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STRUCTURE DESIGN AND MOTION ANALYSIS OF 6-DOF SAMPLE POSITIONING PLATFORM*

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Abstract

With the development of synchrotron radiation source technology, some beamline stations require the sample positioning platform to have a large sample scanning stroke while adjusting the resolution at nanometer level. In order to meet this requirement, a six degree of freedom positioning platform is studied. The key technologies such as coordinate parameter transformation, kinematics analysis and adjustment decoupling algorithm of 6-DOF sample positioning platform are mainly studied. The six degree of freedom platform driven by stepping motor is designed and manufactured, and6-DOF sample positioning platform control system based on bus control is developed, and the adjustment accuracy test is completed. 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. The test results verify the correctness of the theoretical analysis and the rationality of the mechanism design. The research of motion algorithm and control system has important reference value for the development of 6-DOF large stroke nano positioning platform.

PREFACE

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 [1, 2]. At present, the sample adjustment platform of synchrotron radiation source beamline station mainly adopts two structural forms: (1) the superposition combination of multi-layer adjustment platform [3]; (2) the parallel six degree of freedom platform based on Stewart Structure. For the nano parallel 6-DOF sample stage, the adjustment stroke can only stay at the submillimeter level due to the travel limit of the piezoelectric actuator. The traditional nano positioning method adopts the combination of stepping motor adjusting platform and piezoelectric ceramic adjusting platform, but it takes up a large space and has low stability.

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STRUCTURE DESIGN

This paper mainly studies the attitude adjustment algorithm of 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 structure scheme. The structural form of the 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.

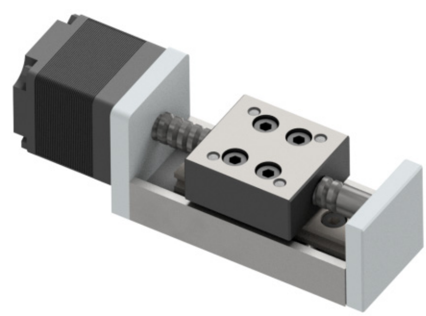

Figure 1: Stepper motor moving stage.

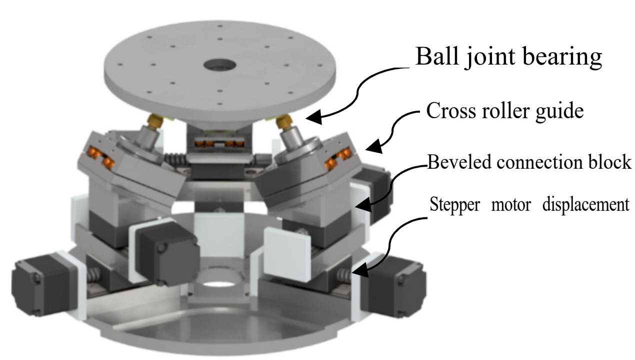

Figure 2: 6-DOF Platform driven by stepping motor.

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COORDINATE TRANSFORMATION OF PLATFORM COORDINATE SYSTEM

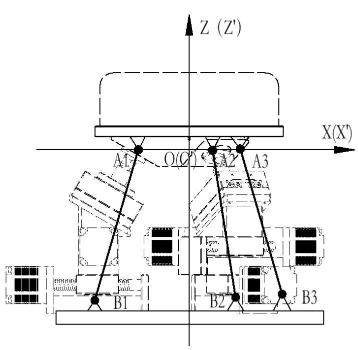
The structure attitude adjustment platform belongs to three-point supporting precision positioning platform. Each supporting point is supported by two orthogonal motion adjustment units to realize six degree of freedom adjustment of the platform. The motion mechanism is simplified as shown in Fig. 3. 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. The coordinate points of the platform are listed as the following expressions in turn.

Hinge coordinates of upper platform:

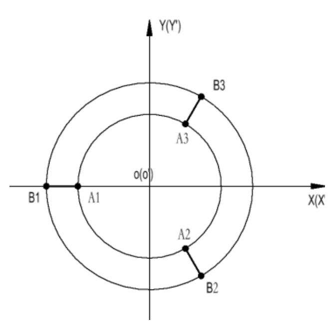
$$\mathbf{A_0} = \begin{bmatrix} r & rcos60 & rcos60 \\ 0 & rsin60 & -rsin60 \\ h1 & h1 & h1 \\ 1 & 1 & 1 \end{bmatrix} . \quad (1)$$

Hinge coordinates of lower platform:

$$\mathbf{B_0} = \begin{bmatrix} R & Rcos60 & Rcos60 \\ 0 & Rsin60 & -Rsin60 \\ h2 & h2 & h2 \\ 1 & 1 & 1 \end{bmatrix} . \quad (2)$$



(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. 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.

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

$$= \begin{bmatrix} 1 & 0 & 0 & m_4 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & m_5 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & m_6 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} cos\theta_3 & -sin\theta_3 & 0 & 0 \\ sin\theta_3 & cos\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} cos\theta_2 & 0 & sin\theta_2 & 0 \\ 0 & 1 & 0 & 0 \\ -sin\theta & 0 & cos\theta_2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & cos\theta_1 & -sin\theta_1 & 0 \\ 0 & sin\theta_1 & cos\theta_1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

After attitude adjustment transformation, the new upper platform coordinate point is $C = T \cdot A$. (4)

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 Figs. 4 and 5. 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 Δ A is shown below.

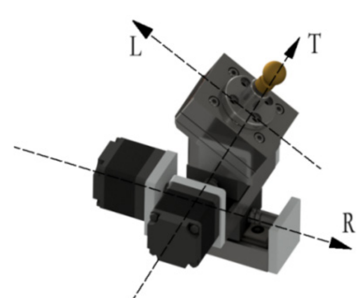


Figure 4: Structure of adjust unit.

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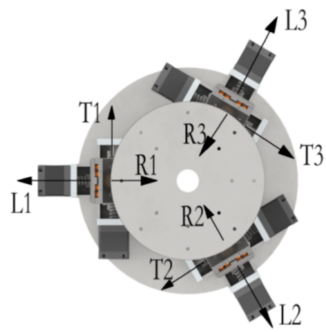

Figure 5: Top view of 6-DOF Platform.

Through the pose matrix $C = T \cdot A$， $T \cdot A = A + \Delta A$, the adjusted hinge coordinates are obtained.And the adjustment matrix Δ RTL of each adjusting component is solved by the following determinant.

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

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. 6 below.

Figure 6: Positioning accuracy test of 6-DOF Platform.

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 rotation positioning accuracy is affected by the machining accuracy of 30 degree inclined plane positioning block, so the maximum error is 0.335 degrees, but the rotation repeated positioning accuracy is better, and the maximum repeated positioning deviation is 0.012 degrees. 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 0.010 mm, the maximum repeat positioning deviation of the whole platform is 0.019 mm, and the expected positioning accuracy is achieved. The feasibility of 6-DOF platform with 20 nm repetitive positioning accuracy was determined by using 5 nm repetitive positioning accuracy piezoelectric ceramic motor.

CONCLUSION

Through the research on the kinematics characteristics of the 6-DOF platform, the coordinate point parametric modeling, dynamic characteristics analysis, inverse kinematics calculation and stroke trajectory description of the platform are completed, which verifies the rationality of the structure design. By building the 6-DOF platform driven by stepper motor, its repeated positioning accuracy is good, and it can become a micron level six degree of freedom platform The structure of the platform. The platform control system adopts the bus control mode, which is easy to be associated with the beam line station control system. The research of this paper will provide theoretical basis and practical experience for the subsequent nano scale large stroke platform.

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