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MicroPositioning Fundamentals

MicroPositioning vs NanoPositioning

MicroPositioning refers to mechanical movement with positioning accuracy and resolution in the micron or high sub-micron range. NanoPositioning refers to positioning with nanometer or sub-nanometer resolution (see the "Piezo Flexure NanoPositioners" section for high-precision NanoPositioning devices).

Design rules for motion systems with millimeter or sub-millimeter resolution do not always apply for the micron and sub-micron range. Resolution in the sub-micron realm cannot always be increased by simple means such as reducing the pitch of a leadscrew or increasing the gear ratio of a motor/gearhead unit. Stiction/friction, play, backlash, tilt, windup and, temperature effects, etc. will also limit accuracy and resolution. Sub-micron positioning systems require a great deal of attention in design, manufacturing and selection of materials.

PI has more than 30 years experience in designing MicroPositioning and NanoPositioning equipment for a wide range of applications. The following pages show a variety of Hexapods, linear, rotation and tilt stages driven by piezo actuators, closed-loop DC-servo-motors, voice-coil linear motors, stepper motors, ballscrews, leadscrews and manual micrometer drives. Positioning systems to suit almost any MicroPositioning application can be created with combinations of these stages.

High-Precision Test Equipment

PI's capabilities include a state-of-the-art, vibration-isolated and 0.1-degree temperature-controlled sub-nanometer metrology lab to certify the performance of our products. Interferometers, autocollimators, CMMs (coordinate measurement machines) and several other ultra-high-resolution metrology systems are employed to measure the assembly precision and guiding / position accuracy of our MicroPositioning and NanoPositioning products (see pages A-6 to A-9).

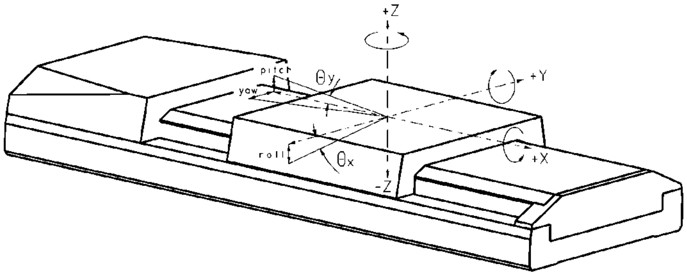
Coordinate measuring machine

Autocollimators

Laser interferometers

MicroPositioning Fundamentals (cont.)

Definition of Axes and Angles



Definition of axes and angles

X: Linear motion in (first) positioning direction

Y: Linear motion perpendicular to X in basic plane (usually horizontal)

Z: Linear motion perpendicular to X and Y (usually vertical)

θ_x: Angular motion around X (roll)

θ_Y: Angular motion around Y (pitch)

θ_Z: Angular motion around Z (yaw)

Glossary

Absolute Accuracy
For any given input this is the maximum difference between the commanded (ideal) position and the actual position. Absolute accuracy is often confused with resolution. For real systems, resolution is usually a great deal higher than absolute accuracy, which is affected by backlash, hysteresis, drift, nonlinearity, and repeatability. Absolute accuracy in the range of 1 µm or better over more than a few mm of travel can usually only be achieved with feedback from external measuring systems, such as laser interferometers or linear glass scales.

Backlash
Motion lost upon reversing direction. This can be due to play in screw/nut fittings, gearheads, bearings, etc. Some manufacturers promote controllers with automatic backlash compensation that add the estimated amount of lost motion upon each reversal. This is a good solution in theory, but limited in practice because backlash varies with load, leadscrew position, temperature, deceleration, direction, wear etc. Backlash can lead to oscillation in closed-loop setups where the position sensor is directly attached to the part to be controlled. Backlash is not to be confused with hysteresis.

Bidirectional repeatability
The accuracy of returning to a position from any position, regardless of direction. Effects such as hysteresis and backlash affect bidirectional repeatability. See also Unidirectional Repeatability.

Cosine Error
An on-axis cumulative error that occurs when a drive system is misaligned in regard to the driven part. The error equals 1 minus the cosine of the angle between the ideal drive axis and the actual drive axis, times the distance moved.

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Degree of Freedom (DOF)
A degree of freedom corresponds to an active axis of a motion system. An XY stage has two degrees of freedom.

DC Servo-Motor
A direct current motor that is operated in a closed-loop system (servo-circuit). Characteristics of DC servo-motors are lack of vibration, smooth running, wide speed range and very good low-speed torque. For optimum performance, a good motor controller with PID (proportional, integral, derivative) algorithm and filter settings is mandatory.

Flexure
See description under "Guiding Techniques", p. 7-13.

Guiding Accuracy
See Runout

Hysteresis
Hysteresis occurs when reversing direction. Unlike backlash, which is lost motion at the beginning of a reversed motion, hysteresis position error results from the relaxation of elastic forces in the drive-train components. Hysteresis is highly variable based on different load and acceleration values.

Design Resolution
The theoretical minimum movement that can be made based on the selection of the mechanical drive components (drive screw pitch, gear ratio, motor angular resolution etc.). Design resolution is usually higher than the practical position resolution (minimum incremental motion). Examples where design resolution is higher than position resolution are motor/gearbox drive systems with very high gear-reduction ratio, or microstepped motors. A linear stage driven by such a motor can require an input of 1,000,000 steps (encoder counts) to move a distance of one mm. In this case one step performed and displayed by the motor controller is equal to 1 nanometer. In reality the stage may not be able to respond with motion to an input of less than 50 steps due to play, windup, friction, backlash, etc.

MicroPositioning
Sub-micron incremental motion with travel ranges of tens to hundreds of millimeters, motorized/manual in nature.

Minimum Incremental Motion
The minimum motion that can be repeatably executed for a given input, sometimes referred to as practical or operational resolution. For systems with microstepped motors or motor/gearbox combinations, design resolution and practical resolution have to be distinguished. Design resolutions of 1 nm or better can be achieved with many motor, gearbox and leadscrew combinations. In practical applications, however, stiction/friction, windup, and elastic deformation limit incremental motion to fractions of a micron.

Repeatable nanometer or sub-nanometer resolution can only be provided by solid-state actuators (PZTs) and PZT flexure stages (see the "PZT Flexure NanoPositioners" and "PZT Actuators" sections for details). See also Design Resolution.

MicroPositioning Fundamentals (cont.)

NanoPositioning
Nanometer to sub-nanometer incremental motion with travel ranges of tens to hundreds of micrometers, solid state (piezoelectric) in nature—no stiction, friction or backlash.

Orthogonality Error
The deviation from the ideal 90° angle between the X, Y and Z motion axes.

Precision
An undefined term used differently by different manufacturers. Precision sometimes refers to absolute accuracy, repeatability, even to resolution.

Pulse Width Modulation (PWM)
A highly effective method of transmitting electrical energy at a variable rate by varying the width of pulses in a train.

Resolution
See Design Resolution and Minimum Incremental Motion. Resolution is often confused with accuracy.

Runout (Tracking Accuracy, Guiding Accuracy)
Deviation from a straight line. For linear stages, the runout describes unwanted motion in all 5 degrees of freedom (off-axis motion) other than the intended motion in the commanded direction. For a translation in X, linear runout occurs in Y and Z, tip and tilt occur in θ_X (roll), θ_Y (pitch) and θ_Z (yaw). Runout is caused by the guiding system itself, by the way the stage is mounted (tension!) and the load conditions. See also wobble.

Stepper Motor
An electric motor designed for open-loop operation providing motion in discrete steps. Open-loop stepper motors (and their controllers) are simple compared to closed-loop servo-systems. They are rugged and provide long lifetimes but reduced dynamic properties compared to DC servo-motors of equal size. They also dissipate more heat at steady state operation and can produce more noise and vibration during motion. Modern, 5-phase designs and microstepped 2-phase motors have largely overcome these problems. Stepper motors yield good results in predictable applications.

Stick/Slip Effect
Limits minimun incremental motion. Caused by the fact that the coefficient of static friction is greater than the coefficient of dynamic friction. When a drive force is applied to a positioner the start of motion is out of phase with the build-up of force. In the beginning, no motion occurs but when the static friction is overcome, a sudden jump occurs. Only frictionless devices such as solid state actuators (piezo actuators) do not exhibit stiction and therefore provide resolution superior to that of "classical" mechanical positioners in the sub-micron to sub-nanometer realm.

Tracking Accuracy
See Runout

Unidirectional Repeatability
The accuracy of returning to a given position from any other position, but always from one direction. Unidirectional repeatability is not affected by backlash. See Bidirectional Repeatability.

Wobble
For rotary stages, unwanted off-axis rotary motion.

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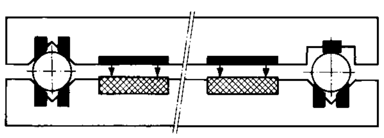
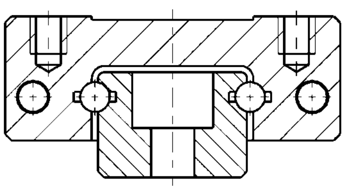
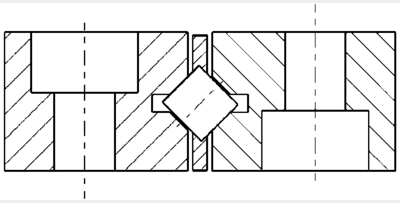
Guiding Techniques



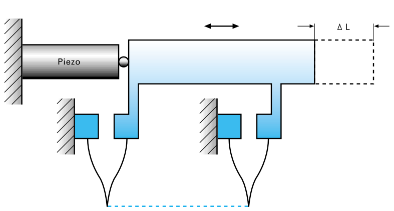
Magnetic-kinematic ball bearings



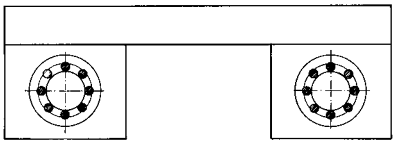
Linear Rails with double row recirculating ball bearings



Crossed roller bearings



Zero-runout flexure guiding system. No friction, stiction and no lateral runout.



Linear guiding rods with ball bearings

Magnetic-Kinematic Ball Bearings
Straightness of travel, symmetrical movement and absence of backlash are especially important for precision mechanical positioning.

M-011 and M-014 magnetically coupled stages use the force of integrated magnets to preload the bearing.

This magnetic preload results in extremely smooth and uniform motion with minimum friction. To guarantee optimum straightness of travel, only one of the two linear bearings guides the stage (V-groove) while the second bearing is for support only (U-groove). Straightness and flatness is better than 0.2 µm over 25 mm. Minimum incremental motion with the optional PZT drive is 5 nm (not limited by the PZT).

Due to the limited magnetic force, only small loads can be handled in vertical applications. The same consideration limits permissible lateral forces.

Linear Guiding Rods with Ball Bearings
Precision-ground rods of hardened steel and linear ball bearings are used for the M-311 and M-110 translation stages. A brass tube serves as ball cage. To reduce backlash and guarantee low friction, the rods and ball bearings have to be matched to very tight tolerances.

Linear Rails with Double-Row Recirculating Ball Bearings
The M-505, M-511, 521, 531, and M-605 series of motorized translation stages are equipped with precision double linear rails. The moving carriage is supported by a total of four preloaded linear bearings with two rows of recirculating balls each. The rails are bolted to the precision-machined stage base by several screws. Precision assembly allows these bearings to yield excellent results in terms of straightness, smoothness and load capacity. They are also immune to the cage migration problems of crossed roller bearings (can be an issue where small ranges are scanned repeatedly) and are maintenance free.

Crossed Roller Bearings
In crossed roller bearings the point contact of the balls is replaced by the line contact of the rollers. They are therefore stiffer and can be operated with reduced preload, resulting in reduced friction. Smoother travel and higher load capacity can also be achieved. Crossed roller bearings are employed in most PI compact translation stages such as the M-105, M-126, M-400 and M-330 series.

Flexures
A flexure is a frictionless, stictionless device that relies upon the elastic deformation (flexing) of a solid material. The flexure design is ideal for actuators where the required displacement is on the order of 10% or less of actuator's outer dimensions. Sliding and rolling are entirely eliminated from the design. In addition to absence of internal friction, flexure devices exhibit zero runout, high stiffness and load capacity, and resistance to shock and vibration.

PI provides piezo-driven flexure stages with sub-nanometer resolution, sub-nanometer flatness and straightness and sub-µrad pitch, yaw and roll (see the "PZT Flexure NanoPositioners" section, beginning on p. 2-1.

MicroPositioning Fundamentals (cont.)

Drive Coupling Systems / Motor Drives

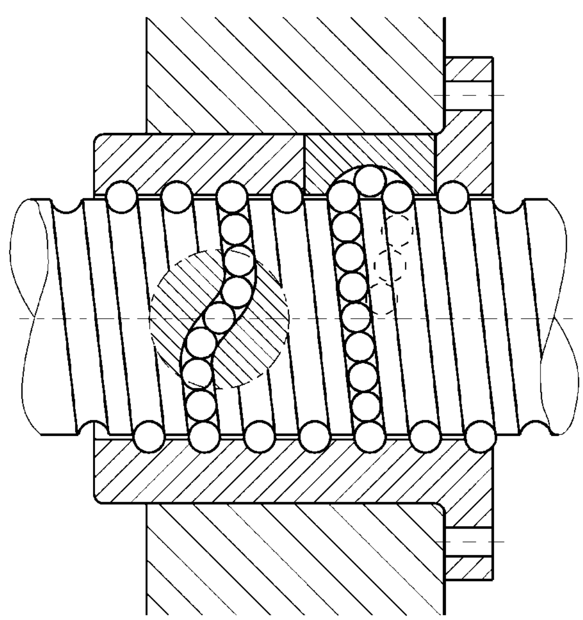
Leadscrews
A drive system consisting of a screw and a nut coupled to the carrier. Leadscrews are self-locking but exhibit higher friction (requiring increased motor output power, and reducing max. velocity) than recirculating ballscrews. M-110, M-126, and M-400 stages are equipped with leadscrews. Standard PI leadscrews have a pitch of 0.5 mm/revolution.

Recirculating Ballscrews
Recirculating ballscrews reduce the sliding friction of leadscrews to that of rolling friction. They consist of a screw, a nut (ball housing) and a number of balls riding between the screw and the nut. When the screw rotates, the revolving balls transmit an axial movement to the housing attached to the carriage. Before the balls reach the end of the thread they recirculate to their original position through a channel in the housing. By selecting a certain ratio of ball diameter and thread diameter a backlash-eliminating preload is generated.

Ballscrews show significantly reduced friction, lower wear and longer lifetime than leadscrews. They reach higher velocities than leadscrews with efficiencies up to 90%. Ballscrews are not self-locking. The M-501, M-505, M-511, M-521, M-531 and M-605 stages and the M-235 linear actuators are equipped with recirculating ballscrews. Standard PI ballscrews have pitches of 1 or 2 mm/revolution.

Piezo Drives
Resolution on the order of 1 nm and better can be achieved with piezo actuators. PZT drive options are available for several of our translation and rotation stages. Piezo translators can move very fast and do not exhibit stiction, friction or backlash. See the “PZT Actuators,” “PZT Flexure NanoPositioners” and “Tutorial: Piezoelectrics in Positioning” sections for further information.

Voice-Coil Linear-Motor Drives
These drives are employed in the PI V-102 and V-106 scanning systems. Voice-coil actuators are non-contact linear motors and provide fast response with zero friction and zero stiction.



Recirculating ballscrew

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ActiveDrive™ DC-Motor
General advantages of DC-motor drives are high speed, high acceleration and absence of vibration. Low heat dissipation at rest and fast response (ideal for tracking and contouring applications) are further advantages.

The unique ActiveDrive™ design features a high-efficiency PWM servo-amplifier mounted side-by-side with the DC motor. The ActiveDrive™ provides several decisive advantages:

- Increased efficiency by eliminating power losses between the amplifier and motor
- Reduced cost of ownership and improved reliability because no external driver is required
- Elimination of PWM amplifier noise radiation by mounting the amplifier and motor together in a single electrically shielded case

Standard shaft-mounted optical encoders provide resolution of 4000 counts/ revolution. Highest positioning accuracy is achieved with integrated linear encoders (available for M-500 series and M-605 series stages).

DC-Motor / Gearhead Drive
Advantages of DC-motor/gearhead drives are very high angular resolution and low power consumption (can be operated by PC controller boards without an external amplifier). Three-watt DC motors with gearheads and motor-shaft-mounted encoders are used. Encoders provide 2000 and 2048 counts/revolution, respectively. Zero-backlash motor/gearhead combinations are available for improved repeatability (C-136, page 7-81).

Stepper-Motor Drives
PI offers both high-resolution 5-phase stepper motors with 2000 steps/rev. and microstepped 2-phase motors with up to 20,000 microsteps/rev. Low vibration and extremely smooth motion are the benefits of both techniques. Compared to closed-loop DC servomotors, open-loop stepper motors are especially suited for applications where predictable positioning is required as opposed to fast response and extreme acceleration.

DC-Mike Drives
These linear actuators are driven by a 2- or 3-watt DC servo-motor / gearhead combinations with motor-shaft-mounted encoders. Ballscrew and leadscrew versions with non-rotating tip constructions are available. Most models come with integrated limit switches. All versions feature sub-micron resolution.