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An infrared zoom imaging system with large zoom ratio based on linear motion mechanism

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Abstract: In order to meet the urgent need of large-scale search and accurate target recognition, an infrared zoom imaging system with large zoom ratio is developed. Two independently moving zoom lenses and one compensating lens are designed, the large zoom ratio can be obtained by the cascade of two zoom lenses. According to the characteristics of multiple moving lenses and complex zoom curves, the zoom motion is realized by linear motion mechanism, and driven by linear motor integrated encoder and thread screw rod. The mechanical analysis of the system is carried out by the finite element simulation, and the maximum displacement of the lenses is 3.04×10^{-3} mm. The imaging system is suitable for the medium-wave infrared cooled 640×512 focal plane area-array detector, and the zoom ratio is 55. The results of laboratory imaging and outfield imaging show that the system has a clear and good imaging quality with a continuous change in focal length from 6 mm to 330 mm, which verifies the performance of the system. The design is reasonable and reliable. The research findings of this paper have broad application prospects in search, tracking, reconnaissance, and surveillance.

Key words: infrared zoom imaging system, large zoom ratio, linear motion mechanism, linear motor

基于直线运动机构的大变倍比红外变焦成像系统

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摘要：针对同时兼顾大范围搜索和精确识别目标的迫切需求，研制了一种大变倍比红外变焦成像系统，设计两片独立运动的变倍镜及一片补偿镜，通过两个变倍镜级联的方式获得大变倍比。结合系统运动镜片多及变焦曲线复杂的特点，采用直线运动机构实现镜片变焦运动，使用集成编码器及螺纹丝杆的直线电机作为驱动。通过有限元仿真开展了系统力学分析，所设计镜片最大位移为3.04×10^{-3} mm。成像系统适用于中波红外制冷式640×512焦平面阵列探测器，变倍比达到55倍。实验室成像及外场实景成像的结果表明，系统在焦距由6 mm至330 mm连续变化的过程中成像清晰、像质良好，验证了系统的连续变焦成像性能，该设计合理可靠。研究成果在搜索、跟踪、侦察、监视等方面有广阔的应用前景。

关　键　词：红外变焦成像系统；大变倍比；直线运动机构；直线电机

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Introduction

China is a country with more than 40,000 kilometers of border and coastal defense lines and 1.4 billion people. It is under great pressure in various fields such as aerospace, military defense and counter-terrorism. As a passive detection method, an infrared imaging system has the advantages of strong anti-interference ability, good concealment, all-weather work and so on, and has played an increasingly important role in these fields. It is also being used more and more widely in the field of civil surveillance identification[1-4]. In recent years, with the development of infrared imaging technology and the expansion of its application, the infrared imaging system needs not only to acquire a large range of scene information, but also to acquire a long-range detection ability and specific information of key targets. However, limited by the current infrared detector technology, it is difficult for fixed-focus imaging systems to simultaneously achieve large-scale search and accurate target recognition[5-6]. Relative to the fixed-focus system, the infrared continuous zoom imaging system is an imaging device which makes the combined focal length of the imaging system continuously change by the movement of the infrared lens[7]. The infrared continuous zoom imaging system with large zoom ratio meets the development needs of infrared imaging technology, but its system design is relatively difficult to realize[8-9].

In 2004 Yoram A et al. designed a 30 times continuous zoom optical system through the thrice-imaging structure[10]. In 2009, Li Yong-Gang et al. completed the structural design of a 25-450 mm mid-wave infrared zoom lens[11]. Mark C. Sanson and James Cornell designed a long-wave infrared zoom system with an F number of 4.5 and a zoom ratio of 30 in 2010[12]. In 2018, ZHANG Jin-Kai et al. designed a zoom lens based on the hybrid lens group model[13]. In 2019, LIU Zhi-Ying et al. designed an offner-type continuous zoom mid-wave infrared spectral imaging system with an F number of 4 and a continuous zoom range of 60-300 mm[14]. DING Xue-Zhuan et al. designed a three-time imaging infrared continuous zoom array scanning optical system with a focal length of 60-360 mm in 2021[15].

According to the results of literature investigation, the research results of infrared continuous zoom imaging system with large zoom ratio, especially the imaging system and the imaging effect of the large zoom ratio are less public. Compared with a few available infrared zoom imaging systems, the zoom ratio is not high and most of the system structures are complex and cumbersome. In this paper, two zoom lenses and one compensating lens were innovatively designed for zoom motion. At the same time, according to the characteristics of many moving lenses and complex zoom curve, the linear motion mechanism was used to realize the zoom motion of the lenses. The linear guide was used as the motion support and the linear motor was used as the drive, which made the system structure simple, the imaging quality high and realize self-locking in the vibration environment. The infrared zoom imaging system developed in this paper has a range of continuous zoom imaging from 6 mm to 330 mm and a zoom ratio of 55 times. The results of laboratory imaging and outfield imaging show that the system can realize infrared continuous zoom imaging from short focal length to long focal length, and the imaging effect is good.

1 System principle

In order to realize the infrared continuous zoom imaging with the large relative aperture and large zoom ratio, the optical model innovatively designed two independently moving zoom lenses and one independently moving compensation lens based on the classical four-component mechanically compensated zoom system[16-17]. The optical design achieved a large zoom ratio by cascading two zoom lenses, and the design retained more freedom to expand the relative aperture. The zoom motion of this new type of infrared optical zoom structure in short focal length state is shown in Fig. 1.

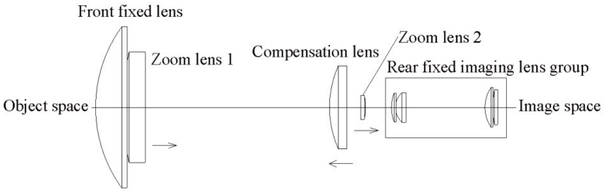


Fig. 1 The optical structure of the infrared zoom lens
图1 红外变焦镜头光学结构

In the actual alignment, the zoom distance had been adjusted according to the machining and assembly errors. The zoom motion curves are shown in Fig. 2. The three curves from top to bottom are the motion trajectories of zoom lens 1, the compensation lens and zoom lens 2. In Fig. 2, the horizontal axis represents the focal length of the system, and the vertical axis represents the zoom motion distance of the lens. The maximum stroke of zoom lens 1 is 76.02 mm, that of the compensating lens is 122.22 mm, and the maximum stroke of zoom lens 2 is 25.65 mm.

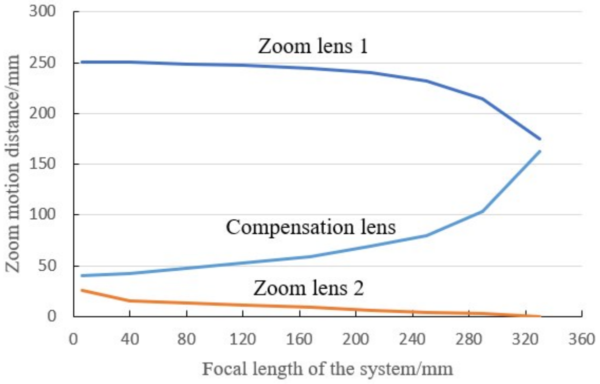


Fig. 2 The zoom motion curves
图2 变焦运动曲线

The traditional zoom system usually uses a zoom cam to move the zoom lens and compensation lens[18-21]. The cam groove on the zoom cam is processed by the zoom curve. In order to ensure the continuity of the cam movement and avoid the mechanism jamming in the movement, the smooth fitting of the zoom curve is an important part of the connection between the optical design and structural design. As shown in Fig. 2, the zoom curves of the system are irregular curves, and there are inflection points locally. The smooth fitting will affect the quality of the optical continuous zoom imaging. At the same time, in order to achieve a large zoom ratio of infrared continuous zoom, the system used three independent motion zoom lenses, and the movement distance was long, which was not conducive to the use of cam mechanism to complete the zoom movement of the system.

In recent years, the linear motion technology has been greatly developed, and the accuracy and integration of linear guides and linear motors have been greatly improved. In addition to the application of ball screw, there are also productized linear motors with integrated encoders and thread screw rods[22-25], whose applications in zoom lens will make the structure more compact and more accurate. Using the linear motion mechanism to complete the zoom motion will make the motion curve need not to be smoothed or fitted, and the imaging system has the advantages of simple processing, low structural complexity, avoiding mechanism stuck and high degree of concentricity in motion. In addition, the linear motion mechanism can realize self-locking under high vibration environment and improve the system performance. Relative to the zoom cam, the cam groove is processed through the zoom curve to complete the movement of the zoom lens, and the linear motion mechanism drives the zoom lens movement through the motion control of the motor. In the later debugging, some fine-tuning processing can be done on the control to eliminate the optical and mechanical processing and assembly errors, and improve the imaging quality.

The structure principle of the infrared zoom imaging system with large zoom ratio based on the linear motion mechanism is shown in Fig. 3. The system used two cylindrical linear guide rails as the linear motion support, and ensured the concentricity of the imaging lens group through the cylindrical surface fit of the linear bearing and the linear guide rail. The system used three linear motors with integrated encoders to drive zoom lens 1, the compensation lens and zoom lens 2 to move independently and linearly according to the zoom curve to achieve the infrared continuous zoom imaging.

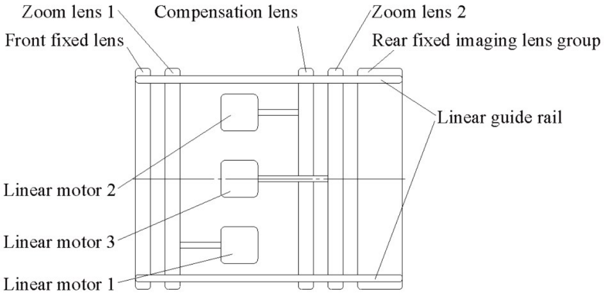


Fig. 3 The principle of the system structure
图3 系统结构原理

2 Imaging system design

1.1 Optical design

The zoom ratio of the infrared continuous zoom imaging system with large relative aperture and large zoom ratio was 55 times, the F number was 2, and the first front fixed lens was the largest lens with an aperture of 168 mm. The system detector was an area-array cooled infrared detector. The imaging system parameters are shown in Table 1.

Table 1 The optical parameters of the imaging system
表1 成像系统光学参数

Parameter	Indices
Zoom range	6‒330 mm
Imaging field angle	91.4°‒2.1°
Detector pixel number	640×512
Detector pixel size	15 μm×15 μm
Band range	3.7‒4.8 μm

The system optical path diagram is shown in Fig. 4, from top to bottom are the system optical path diagrams of long focal length, medium focal length and short focal length. From left to right in each image: the first lens is the front fixed lens, the second lens is zoom lens 1, the third lens is the compensation lens, the fourth lens is zoom lens 2, the fifth lens to the eighth lens are the rear fixed imaging lens group, followed by the detector window and the system imaging focal plane. The front fixed lens was used to converge and collect light so as to compress the size of the rear lens group and correct the correlated aberrations caused by the large aperture. The first two lenses (i. e., the fifth and sixth lenses) of the rear fixed imaging lens group were used for converging the object side scene into the primary image plane of the imaging system, compressing the total length of the optical system, and eliminating the residual aberration of the front lens group. The last two lenses (the seventh and eighth lenses) of the rear fixed imaging lens group, which formed the relay imaging lens group, then re-imaged the scene of the primary image plane of the system to the focal plane of the detector again, and realized a 100% cold stop matching at the same time. Zoom lens 1, the compensation lens and zoom lens 2 respectively moved independently in accordance with the system zoom curve to achieve the continuous zoom with large zoom ratio.

1.2 Structure and motion mechanism design

The system used the linear motor as the drive, the photoelectric switch as the limit position feedback, and the cylindrical linear guide rail as the linear motion support. The system overall dimension was 622 mm (length) × 360 mm (width) × 222 mm (height). The overall structure of the imaging system is shown in Fig. 5. Figure 5 shows the long focal position in the system focal length of 330 mm and short focal position in the system focal length of 6 mm of zoom lens 1, the compensation lens and zoom lens 2. The front fixed lens seat, zoom lens seat 1, the compensating lens seat, zoom lens seat 2 and the rear

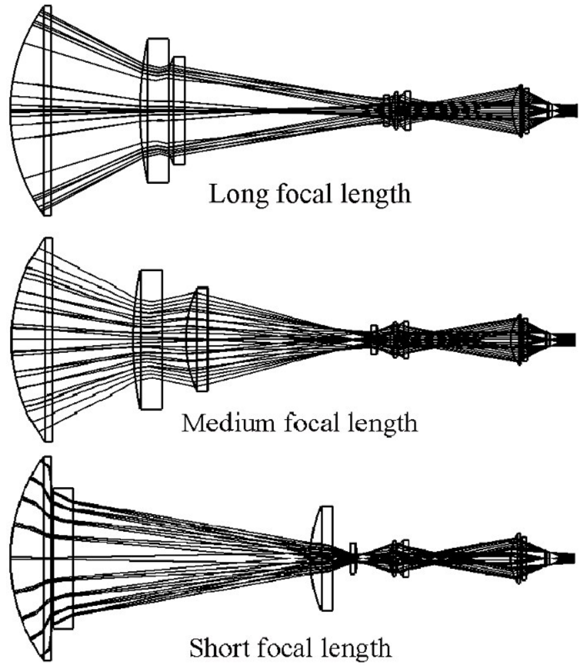


Fig. 4 The system optical diagram
图4 系统光路图

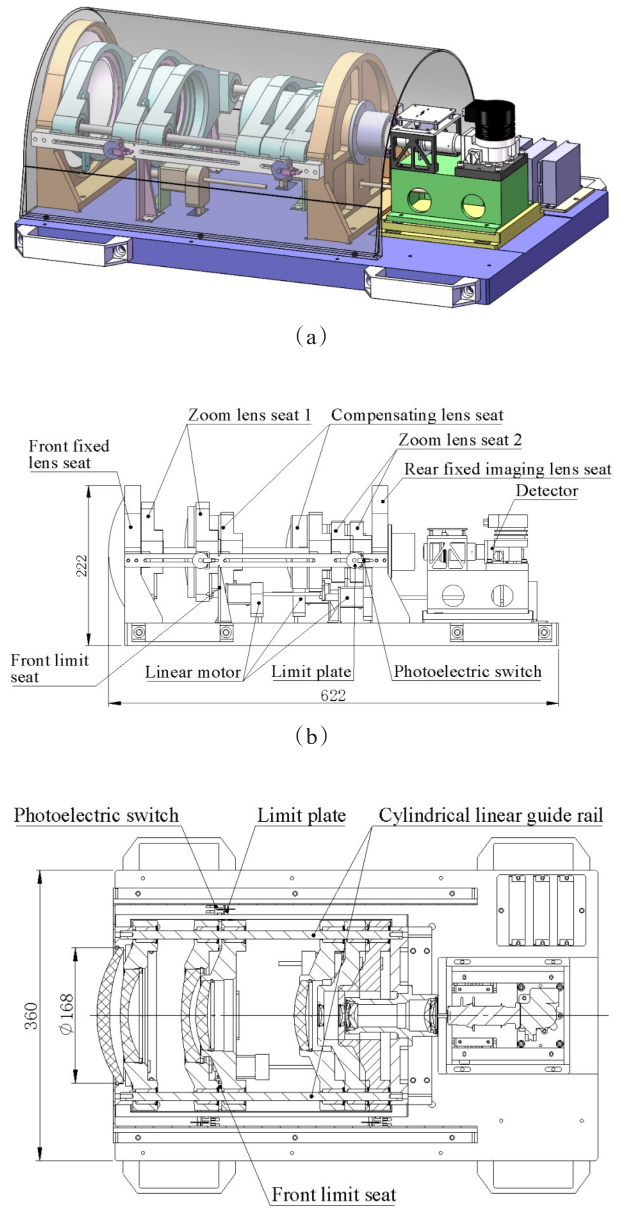


Fig. 5 The general structure of the imaging system (a) the imaging system model, (b) the front view of the imaging system, (c) the cutaway view of the imaging system
图5 成像系统总体结构(a)成像系统模型,(b)成像系统前视图,(c)成像系统剖视图

fixed imaging lens seat were elliptical structures, and their installation position avoided the position of the linear motor. The front fixed lens was mounted in the front fixed lens seat, zoom lens 1 was mounted in zoom lens seat 1, the compensation lens was mounted in the compensating lens seat, zoom lens 2 was mounted in zoom lens seat 2, and the rear fixed imaging lens group was mounted in the rear fixed imaging lens seat. Both ends of the front fixed lens seat and the rear fixed imaging lens seat were fixedly installed with a cylindrical straight-line guide rail, and both ends of zoom lens seat 1, the compensating lens seat and zoom lens seat 2 were fixedly installed with a linear bearing. Both ends of zoom lens seat 1, the compensating lens seat and zoom lens seat 2 were mounted on a cylindrical linear guide rail through a linear bearing to complete the zoom movement. Three linear motors respectively drove zoom lens 1 seat, the compensating lens seat, zoom lens seat 2 to move according to the zoom curve to realize the zoom function of the system.

Zoom lens seat 1, the compensating lens seat and zoom lens seat 2 each installed a limit plate. When the zoom motion made the system in the long focal length state, zoom lens seat 1 and the compensation lens seat were limited by the front limit seat, and zoom lens seat 2 was limited by the rear fixed imaging lens seat. At this time, limit disks mounted on zoom lens seat 1, the compensation lens seat, and zoom lens seat 2 occluded the detection groove of the photoelectric switch to generate a signal, and the control system took this state as the system zero. The zoom imaging system drove zoom lens 1, the compensation lens and zoom lens 2 to perform the continuous zoom motion at the initial zero position. The high-precision position feedback was achieved through the linear motor encoder, and the imaging system had infrared zoom imaging capability with large zoom ratio.

Because the distance between the lenses in the long focal length and the short focal length states in the optical zoom structure was very small, the structure design of lens seat was that the lens was mounted in front of the supporting structure, so that the two ends of the lens seat could be installed suitable supporting surface length linear bearings, thus ensuring the motion stability of the system zoom structure. The zoom motion mechanism needed to ensure the concentricity between the lenses during the zoom process. The linear guide rail and the inner ring of the linear bearing were matched with a small gap within 0. 005 mm at the bearing fit, and the outer ring of the linear bearing and the lens seat were matched with a small gap within 0. 005 mm to prevent the bearing from the radial moving. The system used the custom linear motor that integrated the encoder and the thread screw rod, and the axial displacement of the thread screw rod was eliminated by applying the pre-tightening method of the eliminate clearance nut. The minimum thrust of linear motor was 3. 5 kg, the step length was 0. 006 35 mm, and the step angle was 1. 8°.

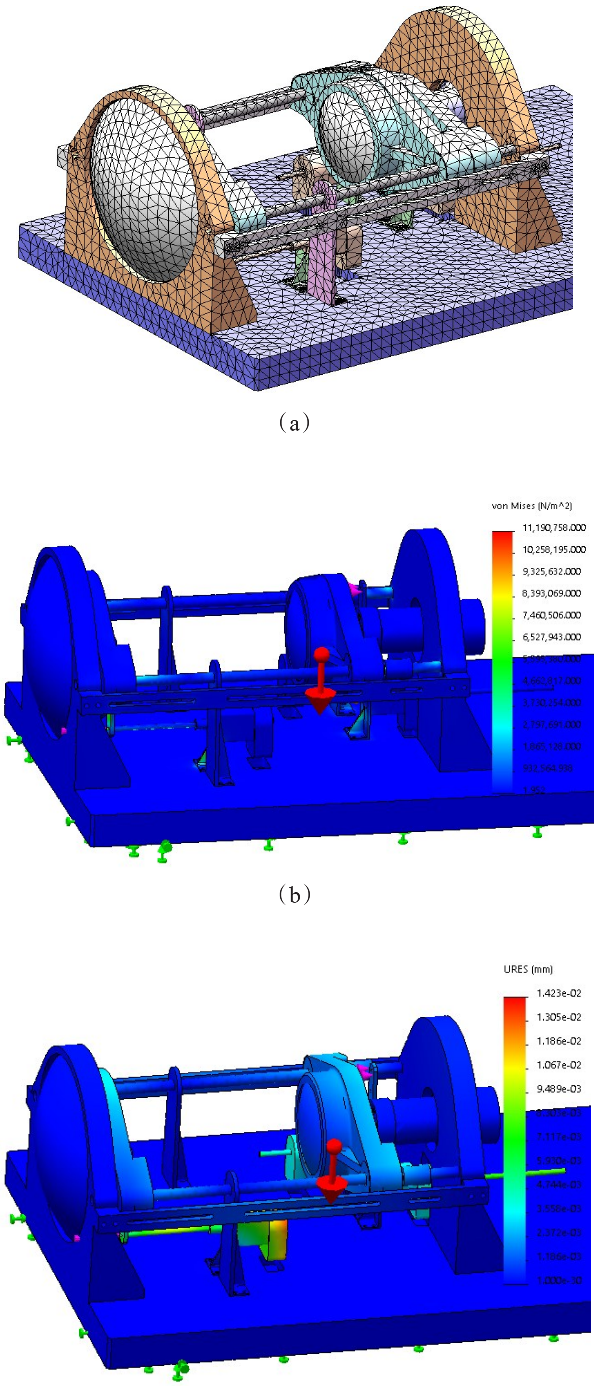
1. 3　Finite element simulation analysis

The imaging system as a whole model was analyzed by finite element simulation analysis. The model was simplified in detail without affecting the simulation results, and the matching relationship was added to the model. Material parameters such as alloy steel, aluminum alloy and optical material were added to the parts, and the fixed constraint was added at the bottom of the system. The gravity load was added to the model, and the motor thrust was added to zoom lens seat 1, the compensation lens seat and zoom lens seat 2 respectively. The zoom imaging system would be mounted on a two-dimensional turntable for imaging, and would be affected by the pitch moment T_1 and the azimuth moment T_2. The pitch moment of inertia J_1 was 1 kg×m^2, the azimuth moment of inertia J_2 was 5 kg×m^2, the pitch maximum acceleration a_1 was 150°/s^2, the azimuth maximum acceleration a_2 was 60°/s^2, there are:

$$\mathrm{T}_1 = \frac{\mathrm{J}_1 \times \mathrm{a}_1 \times \pi}{180} = 2.62N \times m \quad , \quad (1)$$

$$\mathrm{T}_2 = \frac{\mathrm{J}_2 \times \mathrm{a}_2 \times \pi}{180} = 5.24N \times m \quad , \quad (2)$$

T_1 and T_2 were exerted to the simulation model, and the stress and displacement simulation analysis were carried out after meshing, as shown in Fig. 6. The grid had 145306 nodes and 87025 units. Zoom lens seat 2 was hidden in the analysis results to display the simulation result of zoom lens 2. The maximum stress of the system structure was at the reinforcing rib of the linear motor 1 supporting piece, the maximum stress was 11. 19 MPa, the maximum stress of zoom lens 1 was 1. 32×10^{-1} MPa, the maximum stress of the compensation lens was 7. 88×10^{-2} MPa, and the maximum stress of zoom lens 2 was 5. 89×10^{-2} MPa. The stress of the structure was small and would not cause destructive effects on the structure. It could be seen that the structural strength was sufficient. The maximum displacement of the system was at the rear of the compensation lens drive motor, the maximum displacement was 1. 42×10^{-2} mm, the maximum displacement of zoom lens 1 was 2. 81×10^{-3} mm, the maximum displacement of the compensation lens was 1. 71×10^{-3} mm, and the maximum displacement of zoom lens 2 was 3. 04×10^{-3} mm. The allowable relative displacement of each lens was 0. 01 mm. It could be seen that the lens displacement would not affect the imaging quality, and the system design was reasonable and reliable.



(a)

(b)

(c)

Fig. 6　The finite element analysis of the system structure (a) the mesh generation, (b) the structural stress, (c) the structural displacement

图6　系统结构有限元分析(a)网格划分,(b)结构应力,(c)结构位移

3　Experimental results

The infrared zoom imaging system with large zoom ratio based on the linear motion mechanism designed in this paper had been actually processed and assembled, the cross wire imaging was used for infield test after optical

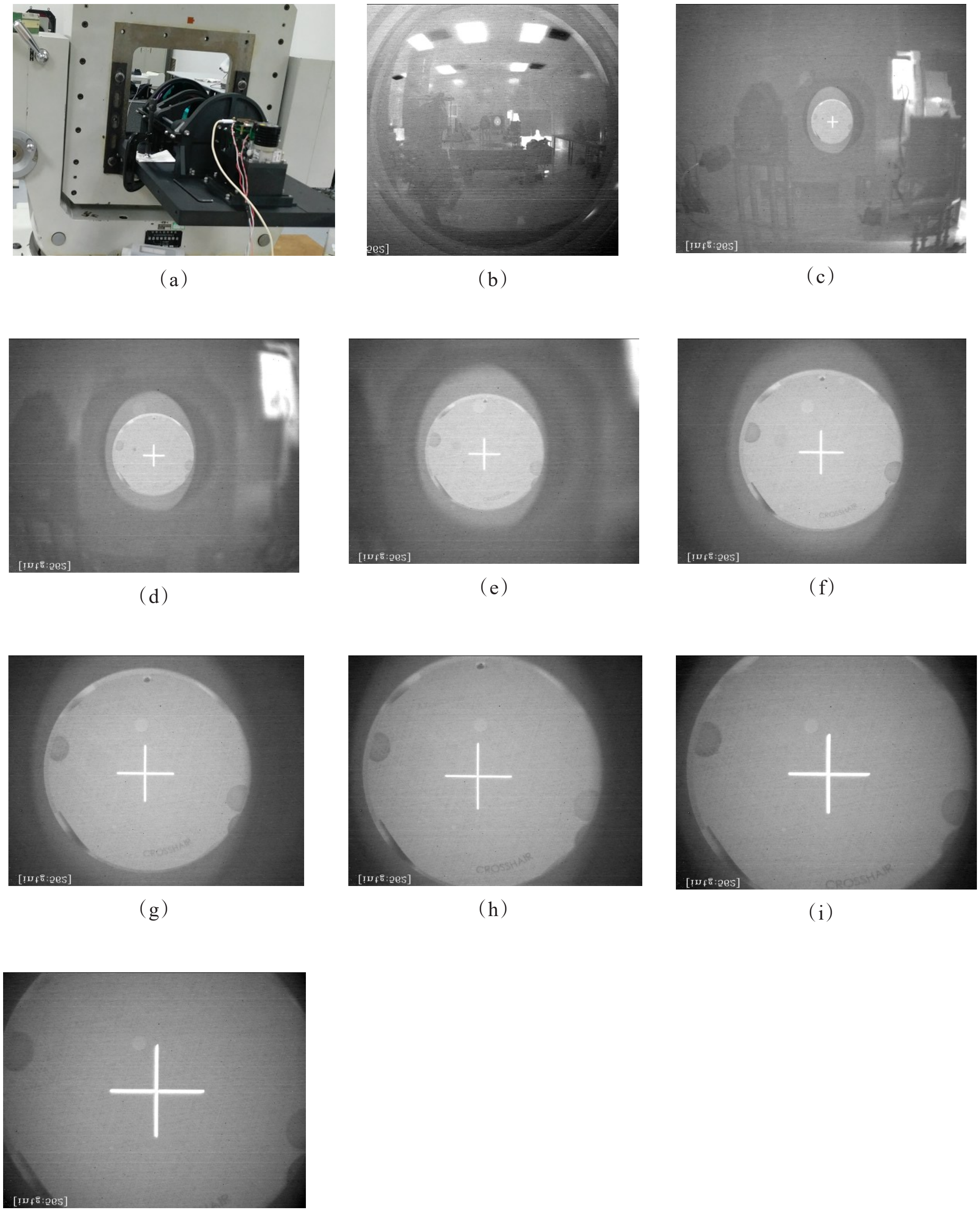


Fig. 7 The laboratory imaging of the imaging system (a) the laboratory imaging, (b) focal length 6 mm, (c) focal length 40 mm, (d) focal length 80 mm, (e) focal length 120 mm, (f) focal length 168 mm, (g) focal length 210 mm, (h) focal length 250 mm, (i) focal length 290 mm, (j) focal length 330 mm
图7 成像系统实验室成像(a)实验室成像,(b)焦距6毫米,(c)焦距40毫米,(d)焦距80毫米,(e)焦距120毫米,(f)焦距168毫米,(g)焦距210毫米,(h)焦距250毫米,(i)焦距290毫米,(j)焦距330毫米

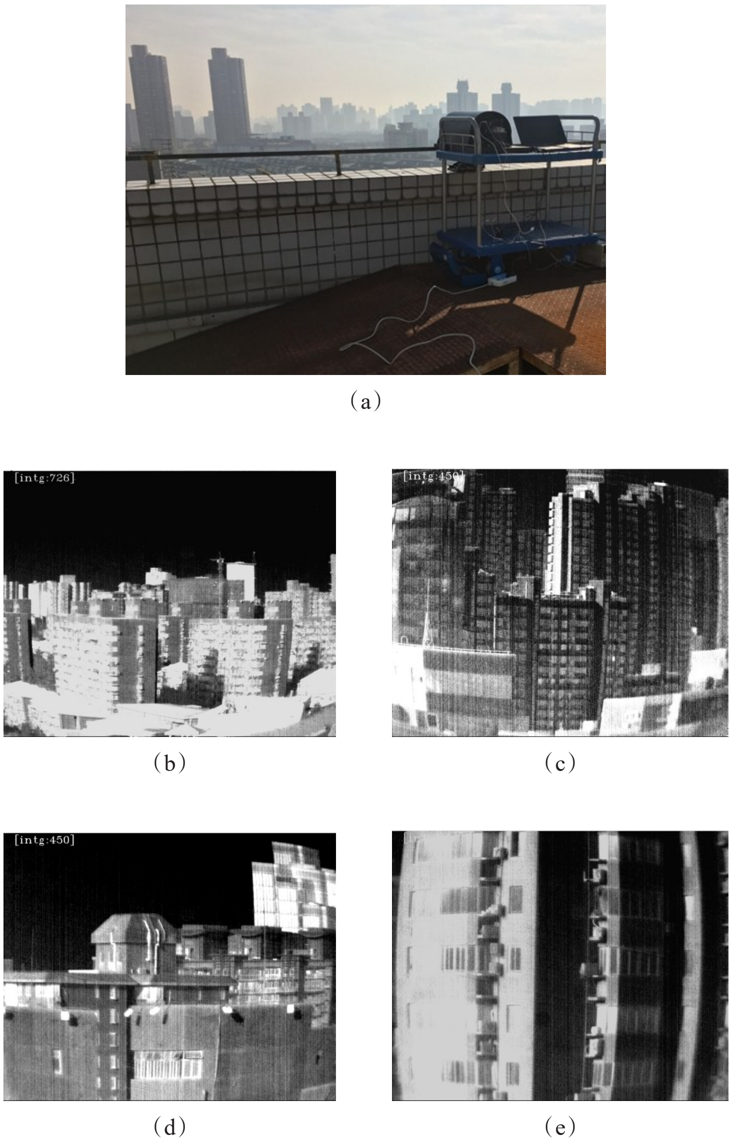
calibration with a two-dimensional turntable in the laboratory. The infrared zoom imaging system continuously performed continuous zoom imaging on the cross wire of the optical calibration experiment, and we compared the imaging images of the focal length of 6 mm, 40 mm, 80 mm, 120 mm, 168 mm, 210 mm, 250 mm, 290 mm and 330 mm. The imaging results are shown in Fig. 7. It can be seen that the infrared zoom imaging system can complete the large field infrared imaging in the laboratory when the focal length is in short state. As the focal length increases, the imaging field becomes smaller, the cross wire and the details around the cross wire become clearer. At the same time, the imaging quality remains good during the zoom imaging process, and the imaging system has verified the system performance in the laboratory.

After the system imaging verification was completed in the laboratory, the imaging system was mounted on a high-rise rooftop for outfield infrared zoom imaging of distant urban buildings. The imaging results are shown in Fig. 8. In Fig. 7(b), at the focal length of 6 mm, the large field of view scene coverage imaging of the system had been verified by imaging the laboratory equipment. At the same time, through the change of focal length in the outfield imaging, the detailed information of the outfield scene was obtained in the zoom to the focal length of 40 mm, 168 mm, 250 mm and 330 mm respectively. Due to the large field of view, most of the boundaries of the laboratory equipment in Fig. 7(b) are not clear. In the outfield imaging at zoom to the focal length of 40 mm, Fig. 8(b) can clearly show the boundary of the building. As the focal length increases, some details of the building can already be obtained in Fig. 8(c). In Fig. 8(d) and Fig. 8(e), the building water pipes, windows, air conditioner and other details can also be clearly observed. The imaging system maintains clear image quality during the zoom imaging.

It can be seen from the above, the imaging system can realize the infrared continuous zoom imaging from the large field of view with the focal length of 6 mm to the small field of view with the focal length of 330 mm, with clear imaging and good image quality.

4 Conclusions

In this paper, a large zoom ratio infrared continuous



(a)

(b) (c)

(d) (e)

Fig. 8 The outfield imaging of the imaging system (a) the outfield imaging, (b) focal length 40 mm, (c) focal length 168 mm, (d) focal length 250 mm, (e) focal length 330 mm
图8 成像系统外场成像 (a)外场成像,(b)焦距40毫米,(c)焦距168毫米,(d)焦距250毫米,(e)焦距330毫米

zoom imaging system with a focal length from 6 mm to 330 mm is designed. The F number of the system is 2, and the zoom ratio is as high as 55 times. It is suitable for medium-wave infrared cooled 640×512 focal plane area-array detector. The large zoom ratio was obtained by cascading two zoom lenses. In view of the fact that there were three moving lenses and unsmooth zoom curves due to the large zoom ratio, we used the linear guides as the motion support and the linear motors as the drive, and innovatively used the linear motion mechanism to complete the zoom motion of the lenses. In the zoom system with the linear motion mechanism, the problem of concentricity and positioning accuracy in lens linear motion needs to be mainly solved. According to the results of laboratory imaging and outfield imaging, the system has clear imaging and good image quality in the process of continuous zoom, which proves that the system design is reasonable and reliable.

The research findings of this paper can be applied to the new infrared search and tracking system. Through the linear motion technology, the complex and even reciprocating zoom motion of multiple moving lenses can be realized, so as to realize the continuous zoom imaging with large zoom ratio. In the large field of view imaging, a short time airspace coverage can be realized, and a wide range of scenery information can be obtained. At the same time, it can obtain long-distance detection ability in the small field of view imaging and improve the resolution of key targets. It has broad application prospects in search, tracking, reconnaissance, and surveillance.

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