Repealing Moore's Law:

Sub-0.25µm Linewidths Drive Metrology, Trajectory-Control Advancements for Positioning Subsystems

Scott Jordan, *Nanopositioning Technologies, Polytec PI, Inc., CA, USA*

ABSTRACT

Many modern industrial technologies demand steadily increasing performance from embedded positioning subsystems. This necessitates more and more sophistication in the design, manufacture and control of nanopositioning devices and the metrology elements they contain. This paper describes the use of diamond-machined capacitive sensors of novel configuration to actively control the trajectories of nanopositioning mechanisms. A six-axis piezoelectric stage and digital control system has been developed in conjunction with these sensors and new flexure design concepts, yielding excellent positioning repeatability and accuracy with a wide range of possible applications

INTRODUCTION

As IC linewidths and feature-sizes compress according to Moore's famous law, see Figure 1, performance requirements skyrocket for the positioning mechanisms embedded in front-end production and metrology tools. This places extreme demands not only on the resolution capability of embedded motion systems but also their bi-directional repeatability, accuracy, trajectory and stability. At the same time, the stability of all attached and adjacent structures must be controlled to nanometer-scale exactitude.

In the case of motion devices used in linewidth metrology, microlithographic mask alignment and other increasingly exacting processes, these trends have driven adoption of advanced, piezoelectric-based positioners incorporating closed-loop mechanisms capable of nanometer-scale positioning resolutions. These devices have evolved rapidly in recent years.

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In particular, denser circuitry has necessitated the development of new technologies to address fundamental trajectory control and stability issues:

- Trajectory control – the ability to translate a mask, wafer or probe within a precisely controlled XY plane – is a common key to emerging fabrication and metrology processes required to support sub-0.25µm linewidths.

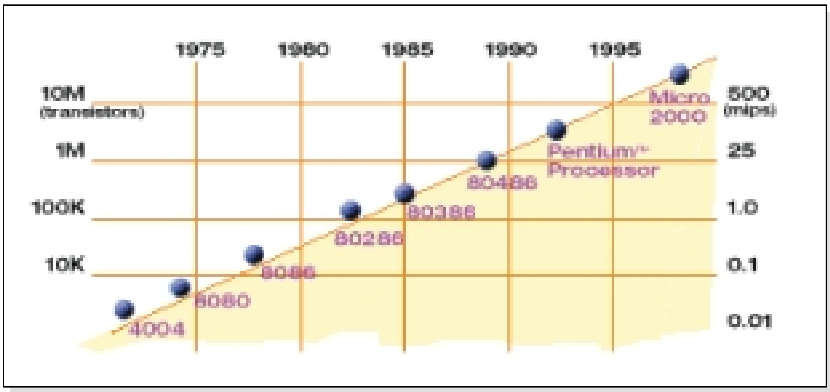


Figure 1
Moore's Law: (Logic bits/cm^2) ~ $2^{(year – 1962)/1.5}$

- Vibration nullification is a key requirement for ensuring the economics of ever-finer semiconductor processes, as settling times exponentiate with tightening tolerances (See Datatech, 4, 2000).

PASSIVE APPROACHES TO TRAJECTORY CONTROL

Elimination of stiction effects in the driven mechanism is a fundamental objective in the design of any mechanism which is to actuate reliably on a nanometer scale. Accordingly, the moving workpiece of a nanopositioning stage is generally constrained in flexures rather than conventional bearings (which suffer non-zero stiction arising from the differential between their static and sliding friction coefficients, plus significant mechanical runout) or air-bearings (which conventionally are, soft, susceptible to Z drift and prone to undamped oscillations when perturbed - characteristics addressed in only the most recent lock-down designs).

Classical flexure designs typically exhibit second-order cross coupling (parasitic motion) between axes, leading to small out-of-plane errors on the order of 0.1% of the distance travelled. The error can be estimated by:

$$\Delta H = (\pm \Delta L/2)^2 / 2H$$

where

ΔH = Lateral runout (out-of-plane error)

ΔL = Distance travelled

H = Length of the flexures

Since many modern applications require better performance than classical flexures can provide, PI designed a near-zero-runout multi-flexure guiding system. This can reduce the orthogonal error to a few nanometers over several hundred µm of actuation. In addition, the interface between the piezo element and the structure of the motion device is a critical contributor to orthogonal motion errors and has been an area of intensive development in recent years. The resulting proprietary configurations, employed in most current PI flexure stages, eliminates the cross coupling inherent in classical parallelogram guiding systems, providing flatness and straightness in the nanometer and microradian range, respectively.

However, mounting and fixturing issues arise that necessitate meticulous setup in order to preserve these properties. This reduces the practicality of industrial applications of even the best current flexure approaches when sub-nm parasitic motions are required, refs [1], [2], [3] & [4].

ACTIVE TRAJECTORY CONTROL

Active control of at least some orthogonal motion errors (runout) has been commonplace for years for some mechanisms. For example, a highly precise L-optic is often used to provide real-time X and Y position data from a wafer positioning stage to two axes of a position-measuring interferometer. As the stage moves in one axis under servo control, the orthogonal axis is corrected by its own servo, resulting in straighter trajectory than can be achieved by conventional bearings.

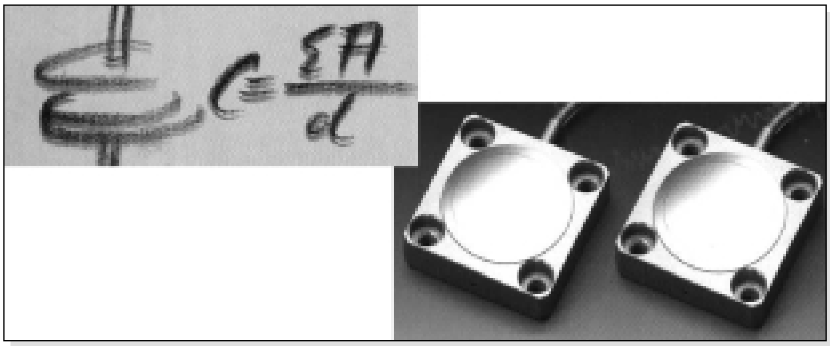
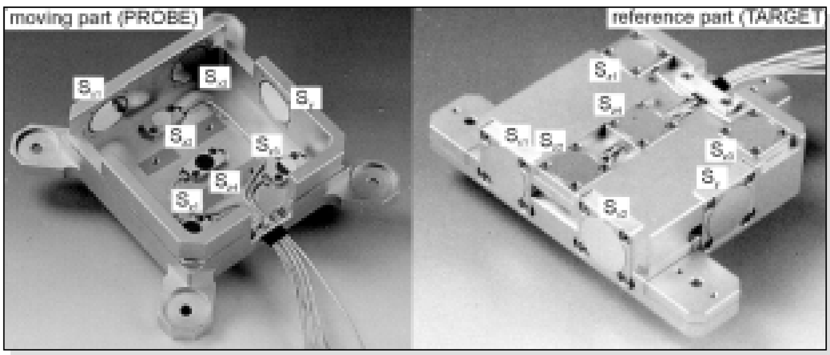


Figure 2 (above)
Capacitive sensors provide sub-nanometer absolute position sensing over ranges of several hundred microns. Courtesy Physik Instrumente

Figure 3 (right)
The six-axis stage is self contained and provides Angstrom-scale trajectory control for precisely planar (XY) scans

Figure 4 (below)
The six-degree-of-freedom positioner, P-915, utilises capacitive sensors and six-space digital controls



However, this is most appropriate for large, long-travel positioning units. Stages such as the piezoelectrically-driven units used for high-speed scanned-probe microscopy and mask alignment processes require higher bandwidths, higher resolutions and smaller package sizes than can be easily accommodated via interferometry. For these often-subnanometer-performance devices, capacitive sensors, see Figure 2, have become broadly accepted. Two diamond-machined parallel plates of special configuration are placed in close proximity. Their mutual capacitance forms a sensitive absolute measure of position.

The compact size and high performance of capacitive sensors suggests their use for multi-axis (not just XY) active trajectory control. The physics and manufacturing challenges are daunting, but these difficulties have been overcome, and a novel actively-compensated six-axis PZT stage is now available, see Figure 3, with the following capabilities:

- Up to 200x200µm planar scan range
- High-throughput actuation
- Angstrom-scale out-of-plane motion via integral, active, real-time compensation
- Fully internalised six-axis metrology; no requirement for bulky and costly external metrology such as interferometers with L-optics

The self-contained, piezoelectrically-actuated stage leverages servo technologies originally developed for adaptive optical systems. It integrates eight servo-controlled PZT actuators and six diamond-machined capacitive sensors of a novel configuration to reduce unwanted out-of-plane motions and rotational errors below 0.5 nm (RMS) and 0.1 arc-second, respectively.

The mechanism utilises six capacitive sensors based on a newly-developed two-plate asymmetric design, and a monolithic stage framework, see Figure 4. The capacitive sensors consist of a probe plate and a slightly larger target plate. This configuration was developed to enhance linearity and insensitivity to the orthogonal axes' motions.

The six diamond-machined target plates form a highly accurate coordinate reference frame. An advanced digital controller provides real-time compensation of orthogonal motion errors. It utilises scan-range-dependent loop gain settings, providing step/settle response <8msec independent of step size. It provides better than 0.033nm (0.33Angstrom) RMS position stability in the critical Z-axis.

Applications include current and emerging laboratory and industrial endeavours such as scanned-probe microscopy, X-ray lithography, near-field optical probing and pole-tip recession metrology. The ability of the system to actuate in a defined plane and correct for sample/fixturing coplanarity errors represents a significant advancement for these and similar processes requiring an exact absolute reference plane.

Stability is another benefit of this approach. Since air is the working fluid for interferometry, that technique is sensitive to environmental disturbances ranging from acoustic couplings and air currents to changes in humidity, barometric pressure and trace gas concentration. The compensated capacitive sensors utilised in the new 6-axis P-915 stage are comparatively immune to these environmental contributors to instability. Alternative multi-axis interferometry designs are also sensitive to setup and handling technique, are bulky and awkward to configure, and pose eye-safety and accessibility concerns in many applications. By contrast, the new stage's extension of proven closed-loop piezo actuation mechanisms and capacitive sensor metrology to the novel multi-axis format results in a compact and fully self-contained package that is easily integrated into sophisticated research and industrial applications.

THE PHYSICS OF MOTION ERRORS

In a single-axis actuation, there are three type of motion errors:

1. The misalignment between the measurement axis and the motion axis introduces Abbè errors and cosine errors. The Abbè error is most significant since it scales with fixturing lever-arms. Referring to Figure 5, the Abbè error is $\delta x_{Abbe} = y_{sx} \cdot \varphi_z - z_{sx} \cdot \varphi_y$
2. The inevitable orthogonal motions introduces further measurement errors:

   $$\delta x_{meas} = \delta x + \frac{\delta f}{\delta y}\delta y + \frac{\delta f}{\delta z}\delta z + \frac{\delta f}{\delta \varphi_x}\delta \varphi_x + \frac{\delta f}{\delta \varphi_y}\delta \varphi_y + \frac{\delta f}{\delta \varphi_z}\delta \varphi_z$$

   where $x_{meas} = x + f(\delta y, \delta z, \varphi_x, \varphi_y, \varphi_z)$
3. Structural deflections within the sensor, or due to cable stresses, etc., cause additional deformations and motion errors which are impossible to model mathematically.

The above errors can be compensated via calibration only if they are repeatable. Usually they are not, and furthermore tend to vary significantly from system to system. Consequently, even closed-loop positioning systems exhibit hysteresis and unit-to-unit variability. Cabling and fixturing stresses add further uncertainty on the nanometer scale.

To eliminate errors (1) and (2), simultaneous real-time metrology and loop closure in all six degrees of freedom (X, Y, Z, φ_x, φ_y, φ_z) is required. It is less costly and more practical to do this than to attempt mechanical perfection or a predictive model which takes into account all the possible interrelating errors.

In the case of a raster scan in the XY plane, it is desired that zero motion occur in Z, φ_x, φ_y, φ_z. Thus, ideally:

$$\delta x_{Abbe} = 0$$

$$\delta x_{meas} = \delta x + \frac{\delta f}{\delta y}\delta y$$

The accuracy of this approach is limited only by the performance of the control system and displacement sensors. To realise the 6 axes closed-loop positioning system, PI developed the novel multi-axis flexure stage, the digital position controller and the asymmetric capacitive sensor. This sensor has excellent insensitivity to lateral motion ($\frac{\delta f}{\delta y}$ can then be neglected).

Six TARGET plates form a coordinate reference block, Figure 4. The sensors S_{x1} and S_{x2} measure the X-displacement and the rotation φ_z while the sensor Sy measures the Y-position. The sensors S_{z1}, S_{z2}, S_{z3} measure the z-position and rotations φ_x and φ_y.

Since the *XY*-plane and the *YZ*-plane are defined by more than one sensor, all TARGET electrodes defining an individual plane are diamond milled in one production step. This ensures excellent orthogonality and allows easy fixing of the sensor position.

The digital controller provides flexibility and the computing power for digital filtering, linearisation of the sensor signals and calculating the individual axis information from multiple sensor inputs as well as the individual PZT actuator drive signals. The digitised sensor signals are filtered and linearised with a 4th order polynomial correction. The nominal range of XY and φ_z is 200 x 200 μm^2 and ±500 µrad, respectively. Figure 6 and Figure 7 show the resulting Angstrom-scale out-of-plane motion throughout an XY scan.

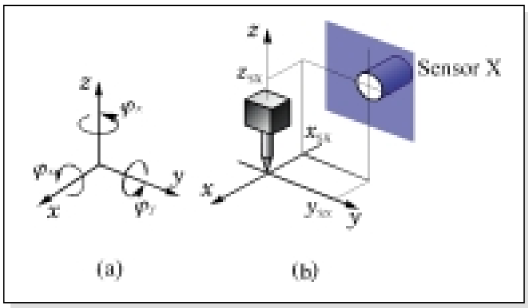


Figure 5 (left)
The Coordinate system

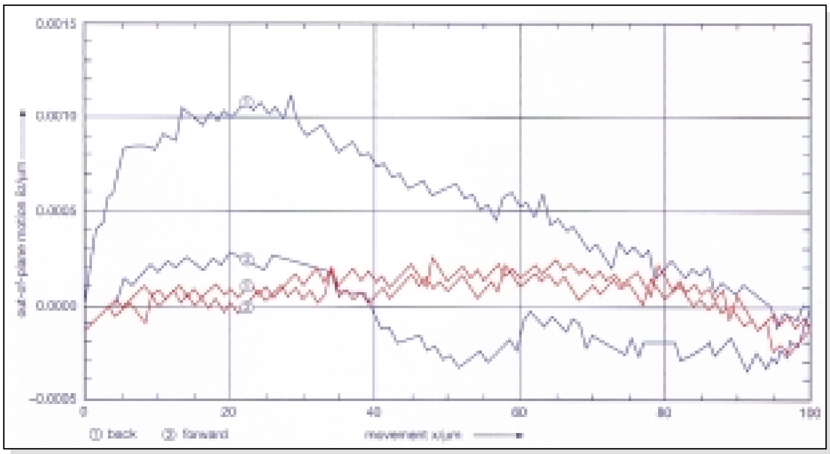


Figure 6 (below)
Single-axis, bi-directional trajectory control: passive (trace 1) and active (trace 2)

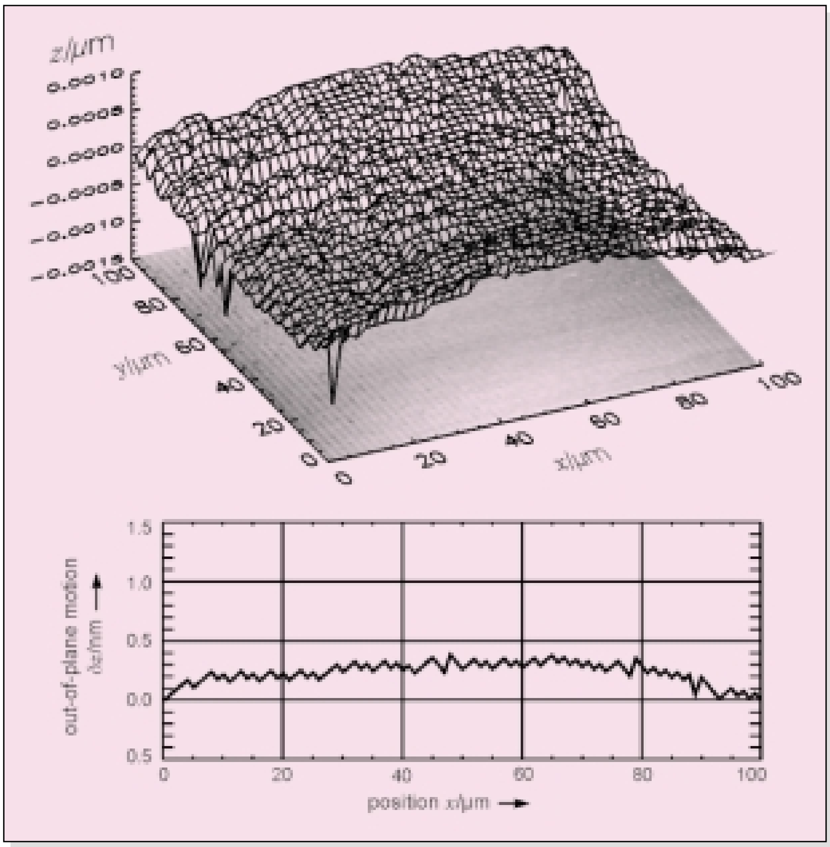


Figure 7 (bottom)
Out-of-plane motion(Z) over a 100 X 100µm scanning range

CONCLUSION

Moore's Law continues to be a fact of life in the semiconductor industry. Innovations in motion systems continue to keep pace with the technical needs of fabrication. In particular, the need for tighter trajectory control is addressed via novel application of accepted metrology and servo techniques. This facilitates a variety of leading-edge front-end fabrication and metrology applications, ranging from next-generation microlithography to sub-atomic-resolution scanned-probe microscopy.

REFERENCES

[1] X.Zhao, H. Marth, "Multi-Axis High Accuracy PZT Stage with Active Trajectory control", presented at Actuators 98.

[2] Jusko, Zhao, Wolff, Wilkening, " Design and three-dimensional calibrations of a measuring scanning tunneling microscope for metrological applications", Rev. Sci. Sinstrum., 65(8), 251491994).

[3] Rohrer, "STM: 10 years after", Proc. 6th Int. Conf. On STM, Interlaken, Switzerland, 1991.

[4] Zhao, "Hochaufloesende Dreidimensionale Positionierungbestimmung bei Rastersondenmikrosckopen mittels kapazitiver Afnehmer", Ptb-Bericht,PTB-f-20, ISSN 0179-0609, Braunschweig, 1995.

ABOUT THE AUTHOR

Scott Jordan is Director, Nanopositioning Technologies at Polytec PI, Inc. He has eighteen years of experience in the photonics, semiconductor and mass storage fields. His education spans physics (MS, Physics, University of California, Irvine, 1983) and high-tech business development (MBA, Finance and New Venture Management, University of Southern California, 1984). His career has included a range of product development, marketing, research and general management roles. He has led several high-tech endeavours to rapid growth through technical and market innovation and close partnership with customers and suppliers. His invention of micro-optical automated alignment techniques remains a significant contribution to ultra-precision process automation. Another was co-development of six-degree-of-freedom production test interferometry, and early work in laboratory and process automation tools. One focus for him at PI is to leverage the latest sub-nanometer and throughput-enhancement technologies in key applications such as head test and scanned-probe profiling. By addressing the overlooked "fourth dimension" – time – PI is focusing on key economic aspects of industrial implementation of NanoAutomation(tm) technologies.

IF YOU HAVE ANY ENQUIRIES REGARDING THE CONTENT OF THIS ARTICLE, PLEASE CONTACT:

Scott Jordan

Director

Nanopositioning Technologies

Polytec PI, Inc.

1342 Bell Avenue

Suite 3 A

Tustin, CA 92780

U.S.A

Tel: +1 (714) 850 1835

Fax: +1 (714) 850 1831

E-mail: info@polytecpi.com

scottj@ca.polytecpi.com

Web site: www.physikinstrumente.com

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