it is equivalent to rotate the SLM in the angle of $\theta_i$. In fact, the inclined illumination is equivalent to add a $\theta_i$ phase on the SLM surface. So if we can impose a suitable phase factor on the SLM (no matter using the optical or digital method), it can achieve the same VA enlargement effect as the curved SLM array, but will be more convenient for experimental construction because of the releasing of accurate curved array configuration in space. It is worth to note that, even if $\theta_i$ is larger than $10^\circ$ (using more SLMs), other suitable phase factor can be added on each SLM to achieve the ECSA as it can be acquired by Eq. (3).

3. Time division and spatial tiling (TDST) system

Based on the ECSA method, we designed an optoelectronic system to enlarge the VA (Fig. 3). First of all, a 4f optical system is used to decrease the pixel pitch of the SLM in the output image plane. Because human eyes are more sensitive to the horizontal parallax than the vertical parallax, we adopted two cylindrical lenses, whose horizontal focal length ratio is $f_1:f_2 = 2:1$ ($f_1 = 300$ mm, $f_2 = 150$ mm) to form such 4f optical system [Fig. 4(a)]. The SLM (Holoeye Pluto, phase-only SLM) is positioned at the front-focal-plane of the first cylindrical lens, so the image of the SLM is compressed to half of its original size in the horizontal direction at the back-focal-plane of the second cylindrical lens, which is denoted as “4f plane” in Fig. 4. As the image at the 4f plane is decreased to half of the original SLM, the pixel pitch is decreased to half as well. Therefore, we can deduct that the horizontal VA increases to twice, which becomes 7.6\(^\circ\). Meanwhile, the cylindrical lenses do not modulate the diffraction in the vertical direction, so the vertical direction of the image is not compressed.

Secondly, TDST technique is developed to compensate the reduced visual area in horizontal direction and construct an equivalent curved array to further enlarge the total VA as well. A 532nm laser is expanded and collimated to normally illuminate the phase-only SLM through a beam splitter cube. At two different moments, we add different phase factors on the phase-only SLM to make the diffraction spatially separate, which are denoted as the two colors- orange and purple in Fig. 4. Two groups of lens pairs in different layer [Fig. 4(b)] are configured to achieve space tiling. At $t_1$ moment, we add a downward phase factor to make the diffraction of SLM deflect onto the mirror-below, and then reflected by the right-mirror to form the image of SLM in the 4f plane (orange optical path). At $t_2$ moment, the diffraction is deflected to the mirror-above due to the upward phase factor on the SLM and then reflected by the left-mirror (purple optical path). The two optical paths of different moments are tiled in the horizontal direction [green arrow in Fig. 4(a)]. For each moment (orange or purple), the image of SLM at the 4f plane is decreased to half in the horizontal direction, so the final visual area is the same as the area before tiling. With the precise adjustment of the mirrors, the angle between each output optical path of different moments at the 4f plane is 6\(^\circ\) ($= 3^\circ + 3^\circ$). This means we use both the digital and optical methods to impose linear phase factors on the compressed SLMs at the 4f plane and form an ECSA in the horizontal direction.
In our previous work, we treated a 3D scene as a combination of triangular patches and have developed a full analytical method for the high-speed CGH computation of triangle-based 3D objects [6, 20]. The cylindrical lens pair in the TDST system, however, will introduce deform reconstruction in the x and y directions if directly applying the previous method. This is because the phase of the propagating field experiences different optical paths in the x and y directions: (1) In the x direction, the phase is the same after the horizontal 4f system and only coordinate scaling ($f_2/f_1$) occurs; (2) In the y direction, there is an additional optical path. Fortunately, our analytical method can deal with the wave propagation in x and y direction independently. Hence, it is straightforward to modify the formula from $cz$ to $cz + f_2/f_1$ in y direction:

$$O_{ij}'(x_1', y_1', z') = \begin{cases} \exp \left[ j \pi \left( \frac{z_1 + z_2}{\lambda} \right) \right] \left( a_{12}a_{11} - a_{12}a_{21} \right) \\ \times \exp \left[ -j \pi \left( \frac{(x_2, f_2)/f_1 - x_1, y_2, z_2}{z_2} \right) + \left( \frac{(y_2 - y_1)^2}{z_2 + 2f_1 + 2f_2} \right) \right] \exp \left[ -j 2 \pi \frac{a_{11}x_1' + a_{12}y_1'}{\lambda z_2} \right] \end{cases}$$

where $a_{ij} = (x_i^i - x_i^j)/20, a_{12} = (2x_1^i - x_1^j - x_1^i)/20, a_{13} = (2x_1^j + x_1^j + x_1^j)/4, a_{21} = (y_1^i - y_1^j)/20, a_{22} = (2y_1^j - y_1^j - y_1^j)/20, a_{23} = (2y_1^j + y_1^j + y_1^j)/4$, $(x_i^j', y_i^j', 0), i=1,2,3$, are the vertices of the triangle in the local coordinate. $r_i = r_i(f_2x_i^j/f_1 - x_i^j) + r_{ij}(y_i^j - y_i^j)/20, r_{ij} = r_{ij}/(f_2x_i^j/f_1 - x_i^j) + r_{ij}(y_i^j - y_i^j)/20, (y_i^j - y_i^j)z_i/(z_i^j + 2f_1 + 2f_2) - r_{ij}z_i - r_{ij}z_i$, and $(x_0^j, y_0^j, 0)$ is the coordinate of the hologram. $r_{ij}' (i, j = 1, 2, 3)$ are the elements of rotation matrix related to the local and global coordinate. $(x_0^j, y_0^j, z_0^j)$ is the object’s centroid in the global coordinate. More detail expressions can be found in our previous paper [6, 20].
In order to test the reliability of the 4f optical system (Fig. 4), we use a threadlike object in the reconstruction. The object is 64.4 mm away from the 4f plane [green solid point in Fig. 5(a)]. In experiment, a camera (Nikon D7000) is used to directly capture the threadlike image, and the angle difference effect is strong to be observed. The image illusively locates near the left (right) boundary of the cylindrical lens when we observe from the right-most (left-most) viewing angle, as illustrated in Fig. 5(b) [Fig. 5(d)]. The green rectangular in figures indicates the lens. We emphasize that the image can be seen continuously when moving the camera laterally. The measured distance between the camera and the image to be about 65 cm, and the moving distance of the camera is 15.4 cm. Hence, the measured VA is about 13.5°. In principle, one can calculate from Eq. (2), that the total horizontal VA is enlarged to 7.6° + 6° = 13.6°. Both experimental and numerical results are consistent with each other. Therefore, we achieve a 3.6 times VA enlargement to the original angle (~3.8°) by employing a single phase SLM while maintain the same visual area and vertical resolution.

As the maximum frame rate of the Pluto is 60Hz, if we directly display two holograms in two individual temporal channels, each channel only has a 30Hz frame rate-30Hz bright-dark changes in each channel. Visible flicker will occur because only more than 40Hz brightness changes can be acceptable for eyes. To solve the flicker problem and get a better observation experience, we developed an interlaced holographic display technique, as indicated in Fig. 6. The original holograms in the two temporal channels (H1 and H2) are divided into four segments (H1_1, H1_2, H1_3, and H1_4; H2_1, H2_2, H2_3, H2_4) and then recombined to form the new holograms (H1’ and H2’) displayed on the SLM for each temporal channel. Hence, at each moment the SLM displays partial holograms for both two viewpoints. Note that unlike the interlaced techniques in the usual stereoscopic display, the unique diffraction property of holography enables each segment of the original holograms (e.g. H1_1 in Fig. 6) to reconstruct the whole 3D object in space. As we divide each hologram in the vertical direction, each moment the partial holograms (for example, H1_1, H1_3 and H2_2, H2_4 at the t1 moment) can still form the ECSA horizontally. Therefore, the flicker effect can be effectively removed.

---

Fig. 5. Viewing angle enlargement based on TDST system. (a) Schematic of the threadlike object (green dot). Reconstructed image is captured by the camera moving laterally. The images captured in the right-most, middle, and left-most viewpoints are shown in (b), (c), and (d), respectively.

Fig. 6. Schematic diagram of interlaced holographic display.
4. Experimental results of augmented reality

Our designed system is expected to provide a larger VA and more convenient observation than the original SLM. To further show the glamour of our system, we combine the holographic reconstruction and the real existed objects for augmented reality, which has become an actively researched field in the recent years [21]. We encode a computer generated 3D object (a pyramid with two Chinese characters on two surfaces) into hologram by the modified analytical method mentioned above, and then use the TDST system to reconstruct it in space. A LEGO® toy is used for the augmented reality. The camera is translated in different positions to capture the different perspective, as shown in Fig. 7(a). In the augmented reality scene, the toy is located close to the holographic-constructed pyramid and “would like to catch” the pyramid. The holographic pyramid is floating in space, and has a vivid effect as the real object. In order to demonstrate the parallax effect, we observe the augmented reality scene from left to right viewpoint. In the left viewpoint [Fig. 7(b)], the left surface of the pyramid is a little larger than the right surface. In the center viewpoint [Fig. 7(c)], both the two surfaces have a similar size. In the right viewpoint [Fig. 7(d)], the right surface becomes larger than the left surface. These results indicate we can indeed observe the holographic reconstruction in different viewpoints thanks to the VA enlargement by using our TDST system.

![Fig. 7. Reconstruction captured from different viewpoints. (a) Schematic of the reconstructed setup. (b)-(d) three different viewpoints of the camera, which is the left-most, middle, and the right-most angle. Note that two surfaces of the pyramid are of different size in three viewpoints, showing the parallax effect in the holographic scene. A more intuitive feeling can be found in the online multimedia (Media 1).](image)

To further show the floating effect in the space, we use the camera to focus on the pyramid, and locate the real toy in different depth, as shown in Fig. 8. Moving the toy from the back to the front, it becomes from defocus blur to clear and to blur again, while the pyramid is always clear. This augmented reality scene shows that the holographic reconstruction is floating in the space and the toy “would like to catch” it from the back to the front.
Unlike the usual stereoscopic 3D display and head-mounted projection-type display [22], holographic 3D display can reconstruct 3D objects at different depth position at the same time, and thus it can provide the correct monocular accommodation effect [3]. In Fig. 8, we construct such a scene that a boy catching the rear “Mars” triangle and the girl catching the front “Venus” triangle. When the camera focus on the rear triangle [Fig. 9(b)], the boy and the “Mars” triangle is clear, while the girl and the “Venus” triangle becomes defocus blur, and vice versa [Fig. 9(c)].

5. Conclusion

In this paper, equivalent-curved-SLM-array is proposed to enlarge the viewing angle of holographic display system. The superimposing of linear phase factor can release the requirement of configuring the SLMs in a curved array in space, and can increase the degrees of freedom for system construction. Based on the cylindrical 4f optical setup, and the time division and spatial tiling system, we achieve a viewing angle as 13.6° by using only a single SLM. The viewing angle is increased to 3.6 times than the origin while retaining the same hologram area. Augmented reality is carried out, which shows the floating effect of the holographic reconstruction. Both parallax and accommodation effects can also be realized by the proposed system. Interlaced holographic display technique is developed to remove the flick effect, which should also benefit other holographic display systems employing time
division method. Because we only use a single SLM here and the TDST system is capable of 
assembling more together, larger viewing angle can be further achieved by utilizing more 
SLMs.

**Acknowledgments**

The authors would like to express the highest respect to Professor He-Zhou Wang. This work 
is supported by National Natural Science Foundation of China (61235002, 11274396, 
11074311), the Fundamental Research Funds for the Central Universities 
(2012300003162498), the Guangdong Natural Science Foundation (S2012010010537), and 
the Open Research Fund of State Key Laboratory of Optoelectronic Materials and 
Technologies. Yuan-Zhi Liu is currently in University of Illinois at Urbana-Champaign. His 
email is lyzhab@gmail.com.