Dual Actuation of Fast Scanning Axis for High-speed Atomic Force Microscopy

Shingo Ito  Daniel Neyer  Juergen Steininger  Georg Schitter

Abstract: In order to overcome the limiting trade-off between the imaging speed and scanning range of an atomic force microscope (AFM), this paper combines two piezoelectric actuators as a dual stage actuator (DSA) for a lateral motion (X axis) of the AFM probe with respect to the sample. As the first actuator, a piezoelectric tube actuator of the commercial AFM is utilized. Although the actuator realizes a relatively large actuation range, it has the first mechanical resonance at a low frequency of 2.5 kHz. In the case of high-speed imaging, this resonance impairs the imaging speed and quality. In order to overcome this, a piezoelectric shear actuator with the first resonance at 19 kHz is selected as the second actuator, combined in the commercial AFM. To generate the X-axis motion by synchronizing those two actuators, this paper proposes a feedback control design for DSAs in the frequency domain, which takes into account the actuator dynamics. In the proposed approach, triangular raster scan is composed as a Fourier series by individually adjusting the complex Fourier coefficients for each actuator. The effectiveness of the DSA and its control is validated by experimental AFM imaging at a scan rate of 200 Hz, where the lowest frequency component is applied to the tube actuator and the other higher components of the scanning signal to the high-speed shear actuator.

Keywords: Micro and Nano Mechatronic Systems, Motion Control Systems.

1. INTRODUCTION

For high-resolution imaging, atomic force microscopy (AFM) requires a highly precise motion of a probe with a sharp tip with respect to a sample surface [Binnig et al. (1986)]. While its vertical (Z axis) position is usually regulated to maintain the probe deflection, the probe moves laterally (X axis and Y axis) by tracking a periodic motion trajectory, such as a triangular wave, for scanning the sample surface [Eaton and West (2010)]. The lateral motion is typically realized by controlling piezoelectric actuators, influencing the achievable performance of AFMs such as imaging speed and area.

When high-speed imaging is desired [Ando (2012)], the lateral actuators need to have a sufficiently high control bandwidth. Without compensation, the scan rate of piezoelectric actuators is usually less than 10% of the eigenfrequency of the first dominant mechanical resonance to prevent its excitation [Schitter and Stemmer (2004)]. Although the bandwidth can be improved by applying motion control, the first mechanical resonance typically restricts the achievable control bandwidth [Fleming (2010)]. Thus, the first resonant frequency is increased by a high-stiffness actuator design, in order to achieve a high control bandwidth for high-speed imaging. Among different types of piezo actuators [DONG (2012)], ones with high stiffness are selected (e.g. piezoelectric stack actuators), and the stiffness can be further increased by using flexures [Schitter et al. (2007); Kenton and Leang (2012); Yong et al. (2013)]. In return, however, such a high-stiffness design strictly limits the actuation range and consequently the imaging area [Yong et al. (2012)].

When a single actuator cannot satisfy requirements, two different actuators are combined to complement each other as a dual stage actuator (DSA) [Schitter et al. (2008); Ito et al. (2015)]. For the Z-axis actuation of AFM, a long-stroke low-bandwidth piezoelectric actuator (e.g. piezo tube actuator) of a commercial AFM is combined with a high-speed piezoelectric actuator with a limited stroke (e.g. piezo stack actuator), achieving a high long-stroke actuator with a high control bandwidth [Fleming (2011); Kenton et al. (2011); Kuiper and Schitter (2012)]. In these systems, the long-stroke actuator and the high-speed actuator are directly fixed to the structural components, which is beneficial for decoupling the two actuator motions. In [Kenton et al. (2011)], an additional actuator is mounted to cancel the counterforce of the high-speed actuator. DSAs are also applied to realize a long-range high-speed lateral scanning motion [Tuma et al. (2014)]. For the lateral scanning, the high-speed actuator is typically mounted on the long-stroke actuator. A concern of such a configuration is that the counterforce of the high-speed actuator excites the long-stroke actuator’s resonances, which may require a remedy [Yan et al. (2015)].

In order to control the two actuators of a DSA in an AFM, typically a low-pass filter and a high-pass filter are implemented for the long-stroke actuator and the high-speed actuator, respectively [Schitter et al. (2008); Fleming (2011); Kenton et al. (2011); Kuiper and Schitter (2012)]. For an accurate single-axis motion, the filters...
need to be carefully designed, such that the two actuator motions do not interfere each other. Particularly when the high-speed actuator's motion is canceled by the long-stroke actuator, the DSA system has a zero that can restrict the achievable bandwidth [Schroeck et al. (2001)]. When the filters are manually tuned for a DSA, their cut-off frequencies are typically relatively low [Fleming (2011)], restricting the achievable actuation range at a high scan rate [Kuiper and Schitter (2012)]. While model-based control synthesis can be used to realize a large actuation range for fast scanning, the resulting filters are usually of high order, requiring controller reduction and powerful real-time hardware [Kuiper and Schitter (2012)].

In order to realize a long-stroke high-bandwidth lateral scanning motion for high-speed AFM imaging, this paper proposes a DSA that decouples the motions of the two actuators. A piezoelectric tube actuator of a commercial AFM is combined with a high-bandwidth piezoelectric shear actuator, which boosts the AFM imaging speed. For a synchronized motion of the two DSA actuators to precisely track a periodic scanning trajectory, this paper also proposes a feedforward control design in the frequency domain that takes into account linear dynamics.

The paper is organized as follows. Section 2 presents the experimental AFM setup, which is analyzed in Section 3. Section 4 introduces the proposed feedforward DSA control design with conventional hysteresis compensation. The effectiveness is experimentally validated in Section 5, and Section 6 concludes the paper.

2. SYSTEM DESCRIPTION

The proposed dual stage actuator for the lateral scanning is illustrated in Fig. 1, and Fig. 2 is a photograph of the implemented experimental setup. As the long-stroke actuator, a piezoelectric tube actuator (AS-12VLR) of a commercial AFM (Multimode V, Bruker, Santa Barbara, USA) is used to generate the motions of \( x_l, y_l \) and \( z_l \). The tube actuator can move the sample 10 \( \mu \)m along the X axis and the Y axis for scanning, and 2.5 \( \mu \)m in the vertical Z direction. While the tube actuator has a relatively large XY scanning range, it has the first mechanical resonance at a relatively low frequency (cf. Section 3). Thus, in order to boost the imaging speed of the commercial AFM, a piezoelectric shear actuator with a nominal actuation range of 3 \( \mu \)m (P111.03, PI Ceramic, Lederhose, Germany) is selected as the high-speed actuator for the \( x_h \) motion.

The shear actuator with a cantilever holder is stably attached to a custom-made rigid adapter by super glue (Fig. 2). To the cantilever holder, an AFM cantilever with a probe is fixed by wax, such that it can be exchanged whenever necessary. This configuration can decouple the \( x_h \) and \( x_l \) motions without crosstalk in-between.

As shown in Fig. 1, the AFM cantilever reflects a laser beam to photodetectors. For topography imaging, the cantilever deflection is measured from the output signal difference between the upper (A, B) and the lower detectors (C, D) [Eaton and West (2010)]. In the constant force mode [Eaton and West (2010)], the tube actuator vertically \( (x_l) \) moves the sample to maintain the measured cantilever deflection, and its control input is used to generate topography images.

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For scanning the sample, raster scan is most commonly used for the simplicity to reconstruct images [Tuma et al. (2013)]. The motion trajectories of the fast and slow axes are typically a triangular wave and a ramp signal, respectively. For the motion of the fast scan axis, the tube actuator typically moves in the direction of \( x_l \). This fast scanning direction is advantageous in that the friction between the probe tip and the sample does not interfere with the cantilever deflection measurement by design [Piner and Ruoff (2002)]. In order to increase the bandwidth of the fast scanning motion, the probe is moved by the high-speed actuator in the \( x_h \) direction. Notice that the probe movement along the \( y \) axis (horizontally perpendicular to \( x_h \)) changes the laser spot's position on the detector, interfering with the cantilever deflection measurement. Therefore, the \( x_h \)-axis probe motion of the shear actuator is beneficial also to reduce the crosstalk with the deflection measurement. Nevertheless, if the residual crosstalk is problematic (e.g. due to assembly precision), a remedy such as a focusing lens [Steininger et al. (2015)] may be integrated.

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Fig. 3 shows the hardware architecture of the DSA system with actuator models. The high-speed shear actuator is connected to a high voltage amplifier for the voltage $v_h$ in Fig. 3. Because the amplifier is regarded as an additional noise source in the DSA configuration, its noise should be sufficiently low. For the experimental setup, a commercial amplifier (WMA-300, Falco Systems, Amsterdam, Netherlands) with noise of 12 mV(RMS) for 5 MHz bandwidth is selected. The terminals of the tube actuator for the $x_l$ motion are connected to a custom-designed voltage amplifier generating $v_l$. The other terminals are connected to the commercial AFM’s controller unit, which is also used for the control of the tube actuator’s $y_l$ and $z_l$ motions in the constant force mode, as well as for data acquisition to record AFM images. The feedforward signals ($u_h$ and $u_l$) for the $x_h$ and $x_l$ motions are designed in a computer and sent to a waveform generator (33500B, Keysight, Santa Rosa, USA), which provides the input signals to the respective actuator amplifiers. For AFM imaging, the waveform generator is synchronized with the commercial controller unit by using a trigger signal.

Piezoelectric actuators can be modeled as a combination of hysteresis and linear dynamics [Leung et al. (2009)]. In Fig. 3, $H_h$ and $H_l$ denote the hysteresis model of the high-speed actuator and the long-stroke actuator, receptively. The transfer functions $P_h(s)$ and $P_l(s)$ are linear models to represent the dynamics of the high-speed and the long-stroke actuator, respectively.

Fig. 3. Hardware architecture and actuator models of the DSA for the fast scanning axis.

3. ANALYSIS OF DYNAMICS

In order to determine the linear dynamic model $P_h(s)$ and $P_l(s)$ of the piezo actuators, frequency responses are measured from $u_h$ to $x_h$ and from $u_l$ to $x_l$, respectively. In this case, the amplifiers’ dynamics are included in $P_h(s)$ and $P_l(s)$ for simplicity of evaluation. The actuator positions are measured by a Doppler vibrometer (OFV-534, Polytec, Waldbronn, Germany). The recorded frequency responses are shown in Fig. 4. The first dominant resonant frequency of the long-stroke actuator is 2.5 kHz. This frequency can vary dependent on the sample mass on the long-stroke actuator [Schitter and Stemmer (2004)].

Thus, applying typical model-based feedforward control is difficult to achieve a high control bandwidth, due to the modeling uncertainties. Furthermore, the first resonance is close to higher modes in the frequency domain, which makes it difficult to operate the actuator beyond the first resonant frequency by using feedback control (cf. [Ito and Schitter (2016)]).

In the case of the high-speed actuator, the first resonance can be seen at about 18 kHz, which is 7.2 times higher than the long-stroke actuator, and the AFM imaging time can be shortened accordingly. Due to its high resonant frequency, the high-speed actuator has a relatively constant magnitude up to several kilohertz in Fig. 4, with which a bandwidth higher than that of the long-stroke actuator can be realized. However, the phase plot of the high-speed actuator shows a phase lag or delay. Because this can be problematic for a synchronized motion of the DSA, the delay is compensated by the feedforward control design in Section 4.3.

For feedforward control design and simulation (not shown in this paper), the linear models $P_h(s)$ and $P_l(s)$ are obtained from the measured frequency responses by using the MATLAB system identification toolbox. The resulting $P_h(s)$ and $P_l(s)$ have an order of 17 and 15, respectively, and their simulated frequency responses are shown in Fig. 4. It can be seen that $P_h(s)$ and $P_l(s)$ capture the magnitude and phase of the responses well at the frequencies lower than the first resonances.

Fig. 4. Measured frequency responses and fitted models from $u_h$ to $x_h$ for the long-stroke actuator $P_h(s)$ and $u_l$ to $x_l$ for the high-speed actuator $P_h(s)$.

4. FEEDFORWARD CONTROL

For a synchronized accurate motion by means of the two actuators, this section presents the proposed feedforward control design. Fig 5 shows the design flow. A triangular wave $r_h$ of raster scan for the fast scan X axis is designed and separated as the motion trajectories of the high-speed actuator $r_h$ and the long-stroke actuator $r_l$ in the frequency domain. The proposed signal separation algorithm can compensate for the linear dynamics of the actuators. In general, piezoelectric actuators have hysteresis, which can be compensated independently of the linear dynamics [Schitter and Stemmer (2004)]. Thus, the control input of the high-speed actuator $u_h$ is generated from $r_h$ by compensating for the hysteresis $H_h$. However, hysteresis compensation is not implemented for the long-stroke actuator (i.e. $u_l = r_l$) as a first demonstration of the DSA.
4.1 Fast scan trajectory $r_s$ of raster scan

As the fast scan trajectory of raster scan, a triangular wave is often used. However, it has infinite frequency components due to its sharp apexes, and mechanical resonances of the high-speed actuator can be excited. Therefore, a band-limited triangular wave is used for the DSA, which is given by the Fourier series expansion

$$r_s(t) = \sum_{k=1}^{l} (r[k]e^{2\pi jk f_s t} + r^*[k]e^{-2\pi jk f_s t}),$$

where the superscript $^*$ denotes the complex conjugate, and $r[k]$ is the complex Fourier coefficient

$$r[k] = -\frac{4A_x}{\pi^2 k^2} \left\{ \begin{array}{ll} 1 & \text{for odd } k \\ 0 & \text{for even } k \end{array} \right. \quad (2)$$

For a demonstration of the high-speed AFM imaging by using the DSA, the amplitude $A_x$ is set to 5 μm and the highest harmonics $l$ is 9. The fundamental frequency $f_s$ is adjusted to 200 Hz. Fig. 6 shows the Fourier coefficients of the designed trajectory.

4.2 Signal separation without dynamics compensation

The Fourier series expansion (1) is utilized to split $r_s$ for each actuator of the DSA system in the frequency domain. For a slow and large motion, Fourier coefficients at low frequencies are assigned to the long-stroke actuator. In contrast, the other high-frequency coefficients are assigned to the high-speed actuator to realize a short-range and high-frequency motion. For the experiments in this paper, only the coefficient at the fundamental frequency $f_s$ is assigned to the long-stroke actuator, and the others are to the high-speed actuator, as illustrated in Fig. 6. This coefficient separation will be optimized in future work. The signal separation concept is formulated as follows.

From Fig. 1, the AFM tip position with respect to the sample is $x_h + x_l$. Thus, when each DSA actuator perfectly tracks its own trajectory, the fast scan trajectory $r_s$ has the following relation

$$r_s(t) = r_l(t) + r_h(t).$$

Based on the above relation, $r_s(t)$ is split into $r_l(t)$ and $r_h(t)$ as follows

$$r_l(t) = \sum_{k=1}^{l_1} (r[k]e^{2\pi jk f_s t} + r^*[k]e^{-2\pi jk f_s t}), \quad (4)$$

$$r_h(t) = \sum_{k=l_1+1}^{l} (r[k]e^{2\pi jk f_s t} + r^*[k]e^{-2\pi jk f_s t}), \quad (5)$$

where $l_1 = 1$ is the highest harmonics for the long-stroke actuator. The resulting trajectories in the time domain are shown in Fig. 7.

4.3 Signal separation compensating for dynamics

The problem of the signal separation in the previous section is that the resulting outputs $x_l$ and $x_h$ deform, dependent on the system dynamics. In the case of the proposed DSA system, the delay observed in Section 3 is a concern. In order to solve this problem, signal separation compensating for linear dynamics is proposed, and (4) and (5) are rewritten as follows

$$r_l(t) = \sum_{k=1}^{l_1} \left( \frac{P_l[k]}{P_f[k]} r[k]e^{2\pi jk f_s t} + \frac{P^*[l]}{P_f[k]} r^*[k]e^{-2\pi jk f_s t} \right), \quad (6)$$

$$r_h(t) = \sum_{k=l_1+1}^{l} \left( \frac{P_h[k]}{P_f[k]} r[k]e^{2\pi jk f_s t} + \frac{P^*[h]}{P_f[k]} r^*[k]e^{-2\pi jk f_s t} \right), \quad (7)$$

where $P_f[k]$ and $P_f[k]$ denote a discrete frequency response of $P_f(s)$ and $P_f(s)$ at $s = j2\pi k f_s$, receptively.

These discrete frequency responses imply that the proposed feedforward control design requires system identification at harmonic frequencies of $r_s$ only. For the DSA system, they are only 5 odd harmonic frequencies since $r_s$ has no even harmonics. Particularly when measured frequency responses are directly used in (6) and (7), the system identification in Section 3 can be significantly simplified, and the transfer function models are unnecessary.
This is beneficial for the elimination of modeling errors resulting from curve fitting.

The proposed feedforward control design has another benefit that it can handle non-minimum phase zeros. This is because (6) and (7) can freely change the phase and magnitude of the sine waves by means of the complex numbers $R_c^{-1}[k]$ and $P_c^{-1}[k]$. This is an advantage in comparison with typical feedforward control design using a plant inverse model, where non-minimum phase zeros turn to be unstable poles [Yamaguchi et al. (2011)].

4.4 Compensation of hysteresis

In order to compensate for the hysteresis of the high-speed actuator, the Preisach hysteresis model [Leang et al. (2009); Zsurzsan et al. (2015)] is used as $H_k$ of Eq. 3

$$w_h(t) = H_k[v_k](t) = \int_{\alpha<\beta} \mu(\alpha, \beta) R_{\alpha, \beta}[v_k](t) d\alpha d\beta,$$

(8)

where $w_h(t)$ is the output, and $\mu(\alpha, \beta)$ is an weighting function. Parameters $\alpha$ and $\beta$ represent a point on the Preisach plane that has Schmitt triggers $R_{\alpha, \beta}[v_k](t)$ [Zsurzsan et al. (2015)].

In order to experimentally determine $\mu(\alpha, \beta)$, a sine wave of 50 Hz is used as the input $v_k(t)$. While the amplitude is gradually increased approximately from 10 V to 200 V, the position $x_4(t)$ is recorded as shown by the black dotted line in Fig. 8. The Preisach plane is discretized with 325 Schmitt triggers, and their weighting function $\mu(\alpha, \beta)$ is determined by fitting the Preisach model to the recorded data set [Stakvik et al. (2015)].

Based on the identified hysteresis model, the control input $u_h(t)$ to the high-speed actuator can be created from $x_h(t)$ to compensate for the hysteresis as follows

$$u_h(t) = H_k^{-1}[x_h](t).$$

(9)

In the above equation, the Preisach model is inverted by using the closest match algorithm [Tan et al. (2001); Stakvik et al. (2015)].

The red solid line in Fig. 8 validates the compensation of the hysteresis. By applying the hysteresis compensation, the full-scale linearity is improved from 8.7 % to 5.7 %.

5. EXPERIMENTAL AFM IMAGING

For a demonstration of the proposed DSA, a calibration grating (STR10-1800P, Bruker, Santa Barbara, USA) having features of a 180 nm height is scanned with 256 lines per image by using the 200 Hz feedforward signals in Section 4. This setting requires 1.28 s to generate an image. For comparison, the grating is also imaged when the tube actuator is fully connected to the commercial controller unit without using the high-speed shear actuator as the standard (single-stage) AFM. For this case, the controller unit generates the scanning signal by taking the tube actuator's nonlinearity into account, and the resulting image indicates the performance of the commercial AFM for benchmarking.

In Fig. 9, the standard AFM shows vertical ripples in the topography and deflection error images. This is due to the excitation of the tube scanner’s first resonance and the crosstalk between the X and Z axes. In contrast to the standard AFM, the DSA significantly reduces the vertical ripples in the bottom images of Fig. 9. The slight residual ripples in the deflection images may be due to the uncompensated hysteresis of the tube actuator. Notice that both AFMs show image distortion on the left side of the height images. Also the vertical position of grating edge does not correspond in the height and deflection error images. These phenomenon can be typically seen when the X axis scanning motion has a delay with respect to the data acquisition for imaging, which will be corrected in future work.

In summary the dually actuated system for the fast scanning axis has been integrated by splitting the scanning signal in its Fourier components and by assigning them to the respective actuators, which has been successfully demonstrated by high-speed imaging with a prototype AFM system.

6. CONCLUSION

In order to boost the imaging speed of a commercial AFM, a piezoelectric shear actuator is installed as the high-speed actuator of a DSA for the lateral scanning motion. While the first resonant frequency of the commercial tube actuator is 2.5 kHz, that of the shear actuator is...
For the synchronized motion of the fast scanning, a band-limited triangular scanning trajectory is designed in the form of complex Fourier coefficients. The sine wave of the fundamental frequency and its harmonics are used as the motion trajectory of the tube piezo and the shear piezo, respectively. The amplitude and phase of the sine waves are adjusted by considering the actuator dynamics. Furthermore, the hysteresis of the shear actuator is compensated by using the Preisach model. The experimental AFM image scanned at 200 Hz demonstrates that a high-speed long-range motion can be realized by assigning a slow motion and a fast motion to the tube actuator and the shear actuator, respectively.

REFERENCES

Ando, T. (2012). High-speed atomic force microscopy coming of age. Nanotechnology, 23(6), 062001.

Binnig, G., Quate, C.F., and Gerber, C. (1986). Atomic force microscope. Phys. Rev. Lett., 56, 930–933. doi: 10.1103/PhysRevLett.56.930.

DONG, S. (2012). Review on piezoelectric, ultrasonic, and magnetoelectric actuators. Journal of Advanced Dielectrics, 02(01), 1230001. doi: 10.1142/S2010135X12300010.

Eaton, P. and West, P. (2010). Atomic Force Microscopy. Oxford University Press.

Fleming, A.J. (2011). Dual-stage vertical feedback for high-speed scanning probe microscopy. IEEE Transactions on Control Systems Technology, 19(1), 156–165. doi:10.1109/TCST.2010.2040282.

Fleming, A.J. (2010). Nanopositioning system with force feedback for high-performance tracking and vibration control. IEEE/ASME Transactions on Mechatronics, 15(3), 433–447. doi:10.1109/TMECH.2009.2028422.

Ito, S. and Schitter, G. (2014). Comparison and classification of high-precision actuators based on stiffness influencing vibration isolation. IEEE/ASME Transactions on Mechatronics, 21(2), 1169–1178. doi: 10.1109/TMECH.2015.2478658.

Ito, S., Steininger, J., and Schitter, G. (2015). Low-stiffness dual-stage actuator for long range positioning with nanometer resolution. Mechatronics, 29, 46–56. doi:10.1016/j.mechatronics.2015.05.007.

Kenton, B.J. and Leang, K.K. (2012). Design and control of a three-axis serial-kinematic high-bandwidth nanopositioner. IEEE/ASME Transactions on Mechatronics, 17(2), 356–369. doi:10.1109/TMECH.2011.2105499.

Kenton, B.J., Fleming, A.J., and Leang, K.K. (2011). Compact ultra-fast vertical nanopositioner for improving scanning probe microscope scan speed. Review of Scientific Instruments, 82(12), 125703. doi:10.1063/1.3664613.

Kuiper, S. and Schitter, G. (2012). Model-based feedback controller design for dual actuated atomic force microscopy. Mechatronics, 22(3), 327–337. doi: 10.1016/j.mechatronics.2011.08.003.

Leang, K.K., Zou, Q., and Devasia, S. (2009). Feedforward control of piezoactuators in atomic force microscope systems. IEEE Control Systems Magazine, 29(1), 70–82. doi:10.1109/MCS.2008.930922.

Piper, R. and Ruoff, R.S. (2002). Cross talk between friction and height signals in atomic force microscopy. Review of Scientific Instruments, 73(9), 3392–3394. doi:10.1063/1.1499539.

Schipper, G., Rijkee, W.F., and Phan, N. (2008). Dual actuation for high-bandwidth nanopositioning. In IEEE Conference on Decision and Control, 5476–5481. doi:10.1109/CDC.2008.4738876.

Schipper, G. and Stemmer, A. (2004). Identification and open-loop tracking control of a piezoelectric tube scanner for high-speed scanning-probe microscopy. IEEE Transactions on Control Systems Technology, 12(4), 449–454. doi:10.1109/TCST.2004.824290.

Schipper, G., Astrom, K.J., DeMartini, B.E., Thurner, P.J., Turner, K.L., and Hansma, P.K. (2007). Design and modeling of a high-speed afm-scanner. IEEE Transactions on Control Systems Technology, 15(5), 906–915. doi:10.1109/TCST.2007.902953.

Schoeck, S.J., Messner, W.C., and McNab, R.J. (2001). On compensator design for linear time-invariant dual-input single-output systems. IEEE/ASME Transactions on Mechatronics, 6(1), 50–57. doi:10.1109/3516.914391.

Stakvik, J.A., Ragazzon, M.R., Eleissen, A.A., and Gravdahl, J.T. (2010). On implementation of the Preisach model: Identification and inversion for hysteresis compensation. Modeling, Identification and Control, 36(4), 133–142. doi:10.4173/mic.2013.1.3.

Steininger, J., Bibl, M., Yoo, H.W., and Schitter, G. (2015). High bandwidth deflection readout for atomic force microscopes. Review of Scientific Instruments, 86(10), 103701. doi:10.1063/1.4923188.

Tan, X., Venkataraman, R., and Krishnaprasad, P.S. (2001). Control of hysteresis: theory and experimental results. In Proc. SPIE 4336, Smart Structures and Materials, 101–112. doi:11109.12.436463.

Tuna, T., Haebler, W., Rothuizen, H., Lygeros, J., Pantazi, A., and Sebastian, A. (2014). Dual-stage nanopositioning for high-speed scanning probe microscopy. IEEE/ASME Transactions on Mechatronics, 19(3), 1035–1045. doi:10.1109/TMECH.2013.2266481.

Tuna, T., Sebasca, A., Lygeros, J., and Pantazi, A. (2013). The four pillars of nanopositioning for scanning probe microscopy. IEEE Control Systems Magazine, 33(6), 68–85. doi:10.1109/MCS.2013.2279473.

Yamaguchi, T., Hirata, M., and Pang, C. (2011). High-Speed Precision Motion Control. Taylor & Francis.

Yan, G.Y., Liu, Y.B., and Feng, Z.H. (2015). A dual-stage piezoelectric stack for high-speed and long-range actuation. IEEE/ASME Transactions on Mechatronics, 20(5), 2637–2641. doi:10.1109/TMECH.2015.2422351.

Yong, Y.K., Moheimani, S.O.R., Kenton, B.J., and Leang, K.K. (2012). Invited review article: High-speed nanopositioning systems. Review of Scientific Instruments, 83(12), 121101. doi:10.1063/1.4765048.

Zsuzsanna, T.G., Andersen, M.A.E., Zhang, Z., and Andersen, N.A. (2015). Preisach model of hysteresis for the piezoelectric actuator drive. In IEEE IECON, 002788–002793. doi:10.1109/IECON.2015.7392524.

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