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<td>Author(s)</td>
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Field curvature correction method for ultrashort throw ratio projection optics design using an odd polynomial mirror surface

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This paper presents a field curvature correction method of designing an ultrashort throw ratio (TR) projection lens for an imaging system. The projection lens is composed of several refractive optical elements and an odd polynomial mirror surface. A curved image is formed in a direction away from the odd polynomial mirror surface by the refractive optical elements from the image formed on the digital micro-mirror device (DMD) panel, and the curved image formed is its virtual image. Then the odd polynomial mirror surface enlarges the curved image and a plane image is formed on the screen. Based on the relationship between the chief ray from the exit pupil of each field of view (FOV) and the corresponding predescribed position on the screen, the initial profile of the freeform mirror surface is calculated by using segments of the hyperbolic according to the laws of reflection. For further optimization, the value of the high-order odd polynomial surface is used to express the freeform mirror surface through a least-squares fitting method. As an example, an ultrashort TR projection lens that realizes projection onto a large 50 in. screen at a distance of only 510 mm is presented. The optical performance for the designed projection lens is analyzed by ray tracing method. Results show that an ultrashort TR projection lens modulation transfer function of over 60% at 0.5 cycles/mm for all optimization fields is achievable with f-number of 2.0, 126° full FOV, <1% distortion, and 0.46 TR. Moreover, in comparing the proposed projection lens’ optical specifications to that of traditional projection lenses, aspheric mirror projection lenses, and conventional short TR projection lenses, results indicate that this projection lens has the advantages of ultrashort TR, low f-number, wide full FOV, and small distortion. © 2014 Optical Society of America

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1. Introduction

Compared with traditional cathode ray tube (CRT) projectors, digital micromirror device (DMD) projectors based on light-emitting diodes (LEDs) have many advantages, such as brightness, resolution, and compact size [1–3]. With the gradually increasing application in the fields of business, education, household, and digital cinema, digital light processing (DLP) projectors have advanced rapidly in recent years due to a fast-growing consumer market. For these applications, a large screen projected at an ultrashort distance is demanded by consumers. Using a conventional projector, the shadow of the presenter or teacher may appear on the screen and the glare of

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the projected light will hit the presenter’s eyes. Moreover, a lot of space is wasted. The entire table needs to be clear or the image is partially obscured. For the current DLP projection optical engine, multiple glass optical elements are generally used to achieve higher optical performance, so as to shorten the projection distance while keeping a large projection size. This inevitably leads to an increased lens diameter because of the wide field of view (FOV). A fisheye lens, which is a wide-angle lens that projects a wide image, can be used; however, distortion is inevitable when we use a fisheye lens with a wide FOV and a low f-number. There has been great demand for the design of an optical system that can project onto a large screen at an ultrashort distance with low distortion and small f-number.

Many remarkable projection display systems have proposed in several patents by the NEC designer Ogawa [4], Hitachi designers Hirata et al. [5], and Inovel designer Lu [6] to achieve an extraordinarily large projection angle with low distortion. The reflecting mirror surface used in these can be concave or convex, and the projected screen may achieve a size from 50 to 80 in. diagonal. The distance between the projector and the screen is less than 1 m. None of them mention the design method of their work in detail.

A freeform mirror surface provides larger degrees of freedom to design an optical surface, and methods such as the partial differential equation [7,8] and simultaneous multiple surfaces (SMS) [9,10] can be used. Freeform optics is always used to achieve a projection lens system that fulfills the above-mentioned requirements. Based on the linear relationship between the angle of incidence of light onto a surface and the angle of reflection onto the imaging device, Hicks [11], derived a differential equation and generated surface shapes. However, this method is not suitable for cameras with relatively large apertures, as the chief ray of each FOV is used to calculate the aspheric mirror profile. For the design of a compact structure, four-mirror aspheric-type projector [12–14] was being designed as a projector. However, the problem of tilt or decenter of the mirror surface makes it difficult for optical designers to fix them. In recent years, Minano and co-workers [15–18] have applied the SMS method to designing the imaging optics. An extremely large image was obtained using two mirrors combined with a conventional projector. However, they also did not put forward the detailed design method in their paper.

In this paper, we propose a field curvature correction (FCC) method to achieve an extraordinary screen size at an ultrashort distance with low distortion, small f-number, and an extraordinarily large projection angle by using an odd polynomial mirror surface combined with a set of refractive optical elements. A curved image that is formed by these elements and the desired large screen with low distortion is magnified by an odd polynomial mirror surface according to the FCC approach. The laws of reflection determine the chief ray from the exit pupil of each FOV from the corresponding predescribed position on the screen, and a freeform mirror surface is calculated with segments of hyperbolic from the differential equation as an initial design profile. The value of the high-order odd polynomial surface is then used to express of the freeform mirror surface. Using this method, an ultrashort TR projection lens with low distortion can be obtained.

The rest of the paper is organized as follows. In Section 2, the FCC approach is introduced, and we also describe the method of designing the initial freeform mirror surface by using hyperbolic segments. In Section 3, a design example is described and its optical performance is analyzed. Finally, the conclusions are drawn in Section 4.

2. Design Methodology

A. FCC Method

Figure 1 shows the design principle of this method of correcting field curvature that is generated by the convex mirror surface. OB and IM are employed to denote, respectively, the object and the image. As shown in Fig. 1(a), OB is an erect, virtual object with respect to the mirror surface and IM is an image of the OB formed by the mirror surface. It is shown that a curvature of field is produced by the convex mirror surface. The IM of plane object OB is curved as image height increases. As shown in Fig. 1(b), OB is the curved, virtual object with respect to the freeform mirror surface and IM is an erect, real image. A virtual object is curved in advance in a direction away from the convex mirror. The field curvature produced by the virtual object is considered to be canceled by the mirror surface and an erect image can be obtained. In this case, the image formed by the mirror surface is erect, real, and is magnified. So, the key to this method is designing a convex mirror surface that can correct field curvature and form a plane image on the screen.

B. Design of the Odd Polynomial Mirror Surface

Figure 2 is a diagram illustrating the layout of the projection system, which is composed of several refractive optical elements and a convex mirror surface arranged along the common optical axis (OA). In Fig. 2, a curved virtual image is formed from the image on the DMD panel. The curved virtual image is curved in advance in a direction away from the convex mirror surface as the DMD panel height increases. The convex mirror surface cancels the field curvature and an enlarged plane image with no curve can be displayed on the screen.

The difficulty of this projection system, which includes a convex odd polynomial mirror surface, lies in the simultaneous design of refractive lenses and reflective mirror surfaces. As in every imaging system, the optical system is described by its entrance and exit pupils. It is difficult to match exit pupil distance and chief ray angle by the reverse design.
approach, so this was given up after several failed attempts. After several trials the forward-design method was chosen.

Since forward-design methodology is applied here, only the exit pupil is considered in the computation of the emergent rays from the exit pupil of each FOV, as shown in Fig. 3. The center of the exit pupil is set as the origin of the Cartesian coordinate system, and a $z$ axis along the OA is established. The emergent rays coming from the same FOV are converged in a direction away from the convex mirror surface. In Fig. 3, the curved virtual image consists of three fields of view: $M_1$, $M_2$, and $M_3$, which are reflected by the convex surface and converge at points $M'_1$, $M'_2$, and $M'_3$ on the screen, respectively.

In contrast to conventional methods, freeform optics provides larger degrees of freedom to design an optical surface. This convex mirror surface could be established by hyperbolic segments [19–21]. An ordinary hyperbolic surface is one that brings light from the first focal point to another target point on the screen, i.e., points $M_1$ and $M'_1$ are the two foci of the reference hyperbolic segment.

For the first FOV, as shown in Fig. 4, we assume that $R$ is the vector of the emergent ray at point $M_1$, and it passes through the center of the original exit pupil that all of the chief rays pass through. The polar radius $\rho$ is the distance between origin point O and point $M_1$ of the intermediate imaging. From Fig. 4, the vector $R$ can be expressed as

$$R_{(m)} = \rho \times m,$$

where $m$ denotes the unit vector of the emergent ray, which is given by Eq. (2) in Cartesian coordinates:
\[ m = [\sin(\varphi) \times \cos(\theta), \sin(\varphi) \times \sin(\theta), \cos(\varphi)]. \]  

Here, \( \varphi \) is the angle between the emergent ray and OA, \( \theta \) is the angle between emergent ray projection on plane XOY and OA, and \( \mathbf{T} \) is the vector of the reflective ray from the freeform mirror surface from point \( e_1 \) to point \( M' \). According to the laws of reflection, the relationship between the unit vector \( \mathbf{m} \) of the emergent ray and the unit vector \( \mathbf{T} \) of the reflected ray at point \( e_1 \) can be written as [22,23]

\[ \mathbf{T} = \mathbf{m} - 2 \times (\mathbf{m} \times \mathbf{N}) \times \mathbf{N}, \]  

where \( \mathbf{N} \) is the unit normal of the freeform mirror surface at point \( e_1 \).

As mentioned above, this method uses the reflective property of hyperbolic segments to establish the reflector surface. In a polar coordinate system, the profile of the hyperbolic surface can be expressed as [21]

\[ \rho(\mathbf{m}) = \frac{d}{\kappa(\mathbf{m} \times \mathbf{v})} - 1, \]  

where \( d \) is the focal parameter, \( \mathbf{v} \) is the vector directing to another focal point of the hyperbolic segment of revolution, and \( \kappa(\kappa > 1) \) is the eccentricity, which can be calculated from the basic properties of hyperbolic segments as

\[ \kappa = \sqrt{1 + \frac{d^2}{|\mathbf{v}|^2} - \frac{d}{|\mathbf{v}|}}. \]  

If we know the initial focal parameter of the reference hyperbolic segment, by using Eqs. (1)-(5), we can get the radius vector \( \mathbf{R} \) of the freeform mirror surface. For a rotationally symmetric optical system, the other two reference rays of each FOV from the exit pupil are defined, such as the upper meridional ray and the bottom meridional ray; \( \mathbf{I}_{1u} \) and \( \mathbf{I}_{1b} \) are incident rays of the upper marginal ray and the bottom marginal ray, respectively. The two edge points of the convex mirror surface, \( e_{1u} \) and \( e_{1b} \), are the points of the intersection of rays \( \mathbf{I}_{1u} \) and \( \mathbf{I}_{1b} \) with the reference hyperbolic segment, which can be calculated by the bisection method [24].

For the second FOV, we place one focus of the hyperbolic segment at point \( M_2 \) and the other focus at given target screen point location \( M_0 \), as shown in Fig. 5. Other segments of the hyperbolic should be larger than the reference hyperbolic segment, and a constraint of all focal parameters must be satisfied as shown in Eq. (6):

\[ d_k > d_1, \quad (k = 1, \ldots, P - 1, P). \]  

where \( k \) is the \( k \)th FOV, and \( P \) denotes the whole FOV. The bisection method is used to compute the other focal parameter \( d_k \) of a hyperbolic segment until the second hyperbolic segment satisfies the continuity condition:

\[ e_{1u} = e_{2b}, \]  

where \( e_{1u} \) denotes the intersection point of the upper meridional ray with the reference hyperbolic segment, and \( e_{2b} \) represents the intersection point of the bottom meridional ray with the second hyperbolic segment. Then, the same procedure is repeated for each of the remaining FOVs of the imaging system. The entire convex mirror surface is assembled by hyperbolic segments. Thus, it can be written as [25]

\[ R_{\text{mirror surface}} = \bigcup_{k=1}^{P} A_k, \]  

where \( R_{\text{mirror surface}} \) is the area of the mirror surface, and \( A_k \) is the region of the \( k \)th hyperbolic segment.

Finally, the convex mirror surface \( R_{\text{mirror surface}} \) is fitted using the odd polynomial surface, aiming to analyze the optical performance of the projection optics. The expression of odd polynomial surface is

\[ z = \frac{c \times r^2}{1 + \sqrt{1 - (1 + k) \times c^2 \times r^2}} + A_1 \times r + A_2 \times r^2 + \cdots + A_{30} \times r^{30}, \]  

where \( z \) is sag; \( k \) is the conic constant; \( c \) is the curvature of the reflective surface; \( r = \sqrt{x^2 + y^2} \) is the height above the OA; and \( A_1, A_2, \ldots, A_{30} \) are

<table>
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<th>Table 1. Optical Specifications of the Ultrashort TR Projector System</th>
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<tr>
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<td>Wavelength (nm)</td>
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<tr>
<td>Effective focus length (mm)</td>
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<tr>
<td>Entrance pupil position (mm)</td>
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<tr>
<td>f-number</td>
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<tr>
<td>Projection distance (mm)</td>
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<td>Screen size (in.)</td>
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coefficients of the odd polynomial equation. The coefficients are used to correct for distortion.

Based on the above design methods, we obtained the initial projection system, which had considerable aberrations and distortion. A damped-least-squares optimization method is used to meet the design requirements.

3. Design Example and Analysis

In this section, an example is presented to verify the design method, and a ray-tracing simulation approach in imaging design software is applied to analyze the optical performance of the proposed projection system.

A. Layout and Specifications

The design optical specifications of the optical system are listed in Table 1, and the corresponding layout of the designed projection system is illustrated in Fig. 6. The projection system is a telecentric system in object space. The projection lens consists of eleven refractive optical elements and an odd polynomial convex mirror surface. The total track of the designed projection system, including the odd polynomial mirror surface, is about 228 mm, which demonstrates the unique behavior of the compact structure. The distance between the projector and the screen is only 510 mm. A diagonal 0.45 in. (11.43 mm) DMD with 1280 × 800 pixels and a 7.5 μm pixel size is chosen as the image panel.

B. Analysis and Comparisons

1. Analysis of the Convex Mirror Surface

The design result of the odd polynomial convex mirror surface is now considered. The initial and final profiles of the odd polynomial mirror surfaces are compared in Fig. 8. A set of discrete data points can be obtained by the approach described in Section 2, and the starting profile is constructed by fitting these points with an odd polynomial surface. The final optimization surface is plotted in Fig. 7 in red. The size of the optimized odd polynomial mirror surface is larger than the initial surface. The three-dimensional profile of the surface is shown in Fig. 8(a) and the corresponding contour map of the profile is shown in Fig. 8(b). The surface is symmetrical about the x axis. Figure 9 shows a three-dimensional representation of the surface. The overall dimensions of this surface are about 98 mm length × 49.2 mm width × 24.6 mm height, which can be fabricated directly on an aluminum block surface by using the diamond

![Fig. 6. Layout of the ultrashort TR projection system.](image)

![Fig. 7. Comparison of the shapes of the odd polynomial mirror surface before and after the optimization process.](image)
turning process. The surface is coated with a high-
reflectance coating (over 99% reflection) during
processing, which has been validated to achieve high
luminous efficiency. The figure indicates that the sur-
face shape is easily fabricated.

2. Modulation Transfer Function

The modulation transfer function (MTF) diagram of
the ultrashort TR projection system is shown in
Fig. 10, aiming to quantitatively evaluate the spatial
resolution of the projection lens. The MTF shifts
slightly with different wavelengths and field angles.
In the image space, the cutoff frequency can be
calculated as follows:

\[
f_{\text{cutoff}} = \frac{1}{\eta} \times \frac{1000}{2 \times a},
\]

where \( a \) is the DMD’s pixel size, and \( \eta \) is the projec-
tion magnification power. The spatial frequency is
about 0.5 cycles/mm according to Eq. (10). The MTF
value of a full field is above 60% at 0.5 cycles/mm for
all optimization fields. It can be seen that almost all
of the field is close to the diffraction limit.

3. Distortion

To evaluate the distortion of the designed projection
lens, we can look at the image distortion grid of the
projection. In [1], an approach for calculating the dis-
tortion of the image is proposed according to Eq. (11).

When the distortion is lower than 1.5%, the image
distortion cannot be observed by the human eye,
so the image distortion of the projectors must be less
than 1.5%. In Eq. (11), \( H_{\text{min}} \) is the minimal real
image height, and \( H_l \) and \( H_r \), respectively, are the left
and right image heights without distortion:

\[
\text{Dist} = \frac{0.5 \times (H_l + H_r) - H_{\text{min}}}{H_{\text{min}}} \times 100\%.
\]

The distortion grid map of the projector is shown in
Fig. 11. The maximum distortion is less than 1% at
the bottom right and bottom left of the field according
to Eq. (11).

4. Throw Ratio

One useful specification relating to the projector lens
is its TR, which is defined as

\[
\text{TR} = \frac{D}{W},
\]

where \( D \) is the distance between the projector lens
and the projection screen and \( W \) is the width of

Odd polynomial mirror surface

![Fig. 9. Model of the odd polynomial mirror surface (overall
dimensions: 98 mm × 49.2 mm × 24.6 mm).](image)

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where \( D \) is the distance between the projector lens
and the projection screen and \( W \) is the width of
the image being projected. A small value represents a larger screen of the same projection distance. The aspect ratio (AR) of the projector screen is 16:9, and the projector’s TR is about 0.46, according to Eq. (12). Undoubtedly, an ultrashort TR projection system is obtained as the TR is less than 0.6.

5. Full Field of View

The relationship between field angle of the refractive optical elements, the field angle of the odd polynomial mirror surface, and normalized FOV is shown in Fig. 12. The field angle of the refractive optical elements increases linearly when the normalized FOV increases. The field angle of the odd polynomial mirror surface increases when the normalized FOV increases. In Fig. 12, the maximal FOV of the odd polynomial mirror surface is nearly 63°; thus, the full FOV is about 126°.

6. Comparisons

Our design of ultrashort TR projection system optical specifications is compared to those of the traditional projection lens [1], the aspheric-mirror projection lens [13], and the conventional short TR projection lens [6]; the results are listed in Table 2. We can obtain a lower TR, low f-number, and wider full FOV than the other designs. In our design, the projection lens is composed of several refractive lenses and a convex freeform mirror surface. This hybrid refractive–reflective (HRX) projection lens has many advantages. There is only one reflective surface, which makes it easy for optical designers to fix it, and it can be fabricated directly on an aluminum block surface by using the diamond turning process. In contrast to aspheric mirror projection lenses, the refractive lens is easier to manufacture. The manufacturing costs of aspheric mirror surfaces are high due to the complex procedures. Therefore, the designed projection lens could be easily fabricated at an extremely low cost. As a result, the designed HRX projection lens has outstanding optical performance and low cost.

4. Conclusions

In this paper, a new method for designing an ultrashort TR projection lens based on the FCC method is presented. This ultrashort TR projection lens is composed of refractive optical elements and an odd polynomial convex mirror surface. A curved virtual image is formed by the refractive optical elements from the image on the DMD panel, and then enlarged on the screen by the odd polynomial mirror surface. Based on the relationship between the chief ray from the exit pupil of each FOV and the corresponding pre-described position on the screen, the initial profile of the convex freeform mirror surface is calculated according to the laws of reflection by using hyperbolic segments. In addition, the freeform mirror surface could be fitted using the odd polynomial surface. Finally, an ultrashort TR projection lens is designed using

<table>
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<th>Table 2. Optical Specification Comparisons among Traditional Projection Lens, Aspheric-Mirror Projection Lens, Conventional Short TR Projection Lens, and Our Designed Projection Lens</th>
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