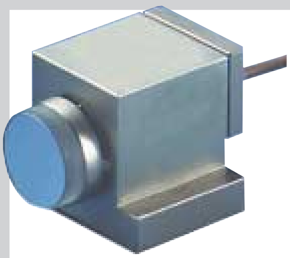
Piezo • Nano • Positioning

High Speed Piezo Steering Mirrors
6-Axis Optical Alignment Platforms

Moving the NanoWorld www.pi.ws

Standard High Speed Tip/Tilt Platforms

Piezo-Driven, Frictionless Flexure Guides, Parallel Kinematic Designs



S-224 / S-226 High-Speed Miniature Piezo Tilt Mirror; Nano-rad Resolution; to 100 µ-second Response; Up to 4.4 mrad Optical Beam Deflection; Closed-Loop Option

S-334 Ultra-Long-Range Piezo Tip/Tilt Mirror. Optical Deflection to 100 mrad (~6°). 1.0 kHz Resonant Frequency with Mirror. Closed-Loop.
2 Orthogonal Axes with a Fixed Pivot Point

S-310 – S-316, High-Speed Multi-Axis Tip/Tilt Platforms and Z Positioners; 10 mm Clear Aperture; Piezo Tripod Design Allows Z Motion and Tilt; Up to 2.4 mrad Optical Beam Deflection; Piston Movement up to 12 µm; Closed-Loop, Parallel-Kinematics Design

S-325 High-Speed Piezo Tip/Tilt/Piston Platform. Piezo Tripod Design, 10 mrad Optical Beam Deflection, Piston Movement up to 30 µm, Closed-Loop, Zero Friction Flexure Guides, Single-Moving-Platform, Parallel-Kinematics Design

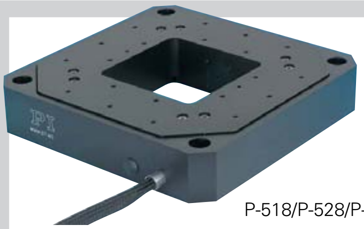
S-340 High-Speed Piezo Tip/Tilt Platform. Fixed Orthogonal Axes; 4 mrad Optical Beam Deflection, Mirrors to Ø100mm; Closed-Loop; Differential Drive / Sensors Parallel-Kinematics Design

S-330 High-Dynamics Large-Angle Piezo Tip/Tilt Platforms. Resolution to 20 nrad, Excellent Position Stability, Optical Beam Deflection to 20 mrad (>1°) Parallel-Kinematics Design, Sub-Millisecond Response, Closed-Loop

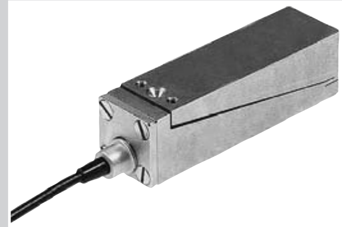
For controllers & drivers see www.pi.ws

Standard High Speed Tip/Tilt Platforms (cont.)

Piezo-Driven, Frictionless Flexure Guides, Parallel Kinematic Designs



P-518/P-528/P-558 Z/Tip/Tilt Piezo Flexure Scanning Platform; Precision Trajectory Control; Parallel-Kinematics/Metrology for Enhanced Responsiveness; Travel Ranges to 200 µm/ 4mrad; 66x66mm Clear Aperture



P-287 Piezoelectric Tilt Flexure Stage Frictionless Precision Flexure Guiding System; Tilt to 0.7 degrees; Non-Magnetic Stainless Steel Design

S-303 High-Speed Piezo Phase Shifters with Direct Metrology Option; 25 kHz Resonant Frequency for Sub-Millisecond Dynamics; <0.1 nm Resolution; Capacitive Sensor Option; Invar Option; Optional Aperture

P-541.TCD, Large Aperture Piezo Z/Tip/Tilt Stage
100 µm/1mrad; 16.5 mm Profile for Easy Integration
Fast Response; 80 x 80 mm Clear Aperture

For controllers & drivers see www.pi.ws

Custom Systems for Telescopes

PI Steering Mirrors and Low-Speed Alignment Systems in Astronomy

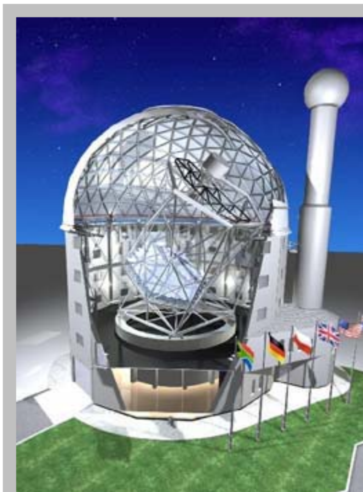

Keck I and Keck II observatories and NASA Infrared Telescope Facility (IRTF)(silver dome), Mauna Kea, Hawaii; Photo: K. Spanner.


The Horsehead Nebula; Photo: Brian Lula.

Resolution in large earthbound telescopes is limited by atmospheric turbulence and vibrations. During the last 15 years PI has designed several large-aperture tip/tilt systems for image stabilization. Piezoelectrically driven active secondary mirrors can improve the effective resolution up to 1000% by correcting for these image shifts in real time, especially during long integrations with weak light sources.

Momentum Compensation

Due to the inertia of the large mirrors and the high accelerations required to correct for image fluctuations, significant forces can be induced in the telescope structure, causing unwanted vibrations. PI has developed momentum compensation systems integrated into the tip/tilt platforms which cancel undesirable vibrations and thus offer significantly better stabilization than uncompensated systems.



Example of a combined high-speed piezo tip/tilt plaftform with a long range, low-speed 6-axis hexapod alignment system

High-Resolution Linear Actuators
273 PI actuators are used for tip/tilt/piston movement of segmented mirror panels in the SALT Telescope. Features: 16 nm design resolution; 0.15 µm minimum incremental motion; non-rotating tip, compact design.

Spectrum of Specifications

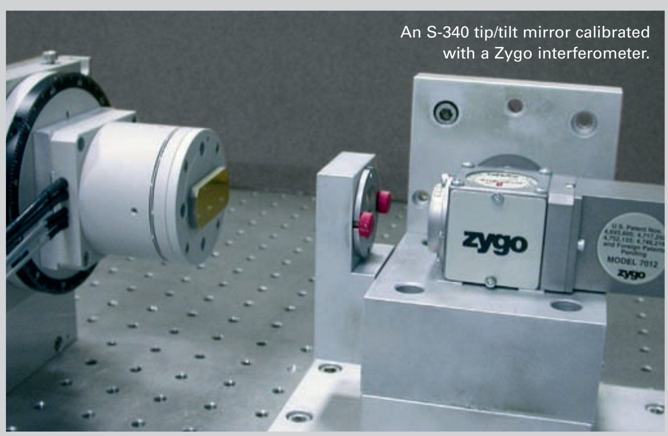
High & Low Speed Systems

	High Speed, Small Angle	Low Speed, Large Angle & (Hybrid)
Aperture	Fiber to 20″	2.5″ to 30″
Mass	50 g to 10 kg	1 kg to 400 kg
Load Capacity	50 g to 100 kg	2 kg to 1000 kg
Dimensional Profiles	**Cylindrical**: Ø30x20mm to Ø500x100 mm **Square**: 35x35x20mm to 500x500x100mm	**Cylindrical**: Ø100x118mm to Ø1000x600 mm **Square**: 200x230x160mm to 1500x1500x200mm
Bandwidth	200 Hz to 5 kHz	to 2 Hz / 500 Hz (coarse fine mode)
Tilt Angles	to 50 mrad (small systems) to 2 mrad (large systems)	to 30 deg
Resolution	to 5 nano radian	to 1 µrad
Materials	Al, Ti, Invar, Stainless Steel	Al, Ti, Invar, Stainless Steel
Temperature Range	to 77k and below / to 150°C	to -40°C to 80°C (DC Servo) to 77k / to 150°C (Piezo Motor)
Environmental	Vacuum compatible versions to 10-9 torr	Vacuum compatible versions to 10-6 torr
Sensor Type	SGS, Capacitive, LVDT, Eddy Current	Incremental rotary and linear encoders
Actuation Drives	Monolithic piezo stack, ceramic encapsulated	DC servo + ballscrew / roller screw, PiezoWalk® self-locking high force ceramic linear motor

Test and Calibration—Why High-Quality Nanometrology Equipment Matters

Piezo nanopositioning systems are significant investments and PI believes in optimizing the performance of every customer's system. PI individually calibrates every stage and optimizes the dynamic performance for the customer's application. Furthermore, PI makes significant continuing investments in improved-quality, higher-performance nanometrology equipment so that we can deliver better value to our customers.

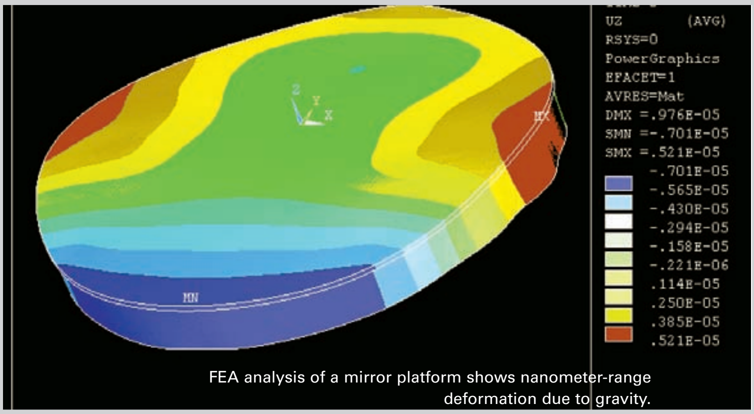
Because a nanomechanism can only be as accurate as the equipment it was tuned and tested with, PI closed-loop systems are calibrated with the prestigious Zygo ZMI-2000 and ZMI-1000 interferometers and Moeller Wedel electronic autocollimators. PI's nanometrology calibration laboratories are seismically, electromagnetically and thermally isolated, with temperatures controlled to better than 0.25 °C / 24hr. We are confident that our calibration capabilities and procedures are the benchmark for the industry.



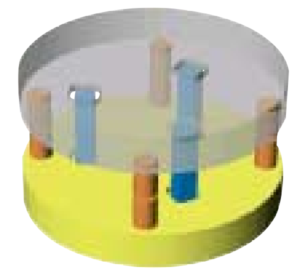
An S-340 tip/tilt mirror calibrated with a Zygo interferometer.

An S-334 tip/tilt mirror calibrated with an autocollimator

Active Optics / Steering Mirrors



FEA analysis of a mirror platform shows nanometer-range deformation due to gravity.

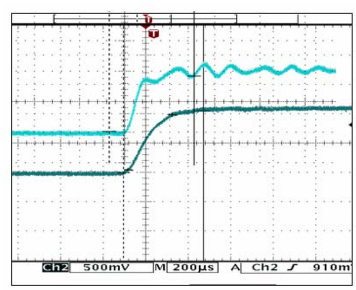

Basic design of a piezo tip/tilt platform featuring three actuators and four sensors. Large platforms handle optics to Ø500 mm

Fast Steering Mirrors: Why Piezo?

- Faster and more precise than conventional actuators
- Better stability through differential drive designs
- Stiff mechanical interface, 1 DOF only
- Tip/tilt & piston movements
- Up to Ø50 cm apertures

Applications of Fast Steering Mirrors

- Fast beam steering, alignment, switching
- Image resolution enhancement (pixel multiplication, dithering)
- Optical path length stabilization
- Vibration cancellation (laser systems, imaging)
- Interferometry, Fabry-Perot filters
- Image stabilization, high speed background subtraction
- Laser beam stabilization (resonators, optical setups)
- Laser beam scanning (lithography, optical setups)
- Laser beam steering and tracking (telecommunication satellites, etc.)
- Bore-sight systems
- Dynamic error correction (e.g. in polygon scanning mirrors)
- Mass storage device testing and manufacture



Fast: 200µs step response. Standard (top), optimized amplifier (bottom), 0.2 µrad steps

High & Low Bandwidth Systems

Piezo Steering Mirrors & Long Range Hexpod and Tripod Platforms

PI has several decades of experience with active optics systems ranging from high-bandwidth, piezo-driven fast steering mirrors to large aperture hexapod structures providing 6 degrees of freedom for tracking and alignment of large optics and mirrors.

PI's piezo-driven piezo tip/tilt platforms and scanners (steering mirrors, beam deflectors, phase shifters) are designed for the demanding applications in industry and cutting edge research, from high-energy physics, laser technology, to astronomy and microscopy.

Long-Life Ceramic-Encapsulated Piezos, Extreme Temperature Range

PI uses specially designed monolithic, ceramic encapsulated piezo actuators to drive the steering mirrors. Independent testing and research show, that these actuators provide significantly longer service life (up to 10X and more) than conventional, epoxy-coated piezo drives and are functional over a very wide temperature range from liquid nitrogen to 150°C. They are vacuum compatible with basically no outgassing.

High Stiffness / Holding Forces, no Heat Generation at Rest, Small Heat Signature

Piezo drives are much stiffer and faster than voice-coils, galvos and other actuators and offer higher resolution. Because of the intrinsic stiffness, they can respond faster to control signals (milliseconds to microseconds) and and can also hold a position with virtually no heat dissipation.
This provides a small heat signature which makes them particularly suitable for IR imaging.
The PI piezo-driven systems can perform optical beam steering over ranges of up to 100 mrad. Resolutions in the nanoradian range are feasible. They are ideal for dynamic operation (e.g. tracking, scanning, drift and vibration cancellation) as well as ultra-high-stability alignment applications of optics and samples.

Hybrid Type Piezo Tip/Tilt/Piston Platforms (Tripods)

PiezoWalk® driven platforms combine the advantages of long range linear motors with the high dynamics of direct piezo drives.

Long Range, Low Bandwidth Hexapod Alignment Systems

For large angle alignment, PI has designed a number of Stewart-Platform-type, large aperture, electromechanical hexapod systems. These are available with payloads from 2 kg to 3000 kg and have been employed in many astronomical telescopes around the world and other industrial high-performance optical alignment applications.

Angles range from 6° to 30° in tip/tilt and up to 60° around Z with typical resolution in the microradian range and below. Linear motion up to 100 mm is feasible. Typical drives are servo-motor / roller screw assemblies. High-force, non-magnetic, PiezoWalk® motors with self locking capabilities are also available.

Examples of Custom Systems

System Experience: High-Bandwidth Piezo Steering Platforms

PI offers the largest selection worldwide of high-resolution piezo actuators, nanopositioning systems and high-bandwidth tip/tilt systems for industrial and scientific applications. The following page shows but a few examples of the steering mirrors developed over the last few years. The systems shown were designed for special customer applications and are not available off the shelf; many other custom systems are subject to non-disclosure agreements and cannot be shown at all.

Custom tip/tilt mirror system with controllers for the Subaru telescope.

Custom high-speed tip/tilt mirror system.

Custom 2-axis tip/tilt mirror system.

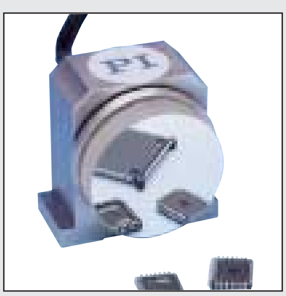
Custom Z-Tip-Tilt focusing and alignment system. Clear aperture: 75 mm, position measurement with 3 capacitive sensors.

Custom 2-axis tip/tilt mirror system (100 mm Diameter).

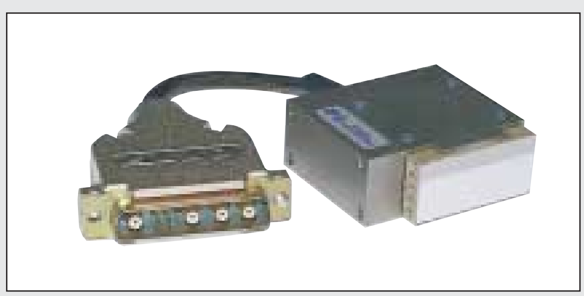
Custom high-speed tip/tilt platform w/ manual flexure coarse adjustment

250 mm tip/tilt mirror system for astronomical telescopes, with digital servo-controller, fiberlink and digital transmission system for the capacitive sensor signals.

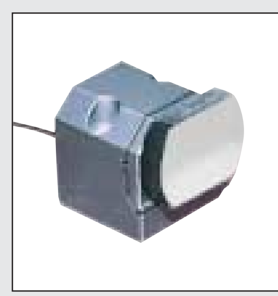
2-axis tip/tilt mirror system (200 mm) with eddy current sensors



Custom tip/tilt mirror system with capacitive sensors.



Custom high-speed tilt mirror system with capacitive sensors for closed-loop position control.



Custom high-speed tilt mirror.

Z/Tip/Tilt stage, Z: 200 µm
4 mrad, to 1 nm and 50 nrad res.
150x150x30 mm, 66 mm Aperture

PiezoWalk® Tripod: Z/Tip/Tilt Stage
Ø300 mm, 200 N load capacity,
1.3 mm piston, 10 mrad tilt range

X/Y/Z/Tip/Tilt stage, XYZ: 100 µm
5 mrad Dim.: 80 x 80 x 55 mm
LVDT, clear aperture: 20 x 20 mm

Z/Tip/Tilt stage, Z: 200 µm
Rotation: 2 mrad, clear aperture:
100 mm, height: 20 mm

Piezo Tip/Tilt Mirrors Fundamentals

Single Axis Designs

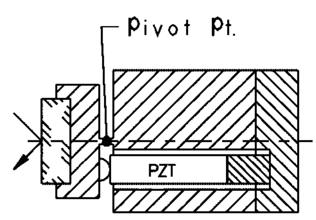


Fig. 1. Single-flexure, single-piezo actuator tilt platform design.

Single-Axis Systems / Scanners

Two designs of single-axis (θ_x) tilt platforms are available:

I. Single-Flexure, Single-Actuator Tilt Platform

Examples: S-224 and S-226

The platform is supported by one flexure and pushed by one linear piezo actuator (see Fig. 1). The flexure determines the pivot point and doubles as a preload for the piezo actuator. The advantages of the single-flexure, single-actuator design are the straightforward construction, low cost and small size. If angular stability over a wide temperature range is a critical issue, the differential piezo drive is recommended.

II. Differential-Piezo-Drive Tilt Platform

This design features two piezo actuators operating in push/pull mode supporting the platform (see Fig. 2). The actuators are wired in a bridge which is supplied with a constant and a variable drive voltage. The case features integrated zero-friction, zero-stiction flexures which assure excellent guiding accuracy.

The differential design exhibits excellent angular stability over a wide temperature range. With this arrangement, temperature changes only affect the vertical position of the platform (piston motion) and have no influence on the angular position. In the closed-loop models, availability of two sensor signals permits better linearity and resolution.

A variety of single- and multi-axis implementations is possible.

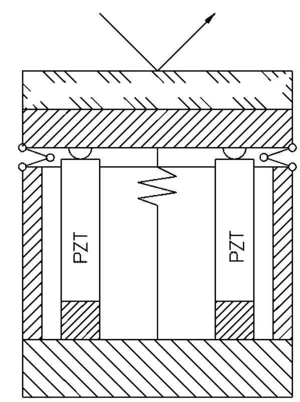


Fig. 2. Design of a differential-piezo-drive tilt platform.

Multi-Axis Tip/Tilt Systems / Scanners

PI offers two standard designs, both using parallel kinematics. Parallel kinematics systems have the following advantages over serial systems: only one moving platform, fixed pivot point, better dynamics, smaller form-factor. In addition, the design offers better linearity than attainable with two single-axis systems (e.g. two galvoscanners) in a stacked configuration.

I. Piezo Tripod Z/Tip/Tilt Platform

Examples: S-315 and S-316, S-325.

The platform is supported by three piezo actuators spaced at 120° intervals. Because expansion of an individual actuator affects both θ_x and θ_Y, more complex control algorithms are required.

With coordinate transformation, platform position commands can be resolved into targets for individual actuators (see the equations and Fig. 3 for details). The piezo tripod has one advantage over the differential drive: in addition to tilt motion, it allows active vertical control (piston motion) of the platform—an important feature for applications involving optical path-length adjustment (phase-shifting).

Also, the design allows for a central clear aperture, ideal for transmitted-light applications. As with the differential drives, temperature changes have no effect on the angular stability.

II. Differential-Piezo-Drive Tip/Tilt Platform

Examples: S-334, S-330, S-340.

The platform is driven by two pairs of piezo actuators arranged at 90° angles. Each pair is controlled as a unit in push-pull mode. The four actuators are connected in a bridge circuit and supplied with one fixed and two variable voltages. Because each actuator pair is parallel to one of the orthogonal tip/tilt axes θ_X and θ_Y, no coordinate transformation is required.

Like the piezo tripod design, the differential drive exhibits excellent angular stability over a wide temperature range. In the closed-loop models, availability of two sensor signals permits better linearity and resolution.

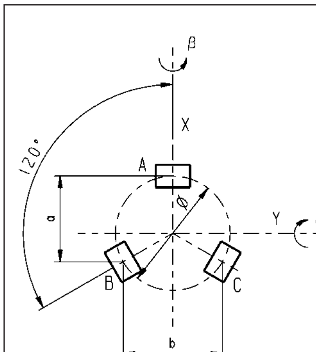


Fig. 3. Piezo tripod drive: A, B, C are the linear displacements of the respective actuators.

$\alpha = \frac{2A - (B+C)}{2a}$

$\beta = (B-C) / b$

$z = (A+B+C) / 3$

Example:
S-315 tip/tilt platform (see page 3-16).
Ø = 13.9 mm
a = 10.4 mm
b = 12.0 mm
A, B, C 0 to 12 µm

Dynamic Behavior of Piezo Steering Mirrors

The maximum operating frequency of a tilt platform is heavily dependent on its mechanical resonant frequency. The performance characteristics of the amplifier, servo-controller and sensors are also very important. To estimate the effective resonant frequency of the tilt mirror system (platform + mirror), the moment of inertia of the mirror substrate must first be calculated.

Moment of inertia of a rotationally symmetric mirror:

$$I_M = m\left[\frac{3R^2 + H^2}{12} + \left(\frac{H}{2} + T\right)^2\right]$$

Moment of inertia of a rectangular mirror:

$$I_M = m\left[\frac{L^2 + H^2}{12} + \left(\frac{H}{2} + T\right)^2\right]$$

where:

m = mirror mass [g]

I_M = moment of inertia of the mirror [$g \cdot mm^2$]

L = mirror length perpendicular to the tilt axis [mm]

H = mirror thickness [mm]

T = distance, pivot point to platform surface (see technical data table for individual model) [mm]

R = mirror radius [mm]

Using the resonant frequency of the unloaded platform (see individual technical data table) and the moment of inertia of the mirror substrate, the system resonant frequency is calculated according to the following equation:
Resonant frequency of a tilt platform/mirror system

$$f' = \frac{f_0}{\sqrt{1 + I_M/I_0}}$$

where:

f' = resonant frequency of platform with mirror [Hz]

f_0 = resonant frequency of unloaded platform [Hz]

I_0 = moment of inertia of the platform (see technical data table for the individual model) [$g \cdot mm^2$]

I_M = moment of inertia of the mirror [$g \cdot mm^2$]

For more information on static and dynamic behavior of piezo actuators, see pp. 4-25 *ff.* in the “Tutorial” section.

Examples of Custom Systems for Telescopes

High Speed Steering Mirrors & Coarse Alignment Systems for Astronomy

View of the 8.2 m Subaru infrared telescope in Hawaii (from http://SubaruTelescope.org/Index.html), printed with permission of NAOJ.

Active tip/tilt mirror for the Subaru Telescope (Mauna Kea, Hawaii).
Mirror diameter: 150 mm
Tip/tilt range: ±600 µrad
Resonant frequency: 610 Hz

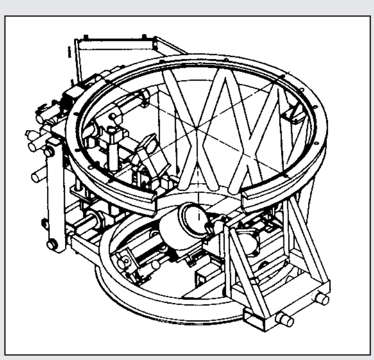
Active tip/tilt mirror for the Subaru telescope, rear view.

Active tip/tilt mirror for the United Kingdom infrared telescope (UKIRT) on Mauna Kea, Hawaii with Hexapod 6-D alignment system (for information on Hexapod systems, see the "Hexapods / Micropositioning" section).
Mirror diameter: 314 mm
Tip/tilt range: ±500 µrad
Resonant frequency: 280 Hz

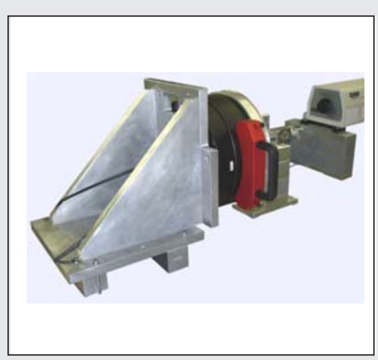
Active secondary mirror for NASA Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii,with Hexapod 6-D alignment system (for information on Hexapod systems, see the "Hexapods / Micropositioning" section).
Mirror diameter: 244 mm
Tip/tilt range: ±250 µrad
Resonant frequency: 490 Hz

Active tip/tilt mirror system for the Keck Outrigger telescope in Hawaii. The units are controlled by a high-performance digital controller with a fiber optic interface (not shown).
Mirror diameter: 250 mm
Tip/tilt range: ±150 µrad
Resolution: nanoradian range
Position measurement: capacitive

Active secondary tip/tilt mirror for the 2.2 m ESO (European Southern Observatory) telescope in La Silla, Chile.
Mirror diameter: 100 mm
Tip/tilt range: ±400 µrad
Resonant frequency: 900 Hz



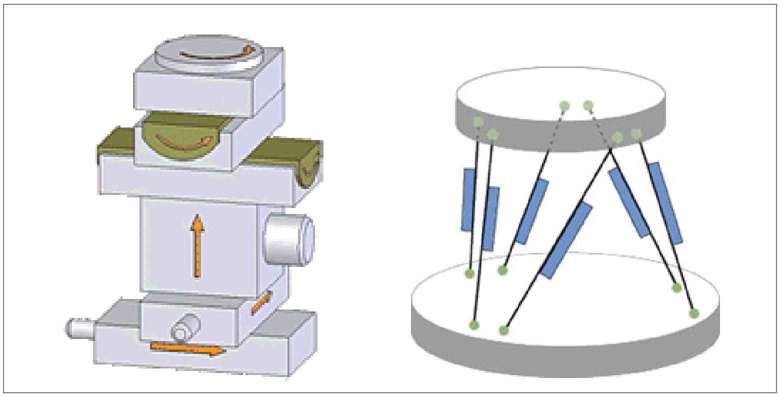
Telescope structure with active secondary mirror (from "Progress Report on DISCO: A Project for Image Stabilization at the 2.2 m Telescope," F. Maaswinkel, S. D'Odorico und G. Huster, ESO, F. Bortoletto, Istituto di Astronomia, University of Padova, Italy).



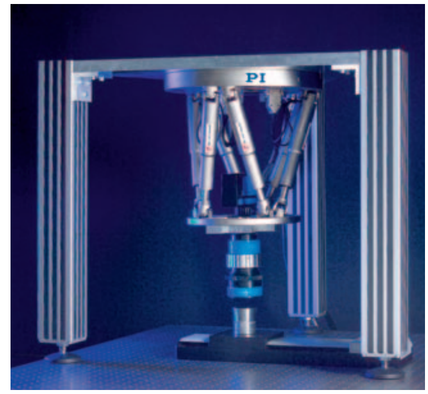
Tzec Maun Telescope Secondary Tip/Tilt Mirror
Ø290 mm, 100 µrad Tip/Tilt, 50 Hz Bandwidth
100 nrad Resolution, > 650 Hz F_{res}
Rise time 3 ms (small angle), 5 ms (large)

Parallel Kinematic (PKM) Low-Speed Systems

Controlling Motion in up to 6 Degrees of Freedom



Stacked serial kinematics 6D system vs. Hexapod parallel kinematics system designs. Advantages such as compactness and minimized inertia (one platform for all sixactuators) are easily seen. The reduced inertial mass makes for significantly faster response than with serial kinematics. Because there are no moving cables to cause friction, repeatability is increased also.



PI Hexapod in an optics testing application. The parallel kinematic design and large aperture allow for the interferometer to be integrated into the Hexapod. Images are captured by a CCD camera and evaluated in real time. A MATLAB program, controls the position of the Hexapod. (Photo: PI / Fraunhofer Institute for Production Technology, IPT)

Advantages of PKM

- Lower Inertia
- Better Dynamic Behavior
- Smaller Package Size
- Higher Stiffness
- No Accumulation of Position Errors
- Reduced Runout Errors
- No Moving Cables: Better Repeatability

PI's Hexapod Spectrum

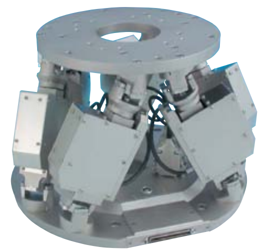
Variety of Hexapod parallel kinematics micropositioning systems.

Large custom Hexapod with a positioning frame measuring some 1.0 x 1.5 meters.

Standard Low Speed Alignment Systems

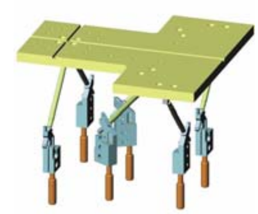
Servo Motor-Driven, Parallel Kinematic Designs

M-850 High Load 6-Axis-Alignment System; Works in Any Orientation; No Moving Cables; 200 kg Load Capacity (Vertical); Heavy-Duty, Ultra-High-Resolution Bearings for 24/7 Applications; Repeatability to ±1 µm; Encoder Resolution to 0.005 µm; MTBF 20,000 h

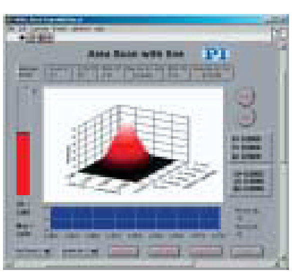


M-824 Vacuum-Compatible Compact 6-Axis Alignment System; Folded Drives; Travel Ranges to 45 mm / 25°; Load Capacity to 10 kg; Resolution to 7 nm; Repeatability ±0.5 µm; Velocity to 25 mm/sec

M-840 Medium Load 6-Axis Alingnment System; Velocity up to 50 mm/s; Travel to 100 mm/60°; Load Capacity 10 kg; Repeatability up to ±2 µm; Encoder Resolution to 0.016 µm; Vacuum Option; MTBF 20,000



F-206 Flexure Hexapod 6-Axis Alignment System; 0.033 µm Actuator Resolution; Repeatability 0.3 µm in Space; No Moving Cables; For Scanning and Alignment; Choice of Optional Photometers



HexControl™ software showing optical power distribution

F-361 High-speed optical power meter

Rack-mount 6-Axis Hexapod controller with sophisticated, yet, very user-friendly positioning and alignment sofware.
Modular design, firmware and software optimized over 15 years and hundreds of Hexapod systems. Very robust system, easy firmware and calibration data update, ultra fast axis synchronization.
Keypad and display are optional.

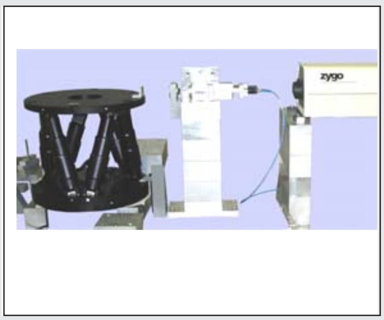
Hexapod / Tripod Systems Experience

Shown here are but a few custom hexapods and tripods developed by PI in recent years.

These systems were designed for special customer applications and are not available off the shelf; many other custom systems are subject to non-disclosure agreements and cannot be shown at all.

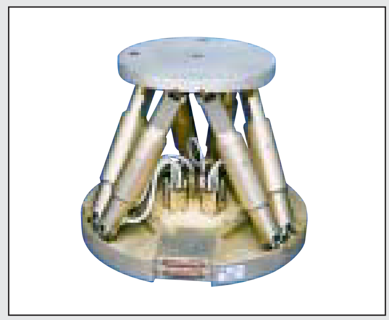
Custom, high-precision, non-magnetic Hexapod with the award-winning piezo-based NEXLINE® nano drives.

1000kg-Class Hexapod Alignment System (Ø1m) Compared to 100kg-Class Hexapod (Ø0.3m)

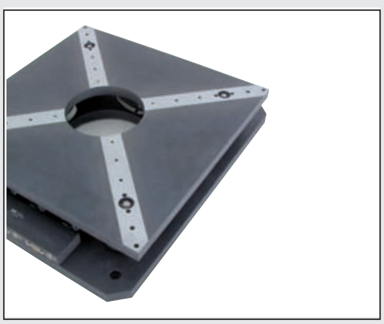


Tzec Maun Telescope Hexapod Secondary Alignment System. Travel XY: 4 mm, Z: 24 mm; Tip/Tilt 2°; <1µm Resolution; 30 kg Load capacity

Custom Hexapod & piezo tip/tilt system for alignment of secondary mirrors in astronomical telescopes.



Custom Hexapod for automatic satellite antenna alignment.



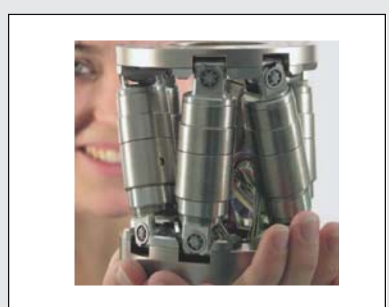
Tripod: XY rot-Z stage. Parallel Kinematics 160 mm Aperture, 1500 N load capacity

Custom Hexapod with active tip/tilt mirror for the UKIRT infrared telescope on Mauna Kea, Hawaii

Custom "6+3" Hexapod with additional struts providing independent position feedback for additional security.

PiezoWalk® Tripod: Z/Tip/Tilt Stage Ø300 mm, 200 N load capacity, 1.3 mm piston, 10 mrad tilt range

Custom high-load, moisture-protected Hexapod for Astronomy applications



M-810, Miniature Hexapod Ø=100mm, H=118mm, max Load= 5kg, X,Y: +/-20mm, Z: +/-6.5mm, rot U,V +/-11°, rot W+/- 30°

PI Wins Substantial Hexapod Contract for ALMA Millimeter Radio Telescope

Six-axis weatherproof secondary Hexapod for the ALMA telescopes

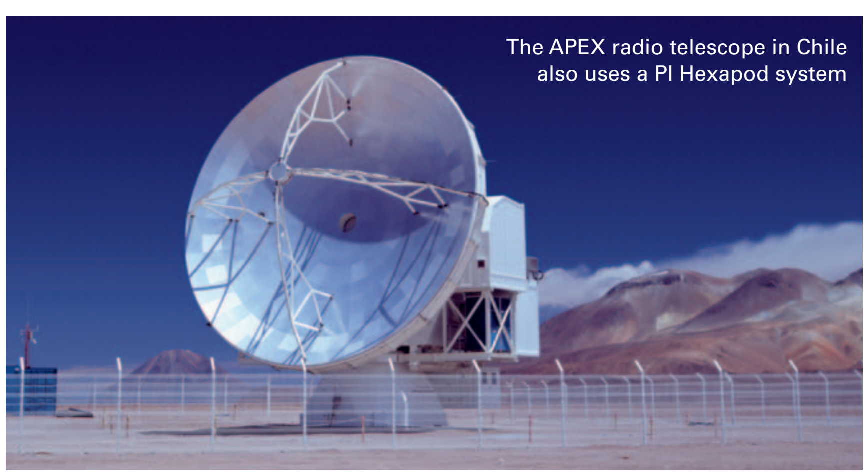
Model of the ALMA telescope

General Dynamics subsidiary Vertex Antennentechnik has ordered 25 high-precision micropositioners for large array radio telescope

The ALMA (Atacama Large Millimeter Array) international partnership is constructing and will operate a radio telescope comprising an array of up to 64 antennas. The partnership is made up of North America (USA and Canada), Europe and Japan, in cooperation with Chile. PI will deliver a total of 25 Hexapod systems for the extremely precise alignment of the telescope's secondary reflectors to Vertex Antennentechnik in Duisburg, Germany by 2011. Hexapods are the first choice of positioning system for astronomical multi-axis alignment tasks. They can provide very high stiffness, a very large aperture, and are devoid of cable management issues.

The PI Hexapod combines a load capacity of 200 kg with sub-micron linear resolution and microrad-level angular resolution. A highly sophisticated digital controller provides advanced features such as a user-programmable virtual pivot point, extremely important in complex alignment applications. Target positions in 6-space are entered in user-friendly coordinates and reached by smooth vectorized motion which saves valuable programming time when integrating the system. Similar six-axis micropositioning systems from PI have already proven reliable in operation at the ALMA VertexRSI test antenna and the Atacama Pathfinder Experiment (APEX) radio telescopes. Millimeter and sub-millimeter astronomy investigates the universe in the spectral range which traditionally stretches from radio waves to the infrared. ALMA will be used in this spectral range to investigate the structure of the early universe as well as galaxies, stars and planets in their formative stages. ALMA is being built in the Chilean Atacama desert at an altitude of over 5000 m, one of the driest places on earth. These are favorable conditions for the best possible observations, since millimeter radiation is absorbed by water vapor in the atmosphere.

Each individual ALMA antenna has a primary reflector 12 m in diameter, higher than a four-story house. The mobile antennas will be used together in various arrangements as a single



The APEX radio telescope in Chile also uses a PI Hexapod system

The ALMA VertexRSI test antenna with PI Hexapod system

telescope. The spread of the antenna array will be between 150 m and a maximum of 12 km. On completion in 2011, ALMA will be the largest and most powerful radio telescope in the world, with a resolution ten times better than that of the Hubble space telescope.

In supplying the six-axis Hexapods and their high-performance controllers, Physik Instrumente is contributing its many years of experience in extremely high-precision positioning to the ALMA project. PI was able to demonstrate the reliability and accuracy of its systems in the ALMA VertexRSI test antenna in New Mexico, USA. ALMA's technological forerunner project, the APEX radio telescope in Chile, is already successfully using the same PI micropositioning system.

PI has been supplying hexapods, micropositioning actuators and active optics for astronomical telescopes, including several infrared telescopes on Mauna Kea in Hawaii as well as telescopes in Chile, South Africa and the Canary Islands, for over 15 years.

http://www.alma.nrao.edu
http://www.eso.org/projects/alma
http://www.apex-telescope.org

Ultra-Precise Hexapod 6D-Measuring System for Optical Surfaces

Inserts for precision optical molds make high demands on the testing process. Today, such testing can easily be automated with the help of interferometric measuring devices. Parallel-kinematics Hexapod 6-axis alignment systems even make it possible to integrate testing directly in the manufacturing process.

Fig. 1: The tighter the tolerances required for a product, the higher the precision required of the testing equipment. The optical mold inserts for production of plastic or glass lenses have especially high precision requirements.
(Illustration: Fraunhofer Institute for Production Technology, IPT)

The integration of testing equipment for optical mold inserts (Fig. 1) directly into the manufacturing cell avoids complex and time-consuming setup steps and completely eliminates rechucking errors. The new testing unit developed by the Fraunhofer Institute for Production Technology (IPT) in Aachen, Germany tests the optical mold inserts directly in-line, on the production machine. Discrepancies are calculated and the error is fed back into the process where it can, if necessary, trigger automatic reworking of the optical surface. Automated interferometric surface testing is the key to the system.

Interferometric testing: non-contact, fast and extremely precise

Interferometric optical mold testing uses the interference pattern (fringe pattern) which gives information about the topography of the test sample. Image processing algorithms automatically recognize and evaluate shape deviations with nanometer accuracy. The interferometer must, of course, be positioned very precisely relative to the optical surface.

First, coarse adjustment aligns the beam reflected off the test surface with the CCD sensor. Then, with the fine adjustment, a well-defined interference pattern is created. The automated fine-adjustment algorithm uses the Fast Fourier Transformation (FFT) technique to analyze the fringe pattern. The adjustment strategy is based on an evaluation system newly developed at the Fraunhofer IPT, which determines the topology from a single interference pattern.

In order to test both spherical and aspherical elements, motion in six degrees of freedom is required (Fig.2). For this purpose, a PI parallel-kinematics positioning system is used. In addition to very high accuracy, it offers further advantages such as low inertia, uniformly high dynamic performance for all motion axes, and a compact design with a large aperture.

Hexapod: Six Degrees of Freedom and Freely Definable Pivot Point

The PI M-840 Hexapod chosen also provides rapid settling after a move, a linear travel range of up to 100 mm and a rotational travel range up to 60°. The large working space makes it possible to measure spherical surfaces with a radius of up to 100 mm. Also important for both the coarse and fine alignment process is the freely definable pivot point, which is not affected by motion. The optical mold testing interferometer system achieves impressive values: 3 µm accuracy in X and Y, 1 µm in Z – with repeatabilities also of 3 µm and 1 µm, respectively. The rotational minimum incremental motion of only 0.017 arc minutes (5 µrad) is over an order of magnitude better than the required 1 arc minute.

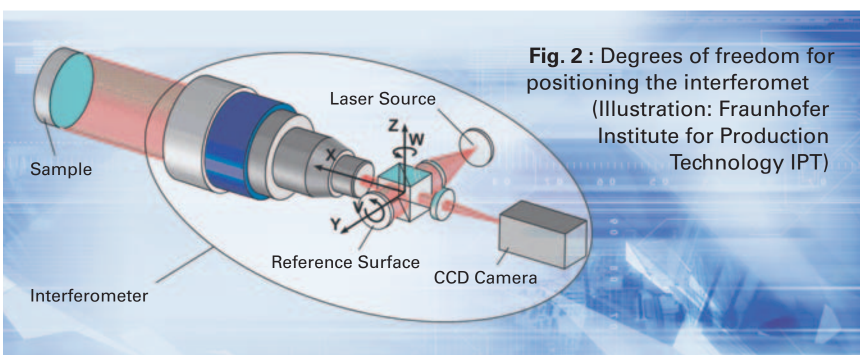


Fig. 2 : Degrees of freedom for positioning the interferomet (Illustration: Fraunhofer Institute for Production Technology IPT)

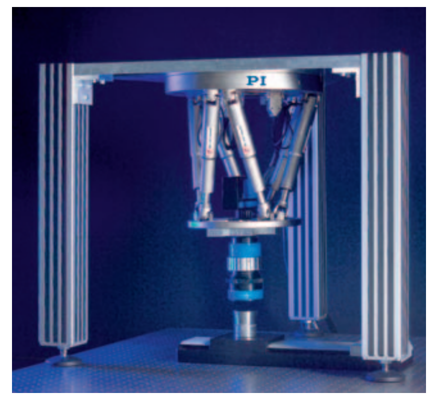


Fig. 3: The Hexapod is mounted on a 20 mm thick aluminum plate. The parallel-kinematic design and large aperture allow for the interferometer to be integrated into the Hexapod. Images are captured by a CCD camera and evaluated in real time. A MATLAB program, controls the position of the Hexapod.
(Photo: Physik Instrumente, PI / Fraunhofer Institute for Production Technology, IPT)

Simple Integration

It was surprisingly easy to integrate the Hexapod into the application's automation environment. Control is simplified by the Hexapod controller's open interface architecture, which facilitates programming with high-level commands using any of a variety of included drivers (COM Object or DLL). The Hexapod controller can thus be operated by external programs, such as the MATLAB programs employed for image processing and analysis in the testing interferometer. The flexibility of the Hexapod system played an important part in making possible the first fully integrated automated testing device for optical components with complex geometries. The new interferometer will significantly simplify quality control while providing higher precision than otherwise possible.

Karl Vielhaber, MSc, scientific assistant at the Fraunhofer Institute for Production Technology (IPT) in Aachen, Germany and Ellen-Christine Reiff, M.A., Editorial Service Stutensee

Program Overview

- Piezo Ceramic Actuators & Motors
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- Active Optics / Tip-Tilt Platforms
- Capacitive Nanometrology Sensors
- Piezo Electronics: Amplifiers and Controllers
- Hexapod 6-Axis Positioners / Robots
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