

Design of an infrared zoom lens for optoelectronic systems used in area defense surveillance

Tong Minh Hoa, Thai Hoai Son*

Institute of Defense Equipment, Academy of Military Science and Technology, 17 Hoang Sam, Nghia Do, Hanoi, Vietnam.

*Corresponding author: thaihoaisonmta@gmail.com

Received 14 May 2026; Revised 15 Jul. 2026; Accepted 15 Sep. 2026; Published 15 Oct. 2026.

DOI: <https://doi.org/10.54939/1859-1043.j.mst.114.2026.142-150>

ABSTRACT

This research presents the design of infrared objective zoom lens for the thermal imaging channel integrated into optoelectronic systems used for defensive area surveillance. The system is required to operate effectively under both day and night conditions, while ensuring both wide-area observation and long-range target recognition. The study focuses on the selection of suitable optical materials, the development of the optical configuration, aberration correction, and system performance evaluation through criteria such as modulation transfer function (MTF), relative illumination, spherical aberration and field curvature, distortion. The results show that the proposed optical system with a focal length range of 31–155 mm and a corresponding aperture from F/1.0 to F/1.6 meets image quality requirements across the entire focal length range. This research contributes to mastering the design methodology of infrared zoom lenses and provides a practical foundation for the development of optoelectronic systems for defense applications.

Keywords: Thermal imaging; Infrared camera; Zoom lens; Optoelectronic system; LWIR; NETD; MTF.

1. INTRODUCTION

In recent years, the rapid development of unmanned aerial vehicles (UAVs) has posed significant challenges to surveillance and monitoring systems. Due to their small size, low radar cross section, and high maneuverability, these targets are difficult to detect using conventional observation methods, especially under low-light conditions or in complex environments. Therefore, multi-channel optoelectronic systems, including thermal imaging channels, have become an effective solution to enhance target detection and tracking capabilities [1].

Thermal imaging operates based on the detection of infrared radiation emitted by objects, enabling continuous operation under all lighting conditions while minimizing the effects of interference factors such as glare, fog or optical camouflage. In such systems, the overall performance of the thermal imaging channel mainly depends on the infrared detector and the objective lens system. Among these, the infrared objective lens plays a decisive role in radiation energy collection, image quality and the effective observation range of the system [2].

For defensive area surveillance tasks, the optical system must simultaneously satisfy two conflicting requirements: a wide field of view for general observation and a long focal length for long-range target detection [3]. These conflicting requirements necessitate the development of variable focal length (zoom) infrared objective lenses. However, designing zoom lenses operating in the long-wave infrared (LWIR, 8 - 14 μm) spectral range remains challenging because of the limited availability of optical materials, severe optical aberrations, and the stringent sensitivity requirements of uncooled infrared detectors. Therefore, the selection of optical materials, optimization of the optical configuration, and effective aberration correction are essential to achieve high imaging performance [4].

In this research, the authors present a design methodology for a variable focal length infrared objective lens used in electro-optical systems for defensive area surveillance. Based on the defined

input parameters, the optical system is designed with a focal length range of 31–155 mm, an aperture of F/1.0–F/1.6, and operation in the LWIR spectral range. The study focuses on the selection of optical materials, development of the optical configuration, design optimization, and performance evaluation using criteria such as MTF, relative illumination, spherical aberration, field curvature and distortion. The proposed design methodology provides a practical basis for the development and domestic manufacture of high-performance infrared zoom lenses for defense applications.

2. DESIGN BASIS

The objective of this study is to design an optical system for a thermal imaging objective lens used in an optoelectronic system for defensive area surveillance. The system is required to achieve a maximum observation range of no less than 4 km for a vehicle-sized target with dimensions of $2.3 \text{ m} \times 2.3 \text{ m}$. To satisfy these requirements, the optical system parameters, including focal length, F-number and field of view, were determined based on the selected infrared detector and imaging requirements. The parameters of selected detector (FLIR Boson Plus): Spectral band from $8 \text{ } \mu\text{m}$ to $14 \text{ } \mu\text{m}$, Pixel size - $12 \text{ } \mu\text{m}$, Sensitivity (NETD) $\leq 30 \text{ mK}$ and Resolution - 640×512 [5].

2.1. Determination of focal length

For an optical system with a given focal length f' , the imaging geometry of a target with size H located at a distance D is illustrated in Figure 1.

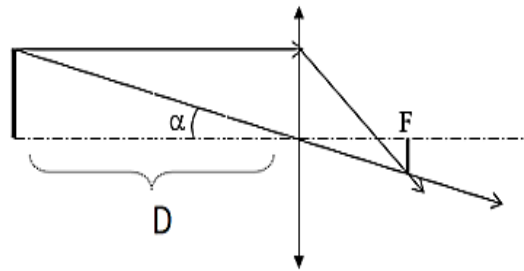


Figure 1. Imaging diagram of the optical system.

The observation distance D is determined by the following equation [6]:

$$D = \frac{H}{\tan \alpha} \approx \frac{H}{(h / f')} \quad (1)$$

where h is the image height on the detector plane, the focal length can be derived as follows:

$$f' \approx \frac{D \cdot h}{H} \quad (2)$$

To observe a target at distance D , at the target recognition range D_{rec} according to the Johnson criteria, the required image height must satisfy: $h \geq 8 \cdot a$, where a is the pixel size.

$$f' \geq \frac{D \cdot 8a}{H} \quad (3)$$

To meet the requirement of increasing the field of view for observation and target scanning in different operation, the research team selected a zoom lens design with a $5\times$ optical zoom ratio.

Accordingly, the minimum and maximum focal lengths of the lens are related as follows:

$$f'_{\min} = \frac{f'_{\max}}{5} \quad (4)$$

Thus, the maximum focal length required for the design is $f'_{\max} \geq 147.6 \text{ mm}$. The research team selected $f'_{\max} = 155 \text{ mm}$, which leads to a minimum focal length of $f'_{\min} = 31 \text{ mm}$.

2.2. Determination of the F-number

The F-number ($F\#$) of an infrared lens is defined as the ratio between the focal length f' and the effective entrance pupil diameter D of the optical system, given by $F\# = f'/D$. This parameter characterizes the ability of the lens to collect infrared radiation. A smaller F-number allows more infrared radiation to reach the sensor, thereby improving the thermal sensitivity (NETD) of the thermal imaging system. $NETD_{kn}$ of the thermal imaging channel depends on the $NETD_{dt}$ of the detector and the F-number according to the following relationship [6]:

$$NETD_{kn} = \left(\frac{1}{F\#} \right)^2 \cdot NETD_{dt} \quad (5)$$

In current thermal imaging camera systems, the objective lens is typically designed with an F-number in the range of $F/1.0$ to $F/1.6$ to ensure efficient collection of infrared radiation, in addition, the NETD is usually within the range of 30 mK to 100 mK. For the selected detector, FLIR Boson Plus, with $NETD_{dt} \leq 30$ mK, if the required system NETD lies between 30 mK and no more than 80 mK, then the F-number should satisfy the condition $F\# = 1.0$ to $F\# \leq 1.63$.

From a theoretical perspective, a smaller F-number is more favorable for improving system sensitivity. However, a smaller F-number implies a larger aperture diameter, which leads to increased size, weight and cost of the optical system. Therefore, selecting ($F\# = 1.0$) at a focal length of 31 mm and ($F\# = 1.6$) at a focal length of 155 mm is a reasonable and practical choice for a zoom infrared objective lens using an uncooled detector in this study.

2.3. Determination of the field of view

Figure 2 illustrates the imaging diagram of the objective lens O with a field of view 2ω .

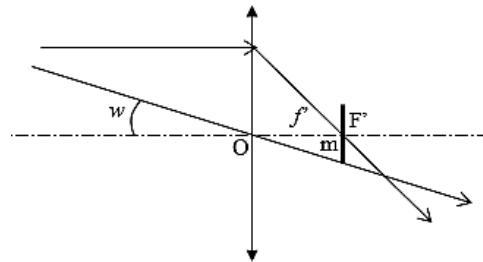


Figure 2. Imaging diagram of the optical system for a target at infinity.

Accordingly, the field of view of the lens is determined by the following equation [7]:

$$\tan w = \frac{m}{f'} \quad (6)$$

where, m is the height of half of the image, which depends on the detector array size.

$$m_x = \frac{X}{2} \cdot a, \quad m_y = \frac{Y}{2} \cdot a \quad (7)$$

where X and Y are the horizontal and vertical dimensions of the detector, respectively; m_x and m_y are the maximum half-image heights in the horizontal and vertical directions.

Accordingly, the horizontal and vertical fields of view can be calculated as follows:

$$\begin{aligned} 2w_{x\max} &= 2 \cdot \arctan\left(\frac{m_x}{f'_{\min}}\right), \quad 2w_{y\max} = 2 \cdot \arctan\left(\frac{m_y}{f'_{\min}}\right) \\ 2w_{x\min} &= 2 \cdot \arctan\left(\frac{m_x}{f'_{\max}}\right), \quad 2w_{y\min} = 2 \cdot \arctan\left(\frac{m_y}{f'_{\max}}\right) \end{aligned} \quad (8)$$

By applying the parameters of the FLIR Boson Plus detector, the calculated results show that the maximum field of view is $14,13^\circ \times 11,32^\circ$; while the minimum field of view is $2,84^\circ \times 2,27^\circ$.

3. DESIGN OF THE INFRARED ZOOM LENS AND PERFORMANCE EVALUATION

3.1. Optical system design

In designing an optical objective lens for any observation system, the first aspect to consider is the selection of suitable optical materials. For thermal imaging channels operating in the mid-wave infrared (MWIR, 3–5 μm) and long-wave infrared (LWIR, 8–14 μm) spectral ranges, there are various material options available for optical design. These materials can be broadly classified into several groups, including natural and synthetic crystals, infrared ceramics and glasses, as well as certain infrared polymer materials. However, practical experience in infrared lens design shows that the most commonly used materials are Germanium (Ge, with $n_0 = 4.00243$) and Zinc Selenide (ZnSe, with $n_0 = 2.42350$). The use of these materials helps reduce the size of the optical system, effectively compensate for aberrations, improve infrared transmission and enhance thermo-mechanical stability.

Due to the high density of crystalline materials used in infrared lenses, the overall weight of the lens assembly is relatively large. To reduce the weight of the optical system, the authors employ aspherical surfaces to decrease the number of lens elements, this is also a current and emerging trend in the design and manufacturing of optoelectronic systems [8].

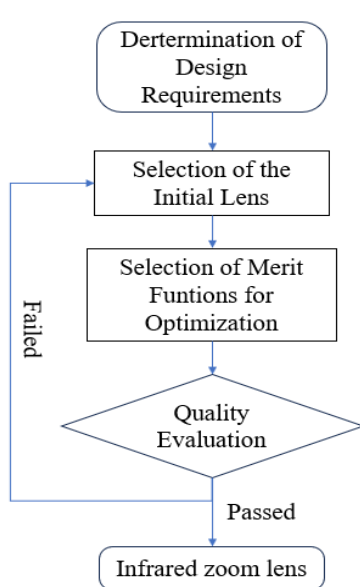


Figure 3. Design process of the infrared zoom lens.

The design process is carried out through the following basic steps in Figure 3. Based on the evaluation of whether the performance criteria meet the specified requirements, the merit function, geometrical parameters, and lens materials are adjusted until the desired performance is achieved. The final outcome of the optimization process is to reach a global optimum, ensuring that the system delivers the best possible performance in accordance with the design requirements.

Multi-Configuration Optimization was employed in this study and implemented using Zemax OpticStudio through the Multi-Configuration design mode. The optical system was defined at four target effective focal lengths (EFFLs): 31 mm, 90 mm, and 155 mm. Simultaneous optimization of these configurations enabled effective control of the trade-off between geometric aberrations and image contrast, as characterized by the modulation transfer function, throughout the entire zoom range. To ensure manufacturability and assembly feasibility, several stringent engineering constraints were imposed, including:

Geometrical constraints: The aperture stop position was fixed throughout the zooming process to simplify the mechanical compensation mechanism and maintain optical axis stability. The image plane location and detector dimensions were also kept constant to match the specifications of the 12- μm infrared sensor.

Merit function: The merit function was constructed by combining multiple Zemax operands to constrain the effective focal length (EFFL), optical element thicknesses (GLCZ), and lens clear apertures (MNCA/MXCA). Furthermore, image quality was optimized using the MTFT (Modulation Transfer Function) operand to ensure that the MTF reached the target value at the cutoff spatial frequency, while simultaneously minimizing the root mean square (RMS) spot radius under different field-of-view conditions.

Table 1. Optical parameters of the infrared zoom lens at $f' = 31$ mm.

Lens	Surface	Radius, mm	Thickness, mm	Material	Semi-diameter, mm
	OBJ	Infinity	Infinity		Infinity
1	1	199.472	13.600	Ge	63
	2	398.682	30.000		61
2	3	-205.435	5.500	Ge	25
	4	-2907.34	67.982		24
3	5	119.189	5.700	Ge	30
	6	68.471	7.218		29
4	7	-70.4293	5.000	ZnSe	28
	8	53.9	42.446		29
5	9	35.603	6.000	Ge	16
	10	121.242	16.554		15
	IMA	Infinity	-		0

For an infrared zoom lens using crystalline materials, the optical system typically consists of 5 to 6 lens elements with different sizes. Therefore, the initial optical configuration is chosen as a 5-element spherical lens system. During the optimization process, the number of aspherical surfaces is gradually increased until the optical system meets the required performance criteria. With current domestic manufacturing capabilities, high-precision fabrication of aspherical surfaces is achievable, ensuring the overall quality of the designed optical system. The design results obtained using Zemax software are for a 5-element aspherical lens system.

The optical parameters at a focal length of $f' = 31$ mm are presented in Table 1.

The aspheric surface parameters of the lens elements are summarized in Table 2.

Table 2. Aspheric surface parameters.

Surface	a_2	a_4	a_6	a_8	K
2	2.052×10^{-4}	9.317×10^{-10}	-3.226×10^{-14}	-3.115×10^{-17}	0
4	2.421×10^{-3}	-4.324×10^{-8}	-2.348×10^{-10}	2.466×10^{-13}	-0.818
6	-6.905×10^{-3}	-2.754×10^{-7}	4.34×10^{-11}	-6.518×10^{-14}	0
8	-15.00×10^{-3}	-1.322×10^{-6}	-2.78×10^{-10}	5.614×10^{-14}	0
10	9.18×10^{-3}	2.732×10^{-6}	6.518×10^{-9}	-1.127×10^{-11}	0

The design simulation of the optical system is shown in Figure 4:

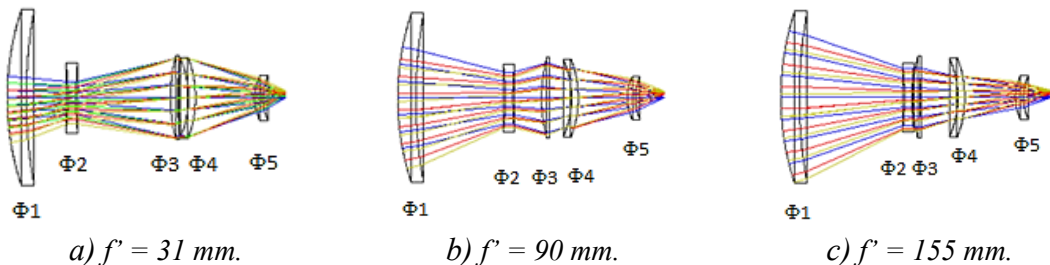


Figure 4. Optical layout of the infrared zoom lens.

3.2. Thermal compensation and tolerance analysis

Thermal infrared objective lenses based on Germanium typically exhibit a relatively large temperature dependence of the refractive index (dn/dT). Consequently, thermal compensation is essential to maintain stable imaging performance over a wide ambient temperature range. In practice, passive athermalization alone may not be sufficient to preserve a stable modulation

transfer function under large temperature variations [9]. Therefore, an active athermalization approach is proposed in this study.

During the optical design process, the existing focus group (lens- $\Phi 5$) is utilized to implement active thermal compensation for the entire objective lens. Instead of introducing an additional dedicated compensating lens or employing specialized athermal optical materials, the proposed approach relies on software control and a motorized focusing mechanism to compensate for temperature-induced changes in focal position and MTF. The specific principle of this mechanism is that the temperature sensor determines the internal temperature of the objective lens, and the signal is transmitted to the central processor. Based on this, the control software calculates the displacement and commands the motor to shift the focusing lens - $\Phi 5$ along the optical axis. This active athermalization strategy continuously maintains the focal plane in precise alignment with the detector surface, thereby preserving near-diffraction-limited image quality across the specified operating temperature range.

The presence of manufacturing and assembly errors in an optical system inevitably introduces additional aberrations, thereby degrading image quality. Therefore, tolerance analysis is a critical step in the optical design process to ensure that the fabricated and assembled system satisfies the required performance specifications [10]. In this study, manufacturing and assembly tolerances were evaluated using the Monte Carlo tolerance analysis implemented in Zemax OpticStudio. The Monte Carlo simulations were performed at two representative zoom positions corresponding to $f_1 = 31$ mm and $f_2 = 155$ mm. The tolerance allocation procedure consisted of the following steps:

Step 1: Identifying the tolerances that have the greatest impact on the optical performance of the objective lens;

Step 2: Assigning initial tolerance values and performing Monte Carlo simulations;

Step 3: Iteratively tightening or relaxing the tolerance limits until 90% of the simulated samples satisfied the specified image-quality criteria.

The resulting manufacturing and assembly tolerance values determined using this procedure are summarized in Table 3.

Table 3. Principal manufacturing and assembly tolerances of the objective lens system.

No.	Parameter	Value			
1	Surface radius tolerance of optical elements ($\lambda = 4,2 \mu\text{m}$)	1 int. fringe	1.4 int. fringe	1.75 int. fringe	2 int. fringe
2	Lens center thickness tolerance, mm	± 0.05	± 0.06	± 0.07	± 0.08
3	Lens spacing tolerance, mm	± 0.05	± 0.06	± 0.07	± 0.07
4	Decentration tolerance of lens curved surfaces, mm	± 0.015	± 0.03	± 0.04	± 0.07
5	Lens decentration tolerance during mechanical assembly, mm	± 0.05	± 0.06	± 0.07	± 0.07
6	Lens tilt tolerance, arcmin	± 0.9	± 2	± 3	± 4
The percentage of samples meeting quality criteria, %		98	90	80	50

The tolerance values obtained from the Monte Carlo simulations are all within the range achievable by current optical manufacturing and assembly standards, demonstrating the practical feasibility of the proposed optical design.

3.3. Quality evaluation

The image quality performance of thermal imaging optical systems using uncooled detectors is typically evaluated by major manufacturers worldwide based on two key parameters: the modulation transfer function and relative illumination. The minimum average MTF values have been published by Ophir (USA), a leading company specializing in the design and manufacturing of thermal imaging optics, as shown in Table 4 [11]:

Table 4. MTF performance criteria for infrared zoom lens.

Pixel size, μm	Spatial frequency, mm^{-1}	Minimum MTF
50	10	0.40
25	20	0.35
12	41.7	0.17 or not less than 50% of the diffraction-limited value

The MTF performance results of the designed optical system in this study are presented in Figures 5a. At a focal length of $f' = 31 \text{ mm}$ and spatial frequency of 41.7 mm^{-1} , the MTF value is no less than 0.3 across the entire field of view. At $f' = 155 \text{ mm}$ when the diffraction-limited MTF value is 0.21 the achieved MTF is no less than 0.12 over the full field. Compared with the required MTF values at 41.7 mm^{-1} given in Table 4 (for a detector with $12 \mu\text{m}$ pixel size), the designed optical system meets the specified MTF performance criteria.

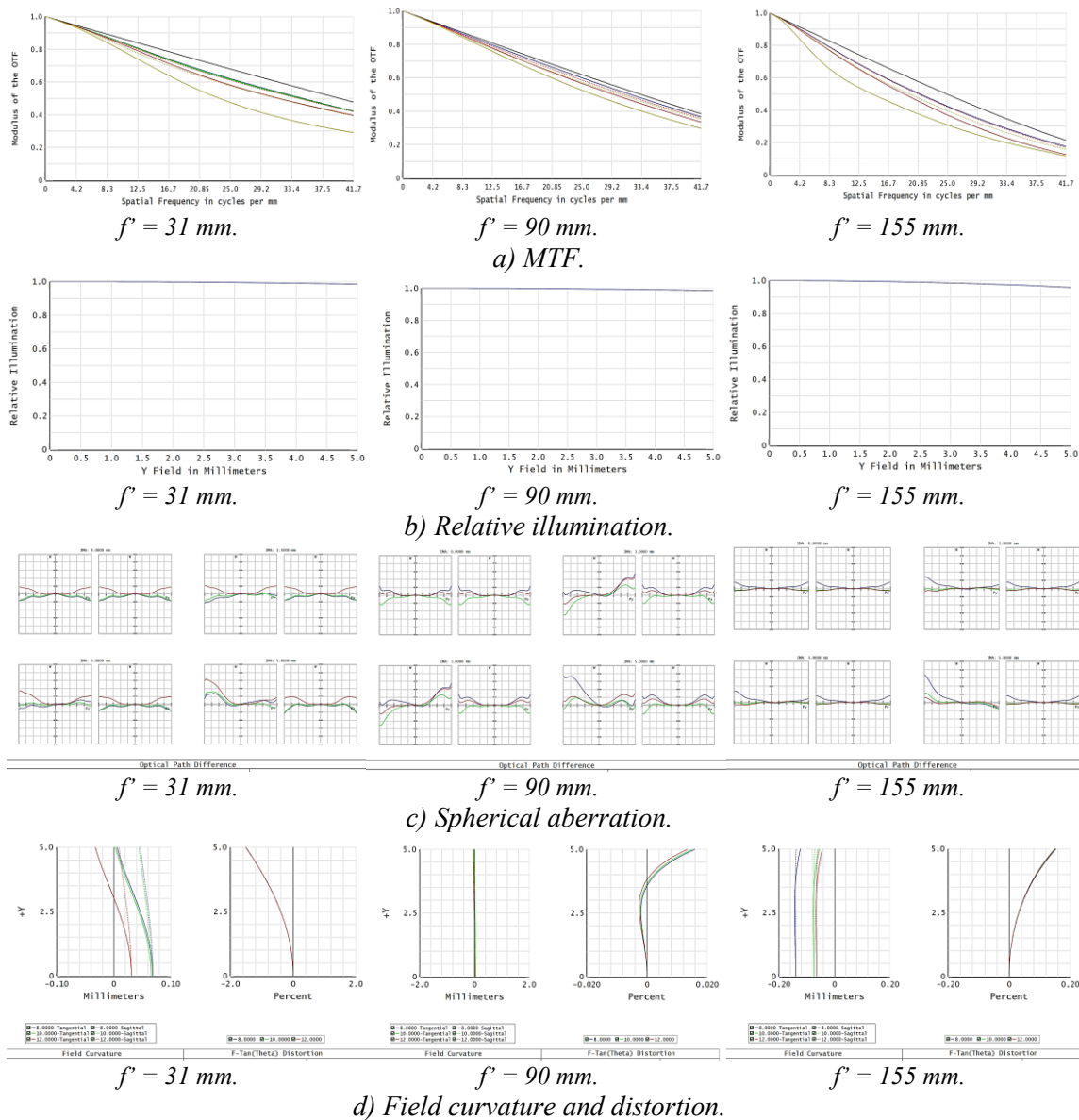


Figure 1. Quality evaluation results of the designed infrared zoom lens.

Based on practical design and manufacturing experience, to ensure uniform brightness across the image, the relative illumination should not be less than 70% along the horizontal edge of the detector field and not less than 60% along the diagonal. As shown in Figures 5b, the relative illumination exceeds 90% across the entire field of view at all evaluated focal lengths. Therefore, the designed optical system satisfies the required criteria for relative illumination.

In addition, evaluation of other optical performance parameters shows that spherical aberration is less than 1λ – Figures 5c; distortion is less than 1.8% at the wide field of view and less than 0.12% at the narrow field; and field curvature is less than 0.2 mm across the entire field at all focal lengths – Figures 5d.

Overall, based on the above analyses and evaluations, the designed infrared zoom lens fully meets the required image quality performance criteria.

4. CONCLUSIONS

This research has presented a design methodology for an infrared zoom lens used in optoelectronic systems for defensive area surveillance. Based on the selection of an uncooled infrared detector with a resolution of 640×512 and a pixel size of $12\ \mu\text{m}$, the optical system was designed with a focal length range of 31–155 mm and an aperture from F/1.0 to F/1.6, meeting the requirements for multi-mode observation from wide field of view to long-range surveillance.

The design results demonstrate that the optical system satisfies image quality criteria across the entire focal length range, with the modulation transfer function meeting the required standards, well-distributed relative illumination, and effectively controlled aberrations.

This research contributes to mastering the design process of infrared zoom lenses in the LWIR spectral range, from material selection and optical configuration development to performance evaluation. It provides an important foundation for the development and manufacturing of domestic optoelectronic systems, effectively supporting national defense and security missions.

In future work, further optimization is needed to reduce system size and weight, enhance passive thermal compensation capability, and integrate advanced image processing algorithms to improve target detection and recognition performance under complex conditions.

REFERENCES

- [1]. R. G. Driggers, M. J. Vollmerhausen and J. A. Robinson, “*Introduction to Infrared and Electro-Optical Systems*”, 2nd ed., Artech House, Norwood, MA, USA, (2012).
- [2]. A. Rogalski, “*Infrared detectors: Status and trends*”, Progress in Quantum Electronics, Vol. 27, No. 2–3, pp. 59–210, (2003).
- [3]. K. Mowafy, T. El-Dessouky and M. Medhat, “*Design of IR zoom lens system for long-range detection in uncooled LWIR camera*”, Journal of Optics, Vol. 52, No. 5, pp. 1–9, (2022).
- [4]. A. Rogalski, “*Infrared Detectors*”, 2nd ed., CRC Press, Boca Raton, FL, USA, (2010).
- [5]. FLIR Systems, “*Boson Thermal Camera Core Datasheet*”, Teledyne FLIR LLC, USA, (2021).
- [6]. A. Grammatin, “*Методы синтеза оптических систем*”, ITMO, (2002). (in Russian)
- [7]. M. C. Dudzik, “*The Infrared and Electro-Optical Systems Handbook*”, Vol. 4: Electro-Optical Systems Design, Analysis and Testing, (1993).
- [8]. ZEMAX Optical Design Program, “*Users Guide ZEMAX Development Corporation*”, (2009).
- [9]. L. V. Nhu, “*Compensation of temperature effects on imaging quality of thermal imaging objectives using deep learning techniques*”, Journal of Military Science and Technology, No. 99, pp. 89–98, (2024).
- [10]. L. V. Nam, “*A method of calculating spectral characteristics applied to optimize the thermal imaging system design*”, Journal of Military Science and Technology, No. 101, pp. 124–130, (2025).
- [11]. Ophir Optonics Solutions Ltd., “*Lens performance criteria for uncooled thermal imaging systems*”, Technical Report, Israel, (2019).

TÓM TẮT

Thiết kế vật kính ảnh nhiệt có tiêu cự thay đổi cho tổ hợp quang điện tử phục vụ cảnh giới khu vực phòng thủ

Bài báo trình bày việc thiết kế vật kính ảnh nhiệt có tiêu cự thay đổi cho kênh ảnh nhiệt tích hợp trong các tổ hợp quang điện tử phục vụ cảnh giới khu vực phòng thủ. Hệ thống được yêu cầu hoạt động hiệu quả trong cả điều kiện ngày và đêm, đồng thời đảm bảo vừa quan sát diện rộng vừa nhận dạng mục tiêu ở khoảng cách xa. Nội dung nghiên cứu tập trung vào lựa chọn vật liệu quang học phù hợp, xây dựng cấu hình hệ quang, hiệu chỉnh quang sai và đánh giá chất lượng hệ thống thông qua các tiêu chí như hàm truyền điều biến (MTF), độ rọi tương đối, cầu sai và độ cong trường, méo ảnh. Kết quả cho thấy hệ quang đề xuất với dải tiêu cự 31–155 mm và khẩu độ tương ứng từ F/1.0 đến F/1.6 đáp ứng các yêu cầu về chất lượng ảnh trong toàn dải tiêu cự. Nghiên cứu góp phần làm chủ phương pháp thiết kế vật kính ảnh nhiệt có tiêu cự thay đổi và là cơ sở thực tiễn cho việc phát triển các hệ thống quang điện tử phục vụ quốc phòng trong nước.

Từ khóa: Ảnh nhiệt; Camera hồng ngoại; Vật kính zoom; Hệ quang điện tử; LWIR; NETD; MTF.