Order and reducibility in the lens design landscape

Bociort, Florian

DOI
10.1364/IODC.2017.IM2A.1

Publication date
2017

Document Version
Final published version

Published in
Optical Design and Fabrication, IODC 2017

Citation (APA)
Bociort, F. (2017). Order and reducibility in the lens design landscape. In *Optical Design and Fabrication, IODC 2017* (Vol. Part F51-IODC 2017). OSA - The Optical Society. https://doi.org/10.1364/IODC.2017.IM2A.1

Order and Reducibility in the Lens Design Landscape

Florian Bociort
Delft University of Technology, Optics Research Group,
Lorentzweg 1, 2628CJ Delft, The Netherlands
email: *F.Bociort@tudelft.nl*

Abstract: We discuss the potential and limits of a recently discovered technique to decompose the search for new local minima in simpler steps and analyze deeper reasons why multiple minima exist in the lens design landscape.

1. Introduction

The presence of many local minima in the error function landscape is perhaps the most difficult challenge in lens design. In general it is very difficult to find a starting point that after optimization leads to the best (or at least to a satisfactory) design. We have recently developed a technique called Saddle-Point Construction (SPC) [1] that makes it possible to switch rapidly between different minima, in the hope that after several switches we reach a satisfactory design. SPC is applicable even for very complex imaging systems (we have used it in the design of lithographic objectives). With SPC, the search for new minima is reduced to one-dimensional searches starting from local minima of simpler systems.

Important questions are, however, how many design solutions existing in a lens design landscape can be obtained with SPC? What percentage of them? Can we at least obtain the shapes that correspond to good designs? An answer to these questions is possible only for design landscapes that are simple enough to be studied in detail (in this talk I will analyze doublets and triplets). For complex systems, the ultimate confirmation (or invalidation) of the utility of SPC will be given by the quality of the practical results obtained with this new method.

For studying error function landscapes, in addition to local minima we must consider other critical points (i.e. points with zero gradient of the error function, such as saddle points) as well. At least for simple systems, the structure of the landscape can be understood in two steps:

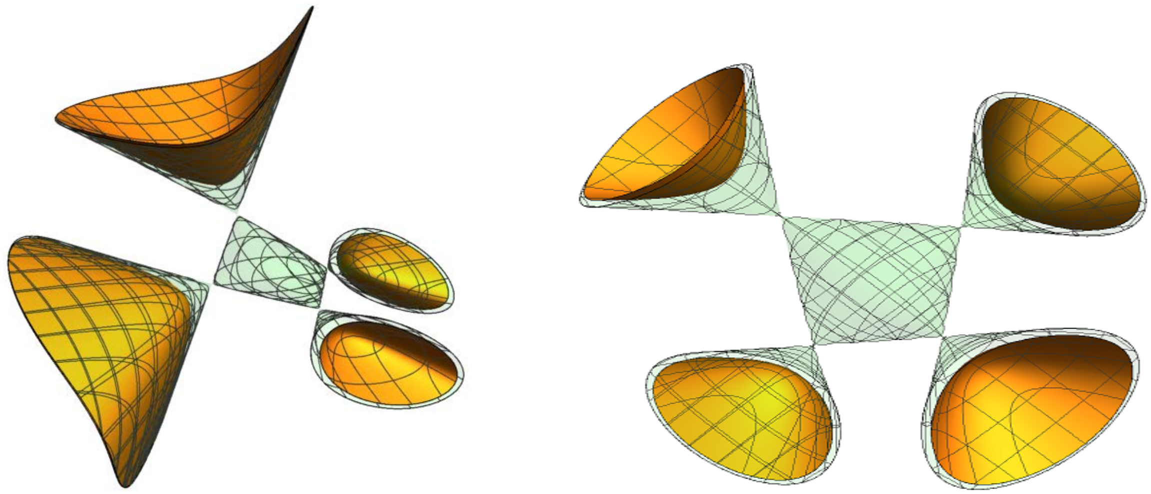
1. There exist specifications for which the set of different types of local minima form a perfectly ordered structure (called "fundamental network") [2]. In this "ideal" case, all types of local minima are obtainable with SPC.
2. General landscapes (e.g. the landscape of the Cooke Triplet global search) can be seen as modifications of the "fundamental network". When parameters change, we observe for certain minima and saddle points changes similar to the phase transitions known e.g. in statistical physics. For those minima, the property of the design space that makes SPC possible is affected by such "phase transitions", but for other minima and saddle points SPC remains applicable.

2. Potential of SPC

As well known, for air-spaced achromatic doublets thin-lens theory predicts that four solutions exist (with 3rd-order spherical aberration (SA3), coma and axial color close to zero)[3]. Why four and not more or less? The answer is determined by the most nonlinear aberration, which for thin lenses is spherical aberration. By first considering only SA3, four distinct surface sheets exist in the design space on which spherical aberration is zero, as shown in the left figure (here the focal length is kept constant). The four zero SA3 sheets are within the conical parts of the SA3 equimagnitude surface passing through saddle points. The extra conditions for other aberrations fix then special points on these surfaces, but qualitatively the structure of the set of minima of the doublet landscape is determined by spherical aberration.

For this reason, for developing a mathematical model that (at least for the simple systems mentioned above) explains the qualitative properties of the landscape I consider only spherical aberration. To achieve this, the starting point is a model based on thin-lens theory for SA3 (called below the "aberration model"). For "ideal" doublets and triplets, the qualitative properties of the design space are explained with a simple polynomial model containing the variables z_i that can be interpreted as the surface powers of the N surfaces and for which the error function is given by

$$f\left(z_1, z_2, \ldots z_N\right) = \left(\sum_{k=1}^{N} z_k{}^3\right)^2 + a\left(\sum_{k=1}^{N} z_k{}^5\right)^2 . \qquad (1)$$



The set of critical points of this model is in very good agreement with the numerical results of Ref. [2]. Also, for the majority of the critical points it can be proven mathematically that there exists a one-to-one correspondence between the polynomial and the aberration model (i.e. we have mathematically a so-called topological equivalence between the critical points of the two models). Specific optical properties such as angles and refractive indices do not appear in Eq. (1) but are absorbed in the corresponding one-to-one transformation. On the other hand, studying the properties of (1) is much easier than for more complex error functions. As an example, the figure on the right, obtained with the polynomial model for doublets, has the same topology as the SA3 aberration figure on the left. The polynomial model explains why in the "ideal" case all system shapes are obtainable with SPC.

3. Limits of SPC

When the deviation of a given landscape from the "ideal" case increases, some of the saddle points that were constructible with SPC may suffer a "phase transition" that transforms them into "usual" saddle points. "Usual" saddle points cannot be used for SPC, but when such "phase transitions" occur somewhere in the design space, all other parts of the design space still remain unaffected. There, the properties inherited from the "ideal case" are still preserved and SPC remains applicable. In the lens design landscapes discussed here most of the existing system shapes (including all the good ones) can still be found with SPC even when we deviate significantly from the "ideal" cases.

4. Conclusion

To show the potential of SPC, a detailed theoretical and numerical analysis of simple design landscapes reveals that there exist "ideal" cases where all design shapes existing in the landscape are obtainable with SPC. When we deviate from the "ideal" cases, the ability to decompose the search in simpler steps disappears gradually. However, in the simple examples discussed here most of the existing system shapes (including all the good ones) can still be found with SPC even when we deviate significantly from the "ideal" cases.

5. References

[1] M. van Turnhout, P. van Grol, F. Bociort, and H. P. Urbach, Opt. Express 23, 6679- 6691, 2015
[2] P. van Grol, F. Bociort, and M. van Turnhout, Proc. SPIE 7428, 742808, 2009
[3] W. J. Smith, *Modern optical engineering: the design of optical systems*, (McGraw-Hill, New York, 2000)