Towards Eyeglass-style Holographic Near-eye Displays with Statically Expanded Eyebox

Xinxing Xia*
School of Mechatronic Engineering and Automation, Shanghai University

Yunqing Guan†
Infocomm Technology Cluster, Singapore Institute of Technology

Andrei State‡
Department of Computer Science, University of North Carolina at Chapel Hill

Praneeth Chakravarthula§
Department of Computer Science, University of North Carolina at Chapel Hill

Tat-Jen Cham¶
School of Computer Science and Engineering, Nanyang Technological University

Henry Fuchs‖
Department of Computer Science, University of North Carolina at Chapel Hill

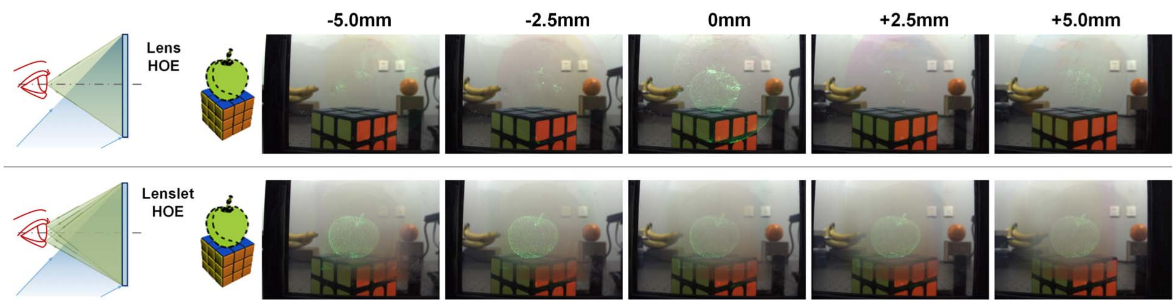

Figure 1: Comparison of the eyebox for holographic near-eye displays with different kinds of holographic optical element (HOE) combiner. The top row demonstrates the captured photos with traditional HOE when the eye moves from -5mm to +5mm horizontally. The bottom row demonstrates the captured photos with our new lenslet HOE when the eye moves from -5mm to +5mm horizontally. In both cases, a virtual object (apple) is placed atop a real object (Rubik's cube) for comparison.

Abstract

Holography is perhaps the only method demonstrated so far that can achieve a wide field of view (FOV) and a compact eyeglass-style form factor for augmented reality (AR) near-eye displays (NEDs). Unfortunately, the eyebox of such NEDs is impractically small ($\sim<1$mm). In this paper, we introduce and demonstrate a design for holographic NEDs with a practical, wide eyebox of $\sim$10mm and without any moving parts, based on holographic lenslets. In our design, a holographic optical element (HOE) based on a lenslet array was fabricated as the image combiner with expanded eyebox. A phase spatial light modulator (SLM) alters the phase of the incident laser light projected onto the HOE combiner such that the virtual image can be perceived at different focus distances, which can reduce the vergence-accommodation conflict (VAC). We have successfully implemented a bench-top prototype following the proposed design. The experimental results show effective eyebox expansion to a size of $\sim$10mm. With further work, we hope that these design concepts can be incorporated into eyeglass-size NEDs.

Keywords: Near-eye displays, Augmented reality, Holographic displays, Expanded eyebox

Index Terms: Computing methodologies—Computer graphics—Graphics systems and interfaces—Mixed / augmented reality; Computing methodologies—Computer graphics—Graphics systems and interfaces—Virtual reality; Hardware—Communication hardware, interfaces and storage—Displays and imagers

*e-mail: lygxia@gmail.com
†e-mail:frank.guan@singaporetech.edu.sg
‡e-mail:andrei@cs.unc.edu
§e-mail:cpk@cs.unc.edu
¶e-mail:astjcham@ntu.edu.sg
‖e-mail:fuchs@cs.unc.edu

1 Introduction

A head-mounted display [32] or near-eye display (NED) is an indispensable component of augmented reality (AR), a technology which is widely recognized as the most promising solution for next-generation computing platforms likely to replace smartphones. Compared with near-eye displays for virtual reality (VR), NEDs for AR can fuse virtual imagery and information with views of the real world seamlessly.

Although various technologies have been developed for AR NEDs, there is a significant unresolved challenge: to provide depth perception of the virtual imagery while satisfying a number of requirements. These include a large FOV, a wide eyebox, compact form factor, variable focus, high resolution, etc. To enable depth perception, most existing designs rely on binocular parallax [10]. However, this may induce a vergence-accommodation conflict (VAC) whereby the eyes converge at the apparent location of an object (based on stereoscopic disparity), but focus on the image plane of the virtual display. A depth mismatch between these can lead to visual fatigue during prolonged use. To solve or mitigate the VAC problem, a number of different techniques have been introduced [7]. For example, methods based on multi-view concepts, such as integral imaging and light fields, reconstruct multiple rays that would be emitted by virtual geometry and project the rays into the viewer's eyes in order to create a visual experience similar to how people naturally view the real world. Unfortunately, these techniques usually suffer from limited field of view (FOV). Other methods, including volumetric, varifocal and multi-focal techniques, reconstruct 3D scenes by creating multiple 2D images as slices in space [8]. However, these methods invariably need mechanical moving devices or multiple high-speed display panels to scan the volume. Hence, the

978-1-7281-8508-8/20/$31.00 ©2020 IEEE
DOI 10.1109/ISMAR50242.2020.00057

form factor of such devices will remain relatively bulky.

Holography is an ideal method for depth perception of virtual imagery since it reconstructs the wavefront of 3D scenes via light diffraction. The drawbacks of traditional holographic 3D displays, e.g. limited viewing range and small display size [8], are not an issue when used for NEDs, as the diameter of the human pupil is also small (3-5mm). Holography is the only method demonstrated so far that can achieve wide FOV and a compact eyeglasses-style form factor [23]. Unfortunately, the eyebox of existing holographic NEDs is impractically small ($\sim$<1mm). A user needs to place his eye very accurately within the display's tiny eyebox, and thus such NEDs do not allow any eye movement.

In this paper, we present our novel design to expand a holographic NED's eyebox without any moving parts, by utilizing a lenslet-array-based HOE, abbreviated as "lenslet HOE." We implemented our design as a bench-top prototype, successfully demonstrating eyebox expansion. Although the lens array function is utilized in our system, it is noted that our display is not a conventional light field display and our lens array HOE does not mimic the lens array in a conventional light field display, where each lens relays a unique angular view of the light field, drastically reducing the effective image resolution. In contrast, our lens array HOE replicates the same spatial frequencies comprising the high-resolution holographic image at each viewing position, effectively expanding the eyebox without sacrificing image resolution.

1.1 Contributions

Concretely, this paper's main contributions include:

1. A novel design for holographic NEDs with both statically expanded eyebox and large FOV, without sacrificing image resolution. The proposed NED can achieve a practically wide eyebox of $\sim$10mm without any moving parts, based on holographic lenslets.

2. A design and fabrication method for a lenslet-array-based HOE to achieve eyebox expansion. It eliminates the need for moving parts needed for eyebox steering in other NED designs.

3. A developed bench-top prototype of the holographic NED with off-the-shelf components, including laser, phase SLM, optical lenses and other components.

2 Related Work

Near-eye displays are crucial for providing depth cues for AR. Variants that have been explored include binocular NEDs, light field NEDs, Maxwellian view NEDs, multifocal / vari-focal NEDs and holographic NEDs.

2.1 Binocular NEDs

Binocular NEDs use parallax images to provide the viewer with depth perception, as found in most commercial AR NED products. Different types of combiners have been designed to allow the viewer to observe both virtual imagery and see-through real scenes without distortion. Among these techniques, waveguide-based combiner structures, in which the virtual image is transmitted inside the waveguide through total internal reflection (TIR), can achieve a compact form factor [26, 36]. However, the FOV is limited by the refractive index of the glass substrate and the size of the in-coupler and out-coupler.

2.2 Light Field NEDs

Light field NEDs transmit and project light field images into each eye of the viewer to enable depth perception, with multi-view, integral imaging, and light field methods typically employed. In one instance [19], a light field display supplying nearly all biological depth cues was implemented using a lens array combined with a micro-display panel. Integral imaging has also been used together with existing freeform-prism-based combiners to solve the VAC problem [13]. The traditional "super multi-view" design for glasses-free 3D displays can be miniaturized to create a light field for each eye [35]. Multi-layer LCD structure has also been utilized to realize compressed light fields for NEDs with correct focus cues [14]. To achieve optical see-through AR, Hong et al. [11] utilized a lens array HOE to implement a full-color light field display with optical see-through function. However, these implementations have limited image quality due to the necessary tradeoff between spatial and angular resolutions.

2.3 Maxwellian View NEDs

Instead of rendering 3D scenes with focus cues, Maxwellian view NEDs, or retina scanning displays, use pinhole imaging to project and focus the virtual imagery at the retina of the eye. To some extent, this method can alleviate the VAC issue. Takahashi et al. [33] utilized a conventional image source with a lens HOE to achieve larger FOV. However, small eyebox size is a major issue with these methods, with several research works exploring eyebox expansion for such Maxwellian view NEDs. Some used scanning of the exit pupil to enlarge the eyebox for Maxwellian view NEDs [18, 34]. Combined with a light field method, pinlight displays can achieve a wide FOV AR eyeglass display with an array of point light sources which is achieved with an edge-lit, etched acrylic sheet [24]. The issue with this technique is the limited imaging resolution due to the diffraction constraint from the modulator. Another technique, Retinal 3D, was proposed for light field retina projection with eye tracking to achieve an expanded eyebox [16]. With the utilization of a LED array, Hedili et al. [9] generated dynamic directional backlight to illuminate the display panel for different pupil locations and thus expand the eyebox of Maxwellian view display. However, this technique needs electrical or mechanical scanning parts (such as a fast steering mirror and eye tracking device) to tilt the direction of the incident light beam which leads to a bulky form factor.

2.4 Multifocal / Vari-focal NEDs

Multifocal / vari-focal NEDs create 2D images at different distances to provide the true depth cues for each eye. These techniques usually depend on high-speed display devices and fast tunable components with electrical or mechanical apparatus [12, 30]. For multi-focal NEDs, a Savart plate [20] or a liquid-crystal-based (LC-based) high-speed switchable lens [22] have been used to create multiple focal planes. Volumetric NEDs that display a series of slices of 3D scenes at different depths have demonstrated multiple focal planes [29].

In contrast to multifocal techniques, vari-focal NEDs only provide a single focal plane at each time instance, which changes with the desired distance of the virtual imagery. For example, a liquid lens [21] or deformable membrane mirror [5] have been employed to implement varifocal NEDs. In [1] and [37], a tunable lens was deployed as the eye piece to achieve variable focus on both virtual and real content, while removing the need for prescription glasses for the viewer. However, these techniques suffer from small FOV due to the aperture of the tunable lens.

2.5 Holographic NEDs

Holography is an ideal approach for displaying 3D scenes since it reconstructs the light wavefront of the scenes, including both amplitude and phase [8]. In principle, holographic techniques can provide accurate focus cues and eliminate the VAC problem. In [25], a combination of an RGB light-emitting diode (LED) light source and LCoS SLM is employed to realize a VR color holographic head-mounted display (HMD). In [23], a holographic VR/AR NED in eyeglass form factor is implemented using a phase-only SLM, a fiber-coupled laser source and an off-axis lens function HOE as the combiner. Although this design can achieve a wide FOV, it has a very small eyebox. A compact on-axis holographic NED prototype [6], uses 4f relay optics with a holographic grating filter to obtain a clearer holographic image. On-axis holography designs have also been reported in [2, 27, 31]. A single HOE can be recorded with multiple optical component functions to compress the optical path for a holographic NED [39]. With the concept of rainbow holography, a color holographic NED with white light source has been implemented with an angular multiplexing method [38]. To enlarge the eyebox, a pupil-shifting HOE was proposed to change the incident light direction for SLM and create the corresponding exit pupil in the eye pupil plane [15]. Combining the method of digital holography with amplitude SLM, Chang et al. [3] integrated the pupil array in the relay optics system to expand the size of eyebox for Maxwellian view dispay. Park et al. [28] presented an optical see-through holographic NED with HOE combiner which can replicate the eyebox with dynamic steering. A HOE customizing method with a holographic printer has been shown to extend the eyebox for AR NEDs, which was verified with a waveguide-based NED design [17].

The rendering of holograms for holographic NEDs is also a key challenge, with much research aiming to improve the image quality for holographic displays. In [4], an improved layer-based method for rapid hologram generation was proposed and verified in a NED system. A method based on complex Wirtinger derivatives was employed to improve the quality of phase retrieval for holographic NEDs [2]. A double-convergence light Gerchberg-Saxton (GS) algorithm was also proposed to improve the image quality for holographic NEDs [31]. An overlap-add stereogram has been used to transform the light field to a hologram for NED, leading to better performance [27].

Holography is the only method demonstrated so far that can achieve a wide FOV in a compact eyeglasses-style form factor for AR displays. However, it is severely limited by the size of the eyebox. As reported in [23], the holographic display has a wide FOV (80° in horizontal) but a tiny eyebox (∼<1mm). Enlarging the eyebox in a holographic NED remains a challenge.

3 System Design

Existing holographic NEDs have limited eyebox size (see Figure 2 (a)). Although some methods proposed the use of a steering mirror to shift the incident reference laser beam, the expansion of the eyebox is still marginal due to limited tolerance angles of HOEs. Unlike such methods, we propose to record and fabricate a lenslet-array-based HOE, abbreviated as "lenslet HOE", to create multiple focal points in the pupil plane (see Figure 2 (b)). When the viewer's eye moves within the bounds of the group of focal points, there will always be at least one reconstructed focal point that falls within the pupil, thus effectively expanding the eyebox.

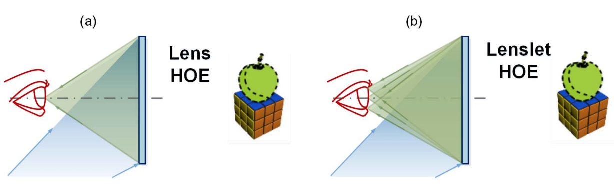

Figure 2: Schematic diagrams of the eyebox for holographic NEDs with traditional HOE (a) and with our new lenslet HOE (b).

We developed a design for holographic NED that uses a lenslet HOE. Figure 3 shows the optical schematic of our design. Our new holographic NED consists of a laser light source, a pinhole spatial filter, a collimated lens (CL), a linear polarizer (LP), a beam splitter (BS), a phase SLM, a converging lens (Lens 1), a mirror (M2) and a lenslet HOE. The laser beam is first filtered and expanded into collimated light that illuminates the phase SLM through reflection from

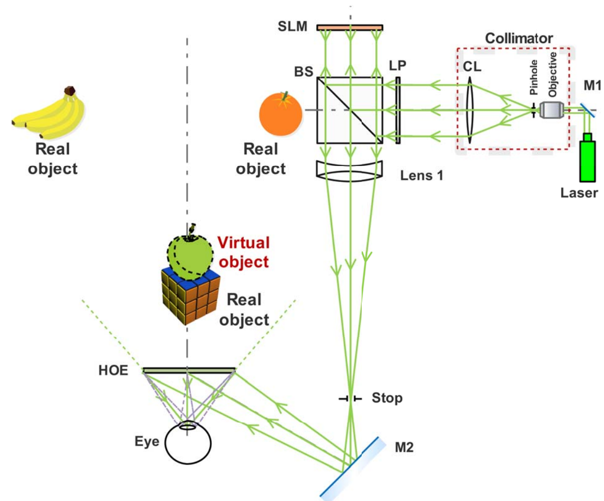

Figure 3: Optical schematic for our holographic NED with expanded eyebox.

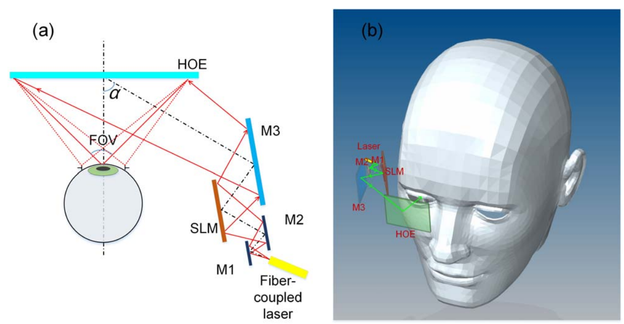

Figure 4: Overview of our design for a compact, wearable holographic NED with expanded eyebox.

the BS. After modulation by the phase SLM, the light is reflected and projected off-axis onto the lenslet HOE via Lens 1 and M2. Virtual imagery is then be reconstructed from the lenslet HOE and projected into the viewer's eye, while the viewer also sees the real world scene through the lenslet HOE. The LP makes the polarization state of the incident collimated beams match the requirements of the phase SLM. The stop located at the focal plane of Lens 1 is employed to filter the high order of diffraction from the phase SLM.

As seen in Figure 3, the lenslet HOE is the crucial component for achieving an expanded eyebox. It not only reflects the off-axis rays at appropriate angles to the viewer's eye, but also creates a focal point array around the viewer's eye to expand the eyebox. This lenslet HOE combiner eliminates the need for moving parts to achieve eye box expansion.

As previously reported by others [23], it is possible to incorporate our design into a compact eyeglass-style NED. Figure 4 shows such a conceptual design for a compact holographic NED. It consists of a phase SLM, a fiber-coupled laser, a lenslet HOE and three folding optical mirrors. In contrast to the design shown in Figure 3, the SLM in Figure 4 is illuminated directly by a divergent beam from the fiber-coupled laser, rather than by a collimated beam. To compress the form factor of the design, no additional conventional optical components are used except for the lenslet HOE and mirrors.

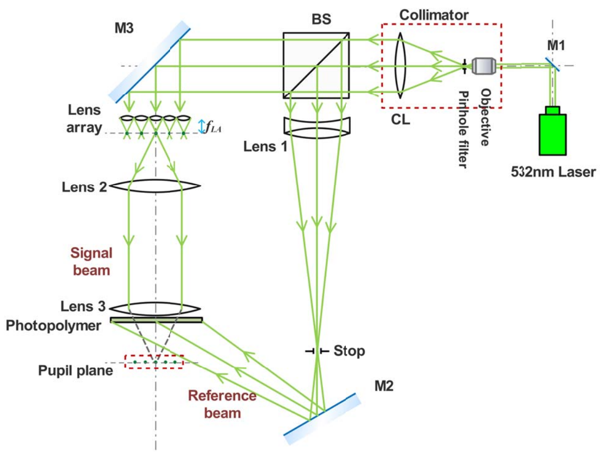

Figure 5: Optical schematic for lenslet HOE fabrication.

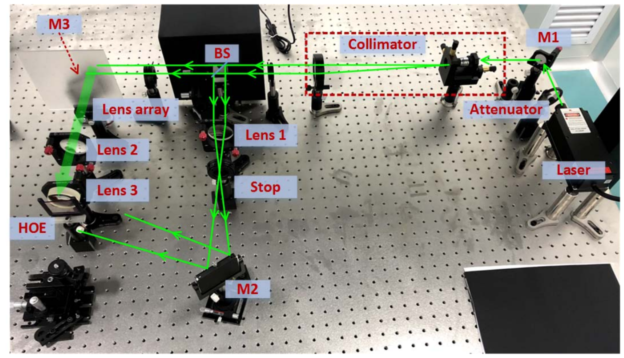

Figure 6: Experimental bench-top setup for fabrication of the lens-array-based HOE.

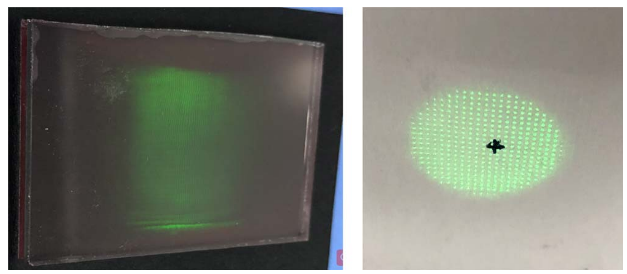

Figure 7: Experimental test of the HOE based on a fabricated lens array.

4 Design and Fabrication of Lenslet Holographic Optical Element

The lenslet HOE utilized in our design is the key component for achieving an expanded eyebox. Our lenslet HOE allows off-axis projection beams to generate multiple focal points in the pupil plane and thus extend the viewing range of the pupil, without the need for any moving parts. Applying these concepts, we designed a hologram recording setup to fabricate this type of HOE via interference.

The optical setup for fabricating the lenslet HOE is shown in Figure 5. After beam expansion, the laser beam with a wavelength of 532nm is collimated and divided into two beams by the beam splitter. The beam reflected by the beam splitter goes through the Lens 1 and is then reflected by Mirror 2 to illuminate the hologram recording plane as a reference beam. This reference beam is the same as the corresponding part of the proposed holographic NED. The beam that traverses the beam splitter illuminates a lens array to create multiple focal points. The beams from the multiple focal points pass through the 4f relay optics (Lenses 2 and 3) and then interfere with the reference beam to record the hologram on the HOE. The hologram recording plane is located at the back surface of Lens 3. If the lens array's focal length is f_{LA} with a pitch of P_{LA}, the pitch of multiple focal points on the pupil plane is:

$$P_{pupil} = \frac{f_3}{f_2} \cdot P_{LA} \quad (1)$$

where f_2 and f_3 are the focal lengths of Lens 2 and Lens 3 respectively.

To fabricate the lenslet HOE, a piece of LitiHolo C-RT20 film is attached to a glass substrate and used as the hologram recording plate. The interference pattern between the signal beam and reference beam is recorded on the hologram film by exposure for several minutes. The lenslet HOE fabrication is completed after bleaching out with an ordinary light bulb. The experimental setup for HOE fabrication is shown in Figure 6. In our experiment, the total size of the hologram film for recording is 50mm × 38mm. It should be noted that the FOV of the fabricated HOE depends on the numerical aperture (NA) of Lens 3, while the size of the effective region on the fabricated HOE depends on the clear aperture of Lens 3. In our setup, a lens with a focal length of 60mm and diameter of 50mm is chosen for Lens 3. The pitch of the lens array is 1mm with a focus of 3.3mm. The off-axis angle of reference beam is around 60°. Considering the distance between Lens 3 and the HOE, the distance between the HOE plane and the focal plane of the signal beam is set at 45mm, which is also the eye relief. The FOV of the fabricated HOE is around 45°. The pitch of the multiple focus points reconstructed from the HOE on the pupil plane is around 0.8mm, slightly below the size of a human pupil.

Exposure time is another key parameter for the diffraction efficiency of the fabricated HOE. Therefore we chose different exposure times to fabricate the lenslet HOE and compared their diffraction efficiency. We determined that a longer exposure time (in our case, 12 minutes) can help produce a lenslet HOE with higher diffraction efficiency. To verify the diffraction efficiency of the fabricated lenslet HOE, we blocked the signal laser and only allowed the reference beam to illuminate the HOE. Figure 7 shows the reconstruction of multiple focus points on a piece of white paper placed at the pupil plane. It clearly shows that the fabricated HOE works as designed.

5 Implementation

5.1 Bench-top Prototype Setup

To test our expanded eyebox design for holographic NEDs, we implemented a bench-top prototype following the optical diagram shown in Figure 3, with Figure 8 showing the physical configuration. The SLM chosen in our bench-top prototype is a HOLOEYE PLUTO liquid crystal on silicon (LCoS) reflective phase-only SLM with a resolution of 1920 × 1080. The pixel pitch of the SLM is 8um, resulting in an active area of 15.36mm × 8.64mm. The BS is rotated counterclockwise by 90°to ensure the light beam illuminates the phase SLM normally. The attenuator is added to control the power of the laser beam, so as to adjust the final observed image intensity for the human eye. A camera is placed at the designed eye location to simulate the human eye and is mounted on a two-axis translation stage for the simulation of eye movement in both horizontal and vertical directions. After the modulation by the SLM, the reflective laser beams carry the corresponding phase information of the virtual image and propagate as the reference beam to the lenslet HOE.

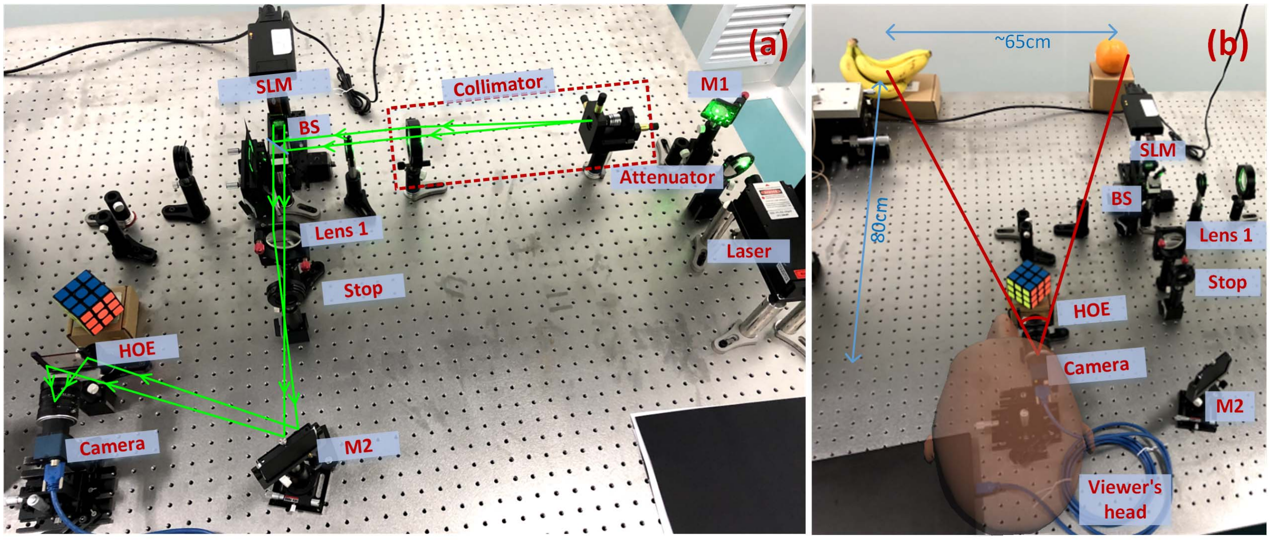

Figure 8: Bench-top system (a) and experimental layout (b) of the proposed holographic NED with expanded eyebox.

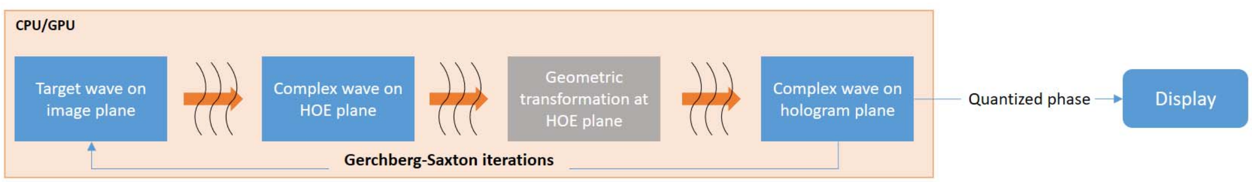

Figure 9: Rendering pipeline of the proposed holographic NED with statically expanded eyebox.

The viewer thus observes the virtual holographic image within the see-through real scene.

5.2 Rendering Pipeline

Our holographic display prototype with the proposed lenslet HOE based combiner for eyebox expansion utilizes an off-axis projection system as shown in Figure 8(a). While ideally, an off-axis wave propagation model is intended for computing the phase-only holograms of a given target image, we utilize the simpler Fourier propagation for an on-axis configuration combined with geometric transformations for the underlying off-axis tilt compensation. Specifically, as described by Figure 9, our wave propagation model from the image plane to the hologram plane (and back) is as follows.

For a given target image, we first compute the complex wave field on the image plane. We propagate this wavefield up to our lenslet HOE combiner. Note that, as shown in Figure 8(a), the wave reaching the HOE plane is off-axis. Therefore, we apply a geometric transformation, such as rotation and keystone correction, on the "off-axis" wave that is propagated to the HOE plane to align it parallel to the target image plane. This "corrected" wave is then Fourier propagated to the hologram image plane, where the SLM is located. Now we enforce the amplitude constraints on the hologram plane and propagate the wave back to the image plane, where we enforce the amplitude constraints corresponding to the image plane. In other words, we use the abovementioned model for iterative computation of forward and backward propagation of the wave, following the well-known Gerchberg-Saxton (GS) algorithm, to calculate the phase-only uniform wavefield on the hologram plane. After convergence, the phase is extracted and quantized to finally display on the SLM.

Although our lens array HOE replicates the same spatial frequencies at multiple viewing positions, the calculation of the spatial frequencies image with the GS algorithm only needs to be done once for the SLM and this will not introduce extra computing load of our holographic displays.

5.3 Experimental Results with Expanded Eyebox

Figure 8(b) shows the layout and setup used to confirm eyebox expansion for our holographic NED. The bananas, the orange and the Rubik's cube are all real objects. The Rubik's cube is placed behind the lenslet HOE, at a distance of 200mm from the camera. To better demonstrate the resolution of the target image, we chose a virtual 3D apple with polygon mesh wireframe as the target image, located at a virtual distance of 200mm from the camera; the virtual apple is displayed atop the real Rubik's cube. The focus of the camera is set at the virtual apple. To verify the eyebox of our holographic NED, a series of photos were taken by moving the camera both horizontally and vertically. The photos are shown in Figure 10. We note that the virtual image can be viewed with similar image quality in an eyebox of size 10mm both horizontally and vertically. And based on each eye location, we re-rendered the holographic images to ensure the virtual apple on the top of the real Rubik's cube and thus generated the motion parallax for the eye movement. To clarify, the original source image is not a continuous-tone rendering of a 3D apple, but of a polygon mesh wireframe of the apple. The empty spaces are not due to reduced resolution, but are present within the mesh. To further demonstrate our design, we fabricated a conventional HOE in the setup shown in Figure 6, without using the lenslet array. Another group of photos was taken for the bench-top setup with the conventional HOE and the camera was shifted horizontally. Figure 1

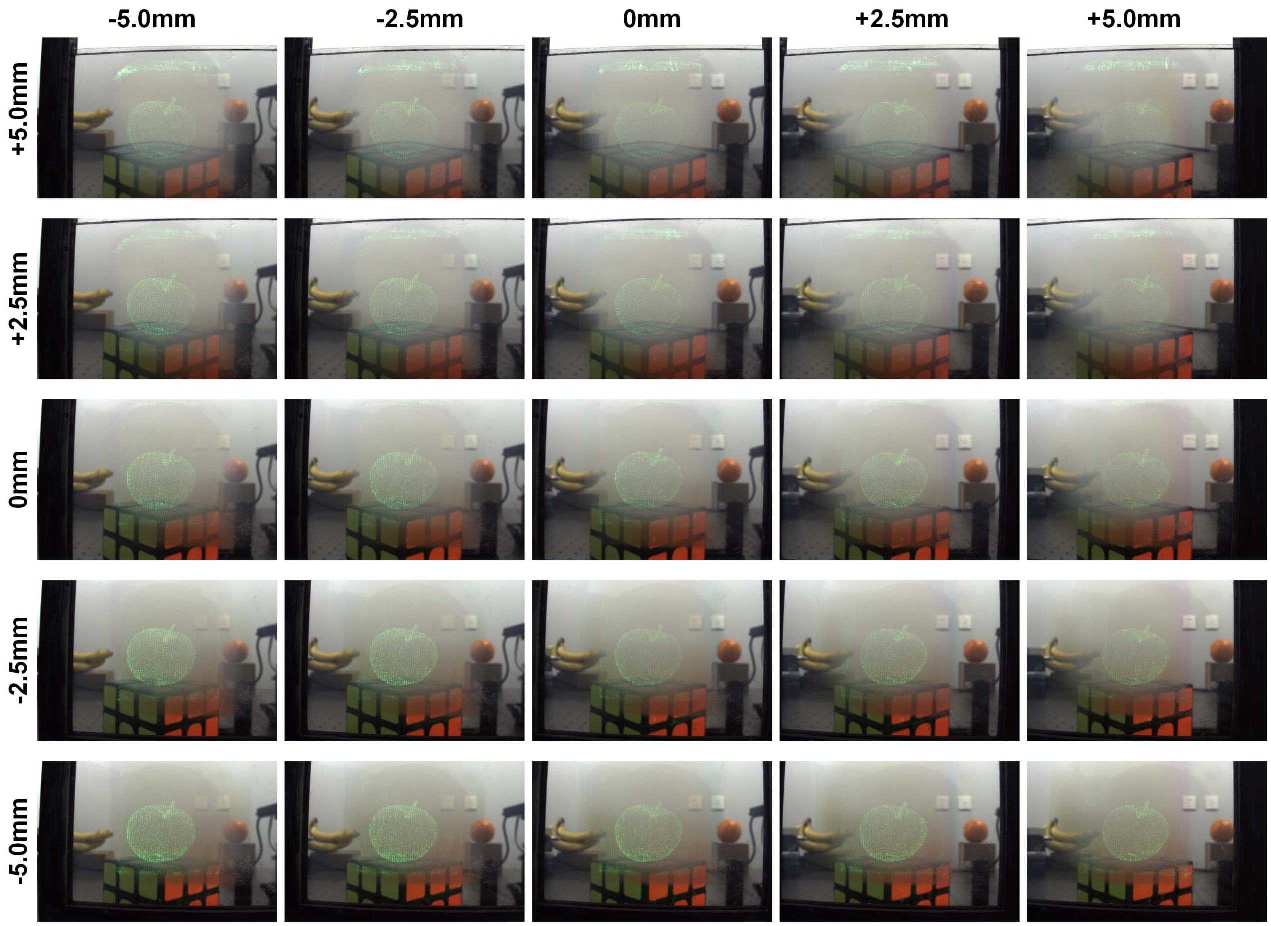

Figure 10: Views through our holographic NED with statically expanded eyebox of 10mm ×10mm: a virtual object (apple) is placed atop a real object (Rubik's cube). Note the varying amounts of horizontal and vertical parallax corresponding to the camera offsets, as visible in the relative positions of the foreground Rubik's cube vs the background objects.

compares the images captured with the conventional HOE and with our lenslet HOE. It is obvious that our lenslet HOE can significantly expand the eyebox size to 10mm for the holographic NED without loss of resolution when compared to the conventional HOE.

6 Discussion and Future Work

We have demonstrated our design towards eyeglass-style holographic NEDs with statically expanded eyebox. Our design utilizes two different holographic techniques. We fabricated an HOE combiner using analog holography, which can integrate multiple optical functions in a single, thin transparent plate. We utilize digital holography to generate the phase pattern for the SLM and thus display the target image for the human eye. In our design, a dense lenslet array is used to recorde and fabricate the HOE. In contrast to light-field displays, our lens array HOE replicates the same spatial frequencies comprising the full resolution of the target holographic image at each viewing position and thus the eyebox is expanded without sacrificing reconstructed image resolution. However, we note several remaining issues to address in future work to further improve the design.

3D depth cues. The étendue of a holographic display [23], is the product of the exit pupil size and the FOV and is linked to the resolution of the SLM. As étendue is always preserved, when a large FOV is achieved for holographic display, the size of the exit pupil at each viewing position will be traded off. If the size of the exit pupil is decreased significantly, the display would be qualified as a Maxwellian view display for each focal point, and as a result, the 3D depth cues offered by holographic displays will be minimized. To enlarge the étendue, thus expanding the exit pupil while retaining the large FOV, we could choose a high-resolution SLM with higher pixel density (e.g. HOLOEYE GAEA) which will allow both a large FOV and wider exit pupil to enable 3D depth cues for each focal point. The depth control method reported by Park and Kim [28] also provides a potential way to enhance the 3D depth cues for holographic NEDs.

Field of View. In contrast to AR NEDs based on a commercial Diffraction Optical Element (DOE), which have difficulties achieving FOVs larger than 50 degrees, holographic displays have the potentialto achieve a large FOV matching human vision. For example, the work done by Maimone and collaborators [23] has shown the potential for a wider FOV up to 80 degrees horizontally with holographic AR NED. Our present design achieves a modest 45-degree FOV due to the focusing power and size of the optical lens used for HOE recording; we are aiming for 90-degree FOV by exploring techniques to replace the optical lens.

Resolution. In our design, the lens array function is used solely to create multiple focal points to expand the eyebox, but does not reduce the image resolution for each focal point. For each focal point, the observed image is nearly the same, with only slight offset and distortion. But compared with bulky traditional optics, the optical performance of a fabricated HOE integrating the same functions is inferior but offers a much more compact form factor. In our experiment, we show the virtual 3D object as a polygon mesh wireframe, and as a result, empty space is visible within the mesh. However, the wireframe of the virtual object is still sharp. But HOE quality and laser speckle have a direct impact on the final observed image quality and resolution. We will fabricate a higher-quality HOE and mitigate laser speckle to improve the image quality in the future.

Brightness. Although the intensity of the signal laser beam is divided among the lenslets and the brightness of the reconstructed virtual imagery for each focal point is reduced, this can be easily mitigated by increasing the output power of the laser source, or by selecting a lenslet array with larger pitch for HOE recording.

Full color. For now, we recorded and implemented a monochromatic HOE; we will work to extend our design to a full-color holographic display.

Eyeglasses. The conceptual design for an eyeglass-style compact NED has already been presented in Figure 4 (Section 3); we will also develop that conceptual design into a practical prototype with compact form factor in the future.

7 Conclusion

AR is widely recognized as the next-generation computing platform with numerous potential applications in various sectors. As an indispensable component for AR, NEDs have been the subject of many investigations by academia and industry and are therefore experiencing rapid progress. Among the reported NED techniques, the holographic NED is probably the only method demonstrated so far that can achieve a wide field of view and a compact eyeglasses-style form factor. To enlarge the eyebox in holographic NEDs, we presented a novel design aimed at eyeglass-style AR NEDs and capable of statically expanding the eyebox. This is achieved by using a lenslet-array-based HOE without moving parts, which expands the eyebox up to 10mm, vs 1mm in other reported techniques. We presented a detailed design, described fabrication of the HOE and implemented a bench-top prototype based on our design. The prototype shows successful eyebox expansion. In the future, we plan to develop our design into an eyeglass-style full-color AR NED.

Acknowledgments

This research is supported by the National Research Foundation, Singapore under its International Research Centres in Singapore Funding Initiative, the Natural Science Foundation of Shanghai (Grant No. 20ZR1420500) and the Seed Grant (R-MOE-A405-G005) from Singapore Institute of Technology (SIT). Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not reflect the views of National Research Foundation, Singapore.

References

[1] P. Chakravarthula, D. Dunn, K. Aksit, and H. Fuchs. FocusAR: Autofocus augmented reality eyeglasses for both real world and virtual imagery. *IEEE Transactions on Visualization and Computer Graphics*, 2018. doi: 10.1109/TVCG.2018.2868532

[2] P. Chakravarthula, Y. Peng, J. Kollin, H. Fuchs, and F. Heide. Wirtinger holography for near-eye displays. *ACM Transactions on Graphics*, 38(6), 2019. doi: 10.1145/3355089.3356539

[3] C. Chang, W. Cui, J. Park, and L. Gao. Computational holographic Maxwellian near-eye display with an expanded eyebox. *Scientific Reports*, 9(1), 2019. doi: 10.1038/s41598-019-55346-w

[4] J.-S. Chen and D. P. Chu. Improved layer-based method for rapid hologram generation and real-time interactive holographic display applications. *Optics Express*, 2015. doi: 10.1364/oe.23.018143

[5] D. Dunn, C. Tippets, K. Torell, P. Kellnhofer, K. Aksit, P. Didyk, K. Myszkowski, D. Luebke, and H. Fuchs. Wide Field of View Varifocal Near-Eye Display Using See-Through Deformable Membrane Mirrors. *IEEE Transactions on Visualization and Computer Graphics*, 23(4), 2017. doi: 10.1109/TVCG.2017.2657058

[6] Q. Gao, J. Liu, X. Duan, T. Zhao, X. Li, and P. Liu. Compact see-through 3D head-mounted display based on wavefront modulation with holographic grating filter. *Optics Express*, 2017. doi: 10.1364/OE.25.008412

[7] J. Geng. Three-dimensional display technologies. *Advances in Optics and Photonics*, 2013. doi: 10.1364/aop.5.000456

[8] Z. He, X. Sui, G. Jin, and L. Cao. Progress in virtual reality and augmented reality based on holographic display. *Applied Optics*, 58(5):A74, 2019. doi: 10.1364/ao.58.000a74

[9] M. K. Hedili, B. Soner, E. Ulusoy, and H. Urey. Light-efficient augmented reality display with steerable eyebox. *Optics Express*, 27(9), 2019. doi: 10.1364/oe.27.012572

[10] D. M. Hoffman, A. R. Girshick, K. Akeley, and M. S. Banks. Vergence–accommodation conflicts hinder visual performance and cause visual fatigue. *Journal of Vision*, 2008. doi: 10.1167/8.3.33

[11] K. Hong, J. Yeom, C. Jang, J. Hong, and B. Lee. Full-color lens-array holographic optical element for three-dimensional optical see-through augmented reality. *Optics Letters*, 39(1), 2014. doi: 10.1364/ol.39.000127

[12] X. Hu and H. Hua. High-resolution optical see-through multi-focal-plane head-mounted display using freeform optics. *Optics Express*, 2014. doi: 10.1364/oe.22.013896

[13] H. Hua and B. Javidi. A 3D integral imaging optical see-through head-mounted display. *Optics Express*, 2014. doi: 10.1364/oe.22.013484

[14] F.-C. Huang, K. Chen, and G. Wetzstein. The light field stereoscope. *ACM Transactions on Graphics*, 2015. doi: 10.1145/2766922

[15] C. Jang, K. Bang, G. Li, and B. Lee. Holographic near-eye display with expanded eye-box. *ACM Transactions on Graphics*, 37(6), 2018. doi: 10.1145/3272127.3275069

[16] C. Jang, K. Bang, S. Moon, J. Kim, S. Lee, and B. Lee. Retinal 3D: Augmented Reality Near-eye Display via Pupil-tracked Light Field Projection on Retina. *ACM Transactions on Graphics*, 2017. doi: 10.1145/3130800.3130889

[17] J. Jeong, J. Lee, C. Yoo, S. Moon, B. Lee, and B. Lee. Holographically customized optical combiner for eye-box extended near-eye display. *Optics Express*, 27(26), 2019. doi: 10.1364/oe.382190

[18] S.-B. Kim and J.-H. Park. Optical see-through Maxwellian near-to-eye display with an enlarged eyebox. *Optics Letters*, 2018. doi: 10.1364/ol.43.000767

[19] D. Lanman and D. Luebke. Near-eye light field displays. *ACM Transactions on Graphics*, 2013. doi: 10.1145/2508363.2508366

[20] C.-K. Lee, J.-Y. Hong, B. Lee, S. Lee, D. Yoo, and S. Moon. Compact three-dimensional head-mounted display system with Savart plate. *Optics Express*, 2016. doi: 10.1364/oe.24.019531

[21] S. Liu, D. Cheng, and H. Hua. An optical see-through head mounted display with addressable focal planes. In *Proceedings - 7th IEEE International Symposium on Mixed and Augmented Reality 2008, ISMAR 2008*, 2008. doi: 10.1109/ISMAR.2008.4637321

[22] G. D. Love, D. M. Hoffman, P. J. Hands, J. Gao, A. K. Kirby, and M. S. Banks. High-speed switchable lens enables the development of a volumetric stereoscopic display. *Optics express*, 2009. doi: 10.1364/OE.17.015716

[23] A. Maimone, A. Georgiou, and J. S. Kollin. Holographic near-eye displays for virtual and augmented reality. *ACM Transactions on Graphics*, 2017. doi: 10.1145/3072959.3073624

[24] A. Maimone, D. Lanman, K. Rathinavel, K. Keller, D. Luebke, and H. Fuchs. Pinlight displays: wide field of view augmented reality eyeglasses using defocused point light sources. *international conference on computer graphics and interactive techniques*, 2014. doi: 10.1145/2601097.2601141

[25] E. Moon, M. Kim, J. Roh, H. Kim, and J. Hahn. Holographic head-mounted display with RGB light emitting diode light source. *Optics Express*, 22(6):6526, 2014. doi: 10.1364/oe.22.006526

[26] H. Mukawa, K. Akutsu, I. Matsumura, S. Nakano, T. Yoshida, M. Kuwahara, and K. Aiki. A full-color eyewear display using planar waveguides with reflection volume holograms. *Journal of the Society for Information Display*, 2009. doi: 10.1889/JSID17.3.185

[27] N. Padmanaban, Y. Peng, and G. Wetzstein. Holographic near-eye displays based on overlap-add stereograms. *ACM Transactions on Graphics*, 38(6), 2019. doi: 10.1145/3355089.3356517

[28] J.-H. Park and S.-B. Kim. Optical see-through holographic near-eye-display with eyebox steering and depth of field control. *Optics Express*, 26(21), 2018. doi: 10.1364/oe.26.027076

[29] K. Rathinavel, H. Wang, A. Blate, and H. Fuchs. An extended depth-at-field volumetric near-eye augmented reality display. *IEEE Transactions on Visualization and Computer Graphics*, 2018. doi: 10.1109/TVCG.2018.2868570

[30] J. P. Rolland, M. W. Krueger, and A. Goon. Multifocal planes head-mounted displays. *Applied Optics*, 39(19):3209, jul 2000. doi: 10.1364/AO.39.003209

[31] P. Sun, S. Chang, S. Liu, X. Tao, C. Wang, and Z. Zheng. Holographic near-eye display system based on double-convergence light Gerchberg-Saxton algorithm. *Optics Express*, 2018.

[32] I. E. Sutherland. A head-mounted three dimensional display. In *Proceedings of the December 9-11, 1968, fall joint computer conference, part I*, pp. 757–764. ACM, 1968.

[33] H. Takahashi and S. Hirooka. Stereoscopic see-through retinal projection head-mounted display. In *Stereoscopic Displays and Applications XIX*, vol. 6803, 2008. doi: 10.1117/12.765786

[34] Y. Takaki and N. Fujimoto. Flexible retinal image formation by holographic Maxwellian-view display. *Optics Express*, 2018. doi: 10.1364/oe.26.022985

[35] T. Ueno and Y. Takaki. Super multi-view near-eye display to solve vergence–accommodation conflict. *Optics Express*, 2018. doi: 10.1364/oe.26.030703

[36] Y. Wang, J. Xie, Y. Chen, Z. Wu, Y. Liu, Y. Hu, H. Zhao, R. Shi, and J. Liu. Chromatic dispersion correction in planar waveguide using one-layer volume holograms based on three-step exposure. *Applied Optics*, 2012. doi: 10.1364/ao.51.004703

[37] X. Xia, Y. Guan, A. State, P. Chakravarthula, K. Rathinavel, T. J. Cham, and H. Fuchs. Towards a Switchable AR/VR Near-eye Display with Accommodation-Vergence and Eyeglass Prescription Support. *IEEE Transactions on Visualization and Computer Graphics*, 25(11):3114–3124, 2019. doi: 10.1109/TVCG.2019.2932238

[38] X. Yang, P. Song, H. Zhang, and Q.-H. Wang. Full-color computer-generated holographic near-eye display based on white light illumination. *Optics Express*, 27(26):38236, 2019. doi: 10.1364/oe.382765

[39] P. Zhou, Y. Li, S. Liu, and Y. Su. Compact design for optical-see-through holographic displays employing holographic optical elements. *Optics Express*, 2018. doi: 10.1364/oe.26.022866