Eholo glass: Electroholography glass. A lensless approach to holographic augmented reality near-eye display

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ABSTRACT

We present a design and rendering method for large eye-box, fully parallax, depth of field included near-eye augmented reality (AR) display. As developments in AR progress, field of view and sense of depth are one of the most crucial factors for rendering convincing virtual objects into real environments. We propose computer generated holography (CGH) that is able to reconstruct image with real world depth of field faithfully as rendering method. Previous studies have proposed various near-eye optic design such as the use of beamsplitter and Holographic Optical Element with 4f lens system. However pure beamsplitter design suffers from the narrow field of view while 4f lens system has lens aberration as well as minimal focusing issues that leads to smaller eyebox. Having a wide field of view that matches our eyes is crucial for having an immersive experience and often narrow field of view may even leads to nausea and negative impacts on comfortability. We propose a design that utilizes a Dihedral Corner Reflector Array and a novel beamsplitter embedded optics as our eyepiece. Our primary contribution is having a reasonably large eyebox while maintaining the simple optical design as well as rendering of virtual objects with depth of field in real time without any special optics or moving parts.

CCS CONCEPTS

• Computing methodologies → Real-time simulation; **• Hardware → Emerging optical and photonic technologies**;

KEYWORDS

computer generated holography, light and compact form factor optical design, augmented reality

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1 INTRODUCTION

AR has been a very competitive topic over the last decade and are deployed in smartphones, automobiles and wearables such as head-mounted display (HMD). In recent years, new computing and display technologies have developed rapidly and have enabled AR applications on wearable devices especially on HMD. However, such application faces a number of challenges e.g., small eyebox and unconvincing virtual objects due to lack of depth of field [Singh et al. 2017]. Having a large eyebox that matches our eyes is crucial for having an immersive experience. Eyebox is mainly restricted by the light path from the source and could be increased by the use of lens or special developed metamaterial glass [Otao et al. 2018]. Various methods are proposed to increase the size of eyebox which we will elaborate in the related work section. Another main factor is the lack of depth of field in objects displayed. This is essential to blend virtual objects in reality as natural as possible. The most straightforward way to implement natural depth of field can be lens integration which works like a camera lens or deformable membrane [Dunn et al. 2017] with eye-tracker. Depth of field can also be synthesized by modulating light with spatial light modulator (SLM) using algorithm. In this paper, we propose the implementation of CGH. CGH is a simulated recording of phase and amplitude of an object wave that is able to reconstruct 3D informations faithfully when illuminated appropriately. In this way, real time adjustable depth of field can be rendered without special optics or lenses. Furthermore, multiple holograms of different depths can be reconstructed into foreground and background objects simultaneously, giving users the freedom to focus on objects they wish to interact without eye-tracker. While light field technology is widely used in AR HMD, CGH-based AR HMD is still a relatively unexplored implementation. This is due to its high computational cost and narrow field of view of 10-30°as reported in CGH related researches [Aoshima et al. 2015]. Our primary contributions in this paper are as follows.

(1) Enlarge eye box by reducing the distance between eye to SLM.
(2) Compact and simple optics design with the implementation of Dihedral Corner Reflector Array (DCRA).
(3) Proposal of a non-waveguide beamsplitter embedded glass eyepiece for see-through rendering.

We built the prototype and discuss its viability as an augmented reality near-eye display. We are able to render 3840×2160 resolution CGH of different depths in real time at 30 Hz.

2 RELATED WORKS

Our proposed method is related to a number of display and holography studies which we will be discussing below.

Several recent near-eye displays combine a holographic projector with various see-through eyepieces: holographic optical elements [Li et al. 2016], waveguides [Yeom et al. 2015], and lenses with beamsplitters [Chen and Chu 2015; Gao et al. 2016; Moon et al. 2014]. These augmented reality displays share some similar characteristics to our display but instead of employing a holographic projector and demonstrate variable focus, we used DCRA and unlike the [Yeom et al. 2015] display we do not need to use holographic correction to fix optical aberrations. We achieved real-time rendering of CGH, with significantly wider fields of view on a simple optical design.

2.1 Near-eye holographic display

This sentence explains about NVIDIA light field-CGH hybrid [Liu et al. 2018; Zeng et al. 2017]. This light field and CGH combination is a very interesting approach as it addresses several major issues in AR applications. Liu employed the image-layer based CGH instead of point source based CGH to achieve a shaded reconstructed image. While this method does not have to deal with occlusion, it heavily relies on the number of layers to have a continuous sense of depth of field as opposed to a dense point-source based CGH. Since the parallax effect of CGH depends on the pixel pitch of the SLM, current SLMs have too large pixel pitch to have a significant parallax effect when viewed. Liu utilizes the light field techniques which divides the image into series of overlapped image patches to achieve both parallax effect and wide field of view. CGH has a high potential for near-eye displays [Maimone et al. 2017] as it provides numerically accurate light rays. Furthermore, it has the potential to solve the accommodation convergence conflict. However, the technique has a high computational cost. In this study, we tackle this problem by developing a GPU-accelerated algorithm for CGH calculation which is 83 times faster than CPU [Araki et al. 2015].

3 SYSTEM OVERVIEW

3.1 Computer-generated hologram

In this study, we implemented the CGH based on in-line hologram in our system. Briefly, in-line hologram is the original hologram that Dennis Gabor proposed in the 1940s where the point source and plane wave are in-line during the process of recording the Fresnel diffraction pattern, also known as Fresnel Zone Plate, onto a photosensitive film. The image is reconstructed faithfully through a reverse process when a hologram is illuminated with a plane wave and by diffraction the resulting field can be observed at the same Fresnel distance away. Here, in-line hologram is computed digitally using a streamlined GPU-accelerated algorithm. In our simulation, each vertex of the 3D object is treated as one self-illuminate object point in the hologram calculation. The formula of the CGH can be expressed as follows:

$$I(x,y) = \sum_{j}^{N} A\cos\left[\frac{\pi(x^2+y^2)}{\lambda R}\right] \tag{1}$$

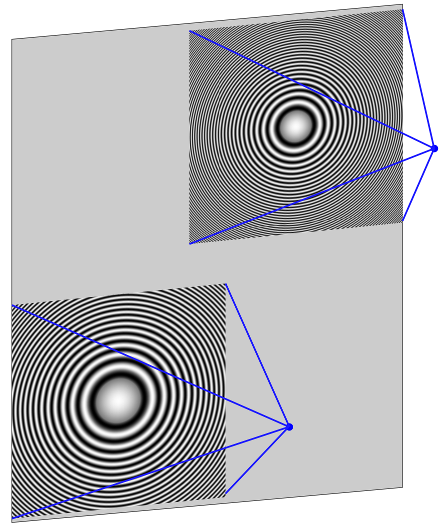

Figure 1: Adjustable focal distance of CGH which contains a phase-altering function that causes light to refract inward much like a refractive lens

where, $I(x_h, y_h)$ is the light intensity on the CGH, (x_h, y_h) and (x_j, y_j, z_j) are the coordinates for the CGH and the 3D object, A_j is the amplitude of the 3D object, λ is the wavelength of the reference light, and $P_j = \pi p^2/(\lambda z_j)$, where p is the sampling interval on the CGH plane. The complexity of the algorithm is $O(NHW)$, where N is the total number of object points, H is the height and W is the width of the hologram. Figure 1 shows the result of a single point object, a sinusoidal zone plate with p as radius that diffracts light in such a way that it is focused to a point. By calculation we can designate the focus distance of the point as shown in Figure 1. The simulation result is displayed on a Liquid Crystal on Silicon (LCoS) SLM where the CGH will be reconstructed.

3.2 4F image reconstruction system vs our system

By arranging 2 consecutive Fourier lens, a 4f image reconstruction system can be obtained. In conventional CGH reconstruction method, this system is used to gain access to Fourier plane that can be utilized to remove zero order light by placing additional filter such as a grating filter [Takaki and Tanemoto 2009]. However, the implementation of 4f system can add to the bulkiness in an AR HMD. In our proposed system, we eliminate the 4f system completely to closen the gap between user's eye and hologram plane. By decreasing the distance of the eye and SLM, we can increase the size of eyebox of the system. The size of eyebox is measured by the horizontal end to end visible area of the CGH. Furthermore, to compensate the absence of Fourier plane filter, the effect of zero order light in our system is mitigated by offsetting the CGH in Y-axis.

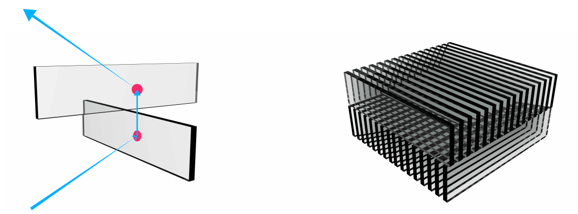

Figure 2: (Left) Reflection path of micromirror in DCRA (Right) Arrangement of micromirror structure of DCRA

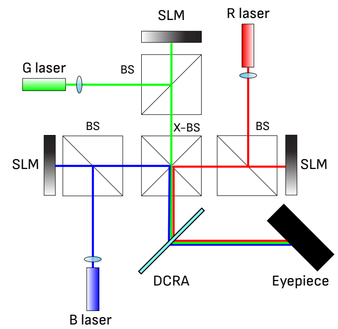

Figure 3: Proposed system with RGB lasers, 3 reflective phase-only LCoS SLMs, the CGHs are combined spatially and reflected by DCRA

3.3 Dihedral Corner Reflector Array

A DCRA consists of micro-mirrors and multiple corner reflectors layered perpendicularly as shown in Figure. Unlike mirrors, DCRAs form real images with retroreflection from the reflected rays of an object but with reverse Z distance. Otao proposed a near-eye see-through light field display using a micro-lens array and a DCRA [Otao et al. 2017]. Both of the previous studies used DCRA directly as an eyepiece. By introducing DCRA in our system, we can eliminate the usage of lenses and thus free from the lens focal length limitation to achieve a simple and compact optical system. Therefore we are able to install the eyepiece very close to the eyes, effectively increase the field of view. The figure 2 shows the reflection path inside the structure and the arrangement of micromirrors in DCRA.

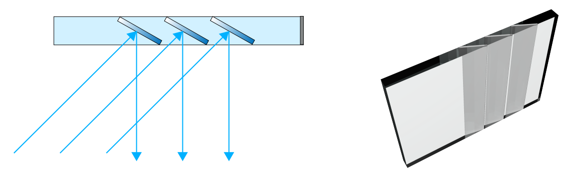

Figure 4: (Left) Reflection path of SASHIMI (Right) Overview of SASHIMI

4 IMPLEMENTATION

4.1 Hardware

We built our prototype display on optical bench as shown in Figure 5. We use laser diodes of 642 nm, 516 nm, 418 nm wavelength as light source. We use Thorlab's exulus LCoS phase-only SLM with a resolution of 3840×2160 and 3.74 μm pixel pitch. The SLMs are connected via a HDMI cable to the PC equipped with Intel i7 5930k processor, Nvidia GTX 1080Ti GPU, and operating on Ubuntu 14.04. Due to the hardware limitations of the SLM used, full color is achieved by using 3 SLMs as shown in Figure 3. The reconstructed images of each SLM are combined spatially via 3 beamsplitters. Here we place a 5 cm $\times$ 5 cm, 0.30 mm mirror pitch DCRA at the output of the system. For eyepiece, we propose a glass with multiple embedded beamsplitters, which we regard as SASHIMI, to be implemented for see-through realization. The beamsplitters are tilted 45° in the glass and allow direct viewing of CGH reflected from DCRA as shown in Figure 4.

Figure 5: Optical setup of eyepiece prototype with key components in red bordered box

4.2 Rendering Method

The computations of the hologram pattern are performed on CUDA 8.0 platform written in C language. The numerical results are then rendered on SLM with OpenGL. We used 3 SLMs to display each Red, Green, Blue wavelength CGH respectively. The CGH is set to focus to 150 mm, 270 mm. We offset the convergence of point in Y-axis on CGH to avoid zero order light contamination. Furthermore, the reconstructed image is slightly stretched in Y-axis in the SASHIMI glass due to the gaps of beamsplitters in-between so we compensate that by stretching the X-axis of the 3D model.

5 EXPERIMENTAL RESULT

We built our prototype with DCRA and SASHIMI as key components. The 3D image reconstructed is captured using the SONY a7RII, with 1/60 shutter speed, $F2.8$ aperture, 35 mm focal length,

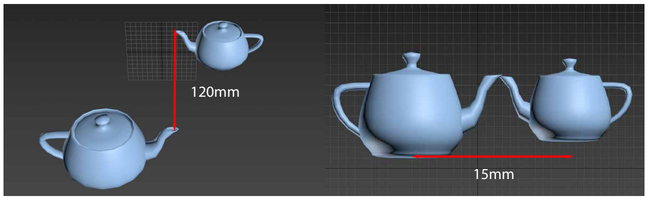

Figure 6: This figure shows 2 3D models "Teapot" positioned in 3D space, 15mm in X-axis and 120mm in Z-axis apart in real world measurements.

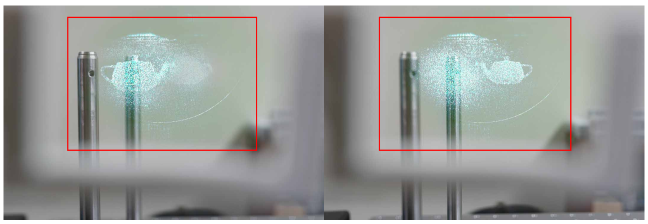

Figure 7: This figure shows the depth of field and eyebox of our proposed system. 2 rods are placed 120mm apart in Z-axis as reference, (left) Teapot1 image reconstruction is captured when camera is focused on the nearer rod. (right) Teapot2 image reconstruction is captured when camera is focused on the farther rod. The size of eyebox is highlighted with red colored border box.

50 ISO with contrast and white balance calibrated to match as close as the human eyes see. We prepared a 3D scene consisting 2 3D models "Teapot", with variations in X-axis and Z-axis position as shown in Figure 6. The models are then computed numerically into CGH , and the reconstructed image is shown in Figure 7. The eyebox is measured in 40 mm.

6 DISCUSSION

As we can see from result, the use of DCRA may deteriorate the image quality of the CGH due to internal reflection. This can be improved by using coatings to reduce the stray lights. Traditionally, CGH computation cost is high so we are limited to simple geometry if we make it portable enough to be carried around. One possible solution is to implement lightweight and powerful embedded system such as Nvidia Jetson.

7 CONCLUSION

In this paper, we successfully built a working CGH near-eye display prototype using DCRA with an eyebox of 40 mm. Since DCRA is very reflective and not suitable for see-through applications, we proposed a beamsplitter embedded glass, SASHIMI as eyepiece in our system. Multiple CGH depths are rendered and the depth of field is verified both by photographs and human eyes. We also challenged the high resolution CGH of 3840×2160 on single eye and successfully rendered in real-time at 30 Hz by utilizing GPU.

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