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An approach for generating the first order structure of multi-movable zoom lens

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ABSTRACT

This work provides a method to obtain the first order structure of a zoom system based on particle swarm optimization (PSO) algorithm. The kinematic rule of a zoom system with fixed image plane is described by differential equations. PSO algorithm is introduced to solve the differential equations with considering both the merit functions and the boundary constraint. The smooth of the kinematic function of the zoom system is checked for considering the fabrication feasibility. Examples with two types of zoom system are presented for verifying the proposed method. This approach provides a powerful and practical tool for construction of a zoom structure.

1. Introduction

Zoom lens system shows wide applications in various areas due to its excellent abilities to furnish a continuous variation of focal length over the zoom range with good image performance and small residual aberrations [1–11]. So far as we know, the zoom lens system can be classified into two types. One is mechanic compensation zoom lens, and another is the modern zoom lens. In terms of modern zoom system, it contains some special lenses, such as liquid lens or liquid crystal lens [12–15]. The variation of focal length is realized by changing the refractive index of the liquid lens or its surface curvature [15]. This method is very smart and can be applied in the compact system such as cell phone camera. However, this optical component is not suitable for large zoom ratio and large relative aperture. On the other hand, mechanic compensation zoom lens system has played an important role in this field. The mechanic compensation zoom lens system can be divided into two mainstream types. One is a module of a variator group and a compensator group. The other is a multi-group optical system without specific variator group or compensator group. In addition, this system can be called as an all-movable zoom system because all the groups are movable to meet the imaging requirements. All movable zoom system is suitable for large zoom range [16]. However, its designing process is very complicated and much more difficult than that of fixed focal lens system.

In general, the magnification of a zoom system is changed by axially shifting a lens component. It is a tough work to design such a complex new zoom system. An important issue in the zoom lens system design is to analyze the first order optical structure. Once the first order structure is determined, the further optimization, which is carried out with the professional optical software, would not make a significant contribution to the optical performance of the zoom lens. In other words, the first order structure design is vital to the performance of a zoom system. From 1830s to 2010s, scientists have made significant contributions to the first order structure design [17–22]. According to the literature research, Capstaff and his coauthor can be regarded as a precursor of the mechanically compensated zoom lens structure design [21]. Consequently, Hopkin [20], Tanaka [3,6], Clark [1] etc. also proposed many types of zoom structures. Then, Mann summarized various type of zoom structure in his book [23]. Among these previous studies, algebraic methods [24], Gaussian brackets [25] and chain fractions [26] are the classic methods for the determination of the first order structure of a zoom system. But these methods are usually applied to specific situations. Recently, Kryszczyñski and his coauthor proposed a matrix method to design the first order structure of all movable zoom system. This method can be used for various types of the zoom structure, such as objective lens, telescope system etc. [27]. Indeed, it is a very clever approach, but still difficult for novices who are entering and working in this field.

Taking account of the issues mentioned above, this paper presents a technique for determination of the kinematics of a zoom system by combining the differential equations and particle swarm algorithm. The mathematical model of the proposed method is introduced in Section 2. Based on the proposed model, optimization model and optimization algorithm are described in Section 3 and

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two kinds of zoom system are designed for verifying the method in Section 4.

2. Theory of all movable zoom lens

As shown in Fig. 1, there are k freely movable optical components included in the system, called all movable zoom lens. The subscript i represent the ith movable component. The corresponding focal length, paraxial magnification, location coordinate and movable length are written as f'_i, m_i, x_i, dx_i, respectively. There are N target focal lengths of the zoom as shown in Fig. 1. Firstly, a single-lens setup is considered as shown in Fig. 2. A is the object point, and B is the image point. The magnification of component G_i is m_i. When the component G_i moved a distance of dx_i, the image point B will shift dx_i' which satisfies the following equation:

$$dx'_i = (1 - m_i^2)dx_i \tag{1}$$

When taking all of the lenses into account, the total image plane shift corresponding to the component G_1 can be expressed as

$$m_k^2 m_{k-1}^2 ... m_3^2 m_2^2 (1 - m_1^2)dx_1 \tag{2}$$

If $i < k$, the total image plane shift corresponding to the component G_i can be described as

$$(1 - m_i^2)dx_i \prod_{j=i+1}^{k} m_j^2 \tag{3}$$

For the last component G_k, its image shift is not correlated with other lenses. Therefore, when the component G_k moves dx_k, the total image shift along the optical axis is $(1 - m_k^2)dx_k$. In the zoom lens design, the image plane is usually stable in a fixed plane. To make the image plane stable, the algebra sum of image point shift corresponding to each component should be zero, which can be expressed by the following equation:

$$\sum_{i=1}^{k-1} \left[(1 - m_i^2)dx_i \prod_{j=i+1}^{k} m_j^2 \right] + (1 - m_k^2)dx_k = 0 \tag{4}$$

According to the Gaussian lens formula:

$$l_i = f_i'(1/m_i - 1) \tag{5}$$

$$l_i' = f'_i(1 - m_i) \tag{6}$$

where l is the object distance and l' is the corresponding image distance. According to Eqs. (1)–(6), we can get the relationship between m_i and dx_i:

$$dx_i = \sum_{n=1}^{i-1} \left[(1 - m_n^2)dx_n \prod_{j=n+1}^{i-1} m_j^2 \right] + \frac{f'_i}{m_i^2}dm_i \tag{7}$$

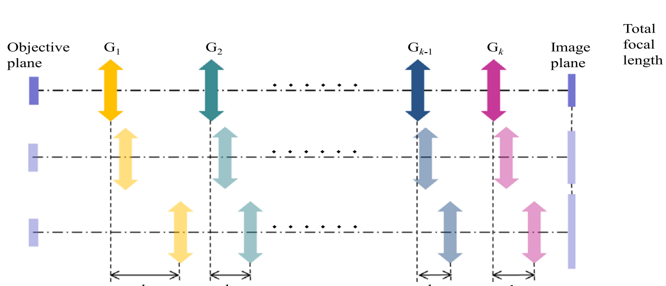

Fig.1. Structure chart of all movable zoom system.

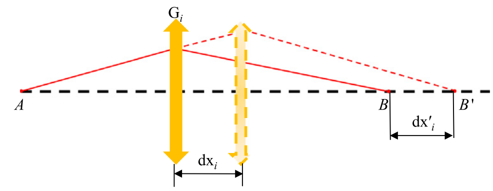

Fig.2. Notation of object and image in group moving for one single lens.

For the component k

$$dx_k = f'_k\, dm_k \tag{8}$$

The all movable functions satisfy the following equation:

$$\sum_{i=1}^{k} \frac{1 - m_i^2}{m_i^2} f'_i\, dm_i = 0 \tag{9}$$

We define the conjugate distance dL_i which can be shown as

$$dL_i = \frac{1 - m^2}{m^2} f' dm \tag{10}$$

Then, we can get the kinematic equation Y in a simple form as

$$Y = \sum_{i=1}^{k} dL_i = 0 \tag{11}$$

According to Eq. (11), the sum of conjugate distance of each component is zero, the image plane will not shift away in all movable zoom systems. The solution of Eq. (11) is the coordinates of each component, which can be expressed as $x_i (i = 1, 2, 3 \cdots k)$. By combining ray tracing code, Eq. (11) could be solved. However, there are infinite solutions due to the ill conditioned equation. Therefore, we need to add some constraints into this equation to solve the problem. There are N zoom positions, the corresponding focal lengths are $F_1', F_2', F_3' \cdots F_N'$. The zoom ratio can be written as $K = F'_N / F'_1$. According to the positions of the lens groups ($G_1, G_2, G_3 \cdots G_N$), the inter space can be defined as $d_{z,1}, d_{z,2}, d_{z,3}, ..., d_{z,k-1}$. Moreover, $d_{z,0}$ and $d_{z,k}$ are the object distance and the back working distance. Here, z is the sequence number of the target focal length. According to Eq. (11), a serial of kinematic equations related to each zoom position sequence can be constructed. In addition, an optimization should be applied to obtain the best solution $d_{z,i} (z = 1, 2, 3 \cdots N; i = 1, 2, 3 \cdots k)$. In the end, the zoom cam curve can be designed accordingly.

For an optimal solution, several constraint conditions should be added into the hyperspace. With regard to a kinematic equation Y_z for a particular focal length F_z, two kinds of constraint conditions should be satisfied.

(1) The error between the received focal length and the target focal length should be limited in a reasonable range. This constraint condition can be indicated as $|F'_z - F'_{z,t}| < 0.01 F'_{z,t}$. Hereinto, $F'_{z,t}$ is the zth target focal length. Then, the separation between each component is in a reasonable range. The separation between two optical elements should not be too large in consideration of compact structure. However, it is impossible for a computer to judge just from the value of the separations, so, other constraints are needed.

(2) Zoom ratio of the cascade zoom position cannot be too large, the constraints hyperspace should be added into the Eq. (11). It is worth to indicate that the constraints should not be an arbitrary small quantity. According to Eq. (1), we can know the relationship between dx'_i and dx_i. If the amount of movement corresponding to dx_i is too small, we can regard m_i as a small increment. Then, there will be quite large calculation effort. Taking $F'_1 = 5$ mm, $F'_N = 500$ mm as an example, this kind of zoom ratio can be regarded as a large ratio zoom system. If the step of