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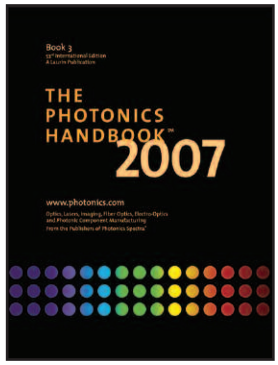

Nanopositioning:

Keeping Pace

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Nanopositioning has enjoyed a blistering rate of innovation, both in new technologies and in rapidly advancing applications. The available array of powerful new technologies is good news for customers, but close partnership between engineer and vendor has never been more important.

Choosing the right nanopositioning system means, ideally, that the vendor understands the complete application, ranging from specifications for resolution, accuracy, travel and throughput to the development environment, interfacing and synchronization needs. And of course cost metrics, which include not only purchase price but cost-of-ownership, should be considered. Deeply functional, well-documented and robust software support libraries are increasingly important to access advanced functionalities, reduce support costs and compress time to market. Custom solutions are often required, and the vendor's wherewithal, technical depth, global support capabilities, adherence to international quality standards and organizational stability are key to successful long-term partnerships.

Increasingly, dynamic issues dominate applications, with novel approaches which benefit real-time/high-dynamic applications. These present new opportunities for optimizing process economics.

Traditional actuation approaches for nanopositioning include leadscrews, flexure reduction mechanisms, voice coil actuators and piezoelectric transducers. Of these, for applications that require translation of up to 1 mm with precision down to the subnanometer range, piezoelectric transducers engineered specifically for nanopositioning offer the optimum mix of performance, cost, size, speed, static and dynamic accuracy and reliability for drivetrain actuation. Mechanisms based on actuation techniques such as hybrid piezo drives have extended nanopositioning into travel regimes of many millimeters.

Jacques and Pierre Curie, finding that pressure applied to a quartz crystal produced an electrical charge, discovered the piezo effect more than 100 years ago. Today's nanopositioning devices capitalize on the inverse effect, using a voltage to provide motion via material expansion. Most such devices use a polarized ferroelectric ceramic material made from lead, zirconium and titanium. Consequently, they are often called piezoelectric transducers, or PZTs — an acronym which reflects their chemical constituents (see sidebar).

The benefits of piezo-based devices include:

- Unlimited resolution: Positioning increments well below 1 nm are possible. However, precision performance requires carefully designed and manufactured mechanisms; otherwise incremental motion can be limited by stick-slip effects, mechanical losses, parasitic motion errors, and suboptimal metrology implementation.
- Fast expansion and response (microsecond time constants).
- Maintenance-free, solid-state construction that reduces wear and eliminates scheduled maintenance, lubrication or adjustment even with heavy usage.
- High efficiency: Electrically, piezoelectric elements resemble capacitors, in that energy is absorbed only to perform movement, not to maintain position.
- Inherent vacuum-compatibility (especially for the newest ceramic-encapsulated piezo stacks).
- High throughput and dynamic accuracy, especially when newer controls technologies are leveraged.
- Finally, piezoelectric technology has been applied in new mechanisms that provide many millimeters of travel while maintaining subnanometer resolution.

To reduce the voltage needed to achieve useful expansion travel, piezoelectric actuators are constructed of many layers sandwiched between electrodes. Piezoelectric stack actuators remained essentially unchanged for decades. Their sandwich structure is similar to that of ceramic capacitors

Figure 1. *Ceramic-encapsulated piezoelectric actuators provide longer lifetime and are vacuum compatible.*

— and like capacitors they have proven to be very reliable. However, exposure to moisture or humidity can reduce their lifetime. Polymer coatings help, and were adopted by all nanomechanisms manufacturers. But polymer coatings also trap moisture, leading to damage. Polymer coatings are not vacuum-compatible, and can limit dynamic actuation capabilities. And it's difficult to repeatably, reliably and stably affix feedback sensors such as piezoresistive strain sensors unless the coating is breached.

Industrial reliability

Although polymer coatings were known to be suboptimal, there was little impetus to develop an alternative. Then, with the advent of high-duty-cycle, high-dynamic, uptime-critical industrial applications, traditional encapsulation began proving inadequate to protect sensitive mechanisms. High-dynamic industrial applications often resulted in heating which could be problematic for polymer coatings, and nanopositioning was increasingly important in vacuum applications such as e-beam lithography and microscopy.

Consequently, all-ceramic piezo actuators were introduced (Figure 1), winning a Photonics Circle of Excellence Award for 2004 as one of the 25 most technically innovative new products of the year, based upon a peer review by members of the *Photonics Spectra* editorial advisory board, a panel of recognized experts in the industry. The novel use of cofired ceramic encapsulation makes these actuators several orders of magnitude more impervious to humidity, greatly improving the reliability of devices based on them, especially when used in challenging environments.

The all-ceramic construction is inherently vacuum-compatible, and the stable, flat and hard outer surface is ideal for sensor application. At the same time, the configuration allowed optimization of stiffness, capacitance, displacement, thermal dynamics, electrode configuration and other material parameters. Ceramic-encapsulated piezo stacks are measurably superior to traditional stacks in industrial applications and high-endurance situations, where they show substantially longer lifetimes both in static and dynamic operation in the presence of humidity. A high Curie temperature of 320 °C gives these stack actuators a temperature range extending to 150 °C, so they can be operated in hotter environments, baked for high-vacuum compatibility, or driven harder and faster in dynamic operation.

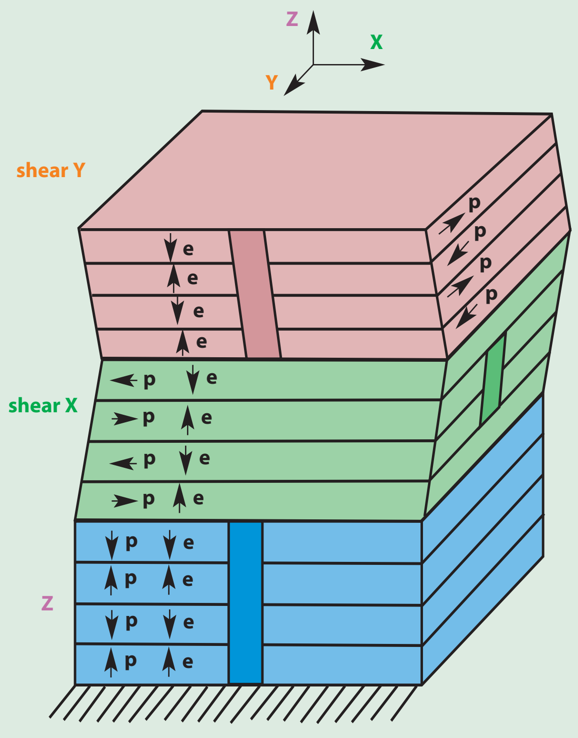


Figure 2. *By combining shear-mode piezo layers with longitudinal layers, the basic element of a novel high-force linear motor capable of millimeters of travel with subnanometer resolution is constructed.*

Long-travel technologies

So far our discussion has centered on stacked actuators where the layers all actuate longitudinally when a voltage is applied, lengthening the stack and providing positioning control well below 1 nm. But layers can also be configured to actuate in shear mode, conferring in-plane motion.

By combining shear-mode layers with longitudinal-mode layers, the basic element of another significant new mechanism is constructed (Figure 2). Groups of these elements are preloaded in arrays about a central rod. A digital controller sequences their operation, providing high-force, long travel step-mode actuation plus picometer resolution fine high-bandwidth actuation. They are inherently vacuum-compatible and provide nanoscale power-off position stability for months and years. Standard designs provide forces to 600 N, resolution to 50 pm and travel to 20 mm. This combination of high force, high resolution, stability and long travel is proving to be an enabling technology for a wide variety of microlithographic, nanoimprint and astronomy applications requiring high force, high stiffness, high stability and picometer resolution over millimeters of travel.

Another use of piezo ceramics technology is in ultrasonic piezo motors. These are not stacked structures but instead are composed of monolithic slabs of piezo ceramic which are used to drive standing waves in the substrate at frequencies of tens to hundreds of kilohertz. A hardened contact-point, or finger, attached at a resonant node-point is thereby made to oscillate in a quasi-elliptical fashion; when preloaded against a slide, this confers linear motion. These piezomotor implementations (Figure 3) achieve up to 800 mm/sec velocity over unlimited travel ranges using this approach while providing submicron resolutions.

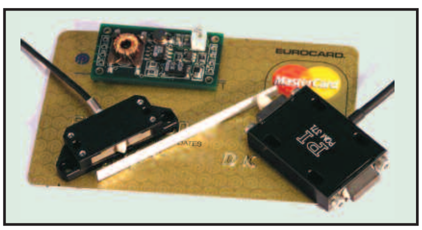


Figure 3. *Examples of ultrasonic piezo motors.*

Nanopositioning goes hybrid

It has always been possible to construct a coarse/fine long-travel assembly by putting a piezo stage on top of a motorized positioner. However, the repeatability of such a mechanism is only as good as the repeatability of the coarse stage. New controller technologies have made it possible to devise hybrid nanopositioning systems employing both PZTs and DC-servomotor drives. These systems combine the piezoelectric properties of unlimited resolution and very fast response with the long travel ranges and high holding forces of a servomotor/ballscrew arrangement. A highly specialized hybrid controller reads the stage position from an integrated, nanometer-class linear encoder and continuously actuates both the piezoelectric and servomotor drives in a way to provide the best possible overall performance. The control loops are automatically coordinated and decoupled so that the servomotor and piezo drives do not mutually cancel out their actions. The result is a fast, long-travel system with extraordinary repeatability as well as resolution.

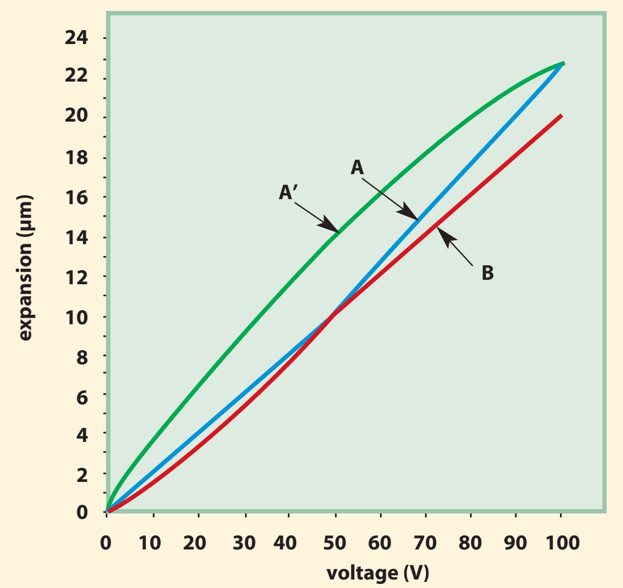


Figure 4a. *Closed-loop (B) position control eliminates hysteresis of open-loop piezoelectric actuators (A, A´).*

Open vs. closed loop

Achieving nanometer and subnanometer precision requires more than a piezo actuated stage capable of making moves on this precision scale. The stage internal metrology system must also be capable of measuring motion on the nanometer scale. The primary characteristics to consider when selecting a stage metrology system are linearity, sensitivity (resolution), stability, bandwidth and cost. Other factors include the ability to measure the moving platform directly and contact vs. noncontact measurement.

Without feedback control, PZTs — like all motive technologies on the nanometer scale — exhibit hysteresis. That means their open-loop response to an applied voltage depends on the prior movement history. Changing the applied voltage from 25 to 50 V will not result in precisely the same position as when reducing the voltage from 75 to 50 V (Figure 4a). In many applications this is not a problem, or some external loop (such as an image's degree of focus) can be used to close the loop and achieve the desired accuracy. In other mechanisms, a built-in sensor powers a closed-loop control system to improve linearity, repeatability and responsiveness (Figure 4b), further leveraging the inherent resolution and responsiveness of piezos.

Four types of sensors are mostly used in nanopositioning applications — capacitive, strain, LVDT and linear encoders.

A linear variable differential transformer (LVDT) consists of a hollow cylindrical shaft inside which the position cylinder slides. The outer cylinder contains a primary coil and two secondary coils on either side. Position cylinder movements are detected as changes in the induced voltage in the secondary coils. The analog output is quite sensitive, easily providing submicron resolutions, and it has the advantage of being noncontact. LVDTs provide absolute position metrology, meaning no initialization is necessary on power-up to determine a zero position. However, they generally cannot be used for resolutions better than a few nanometers.

Linear encoders are familiar devices for position feedback and their resolution enters the nanometer realm. Traditional linear encoders use optical or magnetic scales and readhead elements. Optical units function by observing the first-order diffraction between a scale composed of finely pitched lines or facets and a similar moving reticle. By nanopositioning standards, the period of the scale is often fairly gross, typically several to several dozen microns for moiré scale or holographic encoders.

Position is determined by counting fringe transitions and interpolating between adjacent peaks. Signal-to-noise levels limit even the best encoder systems to the nanometer region, but travel ranges of hundreds of millimeters are possible. Guidance remains a concern: stiction effects limit the effective minimum incremental motion of even the best mechanical bearing systems in long-travel stages. Conversely, stability issues, top speed, size, cost and stiffness limit air-bearing systems' applicability. For these reasons, stack-based nanopositioning systems are generally guided by flexures, which are stictionless yet highly stable and stiff, but with travels limited to the millimeter region and below.

In addition, encoders suffer from cyclic or subdivisional errors, both optical and electronic. This can lead to repeatable results whose inaccuracy varies quasi-sinusoidally with

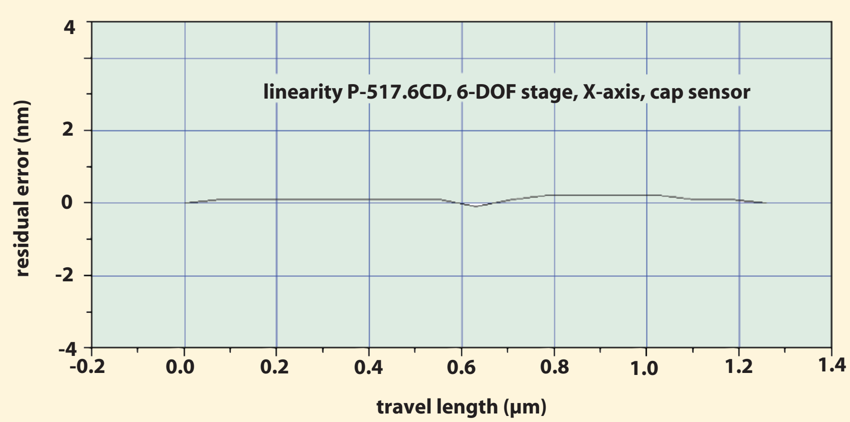


Figure 4b. *A digitally controlled nanopositioning stage with capacitive direct metrology feedback achieves linearity at the nanometer level.*

position. Encoders most commonly provide relative (not absolute) position metrology, meaning the coordinate system must be re-established at each initialization by seeking a reference switch of some sort. The day-to-day repeatability of such a system is only as good as the reference sensing technique.

Cost-effective strain gauges (and the very similar piezoresistive sensors, popular in entry-level mechanisms) use films whose electrical characteristics change with strain. These devices are usually attached to the piezo stack itself, or possibly to a structural element of the stage. Consequently they serve as drivetrain-input metrology rather than direct-motion metrology of the moving platform of the stage. Nevertheless, these are popular and effective position-metrology elements in closed-loop systems. They can provide high sensitivity, are compact, and are adequate for positioning to subnanometer levels. Like LVDTs, they provide absolute position measurement, require no initialization, and can be acceptably stable if good signal conditioning approaches are implemented. Good implementations incorporate multiple sensors and bridge circuits to compensate for thermal changes. But care must be taken when designing them into a mechanism. If there are elastic or frictional elements in the path between the point of motion and the point of measurement, errors will result. Physically small sensors (such as piezoresistive sensors) measure only a highly localized region's strain, from which the overall mechanism's motion must be inferred. And these sensors cannot be configured to compensate for orthogonal (parasitic) errors in multiaxis configurations — only parallel metrology of the actual moving platform can provide this valuable capability.

Interferometry also can be used to measure sample position and provide a feedback control signal. Such systems offer extremely high accuracy and are noncontact, although bulky specialized optics must be mounted onto the moving and stationary elements of the motion system, and safety provisions for beam blockages and eye safety must be considered. Interferometers can be deployed in vacuum systems by feeding laser light through a window or fiber. Some interferometers can provide subnanometer resolution, though cyclic inaccuracy can be noted in some units.

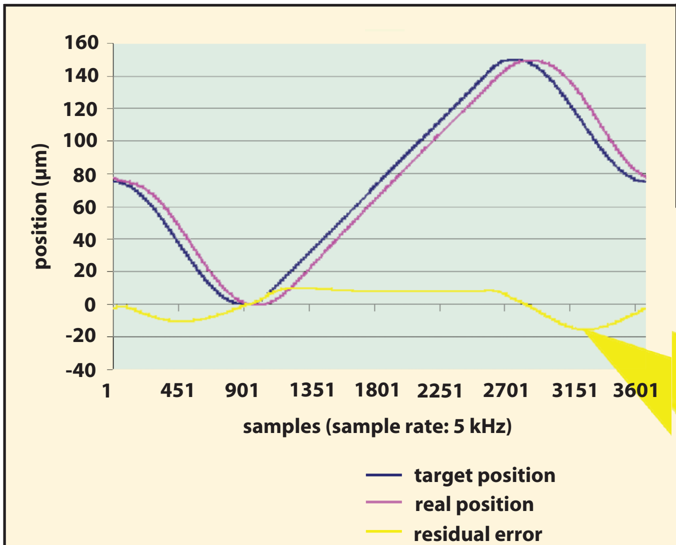
Because interferometers use air as their working fluid, they can be sensitive to environmental factors (temperature, barometric pressure, humidity, trace gas concentration and acoustic perturbations). Interferometry tends to be costly, and drift can be problematic, particularly for lower-cost units. Available interferometers are also relative position devices that must be initialized at a repeatable zero position determined by some other metrology incorporated into the motion system.

Capacitive sensors have emerged as the default choice for many nanopositioning applications. They are extremely accurate, ultrahigh-resolution devices for determining absolute position over ranges of hundreds of microns or even millimeters. The device's positioning motions varies the distance between two nano-machined capacitor plates, providing a sensitive and drift-free positional feedback signal when stimulated by a precision AC carrier. No "home switch" is needed, so day-to-day repeatability is superb.

The best examples of these sensors offer high bandwidth with high precision. They are noncontact and are usually packaged to measure drivetrain output (direct metrology) — eliminating errors otherwise imposed by intervening mechanisms. The physical characteristics of capacitive sensors make them ideal for multiaxis parallel kinematics approaches, where a single monolithic moving platform is actuated simultaneously (and measured simultaneously) in several degrees of freedom. This allows active compensation of parasitic errors, which cannot be achieved with stacks of discrete axes. In addition, parallel kinematics facilitates more compact packaging, greater mechanical rigidity, higher throughput and greater dynamic accuracy in real-time applications. Meanwhile the single-frequency stimulation of capacitance sensors is inherently resistant to external noise sources.

Active optic mounts

Piezoelectric devices lend themselves well to linear or tip/tilt mechanisms and multiaxis configurations



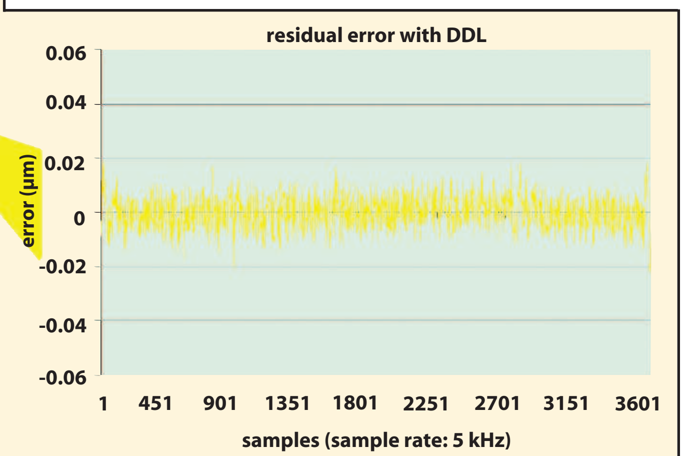


Figure 5. *Digital dynamic linearization (DDL) can reduce residual error of a dynamically driven nanopositioning system by up to 1000 percent.*

combining multiple linear and rotary degrees of freedom. In linear stage or actuator application, they can achieve resolutions well below 1 nm, and in rotary and tip/tilt applications, resolutions surpassing 1/100 arc sec.

Compact piezo-actuated active optic mounts are available with multiple degrees of optical deflection. Two-axis, parallel-kinematic piezo mounts offer gimbal-style actuation with coplanar rotational axes, a significant advantage vs. the separate orthogonal mechanisms that are often required of galvanometer-driven approaches that also bring about the drawback of polarization rotation. Compared to galvos and voice-coil systems, piezo-driven active optic mounts are typically more compact, fieldless, faster, inherently stiffer, and more predictable when power is cut. Lower current requirements mean reduced ohmic losses and heat production, and cabling is thinner and more tractable. Piezos' flat Bodé curve means higher responsiveness through more of their dynamic range than is often possible with alternative drives.

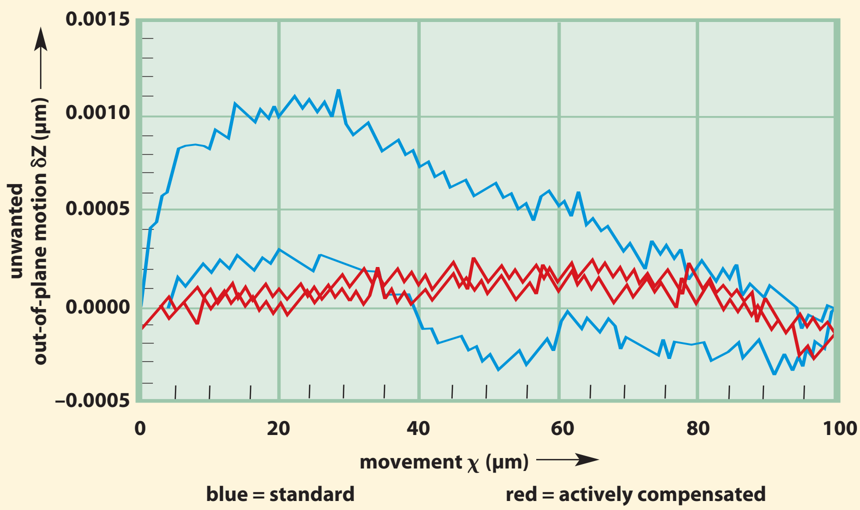


Figure 6. *Out-of-plane motion in nanopositioning systems can be reduced to Angstrom levels with active trajectory control, based on capacitive direct metrology feeback.*

How PZTs Work

Physically, a linear piezo actuator consists of a series of stacked cylindrical PZT ceramic elements (Figure 8). The cross section is usually either square or circular. Each disc has metal contacts for the application of a voltage parallel to the direction of polarization. The ceramic is formulated to present an electrostatic dipole moment on the molecular scale. The applied electric field exerts torque on the dipoles, causing a change in the length of the monocrystalline regions. This causes the stack to expand and contract (or, per Figure 2, shear) in approximate proportion to the applied voltage, allowing control of position to subatomic precisions.

Most piezo actuators are designed to provide motion ranges of 5 to 300 μm. This range is determined by the composition, length of the material, maximum applied voltage and other factors. Typical PZTs feature a 0.13 percent strain, meaning a 100-mm-long stack can expand to 130 μm when the maximum allowable voltage is applied.

The basic piezo actuator stack is the heart of the nanopositioning stage. High-precision, stiction-free flexure lever amplification and guidance mechanisms allow stage travels to 1 mm. Stiction, looseness, rigidities and guidance quality all factor heavily in the device's overall performance and require meticulous and highly specialized design and manufacturing skills. For reproducible nanometer-scale accuracy and reliability in industrial-class applications, extraordinary mechanical quality must be maintained throughout the mechanism.

However, stage design and construction quality can vary greatly, particularly in multiaxis designs where traditional stacking and nesting techniques can compromise performance and throughput. Caution dictates evaluating all aspects of performance, such as out-of-plane motion, step/settle response and EMI immunity, rather than just relying on manufacturers' specifications.

Piezos: fast and precise

If very rapid movements are needed, piezoelectric devices are often the only solution. Piezoceramic positioning devices can have bandwidths of tens of kilohertz or more, and they lack the responsiveness-limiting inertia of leadscrews and other conventional mechanisms.

Unfortunately, advancing resolution needs in industry and research are physically at cross-purposes to advancing speed needs. In this way, applications' increasing need-for-speed coupled with unabated pressure on resolution capabilities exposed fundamental physical limitations of traditional nanopositioning technologies, especially for controls:

• Electronic bandwidths, limited by amplifier, sensor and servo-processing capabilities, cause "rounding of corners" in motion-waveform generation, phase-lags, and nonlinearities in high-dynamic applications.

• Mechanical stiffness, characterized by the lowest resonant frequency (F_{res}) of the mechanism, limits the accurate controllability of a mechanism in high-dynamic applications.

Traditional approaches to improving matters include using higher-power amplifiers, faster servo update rates, stiffer materials, and so on. However, these merely push the margins

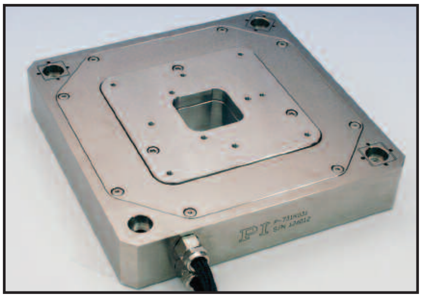


Figure 7. *A six-axis nanopositioning stage with active trajectory control, made from super invar. These types of stages can provide subnanometer resolution and straightness/flatness of travel in the subnanometer range.*

of system performance back incrementally, and sometimes with a very poor cost/benefit ratio. In addition, applications requiring varying loads often force compromises, such as servo settings which are safe for all intended loads but optimum for none.

There are additional error mechanisms that come into play when nanopositioning mechanisms are actuated rapidly in motion waveforms:

Observable resonance

• Actuation profiles which contain Fourier components near F_{res} will result in resonant amplification and possible runaway.

System roll-off and servo lag

• Finite electronic bandwidth in the servo controller and amplifier results in roll-off of high frequency components of the desired motion waveform.

• When F_{res} is on the order of motion waveform components of interest, this can provide additional roll-off behavior on either side of F_{res}.

• The error-driven nature of feedback-based servos imparts a lag between command input and motion output. Combined with frequency-dependent roll-off, this can distort the motion waveform output, shifting it in time and rounding fine features undesirably.

• Propagation delays in some digital implementations can impart additional lags between command and motion.

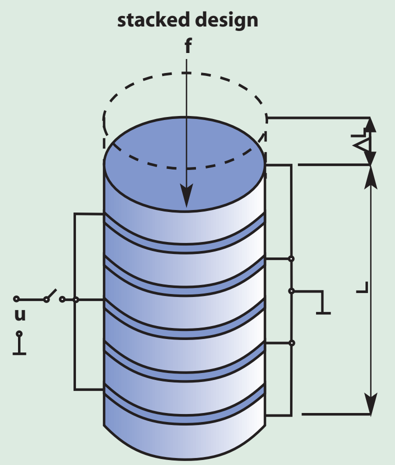
Unobservable resonances

• F_{res} generally refers to the primary resonance of the device, but other resonances can certainly exist in any motion system, especially when external componentry is considered, such as the stage's load, mounting structure and neighboring components — all of which can be driven to ringing by recoil forces in rapid actuation.

Optimizing the mechanics

Obviously, the stiffer the mechanics, the crisper their responsiveness to motion commands: F_{res} rises, and roll-off is pushed to the right in the system's Bodé plot, improving dynamic accuracy.

A highly effective technique for raising F_{res} while simultaneously addressing parasitic motions in multiaxis systems is to "attack the stack," replacing the traditional design approach of using bolted together or nested layers of single-axis mechanisms with a single moving element actuated and monitored by parallel arrays of actuators and sensors. This approach, parallel kinematics, reduces the actuated mass while improving stiffness. Thus both parameters in the Hookes equation for resonance are optimized. A key advantage is seen in the improved runout performance when any given axis is actuated: the other axes will actively cancel unwanted parasitic motions, resulting in truer trajectories and automatic compensation for loads and external forces which might otherwise deflect the mechanism. Parallel-kinematic stages providing two to six degrees of freedom are offered. Systems offering four or more degrees of freedom usually feature digital controllers which automatically perform coordinate-system transformations so the user can work with familiar units and Cartesian conventions.



$$\Delta L = d_{33} \times n \times u$$

where d = charge constant (meters per volt) and n = number of wafers in stack

Figure 8. *Linear piezo actuators are typically built from thin, stacked PZT layers.*

There are a host of other considerations in the motion device design which can impact stiffness. For example, travel and form factor requirements may necessitate lever amplification. Lever amplifiers influence stiffness in motion direction of a nanopositioner; stiffness coefficient diminishes with the square of the lever amplification ratio. The effective stiffness of the mechanism is also impacted by mounting considerations by the user. For the load, the moment arm of the center of mass with respect to the symmetry axis of the motion device's platform should be kept as short as possible. In rapid actuation, CG offsets above or to the side of the symmetry axis can excite pitch and yaw moments, respectively; dynamic accuracy can actually be improved by counterbalancing in these situations, even if this means adding mass. And certainly the mounting hardware should be as rigid as possible; stiffnesses "add" as a sum of quotients.

Optimizing the controls

Conventionally, the various roll-off and lags presented by servo controls, amplifiers and feedback mechanisms can be incrementally improved by selecting higher-power amplifiers, faster servo update rates, and so on. However, these efforts pay diminishing returns and fail to address the root-cause physics of dynamic inaccuracies. Fortunately, recent technical developments present a selection of tools which can improve matters.

Downloadable servo parameters: Digital controllers allow virtually instant download of servo parameters for different loads, rather than forcing the user to deploy a lowest-common-denominator parameter set for safe (but suboptimal) operation with all anticipated loads.

Notch filters: Resonant amplification at F_{res} (and roll-off to either side of it, as is often seen) can be addressed via a notch filter in the controller. Amazingly, not all piezo controllers have notch filters, necessitating softer servo settings to eliminate the risk of oscillation and runaway. Softer settings mean poorer dynamic accuracy.

Simple feedforward: This technique, popular with motor controllers, involves injecting a portion of the command signal directly to the amplifier, bypassing the servo. Since piezo devices operate in the 0th derivative of position, this technique is more problematic than is the case with servomotors, which operate in the 1st derivative. Dynamic accuracy can be reduced in simplistic implementations.

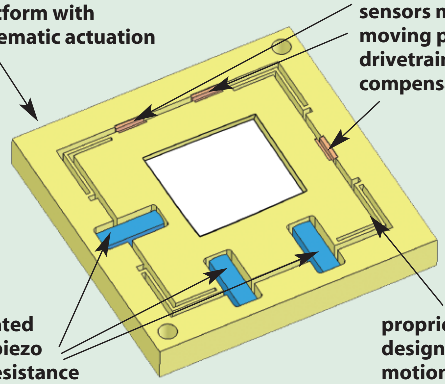


Figure 9. *Nanopositioning stages with capacitive sensors for high resolution, bandwidth and stability enable applications such as nanometrology or optical trapping. Parallel-kinematics/parallel-metrology designs offer superior motion fidelity by positioning and measuring a single platform using multiple actuators and sensors against the same stationary reference.*

Digital dynamic linearization (DDL): This control technique integrates an internal algorithm into the metrology and servo logic; this optimizes the internal command generated for a repetitive waveform according to the error signal that is detected with the internal sensor. It is the latest advancement for improving dynamic accuracy. It was originally deployed in a precision automotive machining application in the 1990s, as a patented off-line technology called Signal Preshaping, where it provided the bandwidth enhancement necessary to machine advanced non-cylindrical pistons at economically acceptable lathe spin speeds. A fully automatic, fully internalized implementation, DDL shipped in 2002. A brief, automatic self-configuration is commanded by the user (or, previously saved optimizations may be reloaded) when changes in motion parameters, desired waveform or loading occur. After this, following errors are reduced to approximately the noise level of the system. Figure 5 shows a test performed with and without DDL. In this test, the following error is reduced from up to 10 µm to 15 nm or less.

Input Shaping: In many applications, fast actuation of the nanopositioning stage causes its load and neighboring components to ring with their characteristic resonant frequencies. These oscillations may not be observable by the motion feedback sensor, so finessing servo parameters is of limited utility. Input Shaping is a patented time-domain feedforward technique which nullifies these unobservable, motion-driven resonances to improve system dynamic accuracy. The systems integrator first quantifies the frequency of the vibrations (often this falls out of the system's work product); the controller is then informed of these by downloading a real-time parameter set into nonvolatile RAM. From that point on, no commanded motion will excite the resonances. The technique accommodates multiple resonances, nonorthogonal resonances which trade energy between themselves, and any degree of damping.

Energy recovery: A novel type of amplifier was developed for high-force/high-dynamic applications utilizing piezo actuators of large capacitance. This amplifier design integrates unique energy-recovery technology and pulse width modulation. Instead of dissipating the reactive power in the heat sinks, charge is recovered so that only the active power used by the piezo actuator has to be supplied. During discharge of the actuator, the energy not used is returned and reused to supply the amplifier. Production versions of this amplifier can output and sink a peak power of 2 kW.

DAC resolution enhancement: Piezo expansion is approximately proportional to the applied voltage. Consequently the smallest motion that can be commanded is approximately proportional to the smallest voltage increment that can be applied. Almost universally, the voltage is ultimately commanded by a digital-to-analog converter (DAC). These can reside in the piezo controller or in the customer's PC. In the latter case, very flexible and sophisticated software programming environments exist for generating waveforms and synchronizing with other processes and instrumentation. Sophisticated digital piezo controllers offer similar functionality, but the flexibility of PC-based analog I/O makes it very popular.

True to their name, DACs take a digital number as their input and produce a voltage in response. Their voltage resolution — their granularity — is equal to their voltage range divided by 2^N, where N is the bit-width of their digital command. A 12-bit DAC can therefore split the DAC's voltage range (e.g., 0 to 10 V or -10 to +10 V) into 4096 distinct values. A 16-bit DAC can divide its voltage range into 65,536 steps.

The most popular instrumentation grade analog I/O cards for PCs top out at 16 bits. However, economic and application prerogatives increasingly necessitate longer and longer travel piezo mechanisms. Precisely guided stages with up to 900 µm travel are now available for these applications. A customer limited to a 16-bit DAC would achieve only about 14 nm resolution from such a stage

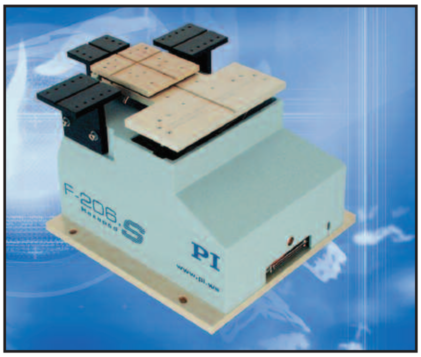


Figure 10. *Six-axis precision hexapods are based on parallel-kinematic flexure designs and provide long travel motion in all six degrees of freedom with a user-definable pivot point.*

due to DAC granularity. In many applications that would not be good enough.

A newly patented technology, HyperBit, takes advantage of the fact that as fast as piezos are, DACs are often faster. By performing high-speed time-domain modulation of the least-significant bits of the DAC at a rate at which the piezo system cannot respond to, many additional bits of resolution positioning can be achieved with no loss in positioning bandwidth or stability. Both waveform and quasi-static positioning, open- or closed-loop, can benefit. The technology preserves legacy investments in software and analog I/O hardware.

Formats and applications

Applications such as the alignment of photonic assemblies, surface profiling, photolithography positioning, wafer/mask inspection and repair systems and optical tweezers already use piezoelectric devices. Near-field probing, scanning-probe microscopy and disk-drive test applications are using a new generation of piezoelectric technology that provides subnanometer and subarc-second precision. These systems employ actively or passively compensated trajectory control (Figure 6) for nanometer-scale flatness, straightness and planarity, and allow bidirectional processing for throughput enhancement.

Systems are available that — besides applying closed-loop principles to single-axis nanopositioning mechanisms — integrate an X-Y nanopositioning stage with six-axis active trajectory control. Active trajectory control requires a parallel kinematics design with noncontact sensors in a parallel metrology configuration (Figure 9). At PI, we have developed one that provides 200×200 µm X-Y motion with compensation for unwanted out-of-plane Z and rotational motions (Figure 7).

Digital control systems offer advantages over analog control systems: real-time linearity compensation, elimination of some drift mechanisms (with high-resolution DAC residing inside the servo loop), advanced interfaces, waveform-generation capability and other features that only a digital architecture can provide. But some digital implementations lack the functionality of a well-designed analog implementation such as high bandwidth, fast settling time, compatibility with advanced feed-forward techniques, stability and robust operation. Engineers would be wise to weigh the advantages of seemingly leading-edge implementations against characteristics such as responsiveness, stability, cost, noise immunity, resolution and the ease of use of proven designs. A vendor's design philosophy can also have profound impact on overall system performance; for example, unsophisticated designs can rely on a comparatively low bit-width DAC inside the servo loop, driving a low-bandwidth amplifier which allows the DAC to meander between adjacent bits, providing resolution at significant cost to short-term stability and throughput.

Another advantage is the integration of a calibration chip into motion devices. This allows the controller to download device-specific parameter and calibration information. Although convenient for repair situations, it is no substitute for a robust and reliable design that avoids repair issues in the first place.

Some recently developed technologies have potential application to both analog and digital control implementations.

A particularly common application of nanopositioners to photonics is in automated alignment. This is a fundamental step in virtually all of today's photonic device-packaging operations, and the speed and reliability of the methodology and devices selected drives the yield and overall economics of the manufacturing operation.

The first automated alignment systems were laboratory-grade instruments that were introduced in the late 1980s. These utilized a piezo dithering mechanism and an analog phase-demodulation scheme which drove a high-resolution alignment stage. Several of these systems are still offered.

The analog phase-demodulation technique is one of several types of "gradient search" methods. Gradient searches are suitable for rapid alignment of clean, unimodal, quasi-Gaussian coupling cross sections, and in these cases their alignment can be very rapid, concluding in a few seconds and tracking drifts from there on. However, this method has a habit of locking-on to the first "flat spot" they encounter in the coupling. Hence, they are inappropriate for many (perhaps most) real-world packaging applications. Brute force raster and spiral scan techniques can be effective in some applications and are the foundation for many heavier-duty systems that have been implemented by device manufacturing engineers and their systems integrators. These are generally based on stacks of mechanical stages from one catalog or another.

Hexapod 6-D systems

Integrated, industrial microrobots have been introduced to address the general case of industrial photonics packaging automation. The most intriguing of these are based on a hexapod design rather than a stack-of-stages. This approach allows tip/tilt alignments to be automated in a very flexible fashion since the hexapod approach lets the rotational pivot point be placed anywhere in space via an internal coordinate transformation in the controller (Figure 10). Rotations can thus be centered on a fiber endface, laser beam waist, lens focal point, array axis, MEMS channel, or any other optically desirable place, regardless of fixturing or device variations. This greatly improves the process by addressing parasitic transverse motions that are otherwise unavoidable.

In a fashion, the introduction of these microrobots repeats a script seen in the semiconductor industry two-and-a-half decades ago. Back then, manufacturing yield issues drove the elimination of manual wafer handling.

The first handlers were straightforward stacks of linear shuttles that bore more than a passing resemblance to the stack-of-stages approach to fiber alignment. Eventually a multilink, coaxially rotating format was introduced. At first dismissed by some as outlandish or needlessly complex, this type of handler quickly gained acceptance thanks to its inherent throughput, cleanliness and real-estate advantages. Similarly — although the field of photonics alignment microrobots is very new — the rapid acceptance of hexapod-format microrobots, thanks to their inherent alignment and format advantages, may represent a new manufacturing standard emerging before our eyes. □

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