

Design and Analysis of a Space Dynamic Test Platform

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Abstract. This paper describes a kind of laboratory simulation test platform. The dynamic coupling model of the simulation test platform has been obtained by using the Newton-Euler equation. According to the inverse-system, the equation can be decoupled, and the decoupling analysis and calculation of the system are performed through the decoupling theorem. As a result, the coupled nonlinear Multiple-Input Multiple-Output system is converted to two linear decoupled Single-Input Single-Output subsystems. The establishment of the mathematical model can provide reference for the design of the controller in the simulation test platform. In order to verify the error of the rotation accuracy of the simulated test platform developed, a reasonable experimental scheme was developed for testing.

Keywords: Simulation Test Platform; Dynamic Coupling; Decoupling.

1. Introduction

The simulation test platform is the key motion environment simulation device in the semi-physical motion simulation. The laboratory uses the motion simulation platform to gradually replace the traditional outdoor test detection method. According to the analysis of the results, the existing problems are found, and the structural part is optimized and designed, which not only shortens the processing time, also greatly reduces the investment of funds and personnel [1]. However, in the actual operation process, there will be a certain coupling relationship between the frames of the simulation test platform, and the coupling effect will have an influence on the interference suppression of the motion control, and a large interference effect will obviously reduce the performance of the entire simulation test platform. It will lead to the loss of control of the entire control system [2,3]. When the two axes of the simulation test platform move at the same time, the moment of inertia of the two axes will change continuously, and then there will be a certain torque coupling between the two axes, and the dynamic coupling will directly affect the static and dynamic properties of the entire system. performance. Therefore, in order to improve the system stability of the simulation test platform and improve the frame coupling effect, the influence of the dynamic coupling effect must be considered. At present, domestic and foreign scholars have done a lot of research on the decoupling of dynamic couplants, and have proposed many decoupling control methods [4,5], such as feedback control decoupling method [6], adaptive robust control method [7], neural network control [8], and acceleration feedforward method [9]. Both the dynamic coupling and the rotation accuracy error will affect the static and dynamic performance of the simulation test platform. Therefore, the dynamic decoupling analysis and the measurement of the rotation accuracy error are carried out in this paper to provide a reference for the structural design and control system design of the simulation test platform.

In this paper, the structure and function of the designed simulation test platform are described, and the dynamic model of the two-axis simulation test platform is established according to the traditional Newton-Euler method. According to the established model, the nonlinear coupling between the pitch frame and the roll frame caused by the angular motion is analyzed in turn. The nonlinear and coupled problems are solved by an inverse systems approach, which transforms the coupled nonlinear dynamic model into two decoupled single-input single-output linear subsystems. In order to verify whether the developed simulation test platform meets the index requirements, the autocollimator method is used to measure the rotation accuracy error of each shaft system.

2. Establishment of Simulation Test Platform Model

When the simulation test platform shown in Fig. 1 is used to simulate the flight attitude of the UAV and carry components for testing, the performance of the simulation test platform will directly affect the performance of the tested components. The simulation test platform mainly has two degrees of freedom, which can realize pitch motion and roll motion. The pitch frame bracket adopts a U-shaped frame, and the roll turntable adopts a T-shaped structure. The shaft system of the pitch frame mainly includes a driving shaft and a driven shaft. The supporting method of the driving shaft adopts double-row angular contact ball bearings with pre-tightening force, which can increase the bearing width of the shaft system and achieve better supporting rigidity moment. The motor directly installs the rotor on the shaft with interference fit, and directly drives the shaft to rotate; the driven shaft is supported by a single bearing; the shaft of the roll turntable is fixed on the working surface of the turntable by screws, and the shaft adopts double-row tapered rollers. Bearings, which can bear radial load and axial load at the same time, can also limit the axial movement of the shaft and the housing within the axial clearance range of the bearing. The rotation angle of each shaft is measured and fed back by the encoder in real time.

Table 1. Main technical indicators of the simulation test platform

	Pitch axis	roll axis
Range of motion($^{\circ}$)	± 45	± 45
$\omega_{max}(^{\circ}/s)$	≥ 90	≥ 90
$\omega_{min}(^{\circ}/s)$	≤ 0.01	≤ 0.01
$\alpha(^{\circ}/s^2)$	150	250
Rotation accuracy(")	± 15	± 15

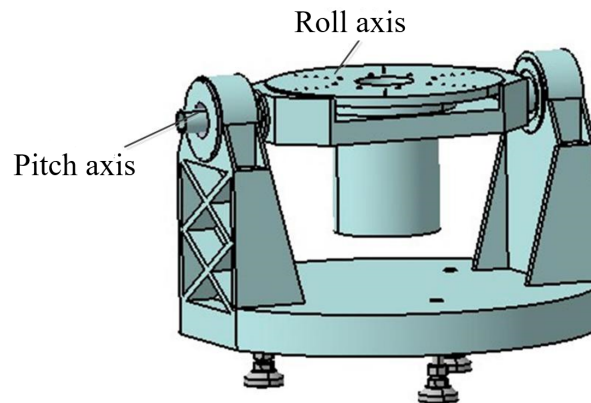


Figure 1. Simulation test platform structure diagram

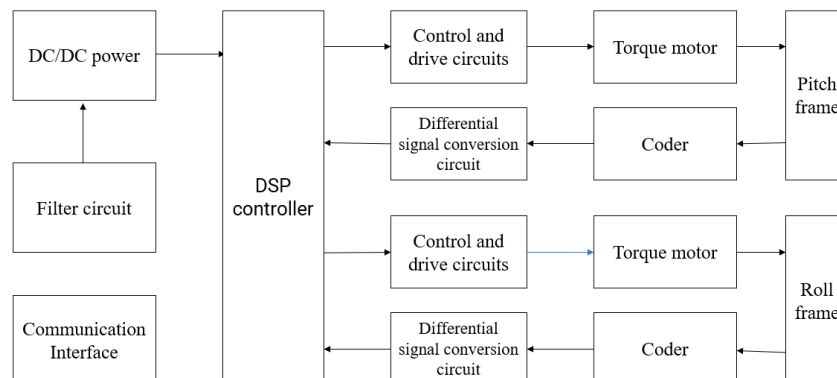


Figure 2. The block diagram of the control principle of the simulation test platform

During the entire motion simulation process, the simulation test platform mainly receives the program input from the computer, sends out signals through the signal processor and drives the torque motor, and simulates pitch and roll motions according to the commanded test platform according to a certain angle, simulating the drone mounted The flight attitude of the airborne aerial camera, the measuring element collects data, transmits the measured angle, angular velocity and other signals to the signal processor, and finally sends the processed feedback signal to the computer to form a closed-loop control. The control principle block diagram of the simulation test platform is shown in Fig. 2.

3. Establishment of Mathematical Models

3.1 Establishment of Dynamic Coupling Equations

In order to obtain a reasonable control scheme, the dynamic coupling characteristics of the simulation test platform are studied. When the simulation test platform is in a non-orthogonal state, the coordinate transformation diagram as shown in Fig. 3 is established, Coordinate system $O-XYZ$ represents the base coordinate system, coordinate system $O-X_pY_pZ_p$ Indicates the pitch frame coordinate system, coordinate system $O-X_rY_rZ_r$ Indicates the roll turret coordinate system. The change of the coordinate system starts when the two axes are in orthogonal positions, first, the pitch frame (including the roll turntable) is rotated counterclockwise around its rotation axis $OY_p(OY)$ by a certain angle α , the roll turntable is then rotated counterclockwise by a certain angle β around its axis of rotation $OZ_r(OZ_p)$.

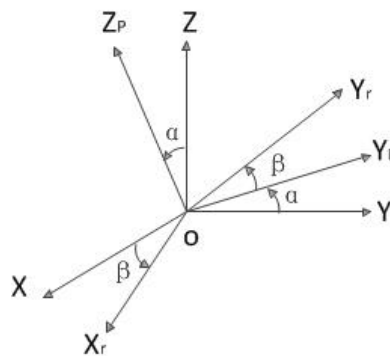


Figure 3. Coordinate system transformation diagram

According to the Euler angle formula, the transformation matrix $R_{\beta\alpha}$ can be obtained as:

$$\begin{aligned}
 R_{\beta\alpha} &= R_r(\beta)R_p(\alpha) = \begin{bmatrix} \cos \beta & -\sin \beta & 0 \\ \sin \beta & \cos \beta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha & -\sin \alpha \\ 0 & \sin \alpha & \cos \alpha \end{bmatrix} \\
 &= \begin{bmatrix} \cos \beta & -\sin \beta \cos \alpha & \sin \beta \sin \alpha \\ \sin \beta & \cos \beta \cos \alpha & -\cos \beta \sin \alpha \\ 0 & \sin \alpha & \cos \alpha \end{bmatrix} \\
 R_p(\alpha) &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha & -\sin \alpha \\ 0 & \sin \alpha & \cos \alpha \end{bmatrix}, R_r(\beta) = \begin{bmatrix} \cos \beta & -\sin \beta & 0 \\ \sin \beta & \cos \beta & 0 \\ 0 & 0 & 1 \end{bmatrix}
 \end{aligned} \tag{1}$$

When the simulation test platform is in normal operation, the relationship between the angular velocity between the relative coordinate system on the pitch frame axis, the roll turntable and the base coordinate system can be known:

$$w_p = [\dot{\alpha} \quad 0 \quad 0] \quad (2)$$

$$w_{p \rightarrow r} = R_{\beta\alpha} w_p = \begin{bmatrix} \cos \beta & -\sin \beta \cos \alpha & \sin \beta \sin \alpha \\ \sin \beta & \cos \beta \cos \alpha & -\cos \beta \sin \alpha \\ 0 & \sin \alpha & \cos \alpha \end{bmatrix} \begin{bmatrix} \dot{\alpha} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \dot{\alpha} \cos \beta \\ \dot{\alpha} \sin \beta \\ 0 \end{bmatrix} \quad (3)$$

Because the angular velocity is a vector, it can be known from the superposition principle of vectors, the angular velocity of the roll turntable fixed coordinate $O-X_r Y_r Z_r$ relative to the base coordinate system $O-XYZ$ is equal to the pitch frame fixed coordinate system $O-X_p Y_p Z_p$. The angular velocity relative to the base coordinate system $O-XYZ$ and the roll turntable fixed coordinate $O-X_r Y_r Z_r$. Relative to the pitch frame fixed coordinate system $O-X_p Y_p Z_p$, the vector sum of the transformed angular velocities of, therefore, the angular velocity of the fixed coordinate $O-X_r Y_r Z_r$ of the roll turntable relative to the base coordinate system $O-XYZ$ can be obtained according to the superposition principle of vectors:

$$w_r = w_{p \rightarrow r} + w_p = \begin{bmatrix} \dot{\alpha} \cos \beta \\ \dot{\alpha} \sin \beta \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \dot{\beta} \end{bmatrix} = \begin{bmatrix} \dot{\alpha} \cos \beta \\ \dot{\alpha} \sin \beta \\ \dot{\beta} \end{bmatrix} \quad (4)$$

Define the moment of inertia of each axis system: J_{x_p} is the moment of inertia of the pitch frame rotating around the x_p axis, J_{y_p} is the moment of inertia of the pitch frame rotating around the y_p axis, J_{z_p} is the moment of inertia of the pitch frame rotating around the z_p axis; J_{x_r} is the moment of inertia of the roll turntable rotating around the x_r axis, J_{y_r} is the moment of inertia of the roll turntable rotating around the y_r axis, J_{z_r} is the moment of inertia of the roll turntable rotating around the z_r axis.

Set $\bar{M} = (M_x \quad M_y \quad M_z)^T$ as the moment attached to the rigid body, then according to the second kind of Lagrangian equation of mechanics:

$$\begin{cases} J_x \frac{dw}{dt} - (J_z - J_y)w_y w_z = M_x \\ J_y \frac{dw}{dt} - (J_x - J_z)w_x w_z = M_y \\ J_z \frac{dw}{dt} - (J_y - J_x)w_y w_x = M_z \end{cases} \quad (5)$$

According to the above analysis, the rotational moment components of each axis of the pitch frame and roll turntable coordinate system can be given as follows:

(1) In addition to the axial torque (rotation shaft drive motor), the rotational torque on the roll turntable axis is also subjected to two coupling torques in mutually perpendicular directions, which act on the pitch frame and are directly transmitted to the pitch frame and the base on the stand. The rotational moment of the roll turntable itself can be obtained from formula (5).

Substituting equation (4) into equation (5), we can get:

$$\begin{cases} M_{x_r} = J_{x_r} (\ddot{\alpha} \cos \beta - \dot{\alpha} \sin \beta) - (J_{z_r} - J_{y_r}) \dot{\alpha} \sin \beta \dot{\beta} \\ M_{y_r} = J_{y_r} (\ddot{\alpha} \sin \beta + \dot{\alpha} \cos \beta) - (J_{x_r} - J_{z_r}) \dot{\alpha} \cos \beta \dot{\beta} \\ M_{z_r} = J_{z_r} \ddot{\beta} - (J_{y_r} - J_{x_r}) \dot{\alpha}^2 \sin \beta \cos \beta \end{cases} \quad (6)$$

The axial torque of the roll turntable can be obtained:

$$M_{z_r} = J_{z_r} \ddot{\beta} - (J_{y_r} - J_{x_r}) \dot{\alpha}^2 \sin \beta \cos \beta \quad (7)$$

(2) The rotational torque of the pitch frame is mainly composed of the torque driven by its own torque motor and the coupling torque transmitted by the rotation of the roll turntable. The torque generated by the pitch frame itself driven by the motor can be expressed as:

$$\begin{aligned} M_{x_p} &= J_{x_p} \frac{dw}{dt} + (J_{z_p} - J_{y_p}) w_{z_p} w_{y_p} \\ &= J_{x_p} \ddot{\alpha} \end{aligned} \quad (8)$$

Let the rotational moment of the rotational moment M projected on the coordinate system $O-x_r y_r z_r$ to the coordinate system $O-x_p y_p z_p$ be $H = (H_{x_p} \ H_{y_p} \ H_{z_p})^T$, namely:

$$\begin{aligned} \begin{bmatrix} H_{x_p} \\ H_{y_p} \\ H_{z_p} \end{bmatrix} &= T_\beta^{-1} \begin{bmatrix} M_{x_r} \\ M_{y_r} \\ M_{z_r} \end{bmatrix} = \begin{bmatrix} \cos \beta & -\sin \beta & 0 \\ \sin \beta & \cos \beta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} M_{x_r} \\ M_{y_r} \\ M_{z_r} \end{bmatrix} \\ &= \begin{bmatrix} \cos \beta M_{x_r} - \sin \beta M_{y_r} \\ \sin \beta M_{x_r} + \cos \beta M_{y_r} \\ M_{z_r} \end{bmatrix} \end{aligned} \quad (9)$$

Then according to the force balance principle, the axial moment of the pitch frame can be obtained:

$$\begin{aligned} M_{x_p}' &= M_{x_p} + H_{x_p} = M_{x_p} + \cos \beta M_{x_r} - \sin \beta M_{y_r} \\ &= J_{x_p} \ddot{\alpha} + \cos \beta \left[J_{x_r} (\ddot{\alpha} \cos \beta - \dot{\alpha} \sin \beta) - (J_{z_r} - J_{y_r}) \dot{\alpha} \sin \beta \dot{\beta} \right] \\ &\quad - \sin \beta \left[J_{y_r} (\ddot{\alpha} \sin \beta + \dot{\alpha} \cos \beta) - (J_{x_r} - J_{z_r}) \dot{\alpha} \cos \beta \dot{\beta} \right] \end{aligned} \quad (10)$$

which is:

$$\begin{aligned} M_{x_p}' &= J_{x_p} \ddot{\alpha} + J_{x_r} \ddot{\alpha} \cos^2 \beta - (J_{x_r} + J_{y_r}) \dot{\alpha} \sin \beta \cos \beta - \\ &\quad J_{y_r} \ddot{\alpha} \sin^2 \beta + (J_{y_r} + J_{x_r} - 2J_{z_r}) \dot{\alpha} \dot{\beta} \sin \beta \cos \beta \end{aligned} \quad (11)$$

Through finite element calculation, the moment of inertia of each frame is obtained as: $J_{x_r} = 0.603 \text{Kg.m}^2$, $J_{y_r} = 2.871 \text{Kg.m}^2$, $J_{z_r} = 2.678 \text{Kg.m}^2$, $J_{x_p} = 2.616 \text{Kg.m}^2$, $J_{y_p} = 3.453 \text{Kg.m}^2$, $J_{z_p} = 2.635 \text{Kg.m}^2$, taking it into equations (7) and (11), we can get:

$$\begin{cases} M_{z_r} = 2.678 \ddot{\beta} - 2.268 \dot{\alpha}^2 \sin \beta \cos \beta \\ M_{x_p}' = 2.616 \ddot{\alpha} + 0.603 \ddot{\alpha} \cos^2 \beta - 3.474 \dot{\alpha} \sin \beta \cos \beta - \\ 2.871 \ddot{\alpha} \sin^2 \beta - 1.882 \dot{\alpha} \dot{\beta} \sin \beta \cos \beta \end{cases} \quad (12)$$

3.2 The Establishment of the Mathematical Model of Driving Torque

From the perspective of practical engineering applications, when the motor is working in a stable state, the influence of inductance can be ignored, and the balance equation of the motor voltage can be expressed as:

$$U = T_a \frac{di_q}{dt} + R_a i_q + E_q \quad (13)$$

Where, U is the motor input voltage (V); R_a is the equivalent resistance of the motor (Ω); i_q is the equivalent current of the motor (A); E_q is the equivalent back EMF of the motor (V); Δu is the saturation voltage drop (V).

The relationship between motor torque and motor current can be expressed as:

$$U = R_a i_q + E_q + \Delta u \quad (14)$$

Among them, M_q is the motor torque (N.m); K_m is the motor torque coefficient (N.m / A).

The back EMF of the motor can be written as:

$$E_q = K_E w \quad (15)$$

Among them, K_E is the back EMF coefficient of the motor V.s / rad; w is the motor speed rad / s.

Combining equations (13)-(15) and combining them with equation (12), the models of the two axis control systems can be obtained, namely:

$$U_r = R_{ar} \frac{2.678 \ddot{\beta}}{K_{mr}} - R_{ar} \frac{2.268 \dot{\alpha}^2 \sin \beta \cos \beta}{K_{mr}} + K_{Er} \dot{\beta} + \Delta f_r \quad (16)$$

$$\begin{aligned} U_p = R_{ap} \frac{2.616 \ddot{\alpha}}{K_{mp}} + R_{ap} \frac{0.603 \ddot{\alpha} \cos^2 \beta - 3.474 \dot{\alpha} \sin \beta \cos \beta - 2.871 \ddot{\alpha} \sin^2 \beta}{K_{mp}} \\ - R_{ap} \frac{1.882 \dot{\alpha} \dot{\beta} \sin \beta \cos \beta}{K_{mp}} + K_{Ep} \dot{\alpha} + \Delta f_p \end{aligned} \quad (17)$$

Among them, Δf_r and Δf_p both represent uncertain interference items.

By simplifying the transformation of equations (16) and (17), we can get:

$$\ddot{\beta} = \frac{K_{mr}}{2.678 R_{ar}} U_r + 0.847 \dot{\alpha}^2 \sin \beta \cos \beta - \frac{K_{mr} K_{Er}}{2.678 R_{ar}} \dot{\beta} - \frac{K_{mr}}{2.678 R_{ar}} \Delta f_r \quad (18)$$

$$\begin{aligned} \ddot{\alpha} = \frac{K_{mp}}{2.616 R_{ap}} U_p - 0.231 \ddot{\alpha} \cos^2 \beta + 1.328 \dot{\alpha} \sin \beta \cos \beta + 1.097 \ddot{\alpha} \sin^2 \beta \\ + 0.719 \dot{\alpha} \dot{\beta} \sin \beta \cos \beta + \frac{K_{mp} K_{Ep}}{2.616 R_{ap}} \dot{\alpha} - \frac{K_{mp}}{2.616 R_{ap}} \Delta f_p \end{aligned} \quad (19)$$

According to equations (16) and (17), when the flight simulation platform only performs roll motion, there is no coupling condition, but when the flight simulation platform performs roll motion

and pitch motion at the same time, each moment of inertia will occur to a certain extent. changes, and torque coupling also occurs. In addition, the size of the motion angular velocity and angular acceleration of the flight simulation platform will directly affect the size of the coupling torque, so this factor should be taken into account in the process of building the control system.

3.3 Coupling Analysis and Decoupling Design

Suppose the system state variable is $x_1 = \beta$, $x_2 = \dot{\beta}$, $x_3 = \alpha$, $x_4 = \dot{\alpha}$, then the state equation of the flight simulation platform can be expressed as:

$$\begin{cases} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} x_2 \\ \frac{K_{mr}}{2.678R_{ar}}U_r + 0.847\dot{\alpha}^2 \sin \beta \cos \beta - \frac{K_{mr}K_{Er}}{2.678R_{ar}}\dot{\beta} - \frac{K_{mr}}{2.678R_{ar}}\Delta f_r \\ x_4 \\ \frac{K_{mp}}{2.616R_{ap}}U_p - 0.231\ddot{\alpha} \cos^2 \beta + 1.328\dot{\alpha} \sin \beta \cos \beta + 1.097\ddot{\alpha} \sin^2 \beta \\ + 0.719\dot{\alpha}\dot{\beta} \sin \beta \cos \beta + \frac{K_{mp}K_{Ep}}{2.616R_{ap}}\dot{\alpha} - \frac{K_{mp}}{2.616R_{ap}}\Delta f_p \end{bmatrix} \\ \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} x_1 \\ x_3 \end{bmatrix} \end{cases} \quad (20)$$

Among them, y_1, y_2 are the angle outputs of the roll turntable and the pitch frame.

The state equation of the system can be expressed as:

$$\Sigma: \begin{cases} \dot{x} = f(x, u), x(t_0) = x_0 \\ y = h(x, u) \end{cases} \quad (21)$$

where $x \in R^n$ is the system variable, $u \in R^m$ is the system input, $y \in R^s$ is the system output, f, h, x and u are the system analytic function vectors.

So we get:

$$\det \left[\frac{\partial}{\partial u} (f^2 h) \right] = \begin{bmatrix} \frac{K_{mr}}{2.678R_{ar}} & 0 \\ 0 & \frac{K_{mp}}{2.616R_{ap}} \end{bmatrix} \neq 0 \quad (22)$$

Therefore, it is proved that the system of the flight simulation platform described by equation (20) is controllable and decoupled.

For formula (20), it is set as:

$$\varphi_1 = R_{ar} \frac{2.678}{K_{mr}} \dot{x}_2 \quad (23)$$

$$\varphi_2 = R_{ap} \frac{2.616}{K_{mp}} \dot{x}_4 \quad (24)$$

You can have:

$$U_r = \varphi_1 - R_{ar} \frac{2.268\dot{\alpha}^2 \sin \beta \cos \beta}{K_{mr}} + K_{Er} \dot{\beta} \quad (25)$$

$$U_p = \varphi_2 + R_{ap} \frac{0.603 \ddot{\alpha} \cos^2 \beta - 3.474 \dot{\alpha} \sin \beta \cos \beta - 2.871 \ddot{\alpha} \sin^2 \beta}{K_{mp}} - R_{ap} \frac{1.882 \dot{\alpha} \dot{\beta} \sin \beta \cos \beta}{K_{mp}} + K_{Ep} \dot{\alpha} \quad (26)$$

Add the networks described by equations (25) and (26) as dynamic compensation and state feedback decoupling network strings before Σ , convert Σ to Σ' , which is:

$$\Sigma' : \begin{bmatrix} \dot{x}_1 \\ x_1 \\ \dot{x}_2 \\ x_2 \\ \dot{x}_3 \\ x_3 \\ \dot{x}_4 \\ x_4 \end{bmatrix} = \begin{bmatrix} x_2 \\ \frac{K_{mr}}{2.678R_{ar}} \varphi_1 \\ x_4 \\ \frac{K_{mp}}{2.616R_{ap}} \varphi_2 \end{bmatrix} \quad (27)$$

$$U = \begin{bmatrix} \varphi_1 \\ \varphi_2 \end{bmatrix}, y = \begin{bmatrix} x_1 \\ x_3 \end{bmatrix} \quad (28)$$

Then the system feedback equation of each frame can be obtained as:

$$\left\{ \begin{array}{l} \Sigma'_1 : \begin{bmatrix} \dot{x}_1 \\ x_1 \\ \dot{x}_2 \\ x_2 \end{bmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{K_{mr}}{2.678R_{ar}} \end{bmatrix} \varphi_1 \\ y_1 = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \end{array} \right. \quad (29)$$

$$\left\{ \begin{array}{l} \Sigma'_2 : \begin{bmatrix} \dot{x}_3 \\ x_3 \\ \dot{x}_4 \\ x_4 \end{bmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{bmatrix} x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{K_{mp}}{2.616R_{ap}} \end{bmatrix} \varphi_2 \\ y_2 = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_3 \\ x_4 \end{bmatrix} \end{array} \right. \quad (30)$$

According to the system feedback equation derived above, Σ'_1 and Σ'_2 are both single-input and single-output systems, which can be designed and analyzed with the relevant theoretical knowledge of linear systems. For the two rotations of the flight simulation platform, the changes in speed and acceleration are related to the angular position, the motor drive and the applied load. In theory, the rotation of one frame will not affect the other frame.

4. Experimental Test

There are many reasons for the error of the simulation test platform during the actual operation, the most important of which are the mechanical device itself and the control system. The rotation accuracy error not only affects the results of the measured components, but also has a certain impact on the accuracy of the control system. Therefore, this paper measures the rotation accuracy of the pitch axis and roll axis of the simulation test platform, and the actual simulation test platform to be tested is shown in Fig. 4.



Figure 4. Physical map of the simulation test platform.

The experimental equipment used in this paper mainly includes NORMAT5000 dual-axis photoelectric autocollimator, multi-tooth indexing plate, plane mirror, adjustable bracket, laser aligner and so on. The working principle diagram of NORMAT5000 dual-axis photoelectric autocollimator is shown in Fig. 5.

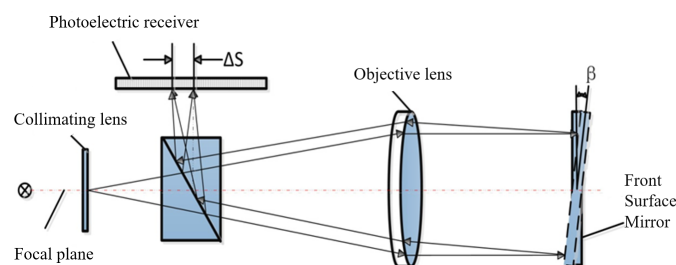


Figure 5. Working principal diagram of NORMAT5000 dual-axis photoelectric autocollimator.

In this paper, two different measurement methods are used to measure the roll axis in the vertical direction and the pitch axis in the horizontal direction. The schematic diagram of the rotation error measurement of the rotary axis is shown in Fig. 6. During the measurement, both methods are rotated 45° clockwise (forward) from the initial position in 15° steps. When measuring the roll axis, a multi-tooth indexing plate and a plane mirror with a bracket are used. Every time the indexing plate is rotated once, the indexing plate is reset to zero at the same angle, and the data is recorded; when measuring the pitch axis, the plane mirror is directly fixed on the shaft end. The rotation angle of each axis of the simulation test platform developed in this paper is not 360°, so the periodic error detection is not carried out. The measurement results are shown in Tables 2 and 3.

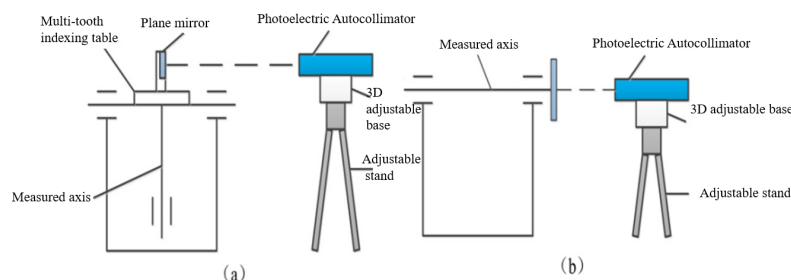


Figure 6. Schematic diagram of rotation error measurement of rotary axis

According to the data in Table 2 and Table 3, the measurement error can be obtained from $\Delta w_1 = \sqrt{\bar{w}_{x1}^2 + \bar{w}_{y1}^2}$, the maximum rotation error of the roll axis is $\pm 3.0''$, less than technical index

$\pm 15''$; the maximum rotation error of the pitch axis is $\pm 3.2''$, less than technical index $\pm 15''$, all meet the design requirements.

Table 2. Roll axis rotation accuracy measurement data

Positive rotation angle	1(")		3(")		5(")		7(")	
	w_x	w_y	w_x	w_y	w_x	w_y	w_x	w_y
0°	0.9	0	1.1	0.2	0.5	0.2	0	0.2
15°	2.5	-1.1	3.2	-0.5	0.5	1.0	2.7	1.4
30°	3.7	1.0	2.5	0.7	2.1	0.6	3.0	1.5
45°	2.8	2.1	4.2	3.1	1.5	-0.3	2.5	0.9
Reversal angle	2(")		4(")		6(")		8(")	
	w_x	w_y	w_x	w_y	w_x	w_y	w_x	w_y
0°	-0.5	0.1	-0.2	0	-1.1	0.1	-0.4	-0.3
-15°	-1.2	-2.3	-1.0	-1.6	-1.1	-1.5	-1.1	0.8
-30°	-2.7	-1.8	-2.1	-0.9	-2.0	-2.3	-2.3	-1.6
-45°	-2.3	-2.1	-3.3	-1.5	-3.9	-2.9	-2.8	-1.0

Table 3. Pitch axis rotation accuracy measurement data

Positive rotation angle	1(")		3(")		5(")		7(")	
	w_x	w_y	w_x	w_y	w_x	w_y	w_x	w_y
0°	1.3	0.4	0.7	0.2	1.4	0.5	0	-0.1
15°	1.8	1.0	1.4	1.0	2.0	1.5	1.0	0.8
30°	2.5	1.4	3.2	2.1	4.2	2.7	2.3	1.2
45°	2.1	2.0	2.5	1.7	3.5	1.9	2.8	2.0
Reversal angle	2(")		4(")		6(")		8(")	
	w_x	w_y	w_x	w_y	w_x	w_y	w_x	w_y
0°	-0.5	-1.0	0	-0.5	-0.7	-0.2	-0.3	0
-15°	-1.6	-1.1	-0.8	-1.2	-2.5	-1.2	-1.8	-0.5
-30°	-2.7	-2.0	-1.5	-1.7	-2.7	-1.8	-3.0	-1.7
-45°	-1.8	-1.5	-2.8	-2.3	-3.2	-2.1	-2.5	-1.3

5. Conclusion

In this paper, the dynamic equation of the simulation test platform is deduced, and its differential equation is deduced according to the established model. The inverse system method is used to prove the decoupling of the equation, and the decoupling analysis of the system is carried out through the decoupling theorem. The nonlinear system is transformed into two linear single-input single-output systems. For the two rotations of the simulated test platform, the changes in velocity and acceleration are related to the angular position, the motor drive and the applied load. In theory, the rotation of one frame has no effect on the other frame. According to the structural characteristics of the simulation

test platform, a reasonable test platform was built, after measurement and calculation, the maximum error of the rotation accuracy of the roll axis is $\pm 3.0'' < \pm 15''$, the maximum error of pitch axis rotation accuracy is $\pm 3.2'' < \pm 15''$, the results meet the requirements of the subject.

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