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Design of dual-band shared-aperture Co-zoom optical system

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HIGHLIGHTS

- Optical system, fusing visible/mid-IR light in the same light path, is designed.
- A method is obtained to compensate zoom ratio difference between visible and mid-IR.
- Volume of dual-band continuous zoom optical system is reduced.
- This optical system can conduct synchronous observation, tracking and measurement with dual-band.

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ABSTRACT

An optical system that features visible plus mid-infrared light, shared aperture, synchronous and continuous zoom is designed with a 10× zoom ratio. Analysis is performed to differentiate visible plus mid-infrared light focal length and zoom ratio during zooming, and the change law of this difference. Upon combination with two-group and three-group zoom theories and upon derivation of the conditions for compensating zoom ratio difference, a method has been obtained to directly compensate this difference. The focal length and the zoom ratio for visible/mid-infrared light at any zoom location are similar with this method, thereby conducting synchronous observation, tracking, and measurement on the target. Design results have shown that the system is small, has a fast response, has an excellent in overall image quality, and is athermal for temperatures between −40 °C and 60 °C.

1. Introduction

A dual-band continuous zoom optical system incorporates the characteristics of a dual-band system (e.g., round-the-clock detection and accurate and comprehensive access to target information) with the advantages of a continuous zoom system (e.g., wide detection range, rapid search, and continuous observation on target). This system has been gained research interest worldwide [1,2]. Vizgaitis [3] has designed an 11.7× military MWIR/LWIR continuous zoom system in 2010 that adopts the reflective-refractive mixed light path and the infrared dichroic focal plane array in concurrent imaging at medium/long-wave infrared band. In his article, Petrushevsky and Tsur [4] has analyzed a Goodrich DB-110 aerial camera having mutually independent visible light and infrared optical systems, which realizes round-the-clock detection and accurate target observation. Han et al. [5] have respectively folded both visible light and infrared dual-band systems via multiple reflections to reduce the system volumes, which is the main problem for these systems. An optical system that fully adopts the refraction form to fuse visible light/infrared in the same light path and realizes synchronized and continuous zoom is yet to be reported.

The standards for optical system performance have increased with the rapid development of social demand and the increasingly complicated environmental applications [6–10]. However, most of the existing visible light/infrared dual-band zoom systems comprise two separate systems with a large system volume and complex reconnaissance equipment structure. Target search and focal length readjustment prior to another target observation are necessary because of external environment changes, such as target obscurity, smoke interference, alternation of day and night, and change in light path, resulting in a long change process and a slow system response. Furthermore, the target may be lost provided that the target being tracked and observed moves fast.

This design obtains continuous zoom for dual bands (visible light/mid-infrared) in the same optical path. Both systems have the same focal length and zoom ratio at any location upon compensating the zoom difference for dual bands. Changing the optical path is unnecessary and can be observed directly upon observation with different bands. This system yields synchronous observation, tracking and measurement on the target with dual bands,

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Table 1
Optical design specifications.

Visible		Mid-infrared	
Wave	0.48–0.64 μm	Wave	3.7–4.5 μm
Zoom ratio	10 ×	Zoom ratio	10 ×
F/#	5	F/#	3.5
Field of view	18–1.8°	Field of view	18–1.8°
Focal length	6.5–65 mm	Focal length	6.5–65 mm

improves the response rate of the optical system, and avoids the target loss during optical path change.

2. Indicator and structural design of optical system

2.1. Optical system design indicator

An optical system is required to implement round-the-clock observation and yield excellent resolution in infrared band, thereby selecting dual bands. The total zoom ratio is designed at 10× to ensure that the system has a larger scope of observation. The overall length of this system is less than 300 mm because of small size and lightweight requirements. Table 1 lists the specific design indicators. The visible-light detector is a 1/4″ CCD having a 6.5 μm × 6.25 μm pixel size; the mid-infrared detector is a 1/4″ uncooled focal plane array having a 25 μm × 25 μm pixel size.

2.2. Optical system structure design

This system is required to realize synchronous continuous zoom at dual bands. However, a traditional zoom system cannot meet structural design requirements, thereby redesigning this structure comprising five parts: public zoom group, dispersion prism, zoom difference compensation group, visible-light fixed rear lens group, and mid-infrared fixed rear lens group (Fig. 1).

(1) The public zoom group comprises three units: front fixation group, zoom group, and compensation group. This portion goes through the visible and infrared light simultaneously, and realizes the synchronous zoom at dual bands.
(2) Dispersion prism [11] allows transmission of visible light and reflects mid-infrared light.
(3) The zoom ratio difference compensation group is set in the reflected light path, which can compensate the difference in focal length and zoom ratio of dual bands via location movement.
(4) The visible and mid-infrared light rear fixed lens groups can respectively correct image aberration and converge light in their respective detectors for imaging.

3. Initial structure design and analysis of the public zoom group

3.1. Initial structure design

Based on design requirements, the zoom ratio is 10×, and the zoom and compensation curves are smooth to subsequently compensate the zoom ratio difference. Thus, the mechanical positive group zoom is appropriate [12]. Zoom design theory states that the displacement relationship between zoom group and compensation group will meet formula (1) when the image plane is stable,

$$\frac{dq_2}{dq_1} = \frac{q_1 - \frac{q_1^3 - 2f_2'f_3'q_1 - 3f_3'q_1^2}{\sqrt{q_1^4 - 4f_2'f_3' - 4f_3'q_1^3}}}{f_2' + q_1} + \frac{-q_1^2 - \sqrt{q_1^4 - 4f_2'f_3'q_1^3}}{2(f_2' + q_1)^2} \quad (1)$$

where q_1 is displacement of zoom group along optical axis; q_1 is displacement of compensation group along optical axis; f_2' is focal length of zoom group; f_3' is focal length of compensation group.

The focal length of the zoom group is a standard value, which is $f_2' = -1$ in the initial structure design. The following results are obtained upon calculation coupled with design experience: focal length of front fixation group is $f_1' = 6$, that of the compensation group is $f_3' = 1.15$, and that of the rear fixed group is $f_4' = 0.6$. A combination is made at respective magnifications $\beta_1 = 1$ and $\beta_2 = -1$ in zoom compensation, and compensation groups in order to the spacing value of each group when the initial system is at the medium focal length; the, spacing value of the front fixed and zoom groups is $d_{12} = 0.95$, that of zoom and compensation groups is $d_{23} = 1.95$, and that of compensation group and rear fixed group is $d_{34} = 0.55$. The actual focal length f_2' in zoom group is -42 mm following the analysis and calculation.

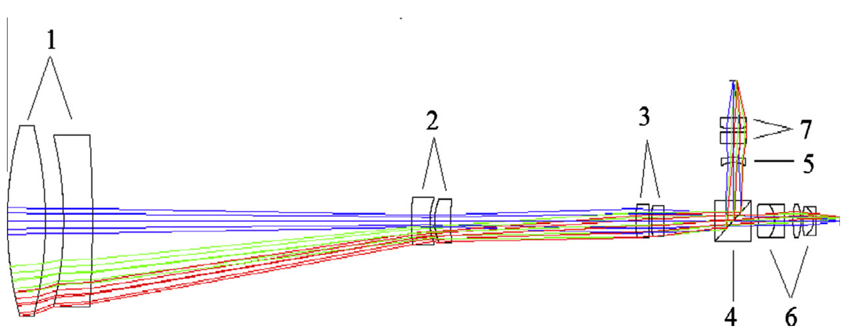

Fig. 1. Schematic diagram of the optical system. (1) front fixed group, (2) zoom group, (3) compensation group, (4) prism, (5) zoom ratio difference compensation group, (6) visible rear fixed group, and (7) mid-infrared rear fixed group.

Table 2
Visible, mid-infrared focal length focus and zoom ratio.

	Short-focus (mm)	Mid short-focus (mm)	Mid long-focus (mm)	Long-focus (mm)	Zoom ratio
Visible	6.509	24.090	43.7376	65.0079	10.00×
Mid-infrared	7.482	24.10	38.2089	51.8958	6.936×
Focal length difference	−0.973	0.01	4.5287	13.1121	
Zoom ratio difference					3.064×