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Optical design of 'first time right' imaging systems

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ABSTRACT

Today's optical design of imaging systems relies mostly on efficient ray tracing and (local or global) optimization algorithms. Such a traditional 'step-and-repeat' approach to optical design typically requires considerable experience, intuition, and sometimes trial-and-error guesswork. Such a time-consuming design process applies especially, but not only, to freeform optical systems. In particular, the identification of a suitable initial design to then adapt and further optimize has often proven to be a laborious process.

We present our developed 'first time right' design method that allows a highly systematic generation and evaluation of directly calculated imaging optics design solutions and thus enables a rigorous, extensive, and real-time evaluation in solution space. The method is based on differential equations derived from Fermat's principle that can be solved effectively by using a power series method. This approach allows calculating all optical surface coefficients that ensure minimal image blurring for each individual order of aberrations. Such directly calculated optical design solutions can be readily used as starting point for further and final optimization. We demonstrate the deterministic and holistic nature of our method and the streamlined design process for various real-world examples ranging from spherical lens designs to freeform imaging systems. The method allows calculating all optical surface coefficients that ensure minimal image blurring for each individual order of aberrations. We demonstrate the systematic, deterministic, scalable, and holistic character of our method for various design examples ranging from spherical lens designs to freeform imaging systems.

Keywords: Freeform optics, optical design, imaging optics, mathematical optics, lens generator, spherical lens design

1. INTRODUCTION

For more than 150 years, scientists have advanced aberration theory to describe, analyze and eliminate imperfections that disturb the imaging quality of optical components and systems. Simultaneously, they have developed optical design methods for and manufacturing techniques of imaging systems with ever-increasing complexity and performance up to the point where they are now including optical elements that are unrestricted in their surface shape. These so-called optical freeform elements offer degrees of freedom that can greatly extend the functionalities and further boost the specifications of state-of-the-art imaging systems. However, the drastically increased number of surface coefficients of these freeform surfaces poses severe challenges for the optical design process, such that the deployment of freeform optics remained limited until today. Today the design of optical systems largely relies on efficient raytracing and optimization algorithms for which a variety of commercial software and optimization algorithms are available. During an optical design cycle, different parameters of the optical system such as the optical material parameters, radii, coefficients and positions of the optical surfaces are varied to optimize a defined merit function that indicates the image quality for a given field of view. These merit functions are typically "wild" with many local minima, and there is no guarantee that local or global optimization algorithms will lead to a satisfactory design solution. A successful and widely used optimization-based optical design strategy therefore consists of choosing a well-known optical system as a starting point (e.g., from literature) and steadily achieving incremental improvements. Such a "step-and-repeat" approach to optical design, however, requires considerable experience, intuition, and guesswork, which is why it is sometimes referred to as "art and science". This applies especially to freeform optical systems. Here, we make use of the recently presented 'first time right' (FTR) optical design method for imaging systems. It is based on solving differential equations derived from Fermat's principle of least time by using a power series approach. The method allows calculating the optical surface coefficients that ensure minimal image blurring for each individual order of aberrations. As such, it offers a disruptive methodology to design optical imaging systems from scratch. A fully detailed mathematical description can be found in our recently published article [1].

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2. 'FIRST TIME RIGHT' DESIGN SHOWCASES

2.1 Three-mirror freeform design

The first reference design example is a catoptric imaging system by Bauer et al. for the visible spectrum with x-z-plane symmetry and the object at infinity [2]. It consists of three freeform mirrors with the stop at the first mirror. The targeted system volume is 60 liters. Thus, the layout of the optical components can be described by three distances (between mirror 1 and 2, mirror 2 and 3, and mirror 3 and the image) and four rotation angles (one for each of the three mirrors, and one for the image), which provides seven geometrical degrees of freedom for the optical designer. These distances and angles can now be (manually) adjusted to create an unobscured starting geometry that meets certain geometrical constraints such as the given target system volume. The calculated design that we obtained by optimizing the seven degrees of freedom of the geometry is shown in Fig. 1a, where the system layout cross-section is combined with the full 3D peak-to-valley freeform departures (PV) from the best-fit base sphere for each mirror, respectively.

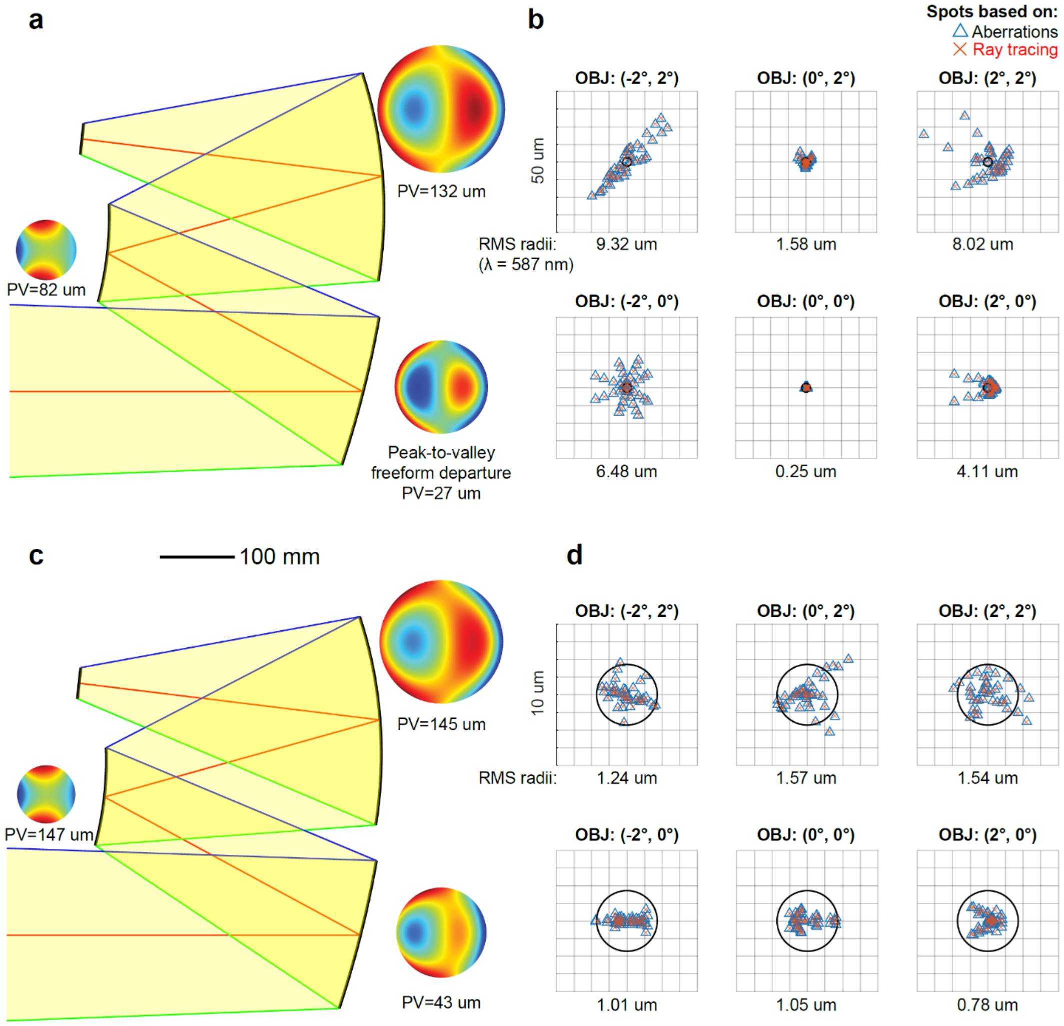

Figure 1. **a** Cross-section of the directly calculated initial system combined with peak-to-valley freeform departures (PV) from the base sphere for the primary, secondary and tertiary mirror. **b** Corresponding spot diagrams for six selected fields based on aberration calculations (blue triangles) and ray tracing (red crosses) in comparison. **c** Cross-section of the subsequently optimized system combined with peak-to-valley freeform departures (PV) from the base sphere for each mirror. **d** Corresponding spot diagrams for the same six fields based on aberration calculations (blue triangles) and ray tracing (red crosses) in comparison.

Fig. 1b shows the spot diagrams for six selected fields based on our aberration calculations up to 8th order. With an average RMS spot radius of about 5 micrometers, our directly calculated system provides an already well-corrected 'first time right' solution that can be readily further optimized. Next, all forty previously calculated surface coefficients and the initial seven degrees of freedom are used as variables for further optimization, e.g., using MATLAB's lsqnonlin solver. After ten iterations, which only take few minutes, the system already reaches diffraction-limited performance for almost the full field of view. The optimized design shows slightly increased and moderate freeform departures distributed among the three mirrors. The results are shown in Fig. 1c and 1d accordingly. The aberration-based performance estimation of our method was found to be in excellent agreement with spot diagram data from classical ray tracing (calculated using Zemax, overlaid red cross symbols in Fig. 1b and 1d). We have developed a web-based user application for the three-mirror design case that allows to experience this unique design method hands-on and in real time. The graphical user interface and the usage of the app are explained in depth in the Supplementary Information document of our recently published article [1].

2.2 Catadioptric freeform objective design

As a second example from literature, we have selected a monolithic freeform objective for a very compact infrared camera with four optical surfaces [3]. We chose this example to illustrate the scalability of our design method, well beyond the capabilities of most present-day direct freeform design approaches. We furthermore highlight its holistic character, since in this case we are dealing with a catadioptric system with freeform and aspherical surfaces. Here we design an objective consisting of three aspheres and one freeform at the second surface, with the stop placed at the first surface. We follow this reference as closely as possible with the following system requirements: An F/1.4 design covering a 37×25-degree field-of-view, an 8.4 mm entrance aperture, made of optical-grade germanium and operating in the long-wave infrared region (LWIR) from 8-12 um. With the object at infinity, the layout of the system can be described by four distances and five angles, defining the principal ray path from object to image and the respective positions and orientation of all surfaces and corresponding rotation matrices. Optimizing the 9 initial degrees of freedom of the geometry yields an already well-corrected and unobscured system. Fig. 2a shows the configuration of the system of comparable size to the cited reference design. The peak-to-valley freeform departure (PV) from the best-fit base sphere for the second freeform surface is added next to it. Fig. 2b shows the corresponding spot diagrams for six selected fields (we used 15 fields for the optimization) based on our aberration calculations. With an average RMS spot radius of about 51 micrometers, we achieved an excellent starting point for further optimization. All surface coefficients are now set as variables for further optimization using e.g., MATLAB's lsqnonlin solver. The results are shown in Fig. 2c and 2d.

Within few minutes, the system reaches a close to diffraction-limited performance in the LWIR band for the full field of view with an acceptable distortion of less than 5%. Chromatic aberrations are very well controlled due to the relatively low dispersion of Germanium in the LWIR band. In addition, the relatively small angles within the monolith due to the high refractive index lead to a better aberration control in general. This spot diagram-based performance is in excellent agreement with spot diagram data from classical ray tracing.

This example clearly demonstrates again the highly effective nature of our proposed design and evaluation method. In addition, it highlights two further important features: 1) our method allows to simply combine refractive and/or reflective surfaces of spherical, aspheric or freeform shapes; 2) the method also straightforwardly enables to increase the number of calculated surfaces of an optical system without considerably increasing the computational complexity of the problem. This direct path to scaling the number of calculated surfaces is a result of the fact that the intermediate optical path length distance expressions do not depend on the number of considered surfaces.

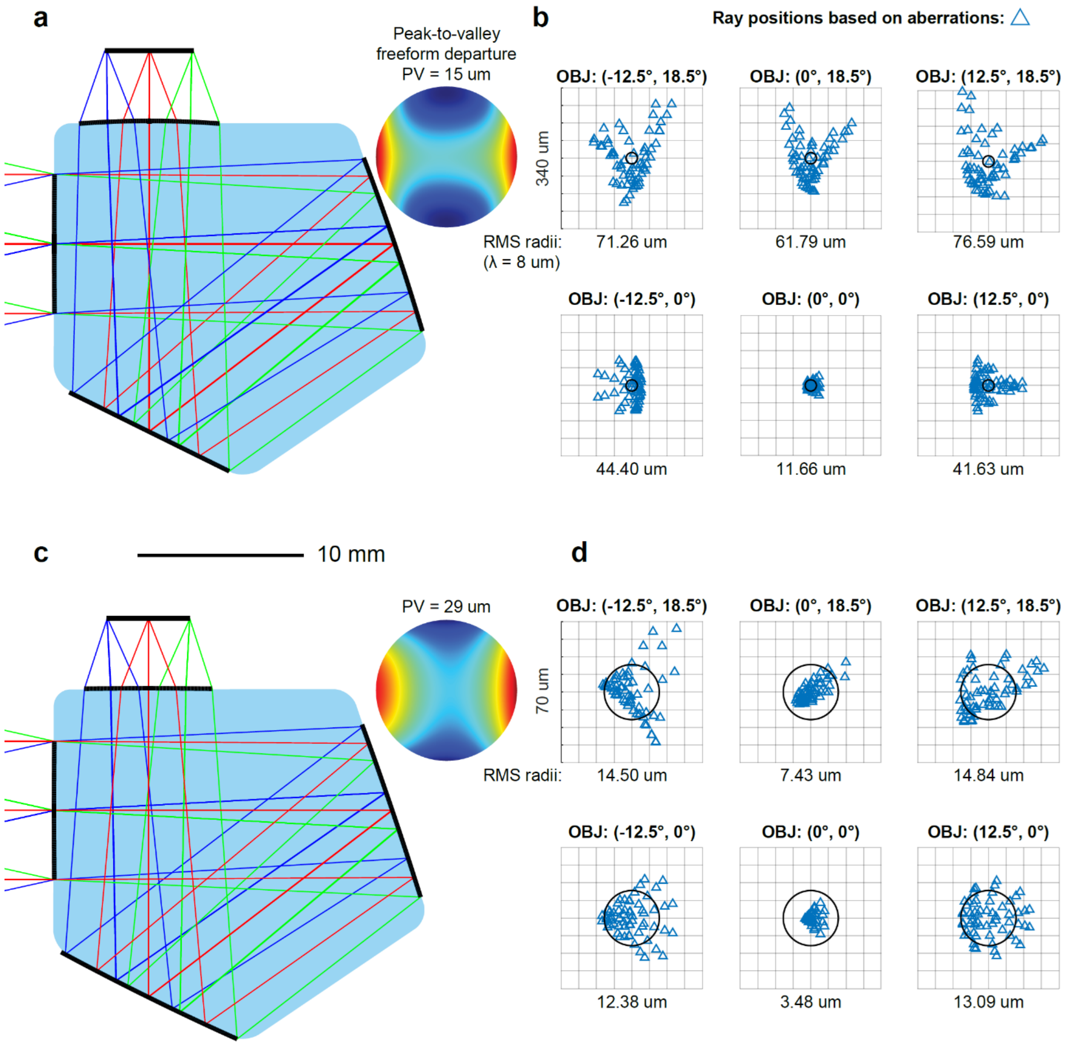

Figure 2. **a** Cross-section of the system from direct calculations with peak-to-valley freeform departure (PV) from the base sphere for the second and only freeform surface. **b** Corresponding spot diagrams for six selected fields based on aberration calculations. **c** Cross-section of the subsequently optimized system combined with peak-to-valley freeform departure (PV) from the base sphere for the second surface. **d** Corresponding spot diagrams for the same six fields based on aberration calculations.

2.3 Three-mirror, four-reflection design

Despite faster F-numbers and larger FOVs, freeform four-mirror designs bring in extra complexity to both mirror fabrication and system assembly compared to three-mirror designs. As a promising alternative, we have investigated a revived type of multireflection mirror systems where at least one of the mirrors is passed twice in the ray path with desired overlap (not mutually centered to provide more flexible designs) [4]. This contrasts the well-known Offner designs where two individual mirrors share separate parts (no overlap) of a joint substrate without a desired overlap in their footprints.

Regarding the four-reflection cases, there are three possibilities to generate the “double-pass surface”, respectively mirrors M1/3, M1/4 and M2/4. Several showcases of each type have been calculated by the proposed 'first time right' method, summarized in Fig. 3.

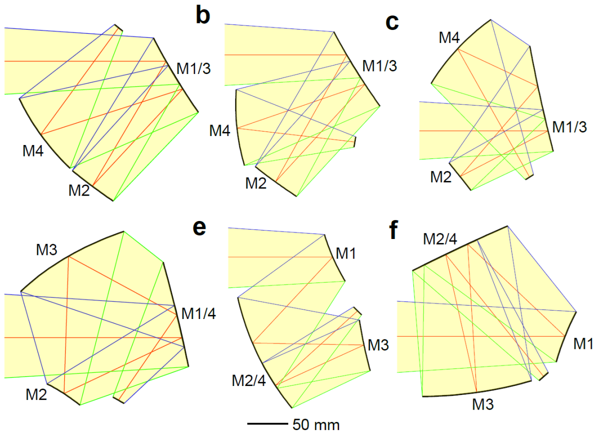

Figure 3: The proposed freeform optical design method unlocks a new class of three-mirror, four-reflection freeform systems with three different "double-pass surface" options. (a)-(c) M1/M3. (d) M1/M4. (e)-(f) M2/M4. Note all the layouts are based on real raytracing with the design parameters for visualization: focal length 250mm, F/2.5, FOV 7.2°×7.2°.

In summary, the presented three-mirror, four-reflection concept can yield high-performing yet compact designs, opening a largely extended design space to explore and seek new competitive freeform systems, please see also [5].

2.4 All-spherical start lens designs

The rapid generation of promising initial designs is likewise useful for rotationally symmetric all-spherical lens systems. Often, the complexity of a lens design task does not mainly arise from the required optical performance, but from additional constraints that must be met. For example, reaching certain performance metrics might not be a problem to achieve in an entirely unconstraint system. However, if for example the total track length of the lens system is clearly limited, this can easily change. Further system constraints such as the aperture stop position, a fixed back focal length, lens diameter restrictions or telecentricity requirements can similarly pose additional challenges to the optical designer. Finally, glass availabilities (properties, cost) can have a major impact when it comes to chromatic aberration correction. We have further developed the 'first time right' method to design (a)spherical lens-based imaging systems from scratch. A designer only needs to provide the required system specifications and any imposed constraint. Due to the fast speed, a wide range of lenses are calculated and validated fully automatically. In return, the designer receives several generated start lenses that (almost) meet all constraints while showing already well-balanced optical performance. The FTR start lens generator (SLG) has been successfully tested for a wide range of lens applications. In the following, two examples are presented for illustration purposes.

1st example: a fast near infrared (NIR) lens

In reference paper [6], the authors applied and compared different global optimization strategies starting from a known six element lens design. The system specifications and constraints are as follows: a front stop, 100 mm focal length, f/1.5 (66.7 mm entrance pupil diameter), 16 degrees full field of view, distortion ≤ 5% (not disclosed, fixed by us), total track length ≤ 181.5 mm; back focal length ≥ 4 mm and NIR wavelength range from 0.9 to 1.7 um. The best reported result in this paper has been achieved using Zemax 'Hammer' optimization, with ~55um average RMS spot size and a rather moderate color-correction. We used the FTR-SLG with these specs and constraints, generating several potentially interesting lenses within few minutes of runtime. Figure 4 shows an exemplary calculated FTR result on the left, and the result after further optimization and forming a cemented doublet for the front element on the right.

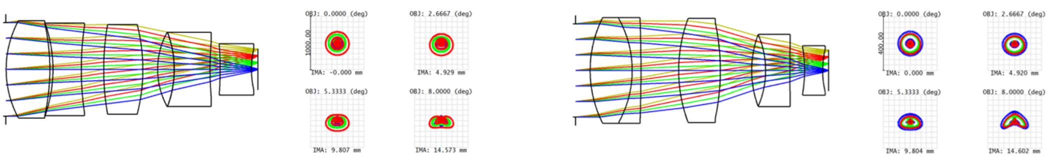

Figure 4: (left) FTR-SLG result shows already great initial performance while meeting all the imposed constraints. (right) The further optimized lens with an introduced cemented front lens element shows excellent final performance.

The optical performance of the generated lens is already very good with ~70um mean RMS spot size. The final optimized system further improved to ~30um mean RMS spot size with well-corrected chromatic aberrations.

2nd example: a double-telecentric machine vision lens

In reference paper [7], the authors presented a double telecentric lens design with large aperture for machine vision applications. The system specifications and constraints are as follows: a stop within the system, -0.053x magnification, 0.00318 object space NA, 300 mm object diameter, 550 mm object working distance, distortion & telecentricities ≤ .1%, total length ≤ 900 mm, back focal length ≥ 50 mm, visible wavelength range from 0.4 to 0.7 um. Their reported system design is clearly diffraction-limited across the fields and spectrum. As before, we used the FTR-SLG for the given specs and constraints, generating several potentially interesting lenses within few minutes of runtime. All constraints are approximately met, while the tight 0.1% distortion & telecentricities values are slightly exceeded. Figure 5 shows an exemplary calculated FTR result at top, and the result after further optimization at the bottom.

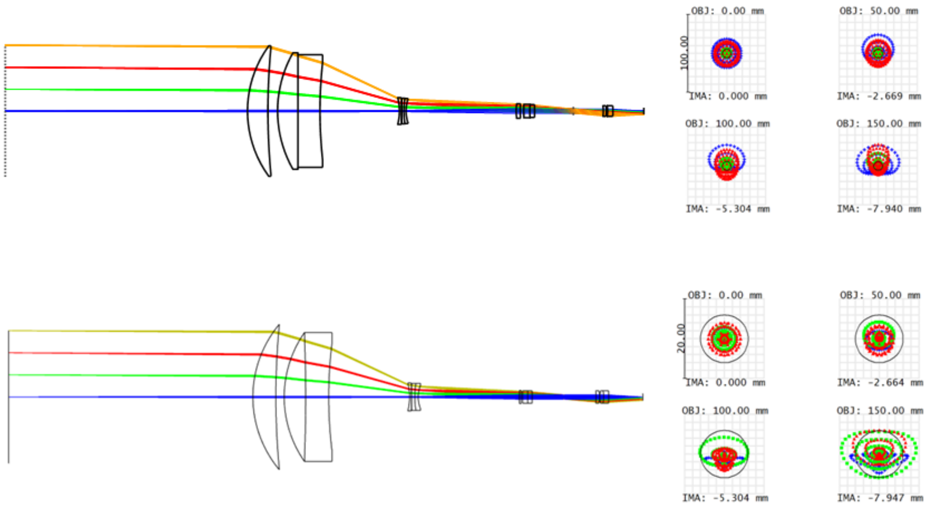

Figure 5: (top) FTR-SLG result shows already great initial performance while meeting almost all the imposed constraints. (bottom) The further optimized lens shows excellent diffraction-limited performance, meeting all specs and constraints

The final system has a diffraction-limited MTF, less than 0.1% distortion & telecentricities, and well-corrected chromatic aberrations. A further tweaking or exploration of additionally generated start lenses is possible, if needed. In summary, the FTR-SLG is very versatile and provides a highly efficient tool to find start lens designs from scratch. It is fully automated and can generate a variety of potential initial lens designs for given system specifications and constraints.

3. CONCLUSIONS

Equipping lens- and/or mirror-based optical systems with freeform optical surfaces makes it possible to deliver highly original imaging functionalities with superior performance compared to their more traditional (a)spherical counterparts, such as enhanced field-of-view, increased light-collection efficiencies, larger spectral band and higher compactness. Until now mathematical models and design strategies for freeform optics remained limited and failed to provide deterministic solutions. In particular, the identification of a suitable initial design has often proven to be a painstaking and time-consuming trial-and-error process.

In this article, we reviewed the first deterministic direct design method for imaging optical systems that is not restricted by the aberration terms that can be controlled. The method relies on Fermat’s principle and allows a highly systematic generation and evaluation of directly calculated optical design solutions that can be readily used as starting point for further and final optimization. As such, this new method allows the straightforward generation of 'first time right' initial designs (spherical and/or freeform) that enable a rigorous, extensive, and real-time evaluation in solution space when combined with available local or global optimization algorithms.

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