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Closed Loop PZT Actuators Provide Sub-Nanometer Resolution

Where is the limit?
Theory says the resolution of a PZT actuator is only limited by the electric noise of the driver. Our customers ask "what resolution can you expect from the best closed loop systems on the market under real world conditions?" We got to the bottom of this question (in our metrology lab in the basement of our factory) and can prove that even our lowest cost closed loop actuators can easily get under the 1 Nanometer hurdle.

P-751.1C PZT Flexure Stage P-841.10 Closed Loop PZT Actuator

Measurement Prerequisites
Noise and resolution of state-of-the-art piezo actuators/controllers cannot be measured with conventional instruments. Even sub-nanometer resolution sensors will only provide relevant information if external influences such as vibration and temperature fluctuations are eliminated.

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Here's an example: a 100 mm (4 inch) steel rod will expand by 100 nanometers when the temperature changes by only 0.1° Kelvin; foot steps in the hallway cause vibration that make nanometer measurements impossible if not isolated adequately.

That's why measurements at PI are carried out in a state-of-the-art metrology lab. The foundation of this lab is separated from the rest of our factory's basement. Test equipment and sample are mounted on a vibration isolated honeycomb tabletop whose base area is once again separated from the rest of the floor. The lab and table are temperature stabilized by several nested air conditioning systems, providing an overall stability of 0.1 K/24 hours. A high resolution Zygo laser interferometer and several capacitive displacement sensing systems are at the disposal of our test engineers. For the test results below, a capacitive system providing 20 picometers resolution at a sample rate of 16666/s was used.

Results
The graphs of the P-841 actuator and P-751 flexure stage, (see page one) represent our two product lines "Closed loop PZT Actuators" and "Closed Loop PZT Flexure Positioners". Both provide a travel range of 15 µm. The P-841 PZT stack actuator is equipped with strain gauge feedback sensors, the P-751 flexure stage employs capacitive feedback sensors. The three graphs (on page 1) show:

- Basic noise of the test setup with shorted PZT actuators. The figure of 0.142 nm (RMS) includes noise of all mechanical and electronic components.
- Stability with activated closed loop control
- Response to a control input signal equivalent to 3 nm stroke. (1 Hz square wave, 3 mV p-p).

	P-751.1C PZT Flexure Stage	**P-841.10 LVPZT Stack Translator**
Travel	15 µm	15 µm
Integrated Sensor	capacitive	strain gauge
Controller Module	E-509.C1	E-509.S1
Amplifier Module	E-503.00	E-503.00
Settling Time	3 ms	2 ms
Test Bandwidth	240 Hz	240 Hz

Discussion
It is obvious that stability of the P-751 flexure stage is close to the resolution limit of the test system. Even the low-cost PZT stack actuator with strain gauge sensor can reproduce sub-nanometer motion without problems. The crisp response of both systems to a square-wave input show the unbeatable performance of PI PZT positioners.

F-206 Six Axis Parallel Manipulator

The new PI F-206 Six Axis Parallel Manipulator is the result of more than 5 years of experience with hexapod micropositioning systems. It provides **six degrees of freedom**, 0.1 **µm resolution** and allows the user to **define the pivot-point** anywhere inside or outside the F-206 envelope.

The F-206 combines the advantages of the hexapod principle with the straight forward manufacturing technology of standard linear positioners. In a hexapod ("six-legs") positioner, the drive system and guiding system cannot be distinguished (see article "Hexapod-Robot Further Improved"). The position of the top platform is defined by six struts which vary in length. With the new F-206, the "legs" are passive elements. It employs six DC servo motor drives (in one plane) moving the bottom end of each strut up and down (see fig. 2). Advantages of this construction are:

- Wire flexure joints reduce costs and provide zero-backlash coupling
- Reduction in moved mass provides for higher dynamics
- Compact design, all 6 drives in one plane

To take full advantage of the new design, complex control algorithms had to be designed. Currently, several prototypes of this revolutionary concept are being tested at PI. The final specs of the system are given below:

Travel X /Y / Z [mm]	±**7**
Travel ΘX/ΘY/ΘZ [°]	±**5**
Resolution X/Y/Z [µm]	£ **0.1**
Repeatability X/Y/Z [µm]	£ **0.1**
Max. Velocity (X,Y,Z) [mm/s]	**15**
Load capacity [kg]	**2**

Application examples: Optical device testing, semiconductor handling systems, fiber optics, integrated optics, micro-machining & manufacturing.

Fig. 1: F-206 Parallel Manipulator
Fig. 2: F-206 Principle Design

M-850 Hexapod Robot Further Improved

A Hexapod Robot is a multi-axis positioning system featuring the following advantages:

- Motion in all 6 degrees of freedom
- Superior size/travel range ratio
- Minimum moved mass
- High stiffness
- Actuators only see push/pull forces
- No cables to be moved

On the other hand, development costs, especially for the control algorithms are relatively high. PI now introduces the new M-850.50 system, an evolution of the hexapod systems developed in the last 5 years (see fig. 3). The M-850.50 features base plate integrated servo amplifiers for higher velocity (8 mm/s, 0.5 µrad resolution) and reduced sensitivity to electrical noise. The controller was also improved with regard to EMI compatibility and suitability to industrial applications. New control algorithms and a faster processor improve trajectory accuracy.

Applications of the M-850 Hexapod Robot are almost unlimited. The high stiffness and short settling time make the system ideal for production and handling tasks. Fig. 1 (2) shows the settling time for 10 µm (500 µm) steps with the most aggressive PID settings. The positioning process is completed in 2 hundredths of a second with overshoot of only 2 µm. Conventional (stacked) 6-axis positioners featuring similar load capacity (> 100 kg) cannot compete here.

Fig. 1 M-850.50 settling time for 10 µm steps
Fig. 2 M-850.50 settling time for 500 µm steps
Fig. 3 M-850.50 Hexapod Robot

Modular Nanopositioners Provide up to 6 Degrees of Freedom

The new P-517.1C and P-527.2C are the first members of a new generation of multi-axis piezoelectric nanopositioners. Providing a travel range of 100 x100 µm and 200 x 200 µm, respectively and a clear aperture of 66 x 66 mm, the stages are ideally suited for mask alignment, near-field scanning microscopy, confocal microscopy or other transmitted light applications.

Other features are:

- Sub-nanometer resolution (capacitive feedback sensors)
- Fast response (10 msec range)
- Choice of analog and digital controllers (see article "E-710 Digital Controller...")

Working principle: Low voltage PZTs (0 to 100 V) and flexures are employed as the drive and guiding system. The flexures provide for zero-backlash motion and excellent guiding accuracy. Integrated capacitive displacement sensors measure the position of the moving frame

The new flexure stages are the result of intensive research on adaptive mechanics. The modular design allows for versions with up to 6 degrees of freedom. Active compensation of all off-axis errors allows for 100 x 100 µm scans with sub-nanometer flatness/straightness and sub-µrad yaw, pitch and roll.

Apart from the recently introduced XY versions, XYZ, XYθ_Z, and Z$\theta_X\theta_Y$ versions will be available in the near future.

Abbildung: P-527.2C 200 x 200 µm Flexure Stage

E-710 Digital Controller for P-500 Series PZT Flexure Stages

The new E-710 Digital Piezo Controller was introduced as a supplement to the E-500 modular controller family. The digital controller contains 4 independent power amplifiers for Low Voltage PZTs (6 W, -20 to 120 V) and four sensor/control channels. In contrast to analog multi-axis controllers, the E-710 has a distinct advantage: sensor and output channels of two or more axes can be combined by an internal coordinate transformation. Example: three linear sensors and 4 linear actuators suffice for precise $XY\theta_Z$ position control.

Positioning commands are in international units such as micrometers, microradians etc.

Other features are:

- Integrated, fully programmable low pass and notch filters
- Integrated 4^{th} order polynomial linearization (channel independent)
- Integrated coordinate transformation for random sensor/actuator geometry
- Automatic zero adjust after power up
- All control parameters are long term stable, defined by mathematical algorithms
- All settings are non volatile, user accessible
- Standard RS-232 and IEEE 488 interfaces

E-710 was primarily developed for the new P-500 series of modular PZT flexure stages (see article to the right) but can also be used to control any other capacitive sensor equipped PI PZT positioner.

Abbildung: Digital PZT Controller

Photonic Switching with PI Ceramic Piezo Multilayer Benders

Bringing your data communications systems into the 21st century with multiple FDDI and other optical LANs can mean headaches along with productivity boosts. While interdevice communications are greatly improved, you must also deal with managing, testing, reconfiguring and switching the fiber channels in the fiber optics network. Additionally, there are routing, bandwidth, connectivity, security, conversion delay and network backup nightmares.

Astarte Fiber Networks, Boulder, Colorado, using specially designed PI Ceramic PZT multilayer bender elements, relieves those headaches with the StarSwitch™ line of optical matrix switches (see figure). The StarSwitch™ lets you configure and cross connect point-to-point fiber optic networks and access additional high-speed networks photonically without electronic conversion or manipulators which increase system noise and decrease bandwidth.

The Astarte StarSwitch™ is available from a 16x16 matrix up to an incredible 72x72 matrix switch. With customers ranging from NASA to Boeing to Bell South and British Telecom, Astarte has earned a solid reputation for its advanced photonic matrix switches.

According to company founder Herzel Laor, system reliability is critical. “The StarSwitch™ must perform flawlessly; therefore, we have taken great care in the design, component selection and manufacturing process to build these devices.” Herzel chose PI Ceramic as supplier for the piezo benders after visiting our manufacturing facility and working with our engineers to identify the optimum solution for the StarSwitch™ application.

Abbildung: Astarte StarSwitch™ , courtesy of Astarte Fiber Networks

OEM PZT Translators

Cost effective piezo technology not only for bulk buyers.

OEM means original equipment manufacturer. The PZT translators shown in fig. 1 were initially developed for OEM customers, with the objective of eliminating all options (integrated sensors, bulky case, threaded tips, etc.) not required in OEM applications.

These basic actuators have several advantages:

- smaller dimensions
- lower prices
- faster delivery

Preload and mounting flanges can be designed by the customer. Like standard PI PZT actuators, the OEM translators feature sub-nanometer resolution, sub-millisecond response, absence of stiction/friction and no wearing parts.

Low Voltage (-20 to 120 V) OEM models are available with displacement from 6 to 60 µm and load capacity from 100 to 3000 N. High Voltage Versions are available in almost any shape and load capacity to 50,000 N.

Abbildung: Various OEM LVPZT Translators

New Windows™ Virtual Control Panel for E-500 PZT Controllers

The new PZTMove virtual control panel was designed to facilitate operation of the E-500 series modular PZT controllers. Features are

- Direct input of position or drive voltage for 3 channels
- Programming of sinusoidal and triangular waveforms with graphical display for channel 1, 2 and 3 with the click of a mouse
- Display of status information
- Integrated command interpreter for E-255 compatible mnemonic code

PZTMove is available for Windows™ 3.1 and Windows™ 95 platforms.

The figure to the right shows various windows for installation, static and dynamic operation.

PZTMove Virtual Control Panel

Piezo Servo Controller with RS-232 Interface

The new E-662 series Desktop LVPZT Amplifiers/Servo Controllers are our most economic PZT controllers with integrated computer interface.

They are designed for closed loop Low Voltage piezos with strain gauge feedback sensors (E-662.SR) and LVDT feedback sensors (E-662.LR), respectively. Apart from manual control (via a high resolution 10 turn potentiometer) and external high bandwidth control via a BNC input (0 to 10 V), an RS-232 interface with 12 bit D/A converter is standard.

The well structured SCPI command language facilitates programming providing more than 40 commands including complex functions such as sinusoidal and triangular waveforms.

E-662 LVPZT Amplifier/Controller

High-Power PZT Amplifier for Precision Machining

The new E-470, E-471 and E-472 High Power HVPZT Amplifiers and Controllers provide 500 W peak output power (100 W continuous) and an output voltage swing of 1000 V.

They are ideally suited for driving PZTs in dynamic applications such as out-of-roundness turning, grinding or boring and active vibration cancellation.

E-470 is a bench-top single channel device, E-472 a 19" rack-mount two channel unit and E-471 a modular single channel device with the following upgrade options (similar to the

E-500 controllers): E-515.01 Display Module, E-515.i1 Display /Computer Interface Module and E-509.xx Servo Controller Module

PI Expands R&D Department

PI has expanded its R&D department again. As of April 1, a team of 15 engineers and physicists help us solve your problems by developing innovative, user-oriented products for nanopositioning.

