Improvement of scanning accuracy of PZT piezoelectric actuators by feed-forward model-reference control

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For ultraprecision, three-dimensional surface metrology such as atomic force microscopy, PZT ceramic actuators are popularly used to scan a testpiece in the lateral directions while its vertical dimension is traced by a measuring probe. In this type of scanning microscopy, the measuring accuracy in lateral dimensions is critically limited by hysteresis errors in PZT ceramics when operated by simple open-loop control. We describe a feed-forward control method to effectively reduce scanning errors by using deterministic hysteresis path models. Experimental results prove that this method can enhance scanning accuracy by an order of 10 as compared with conventional open-loop scanning.

Keywords: PZT ceramics; piezoelectric actuators; hysteresis effects; hysteresis suppression; feed-forward control; scanning microscopy

Introduction
Piezoelectric materials such as natural crystalline quartz and piezoelectric transducer PZT ceramics [Pb(Zr, Ti)O 3] produce fine mechanical displacements when they are subject to an external electric field. This converse piezoelectric property can be used in various types of microactuators for positioning with nanometer resolution. Microscanning is an outstanding application of such microactuators, in which a load is moved in a repeated and reciprocated manner with a fine pitch, as illustrated in Figure 1. This type of microscanning plays an important role in ultraprecision three-dimensional surface metrology such as scanning tunneling microscopy, atomic force microscopy, and phase shifting interferometry. Synthetic PZT ceramics are more preferably used because they have many advantages of manufacturability.

However, PZT ceramics exhibit a significant amount of hysteresis, which is clearly observed in open-loop control as demonstrated in Figure 2. The output displacement responds to the input voltage with a remarkable mean sensitivity, but its global behavior appears in a nonreproducible manner. Therefore, a large band of positioning uncertainty inevitably results. One practical
engineering solution to suppress the undesirable hysteresis effect is to adopt a sensitive position transducer and perform closed-loop feedback control, as illustrated in Figure 3. The transducer for this purpose may be a capacitance pickup or laser interferometer, with which measuring resolution can reach to nanometer ranges. However, the use of transducers is very often found not feasible; they may be relatively bulky and heavy to be incorporated in piezoelectric microactuating systems.

In this study, a feed-forward control method is presented with aims of reducing the hysteresis effect of open-loop control by using deterministic hysteresis path models. This method is performed in an open-loop way, as illustrated in Figure 4. Three different models are suggested, and their respective performances are compared with each other. Experimental results prove that the models can improve scanning accuracy by an order of 10 as compared with conventional open-loop scanning.

**Computer aided model-reference control**

The experimental apparatus prepared to implement the feed-forward model-reference control under consideration is configured as in Figure 5. It is a
Figure 1  Microscanning operation of PZT actuators. (a) Lateral scanning in x and y directions. (b) Scanning sequence of x-axis

Figure 2  Positioning uncertainty due to hysteresis effects in PZT ceramic actuators. (a) Open-loop positioning control and (b) typical hysteresis response

Figure 3  Closed-loop feedback control of a PZT actuator
A single-axis microscanning system is employed. A mass is moved in a linear direction being suspended and guided by pairs of parallel leaf springs. A PZT ceramic actuator is rigidly connected to the mass, and its input voltage is controlled by a microcomputer based on the reference-models suggested in this study to generate the required output displacement sequence of scanning.

The entire microscanning system is placed on an air-damped structure isolated from external vibrations. The environmental temperature is maintained at 20.0 ± 0.1°C to avoid thermal disturbances. The actual displacement of the mass is monitored by a helium-neon (He-Ne) laser heterodyne interferometer.

Table 1: Mechanical and electrical properties of the PZT actuators tested

<table>
<thead>
<tr>
<th>Type</th>
<th>Actuator 1</th>
<th>Actuator 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>15 μm/100 V</td>
<td>6 μm/1,000 V</td>
</tr>
<tr>
<td>Maximum</td>
<td>150 V</td>
<td>1,000 V</td>
</tr>
<tr>
<td>voltage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>100 kHz</td>
<td>5 kHz</td>
</tr>
<tr>
<td>response</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacitance</td>
<td>6.5 μF</td>
<td>17 nF</td>
</tr>
<tr>
<td>Model</td>
<td>NLA10X10X18 (Tokin)</td>
<td>PZ-90 (Burleigh)</td>
</tr>
</tbody>
</table>
ferometer (Hewlett-Packard 5528A) with a resolution of 0.01/μm. Two different types of PZT actuators are tested: one is a single element, and the other is a stack type. Their detailed mechanical and electrical characteristics are listed in Table 1.

Scanning errors due to hysteresis
As illustrated in Figure 6, the position sequence to be generated by the PZT actuator for a complete cycle of lateral scanning may be described by a set of displacements as

\[ Y = \{ (y_i) | i = 0, 1, 2, \ldots, n \} \]  \hspace{1cm} (1)

Because the above sequence is a reciprocative type, the following symmetric property holds:

\[ y_i = y_{n-i}, \hspace{1cm} i = 0, 1, 2, \ldots, n/2 \]  \hspace{1cm} (2)

For convenience, the complete cycle may be divided into two subsequences: the forward sequence \( Y_f \) and reverse sequence \( Y_r \). These may be explicitly defined as

\[ Y_f = \{ (y_i) | i = 0, 1, 2, \ldots, n/2 \} \]  \hspace{1cm} (3)

and

\[ Y_r = \{ (y_i) | i = n/2, \ldots, n-1, n \} \]  \hspace{1cm} (4)

Then, the input voltage sequence generated by a reference-model may be expressed by

\[ V = \{ (v_i) | i = 0, 1, 2, \ldots, n \} \]  \hspace{1cm} (5)

This can also be divided into two subsequences, \( V_f \) and \( V_r \), in accordance with \( Y_f \) and \( Y_r \), respectively, as

\[ V_f = \{ (v_i) | i = 0, 1, 2, \ldots, n/2 \} \]  \hspace{1cm} (6)

and

\[ V_r = \{ (v_i) | i = n/2, \ldots, n-1, n \} \]  \hspace{1cm} (7)

If hysteresis in the PZT actuator is neglected, then its input/output relationship may be assumed to be linear, i.e.,

\[ y_i = \kappa v_i \]  \hspace{1cm} (8)

where the constant \( \kappa \) denotes the mean sensitivity. If the above linear model is adopted to decide the input sequence \( V \) for a required output sequence \( Y \), the actual output displacement \( y_i^* \) deviates significantly from the required value \( y_i \), due to hystere...
sis, as exemplified in Figure 7. The positioning error within a scanning sequence may be quantified by the following maximum deviation ratio:

$$\varepsilon_{max} = \max\{(y_i - y_i^*)\}/\{\max[y_i] - \min[y_i]\} \times 100(\%) \quad (9)$$

In general, the hysteresis effect on scanning errors may be explained by three qualitative terms: bidirectionality, nonlinearity, and nonreproducibility. The bidirectionality represents the fact that the forward output sequence is never symmetrical with respect to the reverse sequence, even if a symmetrical input sequence is given, i.e.,

$$y_i \neq y_{n-i}, \text{ even if } v_i = v_{n-i} \quad (10)$$

More precisely, the displacements of the forward sequence become always less than those of the reverse sequence for a same voltage input, i.e.,

$$y_i < y_{n-i} \text{ for } v_i = v_{n-i} \quad (11)$$

The nonlinearity explains that the output displacement is not in exact proportion to the input voltage,
i.e.,

\[
\frac{Y_i}{Y_j} \neq \frac{V_i}{V_j}
\]

The nonreproducibility represents that the output \(Y_i\) induced by a given input \(v_i\) does not turn out to be unique but varies with the cycle, i.e.,

\[
(y_i)_{j-th \ cycle} \neq (y_i)_{j-th \ cycle}
\]

Due to these undesirable effects, the linear model of Equation (8) does not result in good scanning accuracy and its maximum error reaches as much as 13.6% in this study, as shown in Figure 7.

**Reference-models of hysteresis**

Three reference-models are suggested with which the feed-forward control under investigation is to be implemented to minimize the undesirable hysteresis effect of open-loop control and thus improve the overall scanning accuracy. These models are respectively referred to as model 0, model I, and model II for convenience. They are based on three deterministic paths that are valid under specified operating conditions. These paths are established from experimental observations and approximated in nonlinear polynomial forms by using the least-squares method.

**Model 0**

Empirical observation shows that "if the input sequence is initiated from the zero state, then its output sequence always follows an identical path until the input reverses." This path is depicted in Figure 8 and designated \(H_0(v)\). It may be fitted in the follow-
ing polynomial equation for a gwen actuator using experimental data:

\[ y = H_f(v) = \sum_{k=0}^{\infty} \varphi_k v^k \]

where \( \varphi_k \) are the coefficients of polynomial terms.

Then model 0 directly takes the path \( H_f(v) \) for both the forward and the reverse sequence to constitute a scanning cycle. Because the path \( H_f(v) \) is valid only for forwarding, the original reverse sequence \( Y \) of Equation (4) is converted into an equivalent forward sequence as described in Figure 9, i.e.

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**Table 2** Reduction in scanning errors of actuator 1 by feed-forward model-reference control: coefficients of polynomials

<table>
<thead>
<tr>
<th>Function</th>
<th>( \varphi_0 )</th>
<th>( \varphi_1 )</th>
<th>( \varphi_2 )</th>
<th>( \varphi_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_f(v) )</td>
<td>( 8.4351 \times 10^6 )</td>
<td>( 1.5739 \times 10^4 )</td>
<td>( 6.57429 \times 10^7 )</td>
<td>( -4.5822 \times 10^{-3} )</td>
</tr>
<tr>
<td>( \Delta y )</td>
<td>( H_f(v_{n+2}) - H_f(v_{n+2}) )</td>
<td>( \psi_0 )</td>
<td>( 0.99447995 )</td>
<td>( \psi_1 )</td>
</tr>
</tbody>
</table>

**Table 3** Reduction in scanning errors by actuator 1 by feed-forward model-reference control: compensation errors

<table>
<thead>
<tr>
<th></th>
<th>Model 0</th>
<th>Model I</th>
<th>Model II</th>
<th>Linear model</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta_{\max} )</td>
<td>0.50% (0.08 ( \mu )m)</td>
<td>0.95% (0.15 ( \mu )m)</td>
<td>1.25% (0.20 ( \mu )m)</td>
<td>8.22% (1.30 ( \mu )m)</td>
</tr>
</tbody>
</table>

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**Figure 9** Operating sequence for model 0
Then, a complete forward-reverse scanning cycle is performed by two separate forward sequences; the original sequence $Y^{-}$ is first, and the equivalent of Equation (15) is next.

$$Y = \begin{cases} (y_i) | 0, y_i = H_f(v_i) & \text{for } y_i \in Y^{-}, 0, y_i = H_f(v_i) & \text{for } y_i \in Y_{-} \end{cases}$$

In the above equation, the zero input voltage should be inserted before each forward sequence to make sure the operating condition for the path $H^{-}(v)$ is satisfied. The path $H^{-}(v)$ varies with actuators, but it is uniquely determined with a good repeatability of less than 0.5% of maximum error for a given actuator. Results for actuators I and II obtained in this study are listed in Tables 2-5.

Model I

This model is based on a further empirical observation that "the reverse output sequence can also be uniquely determined if it is initiated from the saturated state." This reverse path is designated $H_{r}(v)$ and depicted in Figure 10. When the input exceeds a certain limit, the output no longer increases but remains constant. This limit is represented by the saturation displacement $Y_s$. Then, if the reverse sequence starts from $Y_s$, its decreasing path $H_{r}(v)$ turns out to be unique for a given actuator such as $H^{-}(v)$ and can also be fitted in a polynomial equation as shown in Tables 2-5.

$$y = H_{r}(v) = \sum_{k=0}^{m} \rho_k v^k$$

Figure 10  Empirical observation for model I

Now model I takes the path $H^{-}(v)$ for the reverse sequence and $H_{i}(v)$ only for the forward. Then, as illustrated in Figure 11, the complete scanning cycle of Model I is arranged as
A dummy operation to Ys should be inserted before starting the reverse sequence so as to meet the necessary condition for $H_r(v)$.

**Model II**

The previous two models require the dummy operations in the middle of a scanning cycle, i.e., to 0 in model 0 and to Ys in model I. These operations become unrealistic in many practical applications of microscanning; they require full stretching or shrinking of the actuator during a short period of time, and these sudden lateral movements may cause unexpected collision between the measuring probe and testpiece. Model II takes this fact of safety into consideration by using, instead of $H_r(v)$ and $H_r(v)$, decreasing curves naturally obtained by reversing the input sequence without any awkward jumps. In this case, the reverse sequence becomes

$$Y = \{(y_i) | 0, y_i = H_f(v_i) \text{ for } y_i \in Y_f, y_s y_i = H_r(v_i) \text{ for } y_i \in Y_r\} \quad (18)$$

A dummy operation to Ys should be inserted before starting the reverse sequence so as to meet the necessary condition for $H_r(v)$.

**Figure 11** Operating sequence for model I

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**Table 4** Reduction in scanning errors of actuator 2 by feed-forward model-reference control: coefficients of polynomials

| $H_f(v)$ | $\varphi_0$: $-4.9712 \times 10^{-5}$ |
| $\varphi_1$: $1.10273 \times 10^{-4}$ |
| $\varphi_2$: $6.66604 \times 10^{-7}$ |
| $\varphi_3$: $-4.07464 \times 10^{-9}$ |
| $H_r(v)$ | $\rho_0$: $9.05303 \times 10^{-6}$ |
| $\rho_1$: $1.19136 \times 10^{-4}$ |
| $\rho_2$: $-5.11343 \times 10^{-7}$ |
| $\rho_3$: $1.17552 \times 10^{-10}$ |
| \(\Delta y\) | $\psi_0$: $1.0183665$ |
| $\psi_1$: $-1.3896701$ |
| $\psi_2$: $1.4692587$ |
| $\psi_3$: $-1.9070265$ |
deviated from the path $H_r(V)$ as shown in Figure 12a. The degree of deviation may be defined by the positive difference between the actual displacement and $H_r(V)$ as

$$\Delta y(v) = H_r(v) - y(v)$$

(19)

As seen in Figure 12b, this deviation curve varies with the reversing point $v_r$, but always has its maximum at the very reversing point and decreases to zero as the reverse sequence proceeds to the zero input. The maximum deviation is given as

$$\Delta y(v_{n/2}) = H_r(v_{n/2}) - H_f(v_{n/2})$$

(20)

The deviation of Equation (19) may be normalized by dividing it with the maximum of Equation (20).

Table 5 Reduction in scanning errors by actuator 2 by feed-forward model-reference control: compensation errors

<table>
<thead>
<tr>
<th></th>
<th>Model 0</th>
<th>Model I</th>
<th>Model II</th>
<th>Linear model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_{\text{max}}$</td>
<td>2.24% (0.04 $\mu$m)</td>
<td>3.36% (0.06 $\mu$m)</td>
<td>5.05% (0.09 $\mu$m)</td>
<td>11.22% (0.20 $\mu$m)</td>
</tr>
</tbody>
</table>
Figure 12  Empirical observation for model II. (a) Definition of deviation $\Delta y$. (b) Deviation $\Delta y$

Figure 13  Normalization of the deviation from the saturated reverse path
Then this normalized deviation may be fitted in a normalized polynomial equation such as

\[
\frac{\Delta y(v)}{\Delta y(v_{n,2})} = \sum_{k=0}^{m} \psi_k \left[ \frac{v_{n,2} - v}{v_{n,2}} \right]^k
\]  

Figure 13 illustrates the above fitting in a graphical presentation. The coefficients \( \psi_k \) can be decided independent of the reversing point \( v_{n,2} \). Then, model II takes the above normalized polynomial for the reverse sequence while \( H_f(v) \) is used for the forward sequence. Model II appears as illustrated in Figure 14 and is represented by the following cycle:

\[
Y = \{(y_i)|0, y_i = H_f(v_i) \} \\
\text{for } y_i \in Y_f, y_i = H_r(v_i) \Delta y \text{ for } y_i \in Y_r \} 
\]  

Experiments and discussions

Models 0, I, and II were verified by using the experimental apparatus previously shown in Figure 5. In the first stage of experiment, the polynomial coefficients \( \psi_0, P_k, \) and \( \psi \), for actuators 1 and 2 specified in Table I were obtained to their fourth-order terms as listed in Tables 2 and 3. Then, the three reference models were constructed based on the method explained in the previous chapter and tested under the same environmental conditions. Their respective performances were evaluated by comparing them with each other and also with that of the linear model of Equation (8). Figure 15 summarizes the test results obtained with actuator 1. The scanning cycle was made up with 0.5 mm equal positioning intervals over a range of 16.0 mm in reciprocating mode. The cycle was repeated four times for each measurement. A Hewlett-Packard 5528A laser interferometer with a resolution of 0.01 mm was used in measuring the actual displacement of the actuators for determining the polynomial coefficients and scanning errors.
Figure 15a shows the result obtained with the linear model. In this case, a big discrepancy is found between the forward and reverse sequences, and the maximum scanning error reaches as much as 8.2%. On the other hand, as shown in Figure 15b–d, when feed-forward model-reference control is performed with models 0, I, and II, the errors reduce drastically, and their maximums are 0.50%, 0.95%, and 1.25%, respectively. In conclusion, model 0 gives the best performance because only the single path $H_r(v)$ is taken for both of its forward and reverse scanings; the approximation error of $H_J(v)$ by a limited number of polynomial terms is the main source of its scanning errors. Model I produces slightly larger errors compared with model 0. This is because two approximated paths $H_{\sim}(v)$ and $H_{\sim}(v)$ are used in model I. Model II produces relatively poor positioning accuracy because the approximation of normalized polynomials for $A_y(v)$ has a low repeatability, but its result is much superior to that of the linear model.

The same model-reference control experiment was repeated on actuator 2 of TaMe 1, and the results are summarized in Tables 2 and 3. Similarly to the case of actuator 1, model 0 produces the best performance of 2.2% maximum error, whereas the
Figure 15  Comparison of scanning error. (a) Linear model. (b) Model 0. (c) Model I. (d) Model II.
linear model has 11.4%. It is worthwhile noting that even though model II produces relatively poor scanning accuracy, it can eliminate the dummy operations to 0 or $Y_s$ requested in models 0 and I.

**Summary**

A feed-forward control of PZT ceramic actuators has been investigated with three reference-models to reduce the hysteresis errors of open-loop microscanning control. This method is implemented in an open-loop way with aids of microcomputer control for real-time generation of compensated input voltage sequences. Experimental results prove that scanning accuracy can be improved by an order of 10 as compared with conventional open-loop scanning.

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