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Optical design of an ultra-short-focus projection system with low throw ratio based on a freeform surface mirror

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Abstract: In order to design an ultra-short-focus objective lens with a low throw ratio, a system of ultra-short-focus, low-throw-ratio objective lenses is designed using a freeform surface and refractive-reflective optical structure. The objective lenses consist of a rotationally symmetrical refractive lens group and a freeform surface mirror. A 11.938 mm Digital Micromirror Device (DMD) is used as a spatial light modulator to generate the image source. The normal-weighted iterative optimization method is used to calculate the freeform surface. Finally, the performance of the system is analyzed. The simulation results show that the ultra-short-focus projection objective lens can achieve a 3 048 mm screen projection at a distance of 580 mm. The throw ratio of the system is 0.19, which is extraordinarily low, and the maximum distortion of the system is less than 0.72%. This can meet the design requirements of low throw ratio ultra-short-focus projection objective lenses. This projection system is advantageous for its low throw ratio, low distortion and good imaging quality, which can provide a useful reference for the further development of ultra-short-focus projection systems.

Key words: optical system design; ultra-short-focus projection system; freeform surfaces

基于自由曲面反射镜的低投射比超短焦投影物镜的光学设计

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摘要: 为了设计低投射比的超短焦投影物镜,本文采用自由曲面和折反式的光路结构设计了一种具有低投射比的超短焦投影物镜系统。该物镜由一个旋转对称的折射透镜组和一个自由曲面反射镜组成。采用 11.938 mm 的数字微镜器件

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(DMD)作为空间光调制器产生图像源。采用法线加权迭代优化的方法计算自由曲面。最后,分析了系统的性能。仿真结果表明:超短焦投影物镜可在580 mm的投影距离处实现3 048 mm尺寸的大屏幕投影,系统的投射比低至0.19,系统的最大畸变小于0.72%。能够满足低投射比超短焦投影物镜的设计要求。该投影系统具有低投射比、低畸变、投影效果好等优点,可为超短焦投影系统的进一步发展提供有益参考。

关 键 词: 光学系统设计;超短焦投影系统;自由曲面

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1 Introduction

An ultra-short-focus projection system can achieve a large screen projection at an ultra-short projection distance, which solves the problem of space constraints, thus, it is widely welcomed in the education, entertainment, and military fields. The throw ratio [1] is defined as the ratio of the projection distance to the screen width. Generally, when it is less than 0.38, the projection system [2] can be defined as an ultra-short-focus projection system. There are two main approaches to realize the optical design of an ultra-short-focus projection system. One is to use three or four off-axis mirrors [3-4]. However, this places a high demand on system assembly, which limits the practical application in engineering. The other approach is to introduce a reflective mirror on the basis of the traditional refractive lens group, that is, use the structure of the combination of refraction and reflection [5-6], which is also the mainstream structure of an ultra-short-focus projection system. Unfortunately, as the throw ratio decreases, the Field Of View (FOV) angle of the system increases, and distortion becomes increasingly difficult to correct.

An effective method to correct distortion is to add a freeform surface [7] to the system, which introduces the optical design problem of a freeform surface [8-10] for large FOV imaging systems. At present, some direct design methods for freeform surfaces have been developed, for example, the simultaneous multiple surface design method [11] and the partial differential equation method [12]. However, these methods are not suitable for the design of freeform surfaces in wide FOV systems. Yang *et al*. proposed the point-by-point construction-iteration method [13]. However, in the existing literature, there is no application of this method to the design of large FOV ultra-short-focus projection systems. So we have improved this method.

Considering imaging quality, manufacturing, and practical assembly difficulties, a normal-weighted iteration method is proposed, which can calculate a freeform surface by setting weights for different fields according to normal deviations between the actual normal vectors and the ideal normal vectors. Compared with Yang's method, this method needs not the point-by-point construction process, therefore, time for calculation can be reduced and the calculation of the data points and normal vectors on freeform surface are unaffected by adjacent data points. Furthermore, in this method, we have added a process for reasonably selecting the sampled number of FOV. The main consideration is that the method needs to setting weights for different fields-of-view during the calculation process, so the number of fields-of-view will affect the calculation accuracy and design efficiency.

In this paper, an ultra-short-focus projection optical system with low throw ratio composed of a refractive lens group and a calculated freeform surface mirror is designed. The main advantage of the proposed projection system is that it has low throw ratio of 0.19, which is very low in the existing literatures. Moreover, the system has a maximum distortion of less than 0.72%, which is also very small.

2 Freeform surface design method

For an actual projection system, all fields

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should be considered. When all fields are considered in the design, the footprint areas of the light rays from adjacent fields overlap on the optical surface. The overlapping areas of different fields on the optical surface need to satisfy different object-image relationships simultaneously. Therefore, to obtain good imaging quality for the system for all fields, the optical surface being calculated must be the trade-off result of all fields. Based on this concept, a normal-weighted iteration design method is presented. According to the unit direction vectors of the incident rays and the ideal exit rays, different weights are set separately for all FOVs to calculate the shape of the freeform surface. By this method, the actual exit rays can be redirected to their ideal image points by the freeform surface, and thus distortion can be corrected.

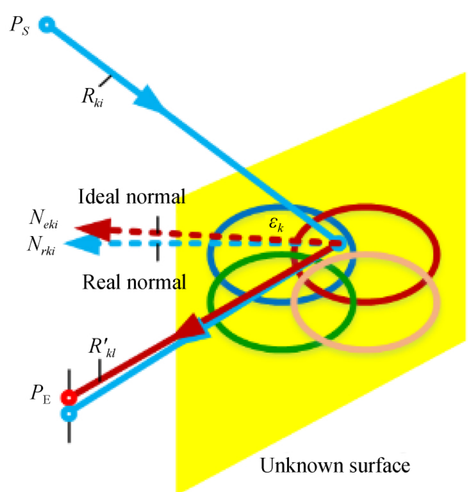

Fig. 1　Illustration of the principle of the design method

In this method, it is assumed that M fields are sampled uniformly spaced over the entire FOV and N light rays of the entire aperture for each field are sampled in the form of rectangular grids. As shown in Fig. 1 (Color online), each circle represents a field and R_{ki} represents the ith incident ray from the kth field. The ray comes from point P_S, and is bent by the unknown surface to intersect with the image plane at point P_E. A spherical surface is set as the initial surface of the expected surface, and the intersections of all the incident rays and the initial surface can be obtained easily. All the expected normal vectors at the intersection points can be calculated according to the law of reflection as expressed in

$$\boldsymbol{N}_{eki} = \frac{\boldsymbol{R}'_{ki} - \boldsymbol{R}_{ki}}{|\boldsymbol{R}'_{ki} - \boldsymbol{R}_{ki}|}. \quad (1)$$

Then, the freeform surface is fitted based on the intersections and the corresponding expected normal vectors using the method of reference [14]. During the surface fitting process, the expected freeform surface can be expressed as continuous polynomials, such as XY polynomials, Zernike polynomials, or any other high-order polynomials, which can be expressed as

$$z(x,y) = \frac{cr^2}{1 + \sqrt{1-(1+k)c^2r^2}} + \sum_{i=1}^{N} A_i f(x,y). \quad (2)$$

The actual surface normal vector calculated based on the initial surface at the intersection can be expressed as

$$\boldsymbol{N}_{rki} = \left(\frac{\partial z}{\partial x_i}, \frac{\partial z}{\partial y_i}, -1\right). \quad (3)$$

At this time, for a light ray, there is a deviation between the expected normal vector and the actual normal vector at the intersection point, which is expressed as

$$\delta_{ki} = \left[N_{ekix} - \frac{\partial z}{\partial x_i}, N_{ekiy} - \frac{\partial z}{\partial y_i}\right]. \quad (4)$$

The normal deviation of each field is the Root Mean Square (RMS) value of the normal deviations of the light rays in this field, which can be represented as

$$\delta_k = \sum_{i=1}^{N}\left\{\left[N_{ekix} - \frac{\partial z}{\partial x_i}\right]^2 + \left[N_{ekiy} - \frac{\partial z}{\partial y_i}\right]^2\right\}. \quad (5)$$

To balance the imaging quality of all fields, different weights are set separately for each FOV as

$$\delta = \varepsilon_1\delta_1 + \varepsilon_2\delta_2 + \cdots + \varepsilon_k\delta_k, \quad (6)$$

where ε_k represents the weights of different fields and the corresponding subscript k is the field number. Thus, by changing the weights of each field, the outgoing directions of the light rays from the o-

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verlapping areas of the adjacent fields are controlled so that they are more inclined to the ideal image point of the field with a large weight, and thereby the imaging quality of all fields can be gradually well balanced. An iteration process is performed to reduce the normal deviations for all fields until the desired freeform surface is obtained when either the accuracy requirement is satisfied or a certain number of iterations are performed. During the iteration process, the weights are modified according to the normal deviations of all fields. The flowchart of the design method is shown in Fig. 2.

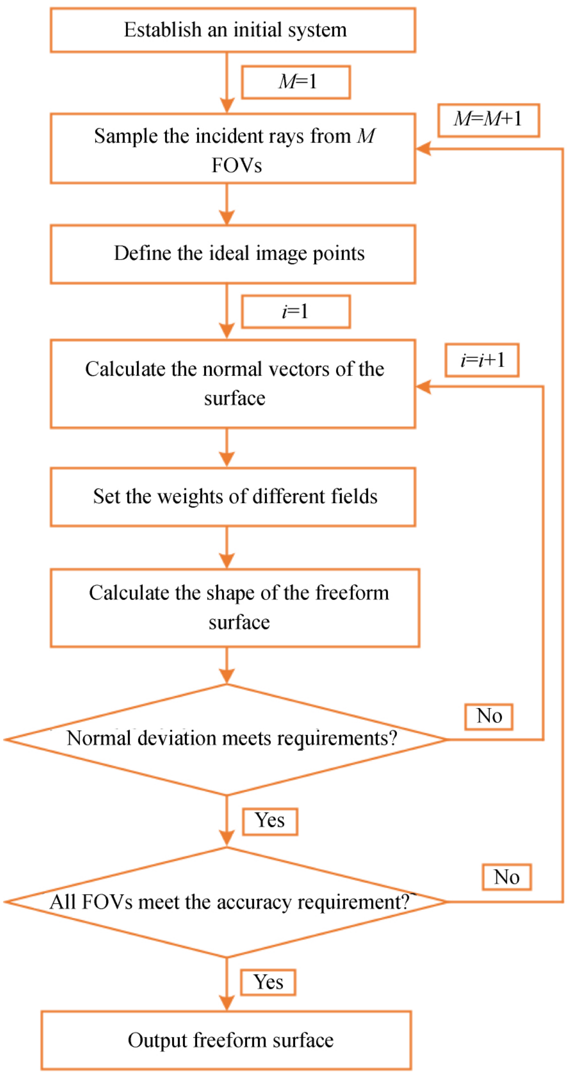

Fig. 2 Flowchart of the design method

During the design process, it is note worthy that the larger the number M of sampled FOVs, the higher the accuracy of the freeform surface, and the longer the calculation time. However, when the number M of sampled FOVs is increased to a certain sufficiently large value, the effect of improving the surface accuracy is no longer obvious. Moreover, the processing difficulty of the freeform surface increases when the surface accuracy is too high, so the bigger the better does not hold for M. Therefore, in the process of the surface shape calculation of the freeform surface, it is necessary to take surface accuracy, calculation time, and processing difficulty into consideration to determine the optimal number M of sampled FOVs. Besides, the weights ε_k are set according to the normal deviations of each field. When setting the initial weight, the weights of all fields are equal. After a round of iterations, the rationality of the weights is assessed according to the normal deviation values, and then the weight is adjusted. The weights of the FOVs with large normal deviations are increased, and the weights of the FOVs with small normal deviations are decreased, that is, the weights are set by feedback from the normal deviations.

3 Optical design of an ultra-short-focus projection objective

According to this freeform surface design method, an ultra-short-focus projection objective is designed. In this design, the Digital Micromirror Device (DMD) with 1 920 × 1 080 pixels and a pitch of 5.4 μm is set as the object, and the screen is considered as the image. The design parameters of the projection system are listed in Table 1.

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Tab. 1 Specifications of the ultra-short-focus projection system

Parameter	Specification
DMD size	11.938 mm(1 920 × 1 080)
Screen size	3 048 mm
Projection distance	580 mm
Throw ratio	0.19
Focal length	2.19 mm
FOV	156°
F number	1.7
Configuration	Refractive-reflective combined
Distortion	<1%
MTF	>50%@0.363 lp/mm
Relative illumination	>90% at all FOVs

The initial optical structure of the refractive part is mainly determined by the angle of the FOV and the F number. Then, its focal length is scaled to be coincident with the design parameters. 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 and its size is smaller; otherwise, the freeform mirror will be more complex and its size is larger. In the design process of ultra-short-focus projection objective, the freeform surface mirror is calculated according to the outgoing light rays emitting from the refractive lens group and ideal image points. Finally, the refractive lenses and the freeform surface mirror are combined as a whole for further optimization. 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. The main off-axis aberrations and chromatic aberrations of the ultra-short-focus projection system are corrected by the refractive lens group.

In order to improve the convergence speed of the algorithm, a spherical surface is taken as the initial surface of freeform surface. After the position of the initial surface is fixed in the projection optical system, the curvature of the initial spherical surface can be calculated approximately according to the focal length of the ultra-short-focus projection system and the focal length of the refractive lens group. In this design, the radius of the initial spherical surface is 62.5 mm. Regarding the freeform surface design, considering the symmetry of the projection system on the YOZ plane, only half the X-FOV is considered during the design process. According to the calculation results of the program and engineering application experience, 30 × 30 fields are sampled in the form of rectangular grids, and 15 × 15 rays from the entire pupil of each field are sampled.

The intersections of the sampled light rays and the last optical surface of the refractive part of the system are defined as the starting points, and the ideal image points on the screen are considered as the end points. The freeform surface is calculated using the normal-weighted iterative method. In this design, during the process of surface fitting and iteration, the freeform surface is represented by XY polynomials which have high representational ability. The expression of XY polynomials is

$$z = \frac{c(x^2+y^2)}{1+\sqrt{1-(1+k)c^2(x^2+y^2)}} + \sum_i A_i x^m y^n. \tag{7}$$

where c is the curvature of the surface, k is the conic constant, A_i is the coefficient of the XY polynomials, and $m+n \leqslant 8$. After many iterations, the RMS deviation of the normal direction vector of all fields meets the accuracy requirement. The accuracy re-

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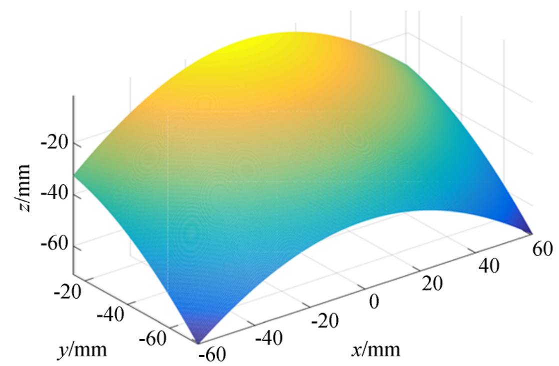
quirement is $\delta = 1.70 \times 10^{-2}$. The freeform surface is obtained as shown in Fig. 3(a) (Color online). It can be seen from the figure that the size of freeform surface mirror is about 120 mm × 60 mm. The sag after eliminating the inclination is shown in Fig. 3(b) (Color online). It can be seen from the figure that the change of the surface sag of the entire freeform surface mirror is not very obvious, and the maximum difference of the surface sag is about 4 mm, which can meet the processing requirements. Then, the initial structure of the ultra-short-focus projection system is obtained by combining the calculated freeform surface mirror with the refractive part. The maximum distortion of the initial projection system is less than 2.3%, which proves the validity of the method.

In order to improve performance of the projection system, it is further optimized with optical design software. During the optimization process, considering the symmetry of the projection system on the YOZ plane, only half the X-FOVs are optimized. The merit function is built mainly considering the RMS spot dimension. The distortion is also considered during the optimization. The radii of refractive lenses and the freeform surface coefficients are defined as variables during the optimization, the projection system quickly converges to a well performed system within a few cycles. The final system is obtained with the focal length of 2.19 mm. The projection distance of the system is 580 mm and the throw ratio is 0.19. The optical structure of the final projection system is shown in Fig. 4.



(a) Surface sag map of the calculated freeform surface

(b) Freeform surface sag after eliminating the inclination

Fig. 3 Surface sag of the entire FOV freeform surface

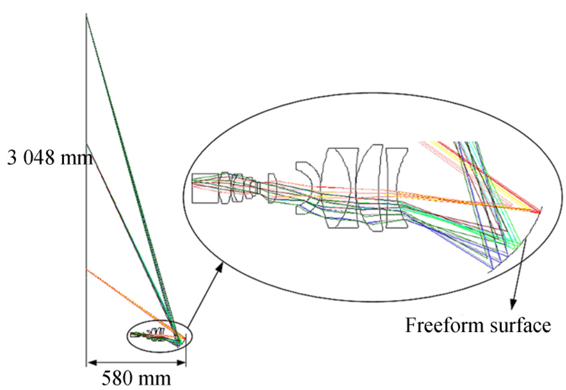


Fig. 4 Optical structure of the final projection system

As the pixel size of DMD is $p = 5.4\ \mu m$ and the magnification of the system is $M = 255$, the corresponding pixel size on the projection screen is $p' = M \times p = 1.377$ mm, and the cutoff spatial frequency on the screen is

$$\frac{1}{2pM} = 0.363\ \mathrm{lp/mm}. \tag{8}$$

The Modulation Transfer Function (MTF) curve of the projection system is shown in Fig. 5 (Color online). It can be seen that the MTF values for all FOVs are larger than 50% at 0.363 lp/mm.

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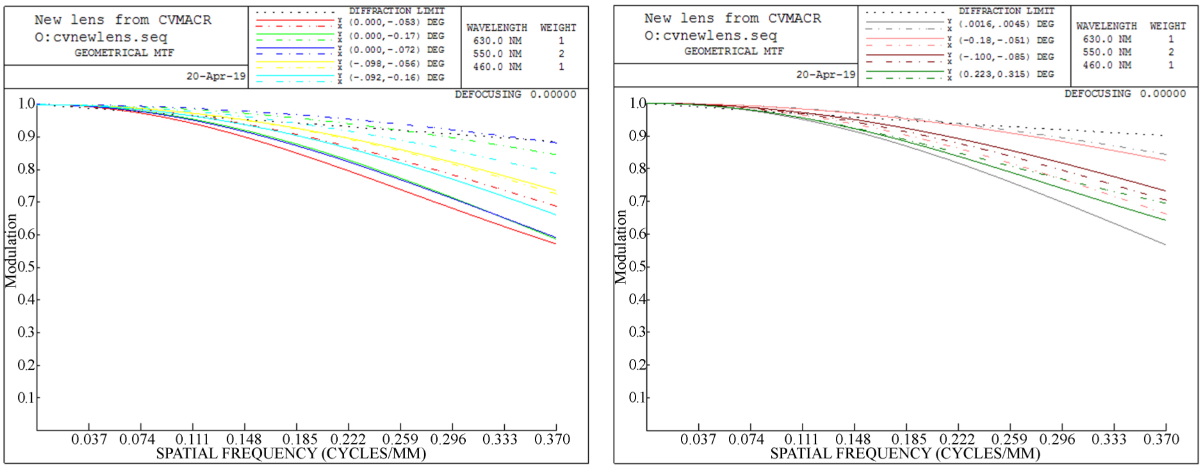

Fig. 5　MTF curve of the final projection system

Fig. 6 (Color online) shows the distortion grid of the system, the central field ($x = 0$, $y = 4.425$ mm) is chosen as the reference field, and the maximum distortion is less than 0.72%. It can be seen from the figure that the distortion is well corrected. The RMS spot diagram is shown in Fig. 7. As 1 pixel size on the screen is 1.377 mm, the RMS spot diameters of all FOVs are within 1 pixel size.

Illumination uniformity is another key performance for projection systems, in general, it is measured by Relative Illumination (RI). The RI curve is shown as Fig. 8. It can be seen that the ratio of RI is more than 91% at all FOVs, which will be fitted for viewers.

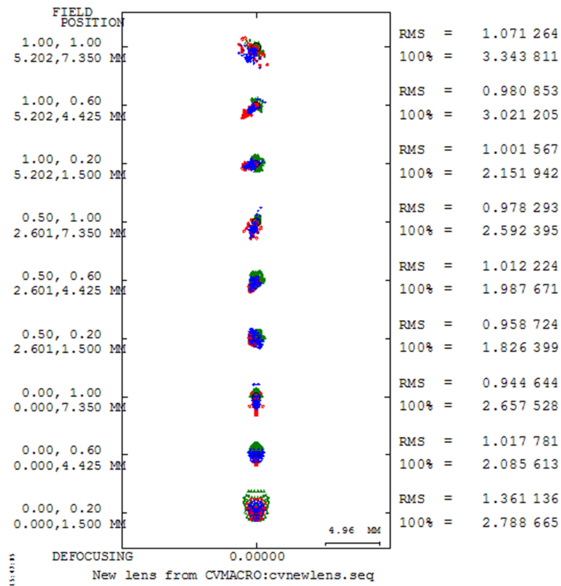

Fig. 7　RMS spot diagram of the final projection system

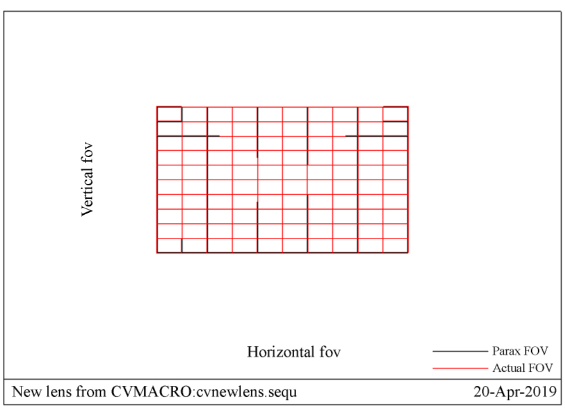

Fig. 6　Distortion grid of the final projection system

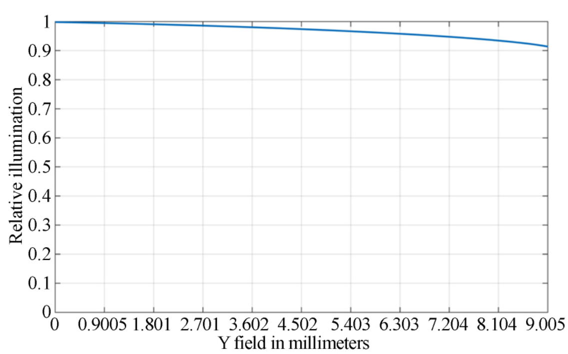

Fig. 8　Relative illumination of the whole FOV

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4 Conclusion

In conclusion, an optical design of ultra-short-focus projection system with low throw ratio was presented, which was composed of a refractive lens group and a freeform surface mirror. The shape of the freeform surface was calculated by setting weights for all fields according to their normal deviations. Then, the imaging quality of all FOVs were balanced by changing the weight of each field. The optical design results demonstrate that the system can produce a 3 048 mm projected image at the projection distance of 580 mm with a maximum distortion of less than 0.72%. The throw ratio of the system is 0.19, which is very low. The system has a focal length of 2.19 mm. The MTF curves of all FOVs are higher than 50% at the cutoff frequency of 0.363 lp/mm. The proposed projection objective system can provide useful reference for further development of ultra-short-focus projection system.

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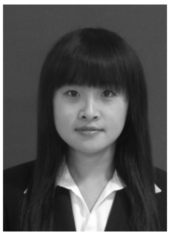

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