Modeling and Simulation Analysis of Optical Axis Pointing Error of Aerial Complex Optomechanical System

Hao Liu[1], Xiaoqin Zhou[1*], Qiang Liu[1], Runda Ma[1], Mingming Lu[2], Jieqiong Lin[2] and Meng Ma[1]

[1]School of Mechanical and Aerospace Engineering, Jilin University, Changchun, Jilin Province, China

[2]School of mechanical Engineering, Changchun University of Technology, Changchun, Jilin Province, China

*Corresponding author

Keywords: Aerial complex optomechanical system, Pointing error, Modeling, Simulation analysis.

Abstract. In recent years, the aerial complex optomechanical system has developed greatly. The imaging quality is the most important indicator for judging the optomechanicall system. And the accuracy of optical axis pointing is the basic guarantee for imaging quality. The geometric error of the shafting existing in manufacturing is an important factor affecting the pointing accuracy of the optical axis. The correspondingly relationship between the shafting error and the optical axis pointing accuracy is established through the modeling and analysis of the geometric error of the shafting. Do the foundation for further deepening research.

Introduction

With the continuous development of science and technology, aerial complex optomechanical system plays an increasingly important role in resource exploration and military reconnoissance, and at the same time puts higher and higher requirements on the optical axis pointing accuracy of optomechanical system[1]. Only the optical axis pointing accuracy meets design requirements to ensure a complete and clear ground image in the aerial working environment. The optical axis pointing error of an aerial complex optomechanical system is caused by a multi-faceted error coupling. The most important error comes from the geometric error of the shafting. In this paper, taking the two-axis optomechanical system as an example, by analyzing the above geometric error sources and the influence on the optical axis pointing accuracy[2], the correspondingly relationship between the error and the optical axis pointing accuracy is obtained, and an accurate mathematical model is established. By importing the mathematical model into the MATLAB, the influence of various errors for the pointing accuracy can be obtained.

Analysis of Geometric Error Sources

The structure of the optomechanical system is mainly composed of two rotating shaft systems and a supported photoelectric imaging system[3]. As shown in Figure 1, the yaw axis connects the whole optomechanical system with the aircraft, and the internal pitch axis is the photoelectric imaging load. Through the rotation of the yaw axis and the pitch axis, the purpose of capturing the ground scene is achieved. And the error mainly comes from the geometric error generated by the two rotating shafting[4]. According to the nature of the error, the above error can be divided into static error and dynamic error. As the name implies, the static error refers to the error in the shafting when it is stationary, mainly including the shaft verticality error and the shaft intersection error[5]; the dynamic error refers to the error generated during the rotation of the shafting, mainly referring to the shaft rotation error. In order to clearly express the geometric error[6], establish the coordinate system as shown in Figure 2.

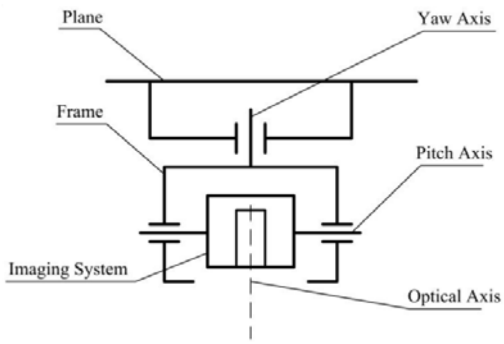

Figure 1. Mechanism of Yaw-pitch aerial camera

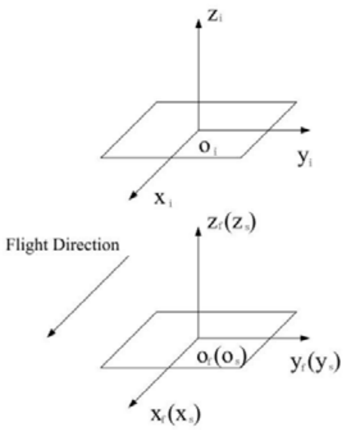

Figure 2. Reference coordinate system

Inertial Coordinate System {i}

This coordinate system is the reference coordinate system, and only the shafting error is considered in this paper, so the origin of the inertial coordinate system is set at the intersection of the yaw axis and the pedestal of the aircraft, and the aircraft coordinate system is considered to be the inertial coordinate system. The x-axis is the flight direction of the aircraft, the z-axis is the vertical axis, and the y-axis is set up in accordance with the right-hand coordinate system.

Frame Coordinate System {f}

This coordinate system is the yaw axis coordinate system. The origin is the intersection of the roll axis and the pitch axis. The x-axis direction is the flight direction of the aircraft, and the z-axis direction is the axial direction of the yaw axis. The y-axis is set up in accordance with the right-handed coordinate system and is obtained by the inertial coordinate system move down x_1 without considering the error.

Imaging Coordinate System {s}

This coordinate system is the pitch axis coordinate system that is the actual imaging coordinate system, and the optical axis pointing vector is **r**. The x-axis direction is the optical axis pointing direction, the y-axis direction is the pitch axis axial direction, and the z-axis direction is determined by the right-hand coordinate system.

Error Modeling

The above analysis establishes the coordinate system of each shafting[7], and then considers the conversion relationship between the coordinate systems in the presence of geometric error, mainly considering the shaft verticality error, the shaft intersection error and the shaft rotation error[8].

The inertial coordinate system {i} to the frame coordinate system {f} is obtained by one coordinate translation without considering the error. In the case of considering the verticality error, there is a yaw axis z_f that is not perpendicular to the plane $x_io_iy_i$. The yaw axis z_f and the yaw axis z_i

has an angle α_1 on the plane $x_io_iz_i$, and the yaw axis z_f and the yaw axis z_i has an angle β_1 on the plane $y_io_iz_i$, as shown in Figure 3. Similarly, it can be concluded that the verticality error of the pitch axis ys and the pitch axis y_f, the pitch axis ys and the pitch axis y_f has an angle α_2 on the plane $x_fo_fy_f$, and the pitch axis ys and the pitch axis y_f has an angle β_2 on the plane $y_fo_fz_f$. The inclination angle error of the yaw axis z_f is α_3 on the plane $x_io_iz_i$ with z_i, and the angle between z_f and z_i in the plane $y_io_iz_i$ is β_3. And the inclination angle error of the pitch axis y_s is α_4 on the plane $x_fo_fy_f$ with y_f, the angle between y_s and y_f is β_4 on the plane $y_fo_fz_f$.

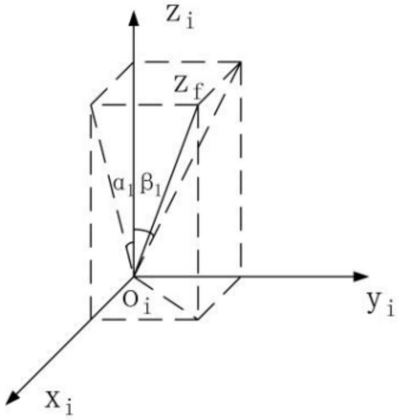

Figure 3. Single angle error ansysis

For the above analysis, the homogeneous transformation matrix between the coordinate systems of the optomechanical system is established by using the multi-body system and the homogeneous coordinate transformation relationship. Without considering the error, assuming that the yaw axis rotation angle is θ and the pitch axis rotation angle is γ, the relationship between the optical axis pointing vector $\mathbf{r_s}$ on the imaging coordinate system {s} and the vector $\mathbf{r_i}$ on the inertial coordinate system {i} is

$$\overrightarrow{r_i} = \overrightarrow{T} \cdot \overrightarrow{r_s} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & x_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos\gamma & 0 & \sin\gamma & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\gamma & 0 & \cos\gamma & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \overrightarrow{r_s} \tag{1}$$

In the case of considering the error, there are many kinds of shafting geometric errors in the process of shafting rotation. It is assumed that the order relationship between the errors is deterministic and correct.

In the conversion process of the imaging coordinate system {s} to the frame coordinate system {f} ,the error angel of the model is α_2,α_4,β_2,β_4.The relationship between the optical axis pointing vector $\mathbf{r_f}$ on the frame coordinate system {f} and the vector $\mathbf{r_s}$ on the imaging coordinate system {s} is

$$\overrightarrow{r_{f'}} = \overrightarrow{T_1} \cdot \overrightarrow{r_{s'}} = \begin{bmatrix} \cos(\alpha_2+\alpha_4) & -\sin(\alpha_2+\alpha_4) & 0 & 0 \\ \sin(\alpha_2+\alpha_4) & \cos(\alpha_2+\alpha_4) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\beta_2+\beta_4) & -\sin(\beta_2+\beta_4) & 0 \\ 0 & \sin(\beta_2+\beta_4) & \cos(\beta_2+\beta_4) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \overrightarrow{r_{s'}} \tag{2}$$

In the conversion process of the frame coordinate system {f} to the inertial coordinate system {i} ,the error angel of the model is α_2,α_4,β_2,β_4.The relationship between the optical axis pointing vector $\mathbf{r_i}$ on the inertial coordinate system {i} and the vector $\mathbf{r_f}$ on the frame coordinate system {f} is

$$\overrightarrow{r_{i'}} = \overrightarrow{T_2} \cdot \overrightarrow{r_{f'}} = \begin{bmatrix} \cos(\alpha_1+\alpha_3) & 0 & \sin(\alpha_1+\alpha_3) & 0 \\ 0 & 1 & 0 & 0 \\ -\sin(\alpha_1+\alpha_3) & 0 & \cos(\alpha_1+\alpha_3) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\beta_1+\beta_3) & -\sin(\beta_1+\beta_3) & 0 \\ 0 & \sin(\beta_1+\beta_3) & \cos(\beta_1+\beta_3) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \overrightarrow{r_{f'}} \quad (3)$$

In the conversion process of the imaging coordinate system {s} to the inertial coordinate system {i}, the error transfer is also performed in sequence. It is concluded that the relationship between the optical axis pointing vector $\mathbf{r_i}$ on the inertial coordinate system {i} and the vector $\mathbf{r_s}$ on the imaging coordinate system {s} is

$$\overrightarrow{r_{i'}} = \overrightarrow{T'} \cdot \overrightarrow{r_{s'}} = \overrightarrow{T_2} \cdot \overrightarrow{T_1} \cdot \overrightarrow{r_{s'}} \quad (4)$$

The pointing accuracy error can be represented by the angle between the two vectors $\mathbf{r_i}$ and $\mathbf{r_{i'}}$.

Error Simulation

Through the modeling and analysis of the geometric error of the shafting, the correspondingly relationship between the optical axis pointing accuracy and the geometric errors of the shafting is obtained, and the imaging accuracy of the optomechanical system can be evaluated to some extent. However, since the obtained formula contains a variety of parameter variables, the evaluation system cannot be obtained intuitively and clearly, so it is considered to further process the data by using MATLAB. To obtain the influence of each error variable for the optical axis pointing accuracy, a single variable is processed on the obtained formula with ensuring that other variables are unchanged. And the shaft verticality error, the shaft intersection error and the shaft rotation error are calculated separately, and the sensitivity of each error to the optical axis pointing accuracy is obtained.

In the analysis process, various data are obtained after parameterizing the actual measured error data, and the random errors choose the appropriate normal distribution random variable. Assume that the pitch axis is rotated by ±20°, and the yaw axis is rotated by ±10°. After the MATLAB analysis, the distribution characteristics of pointing error are shown in Figure 4. The analysis combines the above geometric errors, and have a comprehensive understanding of pointing errors. Then consider whether the impact of a single error on the pointing accuracy can be obtained by analyzing a single error variable. Taking the yaw axis rotation error inclination angle Δθ=20" as an example, the relationship between the yaw axis rotation error inclination angle and the pointing accuracy is obtained as shown in Figure 5.

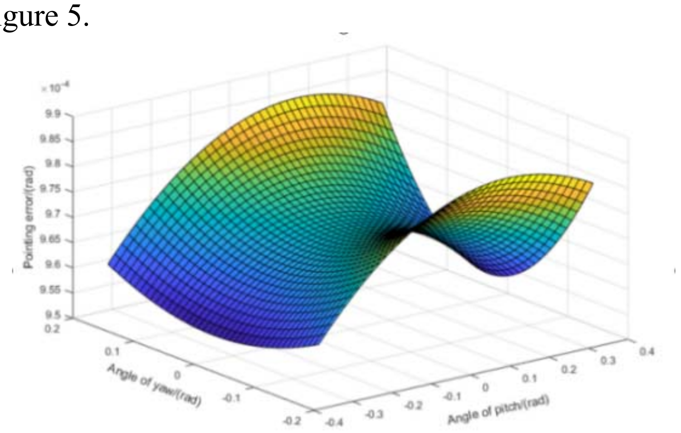

Figure 4. Distribution characteristics of pointing error

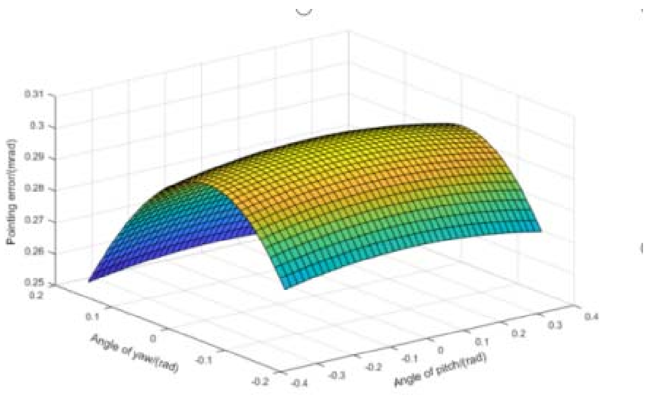

Figure 5. Effect of △θ to pointing error

Conclusion

In this paper, the typical two-axis optomechanical system is taken as an example, through the error modeling and analysis of the optomechanical system, the relationship between the error and the pointing accuracy of the aerial complex optomechanical system is studied. Contributed to subsequent error analysis, compensation and structural optimization.

Acknowledgment

This work was funded by International Cooperation Project of the Ministry of Science and Technology, China (No. 2016YFE0105100) and Graduate Innovation Fund of Jilin University (101832018C191).

References

[1] Alasty A, Abedi H. Kinematic and dynamic sensitivity analysis of a three-axis rotary table[C]// IEEE Conference on Control Applications. IEEE, 2003.

[2] Kiridena V S B, Ferreira P M. Kinematic modeling of quasistatic errors of three-axis machining centers[J]. International Journal of Machine Tools & Manufacture, 1994, 34(1):85-100.

[3] Battistel A, Lizarralde F, Hsu L. Inertially stabilized platforms using only two gyroscopic measures and sensitivity analysis to unmodeled motion[C]// American Control Conference. IEEE, 2012.

[4] Khodadadi H, Motlagh M R J, Gorji M. Robust control and modeling a 2-DOF Inertial Stabilized Platform[C]// International Conference on Electrical, Control and Computer Engineering 2011 (InECCE). IEEE, 2011.

[5] Hurak Z, Rezac M. Image-Based Pointing and Tracking for Inertially Stabilized Airborne Camera Platform[J]. IEEE Transactions on Control Systems Technology, 2012, 20(5):1146-1159.

[6] P. J. Kennedy, and R. L. Kennedy, “Direct versus indirect Line of Sight (LOS) stabilization”, Proc. IEEE Transactions on Control Systems Technology, vol. 11, no. 1, pp. 3-15, January 2003.

[7] J.M. Hilkert, “Inertially stabilized platform technology, concepts and principles”, IEEE Control Systems Magazine, Vol. 28, pp. 26 – 46, 2008.

[8] M. K. Masten, “Inertially stabilized platforms for optical imaging systems, tracking dynamic targets with mobile sensors”, IEEE Control Systems Magazine, Vol. 28, pp. 47 –64, 2008.