Design of freeform surface optical component in helmet mounted display

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ABSTRACT

Helmet display (HMD) is the core hardware of virtual display technology. It is a small display device mounted on the helmet to produce visual images for the user. The MHD system mainly consists of an image source, optical, and support system. Still, the traditional optical subsystem cannot achieve the functions of the ideal optical system, such as being light-weight, small in size, and having an extensive field angle. This paper established the proper initial model, and the optimal control conditions and surface upgrade strategy were determined. Herein, the design scheme of the free-form prism with good performance was obtained. We solve the feature of large volume and complicated structure of optical components of helmet display and describe the design idea of free-form prism in detail. In this paper, the system resolution we designed is 800 × 600, the Modulation transfer function (MTF) value of the prism is more significant than 0.1 at the spatial resolution of 30 lp/mm, and the distortion is less than 5%. The exit pupil diameter of the system is 8 mm, and the field angle is 26°×20°.

Keywords: Helmet display; Optics freeform; Surface; Optical design.

1. INTRODUCTION

With the development of science and technology, helmet display has been widely used in medical, entertainment, and military fields [1]. It requires the optical lens to be light in quality and compact in structure, and the traditional coaxial, optical system is difficult to meet the user's higher and higher requirements. Also, using a free-form prism to design the optical system in helmet displays is becoming increasingly common. Introducing a free-curved prism simplifies the optical system from a group of coaxial lenses to a single prism, thus reducing mass and volume [2-4]. At the same time, introducing a free-form surface in the optical system increases the degree of freedom in the design optimization process, which can better correct the system aberration. However, the factors that need to be considered in the optimization process also increase, and the optimization results and efficiency are poor [5, 6]. The advantages of the head-mounted display made it the most advanced device in modern warfare in just a few years [7]. Today, the superiority of war equipment determines the war's outcome, and it is necessary to strengthen the research, development, and optimization of the leading core equipment. The helmet display has become the core equipment of the modern air force [8, 9]. The research on the optical system of helmet displays in China has been strengthened based on traditional helmet displays [10]. The optical system is the most important in HMD. Still, the traditional optical system can't achieve all features of the ideal optical system simultaneously, such as light-weight, small volume, and large field of view. Herein, the optical system miniaturization of helmet displays is designed and studied. Elaborating on the design steps and methods of free-form surface prism in HMD establishes the appropriate initial model. We determine the proper optimal control conditions and the surface upgrade strategy to get the design proposal of the free-form surface prism, which has high imaging quality. With the development of science and technology, the improvement of user experience and the needs of future air combat, the performance requirements of helmet mounted displays are becoming higher. Compared with previous research results, the HMD in this design is developing towards miniaturization, light-weight and high performance. Therefore, its internal optical system can achieve high imaging quality with a compact structure

2. DESIGNS AND METHODS

2.1. Design principle of optical free-form surface prism

Up to now, the optical system of HMD has been continuously improved to meet users' requirements to the greatest extent. Among them, it constantly reduces the weight of system components, increases the field angle of view of the system, and improves the perspective function so that the helmet-mounted display can serve users more conveniently and accurately. In addition, the practical application also requires that the optical components not only have high optical performance (distortion, minor aberration, and high resolution) but also reduce the energy loss in the process of light propagation. Figure 1 shows the diagram of the freeform prism.

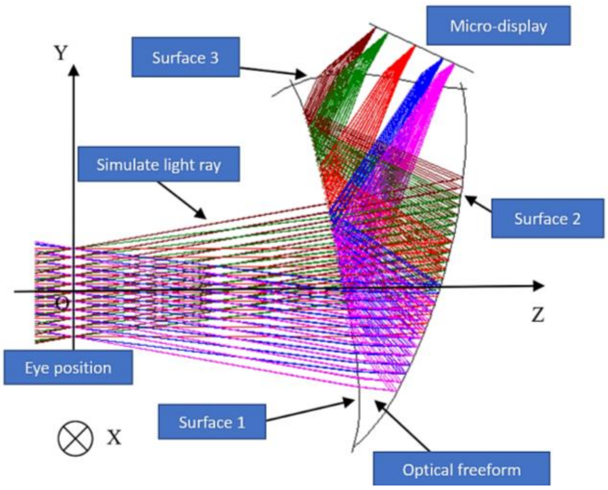


Figure 1. *Diagram of the freeform prism.*

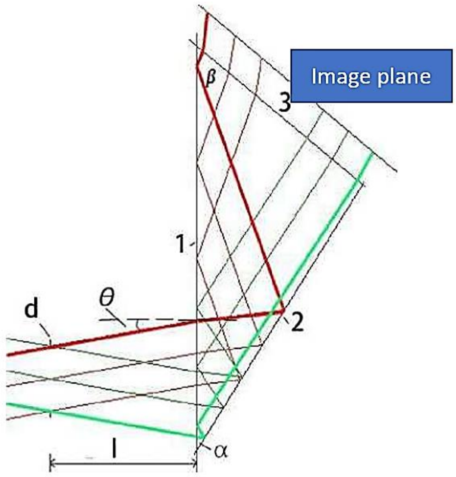


Figure 2. *Diagram of the initial structure of the prism.*

In the specific system design, designers often use the reverse design method, that is, the actual use of the position of the eye as the position of the aperture. Thus, the light enters from the aperture position and is then focused through the prism on the image plane, the microdisplay plane. Among them, the rear surface is a reflective surface, which needs to be coated with a reflective film. In order to ensure that the light can reach the phase surface along the above route, it is necessary to ensure that the angle of incidence of the light passing through the front surface is greater than the total angle of reflection of the material. Where, $\theta = sin^{-1}(1/n)$, n is the refractive index of the prism material. Through practical experience, we know that the incident angle of light is easy to meet the requirements, but the total reflection angle is difficult to achieve. This requires that the total reflection angle of the material is as small as possible, that is, the refractive index of the material is as large as possible. However, due to the refractive index material corresponding to the abbe number is relatively large, and the system is a single-lens structure, cannot correct the color difference. Therefore, from this point of view, the smaller the refractive index of the material, the better to adjust the color difference. Finally, under the careful consideration of imaging quality and economical cost, the material was selected as Poly(methyl methacrylate) (PMMA) with a refractive index of 1.492 and Abbe number of 57.2. In this paper, when designing an optical free-form prism, the miniature projection screen uses an OLED screen with a screen size of 0.61 inches and a resolution of 800*600. Combined with the characteristics of human eye observation, the MTF value of the prism is greater than 0.1 at the spatial resolution of 30 lp/mm, and the distortion is less than 5%. The exit pupil diameter of the system is 8 mm, and the field angle is 26°× 20°.

2.2. Initial structure design

The initial structure design is the key to the optimal design of an optical system, which is particularly important in the optical free-form prism system. The design of the initial Angle and the relative position of each surface determines whether the imaging quality of the optimized system can meet the design requirements. The initial structure of the optical free-form prism in this paper is shown in figure 2. In addition, considering the design requirements of the prism and the comfort requirements of the prism, the diameter of the aperture D is set as 8mm, the distance L between the aperture and surface 1 of the prism is set as 18mm, and the angle edge of the Y-direction field of view is set as 20. The optical indexes of the system design are as follows: (1) OLED display size: 0.61 inches (15.5 mm) diagonal; (2) Screen scale: 3:4; (3) Exit pupil distance: 27 mm; (4) Exit pupil diameter: 4 mm; (5) Focal length: 19.3; (6) Field angle: 27 degrees (V) * 35.6 degrees (H); (7) Distortion < 5%; (8) MTF > 0. 2 @ 30 lp/mm (central field of view); (9) MTF > 0. 1 @ 30 lp/mm (full field of view); (10) Weight: 4.65 g; (11) Volume: 3908.

2.3. Design procedures

The designed system is an off-axis structure, and the field of view is large, which causes significant astigmatism and distortion. The spherical and quadric surfaces are rotationally symmetric, and the radius of curvature in the meridian and sagittal directions are the same, so the optical power is also the same, which is unfavourable to the correction of off-axis aberration. The radius of curvature in the meridian sagittal direction of a free-form surface is different so that the aberration can be corrected independently in two separate plane directions. Therefore, surfaces 1, 2, and 3 are non-rotationally symmetric free surfaces. Face 2 is a deformable aspheric surface (Anamorphic Aspherical Surface-AAS) with two different curvatures and conic constant along the orthogonal direction. The description equation is as follows:

$$Z = \frac{C_x x^2 + C_y y^2}{1 + \sqrt{1 - (1 + k_x) C_x^2 x^2 - (1 + k_y) C_y^2 y^2}} + \sum \alpha_i x^i + \sum \beta_j y^j \qquad (1)$$

Face 3 is an Extended Polynomial surface, and the description equation is:

$$Z = \frac{Cr^2}{\sqrt{1 - (1 + k) C^2 r^2}} + \sum_{i=1}^{N} A_i E_i(x, y) \qquad (2)$$

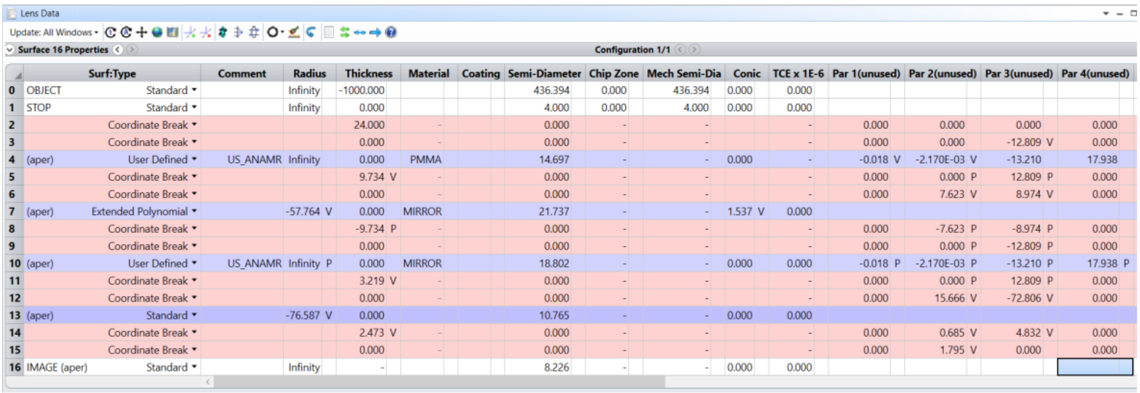
Face 1 is a rotationally symmetric torus, described by the following equation:

$$Z = \frac{Cx^2}{1+\left[1-(1+k)C^2x^2\right]^{1/2}} + \Lambda x^4 + Bx^6 + Cx^8 \qquad (3)$$

When optimizing the structure of the traditional coaxial optical system, it is generally necessary to control the lens center and edge thickness within a reasonable range. The optical system of the free-form prism helmet is an off-axis asymmetric structure. When it is optimized, the boundary conditions become very complex and changeable.

3. RESULTS AND DISCUSSION

The optical transfer function evaluation method is the most commonly used and convenient method for evaluating the imaging quality of optical systems. When the evaluated object is regarded as a linear system, its frequency will not change after passing through the optical system, but its contrast will change, and its phase will also change. This contrast and phase change is changed according to the frequency, and its linear functional relationship is the optical transfer function. This evaluation method is objective and reliable and can be applied to the aberration evaluation of various optical systems. The parameters of the surfaces of the designed optical systems are as follows in figure 3.


Lens Data

Update: All Windows

Surface 16 Properties

Configuration 1/1

	Surf:Type	Comment	Radius	Thickness	Material	Coating	Semi-Diameter	Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6	Par 1(unused)	Par 2(unused)	Par 3(unused)	Par 4(unused)
0	OBJECT Standard		Infinity	-1000.000			436.394	0.000	436.394	0.000	0.000				
1	STOP Standard		Infinity	0.000			4.000	0.000	4.000	0.000	0.000				
2	Coordinate Break			24.000	-		0.000	-	-		-	0.000	0.000	0.000	0.000
3	Coordinate Break			0.000	-		0.000	-	-		-	0.000	0.000	-12.809 V	0.000
4	(aper) User Defined	US_ANAMR	Infinity	0.000	PMMA		14.697	-	-	0.000	-	-0.018 V	-2.170E-03 V	-13.210	17.938
5	Coordinate Break			9.734 V	-		0.000	-	-		-	0.000	0.000 P	12.809 P	0.000
6	Coordinate Break			0.000	-		0.000	-	-		-	0.000	7.623 V	8.974 V	0.000
7	(aper) Extended Polynomial		-57.764 V	0.000	MIRROR		21.737	-	-	1.537 V	0.000				
8	Coordinate Break			-9.734 P	-		0.000	-	-		-	0.000	-7.623 P	-8.974 P	0.000
9	Coordinate Break			0.000	-		0.000	-	-		-	0.000	0.000 P	-12.809 P	0.000
10	(aper) User Defined	US_ANAMR	Infinity P	0.000	MIRROR		18.802	-	-	0.000	0.000	-0.018 P	-2.170E-03 P	-13.210 P	17.938 P
11	Coordinate Break			3.219 V	-		0.000	-	-		-	0.000	0.000 P	12.809 P	0.000
12	Coordinate Break			0.000	-		0.000	-	-		-	0.000	15.666 V	-72.806 V	0.000
13	(aper) Standard		-76.587 V	0.000			10.765	-	-	0.000	0.000				
14	Coordinate Break			2.473 V	-		0.000	-	-		-	0.000	0.685 V	4.832 V	0.000
15	Coordinate Break			0.000	-		0.000	-	-		-	0.000	1.795 V	0.000	0.000
16	IMAGE (aper) Standard		Infinity	-			8.226	-	-	0.000	0.000				

Figure 3. *Structure parameters of optimized prism.*

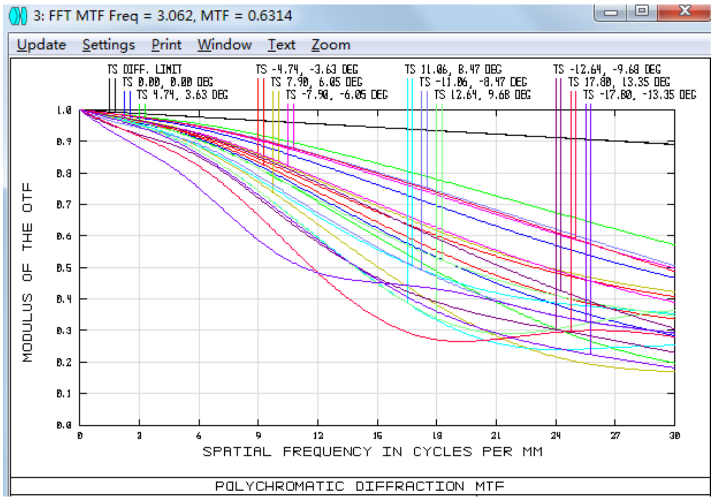


Figure 4. *MTF curves.*

The MTF curve after system optimization is shown in figure 4. From the MTF curve and the optimized system structure, it can be seen that the system meets the design requirements and can meet the operating conditions. That is, the MTF at 30 lp/mm frequency is more significant than 0.1. The system has a compact structure, a small number of lenses are used, the lens thickness is appropriate, and the spacing is reasonable, meeting the miniaturization design requirements of the optical system of the helmet-mounted display.

Figure 5 shows the distorted image of the prism system. It can be seen from the data that the maximum mesh distortion of direct optimization is -4.735%, which meets design requirements of less than 5%.

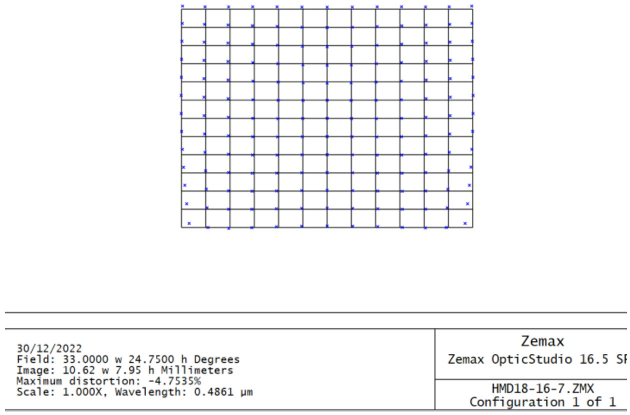


Figure 5. *Distortion image of the prism system.*

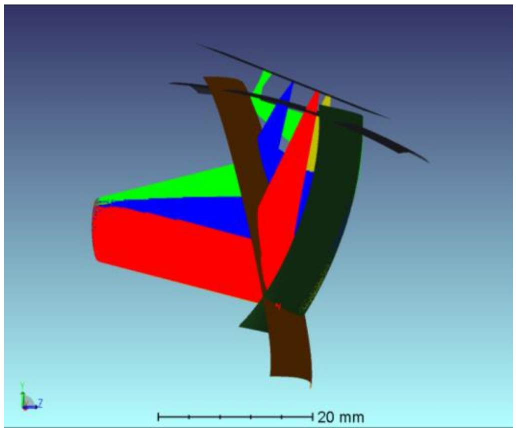
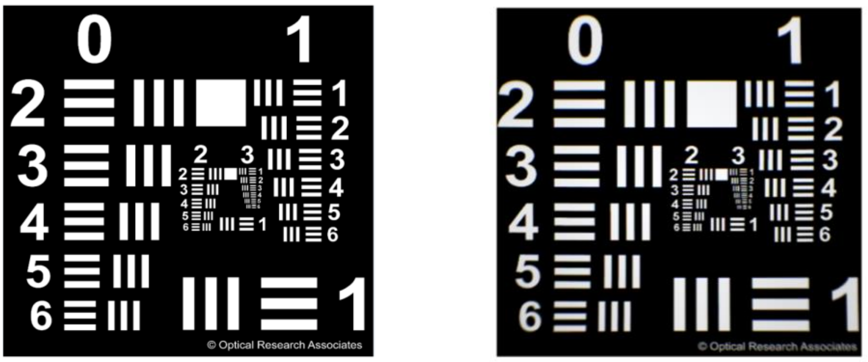


Figure 6. *System design optimized structures.*

From the MTF curve and the optimized system structure, it can be seen that the system meets the design requirements and can meet the operating conditions. That is, the MTF at 30 lp/mm frequency is more significant than 0.1. The system has a compact structure, a small number of lenses are used, the lens thickness is appropriate, and the spacing is reasonable, meeting the miniaturization design requirements of the optical system of the helmet-mounted display. After the light emitted from a point passes through the optical system, due to the existence of aberration, its intersection points on the image plane are no longer located at the same point but form a circle, commonly called a point diagram. Usually, the system's image quality can be measured by the point density. Hence, the optimized structure of the system is shown in figure 6.

The two-dimensional simulation diagram is a comprehensive and intuitive method provided by Code V to analyze the imaging quality of the optical system. The imaging diagram of the original picture transmitted through the optical system is displayed intuitively through the ray simulation tracing method, which comprehensively shows the optical system's performance. It is a primary method for evaluating the imaging system at present. The specific optical two-dimensional simulation diagram is shown in figure 7. The imaging quality of the system can be directly evaluated through the two-dimensional simulation diagram. It can be seen that the resolution of the system can completely meet the resolution of the original resolution image, but the distortion of the system at the edge is still serious, which needs to be optimized in the subsequent design.



(a) Resolution of the original image. *(b) Two-dimensional analysis chart.*

Figure 7. *Two-dimensional analysis diagram of the prim system.*

4. CONCLUSIONS

This scheme is a light and small-large field of view free-form prism helmet display optical system suitable for virtual and augmented reality. The image source element of the system is a 0.61-inch LCD. The scheme has the advantages of being light-weight and compact, with good aberration correction and high light energy utilization, which can ensure that the observer can see a clear image in a wide field of view. In addition, the displayed image does not have significant brightness attenuation, which is not easy to cause observer visual fatigue. Taking the design of a free-form surface with a small field of view as an example, the design method of the free-form surface prism is described in detail. Based on the initial structure, the optimization design is carried out through the gradual fitting transformation of the sphere-asphere freeform surface, with proper optimization sequence and specific constraints. Finally, the prism system of the free-form surface helmet display is implemented to ensure the system's resolution, distortion, and other imaging performance so that it can meet the application requirements.

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TÓM TẮT

Thiết kế lăng kính quang học bề mặt tự do ứng dụng trong thiết bị quan sát mũ đội đầu HMD

Màn hình hiển thị mũ đội đầu HMD là một thiết bị quan trọng ứng dụng công nghệ thực tế ảo. Nó là một thiết bị hiển thị cỡ nhỏ được lắp đặt trên mũ HMD, với mục đích tạo hình ảnh để người dùng quan sát. Công nghệ thực tế ảo và màn hiển thị HMD đã được ứng dụng rộng rãi trong các lĩnh vực quân sự, y tế và khoa học kỹ thuật nói chung. Hệ thống HMD chủ yếu bao gồm nguồn ảnh, hệ thống quang học hợp thành. Hệ quang là thành phần chính của HMD, tuy nhiên, các hệ quang truyền thống có kích thước lớn, thị giới hẹp không đáp ứng đủ nhu cầu của người dùng. Trong bài báo này, chúng tôi dựa trên xây dựng mô hình và phương án thiết kế các bề mặt quang học tự do, để xuất thiết kế lăng kính bề mặt tự do để nhằm giảm thể tích hệ quang, giảm kết cấu phức tạp đồng thời đưa ra phương án thiết kế tối ưu. Hệ thống thiết kế mà chúng tôi đề xuất sử dụng màn OLED có kích thước 0.61 inch, độ phân giải 800x600. Lăng kính có giá trị MTF tại độ phân giải không gian 30 lp/mm lớn hơn 0.1, méo ảnh nhỏ thua 5%, đường kính đồng tử ra là 8 mm và góc thị giới là 26°×20°.

Từ khóa: Hiển thị đội đầu; Quang học bề mặt tự do; Bề mặt; Thiết kế quang học.