Design of a wearable wide-angle projection color display

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ABSTRACT

In this paper, we investigate the design and fabrication of ultra-light weight projection lenses for color wearable displays. Driven by field of view requirements from 40 degree to 90 degrees, we employed the combination of plastic, glass, and diffractive optics to yield <10g optics per eye. The approach centers on the use of projection optics instead of eyepiece optics to yield most compact and high image quality designs. The implementation of the fabricated 52 degrees lens in a teleportal head-mounted display and remote collaborative environment is demonstrated. We also present the design results for a 70 degrees design.

Keywords: HMD, lens design, projection lens, diffractive optics

1. INTRODUCTION

Head-mounted display (HMD) is the key component in 3D visualization tasks such as surgical planning, medical training, or engineering design.[1] The main issues of the conventional eyepiece-based HMD technology include the tradeoffs between resolution and field-of-view (FOV) as well as between compactness and eye clearance, the presence of large distortion for wide FOV designs, the conflict of accommodation and convergence, the occlusion contradiction between virtual and real objects, the challenge of highly precise registration, and often the brightness conflict with bright background illumination.[2-5] The concept of head-mounted projection displays (HMPDs) is an emerging technology that can be thought to lie on the boundary of conventional HMDs, and projection displays such as the CAVE technology.[6-10] It has been demonstrated to yield 3D visualization capability with a large FOV (i.e. up to 70 degrees with a flat retro-reflective screen based on current materials), light weight optics, and low distortion, and the correct occlusion of virtual objects by real objects.[11-12] Thus, the research of this technology is being conducted by a few research groups as an alternative to stereoscopic displays for a variety of 3D visualization applications.[13-17]

We have designed and fabricated a pair of projection lenses for the HMPD using a combination of a diffractive optical element (DOE), plastic components and aspheric surfaces, achieving 52 degree FOV with a weight of only 8g and a 15 mm diameter x 20 mm length lens. We also completed a design of the optics which achieved 70 degree FOV. The contribution of this paper is to present the conception, optimization, and assessment of the ultra-light and compact projection optics. We shall first review the HMPD technology and related research before presenting the conception and optimization of the ultra-light and high-performance projection optics. Especially, the performance of the optics will be assessed in both the space of the miniature flat panel display and visual space in order to provide useful metrics to the end-users of the technology as well.

2. REVIEW OF HMPD TECHMOLOGY

The basic HMPD concept was first presented by Kijima and Ojika in 1997,[6] while a patent was also issued on the conceptual idea of the display to Fergason in 1997.[7] Tachi et al. developed a configuration named X'tal Vision and proposed the concept of object-oriented display and visual-haptic display.[14,17] Independently, the technology of HMPD was developed by Parsons and Rolland as a tool for medical visualization.[9,18]

A HMPD, conceptually illustrated in Fig.1, consists of a miniature projection optics mounted on the head and a supple, non-distorting and durable retro-reflective sheeting material placed strategically in the environment.[10] Inside the HMPD a miniature display located beyond the focal point of the lens is used to display computer generated images. Using a miniature and light-weight projection lens to project an image into the environment, a sheet of retro-reflective material was used to reflect the rays of light back on themselves in the opposite direction, then through a 50/50 beamsplitter placed at 45° with respect to the optical axis in order to bend the rays and image the exit pupil into the users eye. A user can perceive the virtual projected image from the exit pupil of the optics. Ideally, the location and size of the image is independent of the location and shape of the retro-reflective screen. Furthermore, rays hitting the retro-reflective surface will be reflected independently of the incident angle.

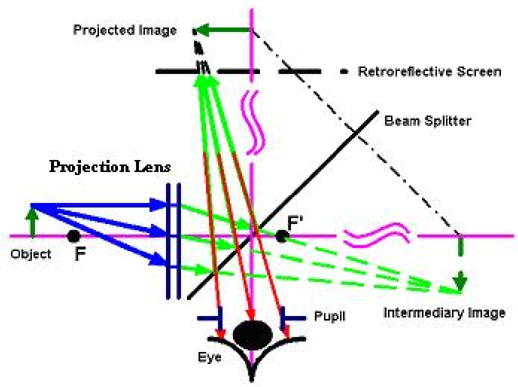

Figure 1: Schematic layout of the HMPD imaging.

Unique to the technology is the property of the technology to provide an optical see-through capability in spite of the screen. The HMPD technology also provides intrinsically correct occlusion of computer-generated virtual objects by real objects. Moreover, compared with conventional eyepiece-based optical see-through HMDs, the utilization of projective optics allows for reduced optical distortion across similar FOVs. Finally, required eye clearance/relief can be achieved by simply adjusting the separation between the beamsplitter and the projection lens without increasing the size of the optics.

3. DESIGN OF A 52 DEGREE OPTICS FOR HMPD

Since the optics of HMPD is a binocular system which consists of two identical optical lenses, for the optical design we simply design one of them and we limit the size of the lenses so that they will not interfere wtih the adjustment of inter-pupil distance (IPD). The difference in the design of a projection lens for the HMPD from other common projection optics is the requirement for light weight and compactness. In the optical design of the HMPD, we employed a combination of plastic, glass, and diffractive optics in order to reach light weight and compactness. The miniature display selected based on availability and cost was a 1.3" backlighting color AMLCDs with (640*3)*480 pixels and 42-um pixel size. Given the miniature display, wide field-of-view (FOV) and high resolution are always two contradictory but desirable requirements.[19] Besides the consideration of resolution, there are two aspects of limitation on the targeted FOV. One aspect is that a flat beam splitter imposes a maximum FOV of 90 degrees. The other aspect is the significant retro-reflectivity drop-off of currently available retro-reflective materials beyond ±35 degrees of incidence, which imposes an upper limit of 70 degree on FOV for a flat retro-reflective screen.[10,15]

Table 1 summarizes the overall design specifications for the 52 degree optics for the HMPD. The starting point of this design is a patented 7-element lens by Hideki Ogawa,[20, 21] which consists of a 51.75mm F/1.46 apochromatic double-Gauss lens with a two-layer diffractive surface on a plane-parallel substrate. To reduce the number of elements to achieve ultralight weight and compactness, first we eliminated the diffractive plate, and then substituted two doublets with one aspheric lens and one diffractive optical element (DOE). This reduced the number of element to 4. Both the aspheric and DOE lenses are made of plastic. The overall weight of the lens system is 8 grams. Figure 2 shows the layout of the optical system.

The purpose of employment of DOE is to correct the secondary spectrum and residual spherical aberrations for apochromatic imaging, in place of using high-index lanthanum crown glasses.[20-22] The detail of the design of diffractive optics in HMPD has been described extensively by Hua (Applied optics 2002).[23]

Parameter	
Object: Color LCD	1.3 inch in diagonal
a. Size	1.3 inch in diagonal
b. Active display area	Square, 26.4mm x 19.8mm
c. Resolution	640 x 480 pixels
Lens:	
a. Type	Projection lens
b. Effective focal length	35 mm
c. Entrance pupil diameter	12 mm
d. Eye relief	25 mm
e. No. of diffractive surface	1
f. No. of aspheric surface	1
Other parameters:	
Wavelength range	656 to 486 nm
FOV	52.4° in diagonal
Distortion	<2.5% over the entire FOV

Table1: Specifications for 52 degree optics

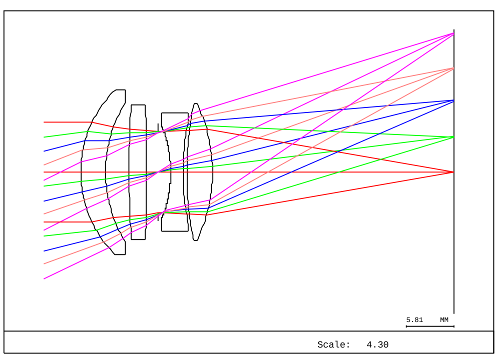

Figure 2: Layout of the 52 degree projection lens

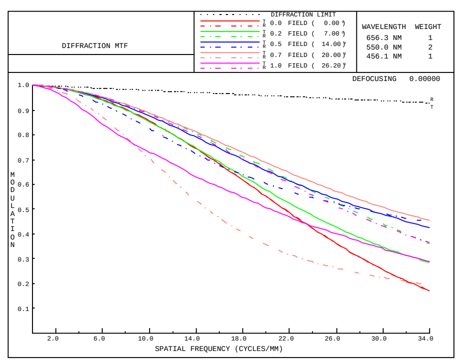

Figure 3: MTF curves for the 52 degree projection lens

The polychromatic diffraction modulation transfer function (MTF) for the full 12-mm pupil is presented across the five representative field angles, shown in Figure 3. The target LCD display (see Table 1) has a spatial frequency of 12lp/mm given a 42-um pixel size. We note that the modulation ratio of the presented design at 12lp/mm is about 60% across the FOV. Therefore, the performance is currently limited by the miniature display resolution. In the HMD optics, the main aberrations fall into astigmatism and image defocusing. A perfect point on the miniature display can either be displayed in visual space as a blurred spot or as an elongated line due to these aberrations. Usually these aberrations are evaluated on the plane of the miniature display, but the result of the assessment can not give direct information to the end users for task-based performance. To help bridge the gap between the optical design engineers and the perceptual scientists, we developed a framework for the comprehensive assessment of HMDs in visual space.[24] Figure 4 shows the accommodation-shift which describes the defocusing of the image across the FOV. Each circle in the plot represents the blurred spot in arc minutes in users' visual space. The size of each blurred spot is described as an angle subtended by the user's 3-mm eye pupil, and according to the distance of the image in visual space. If the angle is smaller than human acuity, which is one arc minute, the aberration will not be detected by human eyes. As shown in the center of figure 4, all the blurred dots smaller than 1 arc minute are set to zero. Similarly figure 5 shows the astigmatism in visual space across the FOV in term of arc minutes and the direction of the lines show the direction of which a perfect point would be elongated in visual space. The result shows that across the FOV, the accommodation-shift and astigmatism are less than 4 arc minutes. This confirms that the performance is currently limited by the miniature display resolution.

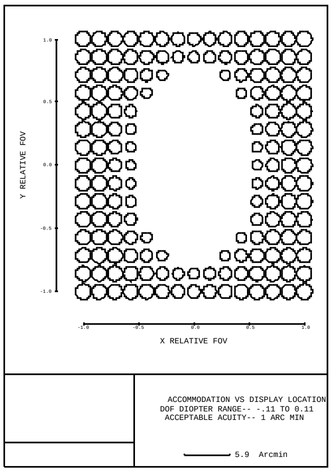

Figure 4: Accommodation-shift in arcmin

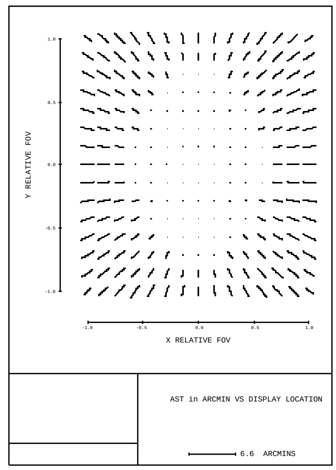

Figure 5: Astigmatism in arcmin

After designing the system, the optics was fabricated. Figure 6 shows the lens assembly and Figure 7 is a photo of the HMPD which was built based on the optics we designed in our lab. The testing of the HMPD showed excellent image quality with the projection optics and the retro-reflective screen as predicted.

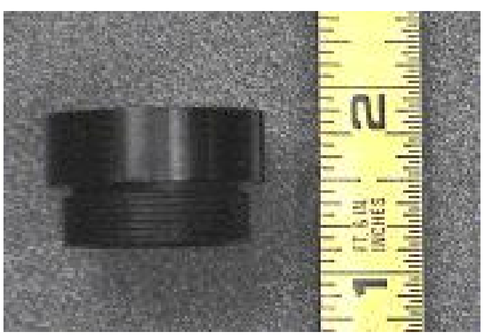

Figure 6: Lens assembly

Figure 7: Head mounted projection display

4. DESIGN OF A 70 DEGREE OPTICS FOR HMPD

To explore the scalability of the previous 52 degree projection lens, given the retro-reflective angle range of the current screen material, we designed a 70 degree optics with the specification shown in table 2.

As shown in Table 2, we employed the same LCD for the miniature display, and the FOV was set to 70 degree. We adopted the 52 degree lens as the starting point, and scaled the lens to 70 degree. Unlike eyepieces which are common in traditional HMDs, the pupil of the HMPD lens is inside the lens, therefore the weight of the lens does not scale as the cubic value of the FOV. To compensate the aberrations due to increased FOV, we substituted the aspheric surface in the previous design with another diffractive surface.

Figure 8 shows the layout of the design result. The two elements around the pupil surface are DOE lenses made of plastic. This keeps the system still ultralight and compact. The weight of the optics is about 7 grams and the size of the optics is about 17 mm in diameter by 16 mm in overall length. Figure 9 is the polychromatic MTF curves of the optical system. The result shows that this design parallels the previous one with an increased FOV.

Parameter	
Object: Color LCD	1.3 inch in diagonal
a. Size	1.3 inch in diagonal
b. Active display area	Square, 26.4mm x 19.8mm
c. Resolution	640 x 480 pixels
Lens:	
a. Type	Projection lens
b. Effective focal length	23.9mm
c. Entrance pupil diameter	10mm
d. Eye relief	25 mm
e. No. of diffractive surface	1
f. No. of aspheric surface	1
Other parameters:	
Wavelength range	656 to 486 nm
FOV	70.0°
Distortion	<2.0% over the entire FOV

Table 2: Specification for 70 degree optics

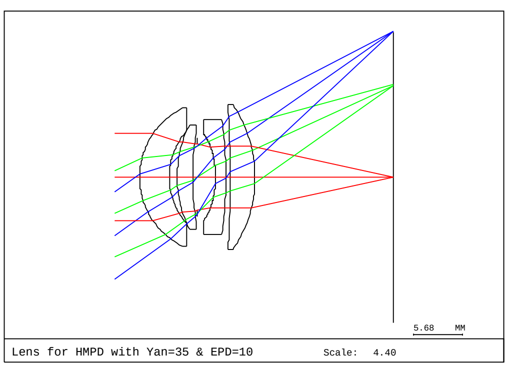

Figure 8: Layout of the 70 degree projection lens

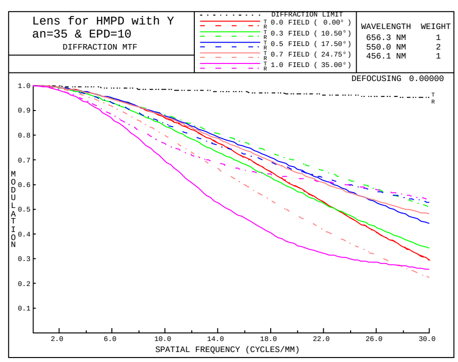

Figure 9: MTF curves for the 70 degree projection lens

5. CONLUSION

Projection optics offers unique solutions for compact light-weight designs for wearable displays. Furthermore, it offers the unique capability to scale field of view to large angles in the order of 70 degrees without cubic scaling of the weight of the optics as a consequence. The main contribution of this paper was to present the conception, design, and assessment of an ultra-light and compact projection lens using the combination of diffractive optical elements, plastic components, and aspheric surfaces for a new generation of HMPD prototypes. Two designs have been presented, one for 52 degrees and one for 70 degrees. The analysis of the system in visual space shows that the resolution of the optics itself parallels the human acuity around the center of the FOV and is smaller than 4 arc minutes at the edge of the FOV. The analysis of the lenses with respect to the miniature display shows that the latter currently limits the resolution to 4 arc minutes.

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