Nanopositioning: how to make the right choices

The range of nanopositioning solutions on the market is broader than ever before as applications continue to drive the technology. **Stefan Vorndran** of PI outlines the options.

For many of today's optical applications, traditional positioning systems based on ballscrew drives or electromagnetic linear motors are not the answer. As new applications continue to demand faster and more precise motion control systems, manufacturers have had to dig deeper than ever before to keep pace.

Until recently, piezoelectric-based positioners offered sub-nanometre precision but only over very short motion ranges. Now, progress in piezo ceramic actuator and motor design, as well as control technologies, has solved this conundrum and users have a wide selection of piezo actuator devices to choose from. This article looks at the applications that have driven the development and the variety of piezo technology that is on the market.

Medical imaging

Semiconductor applications that use e-beam lithography and scanning electron microscopes have driven the development of fieldless and compact piezo devices that can be positioned anywhere inside a machine without causing negative effects. Recently, the medical market has started to adopt piezo systems and is benefiting from years of refinement in other industries.

For medical imaging applications, such as magnetic resonance imaging, 3D optical microscopy or optical coherence tomography (see figure 1), piezo drives offer substantial advantages due to their high efficiency, direct-acting linear motion, high resolution, fast response and non-magnetic characteristics.

Scanning microscopy

In drug discovery, a multitude of samples has to be examined in the shortest possible time. Techniques such as fluorescence imaging are employed and require precise focusing on small amounts of liquid, usually held in multiwell plates (see figure 2).

For long-range, well-to-well positioning, conventional electric motors or voice-coil drives can typically provide the required speed and precision but the focusing is best achieved with frictionless, piezo flexure stages or objective positioners. Response times on the order of a few milliseconds allow extremely fast focusing and rapid data acquisition. The fast response also reduces the risk of photobleaching caused by long-term exposure.


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Fig. 1 (top): OCT scanner (shown with linear piezo motor, on palm) for non-invasive biopsy based on ultrasonic ceramic drive technology provides higher resolution images faster. Fig 2 (bottom): Fast focusing piezo stage with multiwell plate for high-throughput screening drug-discovery applications and fast piezo-Z lens scanning unit.

Near-field scanning microscopy has similar speed/resolution requirements. Here, small samples are scanned, typically $100 \times 100\,\mu m$ to $500 \times 500\,\mu m$, with nanometre lateral resolution. To minimize the scanning time and achieve the high resolution required, flexure-guided piezo stages are the only option. The latest designs employ a parallel-kinematic motion principle, with all actuators acting on one moving central platform, greatly reducing inertia for much improved dynamics. Integrated capacitive sensors take multi-axis measurements against a common fixed reference (parallel metrology). This approach allows drift-free positioning with nanometre straightness, which is not available with classical stacked or nested multi-axis designs. The same approach yields superior surface metrology results in atomic force microscopes.

Industrial metrology

In many of today's industrial production and testing processes, dynamics and throughput are paramount. In disk-drive head/media metrology applications for example, sub-nanometre steps need to be executed and settled to nanometre tolerances in a matter of milliseconds. But in order to test an entire disk, travel ranges in the centimetre range are needed.

Until recently, these were mutually exclusive requirements, but today new controller technologies make hybrid nanopositioning systems a reality (see figure 3, p28). These systems combine the advantages of servo-motor/ballscrews (long travel range, high holding force) with piezo-stage technology (frictionless flexure guides, unlimited resolution, fast and crisp response).

Astronomy

Many optical alignment applications in astronomy would benefit from actuators that simultaneously provide millimetres of backlash-free travel at nanometre resolution and can hold a position against large forces without drift and heat dissipation over long periods of time. These dual requirements were impossible to meet until a robust piezo motor based on the PiezoWalk linear actuator principle became available.

The PiezoWalk principle combines lateral and longitudinal actuation of piezo ele-

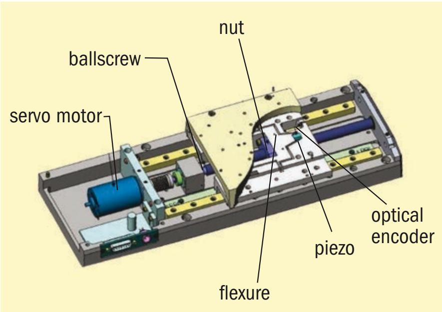

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Fig 3 (left): Hybrid nanopositioning stage design combines properties of piezo ceramic drives and ballscrew drives. Fig. 4 (right): Vacuum compatible, non-magnetic piezo motor actuators and higher levels of integration: XY motor stage and six degrees of freedom hexapod alignment system.

> **"It is more important than ever for the vendor to understand the user's application."**

ments that are preloaded in arrays about a central ceramic runner. A digital controller sequences their operation, providing high force, long travel step-mode actuation plus picometre precision high-bandwidth actuation.

As with all piezo motors, PiezoWalk drives are inherently vacuum-compatible and fieldless, with force generation to 600 N and nanoscale power-off position stability. When arranged in a parallel kinematic hexapod design, they can provide motion in six degrees of freedom (see figure 4).

The hexapod approach with its virtual pivot point and available large central aperture is suitable for optical alignment problems as large as secondary mirrors in the latest generation of astronomical telescopes and as small as fibre-to-photonic-component-alignment in telecommunication chip production.

Autofocus cameras

Another use of piezo ceramics technology is in ultrasonic piezo motors. These are composed of monolithic piezo ceramic slabs electrically stimulated to drive standing waves in the substrate at high frequencies. The latest ultrasonic linear motor implementations come in sizes as small as 8 mm, achieve velocities to 800 mm/s and can provide unlimited travel ranges while maintaining submicron resolution.

Conclusion

Piezo ceramic motion systems have long been the number one choice for ultrahigh precision motion. With the ever increasing requirements from the optics, biotechnology and semiconductor industries, manufacturers were forced to find ways to overcome limitations such as travel range and linearity while preserving their unmatched speed, acceleration and resolution capabilities.

With the abundance of choices available today, it is more important than ever for

A guide to different piezo motor/actuator systems (continued)

Group B: Piezo flexure stages
These more complex systems use frictionless flexures and motion amplifiers to provide extremely straight and flat motion, and often longer travel than can be accomplished with simple piezo actuators. For the highest accuracy, integrated capacitive position sensors provide sub-nanometre precision in multiple degrees of freedom.
Key features:
- Integrated multi-axis systems available
- Frictionless, fast response (0.1–10 ms)
- Sub-nanometre resolution feasible
- Scanning frequency up to kilohertz
- Piezo motion can be amplified by internal flexure amplifier, typically up to 2 mm
- Essential for applications such as nano-alignment, scanning optical microscopy and nanomanipulation
- Ideal for imaging resolution enhancement or stabilization by dithering a lens in front of an optical sensor
- Position feedback sensor can be integrated (strain gauges for entry level, or capacitive for reference class systems/independent multi-axis measurements)

Group C1: Linear ultrasonic piezo motors
These devices are based on high-frequency oscillation of a piezo plate (stator) on the nanoscale.
Key features:
- Oscillation is transferred to a slide or rotor via microfriction
- Unlimited motion range
- High speed (to 1000 mm/s in some of the latest designs)
- Fast response (10–10 s of milliseconds)
- Resolution limited to typically 50 nm
- Relatively low forces, typically 2–30 N (0.5–6 lb)
- Power-off position hold capability
- Small amount of particle generation due to friction

Group C2: Ultrasonic rotary motors/drives
These compact and non-magnetic rotary stages can be designed by tangentially driving a ceramic disk mounted on a bearing with one or more ultrasonic "linear" motors. In addition, there are also "true" rotary piezo motors that mimic classical motors but provide higher torque at lower RPM. Sometimes these are coupled with lead screws to create linear motion. In this case, overall system precision is limited by the mechanical properties of the lead screw (backlash, friction, elasticity).

Group D: Piezo stepping motors (PiezoWalk)
Key features:
- Unlimited motion range
- Based on accumulation of small highly controllable steps
- Picometre resolution by means of direct piezo actuation (analogue/dither mode)
- Compact and high force to 60 kg, but lower speed than ultrasonic motors (to 10 mm/s)
- Fast response (<1 ms feasible)
- Very high stiffness
- Constant velocity mode
- Drift-free power-off position hold

Group E: Piezo inertial motors (stick-slip motors)
These compact motors are based on the stick-slip-effect and suit applications that require low precision, slow motion (<1 mm/s) and low force (<1 N).

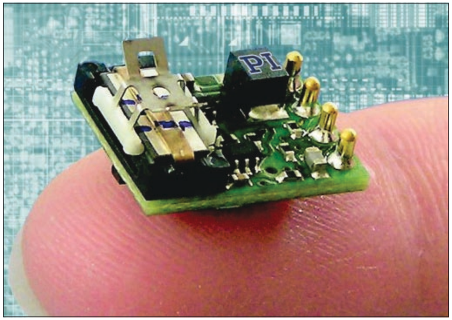

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Fig 5: This shows an example of a miniaturized PCB-mounted piezo motor linear slide for applications such as alignment of micro-optics or autofocus/zoom lenses in mobile-phone cameras.

the vendor to understand the user's application and its requirements on dynamics and precision as well as the control and interfacing preferences of the customer. If the user is willing to do a little homework and engage in a dialogue with a credible manufacturer, the result will be a significant step forward from what was feasible just a few years ago. □

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A guide to different piezo motor/actuator systems

All piezo motors and actuators are intrinsically vacuum compatible and non-magnetic.

Group A: Simple piezo actuators

Key features:

- Expand proportionally with the drive voltage
- Travel range up to 0.2% of actuator length
- High forces to thousands of kilograms available
- Very fast response (microsecond to millisecond range)
- Frictionless, sub-nanometre resolution
- Travel range typically 10–200 µm for stacked actuator and several millimetres for bender actuators (see sub-groups)
- Closed-loop operation with feedback sensor for higher linearity

Sub-groups:

(i) Stacked actuators: these are the most common and are available in co-fired multilayer construction (typically 100 V) and a classical discrete design (500–1000 V). High-force, motion typically up to 200 µm. Also available with aperture.

(ii) Shear actuators: lateral motion allows design of small, very fast XY and XYZ positioners. Also used in piezo stepping motors. High force, travel typically 5–20 µm.

The latest generation monolithic multilayer piezo stacks use ceramic encapsulation.

(iii) Tube actuators: often used in micro-dispensing (pump) applications and as scanner tubes for microscopy. Very fast response (low inertia), low force (fragile), travel range typically <20 µm. XYZ scanner tubes are available.

(iv) Bender actuators: available in multilayer construction (60 V) and classical (bimorph) design (200–1000 V). Low force (<1 kg), very long deflection (to several millimetres), relatively slow response (approximately 10 ms). *(continued on p30)*