Design of dual band common aperture continuous zoom optical system

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Abstract. To rapidly accommodate social demands and the requirements of imaging system under increasingly complex application environment, and to optimize the complex and bulky existing multi-spectrum continuous zoom optical systems, a short-wave (0.9μm to 1.7μm) and long-wave (7.7μm to 9.3μm) infrared radiation common aperture continuous zoom optical system was designed, the focal lengths of short-wave and long-wave infrared radiation were 8mm to 32mm and 30mm to 120mm respectively, the zoom ratio was 4. The system was analysed according to the theory of positive group compensated zoom, powers of the zoom group and the compensation group were well matched, only ZNSE and ZNS materials were applied in the common group. The results of the experiment show that the optical system is compact in structure, and has good image quality in different spectrums, can work around the clock under complex environment.

1. Introduction

The fast-developing social requirements and increasingly complex application environments have raised increasing demands on the performance of video imaging systems, traditional single band video imaging systems can no longer meet the modern monitoring needs. How to obtain target information more comprehensively and accurately has become a research hotspot of video surveillance systems currently. Therefore, it is particularly necessary to design a multi-band continuous zoom system that can work to continue 24x7 in all weathers under complex environments. SWIR (short-wave infrared) can work in harsh conditions such as low illumination, rain, haze, smoke or water vapor. At the same time, SWIR has the advantage of high sensitivity, can not only easily image the target, but further identify or detect the target during the imaging process. SWIR is able to penetrate glass or plastic products, which is different from other spectral bands. LWIR (long-wave infrared) is mainly used to observe objects at normal temperature, and can form a contour image of the object. At the same time, near the heat source or with stray radiation, LWIR can keep stronger observation ability than MWIR (medium-wave infrared). It has high anti-interference capacity for indoor environment with low illumination at night.

Most of the existing dual-band zoom systems are composed of two separate systems, they have large size and complex structure, and have poor ability for continuous tracking of the same target. A few common aperture systems also use the design scheme of dual-band detectors but their costs are high. In 2010, Jay N Vizgaitis et al. designed a military 11x MWIR/ LWIR continuous zoom system, which use the refractive and reflective optical path with the two-color infrared focal plane array to simultaneously...
MWIR / LWIR image. Harbin Institute of Technology has developed a medium-wave / long-wave continuous zoom system with a focal length of 45mm to 300mm. Based on this, a visible / infrared multi-spectrum continuous zoom system was designed. The fore-optical system of the system is off-axis three mirror optical structure, which realizes the 6x continuous visible light zoom, but the system is relatively bulky and the application range is limited.

In view of the above described problems, a SWIR (0.9μm to 1.7μm) and LWIR (3μm to 5μm) common aperture continuous zoom optical system based on the common fixed group, the zoom group and the compensation group was designed in this paper. The system possesses the advantages of compact in structure, low cost, wide working spectrum band, and can work to continue 24x7 in all weathers under complex environments. The common group only uses two materials, ZNSE and ZNS, so that the spectrum bands of system have the same zoom ratio, and can obtain comprehensive target information of different spectrum bands at the same time. The system has extensive application prospects, such as industrial inspection, security, power line inspection and early fire alarm.

2. Design Theory

2.1. Theory of Wide Spectrum Achromatism

According to the application requirements of the system, the optical elements of the common group should enable to both transmit SWIR and LWIR light. Compared with visible optical materials, infrared optical materials have relatively fewer types and quantities, taking the material's characteristics and processing characteristics into consideration, very few types of materials could be used. Commonly used wide spectrum infrared materials are shown in Table 1. As can be seen from the table, the two materials ZNSE and ZNS have obvious advantages in terms of solubility and thermal expansion coefficient.

| Name         | Transmission spectrum range(μm) | Density (g/cm³) | Melting point (°C) | Hardness (Vicker's) | Coefficient of thermal expansion (10⁻⁶/°C) | Solubility (g/100g water) |
|--------------|---------------------------------|-----------------|--------------------|---------------------|------------------------------------------|---------------------------|
| ZNS          | 0.37~14                         | 4.09            | 1020               | 354                 | 7.0                                      | 0                         |
| CAF2         | 0.23~9.70                       | 3.18            | 1360               | 200                 | 18.85                                    | micro                     |
| KCL          | 0.2~30                          | 1.98            | 776                | 7.2                 | 38.2                                     | 34.7                      |
| ZNSE         | 0.5~22                          | 5.27            | 1525               | 110                 | 7.1                                      | 0                         |
| BAF2         | 0.23~10.30                      | 4.89            | 1280               | 82                  | 1.81                                     | 1.7                       |
| CLEARTRAN    | 0.405~13                        | 4.09            | --                 | 160                 | 6.3                                      | 0                         |
| KBR          | 0.2~30                          | 2.75            | 730                | 6.0                 | 37.6                                     | 53.48                     |
| CSBR         | 0.36~39                         | 4.44            | 636                | 19.5                | 46.6                                     | 124.3                     |

Due to the different dispersion properties of different materials in different bands, the system not only has its own chromatic aberration in each band, but also has chromatic aberration between bands. Therefore, it is necessary to study the chromatic aberration cancellation problem of optical systems and material match problem. When the center wavelengths of the different spectral bands are \( \lambda_1 \) and \( \lambda_2 \), the achromatic formula of the two thin lenses can be expressed as:

\[
\begin{align*}
\Phi_1(\lambda_1) + \Phi_2(\lambda_2) &= \Phi \\
\frac{\Phi_1(\lambda_1)}{v_1(\lambda_2)} + \frac{\Phi_2(\lambda_2)}{v_2(\lambda_2)} &= 0
\end{align*}
\]

(1)

Where \( \Phi_1 \) and \( \Phi_2 \) are the optical powers at the center wavelengths of the two thin lenses respectively, \( v_1 \) and \( v_2 \) are the Abbe numbers of the materials of the two lenses respectively, \( v_1 \) and \( v_2 \) can be denoted by
\[v_1(\lambda_s) = \frac{n_1(\lambda_s) - 1}{n_1(\lambda_s) - n_1(\lambda)} \text{, } v_2(\lambda_s) = \frac{n_2(\lambda_s) - 1}{n_2(\lambda_s) - n_2(\lambda)}\]  

(2)

Then, according to the primary aberration theory, the smaller the absolute optical power of the optical system, the smaller the spherical aberration and chromatic aberration of the system. Therefore, in the case of defining the central wavelength of different spectral bands, the achromatic formula of system can be expressed as:

\[
\begin{align*}
\phi' &= \phi_1(\lambda_s) + \phi_2(\lambda_s) \\
S &= \frac{1}{n} \sum_{i=1}^{n} \left| \frac{f_{\lambda_i} - f_s}{f_s} \right| = \frac{1}{n} \sum_{i=1}^{n} \left[ \frac{\phi_1(\lambda_s)}{P_1(\lambda_s)} + \phi_2(\lambda_s) \right] / P_2(\lambda_s)
\end{align*}
\]  

(3)

Where \(\phi'\) is the absolute optical power, \(S\) is the average out-of-focus-amount of plurality of wavelengths in the design spectral band.

\[P_1(\lambda_s) = \left[ n_1(\lambda_s) - 1 \right] / \left[ n_1(\lambda) - 1 \right] \text{, } P_2(\lambda_s) = \left[ n_2(\lambda_s) - 1 \right] / \left[ n_2(\lambda) - 1 \right]\]  

(4)

When the system satisfies formula (3), it can be considered that the system satisfies the achromatic conditions for the defined center wavelength. However, there will be some chromatism at other wavelengths of the SWIR just like LWIR. The remaining focal shifts at other wavelengths are related to \(dn/d\lambda\) of the material and the optical power of optical elements. Good design results can be obtained under the appropriate settings of system achromatic and optical power.

### 2.2. Analysis of Zoom Method

The zoom method determines the realizability and complexity of the system. The commonly used zoom system compensation methods are mainly optical compensation method, mechanical compensation method and full-motion compensation method. The optical compensation method uses the linearity motion of one or two sets of optical elements to achieve the purpose of zoom imaging, this method is low cost, but cannot realize continuous zoom imaging; mechanical compensation method uses two sets of moving optical elements driven by mechanical cams moving with different rules, to achieve the purpose of zoom imaging, this method can realize continuous zoom imaging. The full-motion compensation method uses the movement of all optical elements to achieve the purpose of zoom imaging. This method causes the driving unit has a complicated structure, but it can achieve continuous zoom imaging. The advantages and disadvantages of each compensation method are shown in Table 2.

| Zoom method        | Image plane stability | Movement rule | Realization form | System length | Imaging Quality |
|--------------------|-----------------------|---------------|-----------------|---------------|----------------|
| Optical compensation method | few positions | linearity | non-cams | long | good |
| Mechanical compensation method | continuous | one group linearity and the other group nonlinearity | cams | middle | excellent |
| Full-motion compensation method | continuous | multi-group linearity and nonlinearity mix | cams | short | excellent |

According to the above analysis, the mechanical compensation method has obvious advantages in continuous zoom, complexity, system volume and imaging quality. Therefore, this paper adopted the mechanical compensation method to design a dual-band common aperture continuous zoom system.
The basic structure of the mechanical compensation method is shown in Figure 1. $\phi_1$ in Figure 1 is the fixed group, its position does not change during the zooming process. $\phi_2$ is the zoom group, it shifts $q$ according to its movement rule during the zooming process. $\phi_3$ is the compensation group, it moves $\Delta$ when zooming according to its movement rule to compensate for the image plane change caused during the zooming process. The movement amount of each movement component is controlled by cams, so as to ensure that the image plane does not move when the system has different focus.

![Figure 1. Basic structural schematic diagram of the mechanical compensation method.](image)

3. Design and Analysis of Optical System

3.1. Design Indexes

The dual band common aperture continuous zoom system was required a wide-spectrum continuous zoom imaging in a 24x7 complex weather environment. Therefore, a combination of SWIR and LWIR is selected. At the same time, in order to improve the imaging quality of the system, the LWIR channel uses a cooled detector. The pixel size is 30μm for both spectral detectors. Design specifications are shown in Table 3.

| Sequence | Parameters | Specifications |
|----------|------------|----------------|
| 1        | Spectrum(μm) | SWIR:0.9–1.7  |
|          |             | LWIR:7.7–9.3  |
| 2        | Zoom ratio  | 4x             |
| 3        | F#          | SWIR:4         |
|          |             | LWIR:2         |
| 4        | Focal length(mm) | SWIR:8–32     |
|          |             | LWIR:30–120    |

3.2. Design Results

The dual band common aperture continuous zoom system uses a transmissive optical structure, and uses a dichroic mirror to realize dual band imaging. The fore-optical common zoom group shared by the two spectrum bands is located in front of the dichroic mirror, including the fixed group, zoom group, and compensation group. They all use multispectral ZNSE and ZNS materials with good physical properties, and the correction groups for each spectral band are located behind the dichroic mirror. The transmissive dual band common aperture continuous zoom system can simultaneously realize zoom imaging of SWIR and LWIR. The system structure in condition of SWIR focal length 10mm and LWIR focal length 30 mm is shown in Figure 2.
In Figure 2, G1 is the fixed group, G2 is the zoom group, G3 is the compensation group, D1 is the dichroic mirror for separating SWIR and LWIR, G4 is the SWIR channel imaging lens unit, G5 is the LWIR channel imaging lens unit, FP1 is the SWIR detector, FP2 is the LWIR detector. The optical design results of the LWIR optical path with different focal lengths are shown in Figure 3, and the optical design results of the SWIR optical path with different focal lengths are shown in Figure 4. In order to ensure the cold-shield-match of the LWIR detector, the system uses the secondary imaging structure. A dichroic mirror D1 is placed behind the primary imaging plane, the SWIR beam is reflected and the LWIR beam is transmitted. The lens surfaces are all spherical, and the overall size of the optical system is 320mm × 80mm × 120mm (length × width × height). The system has a good performance on realizability.

Figure 2. Structural schematic diagram of the system.

Figure 3. Optical path of the LWIR beam with focal lengths (a) f=30mm, (b) f=60mm, (c) f=90mm, (d) f=120mm.

Figure 4. Optical path of the SWIR beam with focal lengths (a) f=10mm, (b) f=20mm, (c) f=30mm, (d) f=40mm.
3.3. Analysis of Image Quality

Modulation transfer function (MTF) is an important indicator to evaluate the imaging quality of optical systems. Figure 5 shows the MTF curve of the system at the Nyquist frequency (17lp/mm) when the focal lengths of the SWIR channel are 10mm, 20mm, 30mm, and 40mm respectively. Figure 6 shows the MTF curve of the system at the Nyquist frequency when the focal lengths of the LWIR channel are 30 mm, 60 mm, 90 mm, and 120 mm respectively. As can be seen from the system MTF curve, the modulation of the SWIR channel at the Nyquist frequency is greater than 0.4, the modulation of the LWIR channel at the Nyquist frequency is greater than 0.25, and each channel of the system has good imaging quality over the entire range of focal lengths.

Figure 5. MTF curve of the system of SWIR optical path with focal lengths (a)f=10mm, (b)f=20mm, (c) f=30mm,(d) f=40mms.

Figure 6. MTF curve of the system of LWIR optical path with focal lengths (a)f=30mm, (b)f=60mm, (c) f=90mm,(d) f=120mm.
4. Conclusions
A design is presented in this paper for the SWIR spectrum and the cooled LWIR spectrum detector, the mechanical compensation method is adopted by the design to realize a 4x common aperture continuous zoom optical system of 0.9~1.7μm SWIR and 7.7~9.3μm LWIR. The system avoids the shortcomings of the traditional multi-band zoom system, such as large volume and complicated structure. The wide-band achromatic technology and matching optical material are used to realize the SWIR and LWIR common aperture continuous zoom imaging. The system is simple in structure, small in volume, good in imaging quality, and is easy to realize. It can work to continue 24x7 under complex environment and has a good application prospect.

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References
[1] Optical Design and Stray Light Analysis of the Space Infrared Optical System [J]. Journal of Harbin Institute of Technology (New Series), 2017, 24(1): 32-36.
[2] Chen Xu, Dewen Cheng, Jinjin Chen, Yongtian Wang, Design of all-reflective dual-channel foveated imaging systems based on freeform optics, Appl. Opt., 2016,55, 2353-2362.
[3] Dmitry Reshidko, Jose Sasian, A method for the design of unsymmetrical optical systems using freeform surfaces, Proc. SPIE-OSA 105900V, 2017 ,1-14.
[4] T Agocs, Freeform mirror based optical systems for FAME, Proc. 2017, SPIE 9151.
[5] Y Zhong, H. Gross, A Broemel, S Kirschstein, P Petruck, A Tuennermann, Investigation of TMA systems with different freeform surfaces, Proc. 2015, SPIE 96260X, 1-10.