➲ A piezoelectric microscope nanofocusing device — called a *Z* motor — provides 10 times faster response and resolution than classic motor-driven units.

Piezo PZT-quartz disk at work ➲
The atomizer head of the eFlow Rapid Electronic Nebulizer employs an annular ultrasonic piezo transducer.

Piezomotors and actuators:
Streamlining performance

The latest piezoceramic motors and actuators offer advantages over conventional electromagnetic motors. With higher accuracy and fewer wearing mechanical parts, it's no wonder why these compact devices are becoming the preferred choice of device manufacturers.

Jim McMahon
Contributing writer

Physik Instrumente L.P.
Auburn, Mass.

Motion-device functionality is influenced by a myriad of design requirements. Consider medical-instrument manufacturing: The research, design, modeling, testing, prototyping, and FDA and EU approvals of new mechatronic devices, or the integration of changes to existing designs, usually represents a sizable capital investment well before the equipment goes into serial production.

A key impetus for medical and bioresearch companies is to capitalize on technological advances for the manufacture of better, more efficient equipment: A recent improvement in high-speed laser scanning, for example, spurred Harvard Medical School's latest imaging technique, *optical frequency-domain imaging* or *OFDI*, which is capable of visualizing a patient's coronary arteries in unprecedented 3D detail. OFDI operates at several magnitudes of improvement over its predecessor, *optical coherence tomography*, in turn enabled by laser-scanning advancements 15 years ago. In the same way, recent advancements in piezoelectric motors and actuators are spurring other new designs.

Piezomotor defined

A piezoelectric or piezo actuator is a solid-state actuator that leverages the shape change of piezoelectric material when an electric field is applied. In short, a piezoelectric ceramic element produces mechanical energy in response to electrical signals, and conversely, produces electrical signals in response to mechanical stimulus. Piezoelectric ceramics consist of ferroelectric materials and quartz: High-purity PZT (*plumbum*, *zirconate*, *titanate*) powders are processed, pressed to shape, fired, and electroded. Then high electric fields are used to align material domains along a primary axis and induce polarization.

The use of piezoelectric materials dates back to 1881 when Pierre and Jacques Curie observed that quartz crystals generate an electric field when stressed along a primary axis. The name derives from the Greek word *piezein*, meaning to squeeze or press.

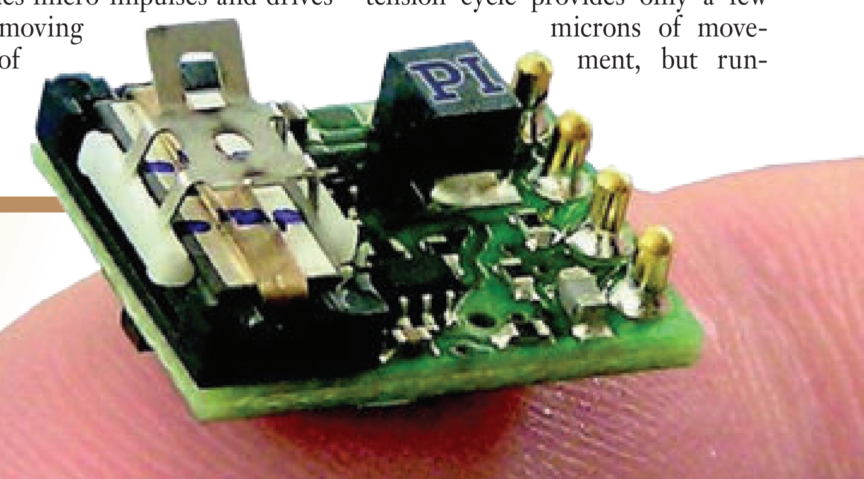
Piezoelectric actuators in their basic form provide very small displacement. To produce longer travel, one of two clever arrangements is used — either running a single piezoelement at its resonant frequency, or operating multiple actuators together. Both of these devices are called piezomotors, and both basically provide unlimited travel.

In **ultrasonic piezoelectric motors**, the piezoelectric ceramic material produces high-frequency acoustic vibrations (inaudible to the human ear) on a nanometer scale to create a linear or rotary motion. A rectangular monolithic piezoceramic plate (the stator) is segmented on one side by two electrodes.

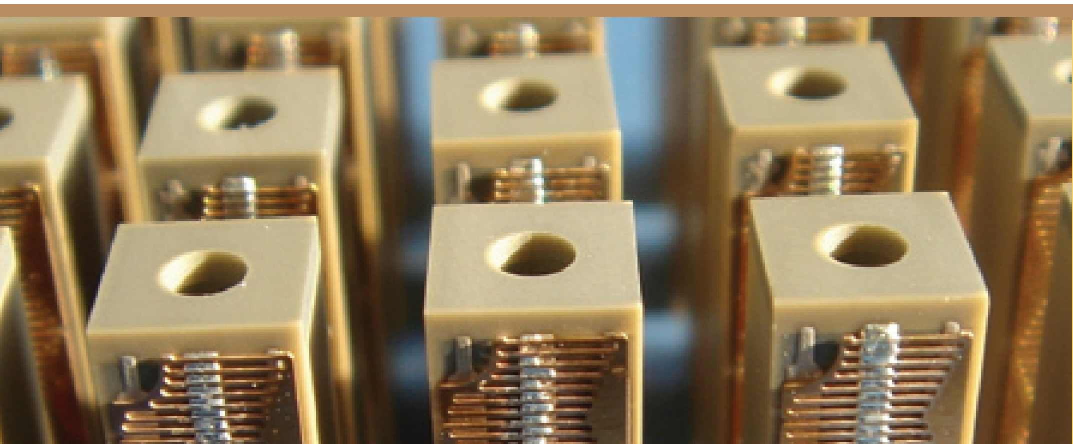
Depending on the required direction of motion, one of the electrodes of the piezoceramic plate is excited to produce high-frequency eigenmode oscillations (one of the normal vibrational modes of an oscillating system) of tens to hundreds of kilohertz. An alumina friction tip (pusher) attached to the plate moves along an inclined linear path at the eigenmode frequency. Through its contact with the friction bar, it provides micro-impulses and drives the moving part of the mechanics (slider and turntable) forward or backwards. With each oscillatory cycle, the mechanics smoothly executes a step of a few nanometers.

Ultrasonic piezoelectric linear motors are useful where both large travel ranges and high speeds are required, even to 500 mm/sec. With resolutions as high as 50 nm, they are also one suitable alternative to electromagnetic motor-spindle combinations: The ultrasonic drives are substantially smaller than conventional motors, and rotary-to-linear drivetrain elements are eliminated.

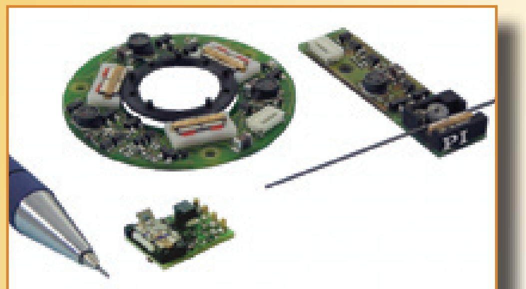
The other option for longer strokes, **piezo stepper linear motors**, usually consists of several individual piezo actuators and generates motion through a succession of coordinated clamp/unclamp and expand/contract cycles. Each extension cycle provides only a few microns of movement, but run-



A miniature piezo linear motor slide with on-board driver can reach velocities of 200 mm/sec. These motors are improving performance in medical applications.

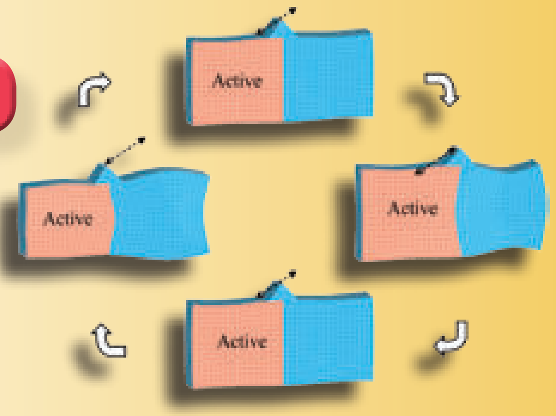


➲ Encapsulated piezo stacks are used for aperture control.



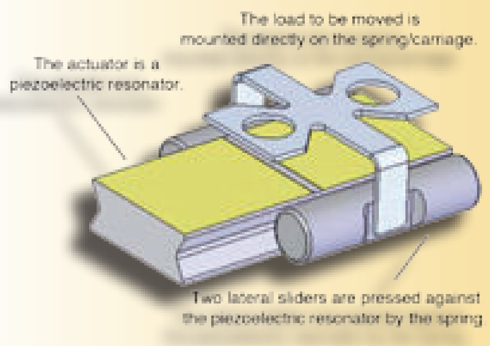
Design options ➲ include miniature piezo ceramic rotary stages, linear stages, and pushers.

Small motors

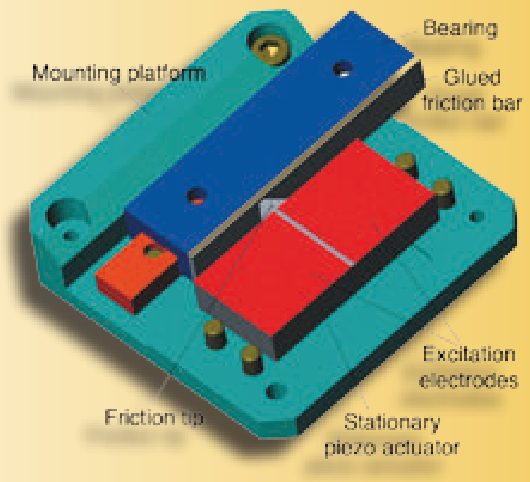


Dynamic phases change in a stator plate of a piezo ultrasonic motor. Such motors can produce accelerations to 10 *g*.

Ultrasonic linear motor

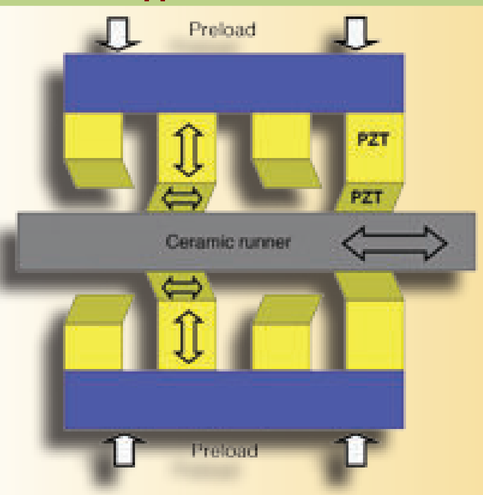


New ultrasonic resonant motors such as the compact PILine reach speeds to 500 mm/sec. They are also stiff — a prerequisite for fast step-and-settle times, on the order of a few milliseconds. Resolution is to 0.05 µm. This CAD shows the elegantly simple motor's four parts.



Ultrasonic piezomotors can also be used to form tiny linear translation stages.

Piezo stepper motor



Linear piezo stepper motors such as the PiezoWalk produce forces to 700 N and resolution to 50 picometers — a scale one trillionth of a meter — for better resolution than ultrasonic piezomotors.

ning at hundreds to thousands of Hertz, achieves continuous motion. The steps are incremental, in the nanometer to micrometer range, but can move along at speeds of about 10 mm/sec, taking thousands of steps per second.

Motors are capable of high-precision positioning over long travel ranges, and when the position has been reached, they deliver highly dynamic motions for tracking, scanning, or active vibration suppression. As with ultrasonic piezomotors, these motions can be conducted in the presence of strong magnetic fields or at very low temperatures.

Piezos for motion control

Piezo actuators and motor types abound. The most common:

• "Simple" piezo actuators expand (and generate motion) proportionally to voltage. The most common subtype is the stacked actuator. These give fast response and short travel. Another type is the shear actuator — which provides fast lateral and XY motion. Here, high forces and frequency are possible, though travel is typically limited to 20 µm. Finally, tube actuators are mostly for micro-dispensing applications and atomic force microscopy scanners, while bender actuators offer long travel (deflection) to several mm, but with limited force and frequency.

• Flexure-guided piezo actuators have frictionless flexures and motion amplifiers for longer travel and extremely straight moves. Motion is basically proportional to the drive voltage. Integrated multi-axis systems move up to 2 mm and longer.

• Ultrasonic friction motors use high-frequency plate (stator) oscillation, which is transferred to a slide or rotor via friction. The latter holds resolution to 50 nm, but motion is unlimited and fast, with response within 1 to tens of a millisecond.

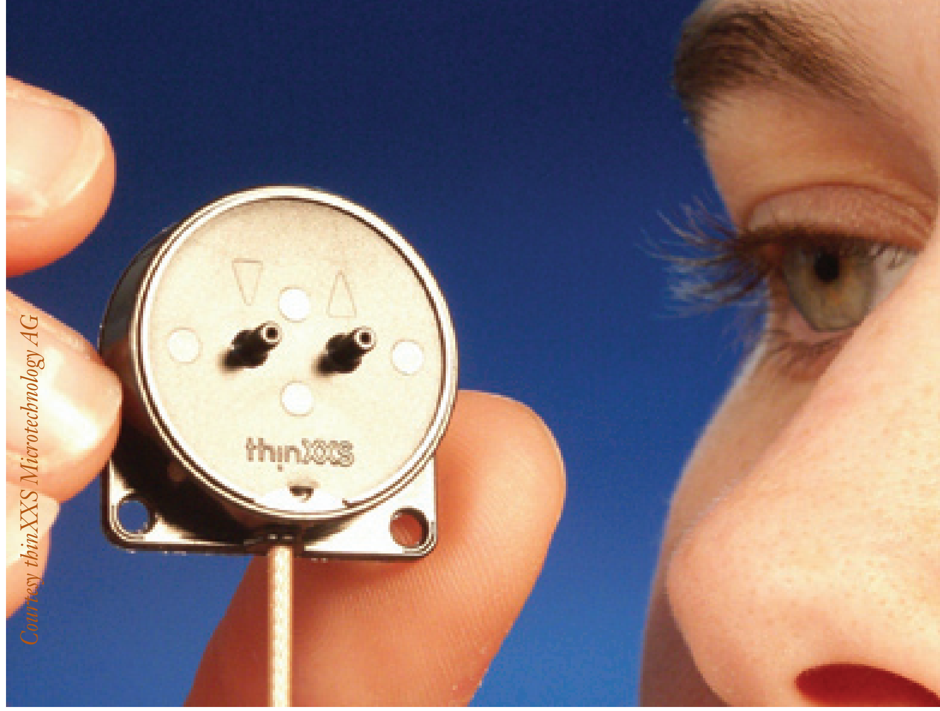
• Piezo stepping motors are based on accumulation of small controllable steps and have unlimited motion range. Picometer resolution dither mode (direct piezo actuation) is possible; off-the-shelf versions produce force to 155 lb. Response is fast — within 1 msec.

• Ultrasonic transducers are plate or disk-driven with a high frequency at resonance. They're used as sensors or transmitters, and in nebulizers.

Improving performance

Piezoelectric motors improve performance in a number of ways.

❶ **Higher force.** Piezoelectric motors can be made smaller and more compact than electromagnetic motors, yet for their size, provide greater force. (*The stored energy density of a piezomotor is ten times greater.*) In addition, electromagnetic motor efficiency falls as dimensions are reduced, with more of the electrical power converted to heat; piezoelectric-motor efficiency stays virtually constant at any size. In fact, advanced piezomotors are configured into micro-positioning stages that are smaller than a matchbox — the smallest used in autofocus devices for cell phone cameras. In short, they reduce equipment and instrumentation size while maintaining or



Here, a PZT disk is used in a tiny pump; it's a custom piezoelectric actuator used to precisely dose liquids and gases in the thinXXS micropump.

Medical equipment manufacturers: Switching to piezoelectrics

Electromagnetic devices dominate the drive mechanisms in today's medical equipment. However, new micron and nanometer accuracy requirements, miniaturization, and interference immunity are pushing the physical limitations of electromagnetic drives. Increasingly, manufacturers are choosing to use piezoelectric motors instead.

Piezoelectric motors are already used successfully in ultrasonic emitters, artificial fertilization, micromonitoring, surgery devices, MRI-compatible robots, microdose dispensing, cell penetration and cell imaging in cytopathology, pick-and-place systems, drug delivery devices, 3D scanning, and laser beam steering in ophthalmology and dermatology.

For example, in Optical Coherence Tomography, piezoelectric motors are used to impart rapid periodic motion to the unit's reference mirror and imaging optics. To enable creation of 3D images from optical interference patterns, optical fibers must be moved both axially and laterally during scans. Here, piezomotors move more precisely for improved image resolution over conventional electromagnetic motors.

For point-of-care and medical test equipment in which extremely fine positioning and measuring is required, piezomotors create precision motion from inches to nanometers. Piezoelectric actuators are also finding use in transdermal drug delivery, as in needle-free insulin injectors. Endoscope-gastroscope monitoring benefits; similary, new biomedical and noninvasive microsurgery tools such as tweezers, scissors, drills, are adapted to a micro-robot base powered by piezomotors.

Another application: 3D Cone Beam Imaging is used in orthodontics and treating sleep-apnea patients. The imaging makes exact mouth models (for fitting oral appliances) using piezoelectric actuators.

Similarly, confocal microscopy in ophthalmology for implant quality control uses piezoelectric motors: Very precise motion of the optics is required to adjust the focal plane and for surface scanning. Piezoelectric positioning systems are integrated directly into the optics.

Several piezoceramic motion control devices are used in bio-medical applications: XY microscope stages, rod-drive pushers, and sub-miniature slides.

boosting performance.

❷ **Positioning accuracy.** Piezomotors direct-drive, so they eliminate transmissions or gear trains found in conventional electromagnetic motors — eradicating the backlash that limits tracing and positioning accuracy in electromagnetic servomotors. Mechanical coupling elements otherwise required to convert the rotary motion of classical motors to linear motion are not necessary. The intrinsic steady-state, auto-locking capability of piezoelectric motors does away with servo dither inherent in electromagnetic motors. Piezomotors can also be designed to hold their positions to nanometer accuracy, even when powered down.

❸ **Faster acceleration.** Piezo devices can react in a matter of microseconds — even in 0.01 msec in some cases — and accelerate at more than 10,000 *g*.

❹ **No magnetic fields.** Piezoelectric motors create zero electromagnetic interference, nor are they influenced by it, eliminating the need for magnetic shielding. This feature is particularly helpful in medical and biotechnology applications with strong magnetic fields, as in MRI equipment, where small piezomotors are used for MRI-monitored microsurgery, and large piezomotors for rotating patients and equipment. Magnetic fields and metal components in conventional electronic motors make it impossible for motorized medical devices to function in MRI equipment.

❺ **No maintenance or lubrication; aseptic enabled.** Because piezo motion depends on crystalline effects and involves no rotating gears or bearings, piezomotors are maintenance free and do not require lubrication. Therefore, they can be sterilized at high temperatures.

➲ Piezo-ceramic disks and tube actuators are used for micropumps and nebulizers.

❻ **Low power consumption.** Static piezo operation, even when holding heavy loads for long periods, consumes virtually no power. Also, because piezoelectric motor efficiency is not reduced by miniaturization, they are effective even when powered at less than 30 W. This makes piezomotors suitable for battery-operated, portable, and wearable devices, because they can extend battery life tenfold.

❼ **No heat generation and nonflammable.** When at rest, piezomotors generate no heat. Piezoelectric motors also eliminate servo dither and the accompanying heat generation, unavoidable with electromagnetic motors. Piezomotors are also nonflammable and therefore safer during overloads or short circuit at the output terminal — a considerable advantage for portable and wearable medical devices.

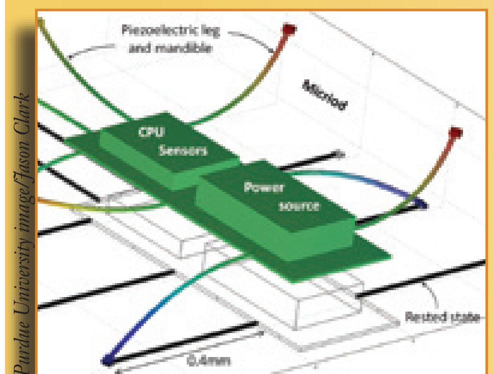
❽ **Vacuum compatible and operable at cryogenic temperatures.** Piezomotors are vacuum-compatible. They also provide trouble-free service at temperatures close to zero Kelvin, making them suitable for operation in medical laboratory storage facilities and cryogenic research.

❾ **Power generation.** Piezo devices can be used to harvest energy — for example, using a person's motion to power small medical or electrical devices such as pacemakers or health monitors.

For more information, call Physik Instrumente's Stefan Vorndran at (508) 832-3456, email stefanv@pi-usa.us.com, or visit www.pi-usa.us.

Piezo insects may run, work in colonies

New robots the size of ants could soon be marching into new applications with solid-state legs and mandibles. Developed by Perdue University researchers, West Lafayette, Ind., the design includes legs made of bundled piezoelectric beams. Computer simulations suggest that the bugs could be mass-produced using manufacturing technologies common to the semiconductor industry, and made to scavenge vibrational energy from the environment to recharge their power supply. A tripod gait — used by most insects — would enable the bugs to remain stable while traversing uneven terrain.



Purdue University image/Jason Clark

According to Jason Clark, assistant professor of electrical, computer, and mechanical engineering at Purdue, the new design differs from previous microscale robots — which use complex moving parts that mesh, touch, wear, and jam. "Because the new microids are solid state without discrete parts such as gears, they will likely be long-lasting and robust. If a microid were stepped on, it would probably just get up and walk away."

Beams of piezoelectric material ordinarily do not expand enough to be useful for robotics, but simulations indicate the new design overcomes this limitation: If the three beams are joined together only at both ends, applying a voltage to one or more of the beams produces a surprisingly large lateral movement.