The Development and Control of a Long-Stroke Precision Stage

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ABSTRACT

A large-stroke precision positioning stage, which includes a planar piezoelectric transducer (PZT) stage and a three-dimensional stepper motor stage is presented here. Stage transfer functions were obtained by experiments. An integral control with gain-scheduling was designed for the PZT stage, while robust loop-shaping control with feed-forward compensation was implemented for the stepper motors. The stages were integrated and a double-layer control structure was designed for the combined stage to allow nanopositioning for long travel. Experiments were then carried out, and the results showed that precision positioning for long strokes could be achieved with our combined stage. Our stage is also suitable for integration with manufacturing modules, such as a two-photon polymerization system for the fabrication of large-scale micro-structures.

KEYWORDS

Piezoelectric transducer; stepper motor; precision positioning stage; robust control; system integration

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1. Introduction

Precision positioning has become essential for many processes, notably for the fabrication of semi-conductors, Microelectromechanical Systems, two-photon polymerization (TPP), and other such micro-structures. Piezoelectric transducer (PZT) is the usual method used for precision positioning stages because it can provide high resolution output and fast responses. However, PZT material has some non-linear characteristics and can suffer external disturbance and noise with subsequent loss of precision. Much research has been focused on PZT actuator control. For example, Leng et al. used an H-infinity controller and a disturbance observer to measure vibration disturbances in the environment and ensure high-precision positioning control using sine wave tracking [1]. Jeong and Park combined a PZT actuator and a flexure hinge mechanism into a precision displacement stage [2]. They used a mathematical model derived from the frequency response in an experimental analysis system, and an H-infinity controller to achieve high-precision positioning. Chen and Liang combined the PZT actuator with a bridge-type mechanism and calculated the control parameters of the PI controller using a fuzzy algorithm to improve displacement precision [3]. Lee et al. used a PZT actuator in conjunction with a neo-type mechanism to devise a three-dimensional precision positioning stage [4]. It is much smaller than conventional mechanisms and is now widely used. Much attention has also been given to the improvement of non-linear characteristics such as hysteresis. For instance, Zhu and Wang presented a new asymmetric Bouc–Wen model operator to improve the conventional model and derive one that is more consistent with an actual hysteresis curve [5]. Song et al. used...
the Preisach mathematical model to create hysteresis curves, using the inverse model to calculate the offset voltage and minimize errors [6]. Chang et al. considered the PZT actuator to be a linear mathematical model with non-linear characteristics contributed by input noises [7]. They improved hysteresis effects without using a mathematical model for the hysteresis curve. Compensating for cross-axis coupling effect and hysteretic nonlinearity with a novel monolithic FBM, Lin et al. made the positioning precision of a XY PZT be within 0.1 μm [8].

The rapid development of high-precision process technology not only demands higher actuator precision, but also the maintenance of high long-stroke precision. While PZT material has excellent precision, travel is usually limited to a few hundred micrometers. To meet this requirement, much research has been focused on a combination of PZT material with long-stroke actuators. For example, Ito et al. used high-precision small-stroke actuators and long-stroke linear motors to produce a travel of 500 mm with a precision of 15 μm in a framework formed by dual control loops [9]. Lin et al. combined a PZT actuator with a long-stroke servo motor and used iterative learning control to design a stage with a precision of 0.1 μm on the X- and Y- axes [10]. By combining a linear motor with a Lorentz motor, Hou et al. used master–slave control architecture to design a PID controller and feed-forward compensator to produce nano-level precision [11]. Yang et al. used a fast high-precision linear motor stage combined with a two-axis PZT stage to produce a movement of 250 mm/s over a range of 300 × 300 mm [12]. Using of a conventional voice coil motor and a piezo-electrically actuated suspension, Raymond et al. designed H-infinity controller which were implemented in real-time in hard disk drive (HDD) [13]. Rahman et al. used dual-stage actuators for positioning servomechanism in HDD with hysteresis compensator to improve the precision [14].

In this study a PZT stage is combined with a stepper motor stage to achieve high-precision long-stroke position control. The experimental hardware, including the actuator, sensor, data acquisition system, and other devices, are described in Section 2. System models were derived from identification experiments and nominal plants are selected in Section 3. Section 4 designs robust controllers for the PZT and stepper motor stages. These are integrated in Section 5 and a control was designed for the integration system to allow long-stoke positioning and tracking experiments. The results of the study are summarized in the last section with suggestions about future development.

2. Experimental Setup and Hardware

This section describes the experimental setup and hardware, including the actuator, sensor, and other devices.

A Physik Instrumente P-517.RCD vacuum PZT stage was selected for the study. This stage (see Figure 1) provides two-axis 100 μm displacement and includes an optical encoder with 1 nm resolution. The specifications of the stage are set out in Table 1.

To ensure the maintenance of precision over long-strokes, we used stepper motors in conjunction with a ball screw mechanism to convert rotational angular displacement to linear displacement for positioning control. We selected the ALS-510-H2P [13] horizontal uniaxial displacement stage (Figure 2) and ALV-104-HP [14] vertical displacement stage (Figure 3) (Chuo Precision Industrial Co., Ltd.) for this study. An optical encoder with 0.1 μm resolution was used to measure the displacements. See Table 2 for the specifications of the stage.

A schematic control architecture is shown in Figure 4. We use Visual Studio C++ 2010 to install the designed controllers in the computer program in the form of differential equations to calculate the control inputs for the actuators, transmitting control digital signals and acquiring digital signals from the sensors via the data acquisition card whose sampling rate is 1 kHz.

3. System Identification

This section covers system identification for the PZT and the stepper motor stages. We derived the mathematical models of the systems by experiments and applied gap metric to select the nominal plants. The results were used to design controllers, as shown in Section 4.

Figure 1. The PZT stage.

Table 1. Specifications of the PZT stage [15].

| Active axis | x, y |
|-------------|-----|
| Closed-loop travel | x, y:100 μm |
| Voltage range | −20–120 V |
| Resonant frequency | 450 Hz |
| Capacitance | 9 μF |
| Sensor resolution | 1 nm |
| Mass | 1.4 kg |
3.1. System Identification Experiment

We used a black box model to describe the system. Specific signals were inputted during the experiments and the corresponding output signals were measured. A sinusoidal signal with a fixed amplitude and variable frequency was inputted, and we create the most suitable transfer function based on I/O signal data using a MATLAB command. Therefore, we can acquire the transfer function, and design the controller based on the model. While controlling the PZT and stepper motors by giving position commands, the controller helps calculate corresponding signal transmitted. The system model might be affected by external factors, noises, and other environmental disturbances, so that tiny differences existed between the measured output signals. These differences were reflected in the derived transfer functions and showed uncertainty in the system. To gather representative data, the system identification experiments were repeated 10 times and the results are shown in Figures 5 and 6. Figure 5(a) and (b) shows the x-axis input and output signals of the PZT and the stepper motor stages, respectively. A description of the y-axis signals is not included because the responses of the x- and y-axes are very similar. Figure 5(c) shows the z-axis input and output signals of the stepper motor stage. Figure 6(a) and (b) show the x-axis transfer function Bode diagram of the PZT and the stepper motor stages, respectively. Again, description of the y-axis signals is omitted because the responses of the x- and y-axes are very similar. Figure 6(c) shows the Bode diagram for the z-axis of the stepper motor stage.

3.2. Nominal Plant

The transfer functions derived from each system’s identification experiments were not at all the same due to uncertainties in the systems. Hence, a representative transfer function (i.e. the nominal plant) needed to be found, so that the controller design can be based on the nominal plants. We used the Left Coprime Factorization (LCF) \[15\] to deal with system uncertainty. Suppose a plant \(G(s)\) was presented in the following LCF:

\[
G(s) = \tilde{M}^{-1}\tilde{N}
\]

(1)

where \(\tilde{M}, \tilde{N} \in RH_{\infty}\) and \(\tilde{M}\tilde{M}^{*} + \tilde{N}\tilde{N}^{*} = I\). A perturbed system \(G_{\Delta}\) can be represented as follows:

\[
G_{\Delta} = (M + \Delta_{M})^{-1}(N + \Delta_{N})
\]

(2)

in which \(\Delta_{M}, \Delta_{N} \in RH_{\infty}\). We defined the gap between \(G(s)\) and \(G_{\Delta}\) as the lowest value of \(\left\|\begin{bmatrix} \Delta_{N} & \Delta_{M} \end{bmatrix}\right\|_{\infty}\) that perturbs \(G(s)\) to \(G_{\Delta}\). We calculated the gap values between different transfer functions and derived the lowest gap based on the following criterion:

\[
\epsilon = \min_{G_i, G_j} \max_{i,j = 1 \sim n} \delta_{ij}(G_i, G_j)
\]

(3)

The nominal plant was the system that had the lowest gap value as indicated below:
Figure 5. I/O signals in the system identification experiment, (a) PZT stage x-axis, (b) Stepper motor stage x-axis, (c) Stepper motor stage z-axis.

Figure 6. Bode diagram, (a) PZT stage x-axis, (b) Stepper motor stage x-axis, (c) Stepper motor stage z-axis.
\[ G_N = \arg \min \max_{G_i} \delta_i (G_N, G_i), \forall G_i \] (4)

The nominal plant for the PZT stage \((G_{P}^{x_n}, G_{P}^{y_n})\) and stepper motor stage \((G_{S}^{x_n}, G_{S}^{y_n}, G_{S}^{z_n})\), respectively, was derived from Equations (3) and (4) as shown in Table 3:

\[
G_{P}^{xy} = \frac{b_2 s^5 + \ldots + b_5 s + b_6}{s^6 + a_3 s^5 + \ldots + a_3 s + a_6}
\] (5)

\[
G_{S}^{xyz} = \frac{b_5}{s + a_6}
\] (6)

4. Design of the Controllers

This section describes the design of the controllers for the nominal plants and further tests experiments.

4.1. Design of the Controller for the PZT Stage

The controllers for the PZT stage were designed with reference to the transfer functions \(G_{P}^{x_n}\) and \(G_{P}^{y_n}\) derived from (5) to ensure good positioning capability and minimize the influence of external disturbances and noises. The applied closed-loop control architecture is shown in Figure 7. In a real system, disturbances are usually low-frequency signals while noises fall mostly within the high frequency range. To ensure the system would respond quickly in the transient state and move rapidly to the steady state, we scheduled the gain of the integral controller according to different error conditions. After repeated calibration using the experimental results and simulations, we designed the following controller:

\[
K_{P}^{xy} = \frac{k}{s} \begin{cases} 
 1, & |e_{p}^{xy}| \leq 0.98 \\
 5, & 0.98 < |e_{p}^{xy}| < 10 \\
 3, & |e_{p}^{xy}| \geq 10 
\end{cases}
\] (7)

Table 3. System parameters and gap values.

| Plant       | \(x\)               | \(y\)               | \(z\)               |
|-------------|----------------------|----------------------|----------------------|
| \(b_{x}/a_{x}\)| 36.8/4 \(\times 10^{15}\) | 17.8/18 \(\times 10^{15}\) | 14.3/2.9 \(\times 10^{12}\) |
| \(b_{y}/a_{y}\)| 43.3/5.2 \(\times 10^{14}\) | 36.1/4.2 \(\times 10^{14}\) | 23.9/5.6 \(\times 10^{9}\) |
| \(b_{z}/a_{z}\)| 16.2/2.9 \(\times 10^{12}\) | 14.3/2.5 \(\times 10^{12}\) | 9.9/10.1 \(\times 10^{8}\) |
| Gap value   | 1816/627.8           | 1886/563.3           | 0.0078               |
| Stepper motor stage | \(x\) | \(y\) | \(z\) |
| \(b_{x}/a_{x}\)| 0.1/0.00             | 0.1/0.00             | 0.025/0.00           |
| Gap value   | 0.0078               | 0.0049               | 0.0254               |

Table 4. Step response rate of the PZT stage.

| Experiment | \(x\) | \(y\) |
|------------|-------|-------|
| Settling time (sec) | 0.110 | 0.102 |
| Overshoot (%) | 1.5 | 0.7 |
| RMSE (nm) | 8.10 | 8.02 |
| MAE (nm) | 20.0 | 21.0 |

Figure 7. PZT stage control block diagram.

We installed the controller and conducted both experiments and simulations and compared the results using MATLAB. The tests were about the responses of 15 μm step and the results are displayed in Table 4 and Figure 8, respectively. The highest overshoot percentage could be suppressed by scheduling the gain of the controller. The maximum absolute error (MAE) was about 20 nm and the root-mean-square error (RMSE) was about 8 nm in the steady state.

4.2. Design of the Controller for the Step Motor Stage

We used the motor stage transfer function \(G_{S}\) derived from (6) and applied robust control and loop-shaping techniques for position control. According to the small gain theory, when the uncertainty of a closed loop system is \(||\Delta_N - \Delta_{M}||_{\infty} < \varepsilon\), the necessary and sufficient condition needed to maintain internal stability of the system is:

\[
\left[ \begin{array}{c} K \\ I \end{array} \right] (I - G_{N}K)^{-1} \tilde{M}^{-1} \leq \frac{1}{\varepsilon}
\] (8)

Using this as a reference, we defined the following stability margin as an indicator for the determination of system stability:

\[
b(G_{N}, K) = \left[ \begin{array}{c} K \\ I \end{array} \right] (I - G_{N}K)^{-1} \tilde{M}^{-1} \left[ \begin{array}{c} I \\ G_{N} \end{array} \right] \leq \frac{1}{\varepsilon}
\] (9)
From the derived weighting function, we calculated the following corresponding robust controller using the MATLAB command `ncfsyn`:

We found the stability margins

\( b(W_G^x, y, S, K_\infty) = 0.75 \)

and

\( b(W_G^z, z, S, K_\infty) = 0.70 \)

using Equation (9). Both values were greater than the gap values 0.002, 0.003, and 0.0005 derived in Section 4.3, indicating that the stability of the system was good.

Although the designed controllers had a good stability margin, tracking capability and resistance to disturbances and noises, phase lag occurred during sine-wave tracking in the high frequency range. To counteract this, we added a feed-forward compensator with architecture as shown in Figure 9. The transfer function of this closed-loop controller system was:

\[
T = \frac{K_\infty W_s G_s}{1 + K_\infty W_s G_s} \quad (11)
\]

We found the stability margins

\( b(W_G^{x,y}, K_\infty) = 0.75 \)

and

\( b(W_G^z, K_\infty) = 0.70 \) using Equation (9). Both values were greater than the gap values 0.002, 0.003, and 0.0005 derived in Section 4.3, indicating that the stability of the system was good.

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T = \frac{K_\infty W_s G_s}{1 + K_\infty W_s G_s} \quad (11)
\]

so that the necessary and sufficient condition for internal stability of a system with \( \| [\Delta_N \Delta_M] \|_\infty < \varepsilon \) is \( b(G_N, K) \geq \varepsilon \).

The weighting functions were derived according to the following guidelines: The system was expected to have high gain at low frequency to ensure errors were small to disturbances. Also, the system was expected to have low gain in the high frequency range to reduce the effect of noises, because noises are normally in the higher frequency range. The gain decay rate (i.e. the slope rate on the Bode diagram) of the system near the crossover frequency should not be too high to ensure that the system is robust and has a good phase margin (PM). After repeated calibration according to the results of the experiments and simulations, we designed the following weighting functions:

\[
W_s^{x,y} = \frac{500(1 + \frac{s}{60})}{(1 + \frac{s}{100})}, \quad W_s^z = \frac{500(1 + \frac{s}{80})}{(1 + \frac{s}{200})} \quad (10)
\]
The following system transfer function could be derived for the closed-loop:

\[ T_{TP} = \frac{GG + K_\infty W_S G_S}{1 + K_\infty W_S G_S} \approx 1 \]  

(13)

This design could substantially compensate for the phase delay, and the compensator helped to improve the sine-wave tracking when compared to an arrangement with a robust controller alone. Figure 10 shows the transfer function and frequency response before and after compensation.

Sine-wave tracking experiments were carried out on the designed controllers (11) (13) to analyze their gain value and phase relationship, and the experimental results were compared with simulations. The amplitude of the testing sine wave was 100 μm at frequencies of 1 Hz (z-axis) and 10 Hz (x- and y- axes), respectively. The results are shown in Figure 11 and Table 5.

5. Integrated Stage

A long-stroke positioning stage with excellent precision was built using a horizontal stepper motor displacement stage and a high precision PZT stage for the x- and y- axes. The PZT stage was used to correct small errors that can arise during movement of the motorized stage and gave excellent plane trajectory. The Z-axis was controlled only by stepper motor. All the hardware devices were assembled on an optical table where they could be isolated from external vibration. Figure 12 shows the integrated hardware setup.

Because a stepper motor and a PZT stage have been combined to make this stage, there are two actuators for each axis in the integrated system. This means that there are two sensor signals in the uniaxial direction, and that the displacements of both were measured to derive the necessary control. Therefore, a dual-loop arrangement, as shown in Figure 13(a), was used for control. The long-stroke stepper-motor stage forms a closed-loop and uses its local sensor signals to fix large positioning errors. The precision PZT stage also forms a closed-loop and uses the combined sensor signals to compensate the small positioning errors which cannot be fixed by the stepper motor stage. In the z-axis direction, control is subject to the local sensor signals of the stepper motor stage, as shown in Figure 13(b). An anti-locking mechanism protects the PZT stage by ensuring the movements of the PZT within its allowed maximum travel.

Finally, long-stroke 2D and 3D tracking experiments were conducted using the assembled stage to verify the

![Figure 11. Stepper motor sine wave tracking experiments, (a) x axis, (b) y axis, (c) z axis.](image)

| Experiment | Axis | Frequency (Hz) | Phase lag (deg.) | Amp. gain (dB) | RMSE (μm) |
|------------|-----|----------------|------------------|--------------|-----------|
| Simulation |     |                |                  |              |           |
| Phase lag (deg.) | 3.6 | 3.6 | 0.0
| Amp. gain (dB) | 0.257 | 0.257 | 0.026

Table 5. Stepper motor sine wave tracking data.
upgraded precision. Figures 14 and 15 show the results of the experiments. Relevant data are shown in Table 6.

6. Conclusion

This paper has presented a long-stroke three-axis precision displacement stage that combines a high precision PZT stage with a long travel stepper motor stage. System identification and controller design were conducted for both stages, and a feed-forward compensator and dual-loop architecture was applied to control the integrated
stage. Both 2D and 3D tracking experiments were tested to verify stage precision. In the future, this stage can be integrated with precision manufacture systems, such as TPP, to make large-size precision products.

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References
[1] Leng T, Yan P, Guo L. Modeling and control of a piezoelectric-actuated nano-positioner: an hierarchial composite anti-disturbance control approach. World Congress on Intelligent Control and Automation (WCICA); China; 2014 Jun; p. 2836–2841.
[2] Jeong K, Park J. Ultra-precision positioning control based on the frequency response analysis. International Conference on Smart Manufacturing Application (ICSMA); Korea (South); 2008 Apr; p. 219–224.
[3] Chen LX, Ling TY. The design and new controller of 1-DOF precision positioning platform. International Conference on Manipulation, Manufacturing and Measurement on the Nanoscale (3M-NANO); China; 2013 Aug; p. 190–194.
[4] Lee JC, Lee K, Yang SH. Development of compact three-degrees-of-freedom compensation system for geometric errors of an ultra-precision linear axis. Mech Mach. 2016;99:72–82.
[5] Zhu W, Wang DH. Non-symmetrical Bouc-Wen model for piezoelectric ceramic actuators. Sens Actuators A: Phys. 2012;181:51–60.
[6] Song G, Zhao J, Zhou X, et al. Tracking control of a piezoceramic actuator with hysteresis compensation using inverse Preisach model. IEEE/ASME Trans Mech. 2005;10:198–209.
[7] Chang S, Yi J, Shen Y. Disturbance observer-based hysteresis compensation for piezoelectric actuators. American Control Conference (ACC); USA; 2009 Jun; p. 4196–4201.
[8] Lin Chih-Jer, Lin Po-Ting. Particle swarm optimization based feedforward controller for a XY PZT positioning stage. Mechatronics. 2012;22:614–628.
[9] Ito S, Steininger J, Chang PI. High-precision positioning system using a low-stiffness dual stage actuator. Int Fed Autom Control. 2013;46:20–27.
[10] Lin CJ, Wu CH, Hwang CC. Tracking control of a motor-piezo XY gantry using a dual servo loop based on ILC and GA. IEEE International Conference Control and Automation (ICCA); New Zealand; 2009 Dec; p. 1098–1103.
[11] Hou BJ, Gao JS, Zhou YF. The development of an ultra-precision dual-stage based on a master-slave control system. Computer Distributed Control and Intelligent Environmental Monitoring (CDCIEM); China; 2012 Mar; p. 727–730.
[12] Yang C, Wang GL, Yang BS, et al. Research on the structure of high-speed large-scale ultra-precision positioning system. Nano/Micro Engineered and Molecular Systems (NEMS); China; 2008 Jan; p. 9–12.
[13] Boettcher U, de Callafon RA, Talke FE. Modeling and control of a dual stage actuator hard disk drive. J Adv Mech Des Sys Manuf. 2010;4(1):107–118.
[14] Rahman MA, Al Mamun A. Nonlinearity analysis, modeling and compensation in PZT micro actuator of dual-stage actuator system. IEEE International Conference Control and Automation (ICCA); Taiwan; 2014 Jun; p. 1275–1280.
[15] http://www.physikinstrumente.com/product-detail-page/p-517-p-527-201500.html