Measuring Picometer Nanospositioner Resolution

A.J. Fleming
School of Electrical Engineering and Computer Science, University of Newcastle, Callaghan, NSW 2308, Australia.

Abstract:
The article describes a new technique for measuring the resolution of nanopositioning systems. By recording the voltage applied to an actuator and performing a filtering operation, the position noise and resolution can be estimated. This technique is simple to apply in practice and does not require any additional sensors or specialized equipment such as laser interferometers. The resolution of a piezoelectric tube scanner is experimentally determined to be 1.4 nm, which agrees with previous results.

Keywords: Nanopositioning, resolution, noise

Introduction

Nanopositioning systems are found in a variety of applications that require positioning with nanometer scale resolution, for example: scanning probe microscopy, nanofabrication, data storage, cell manipulation, beam pointing, and precision optical alignment.

The piezoelectric actuator is the most widely used in nanopositioning systems. Examples include piezoelectric tube actuators and piezoelectric stack positioners. Due to vibration, creep, hysteresis [1], and mechanical drift, piezoelectric nanopositioning systems typically require feedforward compensation [2] and/or a feedback control loop [3].

Although a feedback control loop increases the positioning accuracy, a portion of the sensor noise is propagated to the position output, which reduces the precision or resolution. The resolution is critical for defining the smallest possible dimensions in a manufacturing process or the smallest measurable features in an imaging application. For example, in the hard drive industry, the standard performance metric for resolution is the track pitch and the standard deviation of the measurement [4,5].

The most straight-forward and conclusive method for measuring the positioning noise of a nanopositioning system is to measure it directly. However, this approach is not often possible as an additional sensor is required with lower noise and a significantly higher bandwidth than the closed-loop system. Instead, the position noise is predicted from measurements of the sensor noise [6–9]. However, this approach tends to underestimate the position noise since the influence of the high-voltage amplifier is neglected.

In this work, a new method is proposed for measuring the resolution of nanopositioning systems. While the system is operating at steady-state in closed-loop, the voltage applied to the piezoelectric actuator is recorded, either with a spectrum analyzer or in the time domain. This data is then filtered by a model of the system dynamics to produce an estimate of the positioning noise and resolution. This approach captures the effect of all electronic and sensor noise without the need for additional sensors.

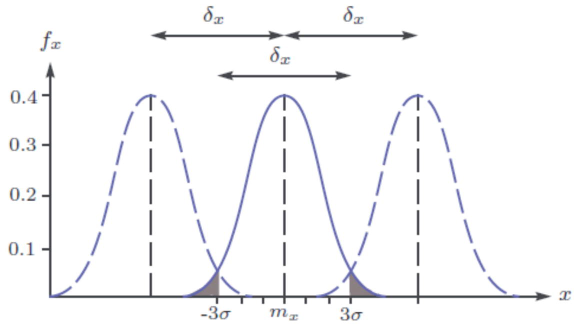

Fig. 1: *The random motion of a one-dimensional nanopositioner. The random motion in the x-axis is bounded by δ_x.The standard deviation and mean are σ_x and m_x respectively. The shaded areas represent the probability of the position being outside the range specified by δ_x.*

Definition of Resolution

When a nanopositioner has settled to a commanded location, a small amount of random motion remains due to the sensor noise, amplifier noise, and external disturbances. The residual random motion means that two adjacent commanded locations may actually overlap, which can cause manufacturing faults or imaging artifacts. To avoid these eventualities, it is critical to know the minimum distance between two adjacent but unique locations.

Since the noise sources that contribute to random position errors have a potentially large dispersion, it is impractically conservative to specify a resolution where adjacent regions never overlap. Instead, it is preferable to state the probability that the actual position is within a certain bound. Consider the example of random positioning errors plotted in Figure 1. Observe that the peak-to-peak amplitude of random motion is bounded by $\delta_x$and δ_y, however this range is occasionally exceeded. If the random position variation is assumed to be Gaussian distributed, the probability density functions of three adjacent points, spaced by δ_x, are plotted in Figure 1. In this example, δ_x is equal to $\pm 3\sigma_x$ or \$6\sigma_x$ which means that 99.7% of the samples fall within the range specified by δ_x. Restated, there is a 0.3% chance that the position is exceeding δ_x and straying into a neighbouring area, this probability is shaded in grey.

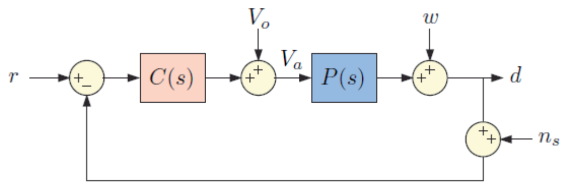

***FIG. 2**. A single axis feedback control loop with a plant P(s) and controller C(s). The additive noise sources are the am plifier output voltage noise V_o, the external disturbances w and the sensor noise n_s. V_a is the voltage applied to the nanopositioner.*

For many applications, a 99.7% probability that the position falls within $6\sigma_x$ is an appropriate definition for the resolution. To be precise, this definition should be referred to as the 6σ resolution and specifies the minimum spacing between two adjacent points that do not overlap 99.7% of the time. If the noise is non-Gaussian, the 99.7 percentile, or peak-to-peak value, must be measured directly rather than predicted from the RMS value.

In other applications where more or less overlap between points is tolerable, another definition of resolution may be more appropriate. For example, the 4σ resolution would result in an overlap 4.5% of the time, while the 10σ resolution would almost eliminate the probability of an overlap. Thus, it is not the exact definition that is important; rather, it is the necessity of quoting the resolution together with its statistical definition.

Although there is no international standard for the measurement or reporting of resolution in a positioning system, the ISO 5725 Standard on Accuracy (Trueness and Precision) of Measurement Methods and Results [10] defines precision as the standard deviation (RMS Value) of a measurement. Thus, the 6σ resolution is equivalent to six times the ISO definition for precision.

Estimating the Resolution from the Applied Voltage

The foremost sources of noise in a nanopositioning application are the amplifier noise, sensor noise and external disturbances. As shown in Figure 2, the amplifier noise V_o appears at the plant input. In contrast, the external noise w acts at the plant output, and the sensor noise n_s disturbs the measurement. For the sake of simplicity, the voltage amplifier is considered to be part of the controller.

Considering the limitations of standard noise prediction techniques discussed in the introduction, there is a need for a practical procedure that can accurately estimate the closed-loop resolution of a nanopositioning system. A new procedure that fulfils this goal is described in the following. The applied-voltage method predicts the positioning noise from a measurement of the closed-loop voltage applied to the nanopositioner.

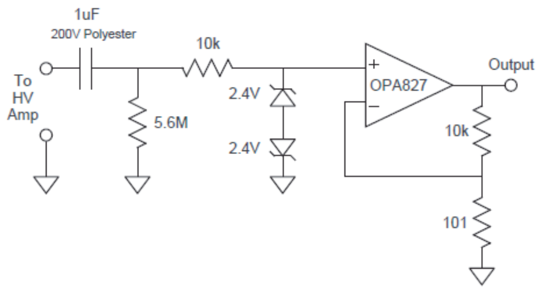

***FIG. 3**. A low-noise AC coupled preamplifier with 0.03 Hz cut-off frequency, a gain of 100, and bandwidth of 220 kHz. All of the resistors are metal-film or thin-film. This circuit should be powered by two 9V batteries and mounted inside a shielded and grounded metal enclosure. If the circuit is likely to be exposed to continuous large AC signals (not recommended), the 10k protection resistor and Zener diodes will need to be rated accordingly.*

The recorded voltage is then filtered by the open-loop response of the plant to reveal the closed-loop resolution. The feedback diagram of a single-axis control loop is illustrated in Figure 2. The output position d is equal to the applied voltage V_a filtered by the plant P(s). Hence, the position noise can be estimated by measuring the closed-loop voltage noise V_a and filtering it by the plant dynamics. This measurement can be performed in the time or frequency domain, is straight-forward, and does not require any additional sensors.

If the power spectral density of Va is recorded, the spectral density of the position noise d is

$$S_d(f) = S_{V_a}(f)|P(j2\pi f)|^2$$

where $S_d(f)$ is the power spectral density of d, $S_{V_a}(f)$ is the power spectral density of V_a, and

$P(j2\pi f)$ is the frequency response of the plant model. The RMS value of d can then be computed from the Wiener Khinchin relations

$$\sigma_d = \sqrt{\int_0^\infty S_d(f)\, df} \quad (2)$$

Assuming a Gaussian distribution, the 6σ resolution is then

$$\delta = 6\,\sigma_d$$

In the time domain, the position noise estimate is V_a filtered by the plant model P(s). Since the simulation of d(t) is from a sample of data, the beginning of d(t) will be affected by the transient response of P(s), which introduces error. To avoid this, a time period equal to the settling time of P(s) should be excised from the beginning of d(t) before computing the resolution. The 6σresolution is the 99.7% percentile bound of d(t), or six times the RMS value, if the noise is Gaussian.

Amplifier Bandwidth	f_V
Anti-aliasing filter cut-off frequency	$7.5\times f_V$
Sampling rate	$15\times f_V$
Record length	100s

TABLE 1. *Recommended parameters for time domain noise recordings*

Practical Considerations

As the output voltage noise of a high-voltage amplifier is typically in the range of 1 to 20 mVp-p, the signal must be preamplified. In addition, the potentially large (hundreds of volts) DC offset must be removed by AC coupling. The AC-coupling frequency in instruments like oscilloscopes and multimeters can imply a cut-off frequency of up to 20 Hz. This is intolerably high in nanopositioning applications where frequencies down to 0.1 Hz are of interest. Noise components with a frequency less that 0.01 Hz are usually referred to as drift and are not considered here. Most specialty low-noise preamplifiers have the provision for low-frequency AC coupling, for example, the Stanford Research SR560 amplifier has a high-pass cut-off frequency of 0.03 Hz. A simple preamplifier circuit that is suited to this application is shown in Figure 3. This circuit is protected from high DC voltages and provides a gain of 100 with an AC coupling frequency of 0.03 Hz.

When utilizing low-frequency AC coupling, it is important to allow the transient response of the filter to decay before recording data. When measuring small AC signals with large DC components, it may take in excess of 20 time-constants for the transient response to become negligible. With an AC coupling frequency of 0.03 Hz, the required delay is approximately 100 s. More generally, the measurement delay TD should be at least

$$T_D = \frac{20}{2\pi f_c}$$

where f_c is the high-pass filter cut-off. The required delay for the circuit in Figure 3 can be reduced to less than 1 second by temporarily switching a 10k resistor in parallel with the 5.6M resistor.

If frequency domain data is recorded, the measured spectrum should be split into two or three decades to provide sufficient resolution and range. For example: 0 to 12 Hz, 12 Hz to 1.2 kHz, and 1.2 kHz to 12 kHz. The data should preferably be recorded in units of V^2/Hz and have a frequency range of at least five times the amplifier bandwidth. The RMS value and 6σ resolution can then be found by evaluating the integral in equation (2). Alternatively, it may be more convenient to use the spectral density with units of $V/\sqrt{Hz}$. In this case, the standard deviation is

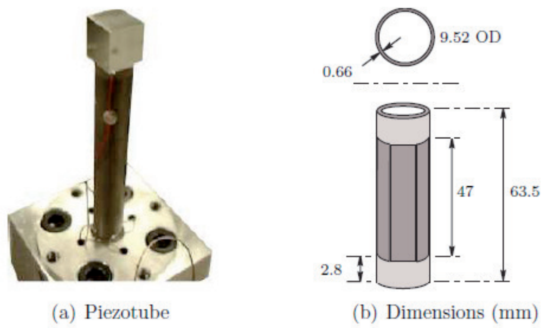

FIG. 4*. A piezoelectric tube scanner. The tube tip deflects laterally when an electrode is driven by a voltage source. The sensitivity is 171 nm/V which implies a range of approximately 68 µm with a ±200 V excitation.*

$$\sigma = \int_0^\infty \sqrt{S_{V_a}(f)}\, |P(j2\pi f)|\, df$$

Time domain recordings require a choice of the recording length and sampling rate. The length of each recording is defined by the lowest spectral component under consideration. With a lower frequency limit of 0.1 Hz, a record length of at least ten times the minimum period is required to obtain a statistically meaningful estimate of the RMS value, which implies a minimum recording length of at least 100 s. A longer record length is preferable, but may not be practical.

The recommended parameters for time-domain noise recordings are summarized in Table 1.

If the noise is not Gaussian distributed, the 6σ resolution can be found using the function Res=2*quantile(abs(d),0.997).

Experimental Demonstration

In the following, the applied-voltage technique is used to estimate the resolution of the piezoelectric tube nanopositioner [11] pictured in Figure 4. The voltage amplifier used to drive the tube is a Nanonis HVA4 high-voltage amplifier with a gain of 40. The position sensor is an ADE Tech 4810 Gaging Module with 2804 capacitive sensor. This sensor has a full range of $\pm 100\ \mu m$ and a sensitivity of 0.1 $V/\mu m$.

The identified plant model is

$$P(s) = \frac{0.01151s^2 + 116s + 2.541\times 10^6}{s^2 + 66.73s + 2.658\times 10^7}\mu m/V.$$

For the sake of demonstration, an analog integral controller was implemented with a closed-loop bandwidth of 10 Hz. After setting the reference input to zero, the voltage applied to the nanopositioner was preamplified by an SR560 amplifier with a gain of 500 and an AC coupling frequency of 0.03 Hz. This signal was recorded for 100 s with a sampling rate of 30 kHz.

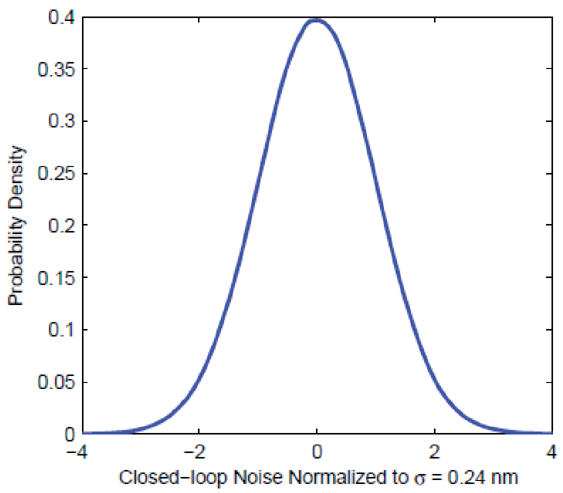

***FIG. 6**. The distribution of position noise in a piezoelectric tube nanopositioner with a closed-loop bandwidth of 10 Hz. The standard deviation is 0.24 nm and the 6σ resolution is 1.4 nm.*

To estimate the closed-loop positioning noise, the noise recording was filtered by the model. The distribution of the resulting displacement estimate, plotted in Figure 6, has an RMS value of 0.24 nm and a 6σ resolution of 1.4 nm. Since 1.4 nm is greater than 6×0.24 nm, the distribution is slightly more dispersed than a Gaussian distribution.

The resolution obtained above can also be compared to that predicted from measurements of the open-loop sensor and amplifier noise [13]. With the same closed-loop bandwidth (10 Hz) the standard frequency domain approach estimates the closed-loop resolution to be 1.5 nm, which compares well to the 1.4 nm predicted by the applied-voltage technique.

Conclusions

The resolution of a nanopositioning system determines the minimum discernible feature dimensions in an imaging or fabrication process. The 6σ resolution is the bound that encloses 99.7% of position observations. This is equivalent to the minimum distance between two non-overlapping positions.

By using the 'applied-voltage' technique presented in this article, the 6σresolution can be measured directly in closed-loop. This closed-loop voltage applied to the system actuators is recorded, then filtered by a plant model to estimate the positioning noise and reveal the resolution.

The applied-voltage technique was demonstrated on a piezoelectric tube scanner to reveal a resolution of 1.4 nm with a 10 Hz closed-loop bandwidth. This estimate agrees with other techniques, however, the applied-voltage method does not require additional sensors, is simple to perform in practice, and does not require specialized equipment such as a spectrum analyzer

References

[1] A. J. Fleming and K. K. Leang, "Charge drives for scanning probe microscope positioning stages," Ultramicroscopy, vol. 108, no. 12, pp. 1551–1557, November 2008.

[2] G. M. Clayton, S. Tien, K. K. Leang, Q. Zou, and S. Devasia, "A review of feedforward control approaches in nanopositioning for high-speed SPM," Journal of Dynamic Systems, Measurement, and Control, vol. 131, pp. 061 101(1–19), November 2009.

[3] J. A. Butterworth, L. Y. Pao, and D. Y. Abramovitch, “A comparison of control architectures for atomic force microscopes,” Asian Journal of Control, vol. 11, no. 2, pp. 175–181, March 2009.
[4] A. Al Mamun and S. S. Ge, “Precision control of hard disk drives,” Control Systems, IEEE, vol. 25, no. 4, pp. 14 – 19, aug. 2005.
[5] D. Abramovitch and G. Franklin, “A brief history of disk drive control,” Control Systems, IEEE, vol. 22, no. 3, pp. 28 –42, Jun, 2002.
[6] A. Sebastian, A. Pantazi, H. Pozidis, and E. Elefthriou, “Nanopositioning for probe-based data storage,” IEEE Control Systems, vol. 28, no. 4, pp. 26–35, August 2008.
[7] S. S. Aphale, B. Bhikkaji, and S. O. R. Moheimani, “Minimizing scanning errors in piezoelectric stack-actuated nanopositioning platforms,” IEEE Transactions on Nanotechnology, vol. 7, no. 1, pp. 79–90, January 2008.
[8] A. J. Fleming, “Nanopositioning system with force feedback for high-performance tracking and vibration control,” IEEE Transactions on Mechatronics, vol. 15, no. 3, pp. 433–447, June 2010.
[9] A. J. Fleming, S. S. Aphale, and S. O. R. Moheimani, “A new method for robust damping and tracking control of scanning probe microscope positioning stages,” IEEE Transactions on Nanotechnology, vol. 9, no. 4, pp. 438–448, September 2010.
[10] ISO 5725 - accuracy (trueness and precision) of measurement methods and results, interational organization for standardization,” 1994.
[11] J. Maess, A. J. Fleming, and F. Allg¨ower, “Simulation of dynamics-coupling in piezoelectric tube scanners by reduced order finite element models,” Review of Scientific Instruments, vol. 79, pp. 015 105(1–9), January 2008.
[12] L. Ljung, System Identification: Theory for the User. Upper Saddle River, NJ: Prentice Hall, 1999.
[13] A. J. Fleming, “Estimating the resolution of nanopositioning systems from frequency domain data,” in Proc. IEEE International Conference on Robotics and Automation, St. Paul, MN, May 2012.

Magnetic Levitation in 6-DOF with Halbach Array Configuration

R. Gloess, C. Mock, C. Rudolf, C. Walenda, Physik Instrumente (PI) GmbH & Co. KG, Karlsruhe, Germany
C. Schaeffel, M. Katzschmann, H.-U. Mohr, Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnuetzige GmbH, Ilmenau, Germany

Abstract
The paper describes the design of a 6-DOF magnetic levitated actuator and a controller structure with nanometer resolution. The magnetic levitated stage is designed with a Halbach array configuration. The movable platform is a passive part without any electrical wiring. The motion range of the stage is 100 x 100 mm, 100µm in Z direction and some hundreds of micro radiant for all rotational axes. Three magnetic Halbach arrays with three double-coil configurations are used to levitate and move the stage.

Keywords: Halbach array, magnetic levitation, nanometer resolution, matrix control structure

Introduction

High resolution motion stages are used in very different industrial and scientific assembly and inspection systems. Often multi-axes systems are used, where individual linear and rotary axes are stacked on top of each other.
These arrangements are not stiff, they need bearings and the upper axis cables have to be driven by the lower axis. Cable drag on the actuator-assembly results in motion inaccuracies. New challenges from e.g. EUVL technology require extreme low particle generation during operation. The combination of these requirements can't be achieved using the classical stacked system concept. The ideal concept would be a planar levitated stage with 6-DOF. [1]
This paper describes a prototype magnetic driven planar stage with all six degrees of freedom. The System design has been minimized to three pairs of coils placed in the stator and three Halbach arrays in the stage to get high vertical and horizontal magnetic field components. A 6D measurement system, placed in the center of the stage was developed to get high accuracy position information on the nanometer level. With cooling being required to prevent thermal deformation during operation, one target for the test setup was the evaluation of the temperature gradient in the coil assembly. The upper platform surface is freely accessible. This is very important for all kinds of inspection systems.

Prototype

The main target for the first prototype is to achieve a minimized design based on vacuum compatible industrial components. A new very compact 6D measurement module with reasonable resolution in the nanometer range has been developed. The following tasks were part of the joint project:

- Evaluation of magnetic levitation technology
- Manufacturing, handling and qualification of Halbach arrays
- Compact 6D sensor design
- Heat pipe technology for thermal power management
- Controller technology for 6-DOF magnetic levitation

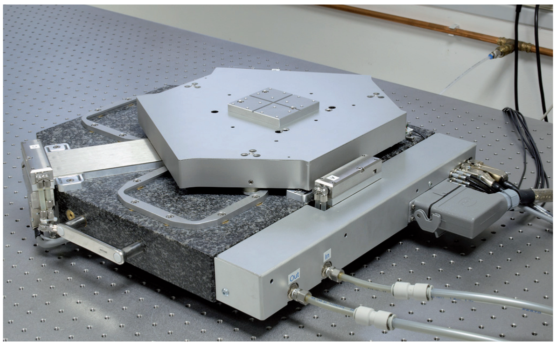

***Fig.1**: Prototype of the planar magnetic levitating system, platform in home position*

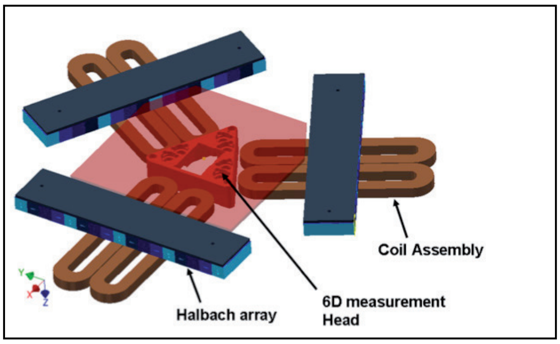

***Fig2**: Setup of the planar magnetic levitating system*