Nanometric Positioning Over a One-Millimeter Stroke Using a Flexure Guide and Electromagnetic Linear Motor

Shigeo Fukada[1,#] and **Kentaro Nishimura**[1]

[1]Department of Mechanical Systems Engineering, Shinshu University, Nagano, Japan
#Corresponding Author / E-mail: sfukada@shinshu-u.ac.jp; TEL: +81-26-269-5147; FAX: +81-26-269-5145

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In this study, we investigated experimentally the potential of a planer positioning mechanism with three degrees of freedom using a flexure guide and an electromagnetic linear motor. The goal was to produce a multi-axis positioning system with nanometric resolution over a 1-mm stroke. An X-Y-θ stage was designed based on previous results from a single-axis prototype and was constructed with a flexure guide mechanism and voice coil motor type linear actuators. We examined the necessity of a driving method and control system to ensure high resolution for multi-axis positioning. Experiments were conducted to evaluate the performance, and the results confirmed the mechanism's potential; fine point-to-point (PTP) positioning was achieved over a 1-mm stroke, with a resolution of 2 nm for translation in X-Y and 0.01 asec for yaw in θ.

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1. Introduction

Industrial systems in many fields use precision positioning mechanisms. These various positioning mechanisms and precision devices can be plotted on a plane with axes of resolution versus stroke (Fig. 1).[1] Current precise positioning mechanisms can be divided into two categories based on their field of application.[2-4] The first category is positioning mechanisms with long strokes from millimeters to meters; these are used in machine tools or semiconductor manufacturing processes. The second category is fine positioning mechanisms with strokes measured in micrometers; these are used in scanning probe microscopes. Piezo actuators are generally used in the

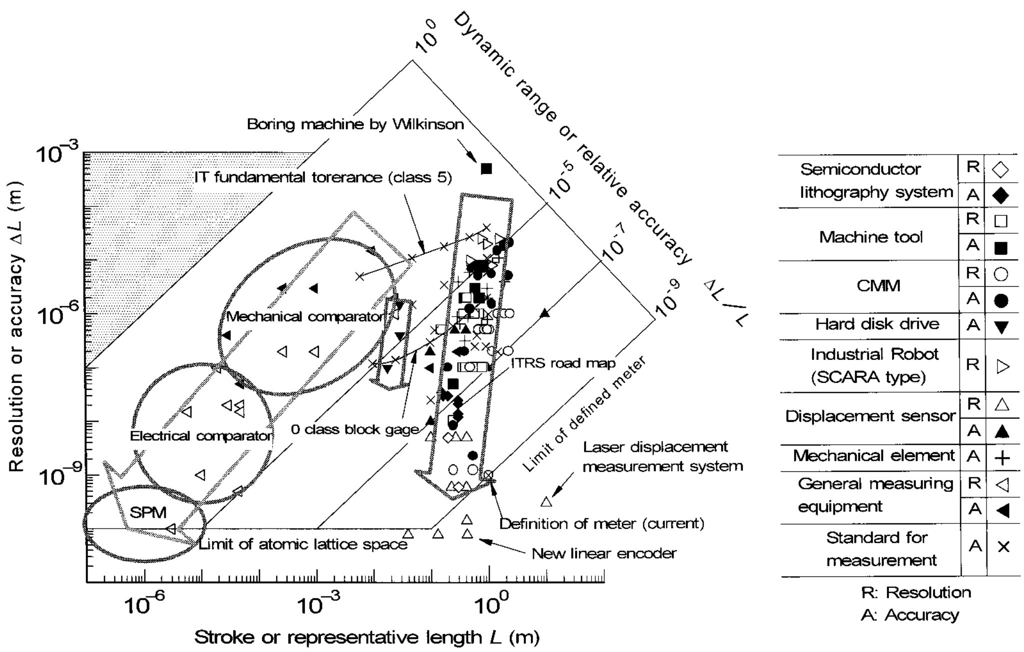


Fig. 1 Performance of various positioning mechanisms and devices[1]

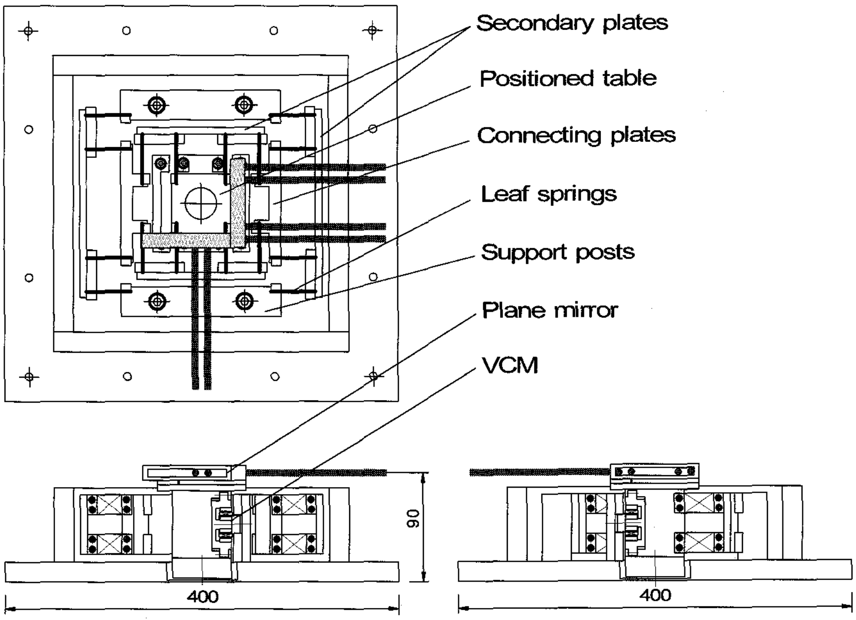


Fig. 2 X-Y-θ stage mechanism

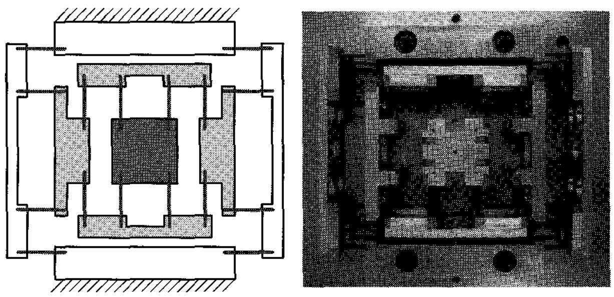


Fig. 3 Flexure mechanism

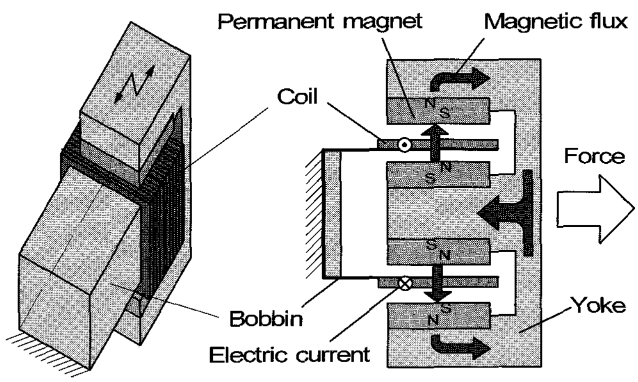


Fig. 4 Structure of the voice coil linear motor actuator

latter to enable nanometric resolution, but this limits the stroke to a few dozen micrometers. We attempted to develop a positioning mechanism using a flexure guide and an electromagnetic linear motor to enable nanometric resolution over a 1-mm stroke, i.e., a device that would fit in a medium range between these two categories. It would require a dynamic range, i.e., a ratio of stroke to resolution, of 10^6 or 2.[20] We developed a planer positioning mechanism with three degrees of freedom based on previous results from a single-axis prototype.[5] We also constructed a control system for point-to-point (PTP) positioning and discuss its positioning performance, as well as strategies for continuous path (CP) motion control.

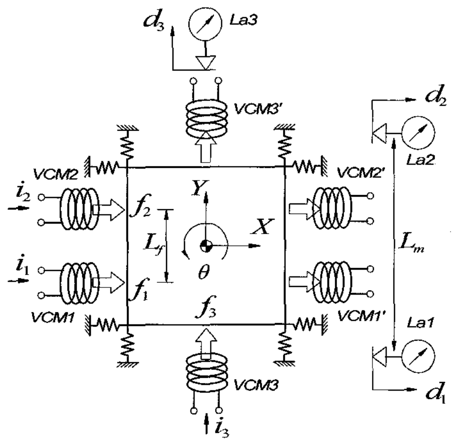


Fig. 5 Arrangement of actuators and sensors

2. Positioning Mechanism

2.1 Flexure guide mechanism

In the proposed positioning mechanism, a positioned table configured as a cube with 60-mm sides is supported by leaf springs made of phosphor bronze, which form double compound rectilinear springs (Fig. 2).[6] In the arrangement of the leaf springs, the X and Y mechanisms have a similar configuration, with the X mechanism supported inside the Y mechanism (Fig. 3). Both X and Y mechanisms have two secondary plates that are joined by connecting plates. Each secondary plate of the Y mechanism is supported by eight leaf springs connected to support posts, and the positioned table is connected to the secondary plates by eight leaf springs. The leaf spring dimensions are 20 × 25 × 0.3 mm for the Y mechanism and 20 × 30 × 0.3 mm for the X mechanism. Flexure compliance and the mass of connected parts were determined painstakingly to ensure that the mechanism's natural frequencies coincided in both the X and Y directions. The guide mechanism has a symmetric configuration with respect to the table centroid, and thus the table is guided into X-Y-θ (yaw) directions without nonlinear effects such as backlash or friction.

2.2 Structure and arrangement of VCM actuators

In the voice coil linear motor (VCM) structure, permanent magnets composed of neodymium are held in a yoke of steel to enable the magnetic flux to circulate efficiently (Fig. 4).[7]

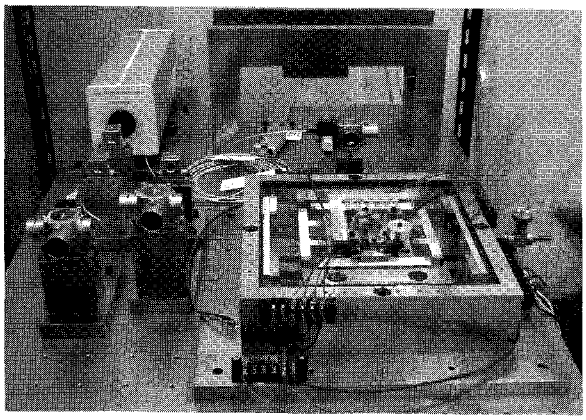


Fig. 6 Experimental positioning system

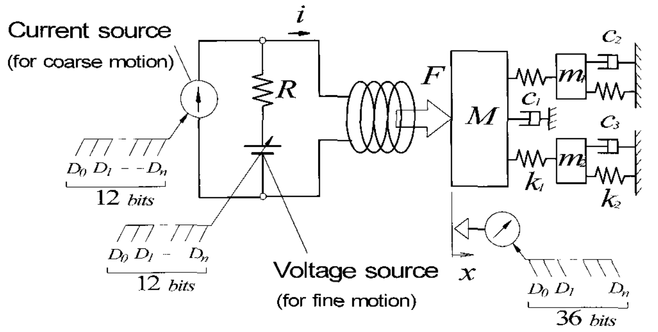


Fig. 7 Dynamical model and driving method

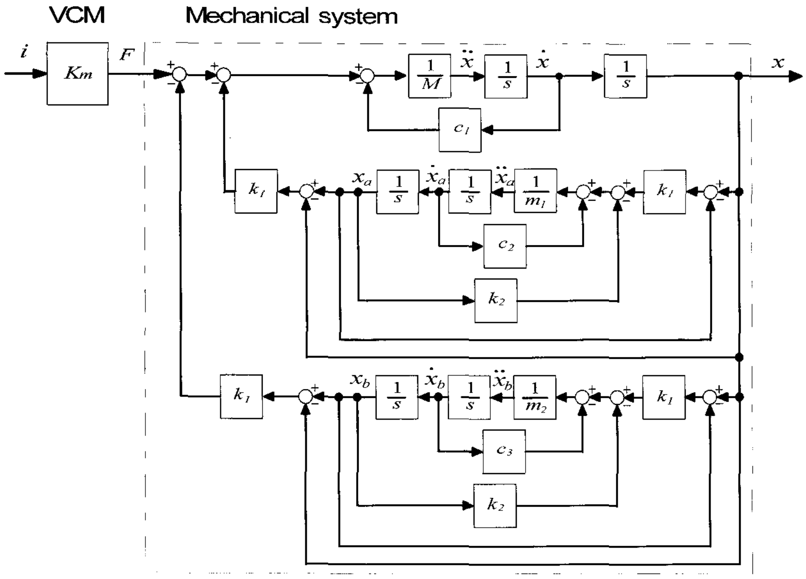


Fig. 8 Block diagram of positioning mechanism (for X or Y motion)

An enameled wire is wound on a bobbin composed of aluminum to construct an electric coil, and the coil is inserted into the yoke without any contact. In the arrangement of the actuators (Fig. 5), VCM are arranged to enable table movement in X-Y-θ directions independently. Yokes are attached to the sides of the table, and stator coils are fixed to the base. Two pairs of VCM drive the table in X and θ directions, and another pair drives it in the Y direction. The resultant force axis and the center of momentum generated by the motors coincide with the table centroid. Force constants of the motors were predetermined to ensure identical positioning resolutions, and the mechanism was designed so that both static and dynamic behavior remained identical in both X and Y directions. The freedom in yaw slightly helps to control table attitude and thereby maintain parallelism and ensures that the range of yaw is limited to 100 asec.

2.3 Measurement system and supporting

Fig. 5 illustrates the arrangement of the measurement systems. In the whole view of the experimental positioning system (Fig. 6), an optical square is set on the table, and three axis laser interferometers with a resolution of 0.6 nm are arranged to measure yawing motion and table displacement along X–Y directions.

To compensate for any damping effect, the mechanism is sunk in silicone oil of 1000 cSt, and then set on an isolated pneumatic bench.

3. Driving Method and Control System

3.1 Current supply circuit

Fig. 7 presents a schematic model for the dynamic system of single axis linear motion in the X or Y direction, and Fig. 8 presents a block diagram derived from the model shown in Fig. 7. Because table displacement responds proportionally to the current that is input to the linear motor, the positioning resolution is determined by the current control resolution. Therefore, the drive circuit supplying current to the linear motor was specifically designed to allow a dynamic range of $2.^{20}$ This circuit consists of power sources used discretely for coarse and fine motions, and their output currents combine to drive the linear motor. Each power source is driven by its own D/A converter of 12 bits, resulting in a theoretical dynamic range of $2.^{24}$

3.2 Control system for PTP positioning

A positioning system is constructed with a full closed feedback loop using laser interferometers. The control system for PTP positioning (Fig. 9) simultaneously controls the three X-Y-θ values and has two separate controllers for coarse and fine operations, with controllers switched sequentially for each range of deviation. In the actual system, the controllers are part of a discrete-time system in a computer with a 2-ms sampling interval. The design of controllers was based on PI-D (proportional plus integral minus derivative of controlled value) operation, with PI-D parameters calculated for each of the X-Y-θ motions in both coarse and fine ranges, requiring tuning of 18 parameters in total. Approximate optimal values of parameters were predetermined based on simulation results using the dynamic model (Fig. 8), and values were adjusted precisely during the experiments.

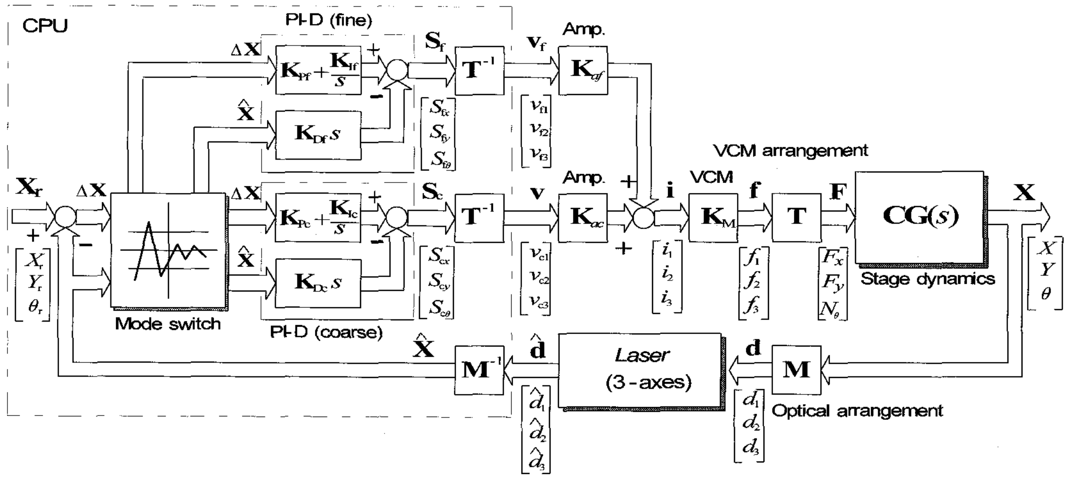
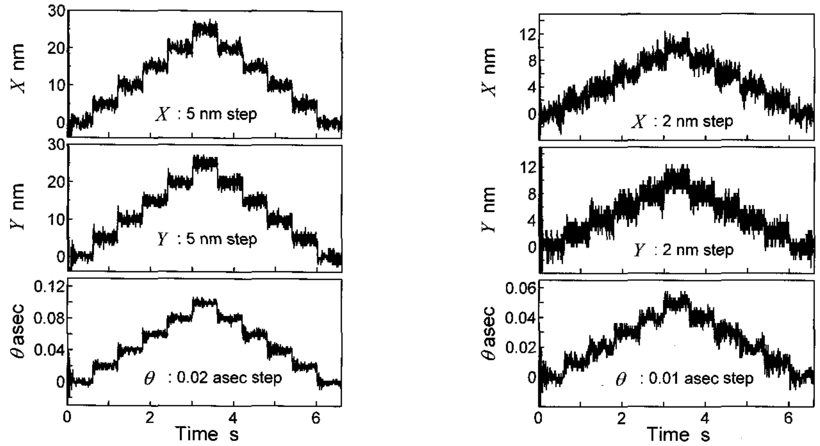
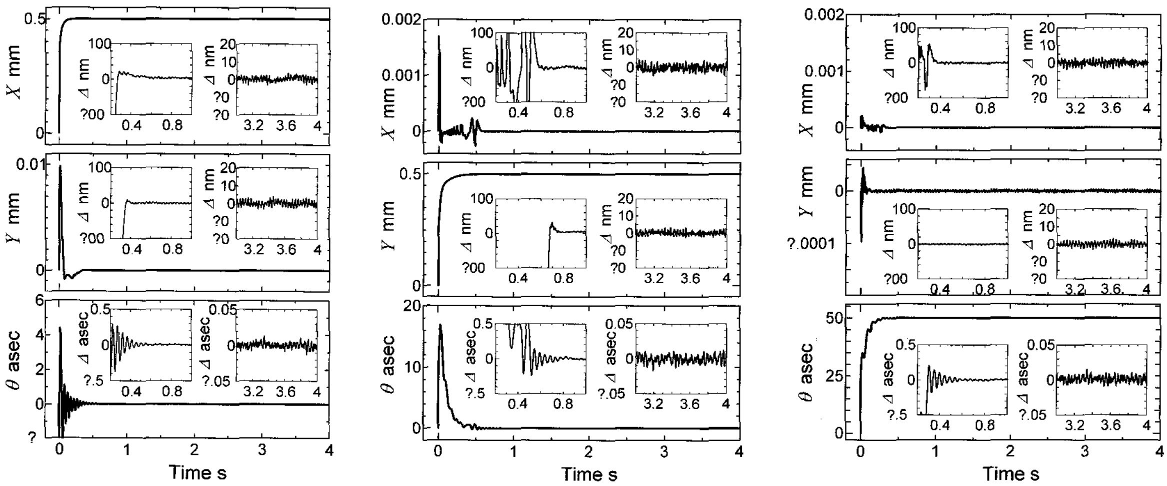


Fig. 9 Block diagram of control system for point-to-point positioning



(a) $X_r = Y_r = 5$ nm, $\theta_r = 0.02$ asec (b) $X_r = Y_r = 2$ nm, $\theta_r = 0.01$ asec

Fig. 10 Positioning resolution



(a) $X_r = 0.5$ mm, $Y_r = 0$, $\theta_r = 0$ (b) $X_r = 0$, $Y_r = 0.5$ mm, $\theta_r = 0$ (c) $X_r = 0$, $Y_r = 0$, $\theta_r = 50$ asec

Fig. 11 Step response to 0.5-mm or 50-asec reference

4. Experiments with PTP Positioning Performance

4.1 Preliminary test and adjustment

First, the static and dynamic properties of the stage were measured. Flexure compliance was 110 mm/N in X, 70 mm/N in Y, and 2400 asec/Nm in θ, which was almost identical to design specifications. The linear motor had a force constant of 8 N/A for X, 9.5 N/A for Y, and 0.05 Nm/A for θ, and the stage moved approximately 0.88 mm/A in X, 0.66 mm/A in Y, and 120 asec/A in θ.

The mechanism exhibited resonant frequency responses of 11 Hz (fundamental) and 41 Hz (secondary) in both X and Y motion.

4.2 Experimental results of PTP positioning

In the experimental results of positioning resolution in each axis of X-Y-θ, fine positioning with resolutions of 2.0 nm and 0.01 asec was achieved around the neutral position of the flexure mechanism (Fig. 10). For responses in 0.5-mm or 50-asec step positioning for each axis (Fig. 11), a step reference was given to one axis in a neutral condition while the other axes were controlled to maintain the initial position. When the step reference was abruptly input to one axis, the other axes were initially stimulated because of mechanical interference among the axes. However, the controllers rapidly reduced deviations and steady state errors settled within 5 nm or 0.02 asec. Similar positioning performance appeared in reverse motions from a neutral position. Finally, positioning with a resolution of 2 nm and 0.01 asec was achieved over a 1-mm stroke. These results confirmed the potentially superior performance of the proposed positioning mechanism with three degrees of freedom using a flexure guide and an electromagnetic linear motor.

5. Strategies for controlling CP motion

The ability of the control system (Fig. 9) to provide CP motion is not yet assured because the controller operates sequentially from coarse to fine motion. Moreover, a simple PI-D controller is insufficient to follow any changing input dynamically. If the table is directed to move accurately along straight or circular paths in the X–Y plane, either the X or Y axis must follow the ramp or sinusoidal reference. In some simulations and experiments, we used only coarse operation and a ordinary PID (proportional plus integral plus derivative) controller, which can decrease the deviation from step input (Fig. 12). Nevertheless, any dynamic change in ramp or sinusoidal (cosine) input results in significant deviation, so a new strategy is needed to control CP motion.

In the proposed control system (Fig. 13), the system incorporates both PID feedback and feedforward controllers to constitute a two-degrees-of-freedom (2-DOF) controller. Feedforward element F should correspond to the reverse model of mechanism G, so in simple terms, F is adjusted to the constant value of mechanism G's static compliance. Using the 2-DOF controller with only coarse operation, residual deviation decreased significantly (Fig. 14; compare with Fig. 12), but micron-level deviations remain.

To reduce the deviations to nanometer-level, the feedback controller is divided into coarse and fine controllers with discrete PID operations. In contrast to the PTP positioning controller (Fig. 9), these coarse and fine controllers operate simultaneously, and the fine controller has a limited operational range. Using the 2-DOF controller, with coarse–fine operation, residual deviation was reduced to the nanometer range (Fig. 15). Nevertheless, 50-nm fluctuations remained for ramp or sinusoidal input. To reduce this fluctuation, the controller's sampling rate needs to be improved.

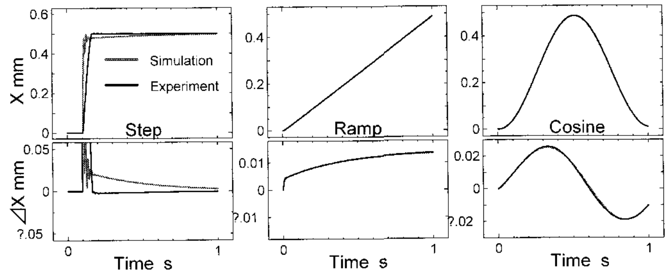


Fig. 12 Positioning results with only the PID controller

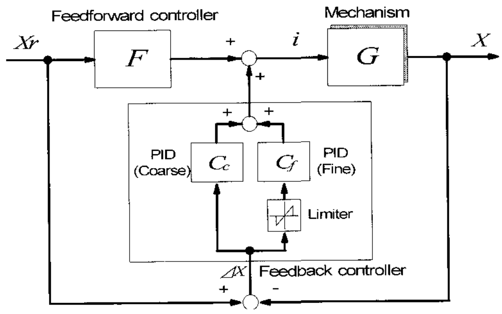


Fig. 13 Block diagram of two-degrees-of-freedom control system

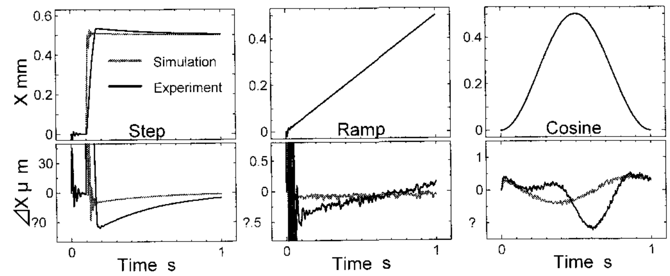


Fig. 14 Positioning results with PID-feedback and feedforwar controllers

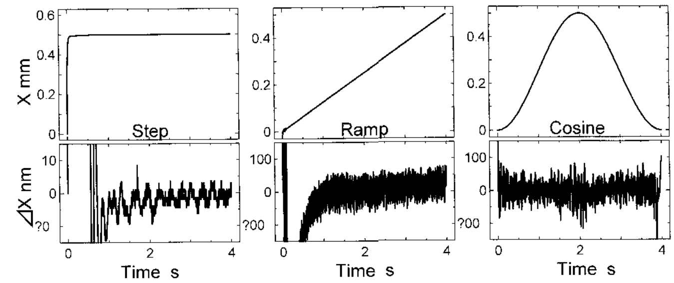


Fig. 15 Positioning results with two-degrees-of-freedom coarse–fine controller

6. Conclusions

(1) We developed an X-Y-θ stage mechanism using a flexure guide mechanism and moving magnet-type linear actuators.

(2) Ultra-precise and ultra-fine point-to-point positioning with resolution of 2 nm for X–Y and 0.01 asec for θ was achieved over a 1-mm stroke.

(3) A two-degrees-of-freedom controller with coarse–fine operation was introduced to enhance continuous path motion positioning, and its feasibility was confirmed using simulations and experiments.

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