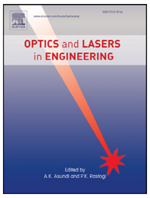
Optics and Lasers in Engineering 106 (2018) 1–9

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng



Deformable mirror-based optical design of dynamic local athermal longwave infrared optical systems

Benlan Shen, Jun Chang*, Yajun Niu, Weilin Chen, Zhongye Ji

School of Optoelectronics, Beijing Institute of Technology, Beijing 100081, China

A R T I C L E I N F O

Keywords:
Local athermalisation
LWIR optical system
Deformable mirror
Thermal aberrations

A B S T R A C T

This paper presents a dynamic local athermalisation method for longwave infrared (LWIR) optical systems; the proposed design uses a deformable mirror and is based on active optics theory. A local athermal LWIR optical system is designed as an example. The deformable mirror is tilted by 45° near the exit pupil of the system. The thermal aberrations are corrected by the deformable mirror for the local athermal field of view (FOV) that ranges from −40 °C to 80 °C. The types of thermal aberrations are analysed. Simulated results show that the local athermal LWIR optical system can effectively detect targets in the region of interest within a large FOV and correct thermal aberrations in actual working environments in real time. The system has numerous potential applications in infrared detection and tracking, surveillance and remote sensing.

1. Introduction

Infrared optical systems are widely used in space exploration, military detection and civilian imaging applications. These systems are small, have anti-interference capability and work day and night. These systems usually operate in a wide temperature range, and imaging quality is affected by temperature due to complex working environments (friction under high-speed motion conditions and heat generated by the internal components working and infrared radiation). An athermal system must be designed to improve the adaptability of infrared optical systems with changing environmental temperatures [1,2]. Conventional compensation methods have been proposed to reduce the influence of temperature on system imaging performance and athermalise infrared optical systems. These methods include electromechanical active, mechanical passive and optical passive compensation [3], the last of which may be the most widely used [3]. However, available infrared optical materials are limited, and their thermal characteristic is finite. And this is not conducive to the athermal design of infrared optical systems. This method is limited by these factors. The adaptability of traditional athermalisation techniques to environmental temperature is poor. In these methods, the imaging performance of athermal infrared optical systems is established according to systems designed under simulated environmental conditions. However, actual working conditions are complex and differ from simulated ones. Consequently, system imaging quality is poor under actual working environments. These traditional methods are thus limited by complex working conditions.

Therefore, a new athermal method must be developed so that infrared optical system imaging performance is not affected by actual working environments. This study proposes a dynamic local athermalisation method for longwave infrared (LWIR) optical systems with large fields of view (FOVs); this technique uses a deformable mirror and is based on active optics theory [4–7] which aims to correct optical system wavefront aberrations by the control of the shape of active optical components, such as deformable mirrors and spatial light modulators. This method applies foveated imaging [8] to correct thermal aberrations in infrared optical systems to realise the dynamic local high-resolution imaging of LWIR optical systems with large FOVs in wide temperature ranges. Foveated imaging [9–11] is a variable resolution technology that can dynamically achieve local high-resolution imaging within a large FOV using active optical elements, such as spatial light modulators and deformable mirrors. The elements are used to alter the optical path difference by the varying refractive index and surface parameters. This technique correct thermal aberrations in a local field of interest (LFOI). This study presents an LWIR optical system with good imaging quality and analyses the system thermal aberrations in the range of −40 °C to 80 °C. The thermal aberrations caused by temperature variation are corrected by the deformable mirror in the system. The system is designed and analysed using the optical design software CODE V. The simulation results are also provided. The results verify the dynamic local athermalisation principle of the LWIR optical system that is based on a deformable mirror. This system can achieve local athermalisation high-resolution imaging in simulated and actual working environments. In an actual working environment, the system LFOI thermal aberrations

---

* Corresponding author.
E-mail address: optics_chang@126.com (J. Chang).

https://doi.org/10.1016/j.optlaseng.2018.02.001
Received 8 November 2017; Received in revised form 31 January 2018; Accepted 1 February 2018
0143-8166/

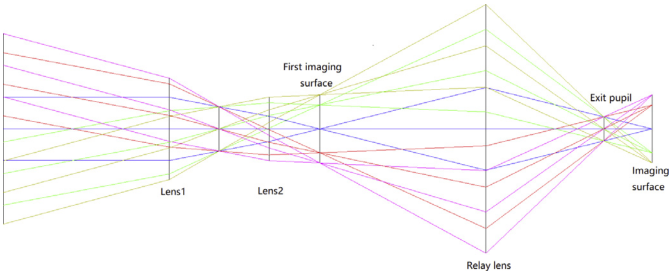


Fig. 1. LWIR optical system scheme.

are corrected by the deformable mirror on the basis of pupil wavefront aberrations, which are calculated according to the expansion of the aberration function in terms of Zernike polynomials [12].

2. Local athermalisation principle of longwave infrared optical system

2.1. Longwave infrared optical system

LWIR optical systems that work within 8–12 μm are used to detect the thermal radiation from the objects. Conventional LWIR optical systems use cooled infrared detectors to achieve maximum detection sensitivity. The systems adopt cold shield matching to block the radiation from other scenes, which should not be detected. Cooled infrared detectors with 100% cold shield efficiency shield the scenes well outside the objects to be observed. This effect can prevent image deformation.

An inexpensive and low-power uncooled infrared detector is selected for this LWIR optical system. The exit pupil of the system is between the last surface and the image plane. This design is called exit pupil matching, which realises good control of capturing the light from the objects to be observed. A deformable mirror is tilted by 45° and placed at the exit pupil of the system. The thermal aberrations are corrected by the deformable mirror, which is then cooled to restrain its thermal radiation and that of the other scenes. This process is similar to the cold shielding in infrared imaging systems that use cooled detectors. According to this system design method, the local athermal LWIR optical system scheme is formed, as shown in Fig. 1.

The LWIR optical system comprises an imaging lens group and a relay lens group, as shown in Fig. 1. The imaging lens group has a symmetrical structure, which includes Lens1, Lens2 and Stop. Stop is positioned between Lens1 and Lens2. The object thermal radiation is imaged by the imaging lens group at the first imaging surface. The object is ultimately imaged by the relay lens group on the imaging surface. The system exit pupil is the image of the imaging lens group exit pupil. The system exit pupil is positioned between the last surface of the relay lens group and the imaging surface. The deformable mirror is tilted by 45° and placed at the exit pupil position to turn the ray tracing by 90°. This positioning contributes to reducing the dimension of the length of the system.

2.2. Local athermalisation of longwave infrared optical system

The glass materials used in infrared optical systems are limited [13]. Meanwhile, system athermalisation is necessary given the thermal imaging characteristics of infrared optical systems. To athermalise infrared optical systems, the traditional optical passive compensation method corrects thermal and chromatic aberrations simultaneously by choosing different types of infrared optical materials and finding an appropriate combination of the thermal refractive index coefficient, thermal expansion coefficient and material Abbe number. Diversifying the types of infrared optical systems is challenging because of the limited infrared optical materials and the difficulty in the simultaneous correction of the thermal and chromatic aberrations in the athermal system. Thus, the development of the new infrared optical system is limited to a certain extent. When the environmental temperature changes, thermal and chromatic aberrations lead to variations in the focal power and back focal length and result in a severe decline in system imaging quality.

Table 1
LWIR optical system specifications.

Focal length	76.47 mm
FOV	30°
Entrance pupil diameter	38 mm
Spectral band	8–12 μm
Infrared optical materials	Ge, ZnS and ZnSe
Detector pixel size	25 μm
Detector pixels	640 × 480

A deformable mirror is used to correct the thermal aberrations to realise the dynamic local athermalisation of the LWIR optical system. However, chromatic aberrations cannot be corrected in this manner and thus have to be addressed by selecting the infrared optical materials according to their dispersion coefficients, which are usually expressed as Abbe numbers. The smaller the Abbe number, the more noticeable the dispersion characteristic. Materials with different Abbe numbers in this system are chosen to correct the chromatic aberration. Some common infrared optical materials, such as Ge, ZnS, ZnSe [14] and SiC, can transmit the wavelength range 8–12 μm. Among these materials, Ge has a remarkably higher refractive index and lower dispersion. However, ZnS and ZnSe exhibit the opposite characteristics. Thus, a positive lens fabricated with Ge and a negative lens fabricated with ZnS or ZnSe are good for the correction of spherical aberration, coma and chromatic aberration. Therefore, Ge, ZnS and ZnSe are chosen for the initial stage of this system design. The imaging quality is good at 20 °C room temperature after the optimisation design. No new materials are added to the system.

On the basis of foveated imaging theory, the deformable mirror is used to correct the thermal aberrations for the local athermal FOVs in the LWIR optical system. The local athermalisation is realised by the surface deformation of the mirror. The Zernike polynomial is selected to simulate the 45°-tilted wave aberrations in the continuous circular region. The wave aberrations are corrected by different Zernike item coefficients. The deformable mirror is modelled as the Zernike polynomial surface in CODE V and expressed as [15]

$$z = \frac{cr^2}{1 + \sqrt{1 - (1 + k)c^2 r^2}} + \sum_{j=1}^{66} C_{j+1} Z_j. \tag{1}$$

In Eq. (1), z is the sag of the deformable mirror surface parallel to the z-axis, c is the deformable mirror vertex curvature, r^2 equals $x^2 + y^2$, k is the surface conic constant, Z_j is the jth item of the Zernike polynomials and C_{j+1} is the coefficient for Z_j.

Each Zernike polynomial mode corresponds to one type of aberration. The thermal aberrations of the local athermal FOVs are corrected by the mirror deformation at different temperatures. The LWIR optical system achieves high-resolution imaging performance for the local athermal FOVs. The deformable mirror is cooled to prevent its surface from becoming deformed while working in the system.

3. LWIR optical system design and thermal analysis

The LWIR optical system works in the range of −40 °C to 80 °C. The system design specifications are listed in Table 1. The infrared optical materials chosen in this system are Ge, ZnS and ZnSe. These materials can correct the system chromatic aberration well. According to the specifications shown in Table 1, the LWIR optical system is designed as follows.

The system is designed in the optical design software CODE V on the basis of the LWIR optical system design scheme. The system structure is designed as shown in Fig. 2. The LWIR optical system