# NANOMETER PRECISE HYBRID ACTUATOR IN POSITIONING MECHANISM WITH LONG TRAVEL RANGE

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**Abstract:**
Nanotechnology requires extreme high resolution and accuracy and at the same time long travel range. Improvement in accuracy can be achieved with mechatronic design principals and integration of piezo technology in the system design. The design rules for extreme high accurate multi axis systems lead to parallel structures. For high linear accuracy and large travel range are developed two new concepts, one use piezo actuator based walking drive mechanism and one use the mechatronic combination of piezo and motorized drives in one incremental sensor loop. The first principle can be used in systems, where high stiffness, compactness but low speed is necessary, the second principle is just unlimited in speed and load, but needs new controller technology. Such a combined positioning system can satisfy the requirements of most experiments that require long-range motion and nanometer precision.

Keywords: piezo, hybrid, controller, nano positioning

## Introduction

Over many years the precise positioning technology was developed primarily for the semiconductor industry. This field requires mainly two-dimensional positioning with high accuracy. With the emergence of nanotechnology came the need for new types of precision positioning tools that go beyond the requirements of the conventional semiconductor sector. The functional structures of nano-devices are on the nanometer or even picometer range. Yet the dimensions of the entire devices are in most cases much larger. Thus, there are two new mechanical requirements: large travel ranges (up to one inch or more) and – at the same time – extremely accurate positioning with nanometer or sub-nanometer resolution. Furthermore, a higher number of axes is often necessary. The opto-electronic telecom market was the starting point for absolutely new technologies for many-axis alignment- often more than 12 axes. Nanotechnology requires still more resolution and accuracy. The paper describes a new design for single axis devices with extreme high resolution, high dynamics and high load capacity.

## System requirements

Nanotechnology envisions future positioning to occur by taking advantage of natural self-reproduction, replication, and nano-scale surface copying techniques. These exigencies can be met with a combination of various techniques: For example, motorized guided systems with incremental sensors can be used for large travel ranges.

Conventional serial positioners consist of several linear and rotary (goniometer) stages, which are mounted together in order to reach the desired number of degrees of freedom. In such a design, each single axis is simple to control, yet the overall system has some disadvantages: The system needs a lot of space, the stiffness decreases with increasing number of axes, and the dynamic behavior is axis-dependent (as the lower stages must carry the weight of the stages stacked on top). The stage cables also need to be moved, resulting in bending and friction. Most importantly, the position errors of the single stages accumulate for the overall system, resulting in large errors, often originating from rotary/tilt stage lever arms.
In high-speed nano-positioning applications, advantages of the parallel-kinematics approach over the stacked or nested serial kinematics systems is the ultra-low inertia resulting in higher resonant frequencies, faster step response, and higher scanning rates.

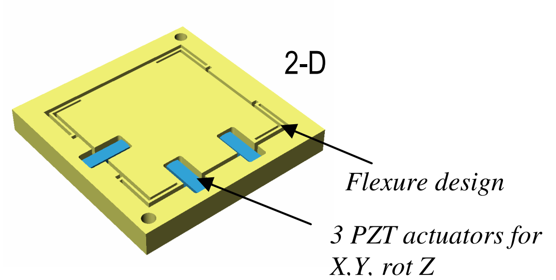


***Fig. 1**: Parallel approach in a piezo stage flexure design*

Another advantage is active trajectory control on a sub-nanometer scale, which is possible when direct output metrology capacitive position sensors are integrated. Since each position sensor monitors the common platform, the smallest axis crosstalk effects are detected and can be compensated for in real time. This results in higher linearity and straighter scanning lines.

**Piezo technology for ultra-high precision positioning**

One of the long-term objectives of nanotechnology – to realize von Neumann architecture for self-replicating systems – is still far from being realized on a large scale. But for studying the molecular structure of materials, accurate positioning systems down to picometer scale are necessary. Specially designed piezo electrical positioners work on this scale. Paired with capacitive sensors, they allow for controlled sub-nm motion [1].

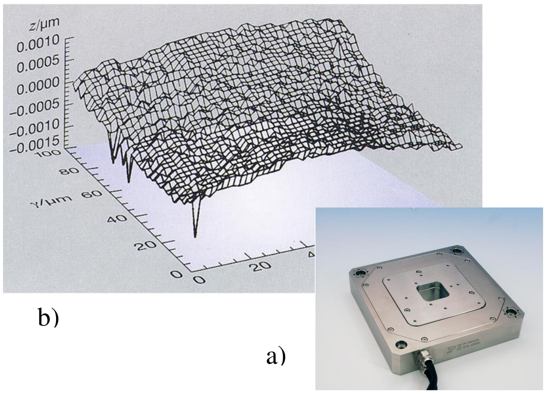


**Fig. 2 a)** Reference-class piezo positioning stage with 6 degrees of freedom, made of Superinvar

**Fig. 2 b)** 2D scan field with active z-error correction. Performance is better than 0.5 nm over 100x100 µm scan range.

The basic control function of piezo systems is more simple than of motorized systems, because piezo systems have a constant transfer function up to the resonance peak.
The linearized transfer function of piezo actuators can be approximated as follows:

$$T_z(p) = \frac{K_a}{1 + 2D\frac{1}{\omega_0}p + \left(\frac{p}{\omega_0}\right)^2} \qquad (1)$$

| | |
|---|---|
| $K_a$ | Gain |
| D | Damping coefficient |
| $\omega_0$ | Resonant Frequency |

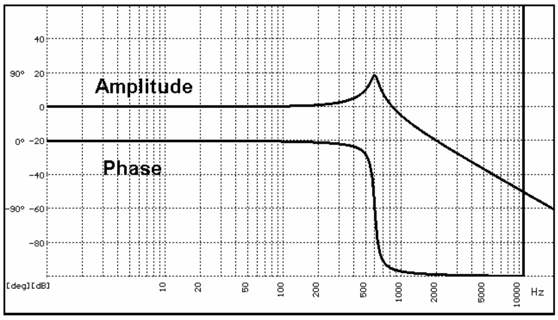


***Fig. 3:*** *Transfer function of a piezo system $T_z(p)$*

With the Nyquist criterion it can be shown that a simple PID controller function may be stable but can not offers very fast control conditions. At least a notch filter should be added into the control path, to cancel the resonant frequency peak and improve the stability. [1]

If $T_l(p)$ is the open loop transfer function defined as:

$$T_L(p) = T_C(p) * T_N(p) * T_A(p) * T_Z(p) * T_S(p) \qquad (2)$$

Where $T_C$ is the PI-Controller transfer function, $T_N$ is for the notch filter, $T_A$ for the amplifier and $T_S$ for the sensor. The Z-plane shows the real and the imaginary part over the frequency.

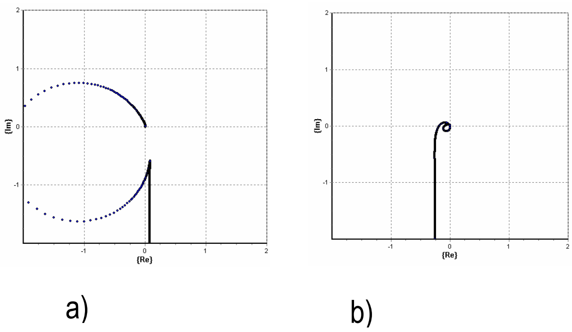


***Fig. 4:*** *Z-plane of the Open loop transfer function a) without notch filter b) with notch filter*

At PI, various methods were developed to overcome the non-linearity (hysteresis effects) as well as the creep of piezo ceramics.

$$T_N(p) = \frac{1 + \left(\frac{p}{\omega_n}\right)^2}{1 + \frac{p}{D_n\omega_n} + \left(\frac{p}{\omega_n}\right)^2} \qquad (3)$$

The Notch filter frequency is set to the system resonant frequency to avoid controller instability at this point.

$$\omega_n = \omega_o \qquad (4)$$

The transfer function of the PI (proportional/integral) term can be set to:

$$T_c(p) = \frac{K_p \cdot \left(T_i \cdot p + T_i T_g \cdot p^2\right)}{T_i p + T_i T_g \cdot p^2} \qquad (5)$$

| | |
|---|---|
| Kp | Gain |
| $T_i$ | I-term time constant |
| $T_g$ | Smoothing term |
| $\omega_0$ | Resonant Frequency |

In combination with analog or digital control methods, including methods to avoid non-linearity and creep, the transfer functions of compensated piezo systems offer linear properties in the frequency domain for amplitude and phase control.

**Hybrid stacked systems**

Electromagnetic drives alone are limited in positioning accuracy due to their noise level and the stiffness relation to the guiding system.
However, in combination with high-precision piezo technology, they are a very powerful tool for nano-positioning over a millimeter range. A special design principle is to combine piezo ultrasonic systems with piezo actuated stages. Piezo ultrasonic systems can reach high dynamic performance and can be controlled to very smooth motion. Additionally, if the ultrasonic system is switched off, the self-locking effect is very helpful for long-term stability and the fine adjustment with the piezo stage.

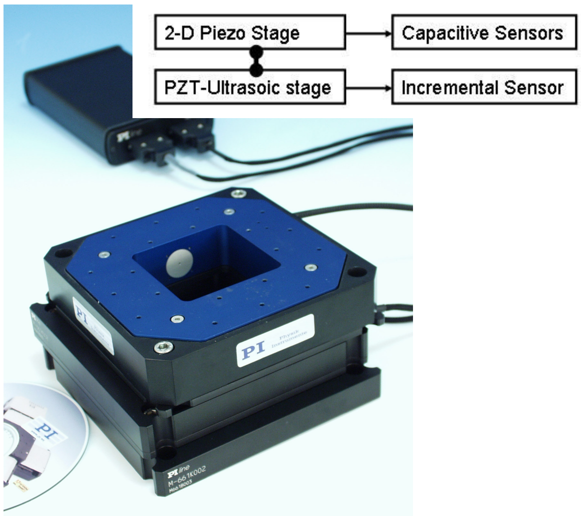


***Fig. 5**: 2-dimensional piezo ultrasonic positioner combined with a 2-D Piezo stage*

**New hybrid positioning systems**

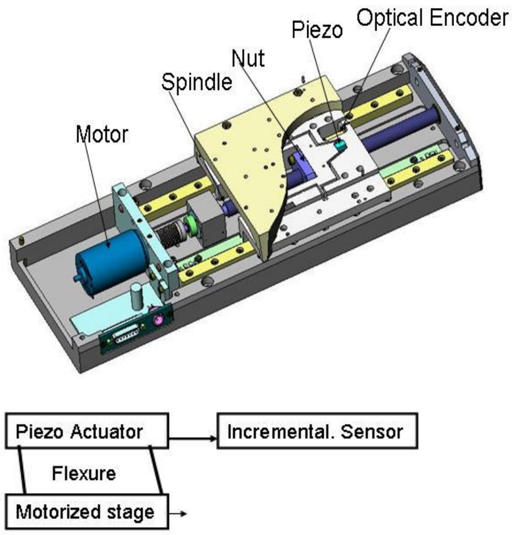


***Fig. 6:** Mechatronic Hybrid system:*
*High resolution optical incremental sensor with 2nm resolution.*
*Motor driven stage combined with flexure guided piezo actuator for 100mm travel range.*

The new hybrid system is the integration of one extreme high resolution incremental sensor into a stage which is driven by both - piezo and motor (or piezo-ultrasonic) actuator at the same time.

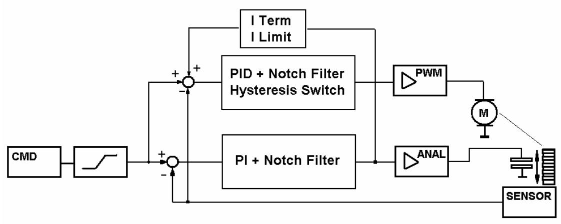


***Fig. 7**: Embedded controller for hybrid system*

The developed controller based on an embedded controller with hardware clock buffered sensor inputs and synchronized output buffer. The motor is driven by a PWM generated signal and the piezo amplifier is driven by a 24bit D/A converter. The sampling rate can be set between 1kHz and 200kHz, 10kHz are used for the first tests. The real time operating system "OnTime" has a very fast interrupt latency time of less than 1.5µs in worst case. Because both actuators – the piezo and the motor are working on the same stage, it is necessary to separate the control frequencies in the controller for both different drives. The piezo is used in a higher bandwidth than the motor is working. The tests show that the frequency separation should be larger than a factor of two.
The structure of the current controller has another feature: there is an integral term added between the

piezo and the motor path. This term degree the piezo voltage for settling down to some volts – save for long term operation.

## Test results

A compact stage with 2µm optical scale from Heidenhain GmbH and a special 1000 time interpolation unit was designed to get a final resolution of 2nm. A super finished spindle and a small piezo with +/-2µm stroke where used. The interfacing between the stage and the controller is done by a SSI bus to get high transfer rate for the sensor data for fast motion. The small range step response is dominated by the piezo part in the system. Because of the flexure design, the stage has a very small hysteresis. Moved steps down to the resolution of the scale can be measured.

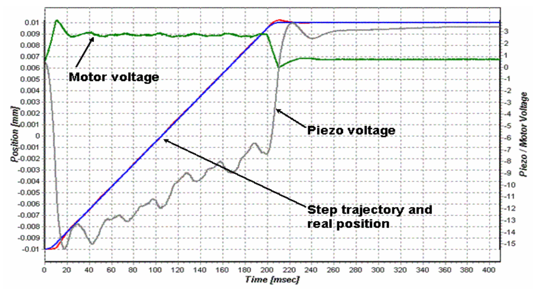


***Fig.8****: 20µm step with small overshoot to demonstrate the continuously driving mode of both actuators. The motor and the piezo are actuated at any time. The piezo voltage is controlled within a range of +/- 10V for the final position (maximum +/- 36 V).*

At any time both actuators – the motor and the piezo – are driven from the controller. If the piezo voltage exceed more than 10V an additional integral-term is used to drive the stage with more motor power into the position stroke of the piezo. The stage design use a piezo stroke of +/- 2µm at the moment.

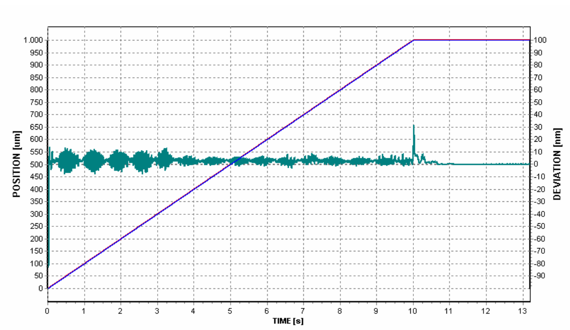


***Fig.9****: Step response of the hybrid stage for 10nm steps measured with external laser interferometer*

In dynamic motion operation the piezo actuator compensates friction and roughness influence as shown in figure 10.

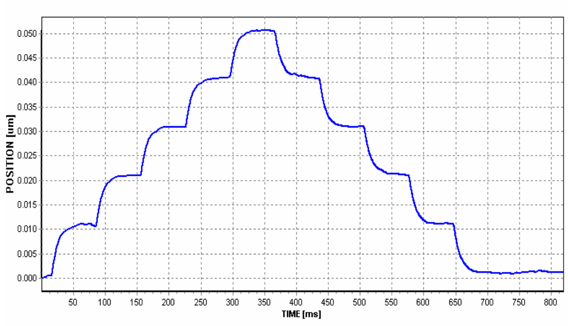


***Fig. 10****: 1mm motion of the hybrid stage (velocity= 100µm/s) The deviation from the trajectory is less than 10nm. Some influence from the resonant frequency should be cancelled in future design*

## 5 Summary

The investigation in nanotechnology requires new positioning tools with extremely high resolution combined with a large travel range. In new hybrid stage design the piezo part should be separated via flexure design and should be operate with only one incremental sensor. For high resolution hybrid systems a new type of embedded controller and a two path control algorithm shows successful results for smallest steps as for long travel range with nano/ picometer resolution.

## References

[1] R.Gloess: „Systeme zur Nanopositionierung“, Teil2, F&M, Jahrg.108 (2000), Carl Hanser Verlag München, ISSN 0944-1018, S. 72-78