Direct design of two freeform optical surfaces for wide field of view line imaging applications

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ABSTRACT

In this paper, we propose a multi-fields direct design method aiming to calculate two freeform surfaces with an entrance pupil incorporated for wide field of view on-axis line imaging applications. Both infinite and finite conjugate objectives can be designed with this approach. Since a wide angle imaging system requires more than few discrete perfect imaging points, the multi-fields design approach is based on partial coupling of multiple fields, which guarantees a much more balanced imaging performance over the full field of view. The optical path lengths (OPLs) and image points of numerous off-axis fields are calculated during the procedure, thus very few initial parameters are needed. The procedure to calculate such a freeform lens is explained in detail. We have designed an exemplary monochromatic single lens to demonstrate the functionality of the design method. A rotationally symmetric counterpart following the same specifications is compared in terms of RMS spot radius to demonstrate the clear benefit that freeform lens brings to on-axis line imaging systems. In addition, a practical achromatic wide angle objective is designed by combining our multi-fields design method with classic optical design strategies, serving as a very good starting point for further optimization in a commercial optical design program. The results from the perspective of aberrations plots and MTF values show a very good and well balanced performance over the full field of view.

Keywords: geometric optics, imaging, optical design, lenses, aspheric, optical systems, freeform optics

1. INTRODUCTION

Optical components with freeform surfaces have already demonstrated their superiority in various off-axis imaging applications, such as three-mirror systems 1,2 and head mounted display 3,4. When it comes to on-axis imaging systems, rotationally symmetric components are typically considered to provide the best solutions. It is obvious that rotational symmetry eases the optical design procedures as the whole surface is determined after the calculation of one two-dimensional (2D) surface profile. In general, it is the optimal solution for those cases where the both the object and image space are close to rotationally symmetric with respect to the optical axis. However, in some cases the object and/or the sensor dimensions are far from being rotationally symmetric, for example in high aspect ratio or line imaging systems. Practical applications for such systems are the pushbroom hyperspectral cameras 5,6 and scanning systems 7.

In general, there are two main options to design freeform optical systems: a multi-parametric optimization based-and a direct calculation based design approach. The first option utilizes common freeform surface descriptions such as Zernike, Chebyshev or XY polynomials, or explores novel effective characterizations of freeform optical surfaces to describe the systems to be designed. After the surfaces are accurately described by equations, the parameters (radii, distances, polynomial coefficients and so forth) of the optical systems are optimized by optical design programs to minimize a predefined merit function. The second option, those direct design methods, relies on solving geometrical or differential equations of the designed optical systems to achieve an optimal solution.

Most existing multiple-surface freeform design methods, such as the Simultaneous Multiple Surfaces (SMS) design method 17,18 and a related analytic design method 19, typically do not include an entrance pupil which is important for correcting off-axis aberrations 20 and the lenses are not always practical, as shown in Fig.1 (a). These methods allow to perfectly focus two or three fields with two optical surfaces, as shown in Figure 1(b) in terms of root mean square (RMS) spot radius. Such an imaging performance is not desired, instead, a well-balanced spot size distribution throughout the FOV as the dashed line indicates in Fig. 1(b) performs better in a wide field-of-view (FOV) imaging system. In a recent article 21, we have proposed a multi-fields 2D direct design method that enables partial coupling of multiple ray bundles with two rotationally symmetric aspheric lens surfaces to balance the performance from tangential rays. However,
astigmatism and field curvature become the dominant aberrations when FOV increases, and the correction of these two aberrations requires for a 3D design method with control on both tangential and sagittal rays.

Figure 1. (a) The example of a direct design method for freeform optics that achieves three perfect image points. (b) The RMS spot radius plot of design (a) and what we actually want to obtain is a well-balanced performance throughout the FOV as the dashed line.

In this paper, we present the generalization of this design approach. In Sec. 2, the procedures to calculate a two-surface freeform optical system including an entrance pupil are explained in detail. An exemplary monochromatic design case is following to demonstrate the functionality of the proposed design method in Sec. 3. The comparison between the multi-fields 2D and 3D design method is described as well. In Sec. 4, the design of a practical achromatic wide field objective lens further shows the superiority of freeform lens to spherical/aspheric lens. Finally, in Sec. 5, conclusions are drawn and the outlook is given.

2. GENERALIZED MULTI-FIELDS DESIGN METHOD

The two unknown surfaces being designed are calculated from the center, and multiple off-axis fields are constructed by sequence afterwards. As illustrated in Fig. 2, the initial setup includes an on-axis object \( E_0 \) (from infinity or finite distance), an entrance pupil \( P \) and its center \( P_0 \), vertex point \( M_0 \) on the front surface \( M \), vertex point \( N_0 \) on the rear surface \( N \) and the on-axis image point \( R_0 \). Generally, these parameters are deduced from the specifications of the optical system. Since the object can be from infinity, the origin of the coordinate is positioned in the center of the entrance pupil. The diameter of entrance pupil \( P \) is defined to constrain the edge rays. The refractive index between the front and rear surface is \( n_1 \), others are \( n_0 \). The complete design procedure consists of four steps:

Figure 2. The initial setup of multi-fields 3D design method

(1) When the initial parameters are determined, the optical path length for on-axis field is calculated as

\[
OPL_0 = n_0 E_0 M_0 + n_1 M_0 N_0 + n_0 N_0 R_0
\]
We define an initial segment $MP_0$ on surface $M$ to couple a small portion of paraxial rays, as illustrated in Fig. 3(a). The dimension of the initial segment is quite small when compared to the final full aperture. The surface sag can be represented by an even-order polynomial to satisfy the symmetry of on-axis field, for example, a 2nd order form

$$z(x, y) = a(x^2 + y^2) + b$$

(2)

Where, the variables on the first surface is sampled by a pattern of rings or rectangular arrays, $a$ is the shape factor, and $b$ is the offset value of the surface to the coordinate origin.

We trace a ray that emits from $E_0$ passing through one specified point $M_0(x, y, z)$ on the first surface and an unknown point $N_0$, finally gets to $R_0$.

The refracted ray vector at point $M_0$ is calculated based on Snell’s law

$$n_0 \left( \vec{E}_0 M_0 \times n M_0 \right) = n_1 \left( M_0 N_0 \times n M_0 \right)$$

(3)

Where, $n \vec{M}_0$ is the surface normal vector at point $M_0$ and obtained by

$$n \vec{M}_0 = (\partial z(x, y)/\partial x, \partial z(x, y)/\partial y, -1)$$

(4)

According to Fermat’s principle, all the rays from one certain field to its ideal image point have constant optical path length (OPL). The point $N_0$ satisfies the constant OPL relation

$$n_1 M_0 N_0 + n_0 N_0 R_0 = OPL_0 - n_0 E_0 M_0$$

(5)

In addition, unknown point $N_0$ is determined by

$$N_0 = M_0 + M_0 N_0 \vec{v}$$

(6)

Where, $\vec{v}$ is the normalized vector of $M_0 N_0$. Solving the equations (5) and (6) we can get the exact position data of $N_0$ and its surface normal.

Therefore, the initial segment (or more precisely points cloud) $NP_0$ on the second surface is calculated by tracing sampled paraxial rays from $E_0$ passing through a small portion of entrance pupil within its diameter $D_0$.

(2) In the second step, one new off-axis fields $E_1$ is constructed by adding an increment angle $\theta$ to the chief ray along the axis $x$. The value of $\theta$ is chosen to be small enough to make sure the chief ray pass through already known segments ($MP_0$ and $NP_0$) on both surfaces, as shown in Fig. 3(b). By calculating the trajectories of the chief ray, its image points $R_{10}$ and $OPL_{10}$ are both determined. More rays from $E_1$ are traced within the range of already known segments on both surfaces. The new image point $R_1$ and $OPL_1$ are the mean values of all sampled rays

$$R_i = \frac{1}{N} \sum_{j=1}^{N} R_{ij} \quad OPL_i = \frac{1}{N} \sum_{j=1}^{N} OPL_{ij}$$

(7)

Where $N$ is the number of the sampled rays, $R_i$ and $OPL_i$ are the image point and optical path length of certain ray from field $i$ respectively. After the optimal image point $R_1$ and $OPL_1$ for current field are determined, it is feasible to calculate more new points on both surfaces by conducting a 3D SMS algorithm between two adjacent fields.

A new ray is then traced from object $E_1$ to one edge point $M_1$ on known segment $MP_0$, passing by an unknown point $N_1$ on the second surface, finally reaching its image point $R_1$. The rays from field $E_0$ and $E_1$ have different incident angles at point $M_1$, and the angle difference leads to new points on the second surface. Since both $OPL_1$ and $R_1$ are known, new point $N_1$ can be determined based on constant OPL condition, similar to the calculation of point $N_0$.

If more such rays are traced from object $E_1$ to other edge points of segment $MP_0$, we can get one set of new points cloud $NR_1$ (or rib from the SMS method) as well as their corresponding normal vectors, as shown in Fig. 3(b).
(3) The iterative ray tracing process begins with tracing rays backwards from image point $R_0$ propagating already existing points cloud $NR_1$ to object point $E_0$. A new set of points cloud $MR_1$ on the front surface is calculated accordingly by using the constant $OPL_0$ condition for the specified field, as shown in Fig. 3(c). Next, another new set of points cloud $NR_2$ on the second surface is calculated based on known $MR_1$, by tracing the rays from object point $E_1$ to image point $R_1$ with the value of $OPL_1$ constant. The iteration between field $E_0$ and $E_1$ is repeated until new sampling rays from $R_0$ to $E_0$ exceed current entrance pupil boundary $D_1$.

The entrance pupil diameter is not the full diameter from the beginning but adjustable for each field to make a balanced entire performance. We define a virtual aperture diameter $D_i$ for each field

$$D_i = W_i D$$

(8)

Where $W_i$ is the weighting factor for each field, $D$ is the full entrance pupil aperture. The distribution function of $W_i$ is chosen based on classical optical design strategy that the entrance pupil fractions are generated for equal areas and slightly optimized in every design. For example, the calculated segment area for normalized 0.707 field is about one half of the final surface area.

(4) When the ray tracing for field $E_0$ is finished, we can introduce a new field $E_i$ in analogy to step (2), calculating new image point and OPL. The existence of image points and OPLs for current field $E_i$ and pervious field $E_{i-1}$ allows the repetition of the design process for new sets of points cloud on both surfaces, similar to the procedures in step (3). Steps (2) and (3) are repeated between two adjacent fields until the maximum field is reached. In each loop, the field data $(E_i, OPL_i, R_i)$ is calculated based on known segments of both surfaces, then new sets of points cloud are created to extend the surfaces. To finalize the last patches for the maximum field $E_{max}$, we collect all the calculated points of the front surface and fit them into a XY polynomial surface, then extend the first surface region to allow all sampled rays from $E_{max}$ covering the full aperture of entrance pupil $D$. Finally, the last patch of the rear surface is calculated by using the constant OPL condition. The illustrative design result is displayed in Fig. 3(d). The resulting data for each surface can be fitted by typical freeform surface expressions to import into an optical design program, where the imaging performance will be evaluated.
Figure 3. Illustration of the design procedures to calculate two freeform surfaces partially coupling N(N>3) ray bundles: (a) define initial segments (b) one new field is constructed by sampling multiple rays to calculate its OPL and image point (c) The points clouds on both surfaces are extended by the addition of new points from iterative calculations between two adjacent fields (d) The lens surfaces are finalized by interpolating known points and extending into full aperture.

3. COMPARISON OF MULTI-FIELDS 2D AND 3D DESIGNS

To evaluate the effectiveness of the multi-fields 3D design method, we design a monochromatic f/4 single lens for line imaging. The effective focal length is 16mm, focusing the object from infinity. All the optical specifications are listed in Table 1. The thickness of the lens is 3mm, and the distance from the entrance pupil to the lens is 3mm. The refractive index of the glass material is set to be 1.5. There is an initial segment on the first surface which we defined as 

\[ z(x, y) = -0.01(x^2 + y^2) + 3 \]

The full field of view is 80 degree, covering a diagonal image height of 23mm. The full 80 degree FOV is divided into 81 fields by a 1 degree chief ray increment during the design process. By initializing the program as in Sec. 2 with those parameters, it finally exports two sets of points to describe the freeform surfaces. Each set of points cloud is fitted by a series of \( x^m y^n \) polynomial terms added to a spherical base. The general expression for the freeform surface is

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

Where, \( c \) is the paraxial curvature of the surface, \( A_i \) is the coefficient of the polynomial terms, and \( m + n \leq 10 \). Given the quadrant symmetry of the imaging system, only even terms of each surface are not zero. Therefore, 20 even terms of XY polynomial coefficients are obtained from the surface fitting program and all imported into Zemax to evaluate the
imaging performance of the freeform lens. A cross section of the single lens system in x-z plane is shown in Fig. 4(a). To distinguish the deviation of the freeform lens from its spherical base, the best fitting sphere is subtracted from each surface to show the contour plots of the remaining part, as shown in Fig. 4(b), which clearly demonstrates a non-rotationally symmetric structure. The curvature radii of the best fitting sphere on the first surface and the second surface are -33.878mm and -6.940mm respectively.

Table 1 Specifications of the exemplary design

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<td>Wavelength</td>
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<td>Focal Length</td>
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</tr>
<tr>
<td>Field of View</td>
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<tr>
<td>Back focal length</td>
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<tr>
<td>Entrance pupil</td>
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Figure 4. (a) The 2D lens profile shows a good converging performance over the whole field when all the coefficients are imported into Zemax. (b) The contour plots of the first and second lens surface where the best fitting sphere is subtracted from each of the calculated surfaces.

The same specifications have been used to design a rotationally symmetric reference lens using the multi-fields 2D design method presented in reference [21]. The performance of both designs are then compared from the perspective of RMS spot radius for the selected fields (0, 10, 14, 20, 28 and 40 degree) on the same scale level, as shown in Figs. 5(a) and 5(b).

Fig. 5. The direct comparison in terms of spot radius for (a) the multi-fields 3D design method and (b) the multi-fields 2D design method clearly shows a better imaging performance for the 3D design method.
We can see that as the FOV increases, the influence of astigmatism and field curvature outreaches other aberrations in the 2D design, which makes the good performance of tangential rays less meaningful as shown in Fig. 5(a). The multi-fields 3D design method achieves a much better performance due to additional control of its sagittal rays as shown in Fig. 5(b). As a result, the RMS spot radius values range from 0.05 to 0.12mm in multi-fields 3D design, compared with 0.08 to 0.16mm in case of the rotationally symmetric 2D design. In terms of MTF values, the multi-fields 3D method also demonstrates a better performance in the sagittal dimension than its 2D counterpart does. However, such an asymmetric configuration is not good at correcting distortion. In both cases, the maximum values of distortion are about -12%. In next section, we will show that by adding a front lens to make a more symmetric configuration, the distortion is greatly reduced.

4. DESIGN OF AN ACHROMATIC WIDE FIELD LINE IMAGING OBJECTIVE

The multi-fields 3D design method, as similar to other freeform direct design methods, is limited to no more than 2 surfaces at the moment. Nevertheless, we can utilize some classic optical design strategy to enhance the effect of single freeform lens, for example, adding a negative front lens to bend rays outward is beneficial for a wide-field lens 27. In addition, the combination of different material glasses is helpful to correct chromatic aberrations, e.g. the fluoro-crown glass FK51 can combine with other crown glasses to form a super-achromatic doublet 28. A wide-angle line imaging objective is designed to demonstrate this hybrid design strategy.

We have chosen an all-spherical wide FOV objective from US patent 2518719 as a reference system which includes four lenses 29, as shown in Fig. 6(a). The whole system has an effective focal length of 16mm, and the f-number is 5, as listed in Table 2. The field of view is 80 degree. The glass materials are keeping the same as stated in the patent. 6 fields (0, 10, 14, 20, 28 and 40 degree) are defined and normalized as rectangular without vignetting factors. The merit function is built by using the Zemax default setting: choosing the chief ray and RMS spot radius as reference and rectangular array 10×10 as pupil integration method. Additional operands are added to control the effective focal length and distortion. Boundary constraints are also set to make the lens physically feasible. The imaging performance is then optimized by making all the surface curvature radii and air thicknesses into variables.

Table 2 Specifications of the wide-field objective design

<table>
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<th>Specifications</th>
<th>Values</th>
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<tr>
<td>Wavelength</td>
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<td>Focal Length</td>
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</tr>
<tr>
<td>Field of View</td>
<td>±40 degree</td>
</tr>
<tr>
<td>F-number</td>
<td>5</td>
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<tr>
<td>Entrance pupil</td>
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Fig. 6. (a) A wide-angle objective from U.S. Patent 2518719 and (b) a hybrid design by combining multi-fields 3D method and classical design strategies

The hybrid design consists of a spherical front lens and a freeform rear lens, as shown in Fig. 6(b). The freeform rear lens is firstly designed by the multi-field 3D design method, complying with the same specification of the whole system and following the procedures in Sec. 2.1. The initialization parameters for the single freeform lens are 3mm lens thickness and 1.5 refractive index for monochromatic design; the distance from pupil stop to the first surface is 3mm in the beginning; the object is from infinity and the image plane is 16mm offset from the rear surface. After calculating the two surfaces directly, we have obtained a single freeform lens similar to the configuration in Fig. 5. The front lens with...
1.5 refractive index is added afterwards with zero power and 3mm thickness so as to not affect the fair performance of the calculated freeform lens. The distance of the rear flat surface to the stop is also set to be 3mm to make the lens arrangement symmetrical, which is helpful for correcting distortion. The hybrid system is then optimized in Zemax by using the default merit function as what have been done for the all spherical design. All the surface radii and the coefficients for the freeform lens, the distances between the pupil stop and the two lens elements as well as the back focal length are made to be variables. Some additional operands are added to control the effective focal length, overall length and distortion.

The above process ensures a good image quality of single wavelength performance in 550nm. The results are shown in our recent work 30. In order to design a practical objective in visible spectrum, we have substituted the virtual glass into real ones. The same design and optimization procedures above have been implemented again, except that the fluorocrown glass FK51 and a crown glass BK7 are chosen to correct chromatic aberrations here, substituting the 1.5 refractive index virtual glasses. After optimization, the achromatic design quickly converges to a good result.

The line imaging performance is evaluated from the perspective of RMS spot radius in 6 selected fields for different wavelengths (486.1nm, 587.6nm and 656.3nm), as shown in Fig. 7. In terms of maximum spot radius, the hybrid design is 7.6µm, about half of the all-spherical design’s 12.1 µm. The values of field curvature are both within the range of ±0.5mm, as given in Fig. 8. The absolute values of the maximum distortion in these two designs are both less than 2%. The average MTF of the proposed design example is about 0.65 at 30lp/mm, compared with its counterpart’s 0.58, as shown in Fig. 9. The comparison clearly demonstrates a better image quality of the hybrid two-lens design than the all-spherical four-lens design.
The performance of one single freeform lens is already very good except for the distortion; after applying a hybrid method to add a front spherical lens and use achromatic glass combination, the performance of one freeform and one spherical lens is even better than the four-spherical lenses design in terms of RMS spot radius, field curvature, distortion and MTF.

5. CONCLUSION AND FUTURE WORK

In this work, we generalized the previously presented two-dimensional multi-fields direct design method to three dimensions. The developed direct freeform design method allows to simultaneously control both tangential and sagittal rays that is crucial to calculate well-balanced solutions. So far, this method allows the simultaneous calculation of two x-z and y-z plane symmetric freeform surfaces with an entrance pupil included, but it has the potential to calculate freeform optical surfaces without symmetries (e.g. in off-axis configurations). The new method does not need a priori information about optical path lengths and image points, largely reducing the dependence on initial parameters. Ray bundles from multiple fields are considered during the procedures to balance the entire image, in contrast that most current direct design methods obtain two or three perfect image points with two surfaces.

An f/4 lens has been designed with this method, achieving a very well-balanced image performance over the full field of view. Another wide-field line imaging objective has been designed by combining classic optical design strategies with the multi-fields design method. It could be a very general idea to design with hybrid methods, especially given the fact that none of current direct design tool is capable of calculating more than two freeform surfaces. As an example, the wide field design with this hybrid strategy shows a better result when compared with its all-spherical four-lens counterpart.

The shown examples clearly highlight the potential to use less optical elements in case freeform surfaces are used. As a rule of thumb, two freeform optical surfaces could perform as well as six spherical optical surfaces.

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