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A Switched Actuation and Sensing Method for a MEMS Electrostatic Drive

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Abstract—MEMS technology is being investigated to improve the performance, integration and cost of nanopositioning systems. The most basic MEMS fabrication processes produce designs etched into a single layer of silicon and electrostatic transduction is often seen as the most viable actuation and sensing technology. This work provides a method to utilize the same electrostatic drive for both actuation and sensing functions. By combining both functions into the one drive, an effective increase in actuator force and sensor sensitivity can be achieved. The sensor utilizes a sigma-delta type arrangement to create a displacement-to-digital converter. With the actuator composed of a switching amplifier, this allows the nanopositioner to be controlled directly from a DSP platform. This work outlines the design of the nanopositioning system, provides the system modeling and identification and characterizes the open loop performance of the nanopositioner.

I. INTRODUCTION

Nanopositioners are devices that actuate and sense motion at nanometer resolutions [1]. Nanopositioners have found applications in areas such as microscopy, data storage, microfabrication and optics [1]–[3]. The use of microelectromechanical system (MEMS) technology to fabricate nanopositioner designs has become of interest to attain improved performance [3]–[5]. MEMS are miniature mechanical systems fabricated using the technology employed in the production of integrated circuits [6]. In miniaturizing the nanopositioner with MEMS technology, researchers hope to produce devices with improved dynamics while at the same time reducing the cost of fabrication allowing the technologies incorporating nanopositioners to become more ubiquitous [3]. In addition the use of MEMS allows for the fabrication of more complex designs, in particular designs which utilize massive arrays of devices to perform tasks in parallel [4].

Actuation in MEMS utilizes a number of phenomena including electrostatic, piezoelectric, thermal and electromagnetic phenomena [7]. Electrostatic is arguably the most common method to implement actuation in MEMS because of its compatibility with any conductive material and low power consumption. Numerous MEMS nanopositioners utilize electrostatic actuation [3]–[5], [8], [9]. Compared to the other phenomena listed the disadvantage of electrostatic actuation is its low force output for the same die area and applied voltage.

Displacement sensing can utilize phenomena such as thermal [3], piezoresistive [3], [8] and electrostatic [9] phenomena. In designs using electrostatic sensing or no sensing

at all [4], [5], the transduction efficiency is improved by utilizing the same drive for both the actuation and sensing functions. Called self-sensing actuation, this simplifies the mechanical design and increases the effective die space that can be dedicated to a single drive. When electrostatic drives are used to sense displacement, the capacitance of the drive is electrically read-out as the capacitance is a function of displacement [7].

Self-sensing electrostatic drives are implemented by time division multiplexing, whereby the drive is switched between actuation and sensing functions [10], [11], or spectral separation, whereby the actuation and sensing signals are separated by frequency [12]. An advantage of time division multiplexing is its suitability to be implemented with switching electronics. However, most implementations of this technique fully discharge the drive during the sensing phase. This reduces the maximum voltage that can be applied reducing the range and maximum control effort achievable in a nanopositioning application [10], [11]. Another issue commonly associated with self-sensing designs is that of electrical isolation. Simple microfabrication processes such as silicon-on-insulator produce devices where all drives share a common ground and are thus incompatible with a number of self-sensing techniques which requires each drive to be electrically isolated from one another [10]–[13].

A capacitive sensing method called charge balance is also suitable for implementation with switching electronics and has a natural affinity to be used in conjunction with time division multiplexing self-sensing [10], [11]. Charge balance, alternately charges a capacitor with a fixed voltage and discharges it onto a charge amp to read-out the measurement [10], [14].

Due to the similarity between charge balance capacitive sensing implementations and switched capacitor type integrators commonly used in $\Sigma\Delta$ modulators, a number of designs have modified the $\Sigma\Delta$ architecture to implement capacitance-to-digital converters [11], [15], [16] including specific applications in MEMS [17], [18]. By using the capacitance-to-digital conversion and a type of switching amplifier like a class D amplifier, this allows the entire nanopositioner to be controlled through digital signals. The utility of this digital interface is the ability to apply DSP platforms to directly control the nanopositioner without the need for additional analog conversion electronics.

Fig. 1. SEM image of the nanopositioner utilized in this work. The central stage is held in place by a set of flexures which also serve to decouple motion along the two axes. A set of four electrostatic comb drives, seen on each side of the stage allow for actuation of the nanopositioner.

This article outlines the design of a switched self-sensing technique for an electrostatic drive. It is applied to the MEMS nanopositioner published by Maroufi *et al.* [19]. Section II introduces the MEMS nanopositioner used in this work, provides modeling for the device and identifies the model parameters. Section III outlines the operation of the actuator and sensor that are used to implement the self-sensing and that provide a digital interface by which an FPGA controls the nanopositioner. Section IV provides preliminary results demonstrating the operation of the system.

II. MODELING OF THE NANOPositionER

The nanopositioner utilized in this work was published by Maroufi *et al.* [19]. An image of the nanopositioner is shown in Figure 1. It is fabricated in a 25 μm layer of single-crystal silicon using the SOIMUMPS process provided by MEMSCAP. It consists of a 3 mm stage that is actuated by four electrostatic comb drives in the positive and negative directions along two orthogonal axes. For an applied voltage the force produced by an electrostatic comb drive is as follows.

$$f = \frac{n\epsilon h}{2g} V^2 \quad (1)$$

The parameters are: n the number of overlapping faces, ϵ the dielectric permittivity, g gap between comb fingers and V is the applied voltage. For one drive in the current design $n = 1694$, $\epsilon = 8.8541879 \times 10^{-12}$, $g = 2 \mu\text{m}$ and $h = 25 \mu\text{m}$.

The mechanical dynamics of a single axis of the nanopositioner is modeled as a lumped second order spring-mass-damper system as shown in the equation below.

$$m\ddot{x} + c\dot{x} + kx = f \quad (2)$$

The ideal mass $m = 6.9752 \times 10^{-7}$ kg and the ideal stiffness $k = 31.6875 \text{ N m}^{-1}$.

The final aspect of the model is the capacitance of an electrostatic comb drive which is used for the sensing aspect

Fig. 2. A single electrostatic drive is actuated with a $\pm 20 \text{ V}$ 1 Hz triangle wave offset at 25 V. The displacement measurement is performed using a laser Doppler vibrometer. The quadratic function $x = 0.003499v^2 + 0.005348v - 2.57$ is fitted to the data with displacement in μm .

Fig. 3. The frequency response of the MEMS device. The input is a small chirp voltage biased at 25 V and the displacement is measured using a laser Doppler vibrometer. A second order system was fitted to the data with a zero frequency gain of 1.222×10^{-5} , a quality factor of 99.32 and a resonance frequency of 1293 Hz.

of the design. The capacitance of the comb drive as a linear function of displacement is shown below.

$$C = \frac{n\epsilon h(x_0 + x)}{g} \quad (3)$$

The only additional parameter to be introduced here is the initial overlap x_0 which is 13 μm .

The purpose of the proceeding nanopositioner design is the control of displacement. The following model describes the mapping from voltage to displacement.

$$\ddot{x} + \frac{\omega_n}{Q}\dot{x} + \omega_n^2 x = \alpha V^2 \quad (4)$$

To identify these parameters, the displacement of the nanopositioner was measured using a laser Doppler vibrometer. Figure 2 shows the static relationship between displacement and voltage and Figure 3 shows the small signal frequency response. From these measurements $\omega_n = 8125 \text{ rad s}^{-1}$, $Q = 99.32$ and $\alpha = 0.231 \text{ m s}^{-2} \text{ V}^{-2}$.

III. DESIGN OF THE SELF-SENSING METHOD

The basic topology of the nanopositioner system is shown in Figure 4. It comprises of a $\Sigma\Delta$ actuator driver to convert the input control action u to a set of switching signals to

Fig. 4. The layout of the nanopositioning system. It comprises of an actuator driver that switches two switching amplifiers to apply a voltage to two opposing electrostatic drives. The sensor circuit and the driver convert the displacement of the drive to a switching signal using a $\Sigma\Delta$ algorithm. Two signals ϕ_1 and ϕ_2 coordinate the logic to alternately switch each system onto the electrostatic drives.

Fig. 5. A charge balance type capacitance sensor is utilize to sense the displacement of the nanopositioner. The electrostatic drives are arranged in as a switched capacitor resistor circuit and the current flowing across them is read into a $\Sigma\Delta$ circuit to digitize the signal. The switch IC is the TS5A23157, the op-amp is the OPA355 and the comparator is the TLV3501, all from Texas Instruments.

drive two switching amplifiers. The two amplifiers drive two opposing electrostatic drives which pull the nanopositioner's central stage in the positive and negative directions. The sensor injects signals into the two drives to measure the displacement of the nanopositioner. The sensor and its driver form a $\Sigma\Delta$ arrangement to provide a displacement-to-digital type sensor.

The sensor and actuator drivers are implemented within an FPGA to allow for digital control of the system. For both systems to use the same electrostatic drives, time division multiplexing is used to perform self-sensing. To perform the appropriated switching, two phase signals are generated within the FPGA. The sensing phase signal ϕ_1 is high when the sensor is connected to the electrostatic drive and the actuation phase signal ϕ_2 is high when the actuator is connected. With the FPGA logic clocked at 200 MHz, the sensing phase is on for 50 cycles followed by a 30 cycle dead-time and the actuating phase is on for 50 cycles followed by a 70 cycle dead-time.

The following subsections describe the theory and operation behind the sensor and actuator circuits. The sensor circuit is described first as its principle of operation influences the architecture of the actuator circuit.

A. Sensor

The sensor circuit, shown in Figure 5, is a charge balance type capacitive sensor with a $\Sigma\Delta$ output stage to digitize the sensor signal. The low voltage sensing circuit is decoupled from the high voltages applied to the MEMS device via decoupling capacitors C_d . The sensor ensures one side of the decoupling capacitors are kept at a fixed low voltage, and the actuators are designed to supply a limited current to ensure over-current conditions do not allow this voltage to rise.

The electrostatic comb drives are represented by the capacitances C_1 and C_2 . To measure displacement, the capacitance of the comb drive can be measured as shown in Equation (3). Given the differential topology of the two comb drives, the capacitance of one drive increases with displacement while the other decreases. To remove the effect of the common mode capacitance and to increase the transduction efficiency, the difference in capacitance between the two opposing drives C_Δ is considered and is proportional to the displacement. The parameter β is defined as the constant of proportionality.

$$C_\Delta = C_1 - C_2 = \frac{2n\epsilon h}{g}x = \beta x \quad (5)$$

Prior to executing a sensing phase, the actuator's output changes to a high impedance state to prevent interference with the sensing signal. This leaves the decoupling capacitors in series with the electrostatic drives. The decoupling capacitors are 1 nF while the electrostatic drives are in the order of 10 pF. Therefore the series combination is dominated by the electrostatic drives. One drive is charged to the positive rail V_s and the other is charged to the negative rail $-V_s$. The supply rails are at ± 1.65 V. When the sensing phase is executed the two drives are switched to ground and a current from the drives flows into the $\Sigma\Delta$ portion of the sensor. The average current that flows from the two drives is as follows.

$$I_1 = -V_s f_s C_1 \quad I_2 = V_s f_s C_2 \quad (6)$$

The switching frequency $f_s = 1$ MHz. The currents I_1 and I_2 combine on the same node and the net current I_Δ flowing into the $\Sigma\Delta$ circuit is proportional to the difference in capacitance C_Δ .

$$I_\Delta = I_1 + I_2 = -V_s f_s C_\Delta \quad (7)$$

The $\Sigma\Delta$ modulator is described by the model shown in Figure 6. First, the difference between the input signal and its quantized version is taken and the error is passed to a filter, in this case an integrator. Note that the op-amp integrator has a negative gain which is canceled by the negative sign of I_Δ . The output of the integrator is quantized using a 1-bit analog-to-digital converter comprising of a comparator and a D flip-flop within the FPGA. This value is then fed-back through a switched capacitor resistor to produce the quantized version of I_Δ . This loop acts to keep the sensor output y proportional to I_Δ and thus displacement x . The values of the 1-bit signal y are taken to represent the values ± 1 . The transfer function from the displacement x to the average sensor output y is as follows.

$$H_s(s) = \frac{y}{x} = \frac{\beta f_s}{C_i s + C_f f_s} \quad (8)$$

Fig. 6. The linear model of the sensor. This charge balance capacitive sensor maps displacement to a current that flows into the $\Sigma\Delta$ feedback loop. The loop filter is an integrator and the 1-bit ADC is modeled as additive quantization noise q_n . The integrator voltage is fed back through a switched capacitive resistor circuit. The sensor output is scaled due to the number representation used within the FPGA.

The parameters f_s and β are set, therefore the gain of the sensor is set by choosing an appropriate feedback capacitance C_f . C_f is also the value of C_Δ that causes the integrator to saturate. With a estimated maximum deviation of 10 pF, C_f is chosen to match. The integrator capacitor is chosen at 100 pF which sets a bandwidth of 15 915 kHz.

B. Actuator

Each axis of the MEMS nanopositioner is actuated by two opposing electrostatic drives. An advantage of this arrangement is that the quadratic nonlinearity of the electrostatic drives can be removed if the two drives are actuated differentially. In this design, the electrostatic drives are driven differentially around a bias of 25 V.

A class D type amplifier was considered appropriate to actuate the design. Class D amplifiers are efficient, simple and are directly controllable from a DSP. The mechanical bandwidth of the nanopositioner and the capacitive nature of electrostatic drives filter the switching harmonics produced. They are suited to implement a self-sensing actuator with the time division multiplexing method as the control can disconnect the amplifier from the electrostatic drive during the sensing phase.

The actuator for a single drive is shown in Figure 7. A $\Sigma\Delta$ modulator is used to perform the analog to digital conversion. The output is gated by the actuation phase signal ϕ_2 , which while low, puts the amplifier into a high impedance state to prevent interference during the sensing phase. A half-bridge circuit is used to amplify the digital signal. The half-bridge output is filtered by an RC filter whose capacitance is dominated by the sensor decoupling capacitor C_d .

Each actuator consists of two class-D amplifiers, one to charge the electrostatic drive and one to discharge. This arrangement provides the mechanism for forcing the amplifier into a high impedance state at high sampling rates. At the output of each class-D amplifier is a diode, denoted the isolation diode, whose orientation in Figure 7 indicates whether the amplifier is used for charging or discharging. In the case of the charging amplifier, the high side MOSFET is switched on to charge the electrostatic drive. When going into a high impedance state, simply switching off the MOSFET is too slow, there are parasitic capacitances within the MOSFET that need to be discharged. Switching on the low side

Fig. 7. The actuator circuit for the electrostatic drive C_{mems} . The FPGA controller uses $\Sigma\Delta$ modulation to perform digital to analog conversion and a half-bridge to amplify the signal. An RC filter suppresses quantization noise. The MOSFETs and their driver are from International Rectifier.

MOSFET turns off the high side MOSFET and in addition the isolation diode switches off moving the amplifier into a high output impedance state. Similar logic applies to the discharge amplifier.

The system input u is a number in the range $[-1, 1]$ and the ideal amplifier maps the input to an actuator voltage v_a in the range $[0, V_{cc}]$. The transfer function of the $\Sigma\Delta$ modulator is a delay of one sample period. For the RC filter, opening the half-bridge every cycle in effect creates a switched resistor RC filter. The switching reduces the average current flowing through the resistor creating a larger effective resistance in the RC filter decreasing its bandwidth. Let D_a be the duty cycle for which the actuation is connected to the RC filter with resistance R_a and thus the equivalent resistance of the switch resistor is R_a/D_a . The transfer function of the actuator is as follows.

$$H_a(s) = \frac{v_a}{u} = \frac{V_{cc}}{2} \frac{D_a}{R_a C_d s + D_a} e^{-sT_s} \quad (9)$$

In the implemented system, $V_{cc} = 50$ V, $R_a = 3.3$ k Ω , $C_d = 1$ nF, $D_a = 0.25$ and $T_s = 1$ μ s. The gain of the system is 25 and the bandwidth is 11 938 Hz.

IV. PRELIMINARY RESULTS

The system was fabricated as shown in Figure 8. The first set of results are to show the correct operation of the time-multiplexed switching scheme. Figure 9 shows the actuator voltage v_a on the opposing electrostatic drives while the input reference is set to 0. The switching cycle begins with the sensing phase which can be seen by a step of 1.65 V in both waveforms in opposing directions. After 250 ns the sensing phase ends and the voltages return to their previous value. After a dead-time of 150 ns the actuation phase begins. To protect the bridge circuits in the amplifier, a shoot through delay of 50 ns causes the delay in the amplifier response. The actuation phase lasts for 250 ns. After which there is a 350 ns dead-time to allow the actuator time to open-circuit.

Fig. 8. The fabricated nanopositioner system. The MEMS nanopositioner is seen in the lower right corner of the circuit board. Adjacent to the MEMS device is the sensing circuitry for the x and y axes. Only the operation of a single axis is demonstrated in this work. The boards stacked under the sensor comprise of the actuator circuits and the power supply. The system is connect to an development board housing the Xilinx Kintex 7 FPGA which controls the system.

Fig. 9. The voltage waveforms at opposing electrostatic drives over 1.6 sampling periods. These waveforms demonstrate the operation of the time-multiplexed self-sensing method. The square pulse at 0.2 μ s and 1.2 μ s is the sensing signal, while the ramp in the center of the waveform is the actuating signal. The dead-time between each phase is sufficient for each system to switch off before the other is switched on. The delay between the actuation phase and the actuation signal is attributed to a shoot-through protection in the amplifier and the time taken for the switches to turn on and off. Note the actuation and sensing signals are of the opposite polarity on each drive.

Fig. 10. The step response of the actuator. The system input u was stepped by a value of 0.7625. The measured response is the actuation voltage v_a at one of the electrostatic drives.

Fig. 11. The static characteristic of the nanopositioning system from the input u to the output y . The system was actuator with a 0.5 Hz triangle wave of amplitude 0.75 while measurements were performed and the signals were filtered to remove the switching harmonics from the sensor signal. The linear fit has a gain of 0.2674 though a distinct nonlinearity is observed in the characteristic.

Fig. 12. The step response of the system from the input u to the output y . The resonant motion of the MEMS device is clearly captured by the sensor.

To show the operation of the actuator, the system was stepped by $u = 0.7629$. The step response is shown in Figure 10. From the fitted exponential lag, the identified model of the actuator is as follows.

$$H_a(s) = 22.85 \cdot \frac{66020}{s + 66020} \quad (10)$$

The reduced gain compared to the theoretical gain of 25 is attributed to the voltage drop across the amplifier switches and the isolating diodes.

The measurements in Figure 11 and Figure 12 show the response of the entire system from the input signal u to the sensor output y . Both measurements are filtered by a 4th order butterworth low pass filter with a cut-off frequency of 10 kHz. The measurements in Figure 11 show the static relationship from input to output. The linear fit has a gain of 0.2674, however, a distinct nonlinearity can be seen in the theoretically linear system. This effect is due to the isolating diodes in the amplifier. When reverse biased, these diodes have a junction capacitance that appears in parallel to the electrostatic drives from the perspective of the sensor. The junction capacitance is a nonlinear function of voltage and the current that flows due to the application of the sensing signal distorts the sensor output. The step response of the system is shown in Figure 12. The system is stepped by $u = 0.7629$ to achieve this response and it clearly shows the sensor has sufficient bandwidth to clearly capture the resonant motion of the MEMS device.

V. CONCLUSION

This work demonstrates the operation of a switched self-sensing method for a MEMS nanopositioner that employs electrostatic transduction. Actuator and sensor circuits have been designed to provide a fully digital interface to allow for easy control and the architecture of the actuator allows for fast switching despite the high voltages needed to drive the MEMS nanopositioner.

The current issue with the device is the nonlinearity that is observed in the static response of the system. This is caused by the junction capacitance of the isolation diodes used in the actuator circuit. Current work is being undertaken to eliminate this nonlinearity with architecture changes to the actuator circuit and appropriate choice of switches to minimize the non-ideal characteristics of semiconductor devices.

Upon addressing this issue future work will identify a linear model and feedback control will be implemented within the FPGA to allow the nanopositioner to be used within an atomic force microscope to perform imaging.

REFERENCES

- [1] N. B. Hubbard, M. L. Culpepper, and L. L. Howell, "Actuators for micropositioners and nanopositioners," *Applied Mechanics Reviews*, vol. 59, pp. 324–334, Nov. 2006.
- [2] B. Sahu, K. K. Leang, and C. R. Taylor, "Emerging challenges of microactuators for nanoscale positioning, assembly, and manipulation," *Journal of Manufacturing Science and Engineering*, vol. 132, p. 030917, 2010.
- [3] M. Maroufi, A. Bazaei, and S. O. R. Moheimani, "A high bandwidth MEMS nanopositioner for on-chip AFM: Design, characterization and control," *IEEE Transactions on Control Systems Technology*, 2015, Accepted for publication, published.
- [4] X. Liu, K. Kim, and Y. Sun, "A MEMS stage for 3-axis nanopositioning," *Journal of Micromechanics and Microengineering*, vol. 17, no. 9, p. 1796, 2007.
- [5] A. G. Fowler, A. N. Laskovski, A. C. Hammond, and S. O. R. Moheimani, "A 2-DoF electrostatically actuated MEMS nanopositioner for on-chip AFM," *IEEE/ASME Journal of Microelectromechanical Systems*, vol. 21, no. 4, pp. 771–773, 2012.
- [6] C. Liu, *Foundations of MEMS*. Prentice Hall, 2011.
- [7] V. Kaajakari, *Practical MEMS*. Small Gear Publishing, 2009.
- [8] L. Sun, J. Wang, W. Rong, X. Li, and H. Bao, "A silicon integrated micro nano-positioning xy -stage for nano-manipulation," *Journal of Micromechanics and Microengineering*, vol. 18, no. 12, p. 125004, 2008.
- [9] B. Koo, X. Zhang, J. Dong, S. Salapaka, and P. Ferreira, "A 2 degree-of-freedom SOI-MEMS translation stage with closed-loop positioning," *Microelectromechanical Systems, Journal of*, vol. 21, no. 1, pp. 13–22, Feb. 2012.
- [10] Y. Liang, L. Xiaowei, C. Weiping, and Z. Zhiping, "High resolution interface circuit for closed-loop accelerometer," *Journal of Semiconductors*, vol. 32, no. 4, p. 045005, 2011.
- [11] P. Lajevardi, V. Petkov, and B. Murmann, "A $\Delta\Sigma$ interface for MEMS accelerometers using electrostatic spring constant modulation for cancellation of bondwire capacitance drift," *Solid-State Circuits, IEEE Journal of*, vol. 48, no. 1, pp. 265–275, Jan. 2013.
- [12] J. Dong and P. M. Ferreira, "Simultaneous actuation and displacement sensing for electrostatic drives," *Journal of Micromechanics and Microengineering*, vol. 18, no. 3, p. 035011, 2008.
- [13] L. Aaltonen and K. Halonen, "Continuous-time interface for a micromachined capacitive accelerometer with NEA of $4\mu\text{g}$ and bandwidth of 300Hz," *Sensors and Actuators A: Physical*, vol. 154, no. 1, pp. 46–56, 2009.
- [14] S. Xia and S. Nihtianov, "Power-efficient high-speed and high-resolution capacitive-sensor interface for sub-nanometer displacement measurements," *Instrumentation and Measurement, IEEE Transactions on*, vol. 61, no. 5, pp. 1315–1322, May 2012.
- [15] J. O'Dowd, A. Callanan, G. Banarie, and E. Company-Bosch, "Capacitive sensor interfacing using sigma-delta techniques," in *Sensors, 2005 IEEE*, Oct. 2005, 4 pp.–.
- [16] D.-Y. Shin, H. Lee, and S. Kim, "A delta-sigma interface circuit for capacitive sensors with an automatically calibrated zero point," *Circuits and Systems II: Express Briefs, IEEE Transactions on*, vol. 58, no. 2, pp. 90–94, Feb. 2011.
- [17] B. Amini, R. Abdolvand, and F. Ayazi, "A 4.5-mw closed-loop $\Delta\Sigma$ micro-gravity cmos soi accelerometer," *Solid-State Circuits, IEEE Journal of*, vol. 41, no. 12, pp. 2983–2991, Dec. 2006.
- [18] J. Wu and L. Carley, "Electromechanical delta; sigma; modulation with high-Q micromechanical accelerometers and pulse density modulated force feedback," *Circuits and Systems I: Regular Papers, IEEE Transactions on*, vol. 53, no. 2, pp. 274–287, Feb. 2006.
- [19] M. Maroufi, A. G. Fowler, A. Bazaei, and S. O. R. Moheimani, "High-stroke silicon-on-insulator mems nanopositioner: Control design for non-raster scan afm," *Review of Scientific Instruments*, vol. 86, no. 2, 023705 (12pp), 2015, published.