

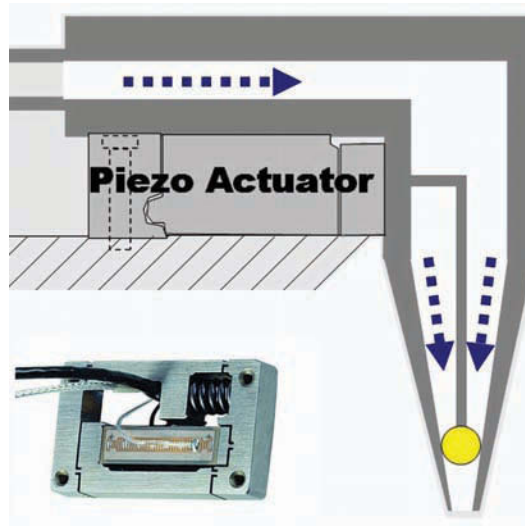
Long-Travel Piezomotors: New Innovations, New Solutions

Piezo actuation is becoming increasingly suitable for applications formerly addressed by magnetic motors.

BY SCOTT JORDAN & STEFAN VORNDRAN, PI (PHYSIK INSTRUMENTE) L.P.

Piezoelectric actuation is the foundation for a myriad of mission-critical high-technology applications, from semiconductor manufacturing to atomic-force microscopy, from optical tweezers to sub-pixel imaging, from battlefield targeting to genomic sequencing and medical devices. Known for nanometer precisions, piezoelectric principles are proving highly adaptable to new configurations and modalities. Recently developed mechanisms built on a variety of novel applications of piezoelectric technology have burst through the former travel limitations familiar from classical nanopositioning mechanisms. But like those time-tested mechanisms, those built on these newer principles offer high axial force, exceptional speeds, compactness, fieldlessness, and stable position-hold without dither. These long-travel piezomotors offer valuable, proven solutions for engineers grappling with tough technical and economic needs.

In a variety of fields, applications are placing conflicting demands on structural and motion subassemblies. Increasingly, positions must be controlled in more degrees of freedom with higher dynamic and static accuracy, yet faster throughputs and longer travels are necessary to meet financial metrics. Compactness is prized, yet high speeds are demanded. These conflicting require-



Piezo Flexure Actuators provide travel ranges from 0.1mm to 2mm with high force and speed. They are optimized for microfluidics and nanodosing in biotechnology or medical design, and are available for fast auto-focus applications. The sketch shows a small low-cost flexure actuator and the basic design of a precision micro-valve.

ments have, until recently, had no solution. Application examples abound:

- Optic assemblies of escalating sophistication require multiple axes of nano-precision alignment yet must remain aligned for months of around-the-clock usage.
- Emerging nanoimprint lithographies demand exquisite positioning and trajectory control yet must retain alignment integrity under significant physical and thermal stresses.

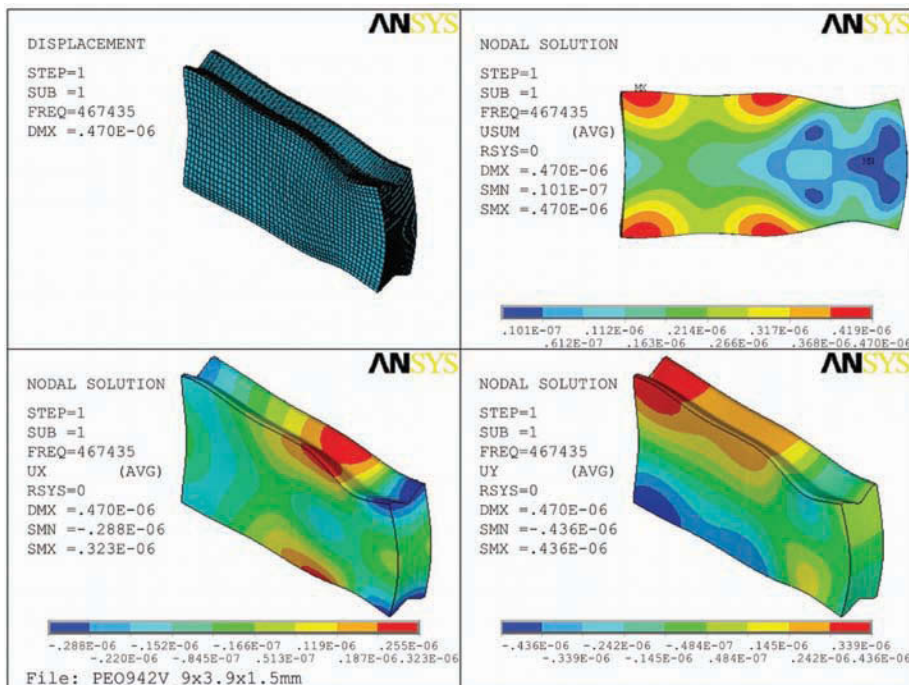
• Applications ranging from cell phone cameras to endoscopy and fluid delivery require exceedingly small but stiff, responsive, and reliable positioning of optics, probes, shutters, and other small loads.

Fortunately, a confluence of new piezo-based approaches has breathed new capability into the nano- and micro-positioning world. Some of these represent significant incremental advancement of essentially traditional mechanisms; others represent significant forks in the road of positioning technology.

NANOMETER PRECISION — OVER MILLIMETERS: LONG TRAVEL FLEXURES

When precision is needed, piezoelectric actuation is the default choice. Similarly, when high force or high dynamics is required, piezoelectric actuation represents the gold-standard. Piezo actuators have long been used in semiconductor manufacturing and testing applications for their extreme speed and precision. Lately, microscope manufacturers and medical device manufacturers have also warmed up to the benefits of this actuator technology that has even been embraced by the automotive industry.

Traditionally, piezo stack actuators offer limited maximum travel, on the order of 0.1 percent of the stack's length. Helpfully effective flexure lever-amplification approaches have been devised over



Vibrational behavior of a piezo ceramic slab in a miniature ultrasonic motor (measured with 3D scanning laser vibrometer).

many years which today provide travels up to 2mm. The downside is that the stiffness of lever mechanisms diminishes as the square of the lever ratio. This limits the bandwidth and thus the tracking performance of traditional servo-control techniques. So, demands for longer travels plus faster actuation or higher holding force are at cross-purposes. Furthermore, at some point the granularity of the driving DAC will begin to be seen, limiting coarse positioning resolution or introducing bit-transition noise in position waveforms.

This is now addressable by novel controls technologies. Digital Dynamic Linearization, a non-traditional algorithm integrated into the latest digital nanopositioning controls, virtually eliminates following errors in repetitive motion patterns and scanning of these long-travel nanomechanisms. The controller integrates the algorithm into the metrology and servo logic; this optimizes the internal command generated for a repetitive waveform according to

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the error signal detected with the internal sensor. A brief (typically <1 second) auto-optimization is commanded by the user (or a reload of previously saved optimizations) when application changes occur. After this, following errors are reduced to approximately the noise level of the system. This capability is supported by internal waveform generators and software drivers including COM objects, DLLs and LabVIEW libraries.

ELIMINATING THE TRAVEL/RESOLUTION TRADE-OFF

Piezo actuation is roughly proportional to applied voltage, typically generated by a digital-to-analog converter (DAC) driving an amplifier. The number of addressable positions for a piezo mechanism is 2^b — where b is the bit-width of the DAC's digital input. Traditionally, the resolution of the nanopositioner can be no better than its travel divided by this number. With today's long-travel flexure nanopositioners, achieving tight resolution goals requires higher and higher DAC bitness.

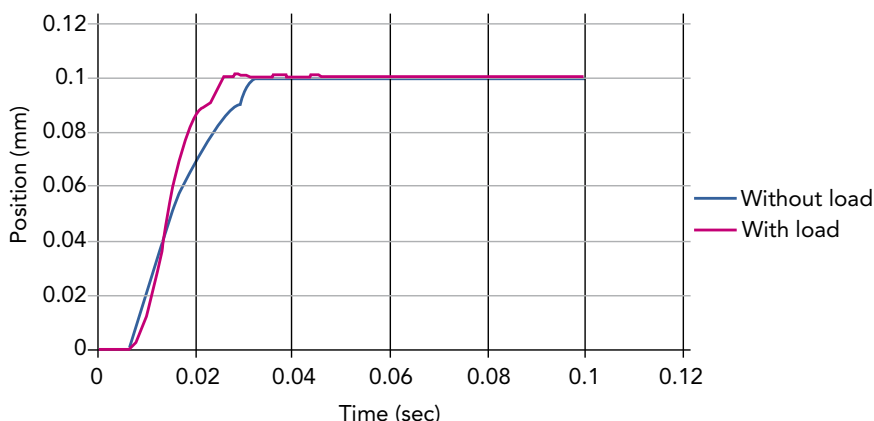


Miniature translation stage with ultrasonic linear motor compared to a 9V block battery. This unit provides 0.8 inch of travel with speed to 20 inch/sec, and 10g acceleration. A high-resolution linear encoder is also integrated. Smaller versions are feasible.

Two-Axis ultrasonic motor controller and a compact XY long travel microscope stage. The intrinsic autolocking principle of the ultrasonic motor provides excellent long-term stability in microscope applications.



Settling Test: M-663 Piezo Motor Stage with C-867 Controller, 215g Load
Actual Position



Settling behavior of an ultrasonic stage shows the extreme accelerations and fast settling this motor/controller combination is capable of.

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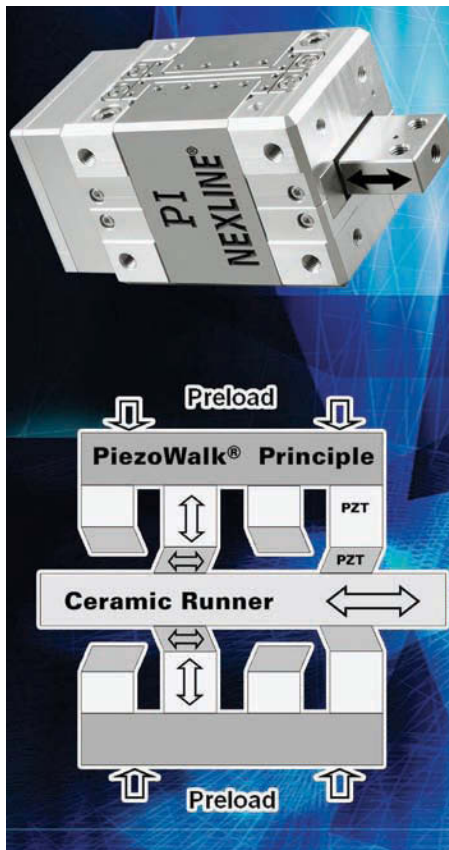
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High Load PiezoWalk linear motor capable of 800N holding force, shown with operating principle.

Until recently, a DAC's limitations were permanent characteristics of the specific chip chosen by the designer. Popular PC analog I/O interfaces like those from National Instruments typically top out at 16 bits, providing 65,536 possible output voltage states, with update rates to several million per second and useful waveform and synchronization capabilities, plus compatibility with popular programming languages like C++, VisualBASIC, and LabVIEW. OEM engineers designing their own controls might choose a 20- or 24-bit DAC for their custom circuit design, but care must be taken, as they can present drift issues, noise, or other drawbacks. Sometimes a new design is not economically practical, necessitating use of lower-bitness legacy DACs, potentially problematic when highly leveraged PZT mechanisms are used.

The recently introduced, patented HyperBit technology leverages the under-utilized time-domain capability of today's DACs, converting it into up to 11 additional bits of physical positioning resolution. HyperBit employs modulation of the DAC's least-significant bits (LSBs) to accomplish this. For example, the LSBs can be dithered using pulse-width modulation at a high rate. The result is higher positioning resolution without trade-offs. Many

mechanisms and devices can benefit; a video which demonstrates this effect using a commonplace panel meter is available at <http://dn.hotims.com/40992-510>. For ease of implementation, this technology has now been built into the industry's first LabVIEW library for analog nanopositioner interfacing.

NANOMETER PRECISION OVER CENTIMETERS

To address applications needing longer travels than can be met via lever amplification of piezo stack actuators, engineers have developed an array of new technologies based on novel configurations and actuation modes of piezo ceramics.

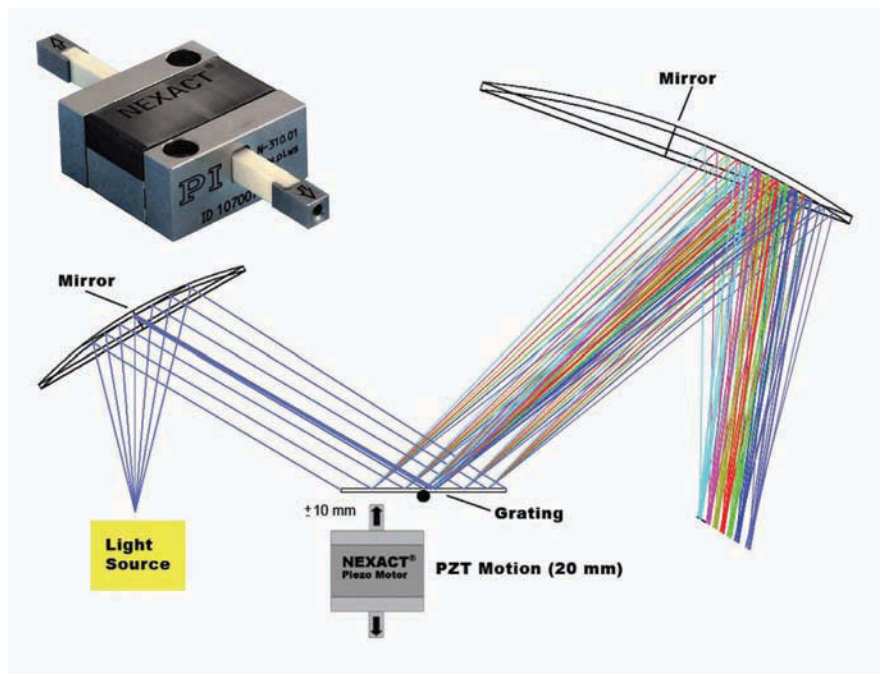
RESONANT PIEZOMOTORS (ULTRASONIC MOTORS)

In one example of this breed of piezomotors, a ceramic wafer is configured so that high-frequency excitation drives one or more resonant modes in its material, conferring a micron-scale oscillatory motion to a friction pusher tip affixed at an antinode. The pusher tip, oscillating like a miniature pogo-stick with nanoscale amplitudes and frequencies of hundreds of kHz, can then be preloaded against a guided workpiece, driving long-travel motion with dynamical behavior somewhat similar to that of DC servomotors.

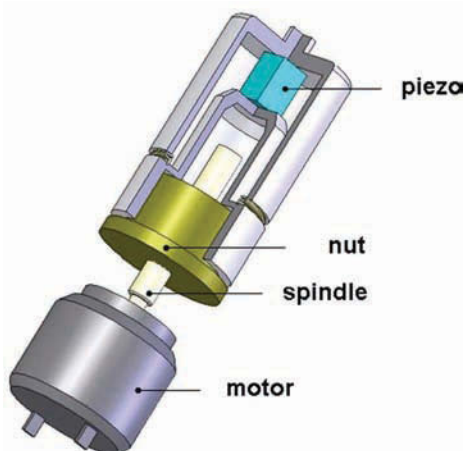
A wide assortment of linear- and rotary-motion configurations have been commercialized by providers in many countries over several decades, both open- and closed-loop. By eliminating lead-screws and their inertia and associated linkages and structures, such mechanisms can be very compact and responsive. For example, off-the-shelf linear stages can provide 19mm of travel at up to 500mm/sec and 10g acceleration with a 0.1µm resolution linear encoder, all in a package 35mm square.

In-position stability is superior to conventional stages since the actuator acts as a brake when quiescent. Fieldlessness, vacuum-compatibility, long life, and other signature advantages of piezo actuation also apply.

The drawback to these piezomotors has traditionally been their difficulty of control. Ideally, any motor would exhibit a linear stimulus-to-velocity curve. A small amount of friction present in most dc-motor mechanisms means a small but non-zero stimulus produces zero velocity — a departure from the desired linearity. Conventional controls technologies over-



Optimized for next-generation microlithography alignment and positioning, NEXACT actuator provides 10N power-off holding force and smooth coarse/fine motion over centimeters with picometer-class resolution in a compact, cost-effective format.

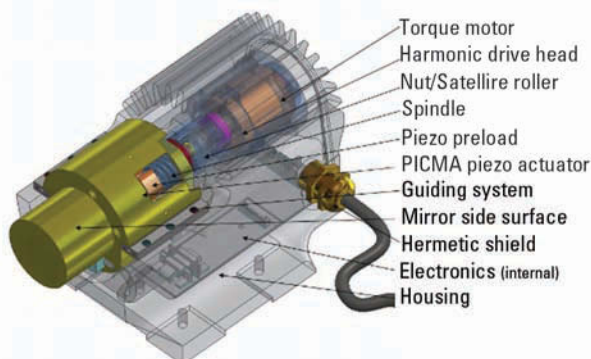


Hybrid leadscrew (spindle)/nut system with piezo fine adjustment for elimination of stick/slip effect and velocity variation. The unit is controlled by a special hybrid dual (PZT/DC servo) controller getting its position feedback from one external high-resolution 1 nanometer class linear encoder.

come this stiction with an integrating filter which escalates the stimulus as needed.

Resonant piezomotors have a similar

Custom Hybrid piezoelectric and (brushless torque) motor actuator system with 0.6 inch travel and 200 lb force for astronomical application. The system provides extremely accurate positioning and tracing within less than 2nm RMS.



behavior, though from a different cause. Just as a child on a pogo-stick must achieve a certain threshold "bounce" before he moves, a certain threshold of stimulus must be applied to the resonant piezomotor before motion begins. This deadband behavior is great for in-position stability, but conventional P-I-D controls tend to be unhappy with it: so much integrator gain must be applied to accommodate the deadband that the setting is incompatible with running-at-speed. The controller oscillator frequency also needs to be in tune with the resonant frequency of the ceramic slab in the piezomotor, a fact that in the past required initial tuning and frequent adjust-

ments during operation of a system.

Both problems were solved with the latest generation of ultrasonic motor controllers developed by PI. An autotuning circuit constantly keeps the oscillator frequency in the optimum range; and a faster processor now automatically switches between gainsets, enabling the user to take full advantage of high velocity constancy and the exceptional stability these friction motors provide at rest.

PIEZO WALKING DRIVES

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posed. These elements can be compressed against a longitudinal rod to confer motion. One familiar progenitor of this family of mechanisms was the Burleigh Inchworm. More recently developed mechanisms offer extraordinary stiffness and holding force and are optimized

for reliability in applications requiring long-term position hold while providing centimeters of travel with picometer-class resolution.

An even newer solution uses cost-effective bender-type piezo elements. Size and cost are substantially reduced; power-off

stiffness is still remarkable, with 10N holding force. This design also provides centimeters of travel range and picometer-class resolution, ideal for applications like optic positioning in microlithography and sample positioning in electron microscopy.

In the case of both these mechanisms, motion occurs in two modes: a long-travel stepping mode, and a fine-motion analog mode in which the actuator elements are sheared but not stepped, providing sub-nm positioning capability.

HYBRID MOTORIZED/PIEZO MECHANISMS

While the mechanisms discussed so far can displace magnetic motors, piezo actuation can also be combined with them for coarse/fine motion. Traditional "stacked" coarse and fine mechanisms operate independently; the piezo mechanism greatly improves the minimal incremental motion capability of the system, but the overall repeatability is no better than the motorized stage alone.

The advent of linear encoders with nm-scale resolution has allowed construction of hybrid mechanisms where both the coarse and fine mechanisms share the same feedback sensor. Coordinated by advanced controls, this hybrid provides piezo-class repeatability and fast dynamics over many cm of travel.

CONCLUSION

The field of piezo motion control has expanded rapidly in recent years, with a wealth of new concepts introduced, all aimed at eliminating piezos' former travel limitations while preserving their unmatched resolution, responsiveness, and throughput capabilities.

Consequently, not only is piezo actuation increasingly suitable for applications formerly addressable only by magnetic motors, but significant benefits accrue in terms of size, speed, fieldlessness, reliability, vacuum compatibility, resolution, dynamics and reliability. These in turn are enablers for significant advances in existing and new applications.

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