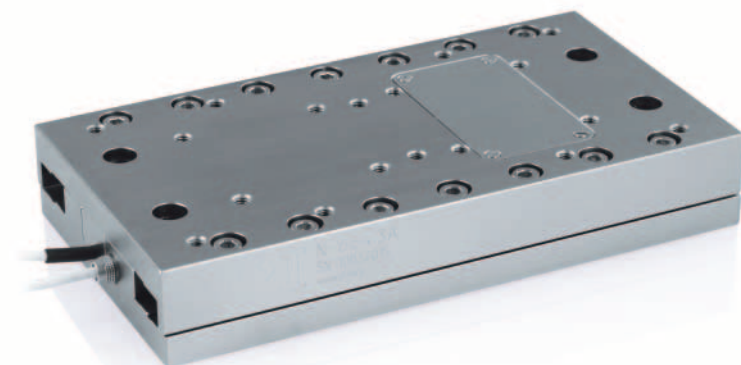


Sensor Technology for Nanopositioning Technology

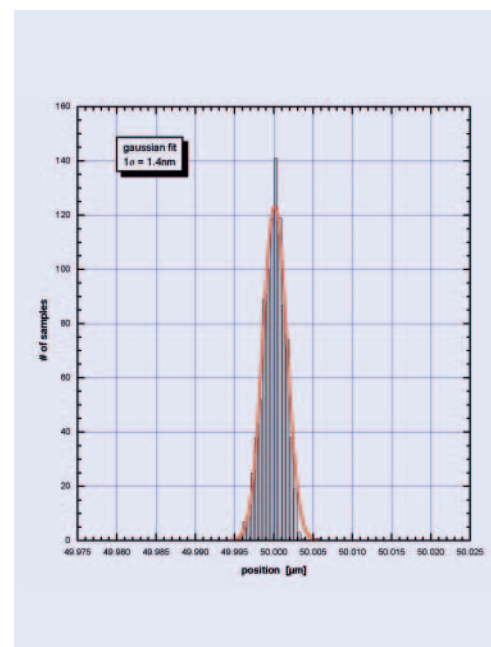


The PIOne linear encoder is used in PI's high-resolution nanopositioning system, such as N-664. This linear positioner is driven by NEXACT® piezo linear motors and, depending on the motion controller, can achieve a position resolution of less than one nanometer at 30 mm travel range

PI offers the widest range of high-dynamics and high-resolution nanopositioning systems worldwide. Their linearity and repeatability would not be possible without highest-resolution measuring devices.

Accuracies in the range of a few nanometers and below require a position measurement method that can also detect motion in this range. The most important specifications for selecting a suitable method are linearity, resolution (sensitivity), stability, bandwidth and, last but not least, the costs. Another important factor is the ability to directly record the motion of the platform. The contact with the movable parts also affects the measuring result; therefore, PI uses noncontact measurement methods as far as possible. Furthermore, the sensors need to be small and may not heat up.

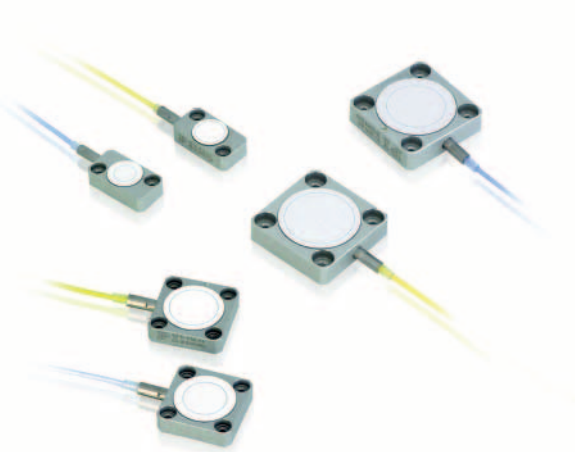
PI nanopositioning systems use three different types of sensors: Capacitive sensors and linear encoders for direct metrology as well as strain gauges for indirect position measurement.



Measurements have confirmed the excellent repeatability of the piezo positioning system with capacitive sensors with 1.4 nm (1σ value) of standard deviation

Maximum Accuracy through Direct Metrology

When directly measuring positions with noncontact sensors, each change in position of the moving platform is directly captured by the controller relatively to the base body. There are no drive or guiding elements, which would affect the measurement, between measured point and moving platform. This method allows a bandwidth in kilohertz range, resolution in sub-nanometer range and excellent stability.



Capacitive Sensors

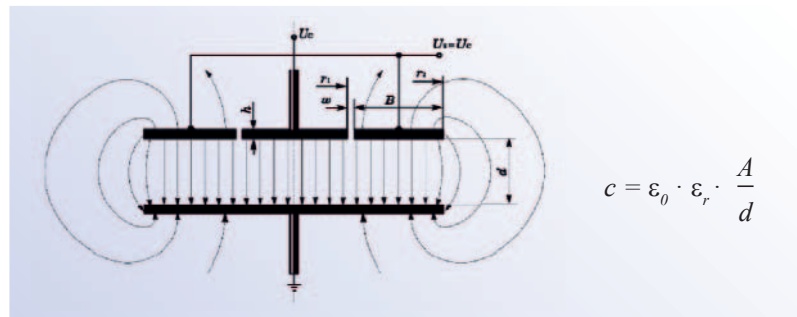
Nanopositioning systems from PI are driven by translation piezo actuators and have travel ranges of a few hundred micrometers up to one millimeter. Capacitive sensors achieve a position resolution in the sub-nanometer range, high stability and bandwidth, as well as the best linearity and accuracy.

Capacitive sensors from PI determine the distance between two plate electrodes without contact. An active guard ring electrode generates a homogenous field in the measurement area. This and the very precise parallel adjustment of the two electrodes guarantees the best possible linearity of the sensor signals over the entire measuring range. These sensors are integrated in the nanopositioning system in such a way that no effects on size and mass (inertia) are to be expected. With a corresponding arrangement, they directly detect the motion of the platform (direct metrology).

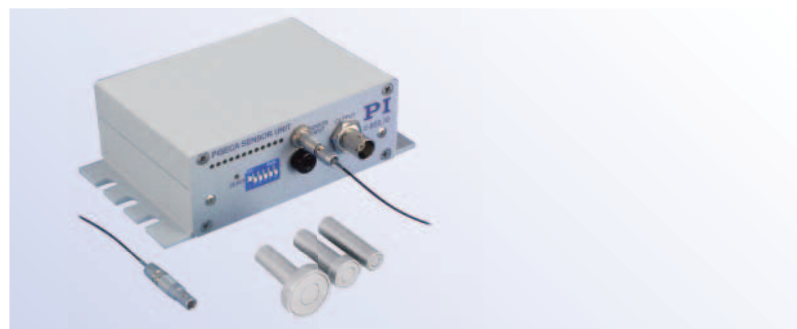
PISeca single-plate capacitive sensors measure against all kinds of conductive surfaces and are easier to handle mechanically, for example during installation or cable routing. Their employment is also more versatile, e.g. for detecting motions perpendicular to the direction of measurement. The quality of the sensor signals, however, strongly depends on the parallelism and condition of the surface measured.

- Noncontact absolute measurement of distance, motion and vibration
- Measuring ranges from a few 10 µm to 2 mm feasible
- Only minimum heating, no scattered light
- Direct metrology: Direct position measurement of moving objects

- Vacuum compatible down to 10⁻⁹ hPa
- Maintenance-free, no wear
- High bandwidth up to 10 kHz
- High temperature and long-term stability (<0.1 nm/3 h)
- Invar versions for highest temperature stability (5 × 10⁻⁶/K)
- Compact one and two-electrode sensors, custom designs
- Processing electronics in various configuration levels, from analog OEM versions to a modular digital controller system that can be expanded at any time



Operating principle of a capacitive sensor. The capacitance C is proportional to the active sensor area A , d is the measuring range (distance from sensor to target surface), ϵ_0 is constant, ϵ_r is the dielectric constant of the material between the plates, generally air. The measured quantity is the change in capacitance of the electric field. An active guard ring electrode generates a homogenous field in the measurement area

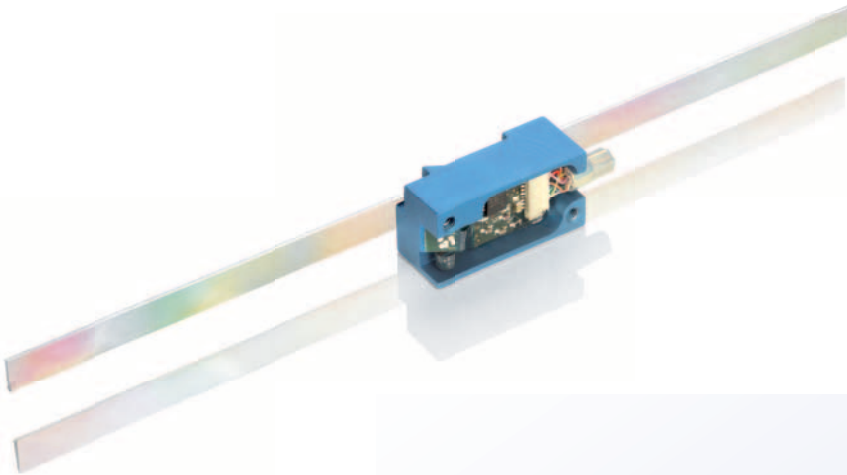


PISeca single-electrode capacitive sensors measure against all kinds of conductive surfaces and are easier to handle mechanically, for example during installation or cable routing. Their employment is also more versatile, e.g. for detecting motions perpendicular to the direction of measurement. The E-852 stand-alone processing electronics for PISeca only shows minimum noise and integrates a linearization system. All systems are calibrated at PI and optimized for the intended bandwidth and the measuring range

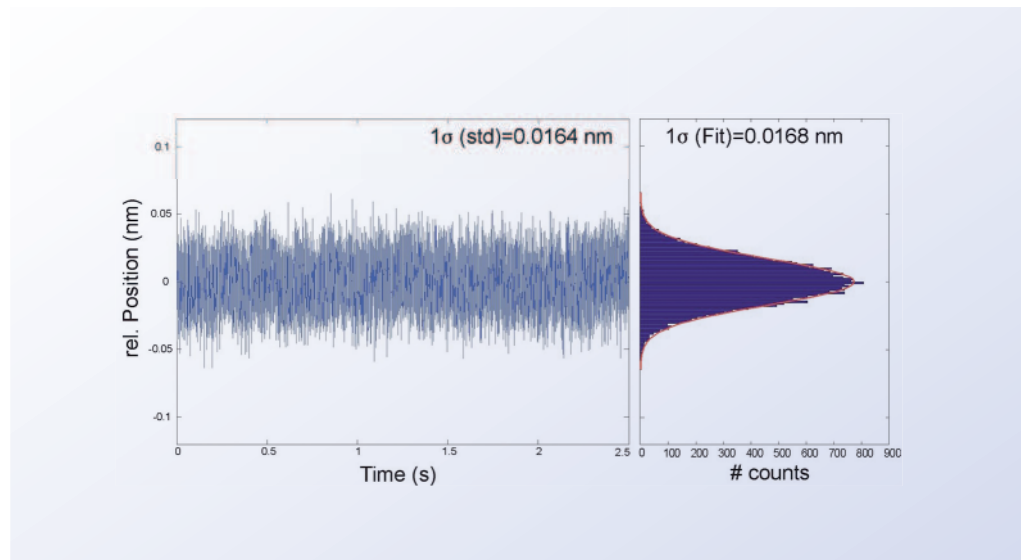
**PIOne Linear Encoders:
Small with Picometer Resolution**

The capacitive measuring systems reach their limits with larger travel ranges: Either sensor areas become larger or resolution and linearity deteriorate. Nanopositioning system with piezomotors, which have travel ranges of several 10 millimeters, use linear encoders as position sensors. These are incremental measuring systems that consist of a scale and sensor head. The high-resolution linear sensor PIONe ensures a position resolution of far less than a nanometer with adequate processing of the measurement.

The sensor head of the PIONe contains a Mach-Zehnder interferometer, which is moved along a linear scale. Sine and cosine signals are generated from the signals of the reflections at the grid. Additional interpolation accounts for the demonstrably small resolution of the system. The sensor head also generates a direction-sensing reference. The sensor head here measures $23 \times 12 \times 9.5 \text{ mm}^3$. PIONe uses a patented technology.



- Resolution to 20 picometer RMS;
0.12 nanometer peak-to-peak
- Velocities up to 0.5 m/s at maximum resolution
- Compact dimensions
 $23 \text{ mm} \times 12 \text{ mm} \times 9.5 \text{ mm}$
- Sine, cosine or quadrature output signals
- Low power consumption and low heat dissipation
- Bakeout temperature up to 80°C



Noise measurement of a positioning system with the PIONe at 1 MHz bandwidth and 18-bit resolution of the sensor input: 16 picometer RMS and 100 picometer peak-to-peak

Indirect Position Measurement with Strain Gauge Sensors

Strain gauge sensors consist of a thin metal (SGS) or semiconductor foil (piezo-resistant, PRS), which is attached to the piezoceramics or, for improved precision, to the guiding system of a flexure stage. This type of position measurement is done with contact and indirectly, since the position of the moving

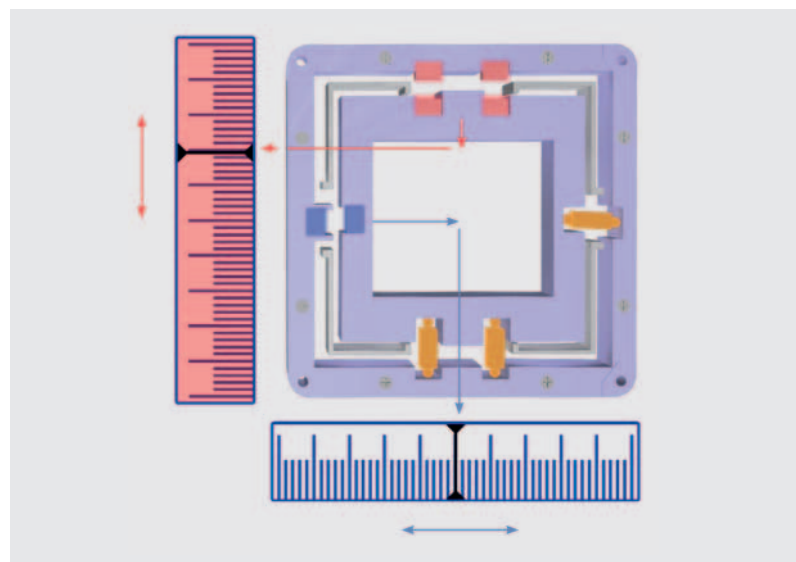
platform is derived from a measurement on the lever, guide or piezo stack. Strain gauge sensors derive the position information from their expansion. Full-bridge circuits with several strain gauge sensors per axis improve thermal stability.

Sensor type	Sensitivity/Resolution*	Linearity*	Stability/Repeatability	Bandwidth*	Measurement method	Measurement range
Capacitive	excellent	excellent	excellent	excellent	direct / noncontact	<2 mm
Strain gauge sensors made of metal foil (SGS)	very good	very good	good	very good	indirect / with contact	<2 mm
Piezoresistive strain gauge sensors (PRS)	excellent	good	average	very good	indirect / with contact	<1 mm
Linear encoders	excellent	very good	excellent	very good	direct / noncontact	up to >100 mm

* The classifications refer to the characteristics of the nanopositioning system. The information on resolution, linearity and repeatability in the respective data sheet reflects the specifications of the overall system, including controller, mechanical system and sensor. They are tested using external measuring instruments (Zygo interferometer)

Direct Parallel Metrology: Multi-Axis Measurements using a Fixed Reference

A multi-axis stage design with parallel kinematics allows you to use direct parallel metrology, measuring all degrees of freedom of the moving platform in relation to a fixed reference. Unintended crosstalk of the motion into a different axis, e.g. as a result of an external force, can thus be detected and actively corrected in real time. This so-called active guiding can keep the deviation from the trajectory down to a few nanometers, even in dynamic operation.



Parallel-kinematic nanopositioning system with capacitive sensors, parallel-metrology arrangement and reduced inertia. The arrows show the signal flow from the sensor to the closed-loop control. Red: X axis, blue: Y axis



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