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Optical design of an ultrashort throw ratio projector with two freeform mirrors

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ABSTRACT

In this work, an optical design approach is presented to design an ultrashort throw distance projection system by combination of an off-the-shelf refractive lens and two off-axis freeform mirrors. These two freeform mirrors are used to greatly shorten the projection distance by more than three times compared to conventional (rotationally symmetric) systems, while still maintaining a good imaging quality.

Firstly, a direct design method that enables the simultaneous calculation of two off-axis freeform-profile mirrors by partially coupling more than three fields is introduced. The specifications of the conventional refractive lens are taken into account during this procedure. The pupil matching principle is applied to ensure good performance between the two sub-systems. The calculated mirrors then serve as a good starting point for optimization using commercial optical design software. To step from freeform profiles to freeform surfaces, the calculated two profiles are fitted into odd polynomials to evaluate the image quality and then re-fitted into XY polynomials for further optimization. Finally, the polynomial coefficients of the two freeform mirrors are imported into the optical design program. The merit function is built from RMS spot radii over the full field, and additional constraints are made for correcting distortion. After optimization, the calculated initial design quickly converges to a well performing imaging system.

As an example, an ultrashort throw distance projection lens with a large 80-inch diagonal image at 400mm throw distance is designed, analyzed and compared with literature data. The values of MTF are over 0.6 at 0.5 lp/mm and the distortion is less than 1.5%: showing a very good and well balanced imaging performance over the entire field of view.

Keywords: geometric optics, ultrashort throw ratio projector, optical design, aspheric mirrors, freeform optics

1. INTRODUCTION

Short throw and ultrashort throw projectors allow large screens in very limited space, without concerning about shadows that obstruct the image or lights that shine in the presenter’s face. In some specified applications such as rear projection systems\textsuperscript{1,2}, ultrashort throw distance is a prerequisite to fulfill the space constraints. A regular projector might need about 240cm away to create an 80 inch diagonal image; while an ultrashort throw ratio (TR = throw distance/screen diagonal) projector only needs about 60cm or less to create the same image. There are two major methods to realize the optical configuration of an ultrashort throw projector. The first one is to use large magnification projection objectives with three or four spherical/aspheric mirrors\textsuperscript{3-5}. The other solution is to combine accessory optics with regular projectors as shown in Fig. 1, to name a few, the simultaneous multiple surface (SMS) optic\textsuperscript{6-8}, distortion correction optic\textsuperscript{9,12} and field curvature correction (FCC) optic\textsuperscript{10,14}.

The SMS design method makes full usage of two skew ray bundles in different apertures to directly calculate two high-order odd polynomials surfaces, which guarantees a good mapping relationship between virtual object points created by the original projector and new image points\textsuperscript{5}. In the distortion correction optic, it regards distortion as the most considerable aberrations in wide field of view system as short TR projectors, therefore one additional aspheric lens
or mirror was introduced to correct distortion and then optimize other aberrations to get a good image quality\textsuperscript{10}. With the FCC method, one additional odd polynomial mirror was added to achieve short TR. Given that one convex mirror inherently induces a curved image, the method was proposed reversely to keep a flat final image, whereas a corresponding field curvature should be reserved for the front regular projector and an integral optimization of the whole system is required\textsuperscript{14}.

To our knowledge, all these proposed accessory optics are based on rotationally symmetric optical elements. However, the essence of the problem is to generate a tailored mapping relationship between two rectangular screens as shown in Fig. 1. The non-rotationally symmetric off-axis layout raises the question if the image quality could be further improved by using freeform mirrors. Like all the optical designs, the optimization of freeform optical systems greatly rely on finding a good starting point. Several direct design methods have been developed so far to calculate freeform surfaces, such as the partially differential equations (PDFs) method\textsuperscript{15-17}, the SMS method for non-imaging applications\textsuperscript{18} and a related analytic method\textsuperscript{19}. However, either a point source or discrete fields are considered in these design algorithms with two freeform surfaces, which hinders their use in wide field of view imaging systems.

![Figure 1. Schematic drawings of (a) a regular projector and (b) an ultrashort throw ratio design concept by adding accessory optics](image_url)

In this paper, we present a novel design method for ultrashort TR projectors based on a partial coupling of multiple fields. The procedures of how to directly calculate two off-axis freeform-profile mirrors is introduced step by step in Sec. 2. In Sec. 3, the application of this method for designing an ultrashort throw ratio projector is illustrated. The image quality of both rotationally symmetric aspheric mirrors and freeform mirrors are evaluated and analyzed in Sec. 4. Finally, conclusions are drawn and the outlook is given in Sec. 5.

## 2. MULTI-FIELDS DESIGN METHOD TO CALCULATE TWO OFF-AXIS MIRRORS

Originally, the multi-fields direct design method was proposed for two on-axis refractive freeform surfaces in imaging lens design with an incorporated entrance pupil\textsuperscript{20, 21}. In this work, it is further extended to solve a tailored imaging problem for off-axis mirror system. The initial setting is illustrated in Fig. 2. In order to avoid vignetting, the entrance pupil \( P \) is assumed to be at the exit pupil of the foregoing projector optical system. A first off-axis field \( E_o \) is constructed with a certain offset distance from the optical axis (horizontal plane). We calculate a bottom ray of field \( E_o \) from \( P_i \) that reflects at \( F_0 \) on the first mirror then passes by \( G_0 \) on the secondary mirror, finally converges to point \( R_0 \) on the image plane. In most imaging systems, the ideal image points are proportional to the focal length of the optical system. However, it is noteworthy that the focal length is not used to determine the ideal image points in this design, since the focal length are calculated by tracing paraxial rays which are not concerned in such an off-axis system, and the improper constraint of the focal length will lead to a large distortion. Therefore, the subsequent image points are constraint with a mapping relationship defined by the magnification between virtual object point \( E_o \) and its final image \( R_0 \) instead, which ensures a low distortion system. Since the configuration only consists of mirrors, and the refractive
indices for all wavelengths are the same, the system is free from chromatic aberrations. The calculation comes from the defined first off-axis field $E_o$ to larger fields. The complete design procedure is composed of four steps:

![Figure 2. The Initial parameters to start the design procedures.](image)

**Step 1:** the initial parameters are predefined with the specifications of the foregoing optics taken into account, including the exit pupil, the virtual object (original screen), actual image plane (tailored screen) and one point on each mirror that connects one specified ray from $E_o$ to $R_o$. After these parameters are determined, the optical path length (OPL) for field $E_o$ is calculated as

$$OPL_o = R_o G_o + G_o F_o - F_o E_o$$

(1)

Next, we define a small initial segment $01F$ on the first mirror by a smooth curve, for example an even polynomial expression $z = ay^2 + b$, covering rays through half of the pupil as illustrated in Fig. 3(a). According to Fermat’s principle, all the rays from one wavefront to its ideal image point have constant optical path length (OPL) 22. Therefore, each ray passing through $F_0F_1$ from $E_0$ to $R_0$ has the same OPL, and a corresponding point and its normal on secondary mirror is determined (for example $G_1$) by both Snell’s law and constant OPL condition 23. Consequently, a segment $G_0G_1$ on secondary mirror is obtained by tracing dozens of rays.

**Step 2:** a ray is calculated that is reflected at point $F_2$ on the first mirror and goes to the upper edge point $G_1$ on the secondary mirror, as shown in Fig. 3(b). The Snell’s law is applied at $F_2$:

$$(F_2G_1 - P_1F_2) \times nF_2 = 0$$

(2)

Where, $F_2G_1$ and $P_1F_2$ are normalized vectors, $nF_2$ indicates the normal at point $F_2$ and is calculated by

$$nF_2 = (\partial z/\partial y, -1)$$

(3)

Solving the Eqs. (2) and (3) we can get the exact position data of $F_2$ and its normal. After $F_2$ is determined, the position of virtual object point $E_1$ is calculated by extension of the ray $P_1F_2$ to object plane. The corresponding image point $R_1$ for the second field $E_1$ is also determined by the magnification coefficient. Then, with those parameters ($E_1$, $F_2$, $G_1$ and $R_1$) known, the OPL of field $E_1$ is calculated.

**Step 3:** an iterative ray tracing between fields $E_0$ and $E_1$ is executed by conducting a SMS algorithm between two adjacent fields 6. As shown in Fig. 3(c), an edge ray from $E_1$ to one edge point $F_1$ on known segment $F_0F_1$ is traced, bringing in a new point $G_2$ on secondary mirror by using constant OPL condition where the ray reflects to imaging point $R_1$. Then, a new ray is calculated backwards from image point $R_0$ to $E_0$, propagating already known point $G_2$ and leading to a new point $F_3$ on the first mirror with OPL constant, as shown in Fig. 3(d). More rays of fields $E_o$
and $E_i$ are sampled from bottom pupil $P_1$ to upper pupil $P_2$ by repeating the procedures in Figs. 3(c) and 3(d) until reaching the pupil boundary.

Step 4: we introduce a new field $E_2$ by firstly calculating a new point $F_4$ on the first mirror then obtaining its image point $R_2$ and $OPL_2$, in analogy to Step 2, as shown in Fig. 3(e). The existence of image points and OPLs for current field $E_2$ and previous field $E_1$ allows the repetition of the design process for new sets of points on both mirrors, similar to the procedures in Step 3.

Steps 2 and 3 are repeated between two adjacent fields in each iterative ray tracing loop until the maximum field $E_i$ is reached. To finalize the last segment for field $E_i$, we collect all the calculated points of the front profile and fit them into an odd polynomial curve, then extend the first profile region to allow all sampled rays covering the full pupil from $E_i$. Finally, the last segment of the rear profile is calculated by using the constant OPL condition. The illustrative design result is displayed in Fig. 3(f).

Figure 3. The multi-fields design procedures to calculate two off-axis mirrors partially coupling N ($N>3$) ray bundles: (a) define initial segments for first field (b) one new field is constructed by calculating a ray that passes one edge point (c) – (d) calculate more points on both profiles by an iterative SMS ray tracing process (e) another new field is constructed in analogy to the second one (f) finalize the maximum field by interpolating known points on the first mirror and tracing rays from full aperture.

3. DESIGN OF AN ULTRASHORT THROW RATIO PROJECTOR

To evaluate the effectiveness of the multi-fields design method, we have used a commercial projector of BENQ (model MH680) as an input system, and then designed the two-mirror sub-system from its exit pupil. The specification of this model is as follows: the throw ratio is 1.15-1.5 (78.3’’@2m), the focal length is 16.88-21.88mm, the f-number is 2.59-2.87, and the native aspect ratio is 16:9 24. Many commercial projectors have similar specifications which means that the method can be applied to other models.

The screen offset is 540mm in the image plane. From the real object space, the height is converted to the minimum radius $r_{min}$ of rotationally symmetric field which is 3mm, as shown in Fig. 4, so the magnification coefficient is $180\times$. Since the screen diagonal is supposed to be 78.3”, the screen width $X_{fld}$ and screen height $Y_{fld}$ are 1728mm and 972mm respectively. The following design and image quality are both from the perspective of object space, therefore the micro display size is calculated to be 9.6mm in $X_{fld}$ and 5.4mm in $Y_{fld}$. The maximum field for rotationally symmetric design is therefore calculated as
As seen from Figure 4, in rotationally symmetric design, a two dimensional profile that couples only tangential rays is calculated to cover the field from \( r_{\text{min}} \) to \( r_{\text{max}} \), which ensures the screen is inscribed in this annular area. Nevertheless, a majority of good image quality that the rotationally symmetric optical system is able to offer is not projected on the screen, resulting ineffective usage of the design degrees of freedom. As a comparison in the rectangular field design with two freeform mirrors incorporated, the focus area is well matched with the screen.

\[
r_{\text{max}} = \sqrt{(r_{\text{min}} + y)^2 + (x/2)^2} = 9.7\text{mm}
\]  

(4)

Table 1 Optical specifications of the ultrashort TR projector

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro display size</td>
<td>9.6 x 5.4 mm²</td>
</tr>
<tr>
<td>Wavelength</td>
<td>430 - 650 nm</td>
</tr>
<tr>
<td>Magnification</td>
<td>180</td>
</tr>
<tr>
<td>F-number</td>
<td>2.6</td>
</tr>
<tr>
<td>Projection distance</td>
<td>48cm</td>
</tr>
<tr>
<td>Screen size</td>
<td>78.3 inch</td>
</tr>
<tr>
<td>Throw ratio</td>
<td>0.24</td>
</tr>
</tbody>
</table>

After all specifications are fixed (as shown in Table 1), the z coordinates for the virtual object plane \((z=733\text{mm})\) and the tailored screen plane \((z=370\text{mm})\), the magnification coefficient and the diameter of pupil as well as the coordinates of \(F_0(19.729,129.961)\) and \(G_0(49.579, -46.997)\) are all implemented in the direct design program. We define the initial segment on the first mirror using an even polynomial expression \(z = -0.0001 \times y^2 + 130\), the area of which is very small compared to the final surface profile. The program stops when reaching the maximum field value 9.7mm. It finally exports two sets of points to describe the rotationally symmetric mirrors. We firstly design the two accessory mirrors with multi-fields direct design method in rotationally symmetric way, then represent the two surfaces with freeform surfaces for further optimization.

4. OPTIMIZATIONS AND IMAGE EVALUATIONS

4.1 Direct design and its rotationally symmetric optimization results

The two calculated profiles are fitted into odd polynomial coefficients, which we can import directly into the commercial optical design program Zemax to evaluate the results. The general expression for odd polynomial surface is given as follows \(^{25}\):

\[
z(r) = \frac{cr^2}{1 + \sqrt{1 - c^2 r^2}} \sum_i A_i r^m
\]

(5)

Where, \(c\) is the paraxial curvature of the surface, \(A_i\) is the coefficient of the polynomial terms, \(m\) is the order, \(m < 10\).  

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To evaluate the modulation transfer function (MTF) performance of the design, we also need the specifications of the micro display in the projector. The MH680 projector is using a 1080p digital micromirror device (DMD). We find such an exemplary DMD for the design, the DLP4710 1080p DMD with 5.4 µm for each micromirror pitch. Therefore, the cutoff spatial frequency is

$$f_{\text{cutoff}} = \frac{1000}{2 \times \alpha} \text{lp/mm} = 92.6 \text{lp/mm}$$

(6)

Where, $\alpha$ is the pixel size of the micro display. Given that the magnification is 180×, so the cutoff spatial frequency on the screen side is 0.52 lp/mm.

The MTF plots for selected fields (-3, -4, -5, -6, -7, -8, -9 and -9.7mm in y axis) of the multi-fields direct design are shown in Fig. 5. From the results, the worst MTFs performance are mainly from the minimum and maximum fields. The similar phenomenon happens in the process of the surface fitting where the fitting error is relatively large in the edge part of the calculated surfaces.

![Figure 5. The MTF diagram of multi-fields direct design in rotationally symmetric system shows a good inner performance and bad edge performance.](image)

Using the direct design data as a starting point, we have optimized the mirrors to reduce some fitting error as well as to improve the imaging performance. Since the design is rotationally symmetric, only half of the fields in radial direction are optimized. The merit function is built by using the root mean square (RMS) spot radius and chief ray setting. The focal length is not controlled during the optimization process, as a substitution we have used operand REAY to make sure the mapping relationship is fulfilled and distortion is reduced to a low level by adjusting the weighting factors. All the aspheric coefficients are defined as variables during the optimization, and the design quickly converges to a well performed system within a few cycles.

The imaging performance of the optimized rotationally symmetric system is also evaluated from the perspective of MTF plots, as shown in Fig. 6. The MTF values for all the selected fields at the cut-off frequency 0.52 lp/mm are higher than 0.43. As shown in [10], where a refractive lens is added as an accessory optic, the MTF value is better than 0.6 at 0.4 lp/mm (the resolution of DMD with 11.4 µm pixel size) for a smaller field of view. In the SMS accessory optic design, it reports a performance of MTF value better than 0.61 at 0.289 lp/mm (the resolution of standard Extended Graphics Array mode known as XGA) with the same field of view in this work. This comparison clearly demonstrates a comparable performance of our design to its counterparts of rotationally symmetric designs.
4.2 The optimization of freeform mirrors and the results

As already mentioned in Sec. 3, a rotationally symmetric design does not provide a well-matched solutions for off-axis imaging systems. Since the virtue of the problem is tailoring the image from the original screen to a desired nearer screen, the freeform surfaces could be better in accomplishing the task.

The odd polynomial surfaces are re-fitted to XY polynomial surfaces that are described by expression

\[ z(x, y) = \frac{c(x^2 + y^2)}{1 + \sqrt{1 - c^2(x^2 + y^2)}} + \sum A_i x^m y^n \]  

(7)

Where, \( c \) is the paraxial curvature of the surface, \( A_i \) is the coefficient of the polynomial terms, \( m + n \leq 10 \). Given that the system is symmetric with respect to the y-z plane, only even x-terms of each surface are not zero. Therefore, the even x-terms of XY polynomial coefficients are obtained from the surface fitting program and all imported into Zemax.

The design is further optimized with two freeform mirrors. The fields are normalized to be rectangular to better match the desired screen. Since the system is still y-z plane symmetric, only half of the fields in +x axis are taken into account. We choose 12 fields for optimization, 3 fields (-0.96, -2.88 and -4.8mm) in half x dimension and 4 fields (-3, -4.8, -6.6 and -8.4mm) in full y dimension. All the even x-terms are made as variables in the optimization process, and the thickness are kept constant; otherwise the dimension tends to become much larger. The final layout from 3D front view and 2D profile of the ultrashort throw ratio projector are shown in Fig. 7. The throw distance is 48cm, projected onto a 2m (78.3 inch) diagonal screen, so the throw ratio is 0.24.

Figure 7. The 3D front view and 2D cross section layout of designed ultrashort throw ratio projector.
During the optimization, the merit function is built by evaluating the RMS spot radius over the selected fields. The chief ray of each field is selected as the reference. The focal length should not be constraint; because the problem to be solved is different from purely finding a solution for good imaging performance, but a re-distribution of image with low distortion is also what we want. Therefore, we control magnification point by point, and the RMS spot radius in default merit function will take care of the image quality. With two freeform mirrors, the system is no longer rotationally symmetric, then not only fields from one radial direction should be controlled, but also from the full rectangular aperture. We choose 4×5 fields that are evenly distributed in –x and full y dimension respectively for distortion correction. As an off-axis imaging system, the centric y field (y=-5.7mm) is selected as the reference field for correcting distortion, and the position of its image point is \((X_{ref}, Y_{ref})\). For one specified field, the ideal position in the image plane is \((X_{ideal}, Y_{ideal})\) when the real position is \((X_{real}, Y_{real})\), then the distortion is defined as

\[
distortion = \frac{\sqrt{(X_{real} - X_{ideal})^2 + (Y_{real} - Y_{ideal})^2}}{\sqrt{(X_{real} - X_{ref})^2 + (Y_{real} - Y_{ref})^2}} \times 100\%
\]

(8)

The distortion for each field is then added in the final merit function, and the weighting factor is properly assigned during the optimization. At the beginning, if other aberrations are possessing a relatively high contribution percentage, a high value of weighting factor for distortion is preferred; otherwise, a small weight is recommended and better for improving the image quality.

After optimization, the design quickly converges to a well-balanced result. The obtained distortion grid is shown in Fig. 8. The red solid grid indicates the ideal image without distortion, and the black dashed grid is plotted by real ray tracing. The aspect ratio of the figure is 16:9, the same to that of the screen. From the result, the distortion is corrected quite well, and the maximum absolute value is lower than 1.5%.

Figure 8. The maximum distortion is below 1.5% on a 16:9 rectangular screen.

Figure 9 shows the image quality from the perspective of MTF values over the equidistance defined 12 fields. The maximum field (-4.8, -8.4) mm is the same as the maximum radius in the rotationally symmetric design when converted to the radial value. As shown in the figure, the MTF performance is higher than 0.58 at the cut-off frequency 0.52lp/mm after optimization with two freeform mirrors, much better than the rotationally symmetric designs targeting the same specifications. It clearly highlights the potential use of freeform optics in increasing off-axis imaging performance and/or solving a tailored imaging problem, where the field of view to be designed is far from being circular symmetric. The RMS spot radii range from 0.161mm to 0.389mm over the full field of view, as shown in Fig. 10. The added black circles in the spot diagrams correspond to the airy disk diameters, which are determined by real ray tracing at the reference wavelength and f-number.

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Figure 9. The MTF performance after optimized with two freeform mirrors is higher than 0.58 at 0.52 lp/mm.

Figure 10. The RMS spot diagrams using freeform mirrors show a well-balanced imaging performance.

To distinguish the deviations of the freeform mirrors from its rotationally symmetric counterparts, Figure 11 shows the surface contour plots of the first and secondary mirrors where the optimized rotationally symmetric bases have been subtracted from the freeform mirrors. In the first mirror, the maximum deviation is about 0.06mm, while in the second mirror the maximum deviation is about 0.5mm, and they are both in the border part of the mirrors, clearly displaying a non-rotationally symmetric surface sag.

Figure 11. The contour plots of (a) the first mirror and (b) the secondary mirror where the optimized rotationally symmetric bases have been subtracted from the optimized freeform mirrors.
4.3 The tolerance analysis of rotationally symmetric and freeform designs

The tolerance analysis plays a very important role in evaluating the as-built performance and optical element manufacturability. If the freeform design is much more sensitive than the rotationally symmetric design, it will make the benefits from using freeform optics less meaningful. We use the same tolerance parameters for both the rotationally symmetric and freeform designs, and choose the MTF performance (average of sagittal and tangential MTF) covering the sampled fields (as mentioned in Sec 4.1 for rotationally symmetric design and in Sec 4.2 for freeform design) at Nyquist Frequency 0.52lp/mm as the criterion. Considering that the two additional optics are both mirrors, refractive index and abbe number are not influential factors. Therefore, mainly the element tilt and displacement are considered. Since one of the designs is freeform, we separate the displacement and tilt errors in X and Y dimensions. The tolerance parameters are listed in Table 2. The position of the image plane is chosen as a compensator, similar to practical procedure in real assembly.

One thousand trials of Monte Carlo ray tracing have been performed to generate a considerable statistical analysis. In both cases, the worst offenders are the element tilt of the first mirror, and they can decrease the MTF by ~10-20% with 0.2 degrees error. Therefore, these errors for mirror 1 are further constrained to be within 0.1 degrees. The predicted as-built MTF performance are shown in Fig. 12, where the last fields are the overall MTF values for each design respectively, using the same weighing factor for the sampled fields. As we can see under the tolerance parameters in Table 2, the predicted MTF values decrease in both designs. In rotationally symmetric design, the nominal MTF value is 0.617 while the predicted as-built MTF value with 1 sigma confidence is 0.562, decreasing about 4.5%. In the freeform design, the nominal MTF value is 0.72 while the predicted as-built MTF value with 1 sigma confidence is 0.685, decreasing about 5%, about the same percentage loss in accordance to their own nominal MTF values. Since the freeform design has a higher nominal MTF value, it can achieve a better as-built performance than its rotationally symmetric counterpart under the same manufacture and assembly level. However, it is worthy of noting that, the edge fields in the freeform design are more sensitive than others, and will probably result in a lower yield. It could be an issue from using non-orthogonal XY polynomial surface type, which easily diverges on the edges, thus lead to very large slopes and quite sensitive to element tilt errors. Recent researches on orthogonal surface type also demonstrate that the usage of the orthogonal polynomials are beneficial for better tolerances in aspherical designs.

5. CONCLUSION AND FUTURE WORK

The multi-fields direct design method has already shown its potential in designing on-axis freeform imaging systems. In this work, we present its application in designing an ultrashort throw ratio projector with an off-axis mirror sub-system.
The final optical system of the projector consists of an off-the-shelf refractive optical lens and two accessory freeform mirrors, which greatly shortens the throw distance from 2m to 48cm for a 78.3 inch screen while obtaining a low-distorted and well-balanced imaging quality.

The essence of designing an ultrashort TR projector by adding off-axis accessory optic is pursuing both good imaging quality and tailored rectangular imaging distribution where the situation is somewhat similar to non-imaging optics. Hence, freeform optics are key to achieve an effective and well-matched rectangular imaging distribution without the mismatched image quality the rotationally symmetric systems do offer.

The presented multi-fields direct design method has demonstrated that it can provide a good starting point for further optimization of such freeform optical systems. In terms of MTF values, the developed freeform mirror system clearly outperforms its rotationally symmetric counterpart while keeping all other specifications the same. Tolerance analysis shows that under the same manufacture and assembly level, the overall MTF performance are almost the same sensitive to element tilts and displacements. Given that the edge fields in the freeform design using non-orthogonal XY polynomials are more sensitive, orthogonal polynomial surface type will be investigated in our future work.

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