# Developing a thermal control strategy with the method of integrated analysis and experimental verification 

Weiyi Liu ${ }^{\text {a,b,* }}$, Honghai Shen ${ }^{\text {a,b }}$, Yongsen $\mathrm{Xu}^{\mathrm{a}, \mathrm{b}}$, Yulong Song ${ }^{\mathrm{a}, \mathrm{b}}$, Haixing Li ${ }^{\mathrm{b}}$, Jiqiang Jia ${ }^{\text {b }}$, Yalin Ding ${ }^{\mathrm{a}, \mathrm{b}}$<br>${ }^{\text {a }}$ Key Laboratory of Airborne Optical Imaging and Measure, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Dongnanhu Road 3888, Changchun 130032, China<br>${ }^{\text {b }}$ Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Dongnanhu Road 3888, Changchun 130032, China

## A R T I C L E I N F O

## Article history:

Received 21 April 2014
Accepted 30 May 2015

## Keywords:

Integrated analysis
Aerial camera
Thermal design


#### Abstract

A low-power limit was encountered during the design of an aerial camera's thermal control system. It must meet both low-power limit and high image quality. In order to ensure the camera's image quality measured by the modulation transfer function (MTF), the authors studied the camera with the method of integrated analysis: First calculating the nodal displacements according to the boundary conditions, after that, using Zernike polynomials to express the surface figure changes, then calculating the MTF. According to this process, the authors studied the temperature field's effect on the MTF, found a suitable one for the camera, and developed a thermal control strategy for the camera which met the low-power limit. The analysis was confirmed by the experimental data and the test results met the requirements of the camera's imaging.


© 2015 Elsevier GmbH. All rights reserved.

## 1. Introduction

An aerial mapping camera was designed for long time surveying work. It was large-array and high-precision one. Long time working outside the aircraft would be subject to the impact of the external environment, which made the camera's temperature distribution changes and reduced the accuracy of surveying and mapping. [1-4] So it needed a temperature control system. The authors' job was to design a suitable one for the camera.

The ideal temperature control system was able to make the whole camera work under conditions at room temperature ( $20^{\circ} \mathrm{C}$ ) all the time. If the camera was in the extreme cold conditions and worked for a long time ( 10 h ), to keep the whole camera being at the design temperature $\left(20^{\circ} \mathrm{C}\right)$, the system required at least 1.6 kW . However, the total power that allocated to the temperature control system was only 900 W .

To solve this problem, the authors need to consult with the general technical unit: either increase the temperature system's power, either reduce the target temperature, or find out a mutually acceptable solution.

[^0]In this paper, the authors reconsidered the camera's thermal control indicators, found a suitable temperature field for the camera by integrated analysis, and then redesigned a thermal control system which met both the low power and high image quality.

## 2. The introduction of the camera

The camera's shape: The camera's overall dimension is $\Phi 400 \mathrm{~mm} \times 500 \mathrm{~mm}$, and it has two symmetrical lens groups inside its interior, as seen in Fig. 1.

The camera's installation: The camera was embedded in aircraft, and was connected to the platform. The lens group was fixed by flanges to the camera (Fig. 2).

The camera's external environment: When the camera was working, the temperature of the air outside was $-17.5^{\circ} \mathrm{C}$; the flight speed was about $120 \mathrm{~m} / \mathrm{s}$; the working time was about 10 h .

## 3. Description of the process of determining thermal control indicators

To reconsider the thermal control indicators, the method of integrated analysis must be used. Integrated analysis method has been applied to various aspects [5-11]. It was a combination process of thermal, mechanical and optic. It should have several preconditions: the optical design and structural design of the camera should


Fig. 1. The overall camera.

atmosphere
Fig. 2. The camera's installation.


Fig. 3. The process's flow chart.
be initially completed; the camera's finite element thermal analysis and finite element analysis of structural mechanics should be done; the camera's MTF could be calculated in accordance with changing conditions. The flow chart was shown in Fig. 3. First, obtaining the temperature distribution by analysis and calculation, or just assuming a temperature field; then building the finite element model, calculating the camera's node displacements according to the temperature field and the support, connections, gravity and other mechanical boundary conditions; third expressing each surface's changes by Zernike polynomials, which were widely used in optics [12-16], according to the node displacements; last calculating the MTF with the changing surfaces and verifying if the temperature field was acceptable.

In this paper, the temperature field analysis, nodal displacement deformation's calculation, Zernike polynomial's fitting, and MTF's calculation were, respectively, performed by software IDEAS-TMG, NX-nastran, Sigfit and Zemax.

According to the boundary conditions of the camera in part 2, if there were no implementation of thermal control measures, the camera's temperature field, nodal displacement deformation and


Fig. 4. Equilibrium temperature and nodal displacements without thermal control.


Fig. 5. MTF at room temperature and outside aircraft.

MTF could be obtained by each corresponding software. The results could be seen as in Figs. 4 and 5. Fig. 4 showed the equilibrium temperature and the corresponding nodal displacement deformation outside aircraft. Fig. 5 showed the MTFs at room temperature (designed MTF) and in the equilibrium temperature outside aircraft, respectively. As could be seen, when the spatial frequency in cycles per mm was 30 , the MTF value had dropped to 0 . So it is necessary to take temperature control. As mentioned in the introduction, the system power was limited. To meet the requirements of the MTF in condition of low power, first, the temperature field's impact on the MTF should be studied.

## 4. The impact of temperature on the MTF

The impact of temperature on the MTF was reflected in two aspects: changes in temperature made the material expansion and contraction, which would cause the optical face's changes; temperature changes cause changes in refractive index of the lens. In this camera's working conditions, the temperature fluctuation's range was not very large(less than $20^{\circ} \mathrm{C}$ ), and the change in refractive index was less than $2 e-5$. So only the optical face's changes would be considered and changes in refractive index would be ignored in this paper.

The following three cases would illustrate the impact of optical face changes caused by temperature on the MTF.

Case1: the camera overall had axial temperature difference, with the upper part $20^{\circ} \mathrm{C}$, and the lower part $0^{\circ} \mathrm{C}$. The temperature gradually decreased from the upper to the lower. The temperature distribution was shown in Fig. 6a. Under this condition, the camera's node displacements and MTF were, respectively, calculated and shown in Fig. 6 b and c , according to the process in part3.

Case2: the camera overall had radial temperature difference, with the edge $20^{\circ} \mathrm{C}$, and the center $15^{\circ} \mathrm{C}$. The temperature gradually decreased from the center to the edge. The temperature distribution was shown in Fig. 7a. Under this condition, the camera's node displacements and MTF were respectively calculated and shown in Fig. 7b and c.

Case3: the camera overall had axial temperature difference, with the upper part $0^{\circ} \mathrm{C}$, and the lower part $20^{\circ} \mathrm{C}$. The temperature gradually increased from the upper to the lower. It was just contrary to the case1. The temperature distribution was shown in


Fig. 6. Temperature distribution, node displacements and MTF in case1.


Fig. 7. Temperature distribution, node displacements and MTF in case2.

Fig. 8a. The camera's node displacements and MTF were, respectively, calculated and shown in Fig. 8b and c.

In case 1 and case2, the maximum temperature differences were $20^{\circ} \mathrm{C}$ and $10^{\circ} \mathrm{C}$, respectively; and the maximum displacements were 0.0235 mm and $8.456 \mathrm{E}-3 \mathrm{~mm}$, respectively. Both the maximum temperature difference and displacement in case1 were larger than in case2, but higher MFT than in case2.

In case 1 and case 3 , both the maximum temperature differences were $20^{\circ} \mathrm{C}$; and the maximum displacements were 0.0235 mm and 0.0203 mm , respectively. The maximum displacements were basically the same while the MTF was much higher in case 1 than in case3.

As could be seen above, the maximum temperature difference and maximum displacement had no direct linear relationship with the MTF; different temperature distribution had different effects on the MTF.

The author's aim was to find a temperature field which was easy to maintain, with low power consumption and little declining on the MTF compared to the case at room temperature.

The authors repeated the steps in part3 and analyzed a variety of temperature fields on the MTF, including axial differences: upper hot while bottom cold and the reverse, middle hot while sides cold and the reverse, uniform temperature distribution; radial difference: edge hot while center cold and the reverse, uniform


Fig. 8. Temperature distribution, node displacements and MTF in case3.
temperature distribution; and permutation and combinations of them - That's 15 temperature fields in all.

The authors found that in a number of calculation results: the MTF was not only related to the optical design, the temperature distribution and optical surface changes, but also related to the mechanical design (connections, supports, fixed mode, etc.).

In this camera, for example, the most sensitive place to the MTF was near the part of camera's support flange, while at a distance from the flange, it was not so much sensitive. In another word, the components near the flange were temperature sensitive parts.

## 5. Integrated analysis

Based on the above analysis, the authors conducted a temperature field design suitable for the mapping camera: the components near the flange portion was pasted on heating film to ensure the temperature stable at $20^{\circ} \mathrm{C}$; the components far away from the flange portion, which were just the parts in contact with the atmosphere, were pasted on both insulation materials and heating films, however the heating target temperature was no longer $20^{\circ} \mathrm{C}$ but lower(from $0^{\circ} \mathrm{C}$ to $10^{\circ} \mathrm{C}$, related with altitude), which could effectively reduce the power. Under this condition, the finite element thermal analysis was simulated. When the camera's temperature got equilibrium, it could be seen as Fig. 9a. The parts near the flange portion maintained the temperature at $20^{\circ} \mathrm{C}$, and the parts in contact with the atmosphere were about $-10^{\circ} \mathrm{C}$. The total power was 700 W , less than the overall 900 W available. Similarly, according to the steps in part3, the calculated nod displacements and MTF were respect shown in Fig. 9b and c. Looking at the results from the analysis, this design met both the low-power and the high MTF.

## 6. Experiment

The purpose of the experiment was to test the camera's MTF in the equilibrium temperature, which was obtained under the combined effects of low temperature environment and thermal control system's working. The equilibrium temperature needed to be simulated in the experiment.

The thermal control system was needed to keep the equilibrium temperature. There were 12 temperature sensors in all to test the temperature during the experiment. They were evenly placed on the lens barrel's upper, middle and bottom, respectively.

The whole camera was placed in the chamber of high-low temperature and pressure. Inside the chamber, the temperature was set


Fig. 9. Temperature distribution, node displacements and MTF with thermal control.


Fig. 10. Experiment equipment.


Fig. 11. Temperatures changing with time.
at $-17.5^{\circ} \mathrm{C}$, and there was air flow circulation. Beside the chamber, there equipped a $2 \mathrm{~m} \times 5 \mathrm{~m}$ optical platform. The CTE Tester was on it and could provide targets and test the MTF through the chamber's optical window. See as Fig. 10.

The chamber and the camera's thermal control system continued to work 5 h to ensure the camera's temperature get equilibrium. The temperatures changing with time were measured by the 12 sensors and they could be seen as in Fig. 11. According to the test data, when it got to 3.5 h , the camera had reached


Fig. 12. MTF of experiment test and theoretical calculation.
temperature equilibrium, and the temperature distribution was basically the same as Fig. 9a.

The MTF was tested and it could be seen in Fig. 12. The real testing MTF's trends were basically the same as the theoretical calculation. The testing value was a little lower. This difference was caused by a variety of factors, such as the difference between the model and the actual device, the difference between the calculation temperature and the real one, the error during testing, the error caused by the instrument, etc. It was inevitable. The test results meet the requirements of the camera's imaging. By now, the contradiction mentioned in the paper has been solved.

## 7. Conclusion

The authors experienced a contradiction between a low power consumption and high MTF requirement in the design of thermal control system. According to integrated analysis, the authors studied the influence of temperature on the MTF, Re-planned the camera's thermal control targets, and found a suitable temperature field for the camera to resolve the contradiction. The experimental data verified the correctness of the analysis, and the test results were consistent with the analysis.

## References

[1] Z.G. Li, X. Huai, L.F Y.J. Tao, et al., Analysis of thermal effects in an orthotropic laser medium, Appl. Opt. 48 (2009) 598-608.
[2] J. Choi, M. Jeong, J. Yoo, M. Seo, A new CPU cooler design based on an active cooling heatsink combined with heat pipes, Appl. Therm. Eng. 44 (2012) 50-56.
[3] W.Y. Liu, Y.L. Ding, Q.W. Wu, J.Q. Jia, L. Guo, L.H. Wang, Thermal analysis and design of the aerial camera's primary optical system components, Appl. Therm. Eng. 38 (2012) 40-47.
[4] Joseph J. Talghader, Anand S. Gawarikar, Ryan P. Shea, Spectral selectivity in infrared thermal detection, Light: Sci. Appl. 1 (2012) e24, http://dx.doi.org/10. 1038/lsa. 24
[5] Wei Xiong, Yun Shen Zhou, Xiang Nan He, Yang Gao, Simultaneous additive and subtractive three-dimensional nanofabrication using integrated two-photon polymerization and multiphoton ablation, Light: Sci. Appl. 1 (2012) e6, http:// dx.doi.org/10.1038/lsa. 6
[6] Hongman Kim, David Fried, Peter Menegay, Grant Soremekun, Christopher Oster, Application of integrated modeling and analysis to development of complex systems, Procedia Comput. Sci. 16 (2013) 98-107.
[7] Qi Wu, Jeremiah P. Turpin, Douglas H. Werner, Integrated photonic systems based on transformation optics enabled gradient index devices, Light: Sci. Appl. 1 (2012) e38, http://dx.doi.org/10.1038/lsa. 38
[8] Daoxin Dai, Jared Bauters, John E. Bowers, Passive technologies for future largescale photonic integrated circuits on silicon: polarization handling, light nonreciprocity and loss reduction, Light: Sci. Appl. 1 (2012) e1, http://dx.doi.org/ 10.1038/lsa. 1
[9] B.S. Rho, S.H. Hwang, J.W. Lim, et al., Intra-system optical interconnection module directly integrated on a polymeric optical waveguide, Opt. Express 17 (2009) 1215-1221.
[10] Jianfa Zhang, Kevin F. MacDonald, Nikolay I. Zheludev, Nonlinear dielectric optomechanical metamaterials, Light: Sci. Appl. 2 (2013) e96, http://dx.doi. org/10.1038/lsa. 52
[11] B.S. Rho, S.H. Hwang, J.W. Lim, et al., Intra-system optical interconnection module directly integrated on a polymeric optical waveguide, Opt. Express 17 (2009) 1215-1221.
[12] Sonam Singh, Dinesh Ganotra, Wavefront fitting and comparison of camera aberrations using Zernike circle polynomials, Optik 124 (2013) 2379-2386.
[13] Peter Liebetraut, Sebastian Petsch, Jens Liebeskind, Hans Zappe, Elastomeric lenses with tunable astigmatism, Light: Sci. Appl. 2 (2013) e98, http://dx.doi. org/10.1038/lsa. 54
[14] Hanshin Lee, Use of Zernike polynomials for efficient estimation of orthonormal aberration coefficients over variable noncircular pupils, Opt. Lett. 35 (2010) 2173-2175.
[15] Z.R. Zheng, X.T. Sun, X. Liu, P.F. Gu, Design of reflective projection lens with Zernike polynomials surfaces, Displays 29 (2008) 412-417.
[16] Q. Zhang, Z. Wu, A carrier removal method in Fourier transform profilometry with Zernike polynomials, Opt. Laser. Eng. 51 (2013) 253-260.


[^0]:    * Corresponding author at: Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Dongnanhu Road 3888, Changchun 130032, China. Tel.: +86 043186708038.

    E-mail address: 2219101@163.com (W. Liu).
    http://dx.doi.org/10.1016/j.ijleo.2015.05.138 0030-4026/© 2015 Elsevier GmbH. All rights reserved.

