Dual-element Off-axis Eyeglass-Based Display

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Abstract: We describe the optical system design and analysis of a wearable dual-element off-axis display based on a magnifier form that supports an 8mm exit pupil and a 20 degree diagonal full field of view.

OCIS Codes: 220.4830 (Optical systems design); 230.4040 (Mirrors)

1. Introduction and related work

Eyeglass-based displays are expected to become a primary visual display option for future wearable computing platforms. There has been several prototypes in the area of eyeglass-based displays. Example of previous designs include the work by Bettinger[1], Spitzer[2] and Kasai[3]. A comprehensive review of designs in the eyeglass form-factor is provided in [4]. In this paper, we explore the possibilities in terms of minimizing the optical element count, having an acceptable exit pupil size and field of view, while having the system operating throughout the photopic visible spectrum. We are focusing on alternatives to holographic optical elements or total internal reflection based waveguiding techniques which also have a potential to be adapted to eyeglass-based displays. A key to low element count is the exploitation of higher degrees of freedom surface shapes for both optical elements while keeping fabrication and design sensitivity limitations in mind. The design presented in this paper is based on a 12-th order aspheric lens with a diffractive optical element and an X-Y polynomial mirror to 4-th degree.

2. First order optical layout

The wearable display presented in this paper is based on a magnifier optical design form. Our design goal can be summarized as building a display that would provide the viewing of a 14" diagonal laptop screen with a 4:3 aspect ratio at one meter distance. Such a requirement would result in 16 degrees full field in the horizontal direction. Parameters relevant to the first order layout of the display as well as the optical system specification are listed in Table 1.

We aim to design an 8mm exit pupil size to allow eye movements. The distance between the center of rotation and the vertex of the cornea is 12.25mm. The distance between the center of the entrance pupil and the vertex of the cornea is 3mm. Therefore, assuming an 8 mm exit pupil, and assuming 50% vignetting, our design supports eye motions of about ±23 degrees. We should note that the pupil of the human eye varies from 2mm under bright sunlight to 8mm in the dark, a typical operational characteristic is around 3-4mm. We specify the spectral band to reside within the photopic regime of the spectrum defined between 490-635nm.

3. Optical system design

It is desirable to achieve the optical design specifications given in Section 2 by using the minimum number of elements to achieve a compact design suitable for the eyeglasses form factor. In Section 4 and 5, we report on the design and assessment of two potential designs: one based on a single element and the other based on dual elements. We document the performance achieved for a single element conventional eyepiece utilizing an x-y polynomial as the freeform surface descriptor, targeting the specification listed in Table 1. A dual element design can achieve the specifications given in Section 2.

International Optical Design Conference 2006, edited by G. Groot Gregory,
Joseph M. Howard, R. John Koshel, SPIE Vol. 6342, 63420W,
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Table 1. Primary microdisplay parameters of interest and optical system specification

Microdisplay parameters			
Display technology	Active Matrix Liquid Crystal	Display panel active area	9.024mm x 6.768mm (4:3 aspect ratio)
		Display interface	Analog RGB
Display mode	RGB stripes on 4.7 x 14.1 µm color dot pitch	Display format	640 (H) x 480 (V)
Display panel diagonal	11.28mm	Power consumption	Not specified in datasheets
Optical System Specification			
Wavelength range	Photopic spectrum 490-635nm	Y-Field of View	12 degrees
		X-Field of View	16 degrees
Effective focal Length	32 mm	Exit pupil size	8mm
Diagonal full field of view	20 degrees	Eye clearance	between 15 and 25mm

4. Single element design

In a single element see-through eyeglass display design one option is to collimate the light collected from the microdisplay and deliver it to the eye by placing the microdisplay at the focal length of the mirror. In terms of constraints, we require at least 17mm eye clearance, maintain the focal length of 32mm, and we require that there is enough tilt to fold the optical path around a human head. We need to move the microdisplay out of the folded optical path and provide enough clearance around a human head by tilting the mirror horizontally or vertically. The optical consequence of increasing the mechanical tilt angles is the increase in the magnitude of aberrations.

The system shown in the X-Z plane in Fig. 1(a) has an 8 degree tilt in the x direction. From the layout shown it is clear that this configuration will not work. Thus even further tilt is necessary to avoid vignetting and provide the necessary clearances. Nevertheless, we analyzed the performance and the modulation transfer function plot is shown in Fig. 1(b) up to the maximum spatial frequency of about 40 cyc/mm based on a 12µm pixel pitch in the denser dimension.

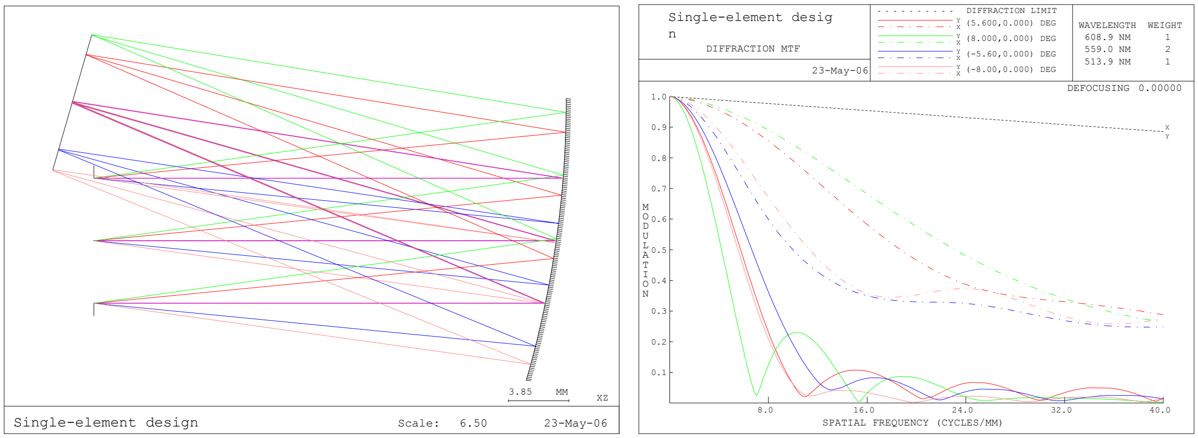


Fig. 1. (a) Optical layout of the single element eyeglass-based display design (b) Modulation transfer function

5. Dual element design

In some optical systems, for analysis and design purposes, especially telescopes, it is possible to conceptually split the aberrations into aberrations influenced by the field and the location of the pupil. At the pupil, the chief ray height is zero and at the image plane the marginal ray height is zero. Therefore, the elements close to the image plane are in a position to impact the field aberrations and elements closer to the pupil can correct aberrations such as spherical aberration and axial color. In the dual element design, we add a lens closer to the image to correct for the field aberrations. The dual element optical system consists of, from the long to the short conjugate, the pupil of the eye, the mirror with the X-Y polynomial surface, and the aspheric lens with a diffractive optical element. The MTF at eight edge fields shown in Fig. 2 achieves 10% contrast at 40 cyc/mm.

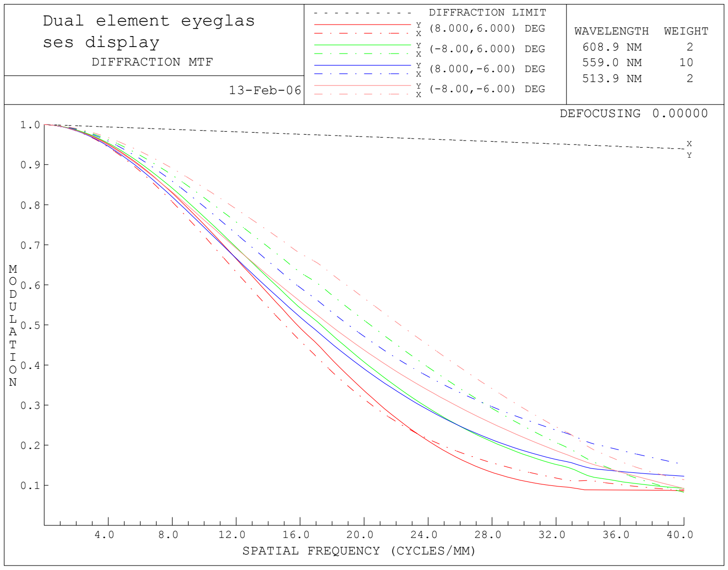


Fig. 2. Modulation transfer function at the edge fields

The minimum feature size for the diffractive optical element is about 19 µm. The minimum feature size was estimated by calculating the difference of radial zone height at the maximum zone and the radial zone height prior to the maximal zone. The scalar diffraction efficiency at the reference wavelength of 550nm is shown in Fig. 3.

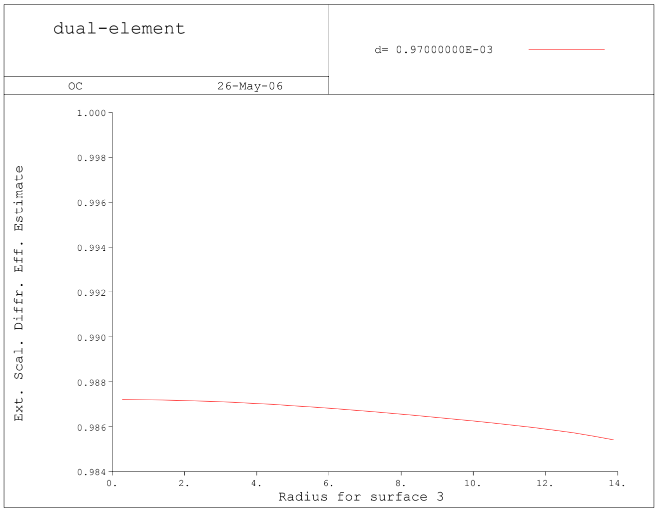
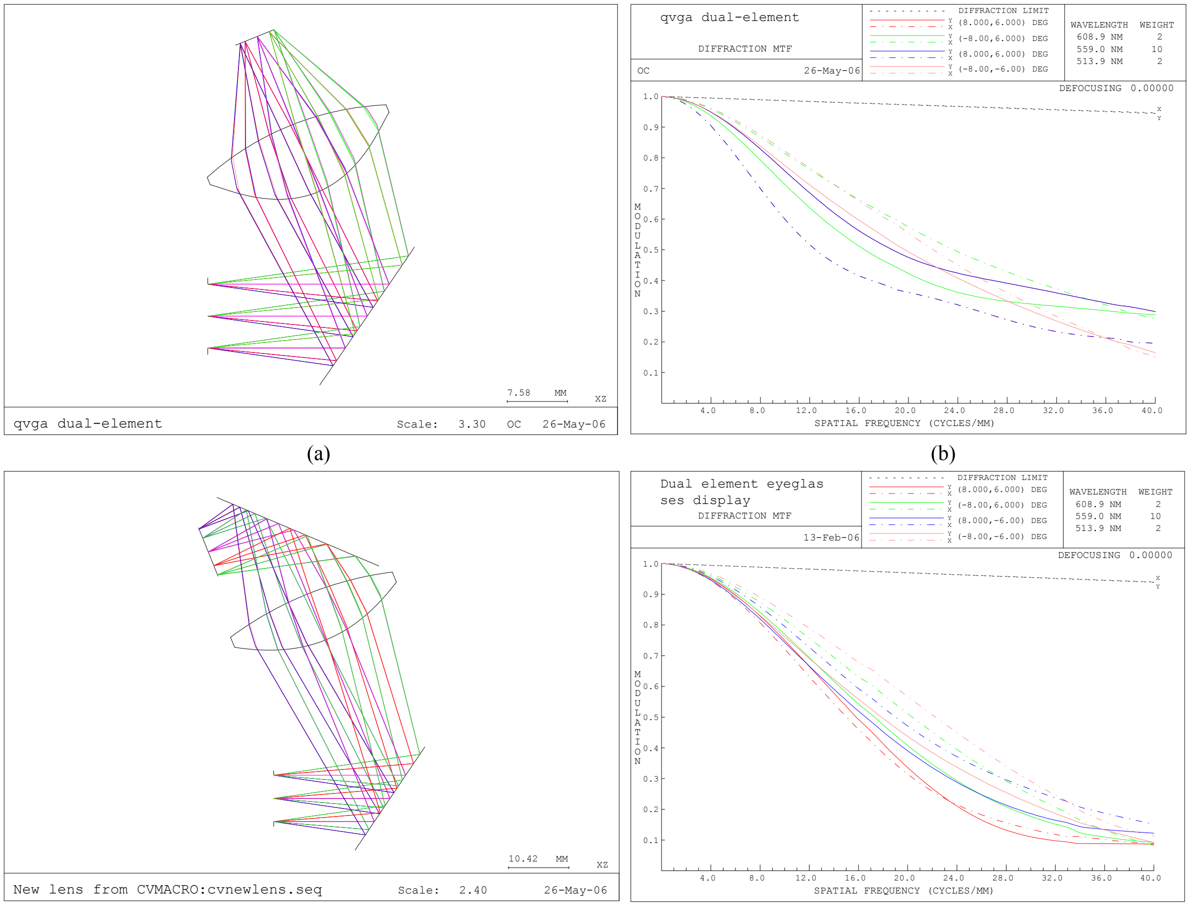
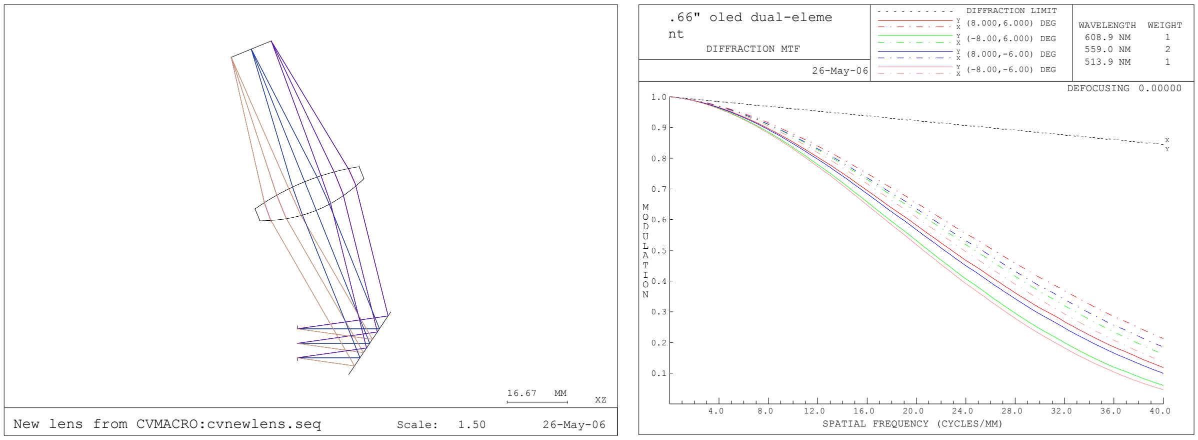


Fig. 3. Diffraction Efficiency at the wavelength of 550nm



(a) (b)

(c) (d)



(e) (f)

Fig. 4. (a) Optical layout of the .25" quarter-vga system (b) MTF of the .25" quarter-vga system (c) Optical layout of the .44" vga system (d) MTF of the .44" vga system (e) Optical layout of the .66" SVGA system (f) MTF of the .66" SVGA system

As the diagonal length of a microdisplay increases, for a fixed field of view, the focal length increases and the corresponding total optical power decreases yielding less curved surfaces as shown in Fig. 4 (a)(c)(e). Going from a .44" to a .66" microdisplay, we have seen that the design performs better due to the reduced angles of incidences on the surfaces.

We should note that the system shown in Fig. 4(e) does not include a fold mirror, however, this system is longer than the one shown in Fig. 4(c) and Fig. 4(a). For a compact design, it would be necessary to include a fold mirror if a .66" microdisplay is to be used in a certain application. We did not include the fold mirror since the system becomes longer than intended for our application. However, the analysis shown above holds without the inclusion of the fold mirror.

6. Opto-mechanical design

During the design of this display, we utilized the U.S. Army CAESAR database [5] which includes 200 male and 200 female laser-scanned human bodies. Using the CAESAR dataset, it has been possible to evaluate the display as it would be worn around the head. This data set comes with a corresponding landmark file for each scan subject. Early in the ergonomics effort, software written to perform statistical analysis and subject-to-subject alignment was compromised by flaws in the landmark data file. Many subjects had dramatically incorrect landmark references. Since the time available for this portion of the work was limited, and we opted to pursue an alternative method by selecting a few subjects at the extremes of inter-pupillary distance, head width and length. The data for these subjects was converted to a CAD compatible format, imported into an industry standard CAD program and aligned by hand. By designing the HMD superimposed over these extreme head shapes we were confident that the design will fit the vast majority of North American Adults.

The minimal tilt angle of about 34 degrees that folds around the human head in the x-direction has been found through iterations between the optical design and a mechanical CAD software. We exported a 3D model of the optics into a mechanical CAD package for each candidate optical design and evaluating the physical clearances around the head. Fig. 5 shows a potential opto-mechanical design for a quarter-vga microdisplay with 320x240 pixels. We refer to the configuration shown in Fig. 5 as 'horizontal mounting'. We also designed a system utilizing a vga microdisplay 640x480. The barrel is envisioned to be designed in acrylic, has an estimated volume of about 25cc, and has an estimated weight of about 35 grams (housing weight). Alternatively the optics can be mounted vertically. If designed properly, a minimal vertical mounting scheme would leave our peripheral vision unblocked, avoiding a tunnel vision effect. However, a vertical mount requires a higher tilt angle and is slightly more challenging to design.

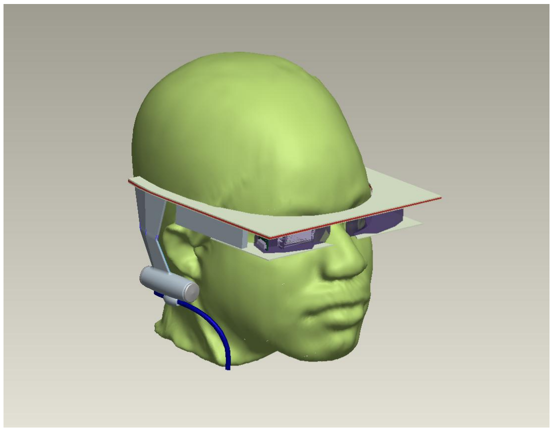


Fig. 5. Opto-mechanical design of a quarter-VGA resolution display

An important finding in this study is that ideal size for a microdisplay for eyeglass-based applications should reside between a .25” diagonal length to .44” diagonal length. For microdisplay sizes between .25” and .44”, if the microdisplay has vga resolution (640x480 pixels), the optics would need to support spatial frequencies of upto around 80 cyc/mm which is challenging.

7. Fabrication

Currently, the fabrication of the freeform mirror and the lens is in progress. The shape of the tilt-removed freeform surface is shown in Fig. 6. The sag range of the x-y polynomial mirror is about 80µm at a 23mm diameter. It has been possible to fabricate this mirror using a Moore 350 UPL with c-axis (slow slide servo). We have also seen that most of the surface sag range is contributed by the tilt terms (e.g., linear x and y), therefore, it should be possible to reduce the surface sag range to by removing the tilt terms from the surface and modifying the tilt angle. It turned out that in this case the surface sag range reduces to about 12 µm. The reduced sag range might help open up alternative fabrication options. In our first iteration we have not taken out the linear x and y terms.

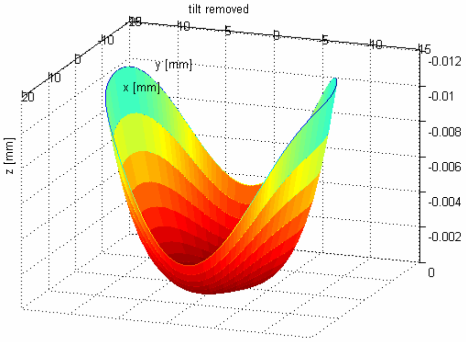


Fig. 6 Plot of the polynomial mirror surface

8. References

[1] Bettinger. Spectacle mounted ocular display apparatus. US Patent 4,806,011. February 21, 1989.

[2] Spitzer et.al. “Eyeglasses-based systems for wearable computing” In Proc. First International Symposium on Wearable Computers (ISWC ’97), Boston, MA, 1997.

[3] Kasai et.al. A Forgettable Near-eye Display. In Proc. 4th International Symposium on Wearable Computers (ISWC 2000), Atlanta, GA.

[4] Cakmakci and Rolland. Head-Worn Displays: A Review. Invited article in preparation for the Journal of Display Technology. February 2006.

[5] Computerized Anthropometric Research & Design Laboratory, Warfighter Interface Division, Human Effectiveness Directorate, Air Force Research Labs. http://www.hec.afrl.af.mil/HECP/Card4.shtml. Last visited on July 22, 2006.

9. Acknowledgements

We thank John Isenberg, Dave Hasenauer, Jim McGuire, and Kevin Thompson for technical discussions. We are grateful to Optical Research Associates for providing a travel grant. We would like to thank the Florida Photonics Center of Excellence (FPCE) for funding this research.