Focus-Aware Retinal Projection-based Near-Eye Display

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Abstract

The primary challenge in optical see-through near-eye displays lies in providing correct optical focus cues. Established approaches such as varifocal or light field display essentially sacrifice temporal or spatial resolution of the resulting 3D images. This paper explores a new direction to address the trade-off by combining a retinal projection display (RPD) with ocular wavefront sensing (OWS). Our core idea is to display a depth of field-simulated image on an RPD to produce visually consistent optical focus cues while maintaining the spatial and temporal resolution of the image. To obtain the current accommodation of the eye, we integrate OWS. We demonstrate that our proof-of-concept system successfully renders virtual contents with proper depth cues while covering the eye accommodation range from 28.5 cm (3.5 D) to infinity (0.0 D).

Keywords: Augmented reality, accommodation sensing, retinal projection, near-eye display.

Index Terms: Computing methodologies—Computer graphics—Graphics systems and interfaces—Mixed / augmented reality Computing methodologies—Computer graphics—Graphics systems and interfaces—Virtual reality

1 Introduction

In Augmented Reality (AR), Optical See-Through Near-Eye Displays (OST-NEDs) play a central role in real-world AR applications [6]. The primary challenge for OST-NEDs is to provide correct optical focus-cues [1], because the user is directly observing the real 3D world. Typical HMDs can only show a stereo image at a fixed distance, so eye convergence is dynamic while accommodation is fixed. This unnatural inconsistency causes the infamous vergence-accommodation conflicts (VAC) [4,5]. VAC is responsible for the fatigue and discomfort of AR and virtual reality glasses [2,7,8,12]. To solve the VAC of OST-NEDs, the essential solution is to present an optical focal cue [5,7]. Common approaches include light field displays [9,10], varifocal displays [1,3]; however, there is a trade-off between the quality of the focus cues and the spatial or temporal resolution of the virtual 3D image.

We address this trade-off by proposing a focus-aware retinal projection display that uses ocular wavefront sensing to render an image simulating depth of field (DoF). RPD is a display technology that projects images directly onto the retina, resulting in a high DoF, virtually always-in-focus view. However, if we can keep updating the input image with a correct representation of the DoF of the current accommodation, then the view the user sees will theoretically be equivalent to they were given proper optical focus cues. We thus combine an RPD with OWS, which is originally used in ophthalmology to directly measure the aberrations of the eye's optical system. We demonstrate a proof-of-concept system which is capable of measuring wavefront information of a model eye and rendering varifocal images.

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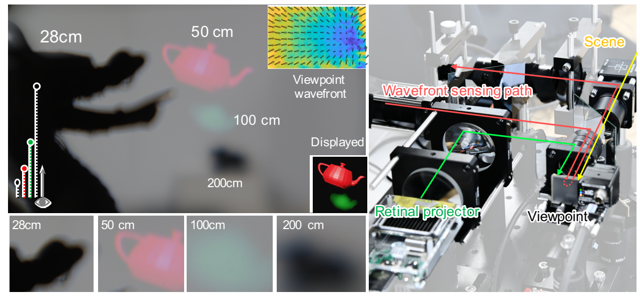

(a) View when focuses at 50 cm (b) Optical setup

Figure 1: Demonstration of a retinal scanning projection display system that reproduces the focus-cue. (left) An eye camera focuses at 50 cm. (right) the prototype with visualization of optical paths of both the retinal scanning projector and the wavefront path.

2 Hardware Setup

Our proof-of-concept implementation is divided into a hardware part and a software part. In the hardware part, we build a benchtop OST-NED setup consisting of a custom RPD and a custom OWS module. In the software part, we estimate the focal length of the eye from the OWS, perform DoF-based rendering, and display it on the RPD.

2.1 RPD Module

The RPD module consists mainly of a handheld laser projector (1280×720, 60 Hz, Ultimems HD301D1), and two achromatic lenses (f=75 mm, dia.=2", Thorlabs AC508-075-A-ML) to achieve Maxwellian view at the viewpoint. The module also shares beam splitters (75×75 mm, VIS Plate Beamsplitter, Edmund Optics) with the OWS module to provide a coaxial optical path. The parameters of the beam splitter are 30R/70T for the first beam splitter from the projector and 50R/50T for the second one. To adjust the brightness of the laser projector, we also installed a neutral density (ND) filter on the projector.

2.2 Ocular Wavefront Sensing Module

The OWS module measures the wavefront of light reflected from the retina. In our proof-of-concept system, we use the diffuser-based wavefront sensor (DWFS), which is optically simple and has high measurement performance [11]. For this sensing approach, our OWS module consists of a holographic diffuser, a USB 3.0 CMOS monochromatic sensor, and two relay lens pairs, which compose 4f optical systems. The light source is a fiber-coupled red LED, collimated and shaped its beam size to 0.8 mm.

3 Experiments

3.1 Evaluation of the OWS Module with Model Eye

First, we verify that our custom OWS module works properly. Instead of real human viewer, we use an ophthalmologic model eye that accurately replicates the optics of the human eye. Since the diopter of the model eye is fixed at 0 D (in focus at infinity), we placed a focus-tunable lens (FTL) in front of the model eye to simulate the diopter change in the range of 0.5 D (focused at 200 cm) to 3.5 D (focused at 28.5 cm).

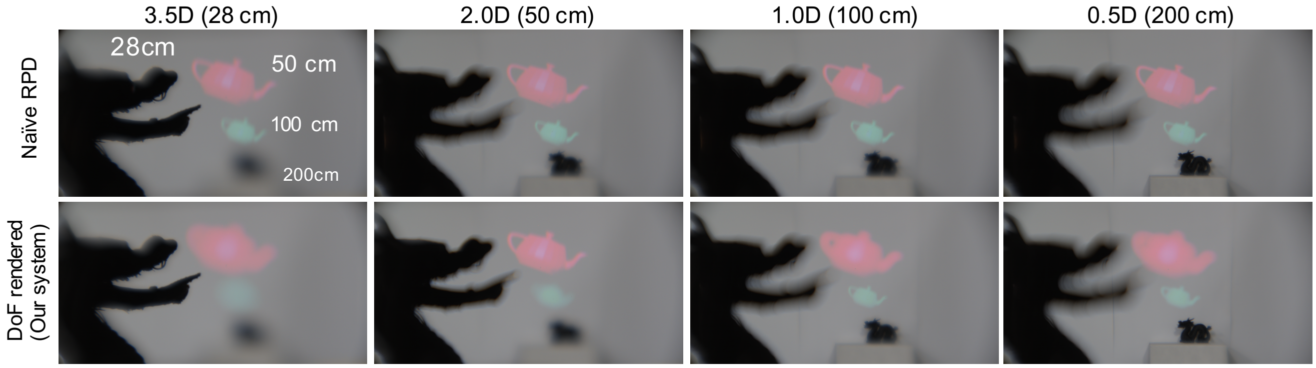

Figure 2: Summary of the DoF-simulated rendering with diopter estimation (Sec. 3.2). The eye camera captures the scene while changing its eye focus. (1st row) Typical AR view with a conventional RPD. (2nd row) Final results of our system. The focus-cue is properly presented.

Throughout the range of diopter measured, the estimation by the DWFS module gives reasonable measurement results. The mean estimation error of each input diopter usually lies within ± 0.2 D.

3.2 DoF-Simulated Rendering with Diopter Estimation

To evaluate the final view of our system, we built a viewpoint module: a simplified eye camera so that it captures the real view and virtual images from the RPD module while the OWS can also estimate the system's focus. We built a diffuse reflection mirror consisting of a mirror (Thorlabs, ME1S-F01) with a diffuser film (Luminit, LSD60PC10-F4), and a color CMOS sensor (XIMEA, resolution:1936 x 1216) can be switched by a linear stage. We also used an achromatic lens (f=30 mm, Thorlabs) to reproduce emmetropic vision and an FTL (Edmund Optics, CA:10 mm, diopter range:-1.5 D to +3.5 D) to reproduce aberration.

The general flow of the process is as follows: the OWS module measures the focal length change of the FTL; the RPD projects the retinal projection image reflecting the DoF according to the measured diopter. We vary the FTL diopter from 0.5 D to 3.5 D in 0.5 D increments. We then matched the diopter estimated by OWS and performed linear fitting. The measurements were repeated three times for each diopter, and the average was used for fitting.

Next, we describe the actual rendering experiment. The experimental setup was as follows: the FTL was set from 0.5 D to 3.5 D in increments of 0.5 D. Unlike Sec. 3.1, each diopter was measured only once. In the real world, two 3D printed Stanford dragons were placed at 28 cm and 200 cm respectively. In the virtual image, two Utah teapots were placed at 50 cm and 100 cm respectively. In this way, the dragons and teapots appear alternately aligned in the depth direction if focus cue is correctly provided. At the DoF rendering, since the pupil diameter of the simulated FTL eye is 10 mm, the pupil was set to 10 mm, which is slightly larger than the maximum human pupil diameter (7-8 mm). The f-stop (f-number) was set at 3.0, which is obtained by dividing the focal length of 30 mm by the aperture diameter of 10 mm. In reality, the focal length varies depending on the FTL, but it was fixed because there was no difference in blur within the measurement range.

Figure 2 summarizes the results of the AR scene taken from the viewpoint position. It shows that focus cue is properly given by our method. In the supplementary material, stop-motion movies are provided for the case of varying from 0 D to 3.5 D in 0.1 D increments. Note that, the diopter for DoF rendering in this case is based on a linear model created during the calibration of the accommodation between FTL and the OWS module.

4 Conclusion

We have proposed a focus-aware RPD that reproduces optical focus cues by DoF simulation rendering with ocular wavefront sensor data. Instead of pursuing to replicate the light field fully optically, this system embeds focus cues into a focus-free image through DoF rendering based on directly measured eye accommodation. As the result, unlike existing OST-HMDs, our system can present focus cues without sacrificing spatiotemporal image resolution. This study shows a new direction of focus cue reproduction in OST-HMDs. We also believe that the integration of OWS into RPDs will open up a new field of OST-HMD technology.

Acknowledgments

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