Precision Positioning Control Based on Two-coordinate Incremental Encoder

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Abstract. To increase the working space of atomic force microscopy, this article presents a precision positioning stage. The structure of this stage is optimized to decrease the largest deformation. The coreless linear motor and two-coordinate incremental encoder are selected to build full-closed loop control. The two-coordinate encoder can measure two-direction position signals which can be sent to the controller. Through the interpolation and digitizing electronics, resolution of control can satisfy precision positioning. The full-closed loop control can also decrease straightness error and improve trajectory tracking accuracy.

Keywords: Precision positioning; Straightness error; Two-coordinate encoder; Trajectory tracking.

1. Introduction
With the development of mechanical, lasering, control, micro and nanotechnology, nano range positioning technology is applied in many fields such as large-scale integrated circuit processing, scanning probe microscopy [1], MEMS processing and assembling, optical fiber butting [2], the processing of large scale diffraction grid and cell operating. Large stroke and high precision positioning are both more and more important for the research in the micro-nano range [3]. For example, to enlarge the scanning scope of atomic force microscopy (AFM), the objective table should move large strokes with nano-positioning accuracy. The processing of integrated circuit requires the manufacturing equipment can achieve nano range positioning in millimeters range [4]. The research of a large-stroke nano position can promote several important scientific fields, which will bring great economic benefit. Mature manufacture and control technology of piezoelectric ceramics increase the development of AFM. As a kind of scanning probe microscope, AFM is one of the most important measurement and handling tools in the nanoscale [5]. However, the driving method limits the working scope of AFM. Combining a macro stage with large stroke and a micro stage with nano-accuracy position, the previous problem can be solved. There have been many kinds of research on large stroke precision positioning stage. For cooperating with the micro stage and scanning probe, the macro stage needs precision plane position ability and large stroke. The stroke of the high precision micro stage is 10-50μm approximately. Then the positioning accuracy of the macro stage should below 10μm, otherwise the micro stage can not compensate for the positioning error of the macro stage.

The two-coordinate incremental encoder has two direction grid that is mutually perpendicular on a plane. Therefore, this encoder can measure the objective position in the plane accurately. Compared to the general linear encoder, a two-coordinate encoder have higher perpendicularity. The scanning head of a two-coordinate encoder can be installed at the end of the stage to measure 2-DOF motion. This feedback
method can eliminate the influence of transmission error. When using linear encoder for each motor, the end position of the stage can also be adjusted by a two-coordinate encoder.

2. Structure Design of Positioning Stage

2.1. Selecting driving motor and guideway

The positioning range of the macro stage is 100×100mm. The two moving axles of the macro stage are in series in the vertical direction preventing coupling error. Without interval from drivers to the effector, the macro stage is driven by coreless linear machines with no interim transmission mechanism as shown in Figure 1. The linear machines have many advantages for positioning facility: easy installing, quick dynamic response, high speed and acceleration, high resolution, high force-mass ratio, and low vibration. One axis is overlaying on another axle, so the load of the underneath axle is bigger than the upper axle. To balance the force-mass ratio which decides the dynamic performance of positioning motion, there are two drivers equipped to the below axil. The safe moving range of linear motor for the macro stage is 180mm.

There are several kinds of straight guideways such as a ball-bearing linear guideway, cylindrical guideway, hydrodynamic sliding guideway, and magnetic guideway, etc. [6]. The cylindrical guideway has high accuracy, small size, relatively high stiffness with appropriate preload force. Besides, the cross cylindrical guideway is mounted in pairs to reduce the interval and to make moving stable. The stage uses a pair of 200mm length linear guideway with 118mm valid moving distance.

2.2. Design and optimization of mechanical structure

To reduce the mounting error of the positioning stage, the number of parts is designed as less as possible. The material of all the structure parts is 7075 aluminum alloy which has a high ratio between Young modulus and density. After calculation, the maximum accelerates of the two axes both exceed 5g. But the maximum speed of the positioning stage depends on the output frequency of the encoder. Model analysis can demonstrate the deformation of the structure at natural frequencies. The lowest natural frequency has the most important influence on structure. A finite element model of the stage is...
established in ANSYS to simulate the inherent frequency. The largest deformation is found at the end platform in the direction of the upper axis as shown in Figure III. Dimensional optimization of the end platform can decrease the deformation to enhance the structure stiffness [7]. To prevent weight increase of stage, topology optimization is the best way to enhance the stiffness of the part. The optimization aim is maximum stiffness with a 40% mass constraint. According to the optimization results of the stage, the structure of the upper axis is modified as shown in Figure IV. Obviously, the deformation decreases dramatically without weight increasing.

2.3. Mounting two-coordinate encoder

The two-coordinate encoder system has two parts, including scanning head and grid plate as shown in Figure II. The grid plate should be fixed on the base of the stage. For the convenience of dismounting, the grid plate is settled by spring screw from the side surface rather than be stocked to basis. Scanning head should be installed on the bottom of the end platform. Several location surfaces are designed to ensure the parallelism tolerance between grid plate and scanning head less than 0.02mm.

3. Controlling of Positioning Stage

The macro stage uses a full-closed loop method with a grating encoder to send a feedback signal to the driver. Then the driver utilizes the PID algorithm to control the electric current loop and speed loop of the linear motor. Finally, the control card sends pulse signals to the driver to achieve position control. The grating distance of the encoder is 40μm. After subdivision, the feedback revolution comes to 0.1μm.

3.1. Semi-closed loop control with linear encoder

Linear motor can not move without closed-loop control system. There must be encoder to provide position feedback signal for linear motor. The simplest method of feedback is semi-closed loop. For semi-closed loop control, the grid of linear encoder is mounted with the motor rotor, and detector head is installed with the motor stator. The encoder sends displacement information to controller to adjust the moving of linear motor. There are some kinds of assembly error, machining error and environment noise which can influence the straightness error. For 2-DOF moving stage, the perpendicularity and straightness are the major error.

The control procedure of experiment is shown in Figure V. The linear motors of two axis must be powered on. Sending the line moving command to one axis of positioning stage, the drift of another axis will be measured by two-coordinate encoder. The straightness error of two axis is shown in Figure VI. Obviously, one axis is drifting linearly when another axis is moving. During 30mm displacement, there is 2μm offset in X axis and 1.4μm offset in Y axis.

![Figure 3. Deformation of natural frequency.](image3.png) ![Figure 4. Deformation of modified structure.](image4.png)

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**Figure 3.** Deformation of natural frequency.  **Figure 4.** Deformation of modified structure.

**Figure 5.** Semi-closed loop control flow.
There are several ways to decrease these straightness errors. The most common method is calibration which record the straightness error of two axis and to import data into controller [8]. Then the controller will compensate the straightness error at every point. However, when the object curve is complex, the compensating error at every point in controller will cost much time. Besides when mechanical structure been changed or assembled again, the straightness error will change. Therefore, the straightness error must be recorded again.

![Straightness error of semi-closed loop control: (a) x axis (b) yaxis.](image)

**Figure 6.** Straightness error of semi-closed loop control: (a) x axis (b) yaxis.

3.2. Full-closed loop control with two-coordinate encoder

According to the above analysis, it is difficult to obtain the desired trajectory accuracy by previous method. Therefore, this article utilizes a full-closed loop control method to enhance positioning accuracy. In order to feedback the end position of moving stage, the sensor need to measure two direction of position. The two-coordinate incremental encoder can satisfy the requirement of two directions measurement. The grating plate of two-coordinate encoder have two-direction grids. The reader head also have two-direction optical receivers. Therefore, this encoder can feedback two direction position of moving stage to controller in the meantime. The same as linear encoder, the signal of two-coordinate encoder is sinusoidal voltage incremental signals. The two-channel sinusoidal incremental signals are phase-shifted by 90° and have amplitudes of typically 1Vpp. The signal period is 4μm. The interpolation and digitizing electronics box can transform the sinusoidal voltage signal into square-wave signal with 10-fold. The incremental signals are transmitted as two trains square-wave pulse, phase-shifted by 90°. The reference mark signal includes a reference pulses, which are gated with the incremental signals. The distance between two successive edges of the two trains incremental signals through 4-fold evaluation is one measuring step. With the help of interpolation and digitizing electronics, the revolution of two-coordinate encoder comes to 0.1μm.

The control procedure of experiment is shown in Figure VII. Connecting the reader head, interpolation electronics box and controller with cables, then the signal of two-coordinate encoder can be used as feedback. Powering on the linear motors of two axis, one of the axes can move with constant slow speed. In the meantime, laser measure system is built to record the drift of another axis. Then repeating previous step, the straightness error of another axis can be measured.

![Full-closed loop control flow.](image)

**Figure 7.** Full-closed loop control flow.
The straightness error of two axes with full-closed loop control is shown in Figure VIII. Compared to semi-closed loop control, the straightness error is much smaller. The straightness error of encoder scale is closed to 0.1μm.

**Table 1.** Roundness error on different radius.

| Control method | R5  | R10 | R15 | R20 | R30 |
|----------------|-----|-----|-----|-----|-----|
| Semi           | 6.9μm | 11.6μm | 15.3μm | 19.2μm | 27.4μm |
| Full           | 1.6μm | 2.8μm | 4.7μm | 5.3μm | 8.1μm |

**Figure 8.** Straightness error of full-closed loop.

4. **Accuracy of Position Stage**

With the help of two-coordinate encoder, the repeated positioning and trajectory tracking accuracy are improved to high level. Circle curve is the most common test trajectory for 2-DOF positioning stage. Recording several groups of moving points, the average diameter and center of circle can be calculated to compare with ideal circle. By maintaining the same linear velocity, this experiment should be repeated with different diameters to cover the working scale as much as possible. These data can be fitted by least square circle (LSC) to get reference circle [9]. The roundness error then can be estimated as the difference between the maximum and minimum distance from this reference circle which is shown in Figure IX. The roundness error of circle trajectory can show the dynamic accuracy of positioning stage [10].

**Figure 9.** Roundness error of trajectory.
Roundness error of trajectory is influenced by mechanical error, control algorithm and feedback accuracy. The two-coordinate encoder can decrease the straightness error to improve roundness error. The roundness error is demonstrated in Table 1. With the radius of circle trajectory increasing, the roundness error augment up to 27.4 μm gradually. The larger stroke stage moves, the bigger roundness error is. However, the roundness is not very big with two-coordinate full-closed control method. The biggest straightness error of full-closed control method is 8.1 μm. On different radius, the trajectory accuracy of full-closed loop control has evident improvement compared to semi-closed loop control. Theoretically the moving range will not influence the roundness error. In realistic experiment, the environment error accumulates when the working time increase.

5. Conclusion
This article introduces a large stroke 2-DOF positioning system with the two-coordinate encoder and linear motor. Compared to semi-closed loop control, full-closed loop control can help positioning stage to decrease straightness error and improve accuracy of trajectory tracking. Therefore, this precision positioning stage can be used in nano positioning research to enlarge the working space of micro stage.

Acknowledgment
This work is supported by the Guangdong Ocean Economic development project (Grant No. GDOE[2019]A40) and the National Natural Science Foundation of China (Grant No. 51905176). The authors gratefully acknowledge these support agencies.

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