MOTION DESIGN GUIDE ON

NANOPOSITIONING AND MINIATURE MOTION SYSTEMS DESIGN

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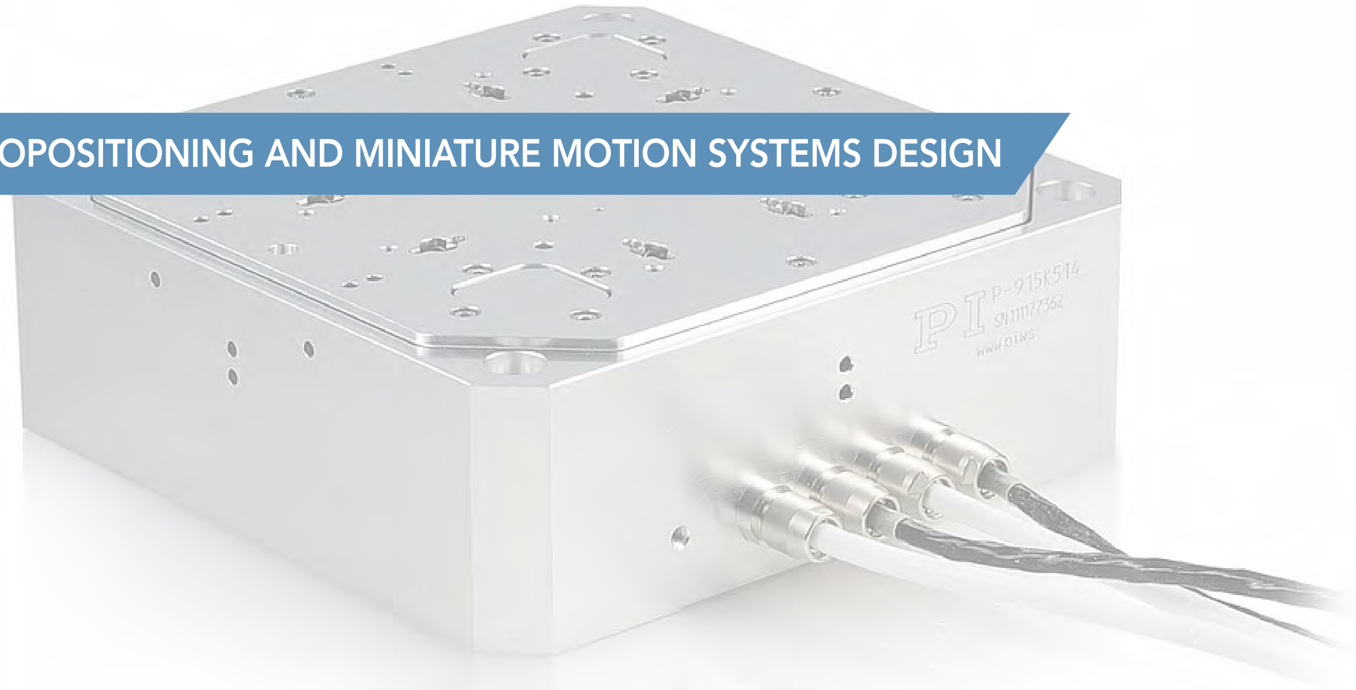
NANOPOSITIONING AND MINIATURE MOTION SYSTEMS DESIGN



Nowhere is the rise of automation more specialized than in the arena of nanopositioning and miniature motion system design — where a proliferating array of miniature motors, mechanical components, and especially electronics have enabled nanopositioning and miniature machine designs for specialty workcells, handtools, and mobile robotics.

In this exclusive Design Guide, the editors of Design World review the technologies and component types used in nanopositioning and miniature motion systems — and detail their typical modes of integration.

LISA EITEL
Executive editor

Danielle Collins
Contributing editor

TABLE OF CONTENTS

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Ultra-precision and miniature linear-motion systems: Where and why?

The L-505 miniature linear-translation stage family from PI (Physik Instrumente) L.P. is available with integrated linear encoders providing 0.05-μm and 0.005-μm resolution. The new design allows for compact multi-axis assemblies at affordable prices. Many motor and drive variations are available, from fast dc-servo motors with linear encoders and low-friction ballscrews to simple open-loop stepper motors. A shorter lower profile version has a "folded" drive train with the motor side-by-side with the platform — and there's longer inline version. Both come in two travel ranges of 13 mm and 26 mm. XY and XYZ combinations are also available. Motor options include servo and stepper motors in direct drive or gearhead configurations. Image courtesy PI (Physik Instrumente) L.P.

Recent decades have seen the unabated spread of automation continues into applications that just a decade or two ago were considered exotic, prohibitive, or downright impossible. Nowhere are the resulting technologies more specialized than those for new nanopositioning and miniature linear-motion designs — where a proliferating array of tiny motors, mechanical components, and especially electronics have enabled nanopositioning and miniature machine designs for specialty workcells, handtools, and mobile robotics. These builds often rely on components pre-integrated into subsystems such as:

- Miniaturized slotless and coreless motors sporting thumbnail-sized drives and encoders within housings are often no larger than a pencil
- Frameless motors that don't come with their own housing, but rely on the OEM's component frame for protection and support
- Linear actuators that tightly integrate shape-memory alloys
- Linear stages with linear rails pre-engineered into the build by the supplier
- Piezo-based hexapods, stages, and other designs sans the unavoidable bulk of copper-wire-based electromechanical actuation

Other examples of pre-integration for compactness abound. No matter how they're built into systems though, nearly all motion components come in diminutive versions that were unimaginable even a decade ago.

In this Design Guide, we'll cover some of these components — including miniature linear slides guides, sensors, encoders, gear, and motors that lend themselves to tiny designs.

TOP MARKETS FOR PRECISION AND MINIATURE MOTION

Semiconductor manufacture continues to spur many of scaled-down machine designs, along with demand for pocket-sized consumer home products and small appliances with motion functions.

Consider the challenging applications of semiconductor manufacturing — including backend wafer inspection. Some operations require motion stages capable of strokes of a few hundred millimeters even while maintaining X and Y-direction accuracy of 1 μm. The extra wrinkle is that some such operations (because of the need for high throughput) must process wafers

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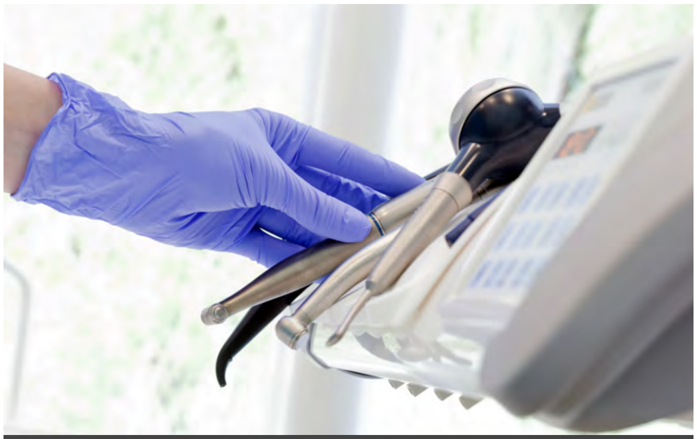
ULTRA-PRECISION AND MINIATURE LINEAR-MOTION SYSTEMS: WHERE AND WHY?

quite quickly — demanding stage speeds of a couple m/sec along with accelerations to 2 g sans significant vibration in the focal Z axis. No wonder the stage kinematics and heat dissipation capabilities as well as its motion-controller sophistication are all so critical.



Miniature motor dentistry application image via Dreamstime

In fact, the manufacture of microelectronics and silicon photonics (ICs employing light along nano-optical structures for driving and fast and efficient data transmission) has grown thanks in part to the kinematics and controls advances for ultra-high-precision motion stages.

Most of these ultra-high-precision motion stages are pre-integrated, as such systems do two things: They free researchers and manufacturers in demanding fields to focus on core competencies, and they outperform serial-kinematic Cartesian-type robots (often built by end users' stacking linear stages into XYZ systems). Such Cartesian-type stages typically require additional degrees of freedom — which are often had through still more (bulky and error accumulating) addition of goniometers and rotational yaw, pitch, and roll stages. In contrast, Stewart (hexapod) platforms deliver motion dictated by the controller and not the mechanical bearings and power-transmission linkages. A user-definable rotational center along with lower inertia and higher stiffness are just a few benefits.

Another option in some instances are ultra-precision motion stages with clever kinematics for well-placed centers of gravity and optimized system dynamics.

Case in point: To address the issue of outer axes causing a moment load on the inner axes, certain gantry systems use two X axes or (in some cases) two Y and two Z axes. Gantries almost always have three axes … X, Y, and Z. The load on a gantry system is located within the gantry's footprint and the gantry is mounted over the working area. However, for parts that cannot be handled from above, gantries can be configured to work from below.

> *Along with inspection, test and measurement, and metrological equipment, aerospace too continues to require pint-sized designs for maximal efficiency and functionality.*

Perhaps the next-biggest driver of miniature motion designs (after the semiconductor industry) is the medical-device industry … a trend likely to grow as COVID demands creative new approaches to medical manufacturing, distribution, and treatment — including more emphasis on automated status-monitoring systems, distributed laboratory operations, and home healthcare.

The medical-device industry necessitates an array of miniature motion designs. Complicating matters is how FDA requirements on medical-device makers and their suppliers continue to include actuator and motor manufacturers in regulatory scrutiny, so controls on design processes continue to tighten — usually as reverification of production lines and test equipment. Overseas competition, medical-device taxes, and withering Medicare reimbursements are also forcing lower costs for devices and the motors for these applications.

A concurrent trend in medical devices — from medical robots to handpieces to implantables — is that they're ever smaller and more compact. So medical continues to adopt technologies from consumer electronics and the small motor-driven designs they enable.

Case in point: Bean-sized mechatronic hexapods employing piezomotors under closed-loop control are indispensable in lens-focusing functions of consumer and smartphone-grade cameras and UAVs. In fact, the six-DOF technology delivers enough precision to drive handheld surgical tools, biometric identification, and in-vitro diagnostics. Some dc motors with diameters of just a few millimeters now have enough power density and reliability to satisfy technical and regulatory requirements for implantable pumps to treat an array of conditions.

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ULTRA-PRECISION AND MINIATURE LINEAR-MOTION SYSTEMS: WHERE AND WHY?

The piezoelectric micromotors in these hexapods are complemented by miniature bearing assemblies, motor mounts, flexures, spring preloads, and miniature drive electronics to cancel hand-tremor movements during the use of microsurgical tools.

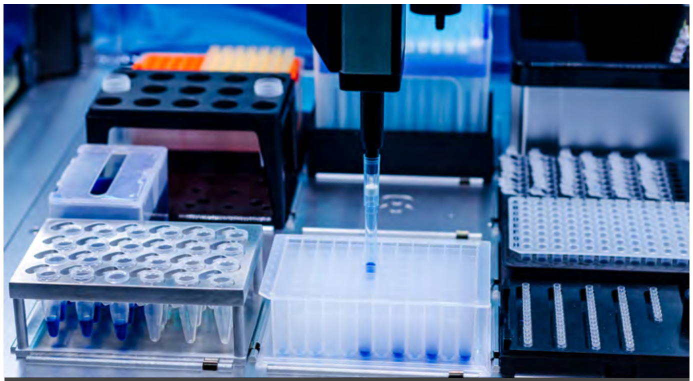
Elsewhere, miniature motion designs automate processes that surgeons still do manually. Consider an implant procedure in which a doctor must physically turn a knob to locate and move a device inserted into a patient's body. Now, automated motion systems integrating tiny gearmotor, leadscrew, and nut can execute such tasks more precisely. Of course, such tools must be extremely small and sterile and (because they're single use) must be inexpensive.

Another application example demanding increased power density and miniaturization is brushless dc cannulated gearmotors — those with gearbox-motor combinations that (among other things) allow for inline driving of *Kirschner wires* and pins in orthopedic surgery. Demand for cannulated gearmotors is rising as orthopedic-drill designers are looking to decrease their designs' overall size.

Where applications require tight integration (as for handheld or mobile designs) shrinking semiconductor sizes have let miniature-component suppliers integrate ever-smaller drives and controls into smaller and smaller motors for top reliability and cost effectiveness.

While the machines and devices get smaller, in many cases they must also be increasingly precise. Consider the interest in making more inpatient procedures into outpatient procedures. To this end, surgeons are now using robots or motor-assist tools to boost accuracy. Even risky forms of eye and brain surgery now rely on motor-driven automation to let doctors treat diseased areas in the body while avoiding healthy tissue.

The medical industry is also prompting electric-motor innovation for smaller and less costly designs. For example, motor-driven tools in operating rooms must draw low voltage and be quiet. Here, traditional peristaltic pumps can be noisy, especially when they're in a bank or driven by brush motors. Some manufacturers have addressed the problem with alternative dc-motor designs paired with quiet planetary gearing. Another example is portable oxygen concentrators that demand long life because they run off batteries. Miniature motion designs in these are increasingly efficient and power dense as well.



A tabletop stage for liquid handling and pipetting might maintain positional accuracy to 50 μm at speed to 20 mm/sec with a load capacity of 500 g. With horizontal and vertical travels measured in a few dozen millimeters, some contexts might classify this as a miniature motion design … while others would not.

CAVEAT ON MOTION-INDUSTRY TERMINOLOGY

The motion-control industry (like any) has its own system of terminology and naming conventions. The nomenclature for motion components and technologies are highly dependent on the discrete-automation market and equipment type at hand. Where nanopositioning or miniature design is not specifically mentioned, design engineers should assume that traditional definitions (associated with more mainstay machine builds) apply. In fact, even the term *miniature* can refer to components and systems in a broad range of footprints.

Other potentially ambiguous motion-industry designations that rely on context include *heavy duty, corrosion-resistant*, and *high speed.* Linear-actuator manufacturers do in fact follow some loose guidelines when classifying and marketing their actuators as high speed. These guidelines are typically based on the drive mechanism, actuator type, and even primary use or industry.

But those definitions of high speed lose their relevancy in micro and nano-positioning applications — for which the actuators of choice are often voice coil or piezo technologies. Ultrasonic piezo actuators can reach speeds of 0.5 m/sec or greater, but they typically have maximum strokes of 100 mm or less. Voice-coil actuators operate at speeds to 2 to 3 m/sec with strokes that are typically to 150 mm … although some variations have strokes to beyond 250 mm. These specifications may not fit the general industry definition of high-speed linear actuators. That

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ULTRA-PRECISION AND MINIATURE LINEAR-MOTION SYSTEMS: WHERE AND WHY?

said, considering the rapid acceleration required to reach these speeds in very short stroke lengths, piezo and voice coil designs are certainly classifiable as high-acceleration actuator options.

> *Piezo actuators (including ultrasonic variations) and voice coil actuators aren't necessarily high-speed actuators, but they certainly qualify as high-acceleration components.*

WHERE MINIATURE MOTION COMPLEMENTS TRADITIONAL BUILDS

It's common for miniature high-precision actuators to complement standard actuators — where they're often put in series for efficient travel over large strokes followed by superfine final positioning. This example is often called a hybrid linear actuator — not to be confused with these based on hybrid stepper (linear or rotary) motors.

Multi-axis surface-roughness metrology equipment image via Dreamstime

Another example is vertical lifts on XYZ stages.

In many applications that require vertical motion, a Z-axis actuator combines with one or two horizontal axes in a Cartesian or gantry-style arrangement. In such multi-axis configurations, the moved load is mounted to the Z axis via a bracket — creating a moment load that affects the Z axis as well as the horizontal (X and Y) axes. This cantilevered load can induce deflection in the supporting linear guides, actuator housings, and brackets … in addition to unacceptable settling times and oscillations in highly dynamic applications. Therefore, applications that require vertical motion with high rigidity and minimal deflection sometimes use a vertical lift stage rather than a traditional Z axis actuator.

A vertical lift stage uses a flat horizontal table to support a load as it moves vertically to eliminate cantilevered loads that can cause deflection. In fact, there are several design variations of vertical lift stages. However, any stage demanding extremely smooth and accurate travel (and high positioning accuracy) typically consists of a table connected to crossed-roller slides in a wedge arrangement. A ball or leadscrew drives the table in the lateral direction, and the wedge arrangement of the crossed-roller slides transforms the horizontal motion from the screw into vertical motion of the table. This design provides very accurate travel and positioning accuracy … but is typically limited to stroke lengths of 25 mm or less.

Another common design for vertical lift stages uses:

- a vertical linear guide at each corner (or in some cases, six linear guides evenly spaced around the table area) and
- a vertical ball or lead screw located in the center.

The guides are typically round shafts with recirculating linear bushings because the latter provide very smooth motion and have a lower tendency to bind when a design needs four (or more) guides in tandem. That's because linear-motion guides based on recirculating-ball linear bushings can accommodate for misalignment.

The benefit of this vertical lift stage design is the ability to carry larger and heavier payloads while maintaining smooth, precise motion and good parallelism between the table and base during motion. Available stroke lengths are also longer than for the screw-driven wedge design — up to several hundred millimeters in some cases.

Note that both types of vertical lift described above are termed stages because they're designed for extremely accurate travel and positioning in the Z direction … much like XY stages that use high precision linear guides and ball or leadscrew drives. However, in the screw-driven wedge design the table surface is typically machined to a very tight flatness tolerance, so it more closely fits the traditional definition of a stage than does the screw-driven linear guide version.

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ULTRA-PRECISION AND MINIATURE LINEAR-MOTION SYSTEMS: WHERE AND WHY?

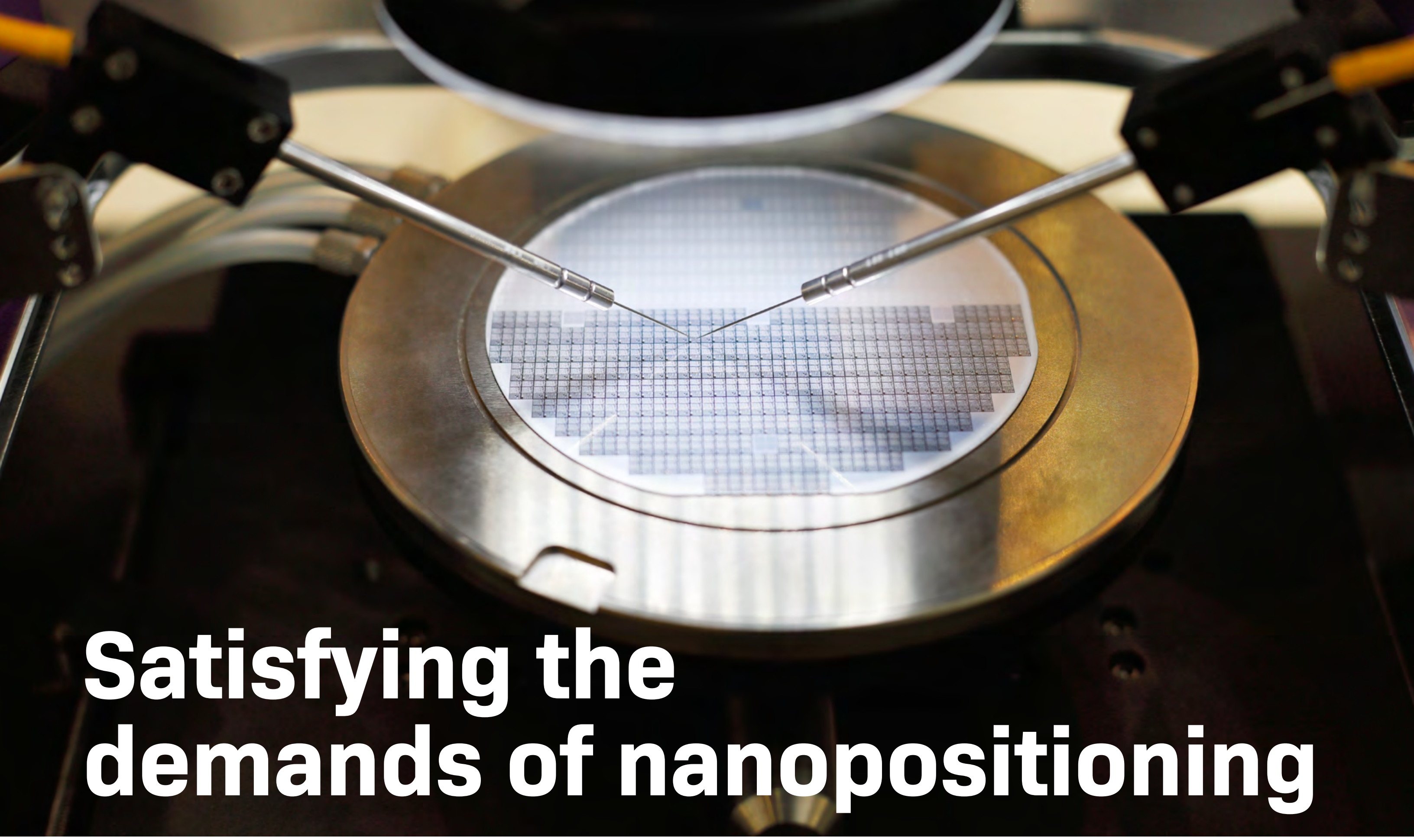
Of course, vertical lifts used in material handling and people-moving applications are vastly different than the vertical motion systems covered here and elsewhere in this Design Guide … and to be clear are often called vertical platform lifts or (where applicable) scissor lifts.

GANTRY ARRANGEMENTS VERSUS TABLES AND CARTESIAN ROBOTS IN PRECISION APPLICATIONS

Gantry-type multi-axis motion systems of any size are suitable in applications with relatively long strokes — generally considered greater than one meter for standard applications and a few hundred millimeters for miniature arrangements. That's because gantries can transport very heavy payloads unsuitable for moving via cantilevered stage kinematics. In fact, one of the most common uses for gantry systems is in overhead transport — as for moving large automotive components from one station to another in assembly facilities.

XY tables are like XY Cartesian systems in that they have two axes (X and Y as their name implies) mounted on top of each other — and typically have strokes of one meter or less. But the key difference between XY Cartesian systems and XY tables lies in how the load is positioned. Instead of being cantilevered as in a Cartesian system, the load on an XY table is almost always centered on the Y axis with no significant moment created on the Y axis by the load.

This is where the end use helps distinguish between the various types of multi-axis systems. XY tables generally work only within their own footprint, meaning the load does not extend beyond the Y axis. This makes them best suited for applications where a load needs to be positioned in the horizontal XY plane. A typical example is a semiconductor wafer being positioned for inspection or a part being positioned for a machining operation to take place.



Satisfying the demands of nanopositioning

Probe testing of semiconductor wafers requires motion designs capable of nanopositioning. Image via Dreamstime

Ultra-high performance piezo nanopositioning stage for 6-axis semiconductor AFM measurements. Image courtesy PI (Physik Instrumente) L.P.

When we talk about linear motion, we typically discuss applications where the travel distance is at least a few hundred millimeters, and the required positioning is in the range of a few tenths of a millimeter. And for these requirements, guides and drives with recirculating bearings are a good fit. Case in point: the lead deviation for a common class 5 ball screw is 26 microns per 300 mm of travel. But when the application calls for positioning in the nanometer range — one-billionth of a meter — engineers must look beyond mechanical rolling and recirculating elements to get the required resolution.

The three most common linear motion solutions for nanopositioning are piezo actuators, voice coil actuators, and linear motor stages. The drive mechanism in each of these solutions is completely free of mechanical rolling or sliding elements, and they can be paired with air bearings for high positioning accuracy and resolution.

Piezo actuators: As we'll cover in more detail later in this Design Guide, piezo actuators (also referred to as piezo motors) take advantage of the reverse piezoelectric effect to produce motion and force. There are many styles of piezo actuators, but

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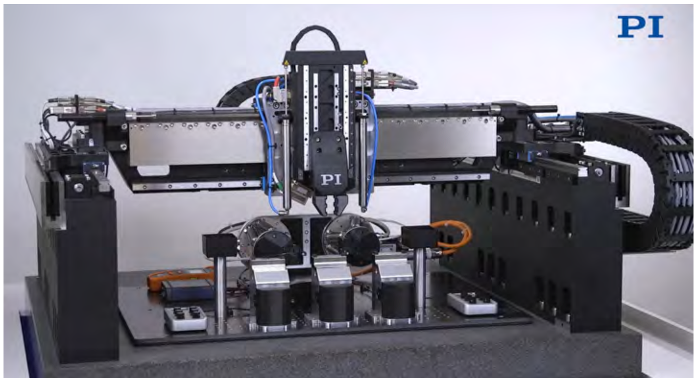
SATISFYING THE DEMANDS OF NANOPOSITIONING



High-speed pick & place gantry linear robot for photonics alignment applications. Image courtesy PI (Physik Instrumente) L.P.

two common ones for nanopositioning are linear stepper and linear ultrasonic. Linear stepper piezo motors use several piezo elements mounted in a row that act as pairs of legs. When an electrical charge is applied, one pair of legs grips a longitudinal rod via friction and moves it forward as the legs extend and bend. When this pair of legs releases, the next pair takes over. By running at extremely high frequencies, linear stepper piezo motors produce continuous linear motion with strokes up to 150 mm and with picometer-level resolution.

Fast focusing Z-stages for high resolution microscopy and surface metrology. The P-725 piezo flexure nanopositioning drive on the left provides up to 800µm travel, sub-nanometer sensitivity, friction-free motion with excellent straightness, and extremely fast response. The voice-coil driven stage with cross-roller bearings on the right incorporates an adjustable magnetic counterbalance and provides 7mm travel with 10nm step size. Image courtesy PI (Physik Instrumente) L.P.

Linear ultrasonic piezo motors are based on a piezoelectric plate. When an electrical charge is applied to the plate, it becomes excited at its resonance frequency, causing it to oscillate. These oscillations produce ultrasonic waves in the plate. A coupling (or pusher) is attached to the plate and preloaded against a longitudinal rod — also called a runner. The ultrasonic waves cause the plate to expand and contract in an elliptical manner, enabling the coupling to advance the rod forward and produce linear motion. Linear ultrasonic piezo motors can achieve resolution of 50 to 80 nm, with maximum travel comparable to that of linear stepper motors — 100 to 150 mm.

M-112.2DG1, Ultra-compact linear translation stage with closed-loop motor and 50nm minimum incremental motion, for focusing, alignment, and precision assembly. X, XY, and XYZ versions available. Image courtesy PI (Physik Instrumente) L.P.

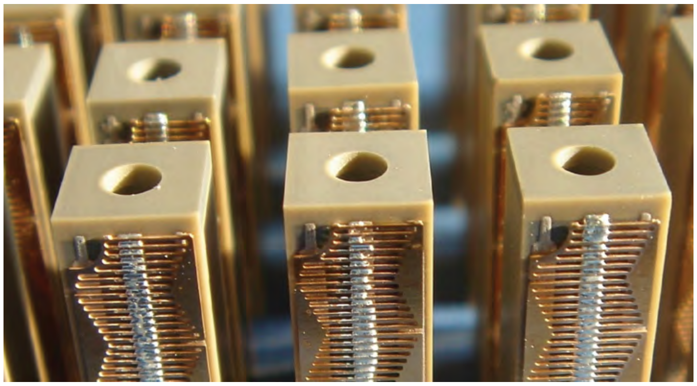
Voice coil actuators: Another solution for nanopositioning applications are voice coil actuators. Like linear motors, voice coil actuators use a permanent magnet field and a coil winding. When current is applied to the coil, a force is generated (known as the Lorentz force). The magnitude of the force is determined by the product of the current and the magnetic flux. This force causes the moving part (which can be either the magnet or the coil) to travel, with guidance provided by either air bearings or crossed roller slides. Voice coil actuators can achieve resolution down to 10 nm, with strokes typically up to 30 mm, although some are available with strokes up to 100 mm.

Solenoids are another solution for nanopositioning applications. However, they are simply on-off devices sans ability to control the stroke, speed, or force. Solenoids are typically used for opening and closing valves and for driving microliter or nanoliter pumps.

Linear motor stages: When nanometer resolution is required over longer strokes, linear motor stages with air bearings are typically the best choice. While piezo and voice coil actuators have limited travel capabilities, linear motors can be designed for travel up to several meters. The use of air bearings as the guide system makes a linear motor stage completely non-contact, with no mechanical transmission elements or friction to affect the motion and positioning accuracy. In fact, linear motor stages with air bearings can achieve single-nanometer resolution.

The downside of linear motor stages for nanopositioning applications is their footprint, which is much larger than that of piezo or voice coil actuators. While they can be challenging to integrate into small devices, they are a good fit for applications needing a relatively long stroke and high resolution, such as medical imaging.

THE WIDE WORLD OF
PIEZO-BASED MOTION ACTUATION



This custom ceramic-encapsulated piezo stack from PI is used for active optics and nano-dispensing applications.

Piezo elements are ceramics that change shape when subject to electricity or (when subject to mechanical loading) output electricity. Manufacturers process and press plumbum, zirconate, titanate (PZT) powder together and fire it into a quartz. Then they integrate the ceramic with ferroelectric material to make electrodes.

Finally, manufacturers apply electromagnetic fields to the piezo elements to align and polarize the material.

Discovered by Pierre and Jacques Curie in the late 1800s, piezo elements are named for the Greek word for press — *piezein*. The Curies found that compressing crystals of potassium sodium tartrate (also called Rochelle salt after the place of its original formulation) create electric voltage … and that electrifying piezo crystal makes it deform. Original-piezo-material-Rochelle-salt Today, other piezo crystals immune to humidity are used in engineered systems … but the shape-changing capacity is what all piezo technologies use today.

TYPES OF PIEZOMOTORS

Piezo elements are at the core of myriad transducers and sensors, and those piezo-based components are perhaps the best known by engineers. Yet piezo-element solid-state piezomotors abound to move loads over short distances.

The most basic piezomotors generate motion by expanding proportionally to voltage. Stacked, shear, and tube piezomotors are three common options here. The former generate high forces but only to 20 µm or so. The latter (common in medical and dispensing applications) can move several millimeters but with less force.

Slightly more complex are flexure-guided piezomotors with motion amplifiers for long and straight moves. Motion is proportional to the drive voltage; multi-axis stages move up items a couple millimeters or more.

Ultrasonic-friction piezomotors have oscillating plates that act as the stator to advance a slide or rotor via friction. These output unlimited motion quickly, sometimes within 0.8 msec from the input command — though resolution is only 60 nm or so.

Note that some sources call ultrasonic piezomotors standing-wave piezomotors for the way in which they output motion. The only catch with ultrasonic piezomotors is that their reliance on friction to advance a slide or rotor can have a limiting effect on resolution.

For stepping piezomotors, manufacturers gang multiple piezo elements together to get actuator setups that can move more than 100 lb. The motors make longer strokes than most other options, and they do it quickly (within 0.8 msec in some cases). Piezo stepping motors can also get picometer resolution under direct piezo actuation under what's called dithering.

PI's PiezoWalk actuators were developed for semiconductor OEMs to deliver top reliability, position resolution, and long-term stability. From left to right are a PiezoWalk N-331 PICMAWalk capable of high velocity (to 15 mm/sec); a compact PiezoWalk N-310 NEXACT with moderate speed capabilities (and forces to 10 N); and a PiezoWalk N-216 NEXLINE delivering feed and holding forces approaching 800 N.

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THE WIDE WORLD OF PIEZO-BASED MOTION ACTUATION

Advancing controls can deliver increasingly stringent performance from piezo-flexure stages that output high-bandwidth actuation over multiple degrees of freedom. These drive advanced microscopies that burst the Rayleigh limit; semiconductor lithography that tracks Moore's Law down to the atomic scale; silicon photonics manufacturing; and genomics analyzers.

Basics of ultrasonic piezomotors: As mentioned, in ultrasonic piezoelectric motors, the ceramic material vibrates over a few nanometers at a time to output linear or rotary motion to 550 mm/sec.

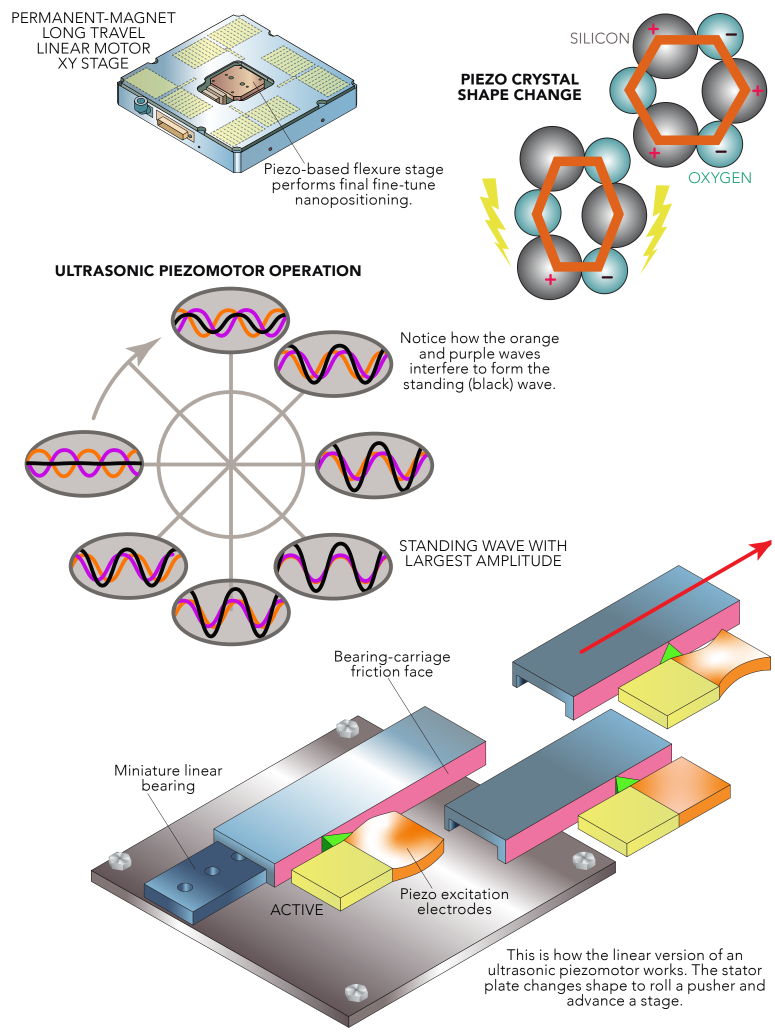
Electricity excites a piezoceramic plate (that acts as the motor stator) through electrodes. That induces oscillations at the material's natural frequency at some number of kilohertz. The plate has a friction pusher that takes it along an inclined path at the eigen frequency. With each oscillatory cycle, the motor advances. Two main benefits of ultrasonic piezoelectric motors is that:

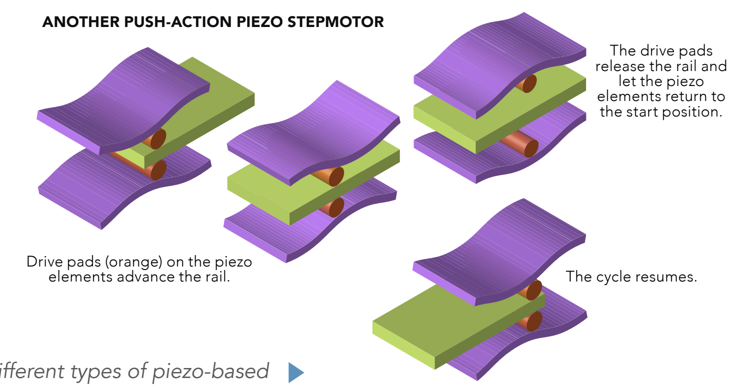
1. They are efficient substitutes for miniature electric-motor spindles
2. They make moves with resolution down to nanometers

Basics of stepper piezomotors: The leading piezo-motor option for longer strokes are steppers. These have an array of individual piezo elements that perform a sequence of expansions and contractions. Each cycle only moves the attached load a few micrometers … but at an average of 500 to 3,000 Hertz, the steps let the motor deliver speeds to 15 mm/sec. Useful for scanning applications, stepper piezomotors can also withstand external magnetic fields.

Rotary step piezomotors cycle frame-affixed crystals through states. One crystal set locks the rotor while a second set moves to advance a third. Controls then release the first crystal set and retract the third. Then both locking sets return to home.

In contrast, linear step piezomotors cycle frame-affixed crystal sets through locked and motive settings. Usually, one set is moving while the other two lock.





Shown here are different types of piezo-based motors and actuator arrangements.

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THE WIDE WORLD OF PIEZO-BASED MOTION ACTUATION

DEEPER DIVE ON LINEAR ULTRASONIC PIEZOMOTORS

Ultrasonic piezomotors create useful rotary or linear motion by exciting a piezo element to produce high-frequency oscillations. In linear ultrasonic piezomotors, the piezo element is a piezoelectric plate. Applying voltage excites the plate at its resonance frequency and creates eigenmode oscillations – meaning all parts of the plate move sinusoidally at the same frequency. The piezoelectric plate is preloaded against a runner (also called a slider) via a coupling, or pusher. Oscillations in the plate cause it to expand and contract, moving the coupling along an inclined patch. The coupling in turn contacts the runner and causes it to linearly move.

Ultrasonic piezomotors are sometimes called ***standing wave piezomotors*** due to the type of wave generated when the piezoelectric material is excited. A standing wave is formed when an incident (original) wave and a reflected wave interfere in such a way that there are points along the medium that appear to be standing still … hence the name ***standing wave***.

A common application for ultrasonic piezomotors is the autofocus mechanism found in cellphone cameras. Image via Dreamstime

Although linear ultrasonic piezomotors are capable of unlimited travel, the length of the runner determines the actual stroke, with maximum travel capabilities of 100 to 150 mm. Linear ultrasonic designs have low inertia with fast response times and can achieve velocities up to 500 mm/sec and accelerations of 10 to 20 *g*. On the other hand, they're also capable of ultra-slow motion, down to just a few nanometers per second. Because they rely on friction between the coupling and the runner, resolution is somewhat limited (relative to other piezomotor designs) to between 10 and 20 nm. But this friction allows ultrasonic piezomotors to be self-clamping in a power-off condition … capable of producing 2 to 3 N of holding force sans heat generation.

This is a PI (Physik Instrumente) L.P. direct-drive micropositioning stage employing ultrasonic piezomotors.

Linear ultrasonic piezomotors are most common in metrology and scanning equipment. Because they're vacuum-compatible and contain no magnetic components, they're well-suited for use in military and aerospace applications, such as guidance systems and antenna positioning. Medical imaging devices often incorporate linear ultrasonic piezomotors for fine positioning of imaging equipment.

Ultrasonic piezomotor performance characteristics: Ultrasonic piezomotors are direct-drive mechanisms, meaning they have no mechanical couplings or gears to induce backlash. However, their reliance on friction between the stator and the rotor (or between the pusher and the slider, in the case of a linear motor), limits their resolution to 10 to 20 nm. This friction does offer an advantage, though — in the form of a holding force when no power is applied.

The working principle of ultrasonic piezomotors, coupled with their low inertia, give them very fast response times, with maximum velocities up to 500 mm/sec (600 to 800°/sec for rotary motion) and accelerations of 10 to 20 *g*. Ultrasonic piezomotors are inherently vacuum compatible … and because there are no magnetic components, they can be used in environments with strong magnetic fields.

Ultrasonic piezomotor applications: The most common application for ultrasonic piezomotors is the autofocus mechanism found in cameras, but high-precision imaging and scanning equipment of all kinds, including surveying and metrology devices, benefit from their speed and resolution. Other applications include military and aerospace equipment — especially the positioning of antennae or fine control

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THE WIDE WORLD OF PIEZO-BASED MOTION ACTUATION

of guidance systems. In the medical industry, ultrasonic piezomotors are used in life sciences equipment for nanoliter pumps, dispensing, and dosing, and in medical devices for control and positioning of imaging equipment.

HOW PIEZO-BASED ACTUATORS ARE CLASSIFIED

Piezo actuators harness the behavior of piezo materials to provide short motion strokes with high frequency and fast response times. They also generate high forces relative to their small size, giving them a significant power-to-size ratio.

Note: Because of their conversion of electrical energy to mechanical energy, piezo devices are often referred to as motors, but the term *actuators* is used interchangeably.

The piezoelectric effect produces motion that is parallel to the electrical field. Some actuators, however, operate on the transverse piezoelectric effect, in which motion occurs orthogonally to the electrical field. There are four main types of piezo actuators, distinguished by the arrangement of their piezo elements and by the type of movement they generate.

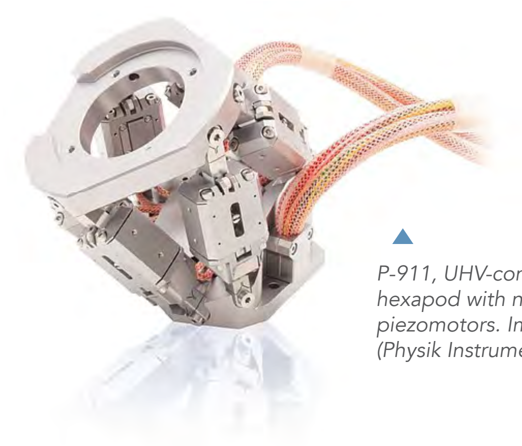
Longitudinal piezo actuators: Also called piezo stacks, longitudinal piezo actuators are created by layering multiple piezo elements on top of each other, thus combining the effect of each element's expansion to produce a useful movement and force. These actuators use the piezoelectric effect to generate linear displacements from 0.1 to 0.15 percent of the actuator length. They have a high force density — typically in the range of 30 N/mm2 — resulting in useful force in the thousands of Newtons. Longitudinal piezo actuators also have high resonant frequencies, which makes them well-suited for dynamic applications. For more information on stacked piezo actuators, read this FAQ: What are stacked piezo actuators and what do they do?

Shear piezo actuators: These are like longitudinal versions in that they consist of multiple layers of piezo elements. But they differ in how the voltage is applied and the type of motion created. For shear piezo actuators, the elements are polarized horizontally, and the electrical field is applied orthogonally. The resulting displacement occurs in the horizontal plane, creating a shear-type motion. The height of shear actuators is limited by shear stresses and bending, but they are often combined with longitudinal actuators in multi-axis systems.

Tube piezo actuators: Tube actuators have radial polarization and use the transverse piezoelectric effect to create displacement. These actuators can experience axial, radial, or lateral (bending) motion depending on how the voltage is applied relative to the electrodes. Piezo tube actuators are not suitable for producing forces, but they provide micron-level travel for scanning microscopes and nanoliter dosing and pumping applications.

Contracting piezo actuators: Flat actuators with two piezo elements can produce contracting (or expanding) motion when both elements act together. These actuators use the transverse piezoelectric effect and typically produce motion in just one direction. Contracting and expanding piezo actuators have small displacements (to 20 μm) but can generate hundreds of Newtons of force.

When a contracting actuator is mounted to a base or substrate, a bending actuator is created. In a bending actuator, the applied voltage causes one piezo element to expand while the other contracts. The result is a bending motion with relatively large displacement (typically several millimeters) but low force generation.



P-911, UHV-compatible miniature hexapod with non-magnetic piezomotors. Image courtesy PI (Physik Instrumente) L.P.

Note: When specifying a piezo actuator, two parameters are usually considered—free deflection Xf and blocking force Fb. Free deflection is the movement achieved when the maximum allowable voltage is applied, and no force is generated. Similarly, blocking force is the maximum force that can be generated when the maximum allowable voltage is applied … and the actuator is not allowed to move. A piezo actuator is optimized for the application when it provides the required force at one-half its free deflection.

As we'll explore in more detail later in this Design Guide, piezo actuators can often replace solenoids in valves, pumps, and dispensing equipment. Plus, they can withstand

(continued)

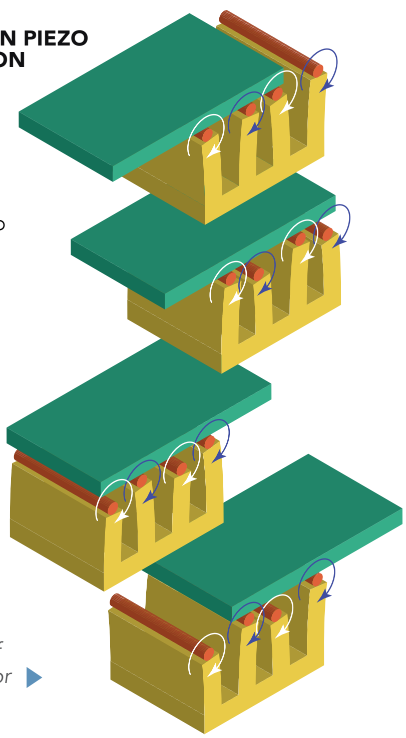
THE WIDE WORLD OF PIEZO-BASED MOTION ACTUATION

PiezoWalk actuator image courtesy PI (Physik Instrumente) L.P.

WALKING-LEGS PUSH-ACTION PIEZO STEPMOTOR OPERATION

Current to all the legs causes them to elongate and bend. Then the first pair of legs lift and advance the output linkage while the other two retract. Then the latter advance the output linkage while the first two retract.

Finally, all four legs return to their start position to repeat the cycle.



Shown here is one type of piezomotor-based actuator based on walking-leg kinematics.

extreme environments — such as the high vacuums found in semiconductor processing equipment and the strong magnetic fields found in MRI machines and aerospace components. Complete piezo stages can be created by incorporating piezo actuators with cross roller bearings or miniature guides, and these stages can be stacked to provide X-Y or X-Y-Z motion.

The most interest in piezomotor-driven miniature actuators is for applications subject to space and power limitations — and exacting precision requirements. After all, piezomotors are smaller and more efficient than traditional copper-winding-based miniature motors … and piezomotor actuators can very stably hold position sans continuous power input or a mechanical brake. The small actuator size allows for the construction of very small positioning stages as well.

DESIGN CONSIDERATIONS WHEN APPLYING WALKING PIEZOMOTORS

Piezomotors that produce linear motion include linear ultrasonic piezomotors, linear stepper piezomotors, and piezo inertia motors. Although their construction and principles of operation are different, all three designs harness the inverse piezoelectric effect — in which a piezo material expands or contracts when electrical energy is applied to produce linear movement in a longitudinal rod.

How do you get a piezomotor to walk? One step at a time. Linear stepper piezomotors are made up of several (typically four) piezo stack actuators mounted in a row. The four actuators can undergo two types of motion (expansion and contraction in length and sideways bending) are activated in pairs … analogous to legs.

Applying voltage to the piezomotor causes one pair of piezo elements (legs) to extend downward and grip a longitudinal rod (also called a runner) via friction elements on the ends of the legs. Next, the legs bend sideways to advance the runner … and then contract to release the runner. As this is happening, the next set of legs is extending downward to grip the runner, advance it forward, and then retract.

The motion produced with each step or cycle is only a few μm, but linear stepper piezomotors make thousands of steps per second, so they can generate long stroke lengths at high speeds. (They can also travel at extremely slow speeds, in the range of a single micron per second, which is a requirement for precision dispensing and measuring applications.) Although the

(continued)

THE WIDE WORLD OF PIEZO-BASED MOTION ACTUATION

N-470, PiezoMike miniature piezo motor actuator, for optical alignment applications. These compact, programmable actuators provide holding force to 100N, step size resolution of 20nanometers, and travel ranges to 13mm. The piezo motor is self-locking at rest with no heat generation. Image courtesy PI (Physik Instrumente) L.P.

piezo actuators can produce unlimited linear motion, the stroke of a linear stepper piezomotor is limited by the length of the runner. Travel lengths up to 150 mm can typically be achieved with speeds to 15 mm/sec.

Linear stepper piezomotors can generate push or pull forces and holding forces of up to 50 N, and the legs can be preloaded to the runner to produce a self-clamping force with high stiffness, even when no voltage is applied.

Because piezo devices produce no magnetic flux, and all parts of the linear stepper piezomotor can be made from non-magnetic materials, they're well-suited for environments with strong magnetic fields. In fact, most designs use inorganic materials for insulation and electrical contacts, so they have very low outgassing and can withstand high bakeout temperatures — in turn making them compatible with ultra-high-vacuum environments.

Linear stepper piezomotors can be used to drive crossed roller slide stages to get extremely low friction and high stiffness. And because there's no backlash in the driving mechanism (the piezo actuators), resolution in the nanometer and (in some cases) sub-nanometer (picometer) range can be achieved when microstepping control is used. This makes stages driven with linear stepper piezomotors ideal for microscopy and scanning applications.

Additional piezo-related articles:

Difference between piezo actuators and piezo motors

Linear motion applications for piezo actuators and piezo motors

Hysteresis and piezo actuator performance

Piezo flexure stages and how they work

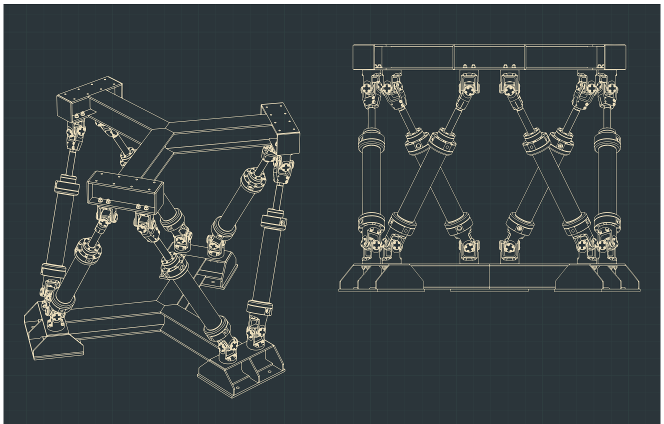
THE SPECIAL CASE OF HEXAPODS

Multi-axis systems can be designed and built with either serial kinematics or parallel kinematics. In systems built on the principle of serial kinematics (including Cartesian robots) one axis sits on top of another axis, and each axis is driven independently of the others. In contrast, parallel kinematic systems (including hexapods and delta robots as shown here) have multiple axes that work together to move a common platform or end effector. The movement of one axis is constrained by the other axes — forming a type of closed kinematic chain.

Today's positioning tables and stages include hardware and software that's more customized than ever to satisfy specific output requirements. That's made for motion designs that move accurately through even complicated multi-axis commands.

Precision feedback is key to such functionality — often taking the form of optical or (electronics-augmented) magnetic encoders for nanometer-scale resolution and repeatability … even over long travel. In fact, miniature stage design is spurring the most innovation from feedback and control algorithms to move even very large loads with sub-sub-micron precision.

First some background: Use of pre-engineered stages and Cartesian robots continues to rise with rapid prototyping, automated research applications, and tighter time-to-market pressures. That's especially true for photonics, medical-device, and semiconductor R&D and manufacturing. In the past, building multi-axis motion for automating or otherwise improving tasks meant design engineers had to source and combine linear stages into X-Y-Z combinations … in-house. Any more degrees of freedom necessitated the after addition of goniometers, rotary stages, and other end effectors.



Stuart platforms constitute a type of parallel kinematics.

Called serial kinematics, such machine builds sometimes result in bulky setups with accumulated error due to tolerance stack-up. In some cases, bearings also limit such assemblies to one rotational center. These are non-issues when the design satisfies its motion requirements — but miniature motion designs aren't so forgiving of such factors.

Contrast these builds with hexapod or Stewart platforms — forms of parallel kinematic actuators for motion. Hexapods are six-degree-of-freedom (DOF) motion systems that derive six-axis movement (XYZ along with pitch, roll, and yaw) from actuators placed in parallel between a top and bottom platform. Available in a variety of sizes with bases ranging from 100 mm to a meter or more in diameter — along with the ability to bear loads of 2 to 1,000 or more kg — hexapods' top traits are stiffness, precision, and controllability.

> *A Stewart platform is a type of hexapod robot for which actuators connect in pairs at the stationary or moving platform … or both.*

At least for miniature multi-axis motion assemblies, these hexapods outperform serial kinematics. That's in part because hexapod output motion isn't limited by bearing (linear and rotary) ratings.

(continued)

THE SPECIAL CASE OF HEXAPODS

Instead, the motion controls execute algorithms to an application-defined pivot point (center of rotation) unencumbered by error accumulation. Lower component count, lower inertia, and higher stiffness are other benefits. As detailed in related articles on linearmotiontips.com, traditional motion systems can often work in conjunction with positioning stages having parallel kinematics — and traditional electromagnetic motors with piezoelectric motors … even on common assemblies or installations.

The term *hexapod* originates from the Latin meaning *six feet* … and hexapod robots fittingly consist of six actuators or legs that connect a stationary platform (typically the base) with a moving platform — typically the top. The legs are extending-rod style actuators — also called prismatic actuators — which can be driven by ballscrews, roller screws, linear motors, or even piezo devices. Ball joints or universal joints connect the ends of the actuators to the stationary and moving platforms.

This PI H-811.F2 high-dynamics hexapod is designed for photonics alignment applications needing six degrees of freedom. Its actuator resolution is to 5 nm and repeatability to 60 nm … at speeds to 20 mm/sec. Bearing loads to 5 kg, the hexapod features a removable magnetic plate to accelerate workflow with fiber-optics components. Travel is to 34 mm and 42° of rotary motion.

Did you know that butterflies are hexapods? Some manufacturers and experts refer to hexapod robots as simply *hexapods* — but the term hexapod also refers to a six-legged arthropod. To avoid confusion, some sources in the automation industry use the more specific term *hexapod robot.*

The first practical applications for hexapod mechanisms were in tire testing and flight simulator equipment, both of which still use hexapod robots today. But hexapod mechanisms are also widely used in photonics and optical alignment, positioning for machine tool equipment, and inspection systems.

H-850k, Hexapod 6-axis stage for satellite test and astronomy applications. Image courtesy PI (Physik Instrumente) L.P.

Hexapod robots are unique among multi-axis systems because they allow a user-defined center of rotation, or pivot point, for all six axes of motion. They also have much higher stiffness and load-carrying capability than serial kinematic robots (Cartesian, SCARA, or six-axis) because their actuators (legs) work together to support the load. The parallel design also means that the errors of each actuator are averaged, rather than accumulating as they do in serial robots.

Because only the top platform moves (and their motors, gearboxes, and other transmission components are stationary) hexapod robots have much lower inertia that serial designs. That in turn renders them very well-suited to highly dynamic moves with large payloads, or for sub-micron precision with light loads. Of course, hexapods integrate various drive systems — including shaft linear motors for precision, torque-motor-and-roller-screw drives for heavy loads and fast strokes, and torque-motor-and-ballscrew drives for moderate loads and speeds.

CONTROLLING HEXAPODS FOR INDUSTRIAL AND RESEARCH APPLICATIONS

From an integration standpoint, hexapod robots are also easier and faster to commission than serial-linkage arrangements. Controllers typically allow a simple input for the pivot point, and hexapod robots often forego servotuning. That's because there is only one moving platform and system stiffness is inherently high. Where tuning is required, the parameters for all six axes are identical — making the tuning process much easier and faster than with serial robots.

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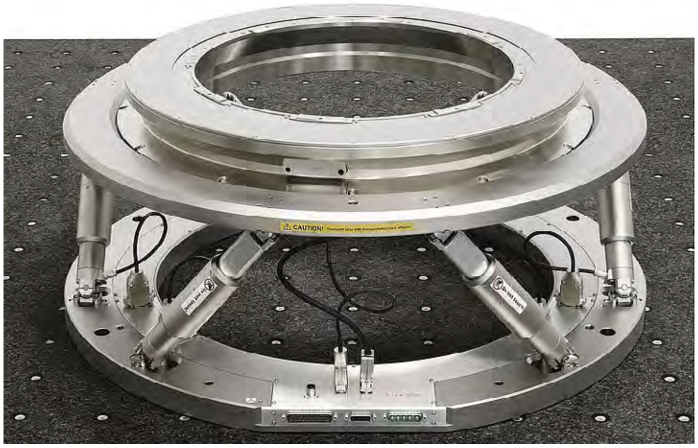
THE SPECIAL CASE OF HEXAPODS



Hexapod with large aperture and additional 7th axis for continuous rotation. Image courtesy PI (Physik Instrumente) L.P.

Hexapod devices are analyzed using reverse kinematics. In other words, rather than the displacement of the moving platform being determined by the actuator movements, the actuator movements are determined based on the displacement of the platform. Reverse kinematic analysis is necessary because a given set of actuator displacements can result in 40 different platform positions … but each unique platform position corresponds to only one set of actuator displacements.

The kinematics of hexapod devices can also give rise to *singularities* — or positions at which the platform becomes uncontrollable. It is at these singularities where position cannot be uniquely determined by fixing the displacements of the actuators. (In extreme cases, a singularity may cause the entire system to effectively collapse.) But users of hexapod robots rarely must deal with the issue of singularities — because manufacturers define the robot's working area to a space that doesn't include any points of singularity.

Complex motion generation is an increasingly important hexapod application — especially for vehicular simulations, airborne platform tests, and operator training. So are structural and active mechanical subsystem analysis and validation. For the latter, hexapods excel in providing highly dynamic motion at sub-micrometer position resolution and stability.

The newest hexapod applications include those related to precision industrial machining and assembly, motion and vibration simulation, image stabilization, and the positioning of optomechanical (as well as other precision components).

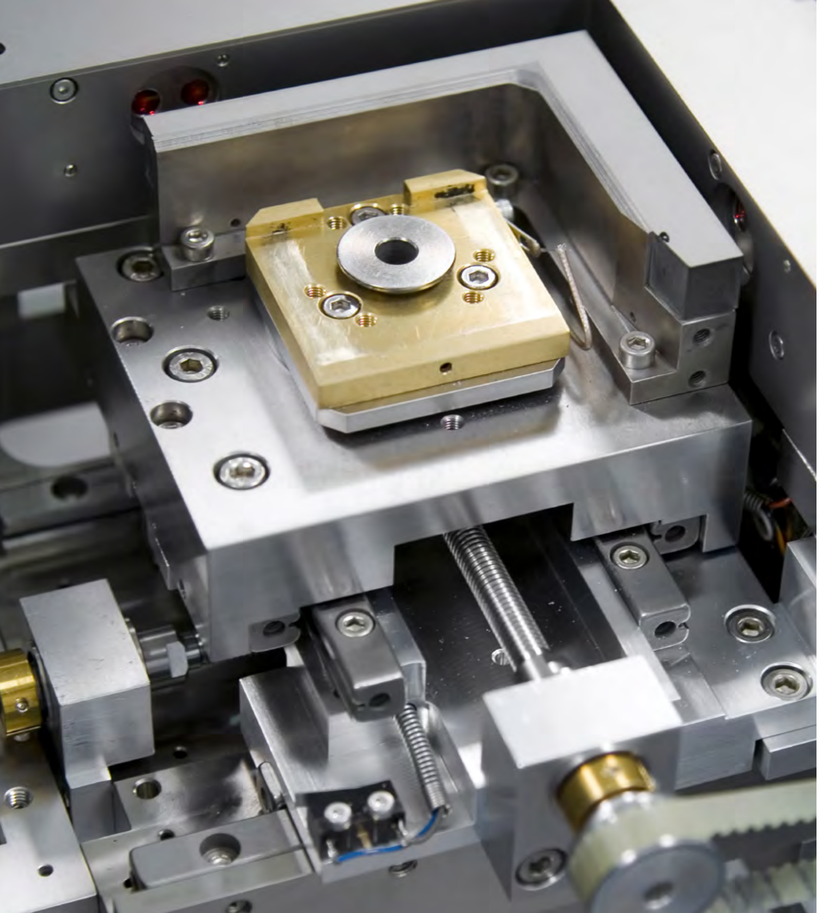
Hexapod motion range is not dissimilar to that of the human hand. Typically, a six-axis vector motion controller provides smooth vectorized motion. The main reference is a user-defined pivot point (center of rotation) adjustable in realtime via software. Alignment, tracking and trajectory tracing are common hexapod-software routines, as are collision-avoidance functions.

FINAL NOTE: HEXAPODS VERSUS STEWART PLATFORMS

Hexapod robots are sometimes called Stewart platforms, but Stewart platforms were originally defined as having actuators connected in pairs at either the stationary or moving platform — or both the stationary *and* moving platforms.

The term ***Stewart platform*** comes from Mr. D. Stewart, who proposed to the UK Institution for Mechanical Engineers in 1965 that hexapod mechanisms be used as flight simulators. However, Stewart was neither the inventor of hexapod mechanisms nor the first to put them to use in a practical application. To find out why a type of hexapod robot is named for him, check out this article on the origins of parallel robots.

H-811, Miniature hexapod 6-axis stage for high precision 6-axis alignment applications. This compact unit provides linear travel ranges to 34mm and rotary ranges to 42° and a load capacity to 5 kg, with minimum incremental motion down to 80 nanometers. Image courtesy PI (Physik Instrumente) L.P.



Notice the miniature linear guides on this scanning electron microscope (SEM) laser stage. Image © Waiheng Dreamstime

Types of bearings found in ultra-precision motion designs

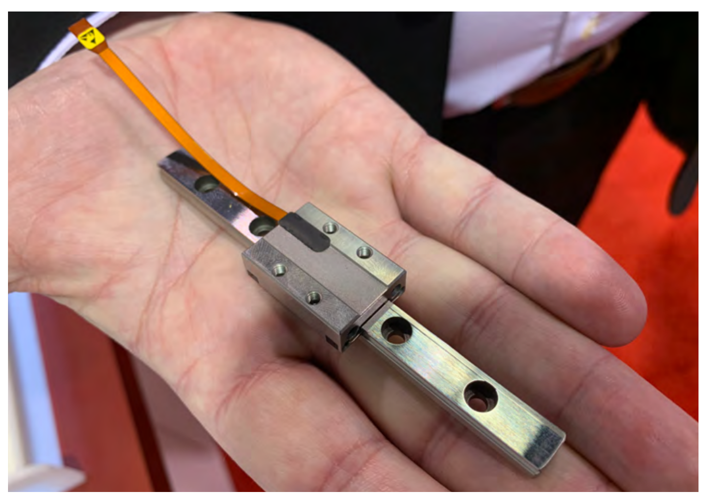
The basic distinction between standard and miniature profiled-rail linear guides is the width of the guide rail: Profiled rails with a width of 15 mm or less — and the carriages that fit on them — are generally considered miniature by bearing manufacturers. However, some manufacturers also produce 15-mm rail guides in standard versions, as we'll explain.

In addition to the width of the rail, there are other key differences between standard and miniature profiled rail guides and carriages of which designers and users should be aware when specifying linear motion components.

Ball and raceway construction: First is the basic construction of the carriage (also called the runner block). Most standard profiled rail carriages use four rows of balls — two on each side of the carriage. But because of their compact dimensions, miniature versions use only two rows of balls — one row on each side of the carriage. This means that miniature profiled rail carriages have relatively lower load and moment capacities than would be expected of four-row carriages.

> *Miniature carriages (just like those of standard linear guides) come in short and long versions … with wide versions sometime able to eliminate the need for two parallel rails in some overhung loading situations. The ability to support loads with a single rail is key in applications where space is at a premium.*

To help counter the loss of two ball rows, miniature guides typically use Gothic arch raceway geometry, which provides four points of contact between the balls and the raceway. This ball-raceway geometry gives the carriage the same load capacity in all four directions — downward, lift-off, and side loading — and provides relatively high moment load capacities.



Some series of miniature profiled rails have rail widths of just a few millimeters or smaller and two rows of recirculating balls. This one also has encoder feedback.

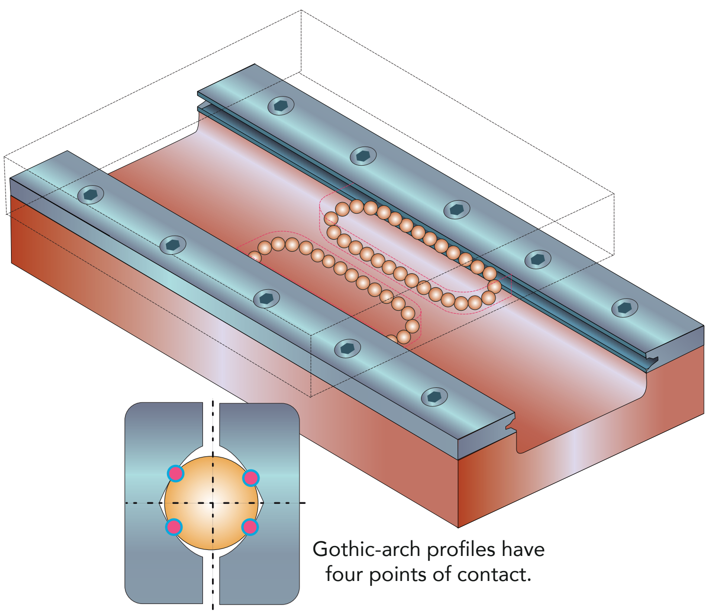
(continued)

TYPES OF BEARINGS FOUND IN ULTRA-PRECISION MOTION DESIGNS

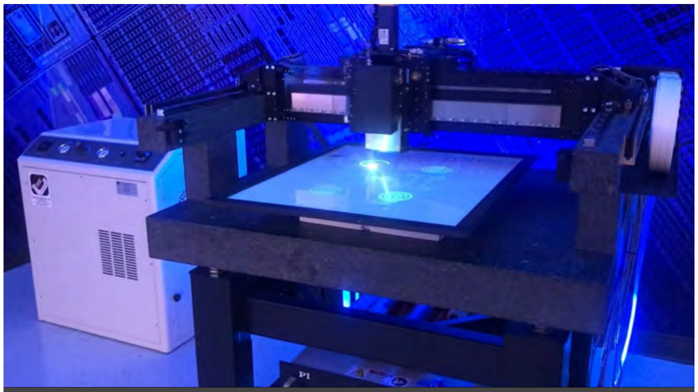
Note that not all miniature profiled rails incorporate retainers to secure the balls in the carriage. Keep this in mind when assembling and disassembling miniature rail and carriage assemblies. If there's no retainer, the balls will fall out of the carriage when it's removed from the rail.

Materials: Another difference between standard and miniature profiled rail guides concerns materials. Where standard profiled rail guides and carriages are made primarily from steel, miniature versions are offered as standard in stainless or corrosion-resistant steel — for both the guide rail and carriage and in some cases, even the balls and recirculation pieces. This is especially beneficial in applications where corrosion-resistance is necessary — involving chemicals, occasional exposure to water or high humidity, or even industry-specific requirements for stainless-steel materials, such as those found in the food and packaging and medical industries.

Miniature rail guides use Gothic arch geometry for four-point contact between the balls and raceways.



Sealing: Manufacturers also take different approaches to sealing for standard and miniature profiled rail guides and carriages. For standard versions, manufacturers often focus on ways to keep even the finest dust and fluid mist out of the carriage and to retain lubrication as efficiently as possible. But miniature versions are often used in applications in the electronics, semiconductor, and medical industries, where the environment is relatively clean or may even be a certified cleanroom. For this reason, miniature profiled rail carriages are typically offered with several sealing options, including the option to omit seals altogether.



High-speed XYZ gantry with linear motors for laser processing. This hybrid bearing unit combines mechanical bearings on the lower axis and air bearings on the gantry axis for extremely smooth scanning with minimal geometric errors. Image courtesy PI (Physik Instrumente) L.P.

For those applications that do require protection against contamination and loss of lubrication, some manufacturers now offer miniature rail carriages with end cap seals that incorporate a lubrication reservoir, to reduce maintenance intervals and ensure sufficient sealing for contaminated environments.

Preload and accuracy class: Miniature rail carriages also have limited preload and accuracy class options. First, because of the small size of the balls used in miniature versions, preload is typically limited to 1 to 2% of the dynamic load capacity (as opposed to 8 or even 13% for standard versions) with clearance (slight play between the carriage and the rail) or light preload being the most common options.

Similarly, miniature profiled rails are typically offered in normal and high accuracy classes, with some manufacturers offering "precision" as the highest accuracy class — unlike standard profiled rail assemblies, which are also offered in super-precision and ultra-precision accuracy classes.

ANOTHER OPTION FOR MINIATURE AND NANOPOSITIONING DESIGNS IS AIR BEARINGS

Bearings are often assumed to be mechanical rolling or sliding elements, but both linear and rotary bearings can also use a thin film of pressurized air to support load. With no mechanical elements to generate friction or heat, air bearings are ideal for applications that require extremely high precision and stiffness.

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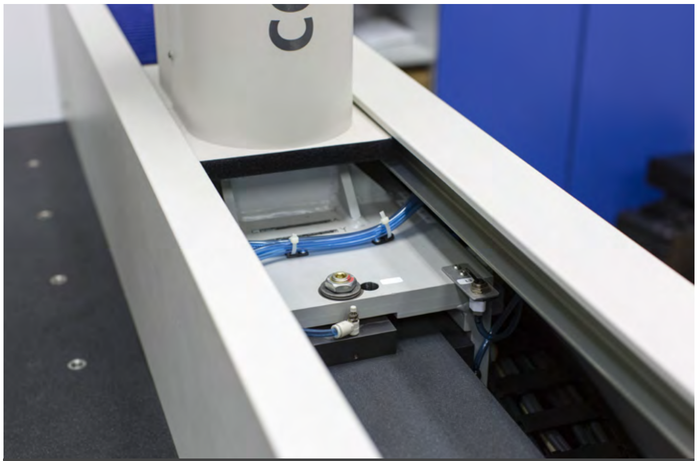
TYPES OF BEARINGS FOUND IN ULTRA-PRECISION MOTION DESIGNS



This is an air bearing integrated into the granite table of a coordinate measuring machine (CMM). Image: Zeljko Santosi Dreamstime

This is an A-688 large-aperture direct-drive air bearing rotary table. Air bearing spindles provide extremely smooth motion with excellent geometric performance, in this case, eccentricity and flatness better than 300 nanometers. The rotary table is equipped with a brushless slotless torque motor and a direct-measuring absolute encoder. Image courtesy PI (Physik Instrumente) L.P.

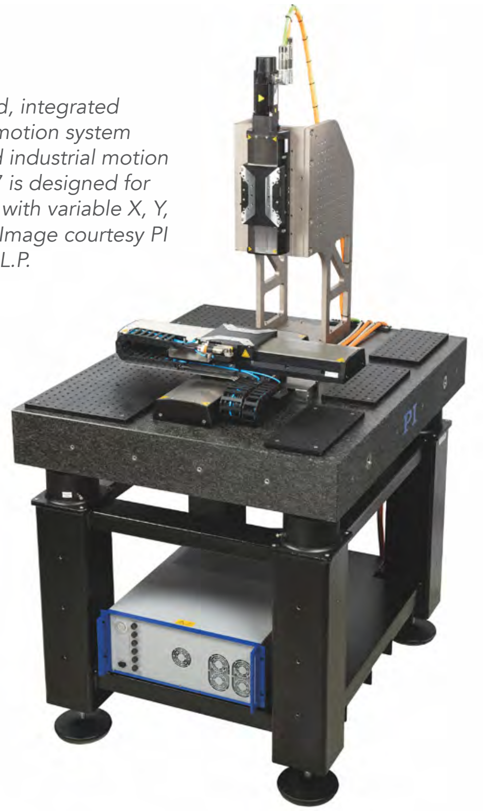
Pressure generation and air delivery: Depending on how pressure is generated, air bearings are classified as either hydrodynamic or hydrostatic. Hydrodynamic air bearings depend on relative motion between the bearing surfaces to generate pressurized air. In contrast, a hydrostatic air bearing relies on an external supply to deliver pressurized air — or other gas. Because they can maintain an air gap even when there is no relative motion between the bearing surfaces, virtually all air bearings used in industrial applications are hydrostatic.

The gaseous medium used for air bearings is typically compressed air, which is readily available in most industrial plants and processes. However, any moisture in the air supply can develop into condensation as the air transitions from high pressure to atmospheric pressure, resulting in corrosion on the bearing surfaces.

When the quality of supplied air is a concern and corrosion would be detrimental, another gas (typically nitrogen) can be used in place of compressed air. This is often the solution for cleanroom environments.

Preload on an air bearing: Adding preload to an air bearing increases stiffness and helps maintain a constant air gap. As air bearings are loaded, the air gap gets smaller and the pressure in the air film rises — both of which contribute to higher stiffness. There are four common methods for preloading air bearings: by adding weight, through magnetic attraction, through vacuum, and by using two opposed air bearings.

The simplest method for creating preload in an air bearing is to use a weight that is heavier than the load to be applied. This makes the air gap smaller, which increases the system stiffness. The drawback of the weight method of preloading is just that —



X-417, Granite-based, integrated multi-axis precision motion system with EtherCAT-based industrial motion controller. The X-417 is designed for quick configurability with variable X, Y, and Z travel ranges. Image courtesy PI (Physik Instrumente) L.P.

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TYPES OF BEARINGS FOUND IN ULTRA-PRECISION MOTION DESIGNS

it adds mass to the system. It is also suitable only for horizontal applications — not inclined or vertical orientations.

Magnetic attraction between the moving and stationary parts can also induce preload. But most air bearings are made of non-magnetic material, so this method requires that that a magnetic material be added to both bearing surfaces.

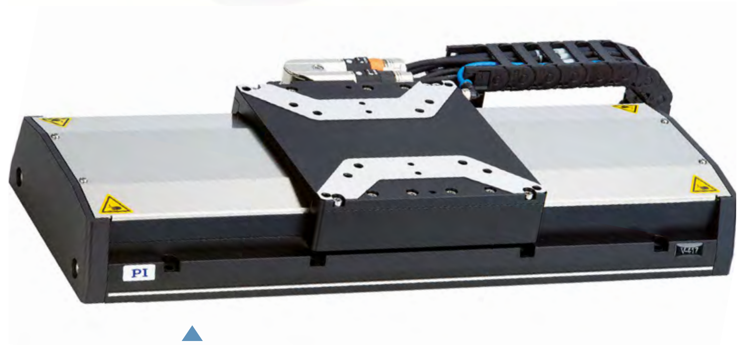
A third way to induce preload is to add a vacuum to the bearing surface, which creates a pressure differential and causes the external atmospheric pressure to exert force on the bearing. However, this method is only useful if a vacuum source is available and practical to install.

The most common preloading method is to configure two air bearings opposite each other. Because stiffness is additive, an assembly preloaded in this manner will have double the stiffness of a single bearing. Another benefit is that the errors on either bearing will be averaged — resulting in much higher accuracy than other preload methods can achieve.

The drawback to using opposing bearings is that the load capacity will be reduced by approximately half. This method also requires additional space and doubles the mass of the bearing components.

Planar XY-air bearing stage with additional Theta-Z rotation range for error correction. This granite based, gantry-style planar scanner is used for high performance applications such as metrology, photonics, and precision scanning as well as in semiconductor or flat panel display manufacturing. Image courtesy PI (Physik Instrumente) L.P.

P-733, XY piezo flexure nanopositioning scanning stage. This compact, closed-loop piezo stage provides 100x100-μm travel and 0.1nanometer resolution, as well flatness of motion in the low nanometer range. Applications are found in scanning microscopy, confocal microscopy, mask/wafer positioning, surface measuring technology, nanoimprinting, micromanipulation, image processing/stabilization. Image courtesy PI (Physik Instrumente) L.P.



V-417, High performance linear motor stage for precision manufacturing and laser processing applications. This unit provides travel ranges to 813mm, an integrated, absolute measuring encoder with 1nm resolution, and velocity up to 2m/sec. Image courtesy PI (Physik Instrumente) L.P.

THE UNIQUE DESIGN FEATURES OF MINIATURE BALLSCREWS

Image of miniature and standard ballscrews and profile-rail linear guides: Surasak Petchang. Dreamstime

Ballscrews are used in a wide variety of applications, but some of the most challenging are those on the extreme ends of the performance spectrum — from large-diameter large-lead screws for machine tools to screws with small diameters and very fine leads for optical and medical applications. For very small high-precision movements, designers and engineers often turn to miniature ballscrews.

While there's no industry standard for what classifies a screw as ***miniature,*** most manufacturers apply the designation to screws with a diameter smaller than 16 mm, while others include 16-mm screws in their "miniature" product line. To further segment the range of sizes, screws with a diameter smaller than 6 mm are sometimes called sub-miniature or ultra-miniature.

Some manufacturers offer a compact range of ballscrews. This term generally indicates that the ball nut uses internal recirculation, giving it a smaller outer diameter — hence the term compact. Despite their name, compact designs often include screws with diameters up to 25 mm — much larger than traditional miniature ballscrews.

In some regards, miniature ballscrews are the same as their larger standard counterparts. For instance, miniature ball nuts are offered in many of the same styles as standard ball nuts, including flanged, cylindrical (also called compact or slim) or with a threaded end for easy mounting into a carriage or table assembly. Ball recirculation can be done inside the ball nut or with external recirculation methods. Lead accuracies and preload classes follow the same designations regardless of the screw diameter. And sizing parameters, such as L_{10} life calculation, buckling load, and critical speed, are the same for both miniature and standard ballscrews.

Miniature ballscrews like standard versions can be manufactured by either rolling or grinding the screw threads. Screw diameters below 8 mm are commonly produced by grinding … although some manufacturers offer screws as small as 6 mm diameter in rolled versions. In some miniature screw sizes, the journal diameter of the screw is too small to accommodate an appropriately sized end bearing. To address this, manufacturers can friction weld a larger journal onto the screw end, providing a sufficient journal for the support bearing.

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THE UNIQUE DESIGN FEATURES OF MINIATURE BALLSCREWS

In addition to small screw diameters, miniature screws offer an advantage over standard versions with their option for very fine leads. The smallest miniature screws have a lead of just 0.5 mm, which means every rotation of the screw produces 0.5 mm of travel. This is a significant benefit in applications that require fine adjustments, such as positioning semiconductor wafers or optical equipment, or driving small medical pumps and dispensing equipment.

Because miniature screws use very small balls for load carrying, preload options are more limited, with only a light preload of 1 to 2% typically achievable, versus up to 5% with standard ballscrews using the oversized ball preload method. But in some respects, miniature screws offer more customization options and more standard variations. For example, combination left and righthand screws (where one segment of the screw has lefthanded threads, and another segment has righthanded threads) are commonly available in miniature designs.

Screws and nuts of stainless steel are also readily available in miniature screw offerings — in contrast with standard sizes for which stainless is quite rare. This can be attributed to the fact that miniature screws typically carry smaller loads, whereas stainless material would not be able to withstand the high loads that larger ballscrews often transport.

Due to their small leads, miniature ballscrews can execute very fine movements … and in vertical applications, these small leads make backdriving nearly impossible. Because ballscrews operate with metal-to-metal contact, they're not good for oscillating applications … even in miniature sizes for which stroke lengths are typically small. In applications with oscillating-type motion, voice-coil or piezo-based actuators may be a better choice.

Brief primer on

VOICE-COIL ACTUATION

Voice coil actuators are a type of direct drive mechanism that provides extremely precise positioning over small displacements. Like linear motors, they work on the principle of a permanent magnet field and a coil winding. When a current is applied to the coil, a force is generated. This force (known as the Lorentz force) is determined by the product of the current and the magnetic flux:

$F = k \cdot B \cdot L \cdot I \cdot N$

Where F = Force, N

k = Force constant

B = Magnetic flux density, Tesla

L = Length of wire, m

I = Current, amps

N = Number of conductors

For a given ***voice coil***, all parameters are fixed except the current. Therefore, the force generated is directly proportional to the input current. The direction of the force is perpendicular to both the direction of magnetic flux and the direction of current. Changing the direction of the current changes the direction of the force.

The term voice coil comes from one of the technology's first applications — vibrating the paper cone of a loudspeaker. In recent years, the most common application for voice coils has been to move the heads inside computer disk drives — but they're also widely found in medical devices, mirror controls, and oscillating systems.

This is a 10-axis custom stage for electronics and touch panel testing — in turn consisting of XY linear motor stage, Z-axis ballscrew stage with brake, six-axis miniature hexapod, and voice-coil actuator with closed-loop position and force feedback. Image courtesy PI (Physik Instrumente) L.P.

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BRIEF PRIMER ON VOICE-COIL ACTUATION

Operationally, the force produced by a voice coil causes the moving part to travel, which in turn pushes or pulls the load in a straight line. The moving part can be either the coil or the magnet, with the advantage of a moving coil being that it has a much lower mass than the magnet assembly. On the other hand, the coil generates heat … so if the load is sensitive to temperature fluctuations, attaching it to a moving magnet may be a better option.

Voice coils are suitable for fixed-stroke applications, with typical maximum strokes of 5 to 6 inches. The force generated is constant throughout the stroke length with a small dropoff (typically less than 5%) at the stroke ends.

The direct-drive nature of voice coils means they have no backlash and can achieve high acceleration and deceleration rates. On the other hand, they also work well in applications with extremely slow speed and low acceleration and deceleration.

For a complete actuator, a voice coil is paired with linear bearings for guidance — typically air bearings or crossed roller guides, although linear shafts and round bearings are also suitable since they have very low friction. A feedback device and servo controller provide a closed-loop system for extremely precise position and velocity control. Even without a feedback device, a voice coil actuator has good force control because the force generated is directly proportional to the applied current.

V-528, Miniature XY-stage with voice coil linear motors for high speed scanning applications up to 10Hz and velocity to 250 mm/sec. Image courtesy PI (Physik Instrumente) L.P.

Voice coils draw current when holding a load in a fixed position, or in vertical applications when counteracting the weight of the load. In addition, when the coil moves rapidly, a back EMF is generated — in turn proportional to speed, current, and magnetic field strength. This back EMF reduces the voltage across the coil, which reduces the current and limits acceleration.

Further reading:

Where voice-coil actuators excel

Moving-coil linear actuation today and on the horizon

More on hollow-core voice-coil actuators

V-931, voice-coil motor driven high-dynamics 2-axs steering mirror for beam steering such as used in free-space laser optical communication, image stabilization and laser processing. The unit provides beam deflection angles to 8° in two orthogonal tip/tilt axes and a common center of rotation. Image courtesy PI (Physik Instrumente) L.P.

SPECIAL ENVIRONMENTAL CONSIDERATIONS

Semiconductor manufacture necessitates the maintenance of a cleanroom setting. Image: Shuo Wang. Dreamstime

Now let's cover the products, materials, and features that designers and engineers should specify when choosing motion components for cleanroom environments. After all, many of the specialized motors, actuators, and electromechanical systems for nanopositioning and miniature machinery described in this Design Guide are ultimately designated for specialty workcells that run in cleanroom settings.

Designers of automation systems are tasked with many competing demands — such as balancing cost and performance; fitting motion components into legacy machinery footprints; and designing for ease of assembly, for example. But when a motion system is destined for use in a cleanroom, an additional layer of complexity is added.

Such machine designs require the selection of motion components that won't degrade or compromise the cleanroom environment.

The level of cleanliness of a cleanroom is determined by the number of particles, broken down into six size ranges, that are present in a specified volume of air. In the U.S., Federal Standard 209E is often used for cleanroom ratings, although it was officially abandoned in 2001. This standard specifies cleanroom levels from 1 (best) to 100,000 (worst) in multiples of 10.

The current and more universally accepted standard is ISO 14644-1, which defines cleanrooms on a scale from 1 (best) to 9 (worst). Each of the ISO classifications has a corresponding FS 209E level, with the exceptions of ISO classes 1 and 2, which are higher (better) than the highest FS 209E classification, and ISO class 9, which is lower (worse) than the lowest FS 209E classification.

One of the two primary sources of particle contamination that can compromise a cleanroom environment is friction from moving components. (The other source is people.) Virtually every motion system involves some amount of friction between sliding or rolling surfaces — whether from linear bearings, rotary bearings, or meshing gears. And when there is friction, particles are generated. Therefore, when specifying motion components for cleanroom environments, reducing friction should be the foremost objective.

REDUCING FRICTION IN LINEAR GUIDES AND DRIVES

To minimize friction from linear guides, choose rolling contact rather than sliding contact and when possible, avoid systems with high preload. For example, a non-preloaded miniature rail guide that uses two rows of recirculating balls emits significantly fewer particles than a preloaded standard guide with four rows of recirculating balls. Plus — because there's little chance of the bearing experiencing contamination in a cleanroom environment — use linear guides with low-friction or non-contact type seals.

Air bearings are another albeit less common technology for guiding and supporting loads. In cleanroom applications, however, air bearings are often the best choice for low particle generation, because they are completely non-contact devices.

When it comes to linear drives, belts and chains should be avoided in cleanroom applications due to the significant contact and wear they exhibit. Similarly, the meshing of gears in rack and pinion systems cause high friction and wear — so these should also be avoided. No wonder ballscrews are typically the default choice for linear drives in cleanroom applications.

That said, ballscrews require lubrication … and the rotation of the screw can cause lubrication to sling or splatter — contaminating the cleanroom environment. Using low-friction or noncontact seals can help keep the lubrication inside the ball nut and protect the cleanroom.

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SPECIAL ENVIRONMENTAL CONSIDERATIONS

> *Motion systems combining air-bearing linear guides and linear motors excel in cleanroom applications in part because they don't shed particulate.*

Like air bearings for linear guidance, linear motors provide a completely noncontact option for driving the load. But in their traditional setup, linear motors operate with the forcer (primary part) moving. This means the cables must move as well, and (as we'll discuss) cables are another source of particle generation. A better configuration for cleanroom applications is to keep the forcer (primary part) and its cables stationary and allow the magnet track (secondary part) to move.

Good: Rolling contact (rather than sliding contact) guides and drives

Better: Air bearing guides and linear motors

Look for: Low-friction or non-contact seals and "cleanroom lubrication" designations

Silicon wafer processing is extremely sensitive to contamination, including both particulates and outgassing. Although epoxy paint is sometimes suitable for motor and gearbox housings, stainless steel versions are better options for cleanroom settings. Image: Phuchit. Dreamstime

REDUCING FRICTION IN CABLES AND CABLE-MANAGEMENT COMPONENTS

Another source of friction and, therefore, particle generation, is the cable management system, including the cables themselves. Traditional round cables can generate particles when they rub against each other or against parts of the cable track.

The best way to reduce particulates from cables and cable management systems is to use components and system design practices that reduce the amount of cabling required — for example, using an integrated motor-drive system instead of separate motor and drive components.

> *Cable carriers used in cleanrooms should have low-abrasion fasteners and smooth interior surfaces to prevent cable abrasion — and should vibrate very little.*

For the power, feedback, and data cables that are necessary in a motion control system, manufacturers offer cable designs with special low-friction coatings to minimize particulates and reduce outgassing. Similarly, several cable track manufacturers offer systems that reduce wear between chain sections using abrasion-resistant joints. And for shorter lengths, so-called trackless cables are self-supporting flat cables that don't require a cable track or carrier.

Good: Round cables with anti-friction coatings; cable carriers with abrasion-resistant joints

Better: Self-supporting flat cables

Look for: Opportunities to reduce cabling

REDUCING FRICTION IN ROTATING EQUIPMENT (INCLUDING MOTORS AND GEARBOXES)

When it comes to rotating equipment in motion applications, the bad news is, motors and gearboxes use rotary bearings, and gearboxes require meshing teeth — all of which are sources of friction and particle generation. The good news is that these components are enclosed, so particles are less likely to "escape" and contaminate the cleanroom environment. And there is a wide range of cleanroom-compatible lubricants that can be used in the high-speed, high-load conditions found in motors and gearboxes.

To improve cleanroom compatibility, it is also possible to add a slight vacuum to the motor or gearbox housing. The vacuum serves to extract and remove particulates, so they don't have an opportunity to contaminate the cleanroom. Note that vacuum purge is also a good option for enclosed actuators that

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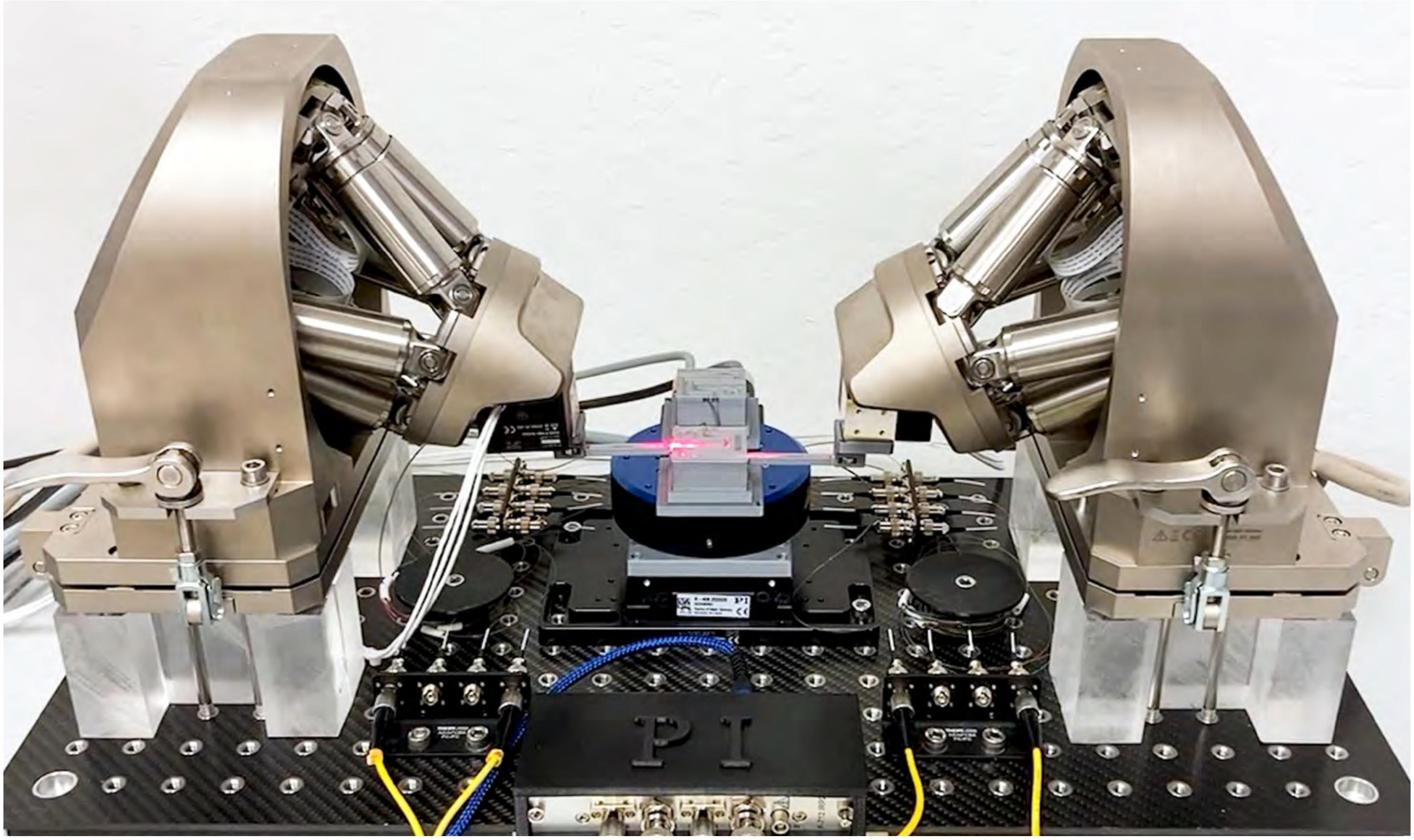
SPECIAL ENVIRONMENTAL CONSIDERATIONS



14-axis photonics alignment system for double-sided silicon-photonics array alignment. Image courtesy PI (Physik Instrumente) L.P.

have a static (non-moving) seal. Although the enclosed design tends to keep particles inside the actuator, adding vacuum purge helps to achieve higher levels (class 100, 10, or 1) of cleanroom compatibility.

Good: Fully enclosed housings

Better: Vacuum purge

Look for: Cleanroom grease options

Now let's consider another source of contamination — outgassing — and how to minimize it.

CLEANROOMS ALSO DEMAND MOTION DESIGNS WITH MINIMAL OUTGASSING

In cleanroom applications that involve the manufacture of LEDs, optics, or glass, or the processing of silicon wafers, a second type of contamination can damage the process or the product: outgassing.

Outgassing is the desorption of vapors or gasses, either from within a material or from the surface of a material. ISO standard 14644-8 addresses outgassing in cleanroom environments and specifically refers to airborne molecular contamination (AMC) as:

The presence in the atmosphere of a cleanroom or controlled environment of molecular (chemical, non-particulate) substances in the gaseous or vapor state that may have a deleterious effect on the product, process, or equipment in the cleanroom or controlled environment.

These types of airborne molecular contaminants take the form of molecular vapor. They're smaller than particles and easily pass through HEPA and ULPA filters, making them particularly difficult to control once released.

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SPECIAL ENVIRONMENTAL CONSIDERATIONS

MINIMIZE OUTGASSING THROUGH STRATEGIC MATERIAL SELECTION

The first criteria when choosing motion components for clean-room environments where outgassing is a concern is to ensure the material has a smooth surface, which makes it more difficult for airborne molecular contaminants to adhere to the surface. Stainless steel and anodized aluminum are the preferred materials, although some epoxy paints are suitable for environments where low-outgassing is required.

Fortunately, numerous motion control components, such as linear guides, motors, and gearboxes, can be made of stainless steel. When possible, plastic end caps on linear guides and screws should also be replaced with stainless steel versions to further minimize the use of plastics. And standard steel fastening hardware, such as screws or pins, should be replaced with stainless steel versions.

When the required material has a high outgassing tendency, other solutions exist. For example, epoxy paint is suitable in some cleanroom environments and can be applied to the housings of linear actuators, motors, and gearboxes. And when steel is required — to maintain hardness, durability, or load-carrying capacity — nickel plating can reduce the tendency of steel to outgas. (Note: Some nickel-plating formulas include a PTFE or Teflon topcoat. The use of Teflon in cleanrooms is generally discouraged, so be sure to choose a nickel plating formula that includes no Teflon.)

Good: Nickel-plated steel, epoxy coated aluminum

Better: Stainless steel or anodized aluminum; minimal use of plastics

Look for: Smooth surfaces (no textured paints)

REDUCE OUTGASSING FROM COMPONENT LUBRICANTS

When it comes to outgassing, lubricants are one of the major offenders, readily spewing molecules of water and oil vapor into the atmosphere. Unfortunately, in most motion systems, the use of components that require lubrication simply can't be avoided. When lubrication is required, ensure the lubricant is suitable for cleanroom environments. Cleanroom-compatible formulas that minimize outgassing while protecting bearing surfaces from rust and friction are widely available.

Good: Cleanroom-rated lubricants

Look for: Opportunities to minimize the need for lubrication through component selection

Further reading:

More on low-outgassing materials for motion components

How to make linear systems cleanroom compatible

Custom vacuum compatible 6-axis precision motion stage for beamline instrumentation. Image courtesy PI (Physik Instrumente) L.P.