Vibration Control of a Novel Tube Scanner Using Piezoelectric Strain-Induced Voltage

Yuen Kuan Yong and S. O. Reza Moheimani

Abstract—Piezoelectric tube scanners are widely used in nanopositioning applications such as in scanning probe microscopy. Capacitive or inductive sensors are used to provide feedback to improve bandwidth and accuracy of these tube scanners. However, these sensors contain certain noise densities which restrict the bandwidth of the closed loop system if nanometer resolution is required. The use of piezoelectric strain-induced voltage as a measurement signal has been recently proposed to provide feedback with a noise profile of up to three orders of magnitude better than capacitive sensors. This technique uses a quadrant of the electrode for actuation and the opposite quadrant for sensing. The major drawbacks of this arrangement are that the travel range of the tube is reduced by half and the tube is not driven symmetrically; thus the tube is not a collocated system. In this article, a novel electrode pattern of a tube scanner which addresses the above issues and allows for simultaneous actuation and sensing is presented. By using the piezoelectric strain voltage as measurement, an Integral Resonant Control (IRC) method combined with a feedforward inversion technique is implemented to achieve high-speed and accurate scanning performances of the tube.

I. INTRODUCTION

Piezoelectric tube scanners have been extensively used for precise positioning applications such as in scanning probe microscopy (SPM) [1]–[4], nano-indentation and nano-patterning for high-density data storage systems [5], [6], and nano-machining [7]–[10]. Piezoelectric tube scanners are simple to construct, easy to integrate into a microscope and relatively inexpensive. As a result, the majority of commercially available SPMs use piezoelectric tubes for x-y-z positioning. The piezoelectric tube reported in [1] consists of a radially poled piezoelectric material, four external electrodes and a continuous internal electrode. For x-y actuation, the internal electrode is grounded. Opposite electrodes are driven by voltages of equal magnitude but opposite polarity. One side of the tube expands, and the opposite side retracts, resulting in bending. For z-actuation, the inner electrode is driven by the z signal.

There has been enormous effort to improve the accuracy and scanning speed of piezoelectric tube scanners using two broad techniques, feedforward [11]–[15] and feedback controls [15]–[20]. Feedforward techniques do not require a sensor for online measurement but an accurate knowledge of the system dynamics is essential. Feedback-based techniques require a displacement sensor; therefore the performance of

a feedback system is dependent on the sensor noise and bandwidth. For example, capacitive sensors are one of the most commonly used displacement sensors for feedback control systems where they provide excellent resolution and signal-to-noise ratio (SNR). These sensors typically have a root-mean-square (RMS) noise of $20\text{pm}/\sqrt{\text{Hz}}$. If high resolutions are required for an application, say a RMS noise of 0.1nm, the bandwidth must be limited to 25Hz. This is inadequate for scanning tunneling microscopy and other applications where resolution and speed are required.

Techniques for simultaneous sensing and actuation of a piezoelectric tube were proposed in [18], [21]. One of the quartered electrodes is used for actuation and the opposite quartered electrode is used for sensing. The noise profile of the piezoelectric strain-induced voltage is measured to be three orders of magnitude lower than the capacitive sensor, allowing a significant improvement in closed loop bandwidth and sensor noise.

The idea of using piezoelectric strain-induced voltage as feedback signals to augment dampings on a tube was implemented in [18], [21] with great success. A controller was designed to impart substantial damping to the first resonant mode of the tube, allowing the tube to raster at a much higher rate. The main disadvantages of operating the tube in this manner are (a) the displacement of the tube is reduced by half since only one side of the tube is actuated, and (b) the tube cannot be considered perfectly collocated because it is driven asymmetrically [22], which complicates the process of designing a controller. The piezoelectric tube scanner with a new electrode pattern presented in this article addresses the above problems with a satisfactory outcome. To evaluate the closed loop performance of the proposed tube, an Integral Resonant Controller (IRC) is designed to damp the first resonance frequency of the tube. The IRC scheme is a simple yet well-performing technique which adds substantial damping to resonant modes without exciting the high frequency dynamics of a system. It has been proposed to damp collocated [23] and non-collocated systems [24] with noticeable success. In this article, the IRC is integrated with the feedforward inversion technique to provide accurate high-speed scanning up to 200Hz.

This article is organized as follows. In Sec. II, the novel piezoelectric tube scanner is described. This is followed by finite-element-analysis (FEA) of the tube performed using ANSYS, simulating the static and dynamic performances of the tube. The experimental setup and system identification of the tube is presented in Sec. III. Sec. IV presents the details of the IRC design and the feedforward inversion technique,

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The authors are with the School of Electrical Engineering and Computer Science, The University of Newcastle, Callaghan 2308, NSW, Australia. [Yuenkuan.Yong, Reza.Moheimani]@newcastle.edu.au

Fig. 1. The 12-electrode piezoelectric tube scanner. All dimensions are in mm.

followed by the comparisons of the open- and closed loop tracking performances of the tube. Sec. V concludes the paper and discusses the future work.

II. THE NOVEL PIEZOELECTRIC TUBE SCANNER

A. Description of the Tube Scanner

Fig. 1 shows the schematics of the novel piezoelectric tube scanner. The tube was made of PZT-5A piezoelectric material and was manufactured by Boston Piezo-Optics. It was poled radially outward. The external electrode is segmented into 12 equal sections of 30° each, whilst the internal electrode is covered with a continuous electrode. The internal electrode is grounded at all times. One end of the tube was fixed to an aluminium holder. A sensing target (in a cube shape), which is also served as a stage to hold a sample, was glued to the free end of the tube.

Unlike the conventional quartered electrode tube scanner, the tube scanner presented in this article can be used for simultaneous actuation and sensing. Fig. 2a illustrates the arrangement of the tube for both actuation and sensing in the x direction. The arrangement in the y direction would be identical to x. The two outer electrodes on opposite sides are used for actuation [22]. Voltages with equal magnitude but opposite polarity are applied to the opposite electrodes. One side of the tube extends and the opposite side retracts, resulting in bending. The stress is antisymmetrical at the opposite sides of the tube and it translates into a voltage at the central electrode of each side due to the piezoelectric effect [25]. Since the voltage induced at the opposite electrodes is equal in magnitude but 180° out of phase, the voltage induced at one of the electrodes is inverted and then added to the opposite electrode (see Fig. 2a). In [22] it is illustrated that in this actuation mode, the displacement range of the tube is improved by over 30% compared to the actuation mode presented in [18], [21] (see Fig. 2b). It also shows an improvement of the SNR at the sensing electrodes.

B. Finite-element-analysis of the Tube Scanner

The FEA method is used to estimate the static and dynamic performances of the tube scanner. The constitutive equations describing the piezoelectric property can be written as [26]

$$\begin{aligned} \mathbf{S} &= \mathbf{s}^E \mathbf{T} + \mathbf{d} \mathbf{E} \\ \mathbf{D} &= \mathbf{d} \mathbf{T} + \boldsymbol{\epsilon} \mathbf{E} \end{aligned} \quad (1)$$

Fig. 2. Actuation and sensing in the x direction of the piezoelectric tube. (a) The arrangement of the 12-electrode tube. (b) The identical arrangement of a quartered electrode tube. v_x and $\bar{v}_x$ are the applied voltages. v_{p_x} and $\bar{v}_{p_x}$ are the piezoelectric strain-induced voltages which are used as measurement signals. d_x and $\bar{d}_x$ are the displacement of the target glued at the free end of the tube.

where $\mathbf{S}$ is the strain vector, $\mathbf{s}^E$ is the elastic compliance matrix, $\mathbf{T}$ is the stress vector, $\mathbf{d}$ is the piezoelectric constant matrix, $\mathbf{E}$ is the electric field vector, $\mathbf{D}$ is the electric displacement vector and $\boldsymbol{\epsilon}$ is the permittivity matrix.

The FEA model of the piezoelectric tube is constructed using three-dimensional elements (SOLID5) in ANSYS. Nodes located at the area of an electrode are fully coupled, thus they have the same degree-of-freedom (i.e. voltage). Our objective is to construct a tube scanner which has (a) a high first mechanical resonance frequency for high-speed scanning, (b) a relatively large displacement range and (c) the capability of providing sufficient piezoelectric strain-induced voltages (v_{p_x}) in order to achieve a good SNR during measurement. Due to the nature of the device, there is always tradeoff between the resonance frequency and displacement range of the tube. v_{p_x} is dependent on the size of the two central electrodes, which is determined by the diameter of the tube. In order to search for an agreeable compromise among the above requirements, a number of modeling and design iterations were conducted in ANSYS until the desired criteria was achieved. The final tube dimensions can be found in Fig. 1 and the material properties of the piezoceramic PZT-5A are shown in Table I.

Fig. 3 shows the mode shapes of the tube. The first, second and sixth resonant modes are bending modes occurring at 733Hz, 4.09kHz and 10kHz respectively. At 4.2kHz, the torsional mode of the tube can be observed. The longitudinal extension mode occurs at 7.7kHz. At 9.8kHz, the circumferential mode of the tube can be observed. There are two identical bending and circumferential modes, each observed in the x and y axis respectively. For brevity, only one of each mode is shown in Fig. 3. Assuming the system is linear, the static (DC) gains of the tube are estimated to be $d_x/v_x = 0.076 \mu\text{m/V}$ and $v_{p_x}/v_x = 0.029 \text{V/V}$. When an input voltage of 400V is applied, the estimated d_x and v_{p_x} are $26.4 \mu\text{m}$ and 11.6V respectively. This provides a reasonable scanning range of the tube. The magnitude of the

TABLE I
MATERIAL PROPERTIES OF PIEZOCERAMIC PZT-5A

Property	Data
Elastic compliance-matrix	$s^E = \begin{bmatrix} 15.0 & -5.74 & -7.22 & 0 & 0 & 0 \\ -5.74 & 15.0 & -7.22 & 0 & 0 & 0 \\ -7.22 & -7.22 & 18.8 & 0 & 0 & 0 \\ 0 & 0 & 0 & 47.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 47.5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 44.3 \end{bmatrix}$ $\times 10^{-12} (m^2/N)$
Piezoelectric coupling	$d = \begin{bmatrix} 0 & 0 & 0 & 0 & 585 & 0 \\ 0 & 0 & 0 & 585 & 0 & 0 \\ -171 & -171 & 374 & 0 & 0 & 0 \end{bmatrix}$ $\times 10^{-12} (m/V)$
Relative Permittivity	$\epsilon/\epsilon_0 = \begin{bmatrix} 1730 & 0 & 0 \\ 0 & 1730 & 0 \\ 0 & 0 & 1700 \end{bmatrix}, \epsilon_0 = 8.854 \times 10^{-12} (F/M)$
Density	$\rho = 7500 \text{ kg/m}^3$

Fig. 3. FEA simulated mode shapes of the tube. From the left, first bending mode: 733Hz; second bending mode: 4.09kHz; first torsional mode: 4.2kHz; First longitudinal extension mode: 7.7kHz; first circumferential mode: 9.8kHz; third bending mode: 10kHz.

piezoelectric strain voltage is deemed sufficient for sensing.

III. EXPERIMENTAL SETUP AND SYSTEM IDENTIFICATION

Fig. 4 shows the experimental setup of the tube. An aluminium target is glued to the free end of the tube. Voltages measured at the central electrodes were fed to the Stanford Research Systems SR560 low noise preamplifiers. The input impedance of the preamplifier is $100M\Omega$. The measured capacitance of each electrode is 4nF [22]. Together with the input impedance of $100M\Omega$ of the preamplifier, this pushes the cut-off frequency of the sensing signal to be less than 1Hz. The piezoelectric tube scanner was driven using a NANONIS bipolar high voltage amplifier HVA4. Two ADE Technologies 8810 capacitive sensors were placed in close proximity to the adjacent surfaces of the sample holder to observe the displacements of the tube along the x and y axis. The static gain of the two sensors is $2.5 \mu m/V$.

TABLE II
A COMPARISON OF THE SIMULATED AND MEASURED RESONANT MODES OF THE TUBE.

Resonant mode	FEA (kHz)	Exp. (kHz)	% diff.
1st mode	0.733	0.708	3.5
2nd mode	4.09	3.7	10

The plant was identified with a bandlimited random noise input of amplitude 500mVpk, ranging from 1Hz to 10kHz, using a HP 35670A dual channel spectrum analyzer. Input voltages applied to actuate the x and y axis are denoted as v_x and v_y (in volts) respectively, and the outputs are the respective displacement d_x and d_y (in μm , measured using the two capacitive sensors), and the piezoelectric strain-induced voltages v_{p_x} and v_{p_y} (in volts).

When actuated in the x direction (for brevity, the y direction will not be discussed as it is identical to x), the tube can be considered as a single-input, two-output system with v_x as the input, v_{p_x} and d_x as the outputs. The transfer function of the SITO system is derived as [22]

$$\begin{bmatrix} v_{p_x} \\ d_x \end{bmatrix} = \begin{bmatrix} G_{vv}^x(s) \\ G_{dv}^x(s) \end{bmatrix} v_x. \quad (2)$$

Fig. 7 shows that the two transfer functions $G_{vv}^x(s)$ and $G_{dv}^x(s)$ have identical poles. Therefore, a controller which improves the damping of $G_{vv}^x(s)$ will have a similar effect on $G_{dv}^x(s)$. As a result, a feedback controller that uses v_{p_x} as a measurement can be implemented to improve the dynamics of the scanner. This removes the need for incorporating a displacement sensor into the system.

In Fig. 7, the first resonant peak of the tube appears at 708Hz which is about 3.5% different from the FEA predictions. There is a small peak observed at 1.1kHz after the first resonant mode. This mode is introduced by the aluminium enclosure, which is a thick cylinder (see Fig. 4), and was not modeled in FEA simulations. The third measured resonant mode appears at 3.7kHz, which corresponds to the simulated second bending mode in FEA. The difference is about 10%.

Tables II and III compare the simulated and measured resonance frequencies of the tube scanner, and the static (DC) gains of the two actuation modes as shown in Fig. 2. The comparison shows that the novel 12-electrode tube is more superior than the quartered electrode tube where it provides a larger displacement range and larger piezoelectric strain voltage for measurement.

IV. VIBRATION CONTROL USING PIEZOELECTRIC STRAIN-INDUCED VOLTAGES

To appreciate the advantage of the piezoelectric tube scanner (i.e. for simultaneous actuation and sensing), an IRC scheme is implemented to damp the first resonant mode by using piezoelectric strain-induced voltages v_{p_x} as feedback signals. There are no displacement sensors used for feedback. However, these sensors were used to observe the closed loop performance of the tube.

Fig. 4. Experimental setup of the piezoelectric tube scanner. The picture shows the setup of the tube with and without an aluminium enclosure. The two capacitive sensors are mounted at right angles to the target.

Fig. 5. Block diagram of the IRC scheme with inversion feedforward.

The dominant resonant mode (i.e. the first resonant mode) appears at 708Hz with a dynamic range of 29dB. As the subsequent modes are far away from the first, only this mode is damped using the controller. The IRC is an effective method of providing damping to the system without exciting the higher-dynamics [24]. The IRC controller design is summarized in the following steps:

- *Step 1:* A second order model is fitted to the frequency response of the plant to accurately capture the dominant mode of the tube. The transfer function of the model is

$$G_m = \frac{-0.4467s^2 - 85.29s + 9.336 \times 10^6}{s^2 + 190.9s + 2.031 \times 10^7} \quad (3)$$

TABLE III

A COMPARISON OF THE SIMULATED AND MEASURED STATIC GAINS OF THE TWO ACTUATION MODES AS SHOWN IN FIG. 2. d_x/V_x IS IN $\mu\text{M}/\text{V}$ AND V_{px}/V_x IS IN V/V .

Acuation mode	FEA		Exp.	
	d_x/V_x	V_{px}/V_x	d_x/V_x	V_{px}/V_x
12-electrode tube (antisymmetric)	0.076	0.029	0.084	0.027
Quartered electrode tube (asymmetric)	0.055	0.012	0.055	0.017

Fig. 6. Root-locus plot of the system, showing the trajectories of the poles with respect to the increase of system gain. Maximum damping is achieved when $K = 4450$.

TABLE IV

POLES AND ZEROS OF THE PLANT MODEL G_m AND THE OVERALL SYSTEM WITH THE FEEDTHROUGH TERM $G_m + D$.

Plant	Poles	Zeros
G_m	$-95.5 \pm 4.51 \times 10^3 i$	$\pm 4.6 \times 10^3$
$G_m + D$	$-95.5 \pm 4.51 \times 10^3 i$	$-95.5 \pm 2.58 \times 10^3 i$

- *Step 2:* As shown in Fig. 5, a suitable feedthrough term, D is implemented to shift the right half-plane zero to the left half-plane when added to the plant. As a result, the overall plant $G_m + D$ is more conducive to integral feedback. The pole locations remain the same. In this case, $D = -0.9$ is chosen so that the system remains its minimum phase. Table IV gives the locations of the poles and zeros of the plant model with and without the feedthrough term D .
- *Step 3:* A root-locus plot of the overall negative feedback system is obtained (see Fig. 6), showing the trajectories of the poles due to the change in system gain. Gain $K = -4.45 \times 10^3$ is chosen in order to achieve maximum damping.

Fig. 7 shows the simulated and measured closed loop frequency responses of the system. The measured result is in close agreement with the simulated result. Since the two transfer functions $G_{vv}^x(s)$ and $G_{dv}^x(s)$ have identical poles, the IRC that augments the damping of $G_{vv}^x(s)$ provides a similar effect on $G_{dv}^x(s)$ (see Fig. 7b). The implemented IRC scheme damps the dominant resonant mode by 28dB. The controller does not disturb the high frequency dynamics of the system.

In order to get the closed loop output close to the desired output, the input to the closed loop is shaped using the inverse of the closed loop model, see Fig. 5. The desired triangular waveform can be broken down into a converging infinite sum of harmonic sinusoids, and the resulting filtered signal is equal to scaling the amplitude of the harmonics by $|\hat{G}_{CL}^{-1}(i\omega)|$ and shifting the phase of harmonics by $\angle \hat{G}_{CL}^{-1}(i\omega)$ at the corresponding frequencies. Moreover, as the closed

TABLE V
RMS ERRORS OF THE OPEN AND CLOSED LOOP TRACES.

RMS error (nm)	10Hz	40Hz	80Hz	100Hz
Open loop	395	401	410	422
Closed loop	11	13	17	18
RMS error (nm)	110Hz	140Hz	180Hz	200Hz
Open loop	-	-	-	-
Closed loop	18	23	23	41

loop model does not have poles on the imaginary axis, $\hat{G}_{CL}^{-1}(i\omega) = \frac{1}{\hat{G}_{CL}(i\omega)}$.

The control strategy was implemented using a dSPACE 1103 PPC controller board. To ensure that there were no aliasing effects during the experiments, a sampling frequency of 40kHz was used.

Triangular waveforms are used to evaluate the effectiveness of the IRC scheme that uses piezoelectric strain-induced voltages as feedback signals. For comparisons, the open loop traces of triangular waveforms with fundamental frequencies of 10Hz, 40Hz, 80Hz and 100Hz are obtained and plotted in Fig. 8a. The magnitude of the triangular inputs is $2.5\mu m$, which corresponds to an input voltage of 37.5V. The voltage range is small enough to avoid hysteresis effects typically present in the tracking results. The displacement was measured using a capacitive sensor. The open loop system traces the 10Hz triangular waveform accurately. However, the 40Hz triangular input excites the first resonant mode of the tube.

Fig. 8b shows the closed loop traces of triangular waveforms with fundamental frequencies of 10Hz, 40Hz, 80Hz and 100Hz. With the IRC and feedforward combined, the triangular waveforms do not excite the resonant mode of the piezoelectric tube. Fig. 8c shows the capability of the closed loop system to trace triangular inputs accurately up to 200Hz. Table V presents the RMS scanning errors in nanometers in open and closed loops. In open loop, the tube scanner can only trace triangular signals up to 100Hz with a RMS error of 422nm. On the other hand, scanning speed of the tube in closed loop is improved by a factor of 2 with the RMS error reduced by a factor of 10. These results demonstrate the usefulness of using piezoelectric strain-induced voltages for vibration control without the need of a displacement sensor. In addition, the tube is actuated antisymmetrically which (a) retains its property as a collocated system, and (b) prevents the travel range of the tube to be reduced to half.

V. CONCLUSIONS AND FUTURE WORK

This article presents a new electrode pattern for a piezoelectric tube scanner. The arrangement of the electrode allows the scanner to be used for simultaneous actuation and sensing. To illustrate the advantage of this electrode pattern, the piezoelectric strain-induced voltage was used as measurement signals and an Integral Resonant Controller was designed to damp the first resonant mode of the tube. Together with the feedforward inversion technique, the closed loop system allows accurate high-speed scans up to 200Hz.

Fig. 7. Measured open (dashed line) and closed loop (solid line) frequency responses of the piezoelectric tube scanner. Diagram (a) shows the frequency responses measured using the piezoelectric strain sensor. Diagram (b) shows the frequency responses measured using the capacitive sensor. Both open loop frequency responses, G_{vv}^x and G_{dv}^x from diagram (a) and (b) respectively, show identical poles. The simulated closed loop frequency response (dot-dashed line, with negative offset for clarity purposes) is plotted in diagram (a). The simulated result is in close agreement with the measured result (solid line). The IRC scheme that imparts damping of $G_{vv}^x(s)$ produces a similar effect on $G_{dv}^x(s)$.

Future work will concentrate on (a) designing a controller for rastering and (b) integrating the tube into an atomic force microscope for fast scanning of images.

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Fig. 8. Tracking of triangular waveforms with an amplitude of $2.5\mu\text{m}$, which corresponds to an input voltage of 37.5V . The displacement was measured using a capacitive sensor. The triangular reference signal (dashed line) and the output signal (solid line) are plotted. (a) Open loop traces of triangular waveforms with fundamental frequencies of 10Hz, 40Hz, 80Hz and 100Hz. (b) Closed loop traces of triangular waveforms with fundamental frequencies of 10Hz, 40Hz, 80Hz and 100Hz. (c) Closed loop traces of triangular inputs with fundamental frequencies of up to 200Hz.

REFERENCES

- [1] G. Binnig and D. P. E. Smith, "Single-tube three-dimensional scanner for scanning tunneling microscopy," *Rev. Sci. Instrum.*, vol. 57, no. 8, pp. 1688–1689, 1986.
- [2] B. Bhushan, Ed., *Springer Handbook of Nanotechnology*, 2nd ed. Springer-Verlag, 2004.
- [3] E. Meyer, H. J. Hug, and R. Bennewitz, *Scanning Probe Microscopy. The lab on a tip*. Springer-Verlag, 2004.
- [4] S. O. R. Moheimani, "Invited review article: Accurate and fast nanopositioning with piezoelectric tube scanners: Emerging trends and future challenges," *Review of Scientific Instruments*, vol. 79, no. 7, p. 071101, July 2008, article Number: 071101.
- [5] B. Bhushan, *Handbook of Micro/Nanotribology*, 2nd ed. Boca Raton, USA: CRC, 1999.
- [6] P. Vettiger, G. Cross, M. Despont, U. Drechsler, U. Dürig, B. Gotsmann, W. Häberle, M. A. Lantz, H. E. Rothuizen, R. Stutz, and G. K. Binnig, "The "Milipede" - nanotechnology entering data storage," *IEEE Trans. Nanotechnology*, vol. 1, no. 1, pp. 39–55, 2002.
- [7] I. Schmitz, M. Schreiner, G. Friedbacher, and M. Grasserbauer, "Phase imaging as an extension to tapping mode AFM for the identification of material properties on humidity-sensitive surfaces," *Applied Surface Science*, vol. 115, no. 2, pp. 190–198, 1997.
- [8] K. Yamanaka, A. Noguchi, T. Tsuji, T. Koike, and T. Goto, "Quantitative material characterization by ultrasonic AFM," *Surface and Interface Analysis*, vol. 27, pp. 600–606, 1999.
- [9] S. Sundararajan and B. Bhushan, "Development of AFM-based techniques to measure mechanical properties of nanoscale structures," *Sensors and Actuators A: Physical*, vol. 101, pp. 338–351, 2002.
- [10] E. L. Leite and P. S. P. Herrmann, *Atomic Force Microscopy in Adhesion Studies*. VSP - An imprint of BRILL, 2005, ch. 1, pp. 3–43.
- [11] D. Croft, S. Stilson, and S. Devasia, "Optimal tracking of piezo-based nanopositioners," *Nanotechnology*, vol. 10, no. 2, pp. 201–208, 1999.
- [12] D. Croft, G. Shedd, and S. Devasia, "Creep, hysteresis, and vibration compensation for piezoactuators: Atomic force microscopy application," *Journal of Dynamic Systems, Measurement, and Control*, vol. 123, no. 1, pp. 35–43, 2001.
- [13] G. Schitter, R. W. Stark, and A. Stemmer, "Fast contact-mode atomic force microscopy on biological specimen by model-based control," *Ultramicroscopy*, vol. 100, pp. 253–257, 2004.
- [14] Y. Wu and Q. Zou, "Iterative control approach to compensate for both the hysteresis and the dynamics effects of piezo actuators," *IEEE Trans. Contr. Syst. Tech.*, vol. 15, no. 5, pp. 936–944, 2007.
- [15] S. Devasia, E. Eleftheriou, and S. O. R. Moheimani, "A survey of control issues in nanopositioning," *IEEE Trans. Contr. Syst. Tech.*, vol. 15, pp. 802–823, 2007.
- [16] N. Tamer and M. Dahleh, "Feedback control of piezoelectric tube scanners," in *American Conference on Decision and Control*, 1994, pp. 1826–1831.
- [17] S. Salapaka, A. Sebastian, J. P. Cleveland, and M. V. Salapaka, "High bandwidth nano-positioner: A robust control approach," *Rev. Sci. Instrum.*, vol. 73, no. 9, pp. 3232–3241, 2002.
- [18] B. Bhikkaji, M. Ratnam, A. J. Fleming, and S. O. R. Moheimani, "High-performance control of piezoelectric tube scanners," *IEEE Trans. Contr. Syst. Tech.*, vol. 15, no. 5, pp. 853–866, 2007.
- [19] B. Bhikkaji, M. Ratnam, and S. O. R. Moheimani, "PVPF control of piezoelectric tube scanners," *Sensors and Actuators A*, vol. 135, pp. 700–712, 2007.
- [20] G. Schitter, P. Menold, H. Knapp, F. Allgöwer, and A. Stemmer, "High performance feedback for fast scanning atomic force microscopes," *Rev. Sci. Instrum.*, vol. 72, no. 8, pp. 3320–3327, 2001.
- [21] A. J. Fleming and S. O. R. Moheimani, "Sensorless vibration suppression and scan compensation for piezoelectric tube nanopositioners," *IEEE Trans. Contr. Syst. Tech.*, vol. 14, no. 1, pp. 33–44, 2006.
- [22] S. O. R. Moheimani and Y. K. Yong, "Simultaneous sensing and actuation with a piezoelectric tube scanner," *Review of Scientific Instruments*, vol. 79, no. 7, July 2008, article Number: 073702.
- [23] S. Aphale, A. J. Fleming, and S. O. R. Moheimani, "High speed nanoscale positioning using a piezoelectric tube actuator with active shunt control," *Micro and Nano Letters*, vol. 2, no. 1, pp. 9–12, 2007.
- [24] Y. K. Yong, S. Aphale, and S. O. R. Moheimani, "Design, identification and control of a flexure-based XY stage for fast nanoscale positioning," *IEEE Trans. Nanotechnology*, vol. 8, no. 1, pp. 46–54, 2009.
- [25] D. J. Leo, *Engineering Analysis of Smart Material Systems*. John Wiley & Sons, Inc., 2007.
- [26] *IEEE standard on piezoelectricity. ANSI/IEEE Std. 176-1987*, Institute of Electrical and Electronics Engineers Inc. Std., 1988.