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Hybrid Diffractive-refractive 60°-Diagonal Field of View Optical See-through Head-mounted Display*

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Abstract Design of a wide-angle off-axis optical see-through helmet-mounted display (HMD) becomes a challenge since its weight and size are constrained by human factors. Diffractive optics has the potential to play a key role in several areas of head-mounted display. They can reduce size and weight while providing some unique functions that would be difficult to implement with conventional refractive optics. A 60°-diagonal field-of-view, wide spectral band hybrid diffractive-refractive see-through HMD using off-axis optics is proposed. It possesses a 10mm exit pupil diameter and a 22mm eye relief, and satisfies the requirements of human factors. In addition, the chromatic aberration is only 14μm, and the whole optical system is suitable for a 15mm-diagonal color liquid crystal display (LCD) with SVGA resolution.

Keywords Optical design; Binary optical element; See-through; Head-mounted display

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0 Introduction

With the rapid-growth of commercial opportunities, the design and manufacture of various kinds of head-mounted displays (HMDs) become significant. HMDs have found applications in a variety of fields: scientific simulation, military, surgery, remote control, entertainment, and portable workstations. HMD applications typically require one of two HMD configuration types: a direct-view display or a see-through display. Direct-view HMD optics is essentially eyepiece optics which is used to magnify the miniature image source. Generally, the eyepiece functional requirements lead to the optical system with a long eye relief, a large exit pupil and a wide field of view. In addition, because of binocular system a diameter limitation is required to accommodate the interpupillary distance, and because of comfortable requirement of the user the eyepiece should have a small size and a light weight. With pure refractive optics, the optical system can′t meet these requirements preferably. Three hybrid diffractive-refractive eyepieces have been reported previously[1~3].

To augment the visual field of the wearer with information necessary in the performance of the current task, the see-through HMD technology is presented. See-through HMDs contain the means for partially reflecting the display image from an optical surface so that the wearer can view the display imagery (or symbology) as an overlay on the external scene. See-through HMD optical design presents several added challenges over that of direct-view HMD optical design. First, the required display illuminance typically must be higher compared to that for direct-view displays. This is needed so that there is sufficient contrast between the projected imagery (or symbology) and the background scene (e. g. sunlit white clouds, snow, etc). To accomplish it, the brightness of the display must be high and the transmission of the optics from the image generator to the eyes must be controlled to ensure sufficient contrast of the virtual graphical objects when superimposed on a real-world scene. Second, the optical eye relief (i. e. distance from the see-through combine surface to the exit pupil location) needs to be greater so that the eye clearance (i. e. distance from the nearest structure to the exit pupil location) is sufficient. A flat-combiner design consists of a miniature display, eyepiece optics and a flat combiner[4]. The main drawback of a flat-combiner system is the limitation on the maximum field of view to 40 deg, imposed by the minimum required eye relief and the large size of the combiner set by the range of interpupillary distance required. Furthermore, the size and consequently the weight of the eyepiece optics behind the combiner scale with the field of view. A dual combiner, made up from a spherical mirror combined with a half-silvered mirror, may be used to increase the field of view[5]. The main drawbacks are the significant loss in see-through transmission due to the multiple mirror reflections, and the existence of ghost images

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created by spurious reflections off the flat half-silvered mirror. An effective way to minimize ghost images is to use a single, tilted component combiner, as in the flat-combiner system, but with added optical power. This allows wider field of view for the same effective eye relief. However adding power to a tilted combiner, introduces severe optical aberrations. Traditional axially symmetric aberration theory is no longer adequate to describe the image characteristics of the optical system. The most significant aberrations associated with the tilted combiner are binodal astigmatism[6], linear astigmatism, perspective distortion and axial coma.

Considering the unique characteristic of the diffractive optical element, a negative color dispersion coefficient[7,8] and a power of realizing arbitrary phase modulation, one wide spectral band off-axis hybrid refractive-diffractive see-through HMD system with a 60°-diagonal field-of-view, a 22 mm eye relief and a 10 mm exit pupil are designed. The proposed optical system possesses good performances. The see-through transmission of real world and virtual world should be up to 50%. The resolution, determined by the optical system resolution power, is 800×600 and the pixel size is 24 μm. The relative change in accommodation at the edge of the display with respect to the center of the display (assuming the eyes gaze at the center) is only 2 diopters, which is within the range of correction of this display. The diameter is less than 46 mm, which is suitable for the binocular. This head-mounted display not only satisfies the demands of human factors in structure, but also satisfies the need of augmented reality with high resolution.

1 Optical design

The design strategies to correct aberrations of the proposed optical system are: 1) using a generalized combiner surface shape to reduce the bias aberration such as binodal astigmatism and axial coma; 2) tilted and decentered relay lens groups to reduce perspective distortion, linear and binodal astigmatism; 3) using wedge to correct axial coma, linear astigmatism and lateral chromatic aberration; 4) using the negative color dispersion coefficient and the power of realizing arbitrary phase modulation of binary optical element to correct chromatic aberration and higher order aberrations. The optical specifications and layout of the optical system is summarized in table 1 and shown in Fig. 1.

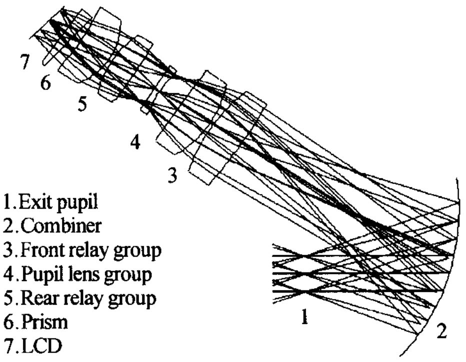

Fig. 1 Layout of the proposed HMD system

Table. 1 Design specification

Parameters	Specification
Object: miniature	
a. Display type	LCD
b. Active display area	15 mm-diagonal
c. Resolution	800×600
d. Color	multicolor
e. Length	88.6 mm
Optical system	
a. Effective focal length	20 mm
b. Exit pupil diameter	10 mm
c. Eye relief	22 mm
Other system parameter	
a. Wavelength range	visible waveband
b. Field of view	48°(H)×36°(V)
c. Vignetting	Unnignetted
image quality	
a. Distortion	Unconstrained
b. Image quality	MTF>20% at 30 lp/mm

Fig. 1 shows that the optical system contains a combiner, a relay lens groups and an image generator (LCD). The relay lens group is a modified triplet lens that has enough inherent degrees of freedom to successfully combat all the Seidel aberrations while maintaining achromatism, which comprises a front-end collimating lens group, a pupil lens group in the middle and a rear-end focusing lens group. The pupil lens group is a plano-concave aspheric lens with the plane surface as the diffractive surface. The tilted combiner and the front-end collimating lens group substantially form an afocal telescope, the afocal telescope relays the exit pupil close to the concave aspheric surface of the pupil lens group to effectively balance spherical aberration, while the binary optical element is used to correct primary and secondary chromatic aberration, spherochromatism and higher order aberration. Consequently, the usable exit pupil is enlarged. The rear-end focusing lens group relays the beams onto the image generator LCD. In addition, the front and rear relay group are tilted and decentered with respect to the optical axis of combiner to correct perspective distortion, linear and binodal astigmatism introduced by the tilted combiner. The prism is also used to reduce axial coma introduced by the tilted combiner.

The system is optimized by virtue of ZEMAX software, and ZEMAX provides a phase surface with an unsymmetrical phase polynomial, described as

$$\varphi(x,y)=k\frac{2\pi}{\lambda}\sum_{i=1}^{m}A_i x^j y^n \qquad i=\frac{1}{2}[(j+n)^2+j+3n] \tag{1}$$

where k is the diffracted order, m is the number of polynomial coefficients in the series and A_i is the coefficient on the i^{th} polynomial term. Let $j=0$ and $n=6$ and solve equation (1) for i, one obtain $i=27$. However, because the design is symmetric about the YZ plane, the odd terms in x are nonexistent, and only exist 15 terms in all. By complementation and quantization, the height of binary surface relief is given by

$$h(x,y)=\text{int}\left[\frac{\text{mod}\,[(\sum_{i=1}^{m}A_i x^j y^n), h_{\max}]}{h_{\max}/N}\right] \tag{2}$$

where $h_{\max}=\lambda/n-1$ denotes the maximum height of surface relief. n is the refractive index of refractive-diffractive lens. N denotes the number of step. Mod () denotes the modulus operator. Int () denotes the integer operator. In addition, the design is symmetric about the YZ plane, requiring optimization across the full field of view in the Y direction but only over half the field of view in the X direction.

2 Design performance

The polychromatic diffraction MTFs for the full unvignetted 10mm pupil are presented for the tangential and sagittal rayfan plots across representative field angles: on axis; vertical fields of 16° and −20°; horizontal fields of 24°; as well as diagonal fields of ±15°(H)×±8°(V). The result is shown in Fig. 2. From these MTF plots, a 30 lp/mm spatial frequency is shown that the MTF value at 0° field of view is greater than 0.3 and greater than 0.2 for all field of view. When the image surface is at infinite, the angular resolution of the proposed optical system is expressed as

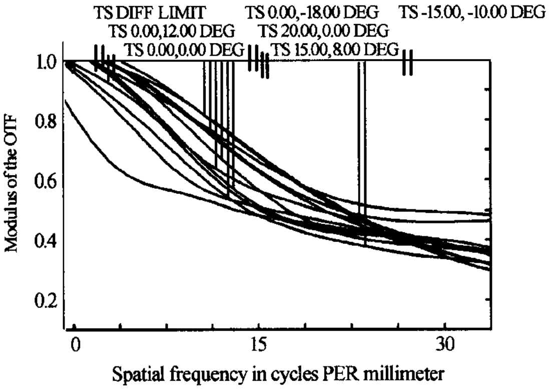

Fig. 2 The MTF of optical system the see-through

$$\theta=\min\left[\frac{2\tan\frac{\omega}{2}}{m},\frac{2\tan\frac{\nu}{2}}{n}\right]\text{(rad)} \tag{3}$$

where ω and ν denote horizontal and vertical full field of view respectively, m and n denote horizontal and vertical pixel number of the active display area (aspect ratio 4:3) of an image source. When a miniature flat panel display (LCD) with 800×600 pixels is used in this HMD, equation (3) can be emplayed to find the angular resolution of the proposed optical system, 0.91 mrad. Because the effective focal length of this proposed optical system is 20 mm, the spatial frequency of the optical system should be up to 27.4 lp/mm to match with the resolution of the LCD. The proposed optical system completely satisfies this requirement.

The field curvature, distortion and axial color of the proposed optical system are shown in Fig. 3.

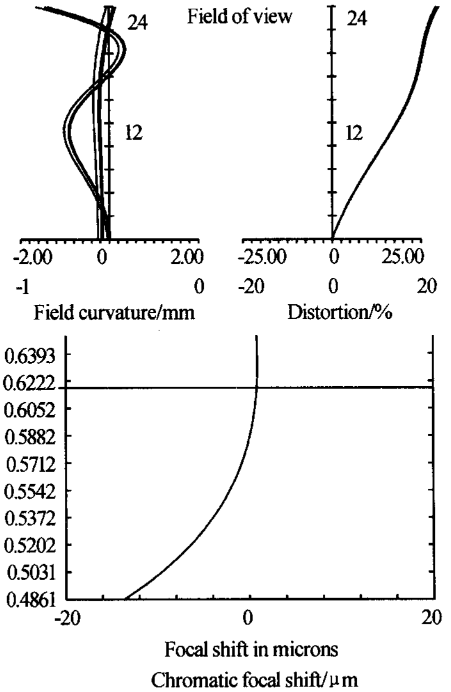

Fig. 3 Field curvature/distortion and axil color error

From Fig. 3, it can be seen that the maximum field curvature is 0.805mm for the tangential and sagittal orientation. Consider the relation between object and image according to Newtonian formula

$$xx'=ff' \tag{5}$$

And diopter is defined as

$$D=\frac{1000}{x'} \tag{6}$$

For the maximum field curvature of the proposed optical system, the corresponding accommodate is

2.01 diopters of focus shift, which is within the range of correction of this display. In addition, Astigmatism can be estimated from the difference in performance between the tangential and sagittal orientations, it is noted that the astigmatism is well balanced over the whole field of view for a pupil of 10mm. From Fig. 3, it can also be seen that the maximum axial color is only 14μm. In addition, the distortion of the optical system is shown in Fig. 3. Distortion can be described as the sum of perspective distortion that occurs uniquely in off-axis designs and the more conventional barrel distortion (plus some higher-order asymmetric component). Since the images are computationally generated, they can be prewarped in such a way as to cancel out the optical distortion generated through the optics. The final computer-generated images are perceived as sharp and undistorted[9,10].

3 Conclusion

The optical system design technologies of the see-through HMD is investigated in this paper. The see-through HMD not only requires the optical system with a wide field of view, a large exit pupil, a long eye relief and a high see-through transmission, but also requires the whole optical system with compact and light structure. Taking the negative color dispersion coefficient and the power of realizing arbitrary phase modulation of the binary element into consideration, it may eliminate the chromatic aberration as well as reduce the high order aberrations of an optical system. The visible waveband off-axis hybrid refractive-diffractive see-through HMD is designed for augmented reality. It possesses good performances and has a 60°-diagonal field-of-view, a 22 mm eye relief and a 10mm exit pupil. The system was analyzed using standard optical design software feature. Within a 48°(H)×36°(V) field of view, results show that the MTFs is larger than 0.2 for 30 lp/mm spatial frequency, therefore, the proposed optical system is suitable for 15 mm-diagonal LCD with SVGA resolution. The relative change in accommodation at the edge of the display with respect to the center of the display (assuming the eyes gaze at the center) is only 2 diopters, which is within the range of correction of this display. In addition, the chromatic aberration of the optical system is only 14 μm, and astigmatism is fairly balanced over the entire field of view for a pupil of 10 mm.

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60°对角视场的折/衍混合透视型头盔显示器

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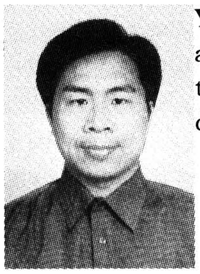
摘　要　分析了离轴、大视场角透视型头盔显示器光学系统的设计方法，提出了利用衍射光学的独特性质设计了大视场、宽波段、离轴折/衍混合透视型头盔显示器光学系统．该系统具有10 mm的出瞳直径和22 mm的出瞳距离，且满足人因素要求．另外，该系统色差仅14 μm，系统口径小于46 mm，满足双目视觉要求．整个系统适合具有15 mm对角直径SVGA分辨率的彩色液晶显示器（LCD）．

关键词　光学设计；二元光学元件；透视；头盔显示器



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