Check for updates

applied optics

Design and engineering verification of an ultrashort throw ratio projection system with a freeform mirror

Baihua Yu,[1,2] Zhihui Tian,[1,3] Dongqi Su,[1,3] Yongxin Sui,[1,3] and Huaijiang Yang[1,3,*]

[1]Engineering Researcher Center of Extreme Precision Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]Changchun National Extreme Precision Optics Co., Ltd., Changchun 130033, China
*Corresponding author: yanghj@sklao.ac.cn

Received 23 January 2019; revised 4 April 2019; accepted 5 April 2019; posted 5 April 2019 (Doc. ID 358588); published 30 April 2019

A refractive-reflective combined ultrashort throw ratio projection optical system is designed. We use a freeform mirror to shorten the projection distance and correct distortion, and a plane mirror to turn back the optical path and reduce system volume. The projection system design method combines refractive lens group design and freeform surface mirror design with integrated optimization. The system's throw ratio is 0.11 with a projection distance of 320 mm and a 130 in. (1 in. = 25.4 mm) screen size, which illustrates the advantages of the low throw ratio. The system's maximum distortion is 0.07%. To demonstrate the proposed system's performance, a prototype is developed. Experimental results confirm that the system performs excellently while meeting the design requirements. The system's advantages include low throw ratio, excellent imaging quality, miniaturization, and engineering feasibility. © 2019 Optical Society of America

https://doi.org/10.1364/AO.58.003575

1. INTRODUCTION

In recent years, projection systems [1–3] have played an increasingly important role in the large-screen display field, and projection objective system development is gradually moving towards the use of ultrashort focal lengths [4,5], large fields of view [6,7], high resolution [8,9], low distortion [10,11], and low throw ratios in particular. The throw ratio, which is defined as the ratio of the projection distance to the screen width, is an important parameter for performance measurement of ultrashort throw ratio projection objective systems. A smaller throw ratio means that a shorter projection distance is then required by the system to present a projection screen of a specified screen size. In order to occupy smaller living space, reduction of the throw ratio of the projection objective system becomes an important development direction for projection optical systems. Freeform surfaces [12–15] are known to provide greater design freedom and can thus improve the imaging quality while simplifying the system structure; these surfaces have therefore been introduced into the optical design of ultrashort throw ratio projection objective optical systems [16,17].

To date, many researchers have studied the optical design of ultrashort throw ratio projection optical systems. Ogawa *et al.* developed a reflective-projection optical system [18] with a throw ratio of 0.32. Their system consists of four aspherical mirrors with projection distances of 0.65 m at 100 in. Nagase and Kono proposed an ultrashort throw ratio projection lens structure in their licensed patent [19] that can achieve a projection screen size of 78 in. at a projection distance of 0.495 m with a throw ratio of 0.31. In 2016, Nie *et al.* proposed a multifield direct design method to calculate the profiles of two freeform surfaces and designed an ultrashort throw ratio projection system with a projection distance of 48 cm, a screen size of 78.3 in., and a throw ratio of 0.24 [20]. Gao *et al.* presented an ultrashort throw ratio catadioptric projection lens with a freeform mirror [21]. This system achieved a 60 in. projection screen size at a projection distance of 440 mm, at which the throw ratio is 0.29. These research results have a lower throw ratio, but in order to achieve large-screen projection at a shorter projection distance, the throw ratio needs to be further reduced.

As we know, good optical design should not only present good performance in the optical design software environment, but should also be able to be assembled in engineering practice. However, most ultrashort throw ratio projection optical systems that have been reported in the literature are simulated examples produced by optical design software alone, and the low throw ratio systems from these designs have not proved to be physically realizable. Optical system design should evolve towards actual engineering applications, so the design of a high-performance, engineered ultrashort throw ratio projection objective system is a significant step.

In this paper, an ultrashort throw ratio projection system is designed while taking the optical system volume, the imaging quality, and potential fabrication and assembly difficulties into consideration. The system was simulated using optical design software. The simulation results show that the system achieves high performance, with a modulation transfer function (MTF) of more than 0.2 for each field of view at the cutoff frequency and distortion of 0.07%. A prototype of the ultrashort throw ratio projection objective system is then established. The experimental results demonstrate that the system satisfies the design requirements of a low throw ratio, excellent imaging quality, miniaturization, and engineering feasibility.

2. REFRACTIVE-REFLECTIVE PROJECTION OBJECTIVE SYSTEM DESIGN

The design process for the proposed refractive-reflective combined projection system comprises the following four steps: determination and analysis of the system parameters, design and optimization of the initial refractive structure, design and optimization of the freeform surface mirror, and combined optimization of the refractive system and the freeform mirror.

A. Optical System Parameters

The projection optical system consists of three main parts: the illumination system, the projection objective system, and the projection screen.

Laser tricolor is a highly saturated spectral color, which can reproduce a larger gamut, and thus a laser source including these three colors is used for projection. The main wavelengths of the red, green, and blue laser sources used in the designed projection system are 635, 532, and 473 nm, respectively. We used a single digital micromirror device (DMD) as the image source with a size of 0.65 in. and pixel size of 7.5 μm × 7.5 μm. The pixel array is 1920 × 1080 in size. The ultrashort throw ratio projection objective is designed to coincide with the aperture size of the illumination system. To obtain higher efficiency, the F number of the illumination system should be smaller than that of the projection objective system. Because the F number of the laser source is less than 3.5, the F number of the projection objective is therefore determined to be 3.5. A telecentric structure is selected to match the pupil of the illumination system. The projection distance is 320 mm and the screen size is 130 in., while the full field of view is 162°. The specifications of the proposed projection objective system are as shown in Table 1.

B. Design of the Refractive Part

Using the parameters detailed above, an ultrashort throw ratio projection objective design is presented. We designed the

Table 1. Specifications of the Projection Objective System

Parameters	Value
DMD size	0.65 inch (1920 × 1080)
Projection system	Telecentric
Projection distance	320 mm
Screen size	130 inch
Field of view	162 deg
F/#	3.5
Resolution	MTF > 0.2 at 0.3335 lp/mm
Maximum distortion	<0.1%

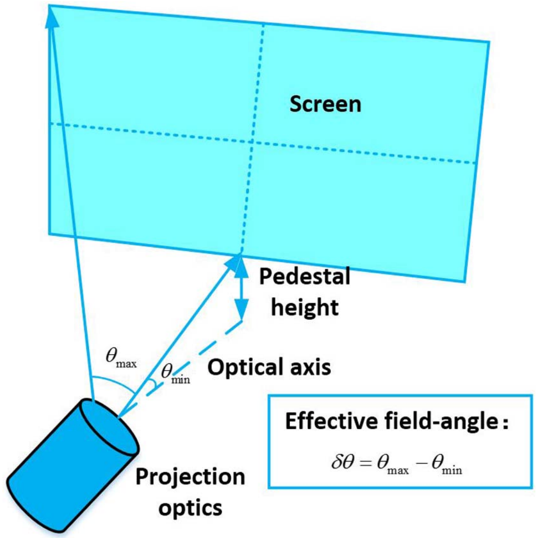

Fig. 1. Schematic diagram of the minimum field angle and effective field angle.

refractive lens group based on the parameters specified in Table 1. In the design of the refractive part, the focal length, the F number, and the field of view angle of the system are the main parameters to be considered. The magnification of the system is the product of the magnification of the refractive part and the reflective part, so the magnification of the two parts needs to be balanced in the optimization process. That is to say, if the refractive part is more complex, then the freeform mirror is simpler; otherwise, the freeform mirror will be more complex. The initial structure is designed based on the initial parameters. A human-computer interaction-based gradual approximation method is used to optimize the system, and the advanced aberrations are further balanced under the premise of satisfying the primary aberration requirements.

To correct the field curvature, we use a method based on increasing the minimum field angle while reducing the effective field angle [22]. The minimum field angle and effective field angle are shown in Fig. 1. By using this method, the field curvature will be controllable without satisfying Petzval's condition, and this will make the lens structure simple.

To correct the chromatic aberration, two groups of double-glued lenses are used, and the use of these glued lenses can also reduce the requirements for the processing, test, and adjustment tolerances. The image on DMD is converged to the intermediate image plane through the refractive lens group. Thereafter, this intermediate image is magnified by the reflective part and then projected on the screen. Figure 2 illustrates the two-dimensional optical structure used for the refractive lenses in the YOZ plane.

C. Design of the Freeform Mirror

After the refractive lens structure was designed, we designed a freeform mirror based on the outgoing rays from the final surface of the refractive lens group and the ideal object-image relationships in combination with the normal-weighted optimization algorithm [23]. In detail, the freeform surface shape is obtained by weighting the normal deviations of the different

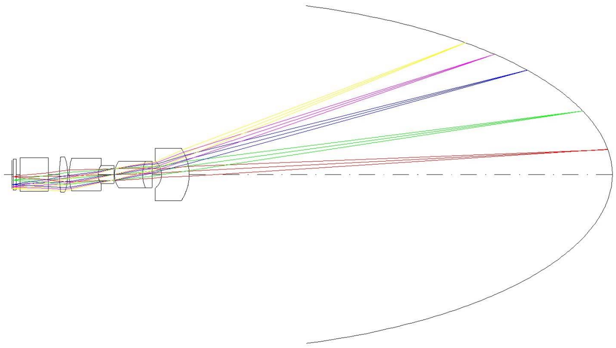

Fig. 2. Optical structure of the refractive lenses.

fields of view based on the unit directions of the incident light ray and the outgoing light ray. By appropriate setting of different weights for the different fields, the light rays will tend to be redirected to the ideal image points of the fields with larger weights, which then enables ideal imaging quality to be obtained for all fields after several iterations. In this way, the required freeform surface can be obtained. The design process is performed using an embedded function that is programmed into the programming software to complete the optimization calculations. In this system, the freeform surface can be expressed as

$$z = \frac{c(x^2 + y^2)}{1 + \sqrt{1 - (1 + k)c^2(x^2 + y^2)}} + \sum_i A_i x^m y^n, \quad (1)$$

where c is the surface curvature, A_i is the coefficient of the XY polynomial terms, and $m + n \le 9$. Because the system is symmetrical about the YOZ plane, only even x terms are used. The surface sag obtained for the freeform mirror is shown in Fig. 3. Figure 3(a) shows the surface sag of the freeform mirror, and Fig. 3(b) shows the freeform surface sag after removing the rotational symmetry terms. Because the freeform surface in this paper is a weak freeform surface, the surface sag of the freeform surface after removing the rotational symmetry terms is small.

D. Combined Design of the Refractive System and the Freeform Mirror

After the refractive system design and the freeform mirror design are complete, they must then be combined to form the initial structure for the final design optimization. In the design process, we need to calculate and optimize the refractive part and the reflective part iteratively. In addition, the illuminance is another important performance indicator that must be considered when designing a large field-of-view projection system. The F number of each pixel on the object plane is the same, which is 3.5. The corresponding F number of the pixel on the image plane is the F number of the pixel on the object plane multiplied by magnification, so the F number of each pixel on the image plane is 700; therefore, the illumination of each pixel on the screen is the same. In the optimization process, the MTF, the spot radius, and the distortion are used as process constraints. The MTF and the distortion are used as indicators for system performance evaluation. When the actual engineering problems and the system volume are taken into consideration, a plane mirror is added to turn the optical path back. The final optical structure of the system is as shown in Fig. 4.

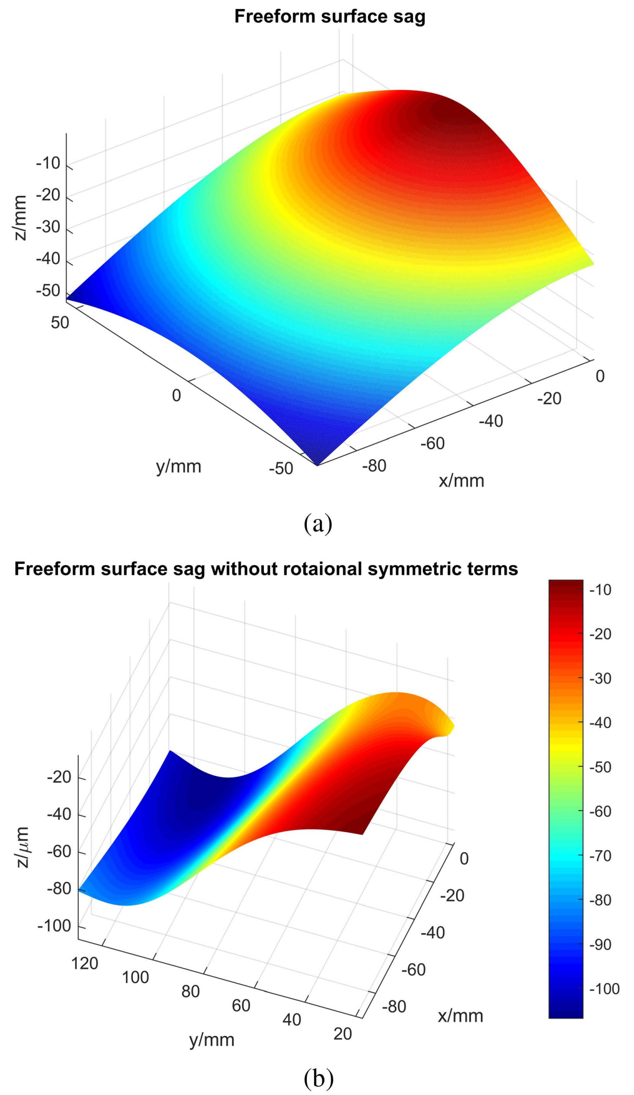

Fig. 3. (a) Freeform surface sag. (b) Freeform surface sag without rotational symmetric terms.

The figure shows that the light bundle turned back from the plane mirror after emitting from the refractive lens group is further reflected back from the freeform surface mirror. Thereafter, the light bundle is projected on the screen.

3. PERFORMANCE EVALUATION

The imaging quality of the system was analyzed according to the design requirements using the optical design software. In this work, the projection screen was assumed to be the image plane. The DMD pixel size is $p = 7.5$ μm, and the system magnification $M = -200\times$; therefore, the cutoff frequency is given by

$$\text{cut off frequency} = \frac{1}{2p \times M} = 0.3335 \text{ lp/mm}. \quad (2)$$

The MTF curve of the designed system is shown in Fig. 5. In the figure, the "T" and "S" refer to the tangential MTF curves and sagittal MTF curves, respectively. The curves of different colors represent MTF curves of different fields of view.

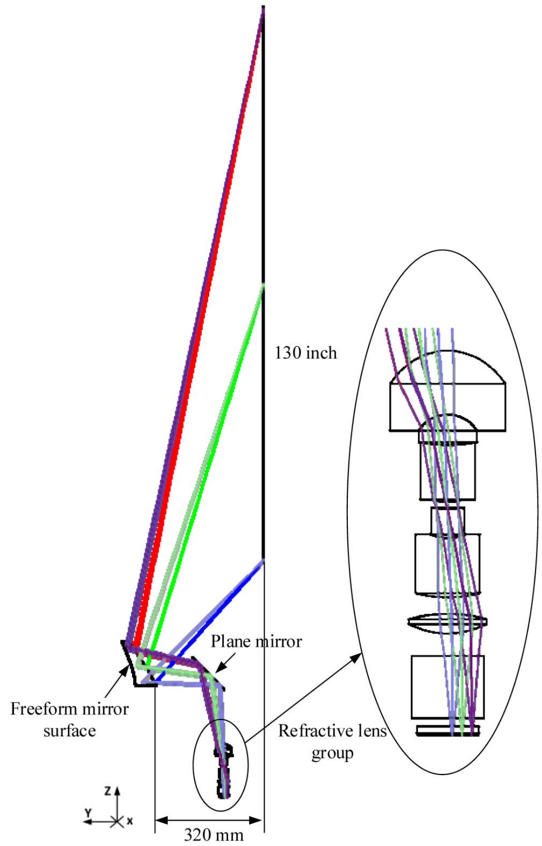

Fig. 4. Optical structure of the final projection system.

The figure shows that the MTF for most fields of view at the cutoff frequency of 0.3335 lp/mm is higher than 0.4; only the maximum and minimum fields of view are higher than 0.2, which is a slightly lower value than that of the other fields of view. This is because the maximum and minimum fields of view are at the lowest point and the corner of the screen, respectively, in practice, and the image viewing power is lower; therefore, during the optimization process, the optimization weight given to these fields of view is smaller than that given to the other fields. The image quality of the relatively important field of view can thus be improved by sacrificing the image quality of some of the edge points. Therefore, the system can meet the requirements for engineering applications well.

In ultrashort throw ratio projection system optical design, distortion is an important performance parameter and is defined as

$$\mathrm{Dist} = \frac{R_{\mathrm{distorted}}}{R_{\mathrm{predicted}}} \times 100\%, \tag{3}$$

$$R_{\mathrm{real}} = \sqrt{(x_r)^2 + (y_r)^2}, \tag{4}$$

$$R_{\mathrm{predicted}} = \sqrt{(x_p)^2 + (y_p)^2}, \tag{5}$$

$$R_{\mathrm{distorted}} = \sqrt{(x_p - x_r)^2 + (y_p - y_r)^2}, \tag{6}$$

where the subscripts r and p refer to the real and predicted coordinates on the image surface relative to the reference field position on the image surface, respectively. The central field is selected as the reference field. The distortion grid for the projection system is shown in Fig. 6, which indicates that the maximum distortion is 0.07%. It can be seen intuitively from Fig. 6 that the distortion is very small, which makes it seem that the two lines of actual image points and ideal image points almost overlap.

The spot diagram for the projection system is shown in Fig. 7. Each blue box in the figure represents a single pixel. The figure shows that most of the fields of view have a regular spot shape and can be concentrated within one pixel, thus indicating that the system aberration is well controlled. The spots in the figure are geometric, and the rms spot is smaller than the spots in the figure, so the image quality can meet the requirements of viewing. Only the spots for the maximum and minimum fields of view are irregular when compared with the other fields of view. This occurs because during the optimization process we consider the maximum and minimum fields of view to be in the corner of the screen; in actual use, the viewing power of the image is smaller, so the optimization weights given to these fields of view are smaller than those of the other fields of view during the optimization process. This means that we sacrificed the image quality at some of the edge field points to

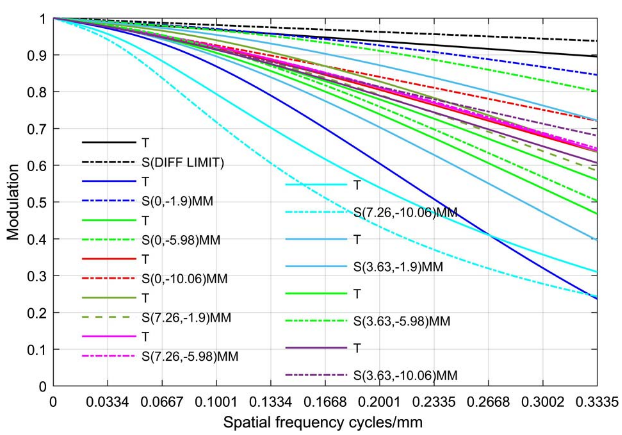

Fig. 5. MTF curve of the projection system.

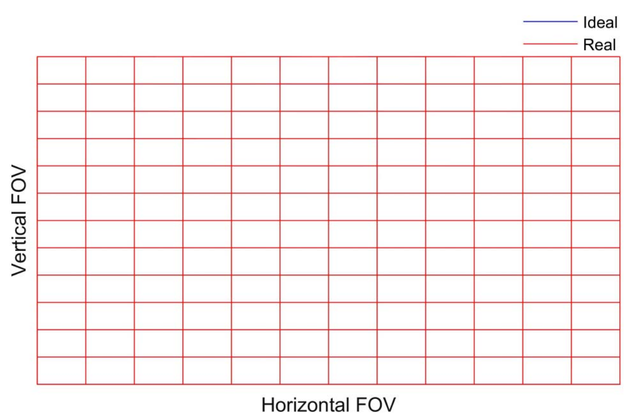

Fig. 6. Distortion grid of the projection system.

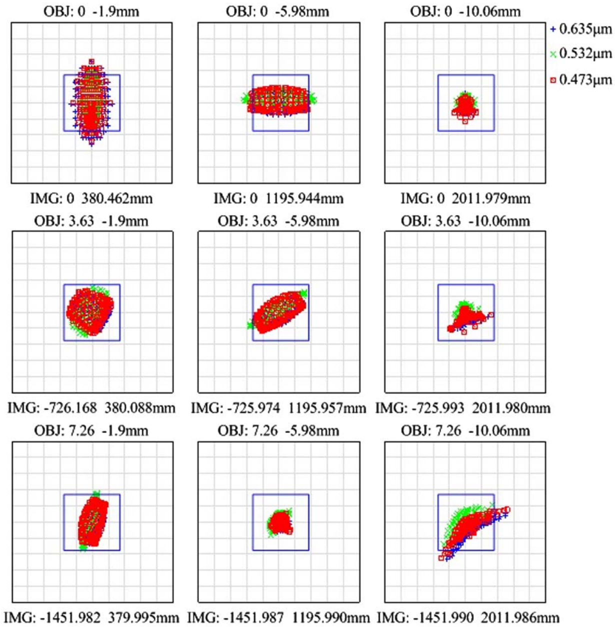

Fig. 7. Spot diagram for the projection system.

improve the image quality of the relatively more important field of view. The simulation results confirm that the system performance satisfied the design requirements.

4. EXPERIMENTAL RESULTS

In order to test the tolerance sensitivity of the ultrashort throw ratio projection system and determine the feasibility of the engineering application, we carried out the rms spot tolerance analysis for the projection system, as shown in Fig. 8. The results of the tolerance analysis show that most of the rms spots of the projection system have a probability of 90% less than 1.5 mm. The rms spot in the minimum field of view has a probability of 90% less than 1.6 mm. The tolerance sensitivity of the minimum field of view is thus slightly higher than other fields of view; this is because during the design process, we consider the minimum field of view to be in the bottom of the screen; in actual use, the viewing power of the image is smaller, so the optimization weights given to this field of view is smaller than those of the other fields of view. The size of a pixel on the projection screen is 1.5 mm, so generally speaking, the optical system can meet the requirements of engineering.

To verify the actual performance of the proposed design, we fabricated a prototype of the ultrashort throw ratio projection system. In this paper, as the core optical element, the freeform surface mirror was machined by the single-point turning method. The optical inspection result of the freeform surface mirror is shown in Fig. 9. Because of our good design results and relatively loose tolerance requirements, the actual system assembly process was very smooth. The prototype of the developed projection system is pictured in Fig. 10, which shows that the projection system offers the advantages of small system

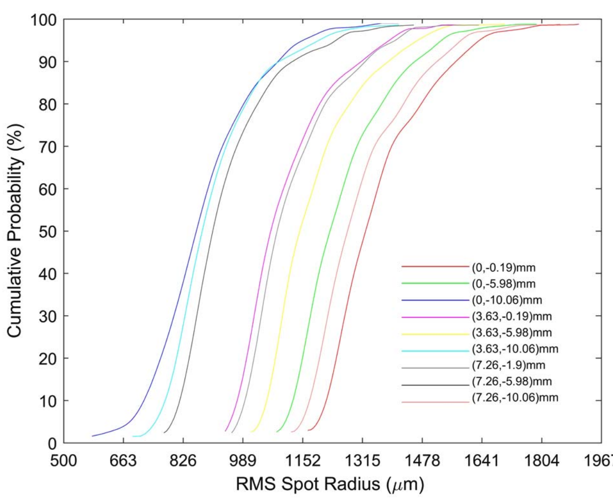

Fig. 8. rms spot tolerance analysis of the ultrashort throw ratio projection system.

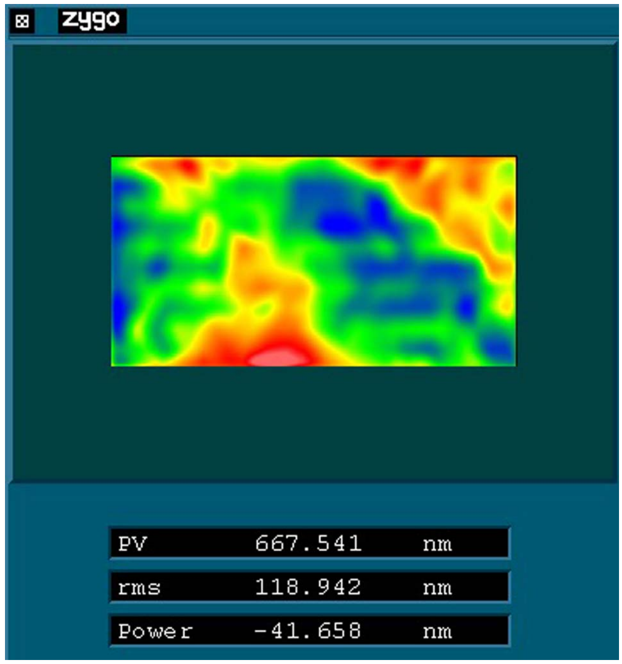

Fig. 9. Optical inspection results of freeform surface mirror.

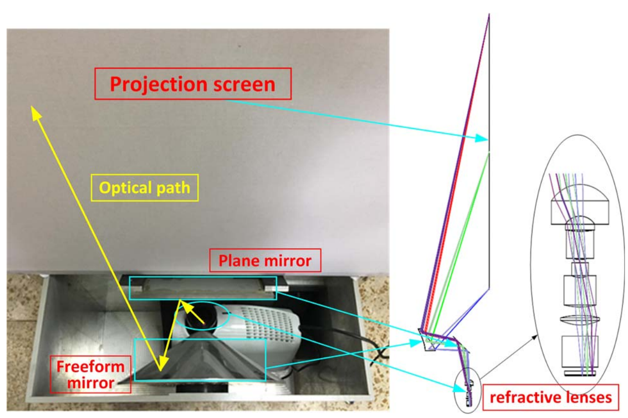

Fig. 10. Prototype of the ultrashort throw ratio projection system.

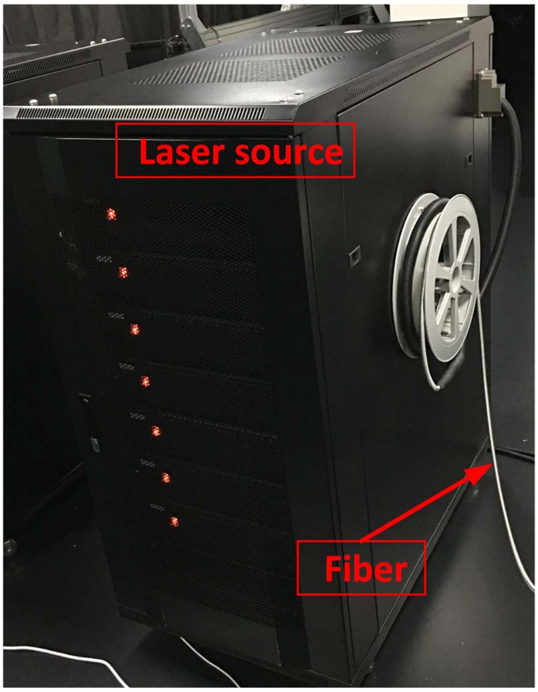

Fig. 11. Laser source with the output fiber.

volume and a short projection distance. The compact structure is highly conducive to space-saving design. Figure 11 shows the laser source used for the system with an optical fiber for light transmission.

In order to test the actual performance of the prototype, we carried out a high-quality projection experiment and tested the distortion performance of the prototype. The actual projection distance is 320 mm, and the screen size of the prototype is 130 in., and thus the throw ratio of the prototype is about 0.11, which is consistent with the design result. The image projected using the prototype is shown in Fig. 12. As the figure shows, the colors in the projected image are vivid, and the detail of the projected image is clear. Distortion test results show that the horizontal TV distortion and the vertical TV distortion of the projected image are 0.55% and 0.74%, respectively. The actual distortion is slightly larger than the design value, which may be caused by the error introduced during the assembly and adjustment process of the prototype, but the distortion performance of the prototype can still meet the requirements in actual use.

Fig. 12. Image projected by the proposed system.

We tested the illumination uniformity of the prototype. In the process of testing, the projection screen is divided into Nine-palace areas. Then, the illumination of nine centers of the Nine-palace areas is tested. In addition, the edges of four corners of the projection screen are tested. The illumination testing results show that the positive illumination uniformity and negative illumination uniformity are +91.8% and –96.1%, respectively, which can meet the usage requirement.

When compared with the traditional ultrashort throw ratio projection systems described in the literature, which mostly report simulation results only, the system presented in this paper not only has a lower throw ratio and better performance parameters and imaging quality, but also has been verified in engineering practice.

5. CONCLUSIONS

In this paper, an ultrashort throw ratio projection objective system that includes a set of refractive lenses, a plane mirror, and a freeform mirror is designed and is superior to traditional projection systems in that it has a lower throw ratio; a prototype of the proposed system is also developed. We have designed a freeform surface mirror using the normal-weighted optimization method to correct distortion and shorten the projection distance and then used a plane mirror to reduce the system volume. We used an independent design method for the refractive lens group and the reflective mirrors. The two designed parts are then combined to form a complete initial structure for further optimization to improve the overall performance of the entire projection system. The results confirm that the system performance meets the designed requirements. The projection system can achieve a 130 in. projection screen size at an ultrashort projection distance of 320 mm, for which the throw ratio is 0.11. In summary, using the design method and design concept proposed in this paper, an ultrashort throw ratio projection system with good performance can be designed, and the design has been verified experimentally. The projected image shows vivid and clear colors. Therefore, the design method, processes, and ideas presented in this paper are of significant importance and can provide a useful reference for use in the design of related systems.

Funding. National Science and Technology Major Project of China (2009ZX02205).

REFERENCES

1. C. K. Lee, T. Lee, and H. Sung, "Analysis and design of wedge projection display system based on ray retracing method," Appl. Opt. **52**, 3964–3976 (2013).
2. S. H. Liu and J. Tsai, "Autostereoscopic eccentric projection display with adjustable image sizes and viewing zones," J. Disp. Technol. **12**, 715–720 (2016).
3. Q. Zhou, X. Qiao, and K. Ni, "Depth detection in interactive projection system based on one-shot black-and-white stripe pattern," Opt. Express **25**, 5341–5351 (2017).
4. J. M. Yang, W. Q. Liu, and X. X. Meng, "Design of coaxial short focal length catadioptric projection system," Chin. J. Liq. Crys. Disp. **30**, 864–871 (2015).

5. Z. Zhuang, P. Surman, and X. W. Sun, “Design of hybrid refractive/reflective projection optics for family theatre,” SID **46**, 511–513 (2015).
6. D. P. Li, J. H. Zheng, and B. Yang, “Zoom projection lens design for small throw ratio and large field of view,” J. Mod. Opt. **65**, 1827–1838 (2018).
7. C. H. Luo, P. L. Yue, and D. H. Zhang, “Optical design of zoom projection lens,” J. Appl. Opt. **38**, 180–186 (2017).
8. J. C. Brazas and M. W. Kowarz, “High-resolution laser-projection display system using a grating electromechanical system (GEMS),” Proc. SPIE **5348**, 65–75 (2004).
9. M. G. Tomilin, “Optical projection systems for simulators,” J. Opt. Technol. **70**, 495–499 (2003).
10. H. Jia, H. Li, and Z. Zheng, “Distortion correction using a freeform lens for projection onto a non-planar surface,” SID **43**, 910–913 (2012).
11. X. J. Yu, Y. L. Ho, and L. Tan, “LED-based projection systems,” J. Disp. Technol. **3**, 295–303 (2007).
12. L. Chang and G. Herbert, “Numerical optimization strategy for multi-lens imaging systems containing freeform surfaces,” Appl. Opt. **57**, 5758–5768 (2018).
13. K. Fuerschbach, J. P. Rolland, and K. P. Thompson, “Theory of aberration fields for general optical systems with freeform surfaces,” Opt. Express **22**, 26585–26606 (2014).
14. J. Reimers, A. Bauer, K. P. Thompson, and J. P. Rolland, “Freeform spectrometer enabling increased compactness,” Light: Sci. Appl. **6**, e17026 (2017).
15. T. Yang, G. F. Jin, and J. Zhu, “Automated design of freeform imaging systems,” Light: Sci. Appl. **6**, e17081 (2017).
16. Z. F. Zhuang, Y. T. Chen, and F. H. Yu, “Field curvature correction method for ultrashort throw ratio projection optics design using an odd polynomial mirror surface,” Appl. Opt. **53**, E69–E76 (2014).
17. D. W. Cheng, Y. T. Wang, and C. Xu, “Design of an ultra-thin near-eye display with geometrical waveguide and freeform optics,” Opt. Express **22**, 20705–20719 (2014).
18. J. Ogawa, K. Agata, M. Sakamoto, K. Urano, and T. Matsumoto, “Super-short-focus front projector with aspheric-mirror projection optical system,” J. SID **13**, 111–116 (2005).
19. O. Nagase and Y. Kono, “Projection optical system, projector and image reading device,” U.S. patent US8419191B2 (16 April 2013).
20. Y. Nie, R. Mohedano, P. Benítez, J. Chaves, J. C. Miñano, H. Thienpont, and F. Duerr, “Multifield direct design method for ultrashort throw ratio projection optics with two tailored mirrors,” Appl. Opt. **55**, 3794–3800 (2016).
21. Y. Gao, D. W. Cheng, C. Xu, and Y. T. Wang, “Design of an ultra-short throw catadioptric projection lens with a freeform mirror,” Proc. SPIE **10154**, 10154S (2014).
22. M. Kuwata, T. Sasagawa, K. Kojima, J. Aizawa, A. Miyata, S. Shikama, and H. Sugiura, “Projection optical system for a compact rear projector,” J. SID **14**, 199–206 (2006).
23. B. H. Yu, Z. H. Tian, D. Q. Su, S. T. Gao, Y. X. Sui, and H. J. Yang, “Multi-fields optimization iterative design method for freeform surface in ultra-short-focus projection system,” Acta Photon. Sin. **48**, 0322001 (2019).