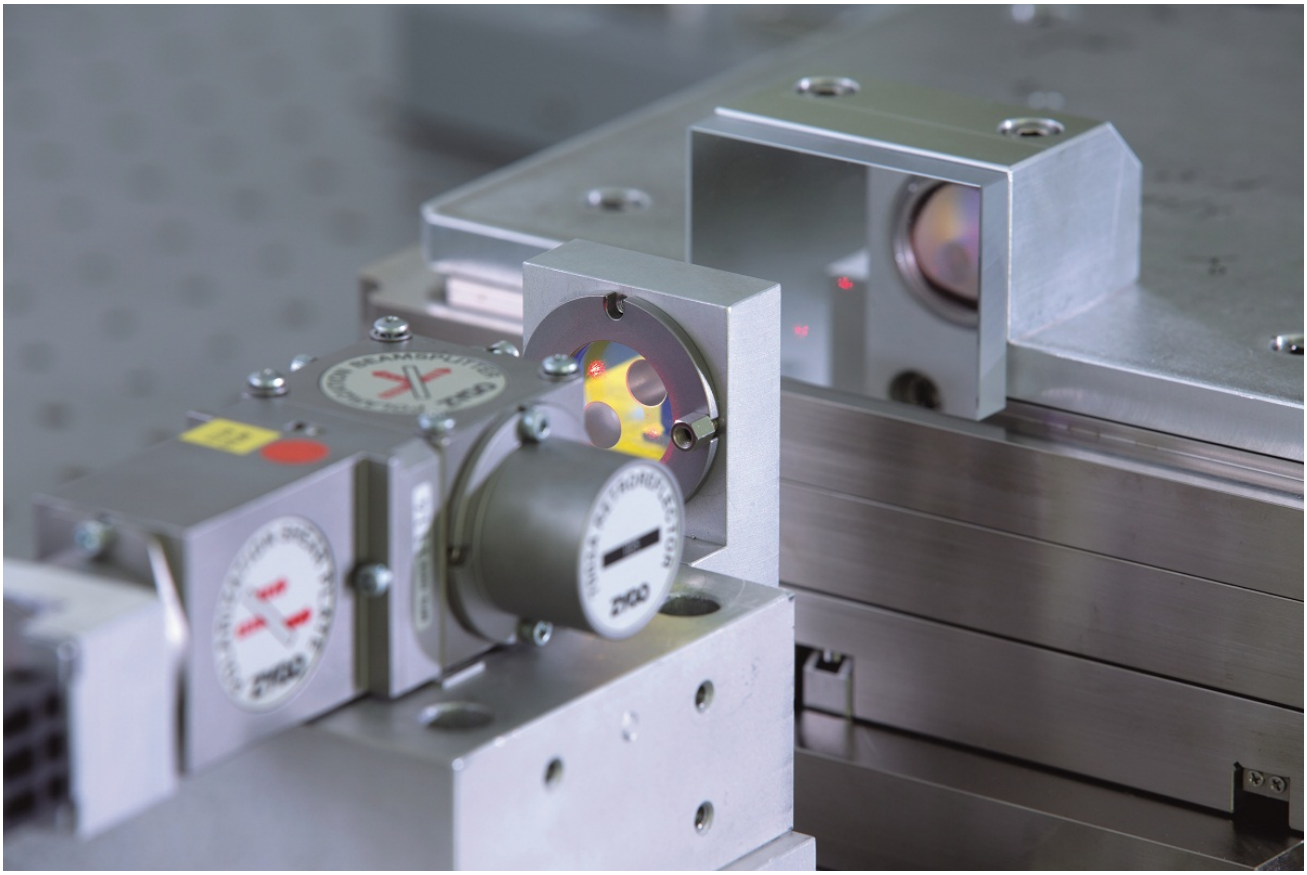
This is how PI Does Measuring - Part I

Measuring Environment / Measuring Equipment Portfolio / Data Evaluation



For PI, each individual measurement and qualification of a positioning and motion system is an instrument for quality assurance. This makes sure that only those products leave the premises that are within the guaranteed specifications. High-precision measuring is necessary for qualifying as well as for final inspection and approval checks of all motion and positioning systems. Both the selection of the measuring environment and setup of the measuring equipment are adapted to the requirements of the respective product line.

The desired resolution, measuring accuracy, tolerances, and sampling rate are the criteria for selection. In addition, the stability of the measuring setup over time plays a decisive role and makes special demands on avoiding drift effects, e.g., by using adequate temperature and vibration isolation.

1 Measuring Environment

1.1 Measuring Laboratories

Precision measuring is done on honeycomb tables that are isolated passively from vibration. The foundation of every measuring room is in turn, isolated from the rest of the building and therefore suppresses seismic influences. All measuring laboratories are air-conditioned.

15 special measuring laboratories with an overall surface of 750 m^2 are available at PI's headquarters in Karlsruhe. Five measuring laboratories with upstream areas for preliminary temperature regulation have special seismic, electro-magnetic, and thermal isolation, which ensures temperature stability better than 0.25 Kelvin over a period of 24 hours. This makes accurate measuring possible down to the picometer range. Long-term measuring of the positional stability is only possible under such conditions.

Fig. 1 View into a nanometrology laboratory with six-fold isolation. Measuring is done fully automatically under controlled ambient conditions.

	Number of laboratories for measuring	Air conditioned and simple seismic base isolation	Multiple seismic, acoustic, and thermal base isolation
VC classification*		VC-D, VC-E, VC-F, VC-G	VC-G, VC-H, VC-I
	5	276 m^2	82 m^2
	10	481 m^2	-

Fig. 2 Laboratories available for measuring.
*The VC classification is different for each room. Simple seismic-decoupled rooms achieve classes VC-D to VC-G. That corresponds to maximum vibration of <6.25 µm/s in a frequency range of 1 to 100 Hz. Multiple seismic-decoupled rooms achieve classes VC-F to VC-I. That corresponds to a maximum vibration of <0.78 µm/s in a frequency range of 1 to 100 Hz.

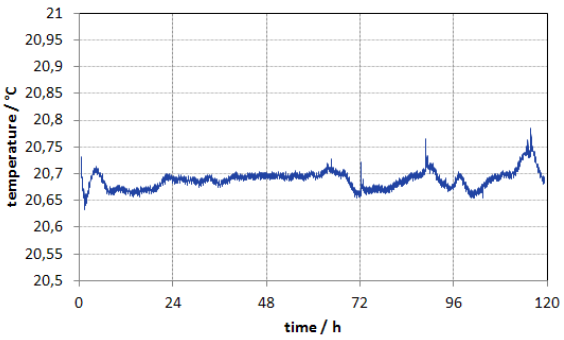


Fig. 3 Temperature stability of a measuring room over several days

1.2 Measuring Technology in the Production Environment

In (large) series production, a large part of the measuring takes place directly in the production environment. This allows deviations in the process to be detected quickly, which helps to prevent rejects or costs for reworking.

For this purpose, PI develops fully and semiautomatic measuring and test stations that are validated for their suitability with the help of a measuring system analysis before they are used in production ("Gage Repeatability & Reproducibility").

Fig. 4 View of semiautomatic test stations for large series production

1.3 Overview of Measuring Capabilities under Specifically Designed Environmental Conditions

In extensively equipped application laboratories, a large number of measurements can be made under specific ambient conditions.

Vacuum chambers with a base pressure to 10^{-11} hPa allow function tests and residual gas analysis. Depending on the application, not only the pressure area is decisive, but also the permissible residual materials inside the vacuum chamber such as for example, in the crystallography or the optical coating.

Cryogenic chambers for measuring to 77 °K (condensation point of nitrogen) allow startup and function checking at extremely low temperatures.

Even long-term examinations and lifetime testing are possible under these special conditions.

Special environmental conditions			
Measuring equipment	**Temperature range**	**Humidity range**	**Test chamber volume**
Climate chamber	-72 °C to +180 °C	10 ... 95 % rel.	190 / 275 l
Cryogenic chamber	77 °K to 300 °K	-	21.2 l
Vacuum chamber	20 °C to approx. 70 °C	-	98 / 106 l
Glovebox	-	approx. 5 ppm	748 l

1.4 Special Equipment

Lifting and tilting equipment with a load capacity of 5000 kg allows qualifying of positioning systems at any angle with application-specific alignment and load.

Qualification of a two-ton hexapod assumes that masses up to five tons can be safely attached for measuring. In the heavy-load hall, three gantry cranes span the working area, and lift and transport the components of the positioning systems.

Fig. 5 At PI in Karlsruhe, lifting and tilting equipment specifically for measuring or qualifying products according to application is available. In this picture, a hexapod with load is measured interferometrically

2 Measuring equipment

All measuring equipment is subject to recalibration and therefore, it is possible to perform suitable measuring with minimal uncertainty. This means that the resulting measurement and the actual value correspond to each other at all times, and can be reproduced with respect to national and international standards. Interferometric measuring systems are frequently used that are particularly distinguished by high resolution, short measuring times, and noncontact, wear-free measuring.

Not all locations have measuring equipment for every resolution.

2.1 Measuring Equipment According to Measurand

Length / Path			
Measuring equipment	**Measuring principle**	**Resolution/DPMI**	**Measuring range**
Tactile measuring sensor	Inductive (incremental)	to 5 nm	to 50 mm
Laser interferometer	Optical (incremental)	to 0.151 nm	to 10 m
Vibrometer	Optical (Doppler effect)	2 nm	40 mm
Multi-sensor measuring machine	Optical and tactile	0.1 µm	300 mm × 300 mm × 160 mm
CNC coordinate measuring machine	Incremental sensor with glass scale	0.1 µm	900 mm × 1800 mm × 800 mm
PISeca	Capacitive sensor	0.001 % of the travel range	to 100 µm

Angle			
Measuring equipment	**Measuring principle**	**Resolution/DPMI**	**Measuring range**
Laser interferometer	Optical (incremental)	to 34 nrad	± 0.11°
Autocollimator (AKF)	Optical (autocollimation)	to 0.05 arcsec	± 0.29° (up to ± 2.3°)
Angle measuring device / rotary encoder	Incremental	to 0.4 arcsec	360°

Velocity			
Measuring equipment	**Measuring principle**	**Velocity resolution**	**V_{max}**
Laser interferometer	Optical (incremental)	to 10 nm/s	up to 4 mm/s
Vibrometer	Optical (Doppler effect)	to 0.005 µm/s	up to 10 mm/s

Surface finish / surface flatness			
Measuring equipment	**Measuring principle**	**Resolution/DPMI**	**Measuring range**
White light interferometer	Optical (incremental)	λ/25	80 mm × 80 mm
White light interferometer	Optical (scanning white light interferometry)	to 1 nm for smooth surfaces	Z=70 mm X=38 mm Y =28 mm
Laser scanning microscope	Optical		X=100 mm; Y=100 mm; 1× - 8× objective

Eccentricity / wobble			
Measuring equipment	**Measuring principle**	**Resolution/DPMI**	**Measuring range**
Static spindle analyzer	Capacitive	80 µV/µm	Low ±125 µm High ±6.5 µm

3 Evaluation of the Measured Data

The DIN ISO 230-2 and VDI/DGQ 3441 standards are the basis for qualification of PI products and evaluation of the measurands.

The qualification data is always verifiable for each individual product. The measured data is compiled in a database and used for process control. Traceability at product level is particularly interesting for large production runs.

The measurement log is provided with many systems such as hexapods or piezo systems. It is therefore possible for the customer to verify the measured performance of the system before it was dispatched and also to see which system components belong together.

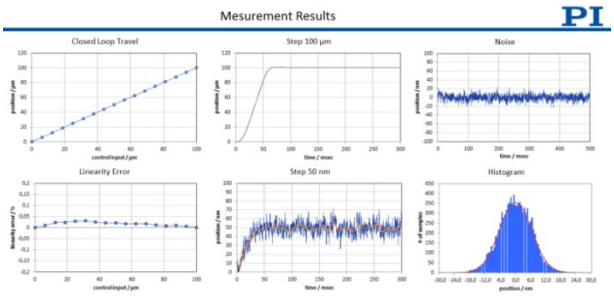


Fig. 6 Typical measurands in a measuring log showing the linearity and impulse response of a piezo system

3.1 Acquiring Measuring Data and Statistical Process Control

The measuring data is transmitted in real time automatically, saved to a database, and then visualized on a web-based user interface. Access to the control charts and the analysis tool is done via a web browser. The technical experts have immediate access to all process data and if required, can intervene immediately.

- Automatic saving of the measured data after measuring
- Real-time display of the measured values in the control charts
- Multi-control charts for maximum process control
- Dynamic calculation of warning and intervention limits
- Download of raw data and customer log
- Calculation of process capability Cpk level
- Pareto chart for process analysis and optimization
- Correlation chart to check the dependence of two measurands
- Various export functions

Fig. 7 Examples of visualizations from the database of measurement results

3.2 Measuring Software

The software for controlling the fully or semiautomatic measuring and test stations is developed in-house by PI. All measuring equipment can be configured directly and read from the software, which means that there are no unnecessary sources of error for the measured values, storing in databases, and creating the log.

Software development makes use of current development standards such as version control systems, bug tracking, automatic build systems, static code analysis, unit tests, and code reviews. This ensures that the software is always traceable and the quality standards are adhered to.

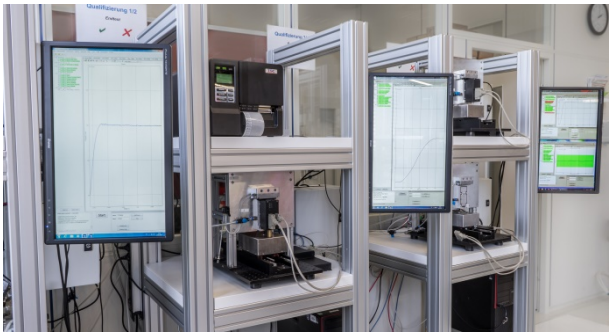


Fig. 8 Standardized process control with full documentation of the individual measuring logs

About PI

Well known for the high quality of its products, PI (Physik Instrumente) has been one of the leading players in the global market for precision positioning technology for many years. PI has been developing and manufacturing standard and OEM products with piezo or motor drives for 40 years. Continuous development of innovative drive concepts, products, and system solutions and more than 200 technology patents distinguish the company history today. PI develops, manufactures, and qualifies all core technology itself: From piezo components, -actuators, and motors as well as magnetic direct drives through air bearings, magnetic and flexure guides to nanometrological sensors, control technology, and software.

PI is therefore not dependent on components available on the market to offer its customers the most advanced solutions. The high vertical range of manufacturing allows complete control over processes and this allows flexible reaction to market developments and new requirements. By acquiring the majority shares in ACS Motion Control, a worldwide leading developer and manufacturer of modular motion controllers for multi-axis drive systems, PI can also supply customized complete systems for industrial applications that make the highest demand on precision and dynamics. In addition to four locations in Germany, the PI Group is represented internationally by fifteen sales and service subsidiaries.