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Why Nanopositioning is More than Just Nanometers —or How to Find a State-of-the-Art System

By Stefan Vorndran

Nanopositioning is a key enabling technology in the important fields of nano-imprinting, scanning microscopy, microlithography and automated alignment. Since nanotechnology became a buzzword, many micropositioning devices have suddenly been upgraded to nanopositioning systems by the simple means of interpolation. However, what works in the microworld very often does not apply to the nanoworld.

This technote reports on recent advancements in nanopositioning technology, such as parallel kinematics, active trajectory control, new control algorithms for vibration suppression and tracking error elimination and their benefits for the user. In addition, the paper provides design engineers with a variety of key questions to ask motion system suppliers when shopping for a high-performance nanopositioning system.

Resolution: Calculated or Measured?

Resolution can mean different things to different people. When the term nanopositioning was coined, a number of clever companies advertised open-loop, stepper-driven leadscrew devices as "nanopositioners." The justification was as simple as one, two three: take leadscrew pitch of 0.4 mm, divide by 20,000 microsteps motor resolution and gearbox ratio 60 and out comes a device "capable" of 0.3 nm resolution. Nowadays, most design engineers don't fall for this simple equation anymore. While yesterday's stepper motor drives have been replaced by closed-loop systems, sometimes with direct-drive motors, manufacturers' claims often remain illusive, now backed up by "nanomath" simpler than before: resolution = encoder pitch divided by interpolation factor.

Yet, a nanopositioning system consists of a lot more than an encoder and interpolator circuit, and as long as friction is involved (and all sliding or rolling bearings produce friction), repeatable nanometer-range motion cannot be achieved in real world conditions (see Fig. 1 for frictionless solid state motion). In addition, guiding errors of the above-mentioned bearings often amount to 1000 times the distance of one nanometer—acceptable in the microworld, but not in the in nanoworld.

True nanopositioning devices provide frictionless motion, virtually instantaneous response, high linearity and stiffness, and trajectory control in the nanometer realm, all on top of sub-nanometer resolution. While conventional motion-control technologies are unable to meet these requirements, parallel advancements in the fields of solid state actuators, flexure design, multi-axis low-inertia parallel kinematics, active trajectory control and high-bandwidth controls engineering provide engineers in the fields of nanotechnology with the tools to solve their positioning, metrology, scanning or alignment problems.

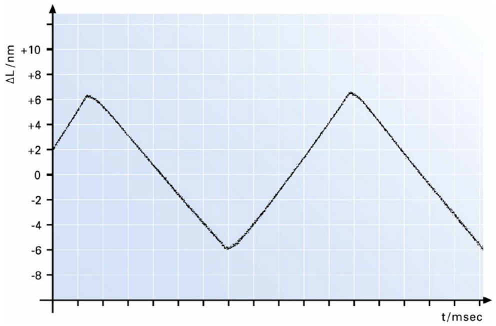

Fig. 1, Response of s frictionless solid state (open-loop) piezo actuator to a triangular drive signal. Only solid state PZT actuators are capable of producing smooth nanometer range motion like this, with instant response and no backlash. Note that the amplitude is only ±6 nanometers

On a spec sheet, many systems look alike. How can one tell a state-of-the-art nanopositioning system and a micropositioning system apart?

Precise Motion Needs Guidance, Not Friction

The first design rule in nanopositioning says friction has to be eliminated. This rules out all devices with ball, roller or sliding bearings, leaving air bearings and flexures. A flexure is a frictionless, stictionless hinge-like device that relies upon the elastic deformation (flexing) of a solid material to permit motion. Air bearings are ideal for long travel ranges, but they are usually bulky, high inertia and expensive to operate (clean air supply). They have another major disadvantage: they do not work in a vacuum, as required by an ever-increasing number of nanopositioning applications.

Flexures, on the other hand only work over short travel ranges, hardly a disadvantage in nanopositioning! Flexures (Fig. 2), if properly designed, are very stiff, provide trajectory control with excellent straightness and flatness, exhibit no wear and can be designed in multi-axis arrangements. They are also maintenance free and have no operating costs. These characteristics make flexures the guiding mechanism of choice in nanopositioning.

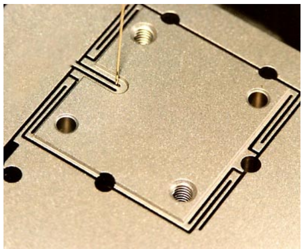

Fig 2. Single-axis nanopositioning stage with anti-arcuate-motion flexure design. The best flexure designs provide guiding precision in the low nanometer range. Active Trajectory Control can further improve guiding precision

What about Drives?
Again, any drive producing friction is not acceptable. Leadscrews, ballscrews, even ultrasonic linear piezo motor drives (friction based) can not surpass sub-micron precision. Electromagnetic linear motors, voice coil drives and solid state piezo actuators are the most commonly used frictionless drives. The first two are fine for larger distances, but have the disadvantages of magnetic fields (not tolerable in e-beam lithography and many other applications), heat generation and only moderate stiffness and acceleration, resulting in a low bandwidth.

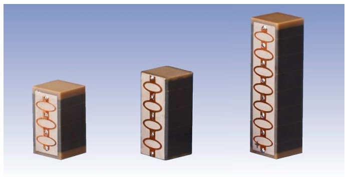

Fig. 3. State-of-the-art PZT actuators are ceramic-insulated rather than polymer-insulated. They offer extended lifetime, even under extreme conditions and exhibit no outgassing in vacuum applications.

Piezoelectric (Fig. 3) often called PZTs, are limited to small distances but are extremely stiff and achieve very high accelerations (up to 10,000 g), a prerequisite for millisecond or sub-millisecond step-and-settle and high scanning rates (today, the best piezo-driven flexure-guided stages have resonant frequencies of 10 kHz).
PZTs neither produce magnetic fields, nor are they influenced by them. A recent breakthrough in production technology now eliminates the need for polymer insulation, bringing the benefits of zero outgassing in vacuum applications, insensitivity to humidity and increased lifetime even under extreme conditions (Fig 4).

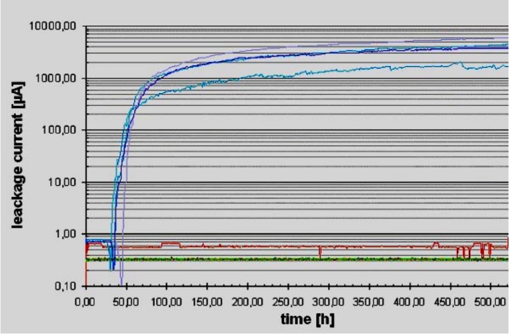

Fig. 4. PICMA Actuators with ceramic insulation (bottom curves) compared with conventional multilayer actuators with polymer insulation. PICMA Actuators are not affected by the high humidity test conditions.
Conventional Actuators exhibit increased leakage current after only a few hours. Leakage current is an indication of insulation quality and expected lifetime. Test conditions: U = 100 V DC , T = 25 °C, rel. humidity = 70%

Sensors: Direct or Indirect Motion Metrology?
Indirect motion metrology is cheap, but does not qualify for state-of-the-art nanopositioning. And of course, any sensor based on friction does not qualify either. Examples of indirect metrology are motor-mounted rotary encoders and piezo-resistive strain sensors mounted on actuators or flexures (measuring the strain of the flexures-thereby inducing friction and errors-instead of the motion).
High-performance nanopositioning systems employ non-contact direct metrology, placed to measure motion where it matters most to the application. Examples of direct metrology are capacitive sensors, laser interferometers and non-contact optical, incremental encoders.

Resolution or Linearity?
Incremental encoders are excellent for long-distance measurements. Most are based on a grating pitch of 20, 10 or, more recently, 2 µm. To get from there to the published 10 or 5 nm resolution, interpolation (with all its limitations) is required. While many encoders are very linear at multiples of the pitch, linearity at the nanometer scale can be as poor as 20% (Fig. 5) In addition, if not mounted coaxially with the drive, any tilt in the guiding system, as caused by motion reversal will further increase the error. What is often overlooked are the small forces induced by the moving cable of an encoder read-head which can cause friction and hysteresis on the order of several tens of nanometers. For true nanopositioning processes, requiring repeatable nanometer-scale step widths, there are better solutions.

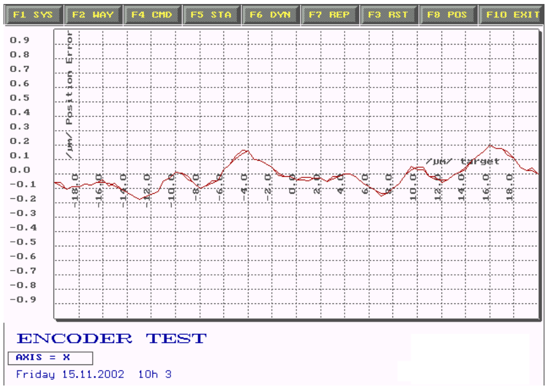

Fig 5, Linearity of high-resolution incremental linear encoders is excellent over long ranges, but often not what one might expect on a nanometer-scale. The above example shows errors of 100 nm and more over small distances (1 to 2 microns).

Laser interferometers are the accepted standard in position measurement. However, due to its operating principle, the output of a heterodyne interferometer is not perfectly linear. This nonlinearity is caused mainly by polarization ellipticity or nonorthogonality of the laser beams, and imperfections in the optics can further contribute to the nonlinearity. The best commercially available interferometers provide linearity of 2 to 5 nanometers, not good enough in some high-end nanopositioning applications (Fig. 6). Profound knowledge of interferometry and special equipment is required to get better performance out of an interferometer, either as a feedback or calibration device.

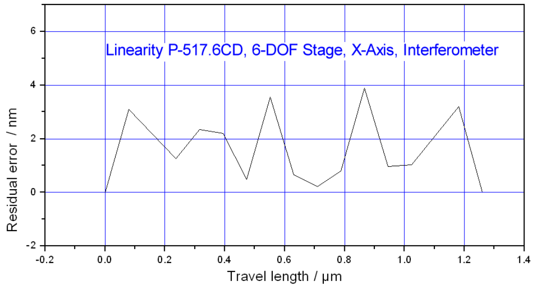

Fig 6. Linearity of a PI P-517 nanopositioning stage, position feedback provided by heterodyne interferometer

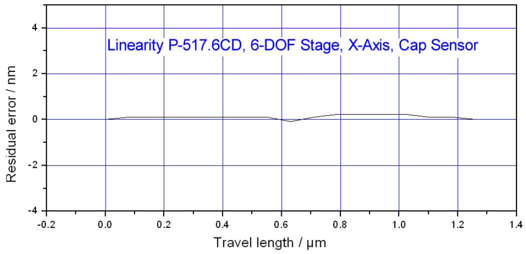

Fig 7. Same nanopositioning stage as in Fig. 6, but controlled with two-plate capacitive feedback

The highest performance is achieved with absolute-measuring, two-plate capacitive sensors (single electrode capacitive sensors are not well suited for nanopositioning). Working best over small ranges, they are a perfect match for flexure guided PZT drives. Capacitive sensors are very compact, vacuum compatible, insensitive to EMI and, if designed properly, provide extremely high linearity (Fig. 7a) with resolution of 0.1 nm and below. Due to the absolute measuring principle, no homing procedure is required and there is no bandwidth-limiting interpolator or counter circuit prone to "lose" motion in high-speed applications, or should ringing occur at the end of a fast step. High-end nanopositioning stages achieve bi-directional repeatability of 1 nanometer, an astonishing figure-, simple to put in a spec sheet but very hard to achieve and prove (Fig 7b) in the real world.

Measurement Device: Zygo Laserinterferometer ZMI2000

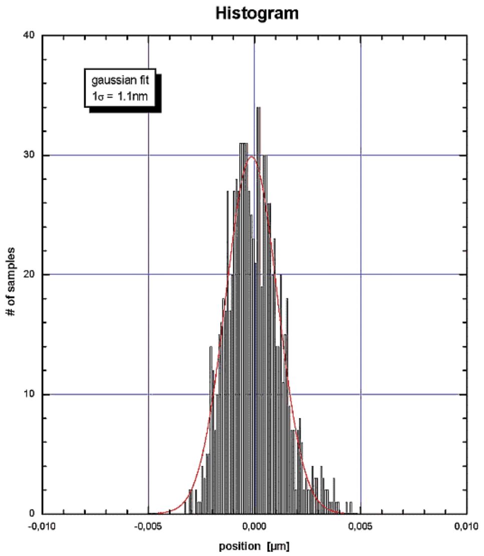

Fig 7b. Bi-directional repeatability of a state-of-the-art closed-loop piezo nanopositioning stage with direct motion metrology capacitive feedback, measured with state-of-the-art interferometer.

Accuracy or Speed?

In today's industrial production and testing processes, throughput and time matter more than ever before. In head/media test applications for example, subnanometer steps need to be performed and a new position needs to be reached and held stable to nanometer tolerances in a matter of milliseconds or less. Every millisecond shaved off the step-and-settle process is worth a large sum of money.

PZT drives can provide accelerations up to 10,000 g and respond to input in less than 0.1 msec, often more than the payload or the supporting structures are designed for. The ultrafast step time of the nanopositioning stage can excite vibrations in its load or neighboring components. To the application, it does not matter how fast the positioning stage can stop, but how fast the load reaches a stable position—a fact often overlooked. Conventional wisdom suggests that besides damping or waiting, there is not much that can be done about such vibrations occurring outside the positioning system's servo-loop.

Today, there is a new tool for eliminating structural resonances. A patented[i], real-time feedforward technology called InputShaping® (Fig. 8a, b) was developed based on research at the Massachusetts Institute of Technology and commercialized by Convolve, Inc., (New York, NY; http://www.convolve.com). InputShaping® eliminates motion-driven excitation of resonances throughout the system, including all fixturing and ancillary componentry. It is now an integrated option for the latest PI digital piezo nanopositioning controllers. InputShaping® does not require feedback and works with *a priori* knowledge of multiple resonances throughout the system. With InputShaping®, the time for a system reach a stable position is equal to $1/f_0$ where f_0 being the lowest resonant frequency contributing to instability in the mechanical setup.

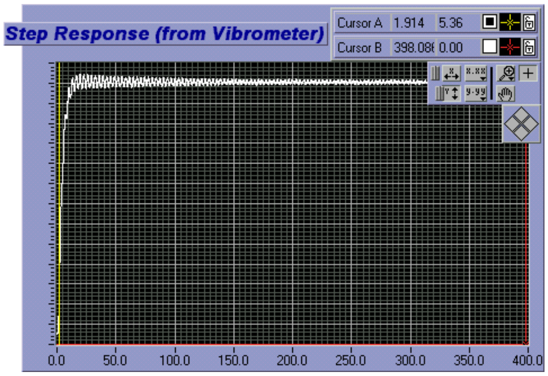

Fig 8 a. Piezo devices are capable of millisecond-scale step-and-settle. However, elements outside the servo-loop may ring (load, neighboring componentry,…). External resonances are visualized here by a Polytec laser vibrometer measuring position vs. time

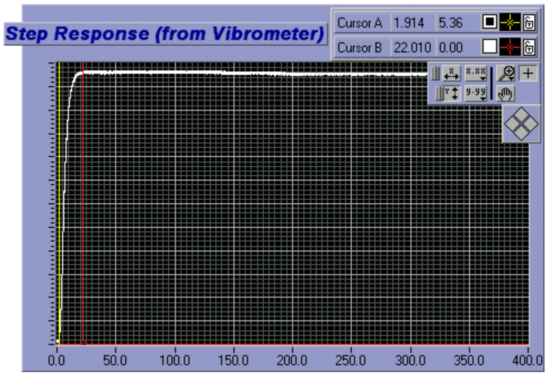

Fig 8 b. Input Shaping® eliminates motion-driven ringing of components outside the servo-loop. Settling after risetime completes by $t \sim F_{res}^{-1}$

Static or Dynamic Accuracy?

Resolution, linearity and accuracy are known to qualify the static performance of a motion system. However, in dynamic applications such as scanning or tracking, static specifications are meaningless. A common way to measure dynamic behavior is bandwidth. Bandwidth specifies the amplitude response of a system in the frequency domain. But static accuracy and bandwidth together still do not give any indication of a system's dynamic accuracy e.g. how straight the lines in a scanning application will be or how far off the expected positions they lie.

To qualify a system in these applications, target data and actual position data for a given waveform have to be recorded and evaluated. The difference is called following error or tracking error. In conventional PZT nanopositioning systems with PID servo-control designs, the tracking error can reach double-digit percentage values even at scanning rates below 10 Hz, and increases with frequency.

It is important to understand, that in dynamic nanopositioning applications the tracking error is a key parameter. Recent advances in digital controller design at PI have led to sophisticated adaptive digital linearization methods, reducing dynamic errors in repetitive waveforms from the micron realm to indiscernible levels, even with high-frequency dynamic actuation under load (Fig 9a, and 9b).

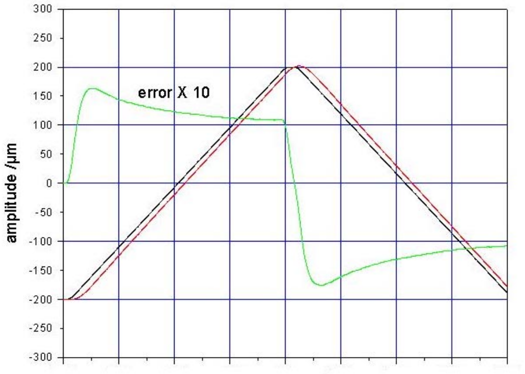

Fig. 9a Conventional PID controller, PZT nanopositioning system, response to a triangular scan signal. Blue: target position; red: actual position; green: tracking error (10X for better visibility).

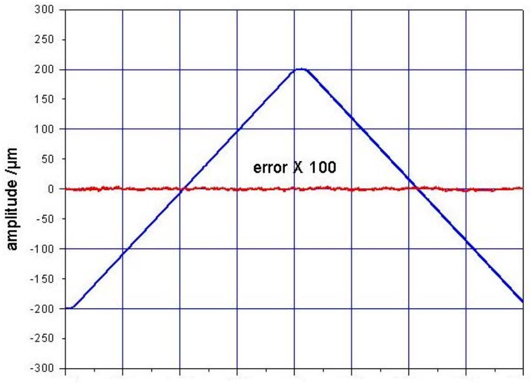

Fig. 9b. Same nanopositioning system, adaptive digital linearization. Blue: target position and actual position (virtually the same). Red: tracking error (100X for better visibility) is reduced by several orders of magnitude.

Serial or Parallel Kinematics?

In high-speed nanopositioning applications, such as scanning microscopy, small areas need to be scanned in two dimensions, with a 3rd axis to be controlled by an external input (e.g. the force in AFM's or current in ATM's). Subnanometer line spacing and scanning rates of hundreds of Hz are desirable in these applications. The only feasible way to achieve this is with parallel-kinematics, multi-axis closed-loop piezo-driven flexure stages.

Rather than stacking single-axis subassemblies, parallel-kinematics stages are monolithic, with actuators operating on a central, moving platform in parallel (Fig. 10a). Not only does this significantly reduce inertia, but yields identical resonant frequencies and dynamic behavior in both the X and Y directions. Alternative, stacked assemblies *always* result in different X vs. Y behavior (though published specifications sometimes fail to reflect this basic physical fact). The consistent X vs. Y dynamic behavior is desirable for accurate and responsive scanning and tracking performance. The use of capacitive sensors to measure the monolithic moving platform means that the orthogonal axes automatically compensate for each other's runout and crosstalk (active trajectory control, or multi-axis direct metrology), whereas with serial kinematics, runout errors of the individual axes accumulate. For example, tilt errors of only ±10 µrad caused by the bottom platform of a hypothetical-4 inch multi-axis stack of stages result in a 2 µm linear error at the top platform. Other shortcomings of serial kinematics in nanopositioning are high-inertia, higher center of gravity, and up to 5 moving cables causing friction and hysteresis (Fig. 8b).

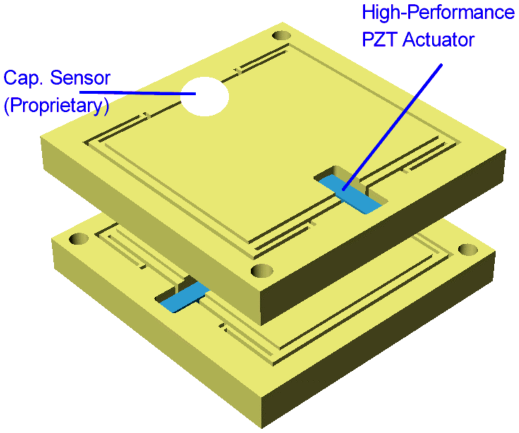

Fig 10a. Stacked serial-kinematics two-axis nanopositioning stages have significantly higher inertia, higher center of gravity and cannot correct for off-axis errors. Moving cables of the top platform induce friction and cause hysteresis.

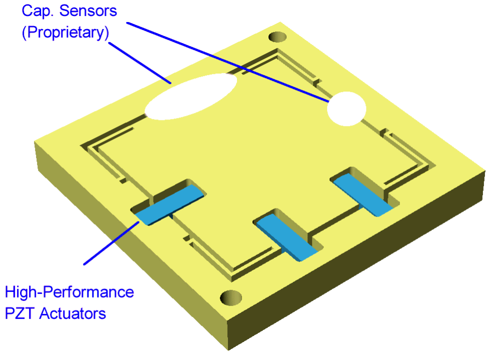

Fig. 10b, basic design of a monolithic 3 DOF (X,Y, Theta-Z) parallel-kinematics nanopositioning stage with PZT drives and wire-EDM-cut flexures. Capacitive position sensors (not shown) directly measure the central moving platform compensating for the slightest off-axis motion in real time (active trajectory control). This is not possible with serial kinematics designs, as shown in Fig. 10a

State-of-the-art nanometer scanning systems based on parallel kinematics control all 6 degrees of freedom automatically compensating for unwanted out-of-plane motion as well as unwanted rotational errors.

Fig 11a. State-of-the-art 6 axis digital controller and custom Super Invar 6D piezo scanning stage (parallel-kinematics mechanics and parallel motion metrology).

This requires parallel motion metrology and a digital controller capable of coordinate transformation (Fig. 11a). The result, a 100 x 100 µm scan with flatness /straightness of 1 nm is shown in Fig. 11b.

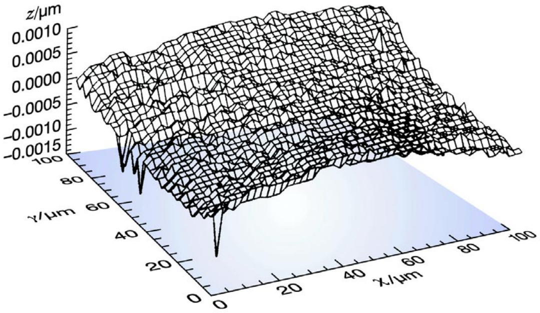

Fig 11b. 6 DOF PZT flexure nanopositioning stage with multi-axis parallel direct motion metrology provides instantaneous information on any parasitic to the digital controller for real-time compensation. The excellent results, 1 nm flatness and straightness, are epicted in this 100 x 100 µm scan.

Best Specs or Best Performance?

The above discussion shows that quantifying the performance of a nanopositioning system can be very complex. To find the highest performing nanopositioning system for an application (not the one with the best specs on paper), the user has to engage in a dialog with the manufacturer and ask the questions relevant to his or her application. When the answers sound too good to be true, they usually are. In addition to posing the relevant questions, it is always worth while to find out how long a manufacturer has been involved in nanopositioning, what quality control system is in place, how specifications have been measured, and what equipment was used.

What Can Be Learned from the Telecom Crash

In the aftermath of the telecom crash, analysts and investors are looking for new promising markets, and nanotechnology seems to be one of them. This is why we will see new companies trying to make a fortune in this field. Start-ups, claiming to have revolutionary nanopositioning solutions, will lure investors into providing them with millions of dollars. Let's not forget that in telecom more than 99% of the revolutionary concepts and ideas soon proved worthless. The real challenge lies not in the concept, but in production, yield and consistent quality, where delivered unit after delivered unit performs as well as the gently assembled prototype, fine-tuned by the chief engineer.

Because nanopositioning is not as simple as one, two three, only companies with experienced, well-equipped design *and* production teams, and proven quality control systems will be able to satisfy the ever-growing demands of the market. Their product specifications may not always seem revolutionary, but will hold up in the application environment.

Ref:

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