Design of cooled MWIR continuous zoom optical system for long-range surveillance

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ABSTRACT

The continuous zoom optical system based on the cooled infrared detector can achieve high-quality imaging in multiple FOVs. Based on the continuous zoom theoretical model, this paper designs a MWIR continuous zoom athermal optical system consisting of only six lenses. The system has an F# of 4.0, a working range of 3.4 - 4.9 µm, a field of view ranging from 21.8°×17.5° to 1.6°×1.3°. All six lenses in the optical system contain aspherical surfaces with two diffraction surfaces to eliminate aberrations, optimizing the size and weight. The optical system compensates for temperature through an active focusing mechanism. The MWIR continuous zoom optical system has a compact structure and good imaging quality in the whole FOV in the temperature range of - 10 ℃ ~ + 60 ℃.

Keywords: Optical design; Continuous zoom lens; Athermalized focus; Cooled detector.

1. INTRODUCTION

In recent years, based on the development of infrared imaging technology, infrared optical systems have performed better and have more complex structures. The zoom optical systems can change their focal length to achieve a variety of FOVs with one system. Compared with fixed-focus systems, zoom systems can observe a wide range and magnify the target of interest for identification, locking, and tracking [1-5]. Due to these advantages, zoom systems are increasingly widely used. There are two types of zoom systems: continuous zoom and step zoom. The step zoom system is more straightforward to design and manufacture, but the image will be blurred when switching the field of view. The continuous zoom image will remain clear during the zooming process, so the target can be monitored and tracked in real time when the FOV is changed. Designing a high-quality, compact continuous zoom system requires combining multiple technologies (such as continuous zoom technology, athermalization technology, aspheric and diffractive surfaces, etc.), and the design process is more difficult [6-8]. Compared with uncooled detectors, cooled detectors have higher sensitivity and better observation quality [9-11]. Therefore, a zoom optical system using cooled detectors can achieve high-quality imaging in various FOVs.

In this paper, we design a cooling MWIR continuous zoom system based on mechanical compensation continuous zoom technology. The system has the advantages of athermalization, large magnification, high imaging quality, and compact structure. The system can be used in military equipment such as observation, detection, tracking, and aiming.

2. PRINCIPLE OF CONTINUOUS ZOOM OPTICAL SYSTEM WITH MECHANICAL COMPENSATION

One method of mechanical compensation zoom is to move two lenses or lens groups. Figure 1 is the principle of a four-lens thermal imaging lens system with two moving lenses [12, 13]. The first and fourth lenses are fixed, and the second and third lenses are movable. Moving the second lens (zoom lens) can change the system's magnification, and moving the third lens (compensating lens) can keep the system's image plane at a fixed position. This optical system has the fewest lenses among the published zoom lens systems. Usually, this optical system will be designed so that one of the two moving lenses moves linearly, and the other moves nonlinearly to compensate.

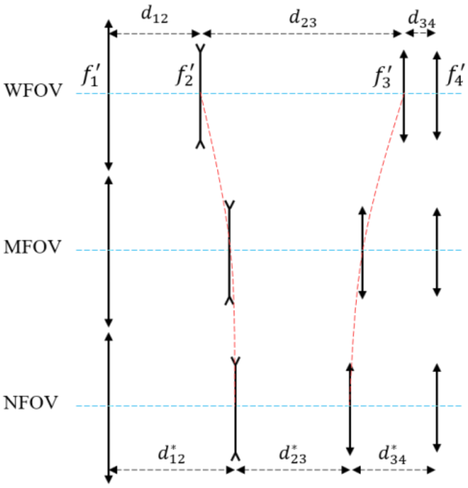


Figure 1. *Principal diagrams of a continuous zoom optical system with mechanical compensation.*

To keep the focal plane of the system fixed, the displacement of the zoom lens and the compensate lens must satisfy the Conjugate equation [14]:

$$f_2'\left(\frac{1}{\beta_2}+\beta_2-\frac{1}{\beta_2^*}-\beta_2^*\right)+f_3'\left(\frac{1}{\beta_3}+\beta_3-\frac{1}{\beta_3^*}-\beta_3^*\right)=0 \tag{1}$$

where, f_2' as the focal length of the zoom lens; f_3' as the focal length of the compensate lens; β_2, β_3 as the initial magnification of the zoom lens and the compensate lens; β_2^*, β_3^* as the magnification of the zoom lens and the compensate lens during the zoom process.

Initial magnification of the zoom lens and the compensate lens, respectively:

$$\beta_2=\frac{f_2'}{f_1'+f_2'-d_{12}} \qquad \beta_3=\frac{f_3'}{f_3'+f_2'(1-\beta_2)-d_{23}} \tag{2}$$

Let *x* be the displacement of the zoom lens, which can be obtained by the following formula:

$$x=f_2'\left(\frac{1}{\beta_2}-\frac{1}{\beta_2^*}\right) \tag{3}$$

Then the magnification of the zoom lens is:

$$\beta_2^*=\left(\frac{1}{\beta_2}-\frac{x}{f_2'}\right)^{-1} \tag{4}$$

Formula (1) shows a constraint relationship between β_2^* and β_3^* during the zoom process. It can be rewritten as follows:

$$\beta_3^{*2}+b\beta_3^*+1=0 \tag{5}$$

where,

$$b=\frac{f_2'}{f_3'}\left(\frac{1}{\beta_2^*}+\beta_2^*-\frac{1}{\beta_2}-\beta_2\right)-\left(\frac{1}{\beta_3}+\beta_3\right) \tag{6}$$

Solving equation (6), we get:

$$\beta_3^*=\frac{-b\pm\sqrt{b^2-4}}{2} \tag{7}$$

Therefore, the displacement of the compensate lens is:

$$y = f_3'(\beta_3^* - \beta_3) \tag{8}$$

The Gaussian optical problem of the mechanically compensated continuous zoom system is determining the focal lengths f_1', f_2' and f_3' of the front fixed lens, the zoom lens and the compensating lens, and the intervals between the lenses during zooming.

3. MWIR CONTINUOUS ZOOM OPTICAL SYSTEM DESIGN

3.1. Parameters of optical system design

This system uses a Neutrino LC cooled detector. The parameters of the detector and system as shown in table 1 [15].

Table 1. *Parameters of the detector and system.*

Parameters/unit	Values	Parameters/unit	Values
Array size, pixel	640×512	Field of view, °	21.8×17.5 ~ 1.6×1.3
Pixel dimension/µm	15	F#	4.0
Detector's NETD/ mK	≤25	Focal length/mm	25 ~ 350
Working waveband/µm	3.4 ~ 4.9	Working temperature/°C	-10 ~ +60
Zoom, X	14		

3.2. Process of optical system design

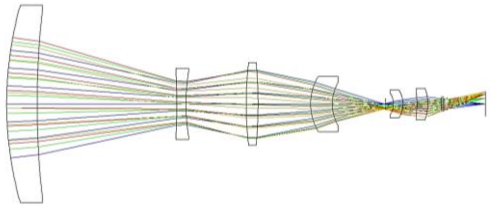


Figure 2. *MWIR continuous zoom optical system with six lens.*

To be used at a variation observation distance and working temperatures, the continuous zoom infrared optical system contains two more movable lenses behind the zoom system. Figure 2 shows the system structure, which contains six lenses. The first four lenses are used to change the focal length and fix the focal plane, and the last two lenses are used to focus and provide temperature compensation. The system design process is as follows.

Firstly, the focal length of each lens is determined according to the system's design parameters, and the spacing between the lenses is solved according to the continuous zoom model (in Section 2). By repeatedly adjusting the initial parameters of the system and observing whether the component spacing and focal length distribution are appropriate, the initial values of the system are finally determined to be: f_2'= -25.14, f_3'=41.76; β_2= -0.27, β_3= 0.33 for short focus, and β_2= -0.91, β_3= 1.66 for long focus. Table 2 shows the spacing parameter distribution results of the various FOVs calculated according to the above initial parameters of the system.

Table 2. *Initial spacing parameters of the optical system.*

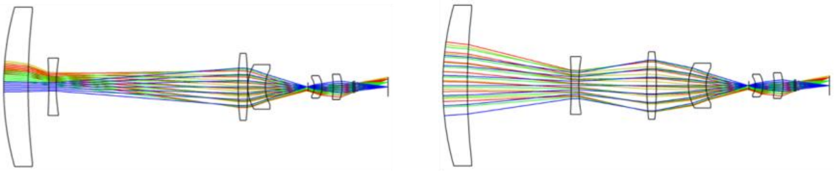
Focal length/mm	**25**	**150**	**250**	**350**
f_1-f_2 spacing/mm	13.01	65.08	72.64	76.37
f_2-f_3 spacing/mm	114.69	42.63	26.03	15.32
f_3-f_4 spacing/mm	0.12	20.11	29.15	36.12

Secondly, the imaging parameters of the initial optical system are calculated and evaluated using the Zemax software. According to the evaluation results, the parameters of the aspheric lens and the diffraction surface are selected to obtain the optimal result.

Finally, the optimization function and optimization parameters are set to optimize the imaging quality of the system and re-evaluate the imaging quality. Repeat the above process until the optimal result is obtained.

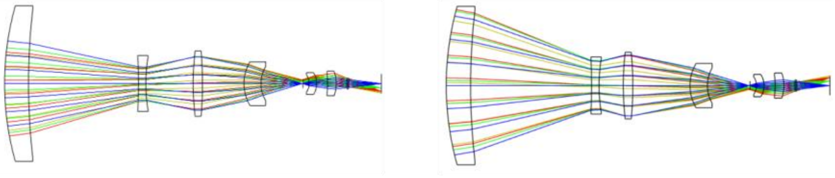
3.3. Design results

The design result of the MWIR continuous zoom optical system is shown in figure 3, where figures 3a to 3d are system diagrams with focal lengths of 25 mm, 150 mm, 250 mm and 350 mm, respectively.



a) f=25 mm

b) f=150 mm



c) f=250 mm

d) f=350 mm

Figure 3. *Design results of the MWIR continuous zoom optical system at various FOVs.*

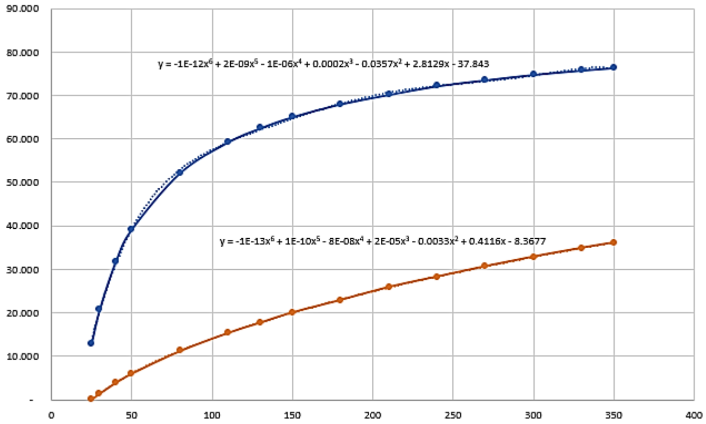


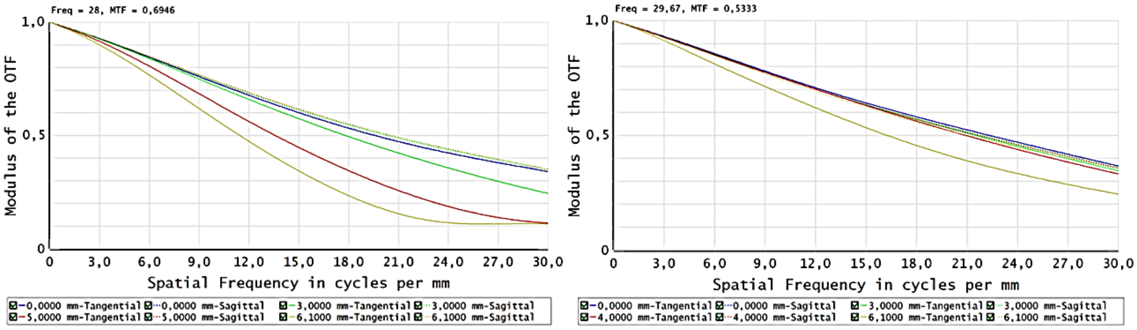
Figure 4. *Cam curves of a continuous zoom optical system.*

The system includes six aspherical lenses, where the fourth and fifth lenses include a diffraction surface (binary surface). Using aspherical and diffractive surfaces improves the imaging quality while reducing the number of lenses and significantly reducing the system's mass. By design, the two moving lenses (the second and third ones) move along two nonlinear curves during zoom process. Figure 4 is the result of designing the cam curves of two moving lenses.

4. IMAGE QUALITY EVALUATION

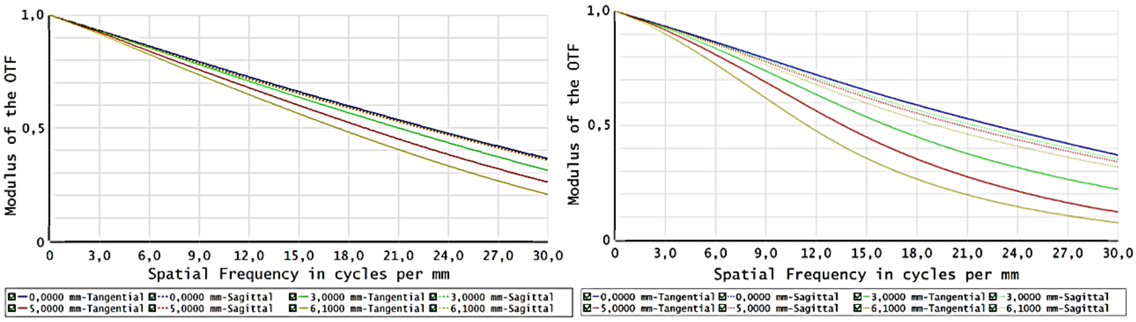
4.1. Modulation transfer function

The modulation transfer function (MTF) can fully represent the imaging properties of an optical system. An optical system whose transfer function reaches the diffraction limit is an ideal optical system with no aberration. Figure 5 shows the optical transfer function of a continuous zoom system at various FOVs. The pixel dimension is 15 µm, so the spatial frequency that the optical system can receive will be less than 33.3 cycles/mm according to the Nyquist-Shannon law. In this paper, we choose the frequency of 20 cycles/mm to evaluate the optical system, and the MTF value is 0.5. In addition, the diffraction limit is the maximum MTF value of an optical system at different spatial frequencies. The MTF of the system at various FOVs is close to the diffraction limit, indicating that the optical system has clear imaging quality and meets the system usage requirements.



a) f=25 mm

b) f=150 mm

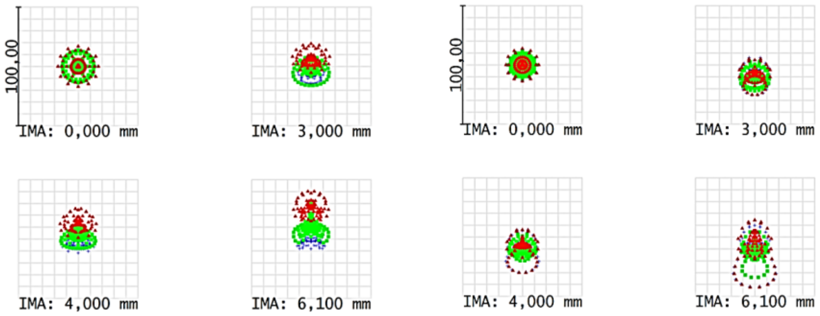


c) f=250 mm

d) f=350 mm

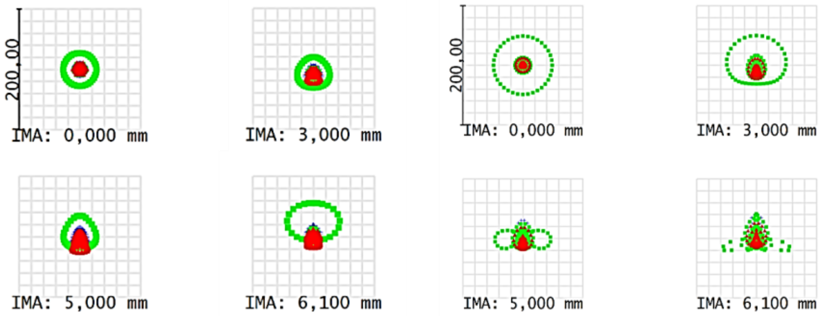
Figure 5. *MTF of the system at various FOVs.*

4.2. Spot diagram



a) f=25 mm

b) f=150 mm



c) f=250 mm

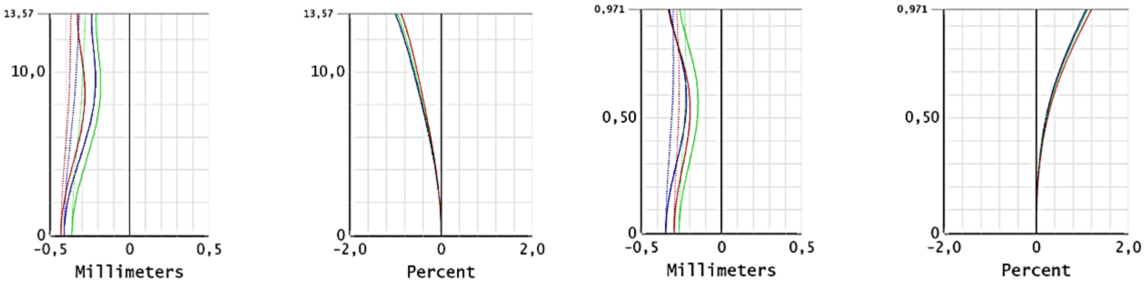
d) f=350 mm

Figure 6. *Spot diagrams of the system at various FOVs.*

The spot diagram (SPT) is the light intensity distribution on the image plane corresponding to a point on the object plane after passing through the optical system. From the spot diagram, we can more intuitively and comprehensively understand the various aberration correction conditions of the system. In figure 6, the spot diagrams of the system at various FOVs are listed. From the diagrams, the maximum root mean square radius value (RMS) of the diffuse spot is 8.1 µm (much smaller than the pixel size), indicating that the imaging quality of the system is good.

4.3. Distortion

Distortion is the deviation between the intersection of the system's principal ray with the Gaussian image plane and the ideal image point. Figure 7 shows the system distortion at narrow (f = 350 mm) and large FOV (f = 25 mm). The results show that the distortion changes little during zooming and is always lower than 1.5% [16]. It shows that distortion has no significant effect on imaging during continuous zooming.



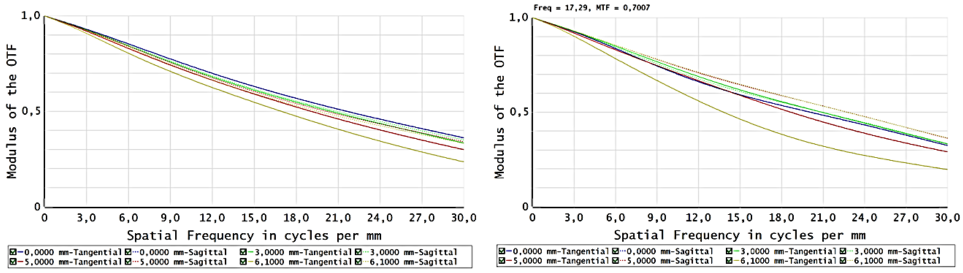
a) f=25 mm b) f=350 mm

Figure 7. Distortion of the system at narrow and large FOV.

4.4. Image quality at high and low temperatures

When the temperature of the environment changes, the shape and size of the lens and mechanical components will change, leading to changes in the position of the image plane. There are two commonly used methods to solve this problem: Method 1: Combine materials with different thermal expansion coefficients to compensate for the thermal changes of the lenses. This method combines various types of glass or materials to manufacture lenses and system components; Method 2: Move one or several optical components of the optical system to compensate for the thermal changes. This movement can be done by motor or manually.

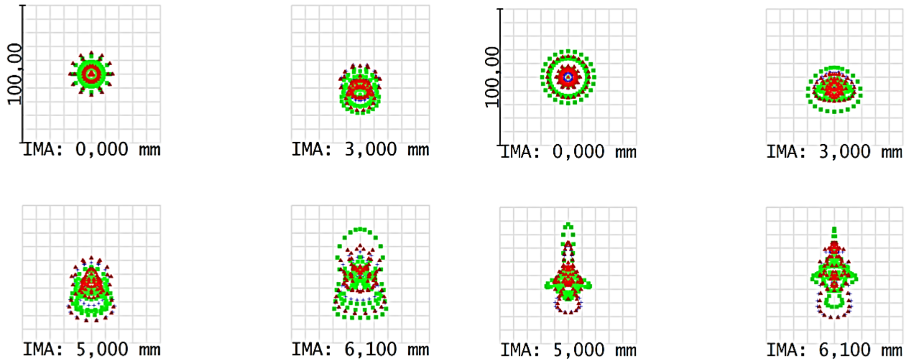
In this paper, we use method 2, where active focusing is performed by moving the group of fifth and sixth lenses. We analyzed the imaging quality of the system after compensation at high and low temperatures at a focal length of 150 mm. Figure 8 is the system MTF after compensation at high and low temperatures. Figure 9 is the system spot diagram after compensation at high and low temperatures. It shows that the system has good imaging quality in the temperature range of - 10 °C to + 60 °C.



a) t = -10°C b) t = +60°C

Figure 8. MTF after compensation at high and low temperatures.

Through calculation, the displacement range of lens group 5-6 when the temperature changes from - 10 °C to + 60 °C is - 0.3 mm to + 0.6 mm. This range is relatively small, showing the feasibility and rationality of the temperature compensation design of this system.



a) t = -10°C　　　　b) t = +60°C

Figure 9. *Spot diagram after compensation at high and low temperatures.*

5. CONCLUSIONS

A mechanically compensated large-magnification, athermal continuous zoom optical system is designed based on a 640 × 512 pixel, 15 µm cooled MWIR detector. The system consists of 6 lenses, with an F# of 4.0, a field of view ranging from 21.8° × 17.5° to 1.6° × 1.3°, and a zoom ratio of 14×. The mass of the optical system is 330 g, the system size is 172 mm × 108 mm, the maximum objective lens diameter is 100 mm, and the imaging quality is maintained from - 10 °C to + 60 °C. This medium-wave infrared continuous zoom optical system has broad application prospects in navigation, search, tracking, warning, and reconnaissance.

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TÓM TẮT

Thiết kế hệ quang hồng ngoại bước sóng trung làm lạnh có tiêu cự thay đổi liên tục ứng dụng trong quan sát tầm xa

Hệ thống quang học có tiêu cự thay đổi liên tục sử dụng đầu thu hồng ngoại làm lạnh có thể thu được hình ảnh chất lượng cao trong nhiều trường nhìn khác nhau. Dựa trên lý thuyết hệ quang tiêu cự thay đổi liên tục, nhóm tác giả thiết kế một hệ thống quang hồng ngoại bước sóng trung bù nhiệt có tiêu cự thay đổi liên tục, hệ quang chỉ bao gồm sáu thấu kính. Hệ quang có F# là 4,0, dải bước sóng hoạt động là 3,4 - 5,0 µm, trường nhìn thay đổi từ 21,7°×17,5° đến 1,6°×1,3°. Tất cả sáu thấu kính trong hệ quang đều có chứa mặt phi cầu và sử dụng hai mặt nhiễu xạ để loại bỏ quang sai, tối ưu kích thước, khối lượng của hệ. Hệ quang được bù nhiệt thông qua cơ cấu điều tiêu chủ động. Hệ quang hồng ngoại bước sóng trung có tiêu cự thay đổi liên tục được thiết kế có cấu tạo nhỏ gọn và chất lượng hình ảnh tốt trong toàn trường nhìn với phạm vi nhiệt độ từ - 10 °C đến + 60 °C.

Từ khoá: Thiết kế quang; Hệ quang thay đổi tiêu cự liên tục; Điều tiêu bù nhiệt; Đầu thu làm lạnh.