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STRUCTURE DESIGN AND MOTION ANALYSIS OF 6-DOF SAMPLE POSITIONING PLATFORM BASED ON SPACEFAB STRUCTURE

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Abstract

A six degree of freedom positioning platform based on SPACEFAB structure is studied. The key technologies such as coordinate parameter transformation, kinematics analysis and adjustment decoupling algorithm of 6-DOF sample positioning platform based on SPACEFAB structure are mainly studied. The three-dimensional moving repeat positioning accuracy of the platform is 0.019mm, and the three-dimensional rotating repeat positioning accuracy is 0.012 degrees.

INTRODUCTION

With the development of synchrotron radiation source, the fourth generation of high energy synchrotron radiation source has more stringent requirements on the space size, pose adjustment and positioning accuracy of the sample positioning platform. Some beam line stations require the sample adjustment platform to have centimeter level scanning stroke and nanometer level positioning accuracy. In order to solve the above problems, the project team carried out the research on the adjustment system of SpaceFAB structure, aiming to develop a six degree of freedom nano positioning and attitude adjustment platform with large scanning stroke. The piezoelectric ceramic inertial motor is used as the driving, and the configuration of SPACEFAB is used to realize the nano level pose adjustment. As the basis of the preliminary research of this project, this paper analyzes the structure and motion principle of SPACEFAB, solves the motion decoupling algorithm of the platform, and verifies the feasibility of the motion model algorithm by building the implementation platform. This research will lay a theoretical foundation for the next step of the realization of nano attitude control platform.

STRUCTURE DESIGN OF 6-DOF SAMPLE ADJUSTING PLATFORM

This paper mainly studies the attitude adjustment algorithm of SPACEFAB platform. Considering the convenience of experimental measurement and the cost of platform construction, a 6-DOF platform with micron level adjustment accuracy is built by using the stepper motor mobile components (as shown in Fig. 1) for testing to verify the feasibility of SPACEFAB structure scheme. The structural form of the SPACEFAB platform is shown in Fig. 2 below. The position and posture of the upper loading plate is determined by three support points (ball center of the bearing), and the position of the support points is moved by three groups of adjusting units. Each adjusting unit is composed of two stepper motor moving components. The bottom stepper motor realizes the radial movement of the support point, and the middle stepper motor realizes the tangential movement of the support point. The top cross roller guide is an adaptive layer to realize the height adjustment of support points.

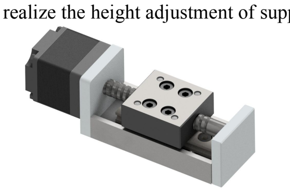


Figure 1: Stepper motor moving stage

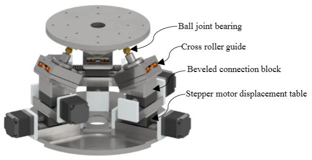
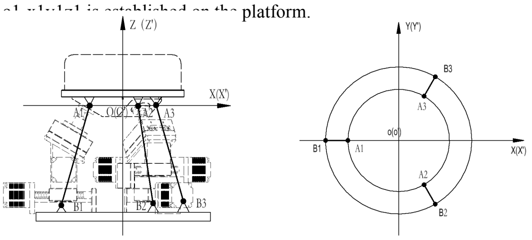


Figure 2: 6-DOF Platform based on SpaceFAB structure driven by stepping motor

COORDINATE TRANSFORMATION OF PLATFORM COORDINATE SYSTEM

The structure of SPACEFAB attitude adjustment platform belongs to three-point supporting precision positioning platform. Each supporting point is supported by two orthogonal motion adjustment units to realize six degree of freedom adjustment of the platform. The motion mechanism is simplified as shown in Fig. 3. The global static coordinate system o-xyz is set at the bottom of the platform, and the moving coordinate system o1-x1y1z1 is established on the platform.



(a)Front view (b)Top view

Figure 3: simplified diagram of 6-DOF Platform

Any transformation of the platform from the global coordinate system to the motion coordinate system can be decomposed into three translation transformations and three rotation transformations, as shown in Fig. 4. The attitude of the platform is uniquely determined by six parameters (roll angle, pitch angle, yaw angle, translation in X, y and Z directions), and the parameters of rotation angle and translation are expressed as $q=[\theta_1, \theta_2, \theta_3, m_4, m_5, m_6]$.

Each translation and rotation of the platform corresponds to a transformation matrix. Assuming that the transformation matrix is T1 to T6, the six motions of the platform are decomposed and multiplied in turn, and the coordinate transformation matrix t of all motion coordinate points of the platform is obtained.

$$T = T_1 \cdot T_2 \cdot T_3 \cdot T_4 \cdot T_5 \cdot T_6$$

$$= \begin{bmatrix} 1 & 0 & 0 & m_4 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & m_5 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & m_6 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} cos\theta_3 & -sin\theta_3 & 0 & 0 \\ sin\theta_3 & cos\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} cos\theta_2 & 0 & sin\theta_2 & 0 \\ 0 & 1 & 0 & 0 \\ -sin\theta_2 & 0 & cos\theta_2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & cos\theta_1 & -sin\theta_1 & 0 \\ 0 & sin\theta_1 & cos\theta_1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

After attitude adjustment transformation, the new upper platform coordinate point is $C = T \cdot A$

INVERSE KINEMATICS ALGORITHM

Inverse kinematics algorithm is to calculate the adjustment of each motor through the moving distance and rotation angle of the platform target. The coordinate changes of each support point of the platform can be calculated by the platform movement and rotation angle, and each support point corresponds to a group of adjustment units. Each adjustment unit contains three layers of cross roller guide, the bottom stepping motor screw assembly realizes the radial movement of the support point along the platform; the middle stepping motor assembly realizes the tangential movement of the support point along the platform; the top cross roller guide realizes the lifting of the support point, as shown in Fig. 5-6. Each layer adjustment corresponds to three variables R, T and L respectively, which can uniquely determine the global coordinates of each upper platform hinge, and its position change matrix ΔA is shown below. Through the pose matrix $C = T \cdot A$, $T \cdot A = A + \Delta A$, the adjusted hinge coordinates are obtained. And the adjustment matrix ΔRTL of each adjusting component is solved by the following determinant.

$$\Delta RTL = \begin{vmatrix} C_{11}+\sqrt{3}C_{31}-\sqrt{3}h-r & -\frac{1}{2}C_{12}+\frac{\sqrt{3}}{2}C_{22}+\sqrt{3}C_{32}-\sqrt{3}h+\frac{1}{2}r & -\frac{1}{2}C_{13}-\frac{\sqrt{3}}{2}C_{23}+\sqrt{3}C_{33}-\sqrt{3}h+\frac{1}{2}r \\ C_{21} & \frac{\sqrt{3}}{2}C_{12}-\frac{1}{2}C_{22}+\frac{\sqrt{3}}{2}r & \frac{\sqrt{3}}{2}C_{13}-\frac{1}{2}C_{23}-\frac{\sqrt{3}}{2}r \\ 2(C_{31}-h1) & 2(C_{32}-h1) & 2(C_{33}-h1) \end{vmatrix}$$

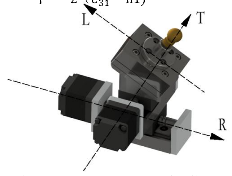


Figure 5: Structure of adjust unit

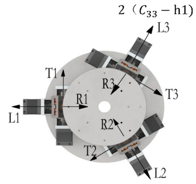


Figure 6: Top view of 6-DOF Platform

DESIGN OF PLATFORM CONTROL SYSTEM

Stepper motor control generally adopts the scheme that PLC sends pulse to stepper motor driver, and the adjustment of the platform needs six stepper motors at the same time, but the common PLC has only two to four high-frequency pulse output ports. For the case of multi motor control at the same time, the cable layout of pulse control mode is more complex.Therefore, this topic uses RS485 bus to drive six stepper motors. The master-slave structure is used between the upper computer and the stepper motor driver. Each driver receives instructions from the upper computer at the same time, as shown in Fig. 7 below.In the process of attitude adjustment of the platform, the closed-loop automatic horizontal adjustment of the platform can be realized through the angle measurement of the inclinometer, as shown in Fig. 8, which is the flow chart of the automatic adjustment of the platform.

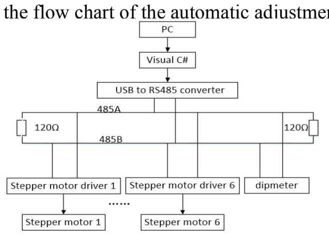


Figure 7 :Structure diagram of platform control system based on RS485 bus

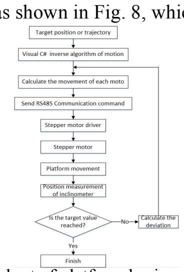


Figure8: Flow chart of platform horizontal adjustment based on inclinometer

ADJUSTMENT ACCURACY TEST

The adjustment accuracy of the six degree of freedom platform is tested by the dial indicator and the inclinometer. The adjustment accuracy of the platform in X, Y and Z directions is measured by the dial indicator, and the rotation accuracy around X, Y and Z axes is measured by the inclinometer. The measurement process is shown in Fig. 9 below.The measurement accuracy of the six degree of freedom platform is shown in Table 1. The three-dimensional movement accuracy of the platform depends on the screw guide pair in the adjusting assembly. The average positioning deviation is 0.018 mm and the maximum repeated positioning deviation is 0.019 mm. The experimental results show that the measured adjustment stroke is consistent with the motion algorithm stroke, which verifies the correctness of the attitude adjustment algorithm. Using the stepper motor moving component with the repeat positioning accuracy of only 0.010mm, the maximum repeat positioning deviation of the whole platform is 0.019mm, and the expected positioning accuracy is achieved. The feasibility of 6-DOF platform with 20nm repetitive positioning accuracy was determined by using 5 nm repetitive positioning accuracy piezoelectric ceramic motor.

Figure 9: Positioning accuracy test of 6-DOF Platform

Table 1：Results of platform positioning accuracy

No.	along X axis /mm		along Y axis /mm		along Z axis /mm		around X axis /°		around Y axis /°		around Z axis /°	
1	-9.983	9.982	-9.981	9.997	5.483	-5.484	9.937	-9.934	7.716	-7.721	14.554	-14.550
2	-9.983	9.978	-9.986	9.995	5.482	-5.485	9.938	-9.932	7.717	-7.720	14.552	-14.550
3	-9.982	9.980	-9.988	9.992	5.482	-5.484	9.935	-9.933	7.715	-7.721	14.552	-14.545
4	-9.985	9.981	-9.992	9.989	5.482	-5.486	9.939	-9.930	7.715	-7.726	14.552	-14.546
5	-9.986	9.985	-9.993	9.990	5.481	-5.484	9.936	-9.936	7.719	-7.727	14.551	-14.546
6	-9.985	9.987	-9.994	9.990	5.481	-5.481	9.930	-9.936	7.719	-7.731	14.551	-14.551
7	-9.980	9.985	-9.995	9.988	5.481	-5.481	9.937	-9.937	7.719	-7.732	14.551	-14.551
8	-9.986	9.985	-9.997	9.984	5.481	-5.481	9.935	-9.933	7.721	-7.732	14.552	-14.551
9	-9.985	9.983	-9.997	9.986	5.481	-5.478	9.935	-9.931	7.721	-7.732	14.552	-14.552
10	-9.983	9.983	-10.000	9.982	5.481	-5.480	9.938	-9.936	7.721	-7.731	14.552	-14.551
average	-9.983	9.983	-9.992	9.990	5.482	-5.482	9.935	-9.933	7.722	-7.728	14.553	-14.551
target	-10	10	-10	10	5.5	-5.5	9.6	-9.6	7.8	-7.8	14.6	-14.6
average positioning error	0.017	-0.017	0.008	-0.010	-0.018	0.018	0.335	-0.333	-0.078	0.072	-0.047	0.049
repeated positioning error	0.006	0.009	0.019	0.015	0.002	0.008	0.009	0.007	0.006	0.012	0.003	0.007

Table 1： Results of platform positioning accuracy

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