Research Article

Development of a Flat Type Six-Axis Stage Based on Piezoelectric Actuators

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This study presents and investigates a six-DOF (degrees of freedom) piezoelectric based stage for positioning error compensation. The relationship between the displacement of the piezoelectric actuators and the stage can be computed according to the geometric relationships of the actuators installed. In this study, a feedforward compensator based on the hysteresis model has been designed for compensation and a PI controller was used for positioning. The combination of a feedforward compensator and PI controller gives the stage good positioning and tracking performance. Stage position information is feedback from a six-DOF optical measurement system comprised of three modular two-dimensional measurement devices. Each module employs a quadrant photodiode (QPD), a laser diode, and a lens. The measurement signal is acquired and processed using an FPGA based processor for real time control. The linear and angular positioning resolution is $0.02\ \mu\text{m}$ and $0.1\ \text{arcsec}$, respectively. When the stage is controlled in a closed loop, the positioning errors are in the range of $\pm 0.1\ \mu\text{m}$ and $\pm 0.5\ \text{arcsec}$. The stage is controlled to track a sinusoidal wave with an amplitude of $2.5\ \mu\text{m}$ and a frequency of $5\ \text{Hz}$; tracking errors were within $\pm 0.1\ \mu\text{m}$ and $\pm 0.2\ \text{arcsec}$.

1. Introduction

The recent developments in nanotechnology have resulted in increased use of piezoelectric stages which are now universally used for ultrahigh precision positioning or compensation at the nanolevel because piezoelectric actuators have high resolution and sensitivity. For example, Lee and Kim designed an ultrahigh precision wafer alignment stage [1] which is a combination of a long stroke stage and an ultrahigh precision compensation stage. The long stroke stage is driven by linear motors and the other by piezoelectric actuators. This kind of stage is commonly used for the production of touch panels and semiconductors. A piezoelectric based stage (PZT stage) usually includes piezoelectric actuators and flexure hinges. There are two types of flexure hinge in common use, the circular notch and the spherical notch types. In addition to this, Jywe et al. developed an arc flexible body

and this was integrated with a spherical notch flexure hinge to make a five-DOF PZT stage [2]. Flexure hinges can be applied to displacement/force transmission, reduction, and enlargement. For instance, Shiou et al. presented a nanostage that can increase the displacement of a piezoelectric actuator [3], and the stage position data is feedback by capacitance probes. The positioning, steady state, and tracking errors of this stage are in the range of $\pm 2\ \text{nm}$ and $\pm 100\ \text{nm}$, respectively. Kim et al. proposed a one-dimensional PZT stage to increase displacement to a few millimeters [4]. Unlike the former, Guo et al. developed a piezoelectric based movement module that reduces the displacement of the stage but increases positioning resolution [5]. Although flexure hinges can be designed to increase the displacement of a stage, it causes positioning performance becoming low as well as they are difficult to design. However, since the moving stroke of an ultrahigh precision production machine is usually less than

FIGURE 1: The six-DOF compensation stage.

twenty micrometers, a flexure hinge to increase displacement is unnecessary. Note that some commonly used measuring devices have been described in Fleming's study [6].

Several kinds of multi-DOF stage have been proposed. For instance, Polit and Dong developed a two-dimensional PZT stage, which is of compact size, light in weight, and controlled by a feedback controller. Stage position was measured by capacitance probes [7]. Shimizu et al. developed a two-dimensional PZT stage where stage position was measured by a laser interferometer; resolution of the stage could be 10 nm [8]. Kim and Gweon presented a compact dimension nanostage [9]. Displacement of the stage was measured by capacitance probes installed inside the stage. Linear and angular positioning resolution of the stage were 5 nm and 0.025 arcsec, respectively. A six-DOF PZT stage, such as that developed by Feserman et al., is generally built up in stacked configuration [10]. In the Feserman device, the x -axis, y -axis, and θ_z movement are driven by linear motors and the z -tilt movement uses piezoelectric actuators. A stacked six-DOF stage is easy to control, and displacement is easy to measure, as compared to the six-DOF parallel mechanism by Brouwer et al [11]. In general, the actuators of a z -tilt stage are usually installed vertically [12]. However, Lee et al. developed a z -tilt stage with the actuators installed horizontally [13]. This kind of stage can be very small and flat but is difficult to design.

The two main problems that influence the performance of piezoelectric actuators are hysteresis and creep. Creep is a static problem that can be easily controlled by feedback, but hysteresis needs to be handled by feedforward compensation. Many different proposals for the compensation of hysteresis have been proposed, for instance, Mayergoyz, Leang, and Devasia used a feedforward compensator based on the Preisach Model [14, 15]. After compensation the tracking error can be smaller than $0.08 \mu\text{m}$ during a 10 Hz sinusoidal wave [16]; Lin and Chen used a parallel dual feedforward compensator [17], and the tracking error was smaller than 30 nm; other investigators also studied the problem [15, 18–22]. In addition to the Preisach Model, many other approaches were made to the problem of hysteresis compensation: the approximated polynomial model [23], the

Bouc-Wen [24], the Duhem [25], the generic differential model [26], the Kim [27], and the Maxwell slip model [28] were all used. Some researchers used the observer [29, 30] and the sliding mode controller [31, 32] to reduce the hysteresis effect. A multi-DOF stage needs a multi-DOF measurement system to measure/monitor the positional values. There are many types of multi-DOF measurement system that have been proposed [33–36]. Though these systems can measure multi-DOF positional value, they are difficult to construct for a flat type of multi-DOF stage and are not easier for analysis.

2. System Construction

2.1. The Six-DOF Compensating Stage. As shown in Figure 1, the proposed six-DOF compensation stage consists of four parts: a base platform, three PZT stages (the x -axis, y -axis, and z -tilt), three modular two-dimensional measurement devices, and a work platform. The y -axis PZT stage is installed on the base platform as seen in Figure 2(a), and the x -axis PZT stage is placed on the y -axis PZT stage as seen in Figure 2(b). The z -tilt PZT stage is installed on the x -axis stage and work platform placed on the z -tilt stage as seen in Figure 2(c). The number and installed position of the piezoelectric actuators is shown in Figure 3. The six-DOF movement is described as follows: the x -axis movement uses P_{x1} and P_{x2} ; the y -axis movement uses P_{y1} and P_{y2} ; Yaw movement (i.e., θ_z motion) uses P_{x1} , P_{x2} , P_{y1} , and P_{y2} ; z -tilt movement uses P_{z1} , P_{z2} , and P_{z3} .

2.2. The Two-Dimensional Measurement Module. The two-dimensional measurement module comprises a laser diode fixed to the base platform, a lens linked with the work platform, and a quadrant photodiode (QPD) fixed to the base platform, as seen in Figure 4. Note that the lens and base platform have no connection. The measurement method is illustrated in Figure 5. When the stage moves with a displacement of ΔL , the displacement of the light spot

FIGURE 2: Illustration of the six-DOF stage construction: (a) Y-axis stage is installed on the base platform; (b) x-axis is placed on the y-axis stage; (c) z-tilt stage is on the x-axis stage and the work platform is fixed to the top of the stack.

FIGURE 3: Number and installed position of each piezoelectric actuator.

FIGURE 4: Structure of the modular two-dimensional measurement device.

FIGURE 5: Measurement concept diagram of the two-dimensional measurement module.

projected onto the QPD, denoted by Δy , can be measured. Let f be the focal length of the lens, and the output signal of QPD of x - and y -axis is V_x and V_y , respectively, in volts. Displacements of the x - and y -axis of the spot measured from the QPD denoted q_x and q_y , respectively, can be calculated by using the following equation:

$$\begin{aligned} q_x &= K_x V_x, \\ q_y &= K_y V_y, \end{aligned} \quad (1)$$

where K_x and K_y represent the voltage-displacement conversion constant. This study employed three sets of the two-dimensional measurement modules, as seen in Figure 6, to

measure the six-DOF displacements of the compensation stage including three linear displacements denoted as δ_x , δ_y , and δ_z and three angular displacements denoted as θ_x , θ_y , and θ_z . Thus, displacement of the stage can be determined using the following equation:

$$\begin{bmatrix} q_{1x} \\ q_{1y} \\ q_{2x} \\ q_{2y} \\ q_{3x} \\ q_{3y} \end{bmatrix} \cong \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & d_1 \\ 0 & 0 & 1 & 0 & d_1 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -|d_2| & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & -|d_3| & 0 \end{bmatrix} \cdot \begin{bmatrix} \delta_x \\ \delta_y \\ \delta_z \\ \theta_x \\ \theta_y \\ \theta_z \end{bmatrix} \triangleq \mathbf{M} \cdot \vec{s}_{\text{stage}}, \quad (2)$$

FIGURE 6: The installed positions of each two-dimensional measurement module.

where q_{ix} and q_{iy} represent the x - and y -axis displacement of the i th two-dimensional measurement module, respectively; d_i is the distance between i th two-dimensional measurement module and the center of the stage.

3. Control of the Stage

3.1. Stage Modeling. Because the y -axis and yaw movement of the compensating stage are operated by the y -axis stage, the stage is analyzed first from the y -axis PZT stage. As can be seen in Figure 7(a), the coordinate systems are defined as follows: $\{R\}$ represents the origin of the stage, which is the reference position of the stage kinematic model; $\{O\}$ represents the center of the six-DOF compensation stage; $\{P_{Y1}\}$ and $\{P_{Y2}\}$ represent the initial position of P_{Y1} and P_{Y2} PZT stages, respectively; $\{P'_{Y1}\}$ and $\{P'_{Y2}\}$ represent the desired position of P_{Y1} and P_{Y2} PZT stages, respectively, when the six-DOF compensating stage is at the required position. Assuming the y -axis linear displacement of the compensating stage is $\vec{s}_y = [0 \ \delta_y \ 0]^T$ (i.e., vector of the stage moved from $\{R\}$ to $\{O\}$), the distance between the P_{Yi} and $\{R\}$ represents $\vec{d}_{yi} = [d_{yi-x} \ d_{yi-y} \ 0]^T$, and displacement of P_{Yi} is $\vec{s}_{yi} = [0 \ \delta_{yi-y} \ 0]^T$ ($i = 1, 2$). Thus, the y -direction kinematic model is

$$\vec{s}_{yi} = \vec{s}_y + \mathbf{R}_{zi} \cdot \vec{d}_{yi} - \vec{d}_{yi}, \quad (3)$$

$$\mathbf{R}_{zi} = \begin{bmatrix} \cos \theta_{z1} & -\sin \theta_{z1} & 0 \\ \sin \theta_{z1} & \cos \theta_{z1} & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

Because $\theta_{z1} \ll 1^\circ$, (3) can be simplified:

$$\mathbf{R}_{z1} \cong \begin{bmatrix} 1 & -\theta_{z1} & 0 \\ \theta_{z1} & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad (4)$$

$$\delta_{yi-y} = \delta_y + d_{yi-x} \theta_{z1}. \quad (5)$$

Similarly, the x -axis kinematic model is

$$\delta_{xi-x} = \delta_x + d_{xi-x} \theta_{z2}. \quad (6)$$

Please note that the x - and y -axes of the PZT stage both contribute yaw motion, and we use θ_{z1} and θ_{z2} to denote the yaw motion contributed by the y - and x -axis PZT stages, respectively. The x -axis PZT stage and the y -axis PZT stage form a four-bar mechanism as shown in Figure 8. Hence, when the stage is rotated by θ_{z1} , (6) and (5) should be corrected, as follows:

$$\delta_{xi-x} = \frac{\delta_x + d_{xi-x} \theta_{z2}}{\cos \theta_{z1}}, \quad (7)$$

$$\begin{aligned} \delta_{yi-y} &= \delta_y + d_{yi-x} \theta_{z1} + \delta_{xi-x} \sin \theta_{z1} \\ &\cong \delta_y + d_{yi-x} \theta_{z1} + \delta_{xi-x} \theta_{z1} \\ &= \delta_y + d_{yi-x} \theta_{z1} + (\delta_x + d_{xi-x} \theta_{z2}) \theta_{z1}. \end{aligned} \quad (8)$$

From (7), because $\cos \theta_{z1} \approx 1$, (7) is completely equal to (5). Similarly, since θ_{z1} and θ_{z2} are both smaller than one degree and the maximum displacement of x -direction is smaller

FIGURE 7: Schematic diagram for kinematic analysis of the six-DOF compensation stage: (a) y -axis and yaw movement; (b) z -tilt movement.

than twenty micrometers (i.e., $\theta_{z2}\theta_{z1} \rightarrow 0$ and $\delta_x\theta_{z1} \rightarrow 0$), (8) is completely equal to (5). Suffice it to say that this kind of construct between the x - and y -axis PZT stages does not cause a position coupling problem.

The kinematic equation for z -tilt motion can be derived according to Figure 7(b). In the plot, coordinate systems $\{P_{Zj}\}$ represent the initial position of P_{Zj} and $j = 1, 2$, and 3 . Similarly, $\{P'_{Zj}\}$ is the position of P_{Zj} after the compensation stage is at the required position, and the vector $\vec{d}_{zj} = [d_{yi-x} \ d_{yi-y} \ d_{yi-z}]^T$ represents the install position of P_{Zj} . The

displacement vector $\vec{s}_{zj} = [0 \ 0 \ \delta_{zj-z}]^T$ of j th PZT can be determined by

$$\vec{s}_{zj} = \vec{s}_z + \mathbf{R}_{YX} \cdot \vec{d}_{zj} - \vec{d}_{zj}, \quad (9)$$

$$\mathbf{R}_{YX} = \begin{bmatrix} \cos\theta_y & 0 & \sin\theta_y \\ 0 & 1 & 0 \\ -\sin\theta_y & 0 & \cos\theta_y \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_x & -\sin\theta_x \\ 0 & \sin\theta_x & \cos\theta_x \end{bmatrix}, \quad (10)$$

FIGURE 8: When the stage rotates along θ_{z1} , x -axis movement produces a displacement component of the y -axis.

FIGURE 9: Control block diagram of the PZT stage in this study.

where $\vec{s}_z = [0 \ 0 \ \delta_z]^T$ represents the required position of the compensating stage. Since $\theta_y \ll 1^\circ$ and $\theta_x \ll 1^\circ$, (10) can be simplified as

$$\mathbf{R}_{YX} = \begin{bmatrix} 1 & 0 & \theta_y \\ 0 & 1 & 0 \\ -\theta_y & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & -\theta_x \\ 0 & \theta_x & 1 \end{bmatrix}. \quad (11)$$

Substituting (11) into (9) gives

$$\delta_{zj-z} = \delta_z + d_{yj-y}\theta_x - d_{yj-x}\theta_y. \quad (12)$$

From (7), (8), and (12), the linearized kinematic equation for the stage is

$$\begin{bmatrix} \delta_{x1} \\ \delta_{x2} \\ \delta_{y1} \\ \delta_{y2} \\ \delta_{z1} \\ \delta_{z2} \\ \delta_{z3} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & d_{x1-x} \\ 1 & 0 & 0 & 0 & 0 & d_{x2-x} \\ 0 & 1 & 0 & 0 & d_{y1-x} & 0 \\ 0 & 1 & 0 & 0 & d_{y2-x} & 0 \\ 0 & 0 & 1 & d_{y1-y} & -d_{y1-x} & 0 \\ 0 & 0 & 1 & d_{y2-y} & -d_{y2-x} & 0 \\ 0 & 0 & 1 & d_{y3-y} & -d_{y3-x} & 0 \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \\ \delta_z \\ \theta_x \\ \theta_y \\ \theta_{z1} \\ \theta_{z2} \end{bmatrix}, \quad (13)$$

where δ_v is the displacement of the PZT of P_v ($v = x1, y2, y1, y2, z1, z2$, and $z3$). To define the equation above

$$\vec{s}_{\text{piezo}} = \mathbf{T} \cdot \vec{s}_{\text{stage}}. \quad (14)$$

3.2. Stage Control. In this study, the compensation stage is controlled by the PI controller combined with the feedforward compensator as shown in Figure 9. The gain denoted by K1 is used for displacement-voltage conversion for PZT, and K2 is the gain of the feedforward compensator. Here, the hysteresis model for the feedforward compensator is based on the generic differential model [26]. The parameters of each PZT are listed in Table 1. The trajectory of PZT1 before and after compensation is shown in Figure 10(a). The voltage-displacement conversion constant can be found by line fitting from the trajectory after hysteresis compensation. Figure 10(b) shows the residual error is in the range of ± 40 nm after hysteresis compensation.

4. Experimental Results

The signal processing flow chart for the six-DOF compensation stage is shown in Figure 11, in which all the signals were

FIGURE 10: After compensation the hysteresis loop can be reduced: (a) voltage versus PZT position curve; (b) residual error after hysteresis compensated.

FIGURE 11: Signal processing flow chart of compensation stage control.

TABLE 1: Parameters of the general differential model for each piezoelectric actuator.

	a	b	α
P_{x1}	0.131	0.090	0.057
P_{x2}	0.131	0.090	0.057
P_{y1}	0.139	0.097	0.048
P_{y2}	0.133	0.093	0.053
P_{z1}	0.142	0.086	0.096
P_{z2}	0.131	0.078	0.091
P_{z3}	0.130	0.077	0.098

processed using an FPGA based processor (NI PCIe 7842R). Before the experiment, the three-DOF measurement system was calibrated by comparison with laser interferometer readings to guarantee the measured positional value. Calibration results are shown in Figure 12.

4.1. Test for Stability and Resolution. Because the compensation stage is driven by piezoelectric actuators and position is feedback from the six-DOF measurement system, creep

and thermal drift might affect positional value stability; system stability should be evaluated by the system stability test which also evaluates system noise. The stability test results (Figure 13) show linear stability is about ± 20 nm and angular stability is about ± 0.05 arcsec (for θ_x) and ± 0.1 arcsec (for θ_y and θ_z). In general, the positioning resolution of a compensation stage can be tested using a stepwise signal and positioning resolution is usually affected by the noise in the measurement system. Thus, the displacement of each step is

(a)

(b)

(c)

(d)

(e)

(f)

—○— Test 1
—□— Test 2
—★— Test 3

—○— Test 1
—□— Test 2
—★— Test 3

FIGURE 12: Residual error of the six-DOF measurements after calibration. (a) x -axis; (b) y -axis; (c) z -axis; (d) θ_x rotation; (e) θ_y rotation; (f) θ_z rotation.

FIGURE 13: Stability test results for each axis over 20 minutes: (a) x -axis; (b) y -axis; (c) z -axis; (d) θ_x ; (e) θ_y ; (f) θ_z .

(a)

(b)

(c)

(d)

(e)

(f)

FIGURE 14: Stepwise test results for each axis: (a) x -axis; (b) y -axis; (c) z -axis; (d) θ_X ; (e) θ_Y ; (f) θ_Z .

FIGURE 15: Single-axis displacement verification result (3x test for each axis): (a) x -axis; (b) y -axis; (c) z -axis; (d) θ_x ; (e) θ_y ; (f) θ_z .

set according to the noise of the measurement system. The stepwise test results are shown in Figure 14.

4.2. Single-Axis Movement Verification. This experiment provides verification of the kinematic equations (13). The stage

is controlled in a closed loop and moved one axis at a time and this was repeated three times for each axis. Displacement of the stage was measured using the six-DOF measurement system. Experimental results are shown in Figure 15 and show a positioning accuracy of under $0.1 \mu\text{m}$ and 0.5 arcsec .

FIGURE 16: 1 Hz sine wave tracking result: (a) x -axis; (b) y -axis; (c) z -axis; (d) θ_x ; (e) θ_y ; (f) θ_z .

This is almost equal to the residual error of the six-DOF measurement system.

4.3. Tracking Test. In this experiment, the stage was operated under closed loop control with feedforward compensation. Single axis tracking allowed the dynamic characteristic of the stage to be observed. Two input signals were tracked, 1 Hz and 5 Hz sine waves, both with amplitudes of $2.5 \mu\text{m}$ and 5 arcsec for the linear and angular axes, respectively. The results of this

single axis tracking experiment are shown in Figures 16 and 17.

Because the orthogonality of a stacked stage is not very good it needs to be evaluated. In general this can be done by circular testing as described in ISO 230-4. The next test that had to be performed was that of dual-axis tracking. For this a circular test was run on three different planes, the XY , XZ , and YZ . The tracking signal used was a 1 Hz sine wave with amplitude of $2.5 \mu\text{m}$. The results are shown in Figures 18(a) to 18(c), where it can be seen that (1) the larger roundness

FIGURE 17: 5 Hz sine wave tracking result: (a) x -axis; (b) y -axis; (c) z -axis; (d) θ_X ; (e) θ_Y ; (f) θ_Z .

error is inclined at -45 degrees in the YZ plane; (2) the larger roundness error is inclined at 45 degrees in the XZ plane; (3) the larger round error is inclined at about zero degrees in the XY plane.

5. Conclusions

A flat six-DOF compensation stage controlled in closed loop has been proposed in this study. The feedback positional values are provided by a six-DOF optical measurement

system comprised of three two-dimensional measurement modules. To reduce the effect of hysteresis, this study proposes a feedforward compensator based on a generic differential model in which hysteresis can be reduced by about 97%. Although the x - and y - axes of the stage were linked as a four-bar mechanism, there was no displacement coupling problem. Positioning accuracy of the linear and angular movements is about $\pm 0.05 \mu\text{m}$ and $\pm 0.5 \text{ arcsec}$, respectively. From Figures 18(a) and 18(b), it can be seen that the z -axis is not exactly orthogonal with the x - and y -axes, or movement

FIGURE 18: Circle test results for the 3-DOF compensation stage: (a) YZ plane; (b) XZ plane; (c) XY plane.

of z -axis is not synchronized with that of the x - and y -axes. The displacement proportional difference between the X - and Y -axes is shown in Figure 18(c).

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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