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A novel method for finding the initial structure parameters of optical systems via a genetic algorithm

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ABSTRACT

A novel method for finding the initial structure parameters of an optical system via the genetic algorithm (GA) is proposed in this research. Usually, optical designers start their designs from the commonly used structures from a patent database; however, it is time consuming to modify the patented structures to meet the specification. A high-performance design result largely depends on the choice of the starting point. Accordingly, it would be highly desirable to be able to calculate the initial structure parameters automatically. In this paper, a method that combines a genetic algorithm and aberration analysis is used to determine an appropriate initial structure of an optical system. We use a three-mirror system as an example to demonstrate the validity and reliability of this method. On-axis and off-axis telecentric three-mirror systems are obtained based on this method.

1. Introduction

The damped-least-squares (DLS) method, as the most popular optimisation algorithm, is extensively used in modern optical design software [1–3]. The DLS method used in the optimisation process involves searching for the minimum of the error function in a multi-dimensional variable space. However, the result obtained via the DLS method is usually a local minimum lying close to the starting point. In other words, the result from the use of commercial optical design software to optimise an optical system is strongly affected by the choice of the initial structure. Sometimes, the initial structure plays the most important role in our optical design process. Typically, optical designers obtain the initial structure parameters of optical systems by referring to existing structures included in overdue patents and collections, and then optimising these structures for their own applications via commercial optical design software. However, this process is time consuming, and a similar structure is not likely to be determined consistently. Accordingly, it would be highly desirable to find a practical and efficient method to calculate the initial structure parameters automatically.

In this paper, we propose an automatic method to calculate the initial structure parameters via GA. GA, introduced by Professor J. Holland in 1975 [4,5], is a powerful optimisation tool for finding the global minima in a high-dimensional, and highly nonlinear parameter space. GA has been introduced into the area of optical system design [6–12], such as optimisation for diffractive optical elements [6], optimisation for a wavefront coding system [7], and optimisation for focusing through turbid media in noisy environments [8]. Here, we use GA to search for high potential initial structures. A three-mirror system is employed as the example to implement the idea. The third-order aberration expressions of the three-mirror system with an aperture stop on the primary mirror are given by aberration analysis. The error function, which indicates the performance of the optical system, is composed of weighted aberrations and some constraints defined flexibly to meet the configuration requirement. The lower the value of the error function is, the higher the image quality of the system. GA is then used to find the suitable initial structure by minimising the error function. With this method, initial structures of three-mirror systems are calculated conveniently. After a further optimisation by commercial optical design software CODE V [13] based on the initial structure, on-axis and off-axis telecentric three-mirror systems are obtained.

This paper consists of four parts. In Section 2, we discuss the fundamental principle of our work. In Section 3, two design examples of three-mirror systems are presented: an on-axis three-mirror system with a 1000 mm focal length, 200 mm aperture and 1° field of view (FOV) and an off-axis telecentric three-mirror system with a 1000 mm focal length, 150 mm aperture and 1° × 20° FOV are designed. Section 4 presents the conclusion of our work.

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2. Principle

2.1. Aberration analysis for three-mirror system

Three-mirror systems are widely used in various fields, such as biological microscopy, thermal imaging systems, infra-red multi-spectral detection, space photography, lithography, and optical remote sensing. The advantages of this system include being free of chromatic aberrations, a large aperture, a small volume, loose heat tolerance, a large rectangular FOV, etc. It is also helpful in solving the obstruction problem by making the FOV off-axis. Using the three-mirror system, it becomes easier to obtain optical systems of high image quality that are also lighter in weight.

The layout of the three-mirror system is shown in Fig.1. The system is composed of three mirrors: a primary mirror (M_1), a secondary mirror (M_2), and a tertiary mirror (M_3). The obscure ratios of M_1 and M_2 are α_1 and α_2 respectively, the magnifications of M_2 and M_3 are β_1 and β_2, respectively, and the conic coefficients employed in the structure of each mirror are $-e_1{}^2$, $-e_2{}^2$ and $-e_3{}^2$, where,

$$\begin{cases} \alpha_1 = \dfrac{l_2}{f'_1} \approx \dfrac{h_2}{h_1}, \quad \beta_1 = \dfrac{l'_2}{l_2} = \dfrac{u_2}{u'_2} \\ \alpha_2 = \dfrac{l_3}{l'_2} \approx \dfrac{h_3}{h_2} \quad \beta_2 = \dfrac{l'_3}{l_3} = \dfrac{u_3}{u'_3} \end{cases} \tag{1}$$

Assuming that the focal length of a three-mirror system is f', based on the definition of magnification and obstruction ratios, the expressions for the radii of curvature of different mirrors and their corresponding thicknesses are calculated according to the paraxial optical theory:

$$\begin{cases} R_1 = \dfrac{2f'}{\beta_1\beta_2} \\ R_2 = \dfrac{2\alpha_1 f'}{\beta_2(1+\beta_1)} \\ R_3 = \dfrac{2\alpha_1\alpha_2 f'}{1+\beta_2} \end{cases} \tag{2}$$

$$\begin{cases} d_1 = \dfrac{(1-\alpha_1)f'}{\beta_1\beta_2} \\ d_2 = \dfrac{\alpha_1(1-\alpha_2)f'}{\beta_2} \\ d_3 = \alpha_1\alpha_2 f' \end{cases} \tag{3}$$

The third-order aberration coefficients are given by the following expressions [14]:

$$\begin{cases} S_{\mathrm{I}} = \sum hP + \sum h^4K \\ S_{\mathrm{II}} = \sum yP - J\sum W + \sum h^3yK \\ S_{\mathrm{III}} = \sum \dfrac{y^2}{h}P - 2J\sum \dfrac{y}{h}W + J^2\sum\varphi + \sum h^2y^2K \\ S_{IV} = \sum \dfrac{\Pi}{h} \\ S_{\mathrm{V}} = \sum \dfrac{y^3}{h^2}P - 3J\sum\dfrac{y^2}{h^2}W + J^2\sum\dfrac{y}{h}\left(3\varphi + \dfrac{\Pi}{h}\right) \\ \quad -J^3\sum\dfrac{1}{h^2}\Delta\dfrac{1}{n^2} + \sum hy^3K \end{cases} \tag{4}$$

where h is the height of the marginal ray in each mirror, and y is the height of the chief ray in each mirror; both h and y are related to the parameters α_1, α_2, β_1 and β_2. Assume that the stop of the three-mirror system is on the primary mirror.

$$\begin{cases} y_1 = 0 & h_1 = 1 \\ y_2 = \dfrac{\alpha_1 - 1}{\beta_1\beta_2} & h_2 = \alpha_1 \\ y_3 = \dfrac{\alpha_2(\alpha_1-1)+\beta_1(1-\alpha_2)}{\beta_1\beta_2} & h_3 = \alpha_1\alpha_2 \end{cases} \tag{5}$$

$$\begin{cases} P = \left(\dfrac{\Delta u}{\Delta\frac{1}{n}}\right)^2\Delta\dfrac{u}{n} \quad W = \dfrac{\Delta u}{\Delta\frac{1}{n}}\Delta\dfrac{u}{n} \\ \Pi = \dfrac{\Delta(un)}{nn`} \qquad \varphi = \dfrac{1}{h}\Delta\dfrac{u}{n} \\ K = -\dfrac{e^2}{R^3}\Delta n \end{cases} \tag{6}$$

Substituting h, y, P, W, Π, φ and K into Eq. (4) by Eq. (5) and Eq. (6), we can obtain the third-order aberrations expressed in terms of the structure parameters α_1, α_2, β_1, β_2, $-e_1{}^2$, $-e_2{}^2$, and $-e_3{}^2$ by tracing the marginal and chief rays.

$$\begin{cases} S_{\mathrm{I}} = \frac{1}{4}[(e_1^2-1)\beta_1{}^3\beta_2{}^3 - e_2^2\alpha_1\beta_2{}^3(1+\beta_1)^3 + e_3^2\alpha_1\alpha_2(1+\beta_2)^3 \\ \quad + \alpha_1\beta_2{}^3(1+\beta_1)(1-\beta_1)^2 - \alpha_1\alpha_2(1+\beta_2)(1-\beta_2)^2] \\ S_{\mathrm{II}} = -\dfrac{e_2^2(\alpha_1-1)\beta_2^3(1+\beta_1)^3}{4\beta_1\beta_2} - \dfrac{[\alpha_2(\alpha_1-1)+\beta_1(1-\alpha_2)](1+\beta_2)(1-\beta_2)^2}{4\beta_1\beta_2} \\ \quad + e_3^2\dfrac{[\alpha_2(\alpha_1-1)+\beta_1(1-\alpha_2)](1+\beta_2)^3}{4\beta_1\beta_2} + \dfrac{(\alpha_1-1)\beta_2^3(1+\beta_1)(1-\beta_1)^2}{4\beta_1\beta_2} - \dfrac{1}{2} \end{cases}$$

$$\begin{cases} S_{\mathrm{III}} = -e_2^2\dfrac{\beta_2(\alpha_1-1)^2(1-\beta_1^3)}{4\alpha_1\beta_1^2} - \dfrac{[\alpha_2(\alpha_1-1)+(1-\alpha_2)\beta_1]^2(1+\beta_2)(1-\beta_2)^2}{4\alpha_1\alpha_2\beta_1^2\beta_2^2} \\ \quad - \dfrac{[\alpha_2(\alpha_1-1)+\beta_1(1-\alpha_2)](1-\beta_2)(1+\beta_2)}{\alpha_1\alpha_2\beta_1\beta_2} + \dfrac{\beta_2(1+\beta_1)}{\alpha_1} - \dfrac{1+\beta_2}{\alpha_1\alpha_2} - \beta_1\beta_2 \\ \quad + e_3^2\dfrac{[\alpha_2(\alpha_1-1)+\beta_1(1-\alpha_2)]^2(1+\beta_2)^3}{4\alpha_1\alpha_2\beta_1^2\beta_2^2} + \dfrac{\beta_2(\alpha_1-1)^2(1+\beta_1)(1-\beta_1)^2}{4\alpha_1\beta_1^2} \\ \quad - \dfrac{\beta_2(\alpha_1-1)(1-\beta_1)(1+\beta_1)}{\alpha_1\beta_1} \end{cases}$$

$$\begin{cases} S_{\mathrm{IV}} = \beta_1\beta_2 - \dfrac{\beta_2(1+\beta_1)}{\alpha_1} + \dfrac{1+\beta_2}{\alpha_1\alpha_2} \\ S_{\mathrm{V}} = \dfrac{2(\alpha_1-1)(\beta_1+1)}{\alpha_1^2\beta_1} + \dfrac{1}{4}\dfrac{(\beta_1+1)(\alpha_1-1)^3(\beta_1-1)^2}{\alpha_1^2\beta_1^3} \\ \quad + \dfrac{3(\alpha_1-1)^2(\beta_1-1)(\beta+1)}{2\alpha_1^2\beta_1^2} \\ \quad + \dfrac{2(\beta_2+1)(\alpha_2-\beta_1-\alpha_1\alpha_2+\alpha_2\beta_1)}{\alpha_1^2\alpha_2^2\beta_1\beta_2} \\ \quad + \dfrac{3(\beta_2-1)(\beta_2+1)(\alpha_2-\beta_1-\alpha_1\alpha_2+\alpha_2\beta_1)^2}{2\alpha_1^2\alpha_2^2\beta_1^2\beta_2^2} \\ \quad - \dfrac{e_2^2(\alpha_1-1)^3(\beta_1+1)^3}{4\alpha_1^2\beta_1^3} \\ \quad (\beta_2+1)[(\beta_2-1)^2 - e_3^2(\beta_2+1)^2] \\ \quad + \dfrac{(\alpha_2-\beta_1-\alpha_1\alpha_2+\alpha_2\beta_1)^3}{4\alpha_1^2\alpha_2^2\beta_1^3\beta_2^3} \end{cases} \tag{7}$$

The error function is composed of weighted aberrations and some constraints imposed by the configuration requirement, which can be expressed as F,

$$\begin{aligned} F &= f(w_i, \alpha_1, \alpha_2, \beta_1, \beta_2, e_1^2, e_2^2, e_3^2) \\ &= w_1|S_{\mathrm{I}}| + w_2|S_{\mathrm{II}}| + w_3|S_{\mathrm{III}}| + w_4|S_{\mathrm{IV}}| + w_5|S_{\mathrm{V}}| + w_6|\mathrm{constraits}| \end{aligned} \tag{8}$$