Optik - International Journal for Light and Electron Optics 224 (2020) 165462

Contents lists available at ScienceDirect

Optik

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

Book review

Research on Precision Thermal Control Technology Based on Aerial Telefocal Common Aperture Photoelectric Platform.

1. Introduction

An aerial photoelectric imaging system is used to acquire information widely, which plays an important role in civil surveying, mapping, and military applications. With the rapid development of drones, the demanding of photoelectric imaging system is increasing as well. On one hand, ranges of flight altitude and speed are increasing, which makes the external environment more complex. On the other hand, the development of remote sensing technology makes requirements for precision and resolution more and more strict, but its sensitivity to temperature is getting much higher. Especially for telefocal common aperture photoelectric platforms, if there is no thermal control measure, due to the complex external temperature environment, the image quality will be worse.

Nowadays, it has been paid more attention to the image quality of optical systems in high altitudes or space environments. Researchers from all over the world have been working hard to develop the optomechanical thermal analysis and improve the thermal control design. At present, a few countries in Europe and America have mastered relatively mature optomechanical thermal analysis and thermal control design technologies [1–5]. Among them, most thermal control researches focus on optical systems in space. Pierre Y. Bely et al. [6] analyzed the temperature field and thermal-structural deformation of the primary mirror of lightweight space telescope using software Nastran, SSPTA and ACCOSV. The results show that the imaging quality of the optical system is affected by the axial temperature difference seriously. Glenn T. Tsuyuki et al. [7] performed a thermal control optimization design on the primary mirror of the sub-millimeter imaging telescope and found that the optical system surface accuracy must be less than $\lambda/20$ to meet the resolution requirements. Yang Wengang et al. [8] proposed thermal control index of a high-resolution space camera based on wave phase difference distribution theory and designed thermal control scheme. It is to be noticed that there are few researches for thermal control of aerial remote sensing platforms. It is known that the aviation environment is much more complicated than the space environment. In the aviation environment, there is deep convective heat transfer between the atmosphere and remote sensors, which makes the temperature of sensors changes greatly. Therefore, the thermal control design of aerial remote sensors is more difficult than that of the optical system working in space. Liu Weiyi et al. [9] studied the effects of temperature uniformity and temperature gradient on the imaging quality of aerial cameras and proposed an improved thermal control scheme for the characteristics of aerial cameras, which effectively reduced temperature gradient and improved imaging quality.

Unlike a single aerial camera, the object in this paper is a whole optoelectronic platform system with many loads inside. Based on the characteristics of telefocal common aperture photoelectric platforms, the influence of temperature level and axial temperature difference of primary and secondary mirrors on the high-resolution image quality is analyzed. Accordingly, to improve image quality, precise thermal control technology combining active and passive measures is studied. Through thermal optics analysis and experiment under extreme operating conditions, it is concluded that the designed precise thermal control measures are effective and easy to implement in engineering.

2. Analysis of factors affecting imaging quality of optical system

2.1. Aerial Telefocal Common Aperture Photoelectric Platform

An aerial telefocal common aperture photoelectric platform is shown in Fig. 1, including two axes and two frames. Two axes are pitch axis and azimuth axis respectively driven by torque motors directly. Besides, there are the front cover, middle cover, rear cover, azimuth seat, etc. Internal optical components are shown in Fig. 2. It can be seen that the visible camera and the infrared camera share a Cassegrain reflective objective lens, wherein the primary mirror is a paraboloid, the secondary mirror is a hyperboloid, and each of the imaging planes is followed by a transmissive image subsystem, to achieve long focal length, large aperture, dual-band imaging. The

https://doi.org/10.1016/j.ijleo.2020.165462
Received 18 June 2020
Available online 30 September 2020

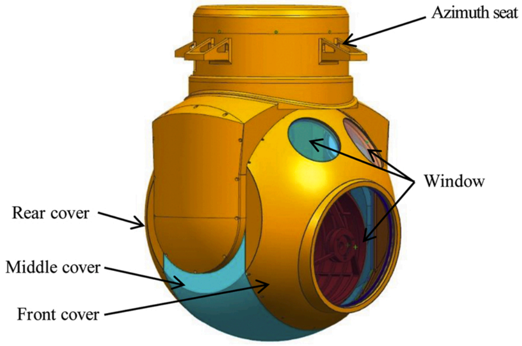

Fig. 1. External structure of an aerial telefocal common aperture photoelectric platform.

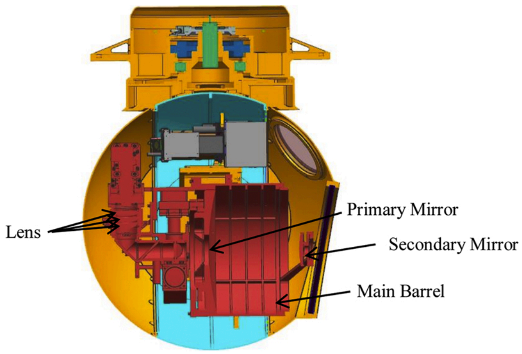

Fig. 2. Optical components inside an aerial telefocal common aperture photoelectric platform.

main barrel is used to support the primary mirror, and the inner frame carries photoelectric platforms. Also, the focal lengths of the visible camera and infrared camera are 1500 mm and 1000 mm respectively, and primary and secondary mirror-shaped precision is processed to $1/40\,\lambda(\lambda\ = 632.8\text{nm})$.

As the aerial telefocal common aperture photoelectric platform system rises from the ground to the air, the external atmosphere changes with altitude, which is always a rapid shock change. For example, the temperature of ambient environment will change from 50 °C to −55 °C in 30 minutes while the aircraft rises from the ground to the air in summer, which means that there are higher demands on thermal control to prevent internal optical system from being affected by changes in ambient temperature. Fig. 3 shows imaging

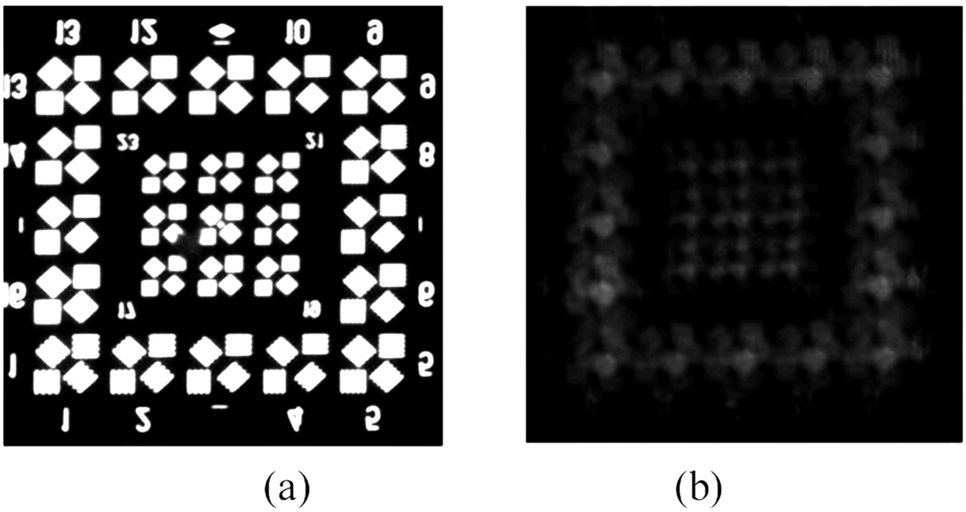

Fig. 3. Target image taken by an aerial telefocal common aperture photoelectric platform without thermal control (a) normal temperature condition (b) simulating the external atmospheric environment.

photos taken by the visible camera with a focal length of 1500 mm, where the left one is acquired under normal temperature conditions and the right one under simulated atmospheric conditions. Two cases are both without thermal control. It is obvious that under simulated atmosphere conditions, the imaging is blurry. The imaging quality is reduced greatly due to the low-temperature environment.

2.2. Thermal optics analysis

According to the previous research, temperature level and axial temperature difference between primary and secondary mirrors have an impact on the imaging quality of optical systems. To investigate the adaptability of telefocal common aperture photoelectric platform to temperature level and axial temperature difference, a thermo-optics analysis was carried out on the temperature level of 20 °C and the axial temperature difference of 20 °C without thermal control. Table 1 shows the results, where the first row and the second row represent optical aberrations of the primary and secondary mirrors, and the last 10 rows represent the aberrations of the respective lens surface, and the SUM row represents the sum of aberrations of all surfaces. SA, TCO, TAS, and SAS are the spherical aberration, coma, meridional image power, and sagittal image power of the optical system. The larger the aberration value is, the greater effect on the imaging quality is. From data in Table 1, values of spherical aberration and coma are much larger than meridional image power and sagittal image power. Thus, the latter two are negligible when considering imaging influencing factors. Besides, the aberration of the lens is much smaller than that of primary and secondary mirrors, which can also be ignored. In terms of factors that have a great influence on image quality—spherical aberration and coma, when temperature level changes, the system has a large spherical aberration and a relatively small coma; when axial temperature difference changes, there appears large spherical aberration and large coma simultaneously. Due to the focusing function of the camera, the effects of spherical aberration can be partially compensated, however, coma cannot be compensated. Therefore, the goal of thermal control design needs to reduce the axial temperature difference first.

According to the results of thermal optics analysis, thermal control scheme for uniformizing temperature of primary and secondary mirrors is designed, and the design target is as follows:

(a) The temperature level of the primary mirror is within the range of -10 to +40 °C;
(b) The axial temperature difference between primary and secondary mirror is less than 2 °C.

Table 1
Three-order aberration analysis of optical system.

(a) temperature level of 20 °C				
	SA	**TCO**	**TAS**	**SAS**
1	−5.097138	0.833200	−0.009876	0.005063
2	2.477660	−0.425941	0.016052	0.000000
3	0.059987	−0.022650	0.002574	0.000702
4	0.016421	0.008033	0.001441	0.000594
5	0.050710	0.103594	0.075309	0.031491
6	−0.018237	−0.051234	−0.049541	−0.020252
7	−0.239838	−0.167497	−0.043074	−0.018011
8	0.003780	0.019331	0.020995	0.000675
9	−0.005835	0.015729	−0.007355	0.002163
10	0.141540	0.089122	0.021392	0.009394
11	−0.005124	0.013311	−0.007858	−0.000077
12	0.015776	−0.010214	0.002168	0.000723
SUM	−2.600298	0.819567	0.022227	0.012465
(b) axial temperature difference of 20 °C				
	SA	**TCO**	**TAS**	**SAS**
1	−5.211499	3.355142	−0.638611	−0.158605
2	2.536341	−1.716229	0.258066	0.000000
3	0.061524	−0.091406	0.041497	0.011318
4	0.017281	0.032641	0.023281	0.009580
5	0.057188	0.430176	1.232672	0.513596
6	−0.021177	−0.214648	−0.815364	−0.331892
7	−0.255248	−0.683044	−0.697381	−0.291197
8	0.004313	0.079608	0.337272	0.010767
9	−0.005732	0.063013	−0.119616	0.034315
10	0.151176	0.364077	0.346858	0.152012
11	−0.005015	0.053220	−0.126959	−0.001451
12	0.016231	−0.041320	0.035062	0.011687
SUM	−2.654617	1.63123	−0.123223	−0.03987

3. Active and Passive Combined Thermal Control Measures

3.1. Thermal Control Measures

3.1.1. Passive Thermal Control Measures

(a) Overall Insulation

For reducing the influence of external environment changes on the temperature inside the system, the camera and outer casing are insulated. The inner surface of the spherical shell is covered with a 4 mm polyurethane foam insulation layer, and then a double-sided aluminum-plated polyester film is attached.

(b) Partial Precision Insulation

To realize active temperature control for the secondary mirror, a heating cover wrapped around the secondary mirror is designed, as shown in Fig. 4. The material of the heating cover is an aluminum alloy. The secondary mirror heating cover is coated with a 1 mm polyurethane foam insulation layer on the side facing the secondary mirror, and a double-sided aluminized polyester film is attached. Moreover, to ensure temperature uniformity of each component inside the system, the main frame, optical component support structure, inner and outer surfaces of the main barrel, and other key parts are blackened by spraying black paint or black anodizing blackening treatment, and emissivity is no less than 0.8.

3.1.2. Active thermal control measures

(a) Precision active thermal control strategy

Active thermal control aims to compensate temperature changes of the environment actively by effective strategies to ensure temperature uniformity. To realize active thermal control measures, firstly temperature sensors are used to measure the temperature of control points. Secondly, temperatures acquired are compared with the target temperature. Thirdly, the working state of heating pieces adhered to the heating cover is adjusted according to temperature difference to ensure the temperature of control points the same as target temperature under ideal conditions. The control range of the primary mirror temperature is -10∼+40 °C. To reduce axial temperature difference of primary and secondary mirrors, the target temperature of the secondary mirror is set to be the average temperature of the current temperature of primary mirror; however, the range of target temperature needs to be controlled within -8 °C to +38 °C to prevent the current temperature of primary mirror deviating too much from its desired temperature. If the primary mirror temperature is less than -8 °C, target temperature of the secondary mirror is set to be -8 °C; if it is greater than 38 °C, the target temperature is set to be 38 °C. The heating area is controlled as the form of switch, and the control threshold is the target temperature ±0.1 °C. Above the target temperature of 0.1 °C, the heating area is powered off; below target temperature of 0.1 °C, the heating area is heated. The control period of the heating area is less than 1 s.

(b) Active Thermal Control Implementation

Electric heating pieces are adopted to realize active thermal control. For the sake of facilitating sticking heating pieces, heating cover conforming to the shape of the spherical shell is added, which is mounted on the spherical shell fixedly. Heating pieces are attached to the side of the heating cover facing the spherical shell, and the whole internal space of system is heated. Fig. 5 shows the front cover with the heat insulation layer and heating pieces attached. What's more, on the back of the primary mirror, there also exists a heating cover, see Fig. 6. The heating pieces attached to secondary mirror heating cover and primary heating cover are shown in Figs. 4 and 6, where heating pieces are attached around the secondary mirror heating cover and to the backside of the secondary mirror, and three fan-shaped heating pieces are attached to the back of primary mirror heating cover to realize temperature control of

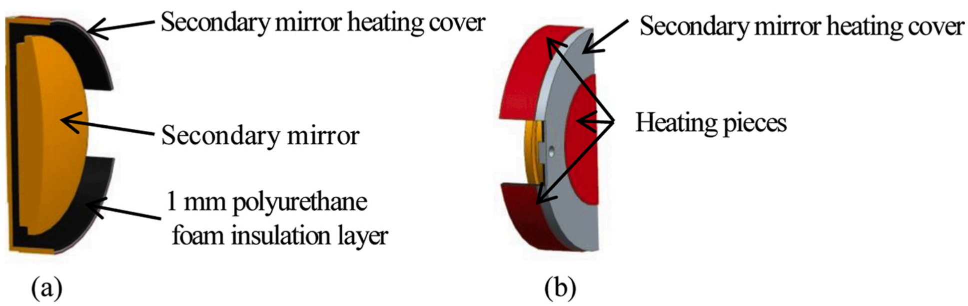

Fig. 4. (a) secondary mirror heating cover and insulation layer (b) heating pieces on secondary mirror heating cover.

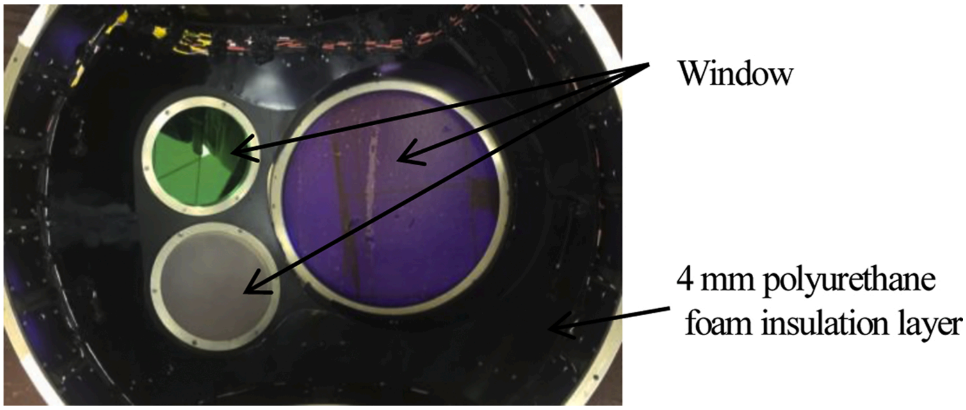

Fig. 5. Front cover with thermal insulation and heater.

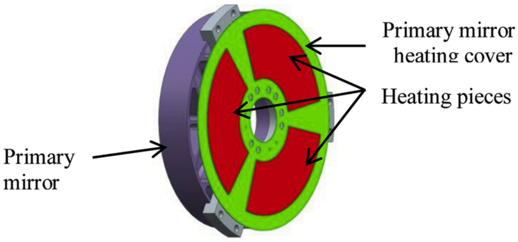

Fig. 6. Primary mirror heating cover and heating pieces on it.

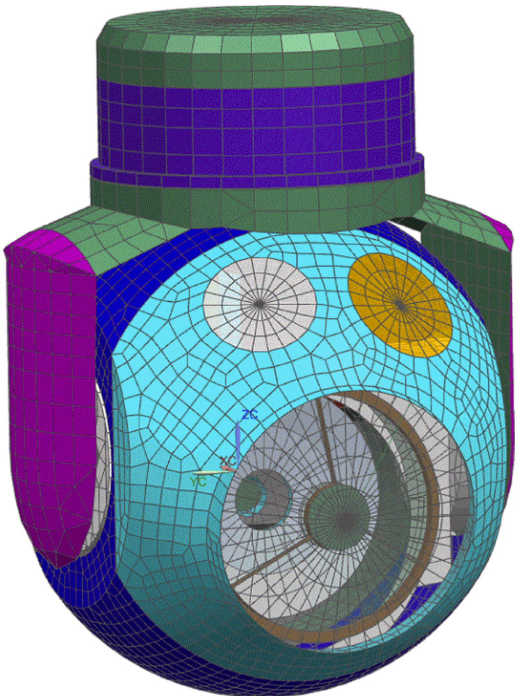

Fig. 7. Photoelectric platform system thermal model.

Table 2
Three-order aberration of telefocal common aperture photoelectric sensor platform system.

(a) three-order aberrations in the system without thermal control				
	SA	TCO	TAS	SAS
1	−5.166513	2.627500	−0.039540	0.009826
2	2.511096	−1.035600	0.015948	0.000000
3	0.060884	−0.421679	0.002548	0.000694
4	0.016935	−0.022369	0.001423	0.000587
5	0.054226	0.007860	0.072927	0.030656
6	−0.018916	−0.098214	−0.047592	−0.019587
7	−0.248359	−0.047947	−0.042377	−0.017756
8	0.003087	0.163013	0.020880	0.000678
9	−0.005776	0.018538	−0.007187	0.002189
10	0.146530	0.086513	0.021000	0.009249
11	−0.005001	−0.010053	−0.007749	−0.000058
12	0.016035	−0.009873	0.002136	0.000712
SUM	−2.635772	1.171176	−0.007583	0.01719
(b) three-order aberrations in the system with thermal control				
	SA	TCO	TAS	SAS
1	−3.208564	1.350010	−0.041165	0.008656
2	2.205493	−1.021467	0.020887	0.000000
3	0.057403	−0.022681	0.002354	0.000723
4	0.028854	−0.011696	0.001112	0.000461
5	0.054000	0.008860	0.068950	0.031228
6	−0.027865	−0.053564	−0.034652	−0.018335
7	−0.055893	−0.100756	−0.064581	−0.016842
8	0.023407	0.037855	0.023859	0.000654
9	−0.015799	0.049331	−0.007350	0.002241
10	0.017021	0.001875	0.025364	0.008336
11	−0.018652	−0.023884	−0.007869	−0.000050
12	0.018854	−0.004652	0.002358	0.000703
SUM	−0.921741	0.249231	−0.010330	0.017775

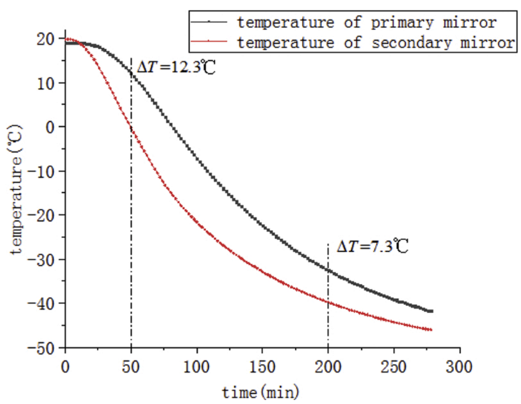

Fig. 8. Temperature curve of primary and secondary mirrors without active thermal control under low-temperature conditions.

primary and secondary mirrors.

3.2. Thermal Optics Analysis

The thermal analysis model of telefocal common aperture photoelectric platform system is shown in Fig. 7. There are 9356 grid cells and 11003 nodes, and 154 thermally coupled heat transfer channels in total. During the simulation process, heat transfer, convection, and radiation conditions are considered.

Mechanical analysis of the system was performed using the finite element model described above by software NX-Nastran. Then the nodal displacement of the optical surface is brought into optical analysis software CODE V for optical analysis. The analysis results of three-order aberrations of the imaging system without thermal control measures and with thermal control measures are obtained respectively shown in Table 2. It can be seen that after adopting the proposed active-passive combined thermal control measurements, the spherical aberration of the system is reduced from 2.635772 to 0.921741, while coma is reduced from 1.171176 to 0.249231. The

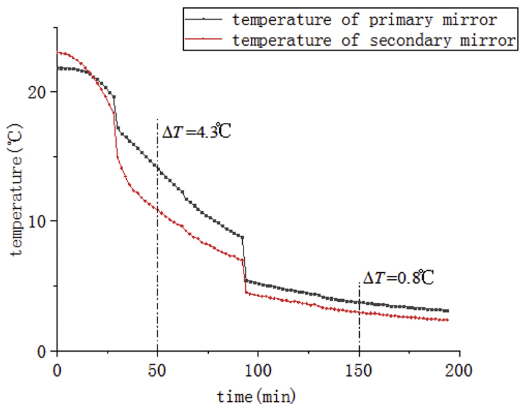

Fig. 9. Temperature curve of primary and secondary mirrors with active thermal control under low-temperature conditions.

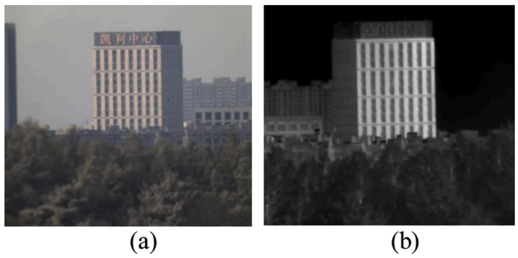

Fig. 10. Actual image of a building by aerial telefocal common aperture photoelectric platform system under active-passive combined thermal control measures (a) image by a visible camera during the day (b) image by an infrared camera at night.

main aberration is spherical aberration, which can be compensated by focusing function. It may be concluded that the image quality can be improved by the proposed thermal control measures.

3.3. Test verification

To further verify whether the proposed thermal control technology can reduce the axial temperature difference between primary and secondary mirrors and guarantee temperature level effectively, the test was carried out under normal operating conditions. The telefocal common aperture photoelectric platform system is placed in a high-low temperature chamber. The initial temperature of primary mirror, secondary mirror and environment are all 20 °C, meanwhile, initial pressure is normal pressure. Within 40 minutes, the environment temperature inside the chamber is lowered to -55 ℃ gradually. When there are only passive thermal control measures, the temperature level of primary and secondary mirrors is shown in Fig. 8. As time goes by, the temperature level of primary and secondary mirrors decreases gradually, finally stabilizes at around -45℃. At the first 125 minutes, decrease speed is quick and then slowed down. During the working period, the axial temperature difference between primary and secondary mirrors is always greater than 5 ℃. According to the discussion in Section 2.2, excessive coma introduced by big axial temperature difference would result in poor imaging quality. Thus, it seems that only the passive thermal control method cannot guarantee the effective operation of the telefocal common aperture photoelectric platform. It is necessary to adopt active thermal control measures.

Fig. 9 shows the primary and secondary mirror temperature change curves under normal operating conditions with active thermal control measures. In the first 50 minutes, the temperature of primary and secondary mirrors also decreases, but decrease speed is slower than that without active thermal control. After 100 minutes, the temperature of primary and secondary mirrors tends to be stable in the range of 0 to 10 °C, which is increased by about 50 ℃ compared to the case without active thermal control. Also, the axial temperature difference of primary and secondary mirrors is always smaller than that of without active thermal control measures. At beginning, the difference is big, then decreases with time, finally stabilizes at around 0.8 °C.

In summary, the active-passive combined thermal control method can guarantee the temperature uniformity of primary and secondary mirrors and reduce the axial temperature difference between the two mirrors under normal operating conditions.

3.4. Actual Imaging Results

Fig. 10 shows the actual image of a building other than 12 km taken by a telefocal common aperture platform at an external field imaging test, of which the window width is 2 m. On the left, there is the image taken by a visible camera during the day, while the right one is the image acquired by an infrared camera at night. During the whole process, the thermal control system is running. From the clear image, it is estimated that the 138 × 14 mmedium-sized ship can be identified and detected more than 50 km.

4. Conclusion

For an aerial telefocal common aperture photoelectric platform, focusing on the characteristics of large changes in working environment temperature, a precise thermal control technology is proposed considering the system structure and the principle of active-passive combined thermal control technology. The simulation results obtained by thermal optics analysis show that the proposed thermal control technology can reduce spherical aberration and coma of the optical system greatly, which is conducive to obtaining high-resolution images. The test under extremely low temperature proves that the temperature level of primary and secondary mirrors is improved and the axial temperature difference between the two mirrors is reduced with the proposed technology. Besides, the actual image obtained by an aerial telefocal common aperture photoelectric platform has a good quality, which verifies further that the precise thermal control technology is valid and reliable.

Funding Information

This research was funded by the National Natural Science Foundation of China, grant number 61905240, and the National Natural Science Foundation of China, grant number 61675202.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgments

We thank for the support from the Key Laboratory of Airborne Optical Imaging and Measurement, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences.

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