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40× zoom optical system design based on stable imaging principle of four groups

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Based on stable imaging principle of four groups and combined with optical design software, a method for initial structure calculation of zoom optical system and optical system optimization design is proposed to solve the problems of difficult initial structure calculation, large volume, and inflection point of zoom curves of a high zoom ratio optical system. First, this paper theoretically derives the four-group stable imaging principle of the zoom optical system. Then, using the derived equations and optical design software, the initial structural parameters of the four-group zoom optical system are solved to ensure that there is no inflection point in the zoom curves. Finally, a lightweight and small 40× continuous zoom optical system is designed to verify the feasibility and effectiveness of the design method proposed in this paper. The zoom optical system has the advantages of good imaging quality, lightweight, small size, smooth zoom, and no inflection point.

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1. INTRODUCTION

With the enrichment of zoom optical system design theory and the continuous improvement of mechanical processing capabilities, the imaging quality of the zoom optical system is basically comparable to that of a fixed focus lens. The zoom imaging system can not only search the interested targets in a large range but also accurately track and observe small targets [1–3]. Therefore, zoom optical system has been widely used in many fields, such as target tracking, photography, and security monitoring [4–7]. In these fields, high zoom ratio lenses are particularly popular. However, the widely used zoom lens with a high zoom ratio is still difficult to design [8–10].

There are two methods to calculate the initial structure of the zoom optical system: one is to obtain the paraxial solution of the lens by PWC method [11], and another is to refer to a specific patent with the similar design targets. The PWC method is an accurate initial structure calculation method, but the calculation process is extremely complicated [12], and sometimes the initial structure obtained cannot meet the design requirements, so it needs to be recalculated. The second method obtains the initial structure very quickly and has a relatively high success rate of design. However, there are few patents available for the zoom optical system with a large zoom ratio. At present, the design methods of zoom optical system can be roughly divided into the following four types [13–17]: optical zoom system, mechanical compensation zoom optical system, dual-group linkage zoom optical system, and full-motion zoom optical system. Generally, the high zoom ratio optical system has the disadvantages of complicated calculation of the initial structure, large volume, inflection point of the zoom curve, and many zoom curves.

In 2009, Hu *et al.* adopted the mechanical compensation method to design a 20× continuous fog transparent zoom system [18], the focal length of the optical system is 20–400 mm, and the total length of the optical system is 280 mm. It realized the observation of conventional color and fog transmission black/white modes and ensured the focal length of the zoom optical system does not drift, but there is an inflection point in the zoom curve. In 2015, Yao *et al.* designed a high zoom ratio lens with a focal length of 10–500 mm by the mechanical compensation method [19]. This optical system uses two novel aspheric surfaces and a group of double-layer harmonic diffractive elements to effectively correct the aberrations. Although the zoom ratio of this optical system is as high as 50×, its volume is very large. In 2020, Liu *et al.* designed a 50× five-group zoom optical system with two moving groups and a focus tunable lens (FTL) by applying Gaussian brackets and lens modules [20]. The zoom optical system has the merits of small size and large zoom ratio, but the zoom curve of the zoom optical system has an inflection point, the lens module needs to be switched during the zooming process, and continuous zooming and clear imaging cannot be guaranteed during the zooming process.

Therefore, focusing on reducing the complexity of the initial structure design of a high zoom ratio optical system and improving the design efficiency of the optical system, a method for calculating the initial structure of zoom optical system based on four-group stable imaging principles combined with optical design software is proposed in this paper. The zoom optical system designed by this method has the merits of small size, less zoom curve, and no inflection point of the zoom curves. The reliability of the design method is demonstrated by a design example of a lightweight and compact 40× continuous zoom optical system in this paper. The zoom optical system only uses spherical lenses instead of aspheric lenses and diffractive optical elements for design. The variation range of the focal length is 7–280 mm, the total length is 210 mm, and the maximum aperture is 72 mm.

2. FOUR-GROUP STABLE IMAGING PRINCIPLE OF THE ZOOM OPTICAL SYSTEM

The optical zoom system has only a few fixed focal lengths for clear imaging. The mechanical compensation zoom optical system can perform continuous zooming, but the volume of the optical system is large, and the zoom ratio is limited. The volume of the dual-group linkage zoom optical system and the full-motion zoom optical system are relatively small. Compared with the dual-group linkage zoom optical system, the full-motion zoom optical system has a smaller volume and a larger zoom ratio. However, the full-motion zoom optical system has the following disadvantages: the complex calculation of the initial structure, inflection points in the zoom curves, and many zoom curves. For solving the above shortcomings, a zoom optical system based on four-group stable imaging with only three zoom curves is proposed in this paper.

To a general non-wide-angle zoom optical system, the focal power of the group 1 is usually negative [21]. According to the imaging principle of the positive group compensation zoom optical system, when the focal power of the group 2 and group 3 are negative and positive, respectively, it is more suitable to reduce the diameter size of the system and achieve large zoom ratio. When the focal power of the group 4 in the four-group stable imaging zoom optical system is negative, the optical system is an anti-telephoto structure, which is more conducive to reducing the total length of the optical system and ensuring a longer back intercept in short focus. Therefore, this paper mainly studies the focal power distribution mode of "+, -, +, -".

The four-group stable imaging principle of the zoom optical system is shown in Fig. 1. The zoom optical system has four groups, which are group 1, group 2, group 3, and group 4. The focal lengths of each group are f_1', f_2', f_3', and f_4', the focal powers of group 1, group 2, group 3, and group 4 are "+, -, +, -", respectively. In the four-group stable imaging zoom optical system, group 1 and the focal plane are fixed, which means the total length of the optical system remains unchanged, and continuous zooming is achieved by changing the relative positions of group 2, group 3, and group 4. Then, compared with the full-motion zoom optical system, the four-group stable imaging zoom optical system reduces the number of zoom curves from four to three, thereby the complexity of the zoom optical system and the design difficulty of the mechanical structure are both reduced.

It can be seen from Fig. 1 that the light parallel to the optical axis is imaged at point M after passing through group 1, then imaged successively through group 2, group 3, and group 4, and finally imaged at point O, which is on the focal plane. Therefore,

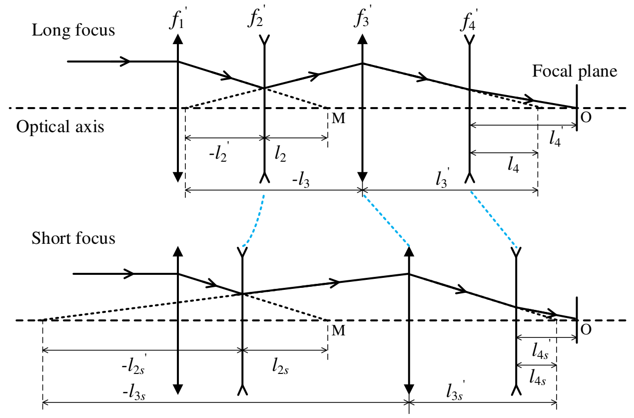


Fig. 1. Four-group stable imaging principle diagram of the zoom optical system.

no matter how the relative positions of group 2, group 3, and group 4 change during the zooming process, the distance between the object point M of group 2 and the image point O of group 4 will be a constant. Thus, Eq. (1) can be obtained as

$$\overline{\mathrm{MO}} = (l_3' - l_3) - (-l_2' + l_2) + (l_4' - l_4) = l_3' - l_3 + l_2' - l_2 + l_4' - l_4, \tag{1}$$

where l_2 and l_2' represent the object distance and image distance of group 2, respectively, l_3 and l_3' represent the object distance and image distance of group 3, respectively, and l_4 and l_4' represent the object distance and image distance of group 4, respectively.

The relationship the focal length f', object distance l, image distance l', and magnification m of the optical system is

$$\begin{cases} l = \frac{1-m}{m} f' \\ l' = (1-m)\ f' \end{cases}. \tag{2}$$

Equation (2) is replaced into Eq. (1), and it is simplified to obtain

$$\overline{\mathrm{MO}} = 2\left(f_2' + f_3' + f_4'\right) - f_2'\left(m_2 + \frac{1}{m_2}\right) - f_3'\left(m_3 + \frac{1}{m_3}\right) - f_4'\left(m_4 + \frac{1}{m_4}\right). \tag{3}$$

Since the distance from point M to point O is a constant, the zoom equation of the four-group stable imaging zoom optical system can be obtained as

$$2\left(f_2' + f_3' + f_4'\right) - f_2'\left(m_2 + \frac{1}{m_2}\right) - f_3'\left(m_3 + \frac{1}{m_3}\right) - f_4'\left(m_4 + \frac{1}{m_4}\right) = \text{Constant}. \tag{4}$$

According to the zoom Eq. (4), the relationship between the magnification (m_{2s}, m_{3s}, m_{4s}) of each group at short focus and the magnification (m_{2l}, m_{3l}, m_{4l}) of each group at long focus is

$$f_2'\left(m_{2s}+\frac{1}{m_{2s}}\right)+f_3'\left(m_{3s}+\frac{1}{m_{3s}}\right)+f_4'\left(m_{4s}+\frac{1}{m_{4s}}\right)$$
$$=f_2'\left(m_{2l}+\frac{1}{m_{2l}}\right)+f_3'\left(m_{3l}+\frac{1}{m_{3l}}\right)+f_4'\left(m_{4l}+\frac{1}{m_{4l}}\right). \quad (5)$$

The zoom ratio of the optical system is the ratio of the longest focal length to the shortest focal length of the zoom optical system as

$$\Gamma=\frac{f_1'\times m_{2l}\times m_{3l}\times m_{3l}}{f_1'\times m_{2s}\times m_{3s}\times m_{3s}}=\frac{m_{2l}m_{3l}m_{3l}}{m_{2s}m_{3s}m_{3s}}. \quad (6)$$

When the magnification of each group of the optical system at the short focus is known, there are many combinations of the magnification of each group at the long focus shown in Eq. (5). Therefore, when solving the magnification of each group at the long focus, first we need to assume the magnification of group 2 and then calculate the magnification of group 3 and group 4 by Eqs. (5) and (6).

When the magnification of each group of the zoom optical system at the short focus is determined, the distances between each group at the short focus are

$$\begin{cases} d_{12s}=f_1'-l_{2s}=f_1'-\frac{1-m_{2s}}{m_{2s}}f_2' \\ d_{23s}=-l_{3s}+l_{2s}'=-\frac{1-m_{3s}}{m_{3s}}f_3'+(1-m_{2s})f_2' \\ d_{34s}=l_{3s}'-l_{4s}=(1-m_{3s})f_3'-\frac{1-m_{4s}}{m_{4s}}f_4' \\ d_{4fs}=l_{4s}'=(1-m_{4s})f_4' \end{cases}, \quad (7)$$

where d_{12s}, d_{23s}, d_{34s}, and d_{4fs} represent the distance between group 1 and group 2, the distance between group 2 and group 3, the distance between group 3 and group 4, and the distance between group 4 and focal plane at short focus, respectively. f_1' represents the focal length of group 1.

When the zoom curves of group 2, group 3, and group 4 in the four-group stable imaging zoom optical systems have no inflection points, Eq. (8) must be satisfied as follows:

$$\begin{cases} d_{12s}<d_{12m}<d_{12l} \\ d_{23s}>d_{23m}>d_{23l} \\ d_{34s}<d_{34m}<d_{34l} \\ d_{4fs}<d_{4fm}<d_{4fl} \end{cases}, \quad (8)$$

where d_{12m}, d_{23m}, d_{34m}, and d_{4fm} represent the distance between group 1 and group 2, the distance between group 2 and group 3, the distance between group 3 and group 4, and the distance between group 4 and focal plane at medium focus, respectively. d_{12l}, d_{23l}, d_{34l}, and d_{4fl} represent the distance between group 1 and group 2, the distance between group 2 and group 3, the distance between group 3 and group 4, and the distance between group 4 and focal plane at long focus, respectively.

According to the geometric relationship in Fig. 1 and Eq. (2), the total length L of the zoom optical system can be obtained as

$$L=f_1'+2(f_2'+f_3'+f_4')f_3'-f_2'\left(m_{2s}+\frac{1}{m_{2s}}\right)$$
$$-f_3'\left(m_{3s}+\frac{1}{m_{3s}}\right)-f_4'\left(m_{4s}+\frac{1}{m_{4s}}\right). \quad (9)$$

Table 1. Design Index of the Zoom Optical System

Parameters	Values
Focal length	7–280 mm
f-number	2.5–5.0
Working spectrum	486–656 nm
Full field of view	1.6°–61°
Distortion	$\leq 3\%$
MTF (104 lp/mm)	≥ 0.3

3. INITIAL STRUCTURE CALCULATION OF A 40× ZOOM OPTICAL SYSTEM

A. Design Index

The design index of the optical system is closely related to the requirements of use and the parameters of the selected detector. The pixel size of the detector selected in this paper is 4.8 μm × 4.8 μm, and the corresponding Nyquist frequency is 104 lp/mm. To achieve large-scale search and small-scale detailed observation, the zoom range of the 40× zoom optical system is 7–280 mm. The detailed design index of the 40× zoom optical system is shown in Table 1.

B. Initial Structure Calculation

The initial structure calculation steps of the four-group stable imaging zoom optical system are as follows:

(1) The focal length f_s' and total length L of the optical system at short focus are known parameters. At short focus, the distance between group 1 and group 2 is the smallest, and the back intercept of the optical system needs to have a longer distance to install the detector. These parameters d_{12s} and d_{4fs} need to be assumed and are also known parameters. Therefore, Eq. (10) can be obtained,

$$\begin{cases} L=f_1'+2(f_2'+f_3'+f_4')f_3'-f_2'\left(m_{2s}+\frac{1}{m_{2s}}\right) \\ \quad -f_3'\left(m_{3s}+\frac{1}{m_{3s}}\right)-f_4'\left(m_{4s}+\frac{1}{m_{4s}}\right) \\ f_s'=f_1'\times m_{2s}\times m_{3s}\times m_{4s} \\ d_{12s}=f_1'-\frac{1-m_{2s}}{m_{2s}}f_2' \\ d_{4fs}=(1-m_{4s})f_4' \end{cases}. \quad (10)$$

(2) Equation (10) has seven variables. First assume the focal length f_1' of group 1 and the magnification m_{4s} of group 4 at short focus and then calculate the focal length of the four groups and the magnification of group 2 and group 3 at short focus. The calculated unknown parameters will be different with different parameter settings, which are only used as a set of tentative solutions here.
(3) Calculate d_{23s} and d_{34s} according to Eq. (7).
(4) According to Eqs. (5), (11), and (12), the magnification of group 2, group 3, and group 4 at long focus can be calculated.

$$L=f_1'+2(f_2'+f_3'+f_4')f_3'-f_2'\left(m_{2l}+\frac{1}{m_{2l}}\right)$$
$$-f_3'\left(m_{3l}+\frac{1}{m_{3l}}\right)-f_4'\left(m_{4l}+\frac{1}{m_{4l}}\right), \quad (11)$$

Table 2. Focal Length of the Four Groups in the Initial Structure

Groups	Group 1	Group 2	Group 3	Group 4
Focal length/mm	124.30	−16.98	33.20	−106.63

Table 3. Spacing between Each Group in the Initial Structure

Groups	d_{12}	d_{23}	d_{34}	d_{4f}
The distance at short focus/mm	16.49	130.49	35.99	7.02
The distance at long focus/mm	96.61	17.34	54.68	21.37

$$f_l' = f_1' \times m_{2l} \times m_{3l} \times m_{4l}. \quad \textbf{(12)}$$

(5) Calculate the distance between each group at long focus. Please refer to Eq. (7) for the calculation formula.

(6) Bring all the calculated parameters into the optical design software for optimization and judge whether the zoom optical system meets Eq. (8) in short focus, medium focus, and long focus. If it is not satisfied, return to the first step for recalculation. If it is satisfied, optimize the parameters again and set the aperture position and f-number of the optical system. In the process of parameter optimization, to reduce the pressure of each group to correct aberrations, try to ensure that the f-number of each group is greater than 1.

Calculate the initial structure of the 40× zoom optical system according to the above steps, assuming that the total length L of the ideal zoom optical system is 190 mm, and the magnification m_{4s} of the group 4 at short focus is 1.1. After several calculations and optimization, the focal lengths of each group in the four-group stable imaging zoom optical system are obtained, as shown in Table 2.

The distances between the groups of the four-group stable imaging zoom optical systems at long focus and short focus are shown in Table 3.

According to Tables 2 and 3, the ideal configuration of the four-group stable imaging zoom optical system can be obtained, as shown in Fig. 2. The total length of the zoom optical system is 190 mm, and the aperture stop is located 5.53 mm in front of group 3. During the zooming process, the aperture stop moves with group 3 at the same speed, and the f-number of the optical system is constantly changing at this time.

In Fig. 2, as the focal length of the optical system gradually changes from 7 to 280 mm, group 2 gradually moves away from the fixed group 1, and both group 3 and group 4 gradually move closer to the fixed group 1. Therefore, there is no inflection point in the three zoom curves during the zooming process.

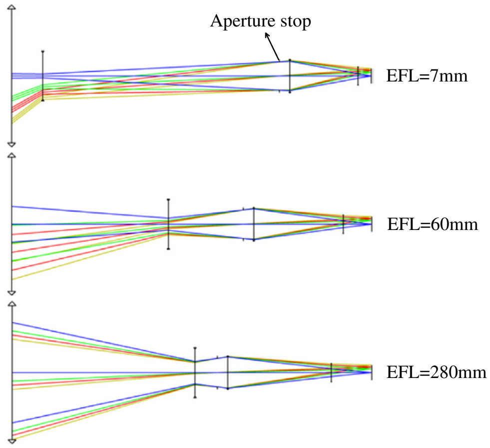


Fig. 2. Ideal configuration of the zoom optical system.

Table 4. Focal Length of the Four Groups in the Final Structure

Groups	Group 1	Group 2	Group 3	Group 4
Focal length/mm	117.64	−17.14	31.87	−89.34

4. OPTIMIZED DESIGN OF THE 40× ZOOM OPTICAL SYSTEM

A. Optimized Design of the Optical System

The four ideal groups (seen in Fig. 2) are taken into the optical design software for optimization design, the ideal optical system is converted into an actual optical system. Finally, the two-dimensional structure of the four-group stable imaging zoom optical system is obtained by optimization design as shown in Fig. 3. During the zooming process of the optical system, only three groups move, and the total length of the optical system is fixed. The total length of the optical system is 210 mm, and the maximum diameter is 72 mm.

The focal length of each group in the optimized four-group stable imaging zoom optical system is shown in Table 4. By comparing and analyzing the parameters in Tables 2 and 4, it can be seen that the calculated initial structural parameters are roughly equal to the optimized parameters.

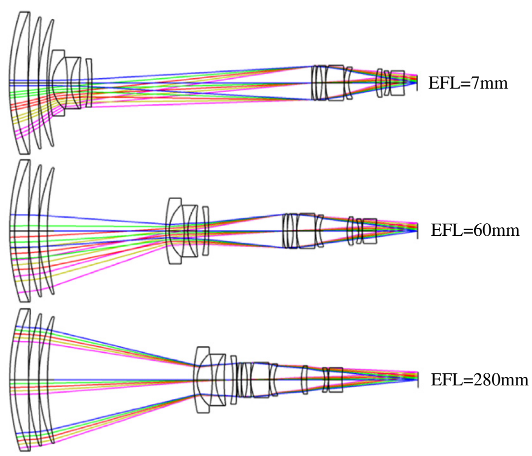
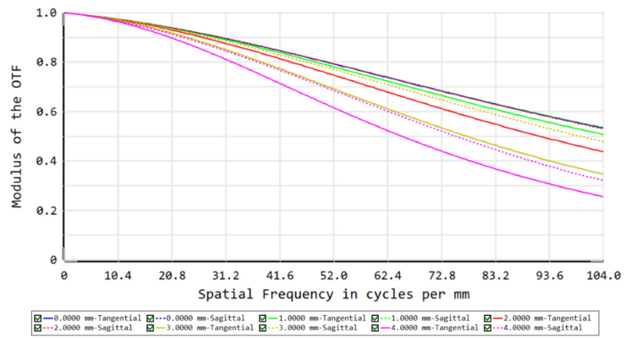
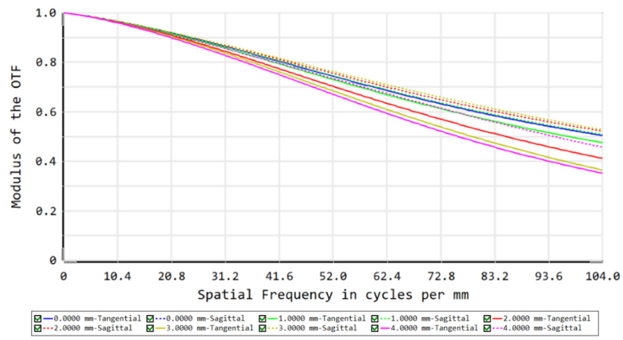


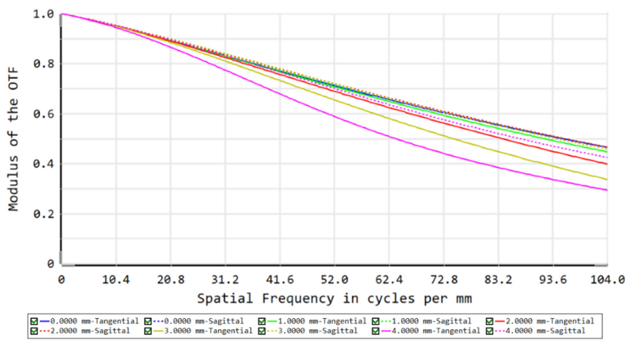
Fig. 3. Final structure of the 40× zoom optical system.



(a) f= 7mm



(b) f=60mm



(c) f=280mm

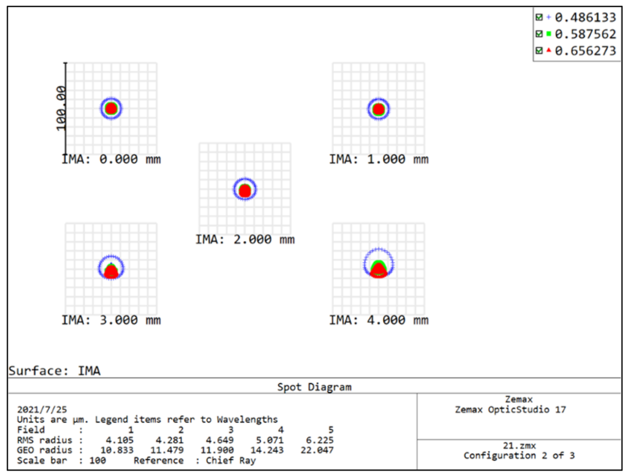
Fig. 4. MTF curves of the zoom optical system [(a) $f = 7$ mm, (b) $f = 60$ mm, (c) $f = 280$ mm)].

B. Image Quality Evaluation

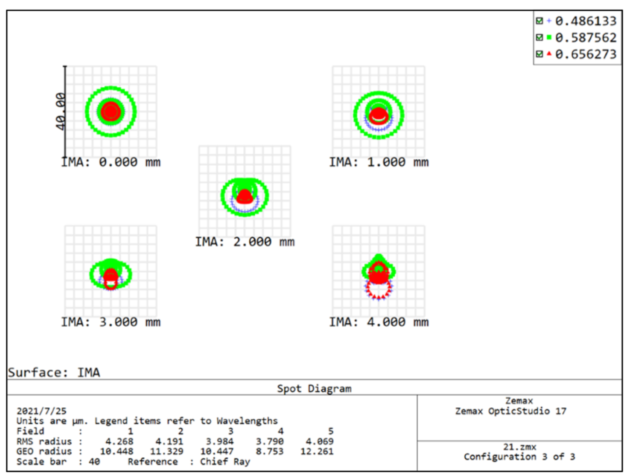
Modulation transfer function (MTF), spot diagram, and distortion are important indicators for evaluating the image quality of an optical system. The MTF represents the modulation variation law of optical system imaging, and the imaging performance of the optical system can be more comprehensively evaluated through the MTF curve. Figure 4 is the MTF curve diagram of the 40× zoom optical system, and when the focal lengths of the zoom optical system are 7 mm, 60 mm, and 280 mm, the MTFs of the optical system at the Nyquist frequency are all greater than 0.3.

Each point in the spot diagram corresponds to a ray, and the size of the diffuse spot completely depends on the position of each ray on the image plane, so it can accurately judge the diffusion of the imaging ray of the optical system. The smaller radius of the root mean square (RMS) diffuse spot shows the better imaging quality of the optical system. Figure 5 shows the

(a) f=7mm



(b) f=60mm

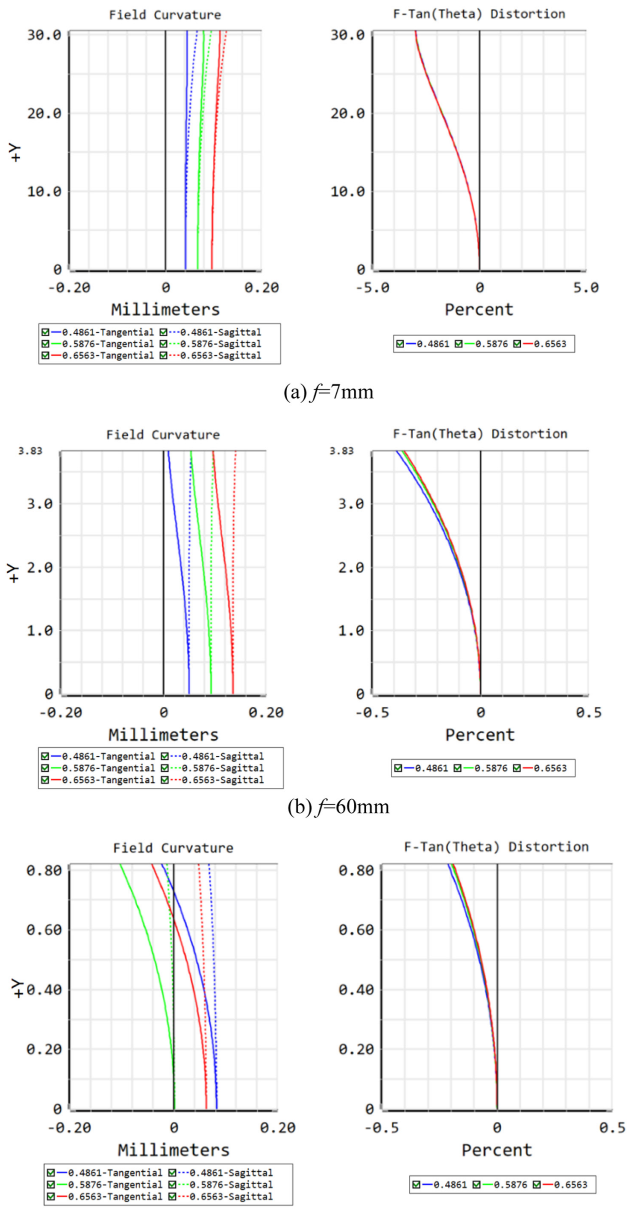


(c) f=280mm

Fig. 5. Spot diagram of the zoom optical system [(a) $f = 7$ mm, (b) $f = 60$ mm, (c) $f = 280$ mm].

spot diagrams of the zoom optical system at a focal length of 7 mm, 60 mm, and 280 mm.

The distortion of the optical system will not cause the image to be blurred but make the image of the object deformed. Figure 6 shows the field curvature and distortion curve of the



(a) f=7mm

(b) f=60mm

(c) f=280mm

Fig. 6. Field curvature and distortion curves [(a) $f = 7$ mm, (b) $f = 60$ mm, (c) $f = 280$ mm].

zoom optical system at the focal length of 7 mm, 60 mm, and 280 mm. The distortion of the zoom optical system is less than 3% seen in Fig. 6.

C. Tolerance Analysis

Tolerance analysis is one of the most important steps before the production of the optical lens. Using the tolerance analysis function in the optical design software, the manufacturing complexity of the lens can be evaluated. Considering the tolerance sensitivity of each optical element of the zoom optical system at long focal length, medium focal length, and short focal length, the tolerance distribution of the zoom optical system is shown in Table 5. According to Monte Carlo analysis, the distribution law of the MTF of the optical system at 104 lp/mm is shown in Fig. 7, which presents that 60% of the systems have an MTF greater than 0.2 in the full focal range.

Table 5. Tolerance Distribution Table of the 40× Zoom Optical System

Tolerance Items	Values
Radius (fringe)	≤ 3
Thickness (mm)	±0.02
Surface decenter (mm)	±0.02
Element tilt (°)	±0.02
Element decenter (mm)	±0.02
Surface irregularity (fringe)	≤ 0.3
Refractive index	±0.001
Abbe number (%)	±0.5

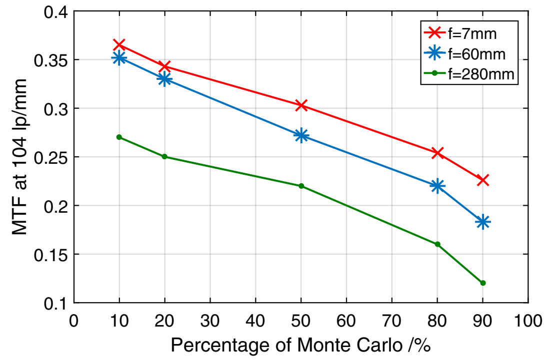


Fig. 7. Probability diagram of Monte Carlo analysis.

D. Zoom Curve Analysis

In the zoom optical system, the design of the cam curve is related to whether there will be a stuck in the zoom process, so the design of the cam curve is very critical [14,22]. To enable the optical system to zoom smoothly, the zoom curves should have no inflection point as possible. At the same time, it is also necessary to optimize the pressure angle of the cam to verify the feasibility of the four-group stable imaging zoom optical system design method with no inflection point of the zoom curves proposed in this paper. The zoom curves (shown in Fig. 8) show that group 2, group 3, and group 4 in the zoom optical system move smoothly and there is no inflection point during the zooming process.

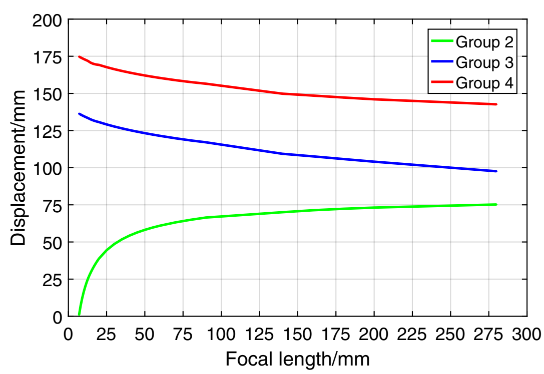


Fig. 8. Zoom curves.

5. CONCLUSION

With the advent of the information age, people are eager to obtain more and more detailed information from the outside world, thus requiring higher and higher zoom ratios for zoom optical systems. To overcome the shortcomings of the large zoom ratio optical system, such as difficult calculation of the initial structure, large volume, and inflection point of the zoom curves, a method for calculating the initial structure of the zoom optical system based on four-group stable imaging principle and optical design software is proposed in this paper. This method can calculate the initial structure quickly and effectively for the zoom optical system. A lightweight and compact $40\times$ continuous zoom optical system is designed applying this method, the total length of the optical system is 210 mm, the focal length is 7–280 mm, the full field of view is $1.6°–61°$, and the f-number is 2.5–5.0. The zoom optical system is designed with a spherical lens and has the advantages of good imaging quality, lightweight, small size, and no inflection point of the zoom curves.

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Data Availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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