Design of a Light and Small Dual-band Airborne Despun Optical System

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In aerial cameras, image quality is easily affected by weather, temperature, and the attitude of the aircraft. Aiming at this phenomenon, based on the theory of two-step zoom optical systems, a dual-band optical-despun two-step zoom optical system is designed. The system has a small field of view of 2.00° × 1.60°, and a large field of view of 4.00° × 3.20°. In the zoom process, the wavelength range is 0.45–0.70 μm and 0.75–1.10 μm, and the size of the optical system is 168 mm (L) × 90 mm (W) × 60 mm (H). The overall lens weight is only 170.8 g, which has advantages for miniaturization and light weight. At the Nyquist frequency of 104 lp/mm, the modulation transfer function of the visible-light optical system is more than 0.44, and that of the near-infrared optical system is more than 0.30, both of which have good imaging quality and tolerance characteristics in the range of −45 to 60 °C.

Keywords: Athermalization, Dual band, Light and small optical system, Optical despun, Two-step zoom

OCIS codes: (120.4820) Optical systems; (120.6810) Thermal effects; (220.3620) Lens system design

I. INTRODUCTION

With the development of science and technology, visible-infrared dual-band optical systems are widely used in military reconnaissance and daily life, and can realize all-weather imaging with strong adaptability to smoke, night, and low light [1–3]. In infrared systems, detectors in the near-infrared band are less expensive and have better imaging resolution than those in the middle- and long-wave infrared.

Compared to a continuous zoom system, a two-steps zoom system has the advantages of simple structure, high transmittance, and fast switching. It can not only realize large-field-of-view search, but also small-field-of-view calibration, which is more conducive to miniaturization of the system. The two-step zoom system is widely used in photoelectric reconnaissance equipment and has replaced the continuous zoom system in many aspects [4–7].

In the tracking and shooting process, the attitude change of the carrier and relative movement of the target cause the optical platform’s visual axis to roll, resulting in rotation of the filmed video image, which is not conducive to observing the target. Compared to electronic despun and mechanical despun, optical despun has the advantages of good real-time performance, no image distortion, and image-rotation compensation under high-speed scanning imaging. Therefore, the optical despun device is introduced [8].

Nowadays, aerial cameras are developing in the direction of miniaturization and lightweight, and the airborne environment has more and more strict requirements for the size and weight of cameras [9, 10]. Therefore, this paper aims to reduce the size and weight of cameras under the premise of ensuring image quality. In 2020, Liu et al. [11] designed a zoom lens of 50–1,000 mm that works in the visible band.

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Color versions of one or more of the figures in this paper are available online.
The whole system consists of 28 spherical lenses, and the total length of the system is less than 400 mm. The system has a large total length, a narrow band, and no racemization function. In 2022, Chang et al. [12] designed a zoom lens of 25–250 mm, with a working band of 0.48–0.68 μm and 0.8–0.9 μm, a total length of 199 mm, and a total lens weight of 203.6 g. The system is heavy, with no racemization function and poor image quality at the edge of the field of view.

An aerial camera is highly affected by temperature, so to adapt to different temperature environments it is necessary to realize athermalization designs for the system [13]. Therefore, this paper designs a light and small dual-band airborne racemic two-step zoom optical system.

II. SYSTEM PRINCIPLE

2.1. Principle of the Two-step Zoom System

The schematic diagram of the axially movable two-step zoom optical system is shown in Fig. 1 [14]. The system adopts the principle of object-image exchange, by changing the axial position of the zoom group to realize the change of the focal length of the whole system. The zoom group has a narrow field of view and a long focal length at the dotted line, and a wide field of view and a short focal length at the solid line. The magnifications of the two object-image exchange positions are reciprocal: \( m_1 = 1 / m_2 \), where \( m_1 \) is the magnification of the long-focus zoom group and \( m_2 \) is the magnification of the short-focus zoom group. The system’s zoom ratio is \( \beta = m_1^2 \). We can conclude that \( m_1 = \pm \sqrt{\beta} \) and \( m_2 = \pm 1 / \sqrt{\beta} \).

By the Gaussian formula for geometrical optics,

\[
\frac{1}{l'} - \frac{1}{l} = \frac{1}{f'},
\]

where \( f' \) is the focal length of the system, \( l \) is the object distance of the system, and \( l' \) is the image distance of the system, we can conclude

\[
l = (1 / m - 1)f_z',
\]

where \( m \) is the system magnification, and \( f_z' \) is the focal length of the zoom group.

When the zoom group is in the position for exchanging the two objects of long focus and short focus, the moving distance of the zoom group is

\[
q = [(1 / m_1 - 1) - (1 / m_2 - 1)]f_z'.
\]

When the system is in the position for narrow field of view and long focal length, let the shortest distance between the zoom group and the front fixed group be \( d \); then the focal length of the front fixed group is

\[
f_1' = d + (1 / m_1 - 1)f_z'.
\]

Let the magnification of the post-fixed group be \( m_3 \), so that the focal length of the whole system when it is in the long-focal-length position is

\[
f_1' = f_1'm_1m_3.
\]

The focal length of the whole system in the short-focal-length position is

\[
f_1' = f_1'm_1m_3.
\]

The axial-movement type of system switches the field of view or focal length by axial movement of the lens group, which can overcome the problems existing in the cut-in type. It also has the advantages of easy assembly and adjustment, and good stability. The above process is the Gaussian-optical solution process for the design of a two-step zoom optical system.

2.2. Optical Despun Principle

Optical despun changes with the real-time change of the relative motion state of several optical elements in an optical system. Because it only controls the movement of individual components in the system, the power of the control system does not need to be very large, and the system structure is easily designed to be very compact. The stability accuracy is high, so it is widely used in despun design.

In optical despun, a Pechan prism has the advantages of small volume and compact structure, and can be used in a convergent light path, so this paper adopts a Pechan prism for despun. A Pechan prism consists of a pair of divided prisms (half-pentagonal prism and Schmidt prism) and an air gap; its main cross section is shown in Fig. 2. When the Pechan prism rotates by 90°, the image of the object rotates by 180°, as shown in Fig. 3. By controlling the rotation speed of the prism to be half of the image’s rotation speed, an immobile image can be obtained on the focal plane [15].
III. DESIGN OF OPTICAL SYSTEMS

3.1. Design Parameters

In this study a grayscale CMOS detector (DS1280-CMOS03 A/G) with a pixel size of $4.8 \mu m \times 4.8 \mu m$ is selected for the optical system, and the pixel number is $1,280 \times 1,024$. Table 1 shows the design indicators of this system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working Band ($\mu m$)</td>
<td>0.45–0.70, 0.75–1.10</td>
</tr>
<tr>
<td>Field of Vision (°)</td>
<td>2.00 × 1.60, 4.00 × 3.20</td>
</tr>
<tr>
<td>Image Distortion (Diagonal Field of View)</td>
<td>≤2%</td>
</tr>
<tr>
<td>Modulation Transfer Function</td>
<td>≥0.2 (104 lp/mm)</td>
</tr>
<tr>
<td>Operating Temperature (°C)</td>
<td>−45 to 60</td>
</tr>
<tr>
<td>Back Focal Length (mm)</td>
<td>≥20</td>
</tr>
<tr>
<td>Outline Dimension (mm)</td>
<td>≤192 (L) × 170 (W) × 112 (H)</td>
</tr>
</tbody>
</table>

According to the given pixel size of the detector, the number of pixels, and the field of view of the system, the focal length of the optical system can be calculated by Eq. (7),

$$ f' = \frac{d}{\left[2 \tan(\omega / 2)\right]}, $$

where $\omega$ is the full field of view of the optical system, $d$ is the CMOS detector size, and $f'$ is the focal length of the optical system. It can be found that the long focus $f'_l$ is 176 mm and the short focus $f'_s$ is 88 mm.

The resolution of the imaging optical system is determined by the angular-resolution formula for the optical system, and the diffraction of the Airy spot by the optical system limits the angular resolution of the optical system. The Airy-spot radius of the optical system is given by

$$ R_{\text{Airy}} = 1.22 \lambda F, $$

where $R_{\text{Airy}}$ is the Airy-spot radius, $\lambda$ is the central wavelength of the system, and $F$ is the F-number of the system.

To improve the energy-utilization rate of the system, the Airy spot should be located within two pixel lengths of the detector, and then the visible-light system $F \leq 9.46$ and the near-infrared system $F \leq 6.55$ values are obtained. Theoretically, if the F-number is reduced, then the light-transmission capability and imaging quality of the system can be improved. However, if the F-number is reduced, the design and processing difficulty of the optical system will correspondingly increase. Considering various factors, the F-number for the optical system is finally selected to be 4.

3.2. Design Result

Under the premise of ensuring the optical performance and high image quality of the system, the two-step zoom optical-despun system in this paper realizes high-definition observation under image rotation, and parfocusing through fog. To keep its structure simple, the optical system adopts the $(+−+)$ optical focal structure. According to the above indices, the initial structure of the system is determined. After repeated adjustment and optimization, the final optical-system structure is obtained, as shown in Fig. 4.

The optical system in this study consists of a front fixed group, a zoom group, a post-fixed front group, a despun-prism group, a post-fixed back group, and a filter. Among them, the front fixed group is the positive-focal-length group, with a focal length of 262 mm, using single-and-double structure. The single lens is a high-refractive-index
lens, which mainly bears the focus of the front fixed group, and the double glued lens is mainly used to correct the chromatic aberration of the front fixed group. The zoom group is a negative-focal-length group with a focal length of −67 mm, which is composed of two lenses; Its main function is to change the magnification of the system, that is, to change the total focal length of the optical system to achieve a change in focal length. The two-step zoom positions designed in this paper are shown in Table 2. The lead of the visible-light system is 47.452 mm, and the lead of the near-infrared system is 47.898 mm. The function of the post-fixed group is to lengthen or shorten the image distance and compensate the aberration; It is a positive-focal-length group with a focal length of 98 mm. The relative aperture and light aperture of the post-fixed group are small, and the aberration in the group is easy to correct. The despun-prism group is placed between the post-fixed front group and the post-fixed back group; Its function is to eliminate image rotation. The setting principle of the racemic prism group is to minimize the light aperture of the prism, thus reducing the rotational resistance and moment of inertia, so that the movement of the prism group is flexible and easy to control. The filter is located between the rear fixed group and the image plane; Its main function is to realize high-definition observation and fog-transmittance observation. To improve interchangeability, the mode switch is performed by using a filter of equal thickness.

There are eight lenses in the system. The first seven have ordinary spherical surfaces, all of which use Chengdu Guangming glass, and the last one has a binary surface made of plastic APL5514ML. The maximum aperture is 60 mm, and the F-number remains constant at 4 for both focal lengths. The overall weight of the lens is only 138.5 g without the despun prism, and 170.8 g with the despun prism. The overall dimensions are 168 mm × 90 mm × 60 mm, which meet the requirements of a light and small design.

### TABLE 2. Zoom positions of the two-step zoom optical system

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>Front Fixed Group to Zoom Group</th>
<th>Zoom Group to Post-fixed Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible-light Long Focus</td>
<td>54.877</td>
<td>4.478</td>
</tr>
<tr>
<td>Visible-light Short Focus</td>
<td>7.426</td>
<td>51.929</td>
</tr>
<tr>
<td>Near-infrared Long Focus</td>
<td>54.960</td>
<td>4.395</td>
</tr>
<tr>
<td>Near-infrared Short Focus</td>
<td>7.062</td>
<td>52.293</td>
</tr>
</tbody>
</table>

To reduce the chromatic aberration of the system, the binary diffraction surface is used as the last surface of the system, which can also simplify the system’s structure and reduce the weight. The parameters of the binary diffractive optical surface are shown in Table 3. Considering the processing cost and difficulty, only two terms are selected for the phase-distribution function of the binary diffractive optical surface. Figure 5 shows the characteristic parameter curve of the binary diffraction surface. It can be seen that the maximum number of zones of the binary diffraction surface is 8, and the line frequency reaches the maximum at the edge of the lens, which is 2.07 periods/mm. The minimum periodic linewidth is 0.519 mm, and the maximum band depth is 1.03 µm. When eight steps are etched every period, the diffraction efficiency can reach 95%, and the corresponding minimum feature size is 0.065 mm. This can be accomplished using existing processing technology [16–18].

### TABLE 3. Parameters of the binary diffraction surface

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>APL5514ML</td>
</tr>
<tr>
<td>Conic</td>
<td>2.543</td>
</tr>
<tr>
<td>Diffract Order</td>
<td>1</td>
</tr>
<tr>
<td>Norm Radius (mm)</td>
<td>8.533</td>
</tr>
<tr>
<td>Maximum Term</td>
<td>2</td>
</tr>
<tr>
<td>Quadratic Coefficient</td>
<td>−53.390</td>
</tr>
<tr>
<td>Quartic Coefficient</td>
<td>−1.262</td>
</tr>
</tbody>
</table>

### FIG. 5. Characteristic parameter curve of the binary diffraction surface.

#### 3.3. Image Quality Analysis

The modulation transfer function (MTF) and distortion meshes can generally and comprehensively reflect the imaging quality of an optical system.

In the optical design, the modulation transfer function is only investigated at the Nyquist frequency, which for the optical system in this paper is 104 mm. The MTF of the system, obtained using optical design software, is shown in Fig. 6. It can be found that the MTF of the visible-light system is greater than 0.44, and that of the near-infrared optical system is greater than 0.30. The MTF of each band and field of view all meet the design requirements.

The final distortion of this optical system is shown in
FIG. 6. Modulation transfer function (MTF) of the final optical system: (a) Visible-light long-focus MTF, (b) visible-light short-focus MTF, (c) near-infrared long-focus MTF, and (d) near-infrared short-focus MTF.
3.4. Athermal Design

The materials of the barrel of the despun optical system are all aluminum alloys. When the optical mechanical structure changes at uniform temperature, the expansion coefficient of its material is linear within the range of temperature change. Table 4 shows the changes of the image quality of the optical system caused by the critical temperatures of −45 °C and 60 °C respectively. It can be seen from the figures that the image quality of the short focus meets the design requirements, but the image quality of the long focus does not meet the design requirements after the temperature changes, so it is necessary to carry out athermal design on the long focus.

Typical athermal design methods include electronically active, mechanically passive, and optically passive [19–20]. Considering the system volume and the difficulty of realizing the compensation method, this study adopts the electromechanical active compensation method for the system’s athermal design. Here the axial movement of the zoom group is used to ensure that the thermal defocus caused by

**TABLE 4.** Effects of −45 °C and 60 °C temperatures on image quality

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>−45</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible-light Long-focus MTF</td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
</tr>
<tr>
<td>Visible-light Short-focus MTF</td>
<td><img src="image3" alt="Graph" /></td>
<td><img src="image4" alt="Graph" /></td>
</tr>
<tr>
<td>Near-infrared Long-focus MTF</td>
<td><img src="image5" alt="Graph" /></td>
<td><img src="image6" alt="Graph" /></td>
</tr>
<tr>
<td>Near-infrared Short-focus MTF</td>
<td><img src="image7" alt="Graph" /></td>
<td><img src="image8" alt="Graph" /></td>
</tr>
</tbody>
</table>

**FIG. 7.** Distortion in the final optical system: (a) Visible-light long-focus distortion, (b) visible-light short-focus distortion, (c) near-infrared long-focus distortion, and (d) near-infrared short-focus distortion.
temperature is within the focal depth of the system. According to Rayleigh’s principle, the defocusing of the image plane caused by temperature change has the following relationship with the defocusing of the system:

\[
\Delta L \leq \pm 2 \times \lambda_{D} \times (f / D)^{2},
\]

(9)

where \(\lambda_{D}\) is the central wavelength in the working band, and \(f / D\) is the F-number of the system.

By substituting the central wavelength into Eq. (9), the focal depth of the visible and near-infrared optical systems can be obtained as 18.82 \(\mu\)m and 27.20 \(\mu\)m respectively. In this study the amount of movement of the zoom group and the amount of defocus of the optical system, in different states under system athermalization, are shown in Table 5, where “+” means the zoom group is close to the detector and “−” means away from the detector. It can be seen that the defocus of the system is far less than the depth of focus after the zoom group moves slightly left or right, which meets the system design requirements. After athermal design, the MTF of the optical system at −45 °C and 60 °C is shown in Table 6. It can be seen that the optical system has a good transfer-function distribution at the spatial frequency of 104 lp/mm.

### 3.5. Tolerance Analysis

In this study the specific tolerance requirements for the system surface are as follows: material refractive-index tolerance is ±0.003, Abbe number tolerance is ±0.3%, aperture number is 3, surface irregularity is 0.5, thickness tolerance is ±0.05 mm, lens-surface tilt tolerance is ±0.025°, lens-surface eccentricity tolerance is ±0.02 mm, element tilt tolerance is ±0.025°, and element eccentricity tolerance is ±0.02 mm.

After the tolerance distribution, the system is analyzed 200 times by a Monte Carlo method with MTF as the evaluation standard. After tolerance analysis, it is found that the

### TABLE 5. Zoom-group movement and optical-system defocus

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Visible-light Long-focus Movement</th>
<th>Near-infrared Long-focus Movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>−45 −0.245 mm −0.318 mm</td>
<td>60 0.231 mm 0.316 mm</td>
</tr>
<tr>
<td>Norm Radius (μm)</td>
<td>0.328</td>
<td>0.103</td>
</tr>
</tbody>
</table>

### TABLE 6. System MTF after athermal design

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Visible-light Long-focus MTF (@104 lp/mm)</th>
<th>Near-infrared Long-focus MTF (@104 lp/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>−45</td>
<td>0.37862342</td>
<td>0.28171511</td>
</tr>
<tr>
<td>60</td>
<td>0.41205376</td>
<td>0.34035715</td>
</tr>
</tbody>
</table>

### TABLE 7. Monte Carlo analysis results

<table>
<thead>
<tr>
<th>Imaging Area (%)</th>
<th>Visible-light Long-focus MTF (@104 lp/mm)</th>
<th>Visible-light Short-focus MTF (@104 lp/mm)</th>
<th>Near-infrared Long-focus MTF (@104 lp/mm)</th>
<th>Near-infrared Short-focus MTF (@104 lp/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>&gt;0.21586483</td>
<td>&gt;0.23040002</td>
<td>&gt;0.21209727</td>
<td>&gt;0.26177946</td>
</tr>
<tr>
<td>80</td>
<td>&gt;0.25699244</td>
<td>&gt;0.28588088</td>
<td>&gt;0.23670890</td>
<td>&gt;0.28657516</td>
</tr>
<tr>
<td>50</td>
<td>&gt;0.31779350</td>
<td>&gt;0.35781398</td>
<td>&gt;0.28171511</td>
<td>&gt;0.31567254</td>
</tr>
<tr>
<td>20</td>
<td>&gt;0.37862342</td>
<td>&gt;0.41205376</td>
<td>&gt;0.33988578</td>
<td>&gt;0.34035715</td>
</tr>
<tr>
<td>10</td>
<td>&gt;0.40152920</td>
<td>&gt;0.44190531</td>
<td>&gt;0.37261527</td>
<td>&gt;0.35092632</td>
</tr>
</tbody>
</table>
MTF at the edge of the field of view is the worst; the MTF at the edge is shown in Table 7. The MTF of the optical system under the four structures has a 90% probability of being greater than 0.21, which shows that the optical system in this paper has good practical processability.

IV. CONCLUSION

In this study, a light and small dual-band airborne despun optical system was designed. The visible and near-infrared bands were selected to deal with various environments, the movable two-step zoom form was selected to realize large-field-of-view search and small-field-of-view calibration, and a Pechan prism was selected to design the system for despun. At the Nyquist frequency of 104 lp/mm, the modulation transfer function’s value for visible light was greater than 0.44, for the near-infrared greater than 0.3, and the distortion was less than 1.36%. All kinds of aberrations were well corrected and balanced. The optical system realized the integration of dual visible-light and near-infrared bands with a common aperture and confocal plane, and optical passive semiathermalization over a wide temperature range with a common aperture and confocal plane, and optical passive semiathermalization over a wide temperature range.

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DISCLOSURES

The authors declare no conflicts of interest.

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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