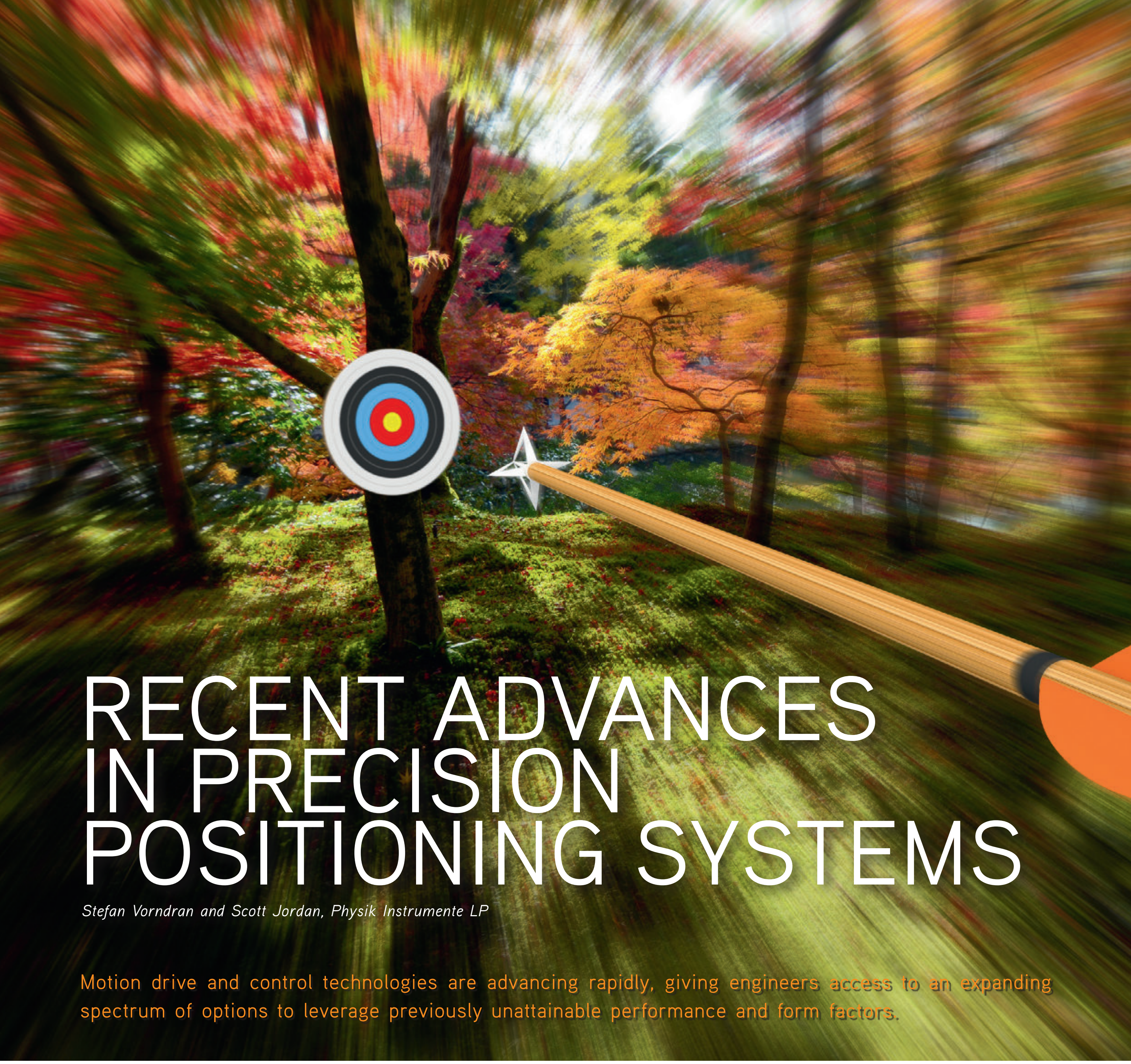

RECENT ADVANCES IN PRECISION POSITIONING SYSTEMS

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Motion drive and control technologies are advancing rapidly, giving engineers access to an expanding spectrum of options to leverage previously unattainable performance and form factors.

Rapidly evolving production processes have driven needs for motion control systems that provide higher accuracy, speed, resolution and repeatability. The motion industry has responded with an expanding palette of technologies including new types of mechanisms, novel position and force feedback technologies, and groundbreaking electromechanical actuation technologies. Together, these are enabling broadly revolutionary new mechanisms and form factors that, in turn, propel fresh ideas for manufacturing. Applications include mission-critical deployments in automation, laser processing, optical inspection, photonics alignment, semiconductor metrology, and medical device and micromachining applications.

Today's broadening spectrum of industrial and research applications has yielded a similarly wide variety of motion technologies — more than a single article can review comprehensively. But it means that designers and motion control engineers in scores of industries have access to precision motorised positioning systems that fit or even enable their applications. These systems provide very few limitations on travel, precision, repeatability and speed.

Motorised linear actuators

A linear actuator is a high-precision positioning device that creates motion in one degree of freedom and typically does not include a guiding system for the payload. For this article we are interested in electrically driven units, though of course micrometer-driven are common, along with screw-driven, pneumatic and hydraulic variants for lower-precision applications.

Piezoelectric actuators

These actuators can achieve extremely fine positioning resolution and there are several types.

Piezo stack actuators

These are layered structures of specialised ceramic interleaved with metallic electrodes. The piezoceramic has the unique property of expanding in a controllable manner with the application of an electric field. These actuators provide short travel ranges (about 1% of their length), subnanometre precision, high forces and sub-millisecond response. These are the mainstay of today's advanced

Figure 1: Miniature actuator driven by a stick-slip actuator.

nanotech applications, both in laboratory research and in industrial applications, such as semiconductor manufacturing and genomic sequencing. Piezo stack actuators are inherently non-magnetic, solid state and vacuum-friendly, with no wear processes.

Ultrasonic piezo motors

Ultrasonic piezo motors are monolithic piezoceramic structures that are stimulated at their resonant frequency, typically above 100 kHz, causing them to flutter on a submicron scale. A friction tip formed or bonded at a resonant node conveys this fluttering oscillation to a workpiece that rides in bearings — the workpiece thereby experiences a force that drives it one direction or the other. These motors can achieve many millimetres of travel and extraordinary speeds in a very small package. Another key attribute is these motors' automatic self-locking behaviour at rest and even when unpowered, preventing drift and dither of the driven stage. Ultrasonic piezo motors can provide an application-enabling alternative to classical motors when small dimensions, high speed and unrivalled energy efficiency are important. Like piezo stack actuators, they are non-magnetic and vacuum-compatible.

Inertia drives

These use tiny piezoceramic elements that are actuated in a sawtooth pattern, driving a shaft or other actuated element via a friction coupling. The sloped portion of the sawtooth actuation is what provides the motion; the rapid retraction breaks the stiction of the coupling and the actuated element does not retract with the piezoceramic element. Artful design can achieve silent, virtually stepless operation and long travels, together with precision in the nanoscale range and self-locking for high stability when stationary.

Walking piezo motors

These use four or more piezoceramic fingers which actuate in a stepping sequence to drive a workpiece in a desired direction. Between steps, subnanoscale actuation can be achieved. High power-off holding forces and essentially unlimited travel characterise these designs and the usual non-magnetic and vacuum-friendly attributes apply. These have proven to be enablers in sensitive optical positioning applications where carefully established positions must be maintained with nanometre stability, without power for months or years.

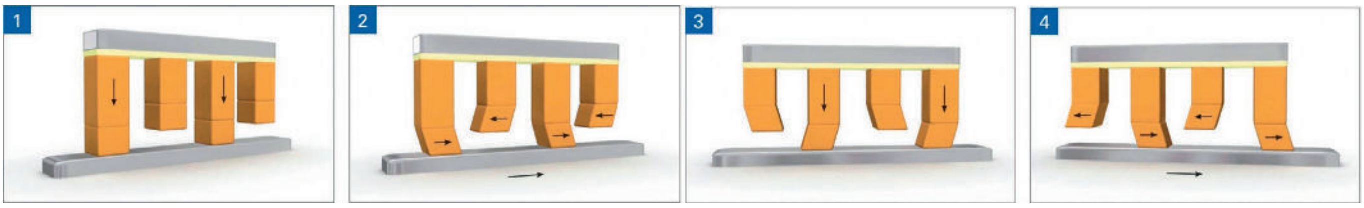


Figure 2: Operating principle of a piezo-walk linear motor.

Figure 4: Miniature linear positioning stage with high-speed ultrasonic ceramic linear motor and linear encoder feedback.

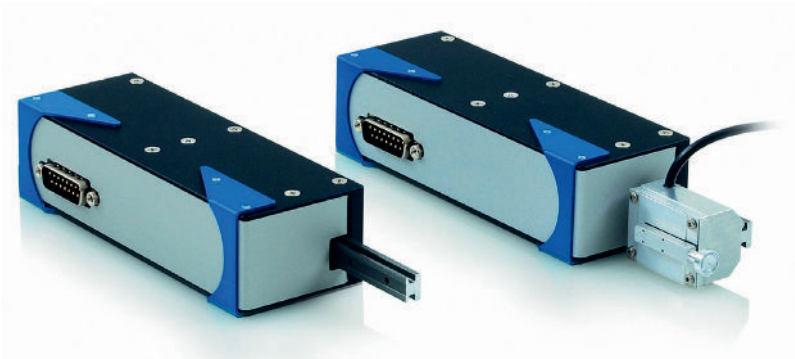


Figure 3: Voice-coil linear motor high-speed actuator with integrated high-resolution position and force sensors for automation applications.

Electromechanical actuators

These are typically based on linear shafts driven by rotational motors via lead nuts or ball nuts. The rotary motion of the motor is converted to linear displacement and the actuators have a generally cylindrical format.

The motors used in these actuators are typically either stepper motors or DC servomotors. Stepper motors actuate a toothed rotor within a toothed, surrounding stator. By configuring the magnetic windings of the stator so that groups of its teeth can be specifically magnetised, the rotor is caused to rotate in steps. It will hold position at these full-step positions without power, and partial steps can be achieved by partially energising the windings. Consequently, a driving mode that yields mini- or micro-steps can be implemented, multiplying the stepping resolution of the motor.

DC servomotors are conceptually simple and, with the addition of a position feedback encoder, provide precise positioning with exceptional responsiveness. Brushless DC motors, with electronic commutation rather than commutation through carbon brushes, provide enhanced lifetime, especially in high-dynamic applications.

In both cases the motors can be operated open- or closed-loop, meaning with or without position feedback. A stepper motor can be actuated through any specified number of steps in either direction and offers a high probability of achieving them, though certainty can only be achieved through the addition of a position encoder. Rotary encoders keep track of the position of the rotating motor; linear encoders directly encode the output position of the driven linear shaft, eliminating backlash and other errors that might otherwise accumulate in the drivetrain where a rotary encoder cannot observe them. Linear actuators with linear encoders are uncommon but offer unbeatable bidirectional repeatability for sensitive applications.

Linear motor actuators

By attaching a linear DC motor to a linear guide and an output shaft, direct linear actuation at very high speeds can be achieved. Linear DC motors can have a multitude of north/south magnetic pairs, depending on how much travel is needed, serving the role of the stator in a rotary motor. Gliding along them to generate force is a three-phase coil assembly. The phases are commutated electronically to generate smooth motion in the desired direction, ensuring long life.

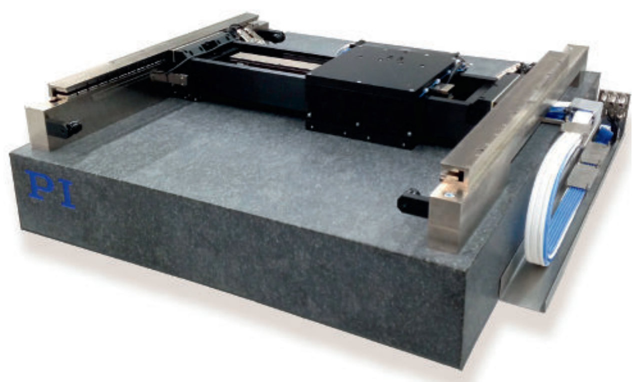
A related type of linear actuator is driven by a voice-coil motor — a nested pair of cylindrical electromagnetic coils which attract or repel each other along their mutual axis. These provide travel in the order of 25 mm and provide extraordinary speeds and accelerations for small loads. Such mechanisms are very long lived and can offer impressive step/settle times owing to their high responsiveness, and their direct actuation of the motion shaft in its low-friction bearings offers exquisite force control when an optional tip-force sensor is incorporated.

Bigger is not always better

The need for miniaturisation in the semiconductor and medical device industry also drives the requirements for smaller motion systems. Smaller also means lower mass and the potential for higher acceleration and throughput, especially when combined with today's most advanced actuation technologies.

Linear positioning stages with piezo motors are a new generation of piezoceramic linear motor that allow for the construction of matchbox-to-thumbnail-sized linear stages with nanometre resolutions and millisecond step and settle times. The direct drive avoids mechanical components such as gears and lead screws, making for reliable and high-resolution drives down to a few nanometres.

> **AIR BEARING STAGES REPLACE MECHANICAL BEARINGS WITH A FRICTIONLESS AIR FILM AND MAXIMISE THROUGHPUT WHILE PROVIDING THE ULTIMATE LEVEL OF PRECISION, ESPECIALLY FOR MULTI-AXIS MOTION.**



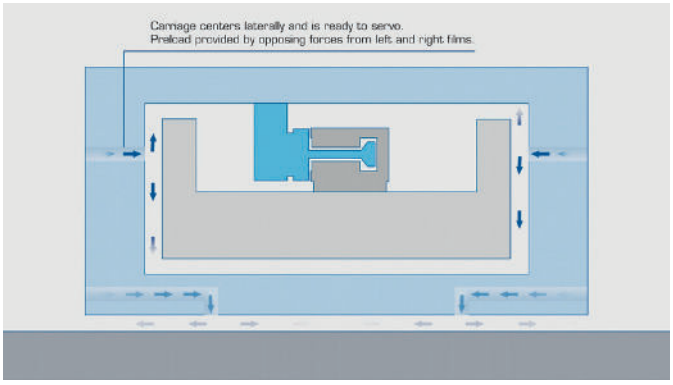


Figure 5: Planar air bearing XY positioning stage (left) and air bearing working principle (above).

Depending on the drive principle, high velocity, high forces or high resolution are achieved.

Long travel for industrial applications

On the other hand, industrial automation processes such as flat panel testing and laser processing require very long travels past one metre with high speed and low runout errors. Air bearing stages with linear motors have emerged as the gold standard for these applications.

Air bearing linear and planar XY stages

Air bearing stages replace mechanical bearings with a frictionless air film and maximise throughput while providing the ultimate level of precision, especially for multi-axis motion. Planar designs use one reference base plane on which magnetically or vacuum preloaded pucks are floating for both the X and Y axes. H-bridge, three-motor designs provide the highest precision, and can be further improved with active yaw control when equipped with three linear encoders and advanced motion controllers. The benefit is vastly improved orthogonality and straightness. Air bearing stages are usually driven by magnetic linear or torque motors that provide smooth motion without cogging effects.

High-speed stages with direct drive

Linear and torque motors can also be combined with mechanical bearings. This combination is often used in industrial applications when the smoothness and straightness/flatness of motion is not quite as critical as with air bearings. Linear motors provide an excellent combination of reliability, precision and speed. Their high dynamics ensure high throughputs for automated tasks in testing systems, for example in the semiconductor industry. They also increase efficiency, for example, in electronics production lines or laser processing.

High-resolution linear encoder feedback

Unlike motion systems that are run by rotary stepper and servomotors and lower-precision rotary encoders, linear motors require linear positional feedback systems. A linear encoder is a digital position transducer that directly measures linear motion where it occurs — as opposed to a rotary encoder mounted at the end of a drivetrain. The linear encoder reads the actual position as close to the point of interest as possible; therefore, the resulting accuracy and repeatability of the payload is higher.

Linear encoders contain a linear track and a read head. The linear track can range in length from a few millimetres to a few metres. Most encoders are based on an optical grating; however, lower-cost magnetic encoders are still available. While resolution in the subnanometre range is common, accuracy is typically limited to 1 µm/100 mm. However, this can be improved significantly with modern controllers if calibrated and compensated for with look-up tables or polynomial error correction. Incremental linear encoders are still prevalent, due to their interfacing simplicity and higher possible resolution down to the picometre range if used with electronic interpolators, but absolute position encoders are catching up, with nanometre-resolution models becoming much more affordable.

Rotation stages

Rotation stages consist of a platform that rotates relative to a base. The platform and base are joined by some form of bearing which restricts motion of the platform to rotation about a single axis.

A variety of motors and drive principles can be employed, from stepper motor-driven worm gear designs to direct-drive, closed-loop torque motors. Low-profile piezo motor stages provide self-locking capabilities with zero jitter and drift and requiring no holding current at rest.

> **A LINEAR ENCODER IS A DIGITAL POSITION TRANSDUCER THAT DIRECTLY MEASURES LINEAR MOTION WHERE IT OCCURS — AS OPPOSED TO A ROTARY ENCODER MOUNTED AT THE END OF A DRIVETRAIN.**

Precision motorised rotation stages are used in applications such as fibre-optic alignment, semiconductor inspection, biomedical applications and X-ray crystallography.

Air bearing rotation stages

These use a thin film of pressurised air to provide an exceedingly low-friction load-bearing interface between surfaces. The two surfaces do not touch and therefore air bearings avoid the traditional bearing-related problems of friction, wear, particulates and lubricant handling — offering distinct advantages in precision positioning and in high-speed applications where the elimination of backlash and static friction are critical.

Typically used for the highest precision and smoothness of motion, air bearing rotation stages deliver ultralow runout and wobble, as well as extremely high resolution and repeatability. Pitch, yaw and roll in the order of 1 arcsecond are feasible. The absence of friction eliminates backlash and gives the air bearing stage ultrahigh repeatability. The durability of air bearings is unlimited if they are calculated, designed and operated correctly.

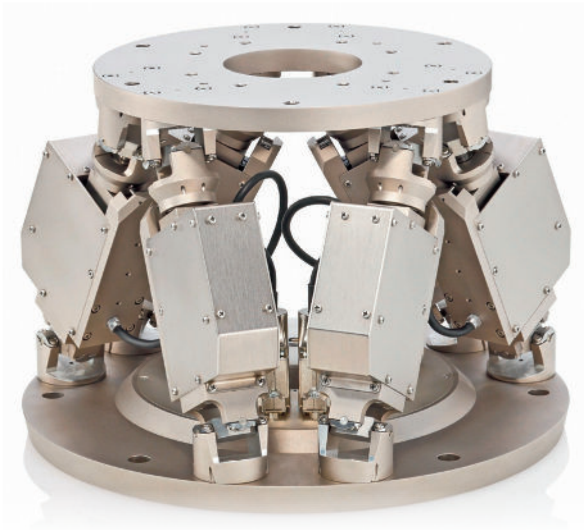


Figure 7: Vacuum-compatible hexapod 6-axis positioning system.

6-DOF parallel kinematic systems

In order to achieve precision at the micron and submicron level in multi-axis motion applications, hexapod parallel positioners have become popular in the last two decades. Hexapods effectively reduce the footprint and moving mass of a traditional serial kinematic stacked-stage positioning system while increasing stiffness and responsiveness. This together with the arbitrary, user-defined centre of rotation and a large, clear aperture make them the positioning system of choice in mission-critical applications including laser processing, photonics alignment and micromachining in medical devices.

Figure 6: Principle of a torque motor-driven rotary stage.

Hexapods, by definition, are six-legged, parallel-kinematic mechanism (PKM) motion systems. In their most common form, consisting of two platforms, a fixed-base platform and a second movable platform are connected and supported by six independent legs (struts or links) that expand and contract in parallel.

Coordinated motion of all struts enables the movable platform, and devices mounted on it, to move in any direction, operating in 3D relative to the base platform. The secondary platform is capable of moving in three linear directions — lateral (X) and longitudinal (Y), vertically (Z) and the three angular directions (pitch, roll and yaw) — by the legs. Because hexapods have all six degrees of freedom, they can perform manipulations that encompass total freedom of motion in a relatively compact space, with high stiffness and (when properly designed) without moving/sweeping cables that can break and foul.

Advanced designs include servomotor-driven systems for moving large optics or mirrors, piezo-based units for nanometre-precision control of processes, and non-magnetic and vacuum-compatible versions.

Recent hexapod designs provide extremely high stiffness and rigidity of their components and all moving parts, such as bearings, joints and drive screws. This characteristic results in high natural frequencies which makes these new hexapods capable of extreme accuracy, and an ideal tool for precision machining, photonics and optics alignment, metrology and medical applications.

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