High-resolution optical see-through vari-focal-plane head-mounted display using freeform Alvarez lenses

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ABSTRACT

With recent developments in the manufacturing of freeform surfaces, Alvarez lenses have recently surfaced as an attractive method to achieve large focal ranges rapidly while still maintaining a compact structure. These characteristics make Alvarez lenses ideal for rendering correct focus cues in virtual/augmented reality (AR/VR), solving the vergence-accommodation conflict. This paper presents a novel design combining a compact eyepiece with two lateral shifting freeform Alvarez lenses to create a compact, high-resolution, tunable see-through head-mounted display (OST-HMD) design capable of optical power shifts from ~ 0-3 diopters. Currently limited by the speed of the actuators that mechanically translates the Alvarez lenses for optical power tuning, the display system is capable of achieving the entire range of focus shift with an update rate of 50Hz. The proposed design renders near-accurate focus cues with high image quality and a large undistorted see-through field of view (FOV), utilizing an 1920x1080 color resolution organic LED (OLED) microdisplay to achieve virtual display FOV greater than 30 degrees diagonally, with an angular resolution less than 0.85 arcminutes per pixel and an average optical performance of > 0.4 contrast over the full field and a contrast above 0.2 at the Nyquist frequency of 63 cycles/mm.

Keywords: Alvarez lenses, vari-focal-plane head-mounted display, augmented reality, freeform

1. INTRODUCTION

One of the major issues facing head-mounted displays (HMDs) today is its inability to render correct focus cues for viewers. Commonly known as the vergence-accommodation conflict (VAC), this problem plays a major role in user visual discomfort [1,2]. Recently there have been several different attempted solutions to alleviate the VAC problem: volumetric displays [3], holographic display [4], multi-focal-plane displays [5-9], and light field displays [9-13]. Notwithstanding, vari-focal-plane display technology still offers a promising solution to the accommodation-convergence mismatch problem, in which a variable lens is used to change the system’s optical power to match the viewer’s natural accommodation so that the 2D perspective image of the virtual object is at the correct focal plane [14,15]. Most vari-focal displays, however, use liquid-tunable lenses, which tend to be slowly varying in focus with small, clear apertures. Due to its ability to quickly achieve a large vari-focal range with a compact structure, the Alvarez lens has recently drawn much attention in the optics community [15-17]. Alvarez lenses offer accurate and high-speed dynamic tuning of optical power through the lateral shifting of two lens elements, making them ideal for AR/VR applications.

In this paper, we present a design that couples freeform Alvarez lenses with ultra-fast, high-resolution piezo linear actuators to render near-correct focus cues by providing dynamic control of the intermediate focal distance position throughout the extended depth of field, corresponding to a shift from 0-3 diopters. An OLED microdisplay is used for the virtual display path to achieve a 30 degree diagonal FOV and 1920x1080 pixel resolution, with an optical performance of greater than 20% modulation contrast over the full FOV, analogous to an angular resolution of 0.81 arcmins per pixel.

2. SYSTEM SPECIFICATIONS

Table 1 shows the system specifications. Our design utilizes a 0.7” Sony color OLED microdisplay for the virtual display path. The Sony OLED, having an effective area of 15.5mm and 8.72mm and a pixel size of 8μm, offers a native resolution of 1900x1080 pixels and an aspect ratio of 16:9. Based on the choices of microdisplay, we designed a Vari-focal OST-HMD with a diagonal FOV of 30°, or 26.3° horizontally and 15° vertically, and an angular resolution of 0.81 arcmins per pixel, corresponding to a Nyquist frequency of
63 cycles/mm in the visual space. We also achieved an exit pupil diameter (EPD) of 10mm, allowing eye rotation of about ±25° within the eye socket without causing vignetting of the optical system, and an eye clearance distance of >20mm.

Table 1. Specifications of the System

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Display FOV</td>
<td>~15°(H)×26.6°(V)</td>
</tr>
<tr>
<td>See-through FOV</td>
<td>~30°(H)×110°(V)</td>
</tr>
<tr>
<td>Entrance pupil diameter</td>
<td>10mm</td>
</tr>
<tr>
<td>Display MTF</td>
<td>&gt;0.2 at 63 cyl/mm for the full FOV</td>
</tr>
<tr>
<td>Display DOF</td>
<td>~ 0-3 diopters</td>
</tr>
<tr>
<td>Shift frequency</td>
<td>150Hz per diopter</td>
</tr>
<tr>
<td>Wavelengths</td>
<td>B:465nm G:550nm R:615nm</td>
</tr>
<tr>
<td>Microdisplay</td>
<td>1920(H)×1080(V)</td>
</tr>
<tr>
<td>Eyepiece</td>
<td>33mm focal length</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>0.81 arcmin</td>
</tr>
<tr>
<td>Eye clearance</td>
<td>20mm</td>
</tr>
<tr>
<td>Piezo linear actuator</td>
<td>PI® M-633.4U Piezo linear stage</td>
</tr>
<tr>
<td>Actuator size</td>
<td>35mm (L) x 35mm (W) x 15mm (H)</td>
</tr>
<tr>
<td>Actuator resolution</td>
<td>0.1 um</td>
</tr>
<tr>
<td>Actuator repeatability</td>
<td>0.2 um</td>
</tr>
<tr>
<td>Relay group</td>
<td>1:1, 31mm focal length</td>
</tr>
</tbody>
</table>

3. Optical Design and Optimization

Figure 1 shows the optical layout of our proposed design, which can be divided into three major parts: the eyepiece, the Alvarez lens group and the 1:1 relay.

The eyepiece design uses 4 stock lens, a stock beam splitter (BS) and cold mirror to create a folded, compact optical path that magnifies the intermediate image and projects it onto the retina. A cold mirror is used not only to fold the optical system but because it allows for a potential eye-tracking path needed for a vari-focal display. Off-the-shelf components were used to create an affordable alternative to an otherwise expensive freeform prism.
The design utilizes two symmetric freeform lenses, which were optimized using CodeV’s xy polynomial terms to the 4th order, to change the optical focus of the system from 0 to 3 diopters in the virtual space. Each 0.83mm linear translation corresponds to a 0.5 diopter shift in focus, giving an overall linear translation of 5.03mm for a 3 diopter shift.

A 1:1 relay made up of 6 symmetrical aspherical lenses was used to relay the pupil location of the eyepiece. To match the relay with the intermediate image, a double telecentric system was designed. The Alvarez lens group was then placed at the intermediate pupil location, to ensure that no change occurred in the system’s chief ray angles for the extended depth of field, allowing the system to maintain a high spatial resolution and constant angular magnification.

Figure 2 shows the optical layout of the finalized Vari-focal OST-HMD design for an optical shift of 0.5, 1.5 and 3 diopter shifts in the virtual image space. For each 1.667mm lateral shift of the freeform surfaces, the intermediate image plane is roughly shifted 1mm toward the entrance pupil, corresponding to a 1 diopter shift in the virtual image plane.

![Figure 2](image1.png)

Figure 2. The finalized optical layout of the Vari-focal OST-HMD design with its virtual image at a depth of (a) 0.5, (b) 1.5 and (c) 3 diopters.

Figure 3 shows the top view of the stereo system fitted to an average-sized human head. The overall length of the stereo system is 200mm, with a depth of 95mm and an intraocular distance of 63mm.

![Figure 3](image2.png)

Figure 3. The optical layout of the system, fitted to an average-sized human head (top view).

For the proposed prototype of the Vari-focal OST-HMD design, a PI® M-633.4U Piezo linear stage was used as the electronic linear actuator to drive the lateral shift of the Alvarez lenses. Figure 4 below shows relative size of the linear actuator.
stage with respect to the 3D model of the stereo, vari-focal plane, OST-HMD prototype. Each stage offers a translation speed of 250mm/s, thereby producing a 50 Hz transition from a 0-3 diopter virtual image shift and a 150Hz transition for a 1 diopter virtual image shift. In the prototyped system, the eyepiece lenses were cropped to achieve an eye clearance of 20mm and a 10mm EPD. Fig. 4 shows monocular mechanical mount of the vari-focal plane OST-HMD while fig. 4(b) stereoscopic fully assembled prototype in relation to an average size human head.

4. SYSTEM PERFORMANCE

To achieve high optical performance, the three major parts of the system (mentioned in section 3) were optimized together for 9 intermediate focal planes. Nine was chosen as a sufficient number of focal planes to create a smooth transition of the optical performance throughout the extended depth of field.

Figure 5 shows the polychromatic modulation transfer function (MTF) curves, evaluated with a 3mm eye pupil, for several weighted fields of the virtual display path for a focal shift of 0.5, 1.5 and 3 diopters, respectively. The virtual display path preserves roughly 40% modulation at the designed Nyquist frequency of 63 cycles/mm, corresponding to the 8μm pixel size of the OLED display. Figure 6 plots the distortion grid of the virtual path, covering the full FOV for 0.5, 1.5 and 3 diopters. The design shows <3% distortion over the full field for the extended depth of field. This small amount of residual distortion can easily be corrected by image processing to pre-warp the original image.
Figure 5. MTF plots of the display path with its virtual image at a depth of (a) 0.5, (b) 1.5 and (c) 3 diopters.

Figure 6. Distortion grid of display path for full field with its virtual image at a depth of (a) 0.5, (b) 1.5 and (c) 3 diopters.
Figure 7 shows the toleranced freeform Alvarez lenses after they have been mounted to the linear actuators for each translation position. Each linear actuator has a step resolution of 100nm and a repeatability resolution of 200nm. As shown in Fig. 7, the system MTF sensitivity due to the freeform surfaces, mechanical mounts and linear stages is negligible.

![Figure 7: Tolerance of freeform Alvarez lenses based on actuator repeatability and resolution for a (a) 0.5, (b) 1.5 and (c) 3 diopter focal shift.](image)

5. CONCLUSION

This paper presents a novel design of a vari-focal optical see-through head-mounted display system using freeform Alvarez lenses to dynamically shift the focus of the virtual image plane from 0-3 diopters. A comprehensive description of the design and stereoscopic prototype is included. Our system offers a >30° diagonal FOV and an angular resolution of 0.81 arcmins, with an optical performance of > 0.4 contrast over the full FOV at the Nyquist frequency of the display. By using 9 optimized focal positions, we were able to achieve near correct focus cues over the extended depth of field at a frequency of 150Hz per diopter. This study demonstrates that a vari-focal OST-HMD system using freeform Alvarez lenses can achieve a high optical performance and a compact form factor, offering a promising solution to the VAC problem.

ACKNOWLEDGMENT

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REFERENCES