See-through and Near-eye Display Based on Computer Generated Holograms with Holographic Waveguide Combiner

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ABSTRACT

We review our recent research results on near-eye computer generated hologram (CGH) display systems based on holographic waveguide combiners. Usually, the holographic waveguide combiner induces astigmatism even with a pair of symmetry holographic optical elements (HOEs) for light in-coupling and out-coupling. A new CGH algorithm has been successfully proposed to correct the induced aberration. The field of view (FOV) of CGH is also usually limited by the finite pixel size of spatial light modulator (SLM). By manipulating the diffraction wavefront of the out-coupling HOE on the holographic waveguide combiner, the FOV of CGH can be expanded.

1 Introduction

In recent years, holographic waveguide combiner has received increasing attention owing to their potential in compact configuration for see-through and near-eye AR displays [1-4]. The information light was guided into a thin planar waveguide via an in-coupling HOE and then is extracted from the waveguide via an out-coupling HOE. The image information diffracted from the out-coupling finally is directed into the human eye. Accordingly, the see-through function is achieved via the holographic waveguide combiner.

CGH is also a promising technique for near-eye AR display. These CGHs are displayed on the SLM to offer holographic images. The holographic image can be reconstructed successfully by using a coherence reading beam to probe the CGHs on SLM. The dynamic holographic displays were generated by displaying the different CGHs on SLM sequentially. One disadvantage of the CGH technique is that the SLMs are difficult to achieve a large display area. Accordingly, the CGH technique is suitable to incorporate with near-eye AR displays owing to the inherent reduced eye relief for near-eye display system. Therefore, several studies combining holographic waveguide element and CGH techniques were proposed recently [4-8].

The disadvantage of the holographic waveguide element is that the final diffraction image locating at the finite distance will become blurred because the effect of astigmatism aberration. In addition, the FOV of CGH is limited by the SLM pixel size and therefore FOV is not large enough. In our study, a new iteration CGH algorithm designed for holographic waveguide elements was proposed to suppress astigmatism aberration [4]. The astigmatism was analyzed by ray-tracing and compensated by using the modified convolution Fresnel diffraction method. And we also find an effective way to extend the FOV of CGH images in holographic waveguide display system [5-6]. With the wavefront modulation of the diffraction beam from the out-coupling HOE on the waveguide, a holographic image with larger dimension and larger FOV than the theoretical limitation can be obtained. In section 2 and section 3 of this manuscript, we review our recent research results on astigmatism correction [4] and FOV expanding [5-6] in waveguide-based holographic display system.

2 CGH Algorithm with Astigmatism Correction

A see-through waveguide device as shown as Fig. 1 was utilized to provide holographic images [4]. The phase-only SLM and the convergence probe beam were employed to provide the holographic information. The glass waveguide with a pair of symmetry HOEs was used to guide the information to the human eye. The thickness of the waveguide is 8mm and the refractive index is 1.52. The HOEs were recorded by two collimated beams. The distance between HOE1 and HOE2 is about 3cm. When the convergence beam probed the SLM, the reconstructed information and the DC noise would be coupled into the waveguide by HOE1 simultaneously. Then the information light and the DC noise would both be coupled out from the waveguide by HOE2. However, the DC noise could be blocked easily because it almost focused on the barrier plane. Then the observer could obtain clear information without DC noise. In our designed, the virtual image will locate behind the waveguide combiner with a distance of 50 cm.

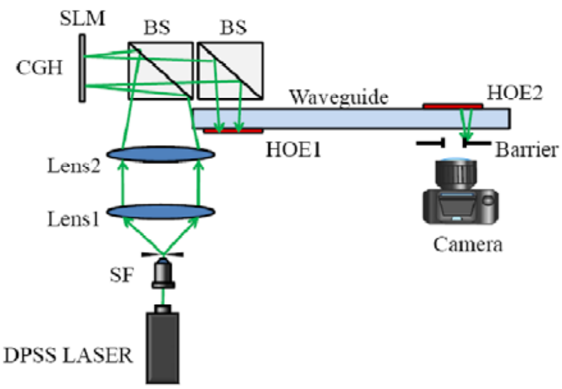
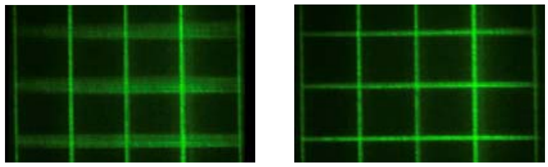


Fig. 1 The see-through AR system composed of a CGH system and a holographic waveguide combiner.

According to the previous studies, the linear grating will cause different propagating distance in the x-z plane and y-z plane, and it leads astigmatism aberration in the system. Accordingly, the human eye could obtain the astigmatism-free image if the CGH source offers an image with inverse-astigmatism aberration, which can be provided by the SLM.

Fig. 2 shows the final CGH images observed from the holographic waveguide display system. The original diffraction image is blurred because astigmatism aberration. With the proposed CGH algorithm, a clear image is obtained as shown in Fig.2 (b).



(a) (b)

Fig. 2 The diffraction image (a) without astigmatism correction; (b) with astigmatism correction algorithm.

The designed CGH algorithm is described in the following. The light field propagating from hologram plane to image plane through an astigmatism space can be described as

$$u_i(x, y) = u_h(x, y) \otimes \exp\left[\frac{i\pi}{\lambda}\left(\frac{x^2}{d_{x-z}} + \frac{y^2}{d_{y-z}}\right)\right]. \qquad (1)$$

On the opposite, the light field inverse Fresnel propagating from image plane to hologram plane can be described as

$$u_h(x, y) = u_i(x, y) \otimes \exp\left[\frac{-i\pi}{\lambda}\left(\frac{x^2}{d_{x-z}} + \frac{y^2}{d_{y-z}}\right)\right]. \qquad (2)$$

$u_i(x, y)$ and $u_h(x, y)$ denote the light field at the image plane and hologram plane separately. The distances of the intermediate imaging points in the x-z plane and the y-z plane were denoted as $d_{x-z}$and d_{y-z}. The proposed method also employed the iteration ping-pong algorithm to enhance image quality.

Fig. 3 shows effect of the ping-pong iteration process. Fig. 3 (a) is a blurred image with astigmatism induced by the waveguide device. Fig. 3 (b) shows the resulting image with astigmatism correction algorithm with only one iteration. Fig. 3 (c) shows the resulting image with astigmatism correction algorithm with 20 iterations. The uniformity and image quality were enhanced with the iteration process.

(a) (b) (c)

Fig.3 The diffraction images of the CGHs (a) without correction; (b) with astigmatism correction and 1 iteration; (c) with astigmatism correction and 20 iterations.

3 Expanded FOV of CGH image

Fig. 4 shows the CGH display system with Expanded FOV based on holographic waveguide combiner [5-6]. The information light in the structure was coupled into waveguide via a wedge surface and coupled out via a HOE. The interference fringes recorded on the out-coupling HOE is generated by a convergent spherical waves and a collimation wave.

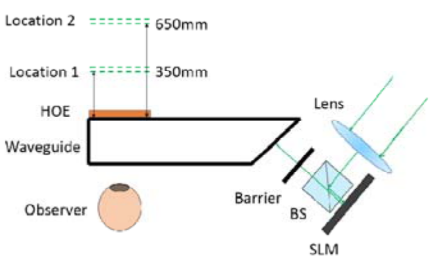


Fig. 4 Holographic waveguide display system with extended FOV of CGH image.

Fig. 5 shows the recording system of the holographic waveguide combiner. In this system, astigmatism is still a main aberration to degrade the image quality. Fortunately, using the similar principle described in section 2, we can suppress the astigmatism by adding an inverse astigmatism phase on the CGH algorithm [8].

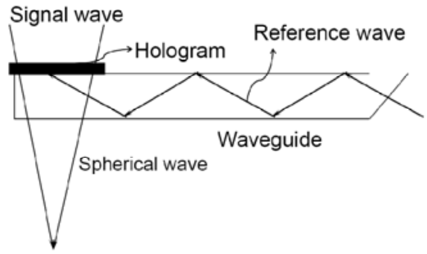
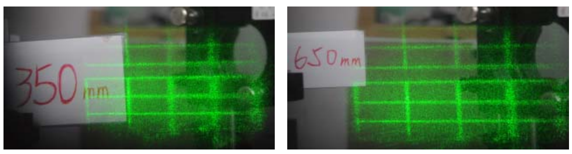


Fig. 5 The recording system for generating the holographic waveguide combiner.

As shown in Fig.4, the CGH display system is probed with a convergent readout beam instead of a collimation beam for the image reconstruction. The CGHs are designed to display two 2D patterns at different distance respectively. One is designed to locate at 350mmm behind the waveguide combiner, and the other is designed to locate at 650mm behind the waveguide combiner. The diffraction results are shown in Fig. 6. The images are captured by using a camera to focus on 350mm and 650mm behind the combiner, respectively. In addition, from our observations of the diffracted images, we can find the depth of field of this display system is quite long. And therefore no matter what the focus plane is used for the camera, both images at different planes can be observed clearly. The advantage of the long depth of field in this system is that we do not need to calibrate the image distance precisely when designing a CGH for displaying of 3D images.



(a) (b)

Fig. 6 Diffraction images of CGHs when the camera focus at (a) 350mmm and (b) at 650mm behind the waveguide combiner.

The FOV of the CGH image in this system can be decided by Eq. (3), where d represents the distance from the observer to the final image, and w represents the dimension of the final image.

$$\theta = 2 \times \tan^{-1} \frac{w/2}{d}. \quad (3)$$

Based on Eq. (3), the FOV of the image is 17.94° horizontally and 8.26° vertically. The theoretical FOV is 4.76° when pixel size is 6.4 μm and λ is 532 nm. The FOV is successfully expanded by using the technique.

4 Conclusions

In this manuscript, we review two different holographic projection systems based on the holographic waveguide combiner. In a near-eye holographic display system with waveguide combiner, the astigmatism performance induced by waveguide element is investigated. The aberration reduction technique is also presented. The correction mechanism is embedded into the CGH algorithm to suppress astigmatism. And with the ping-pong iteration process, the image quality of CGH can be enhanced. In addition, with proper arrangement of diffraction wavfront from the out-coupling HOE, a CGH image with larger FOV than the theoretical FOV limited by the SLM can be obtained.

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