

Sub-Nanometer Precision Hybrid Positioning Systems for Vertical Inspection Tools in Nanotechnology and Semiconductors

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INTRODUCTION

Improvement in the accuracy of motion control tools for nanotechnology can be achieved with adaptronic design principals and integration of piezo technology in the system design. Two new concepts for high linear accuracy and large travel ranges, were developed. The first one is based on a piezo actuator based walking drive mechanism and the second one uses the mechatronic combination of piezoelectric and motorized drives controlled by a common incremental sensor loop. [1] Such hybrid positioning systems can satisfy the requirements of most applications that require long-range motion and nanometer precision.

Test equipment for semiconductor technology requires horizontal and vertical positioning stages for sensors and optics. This paper describes a new adaptronic product design, specially prepared for vertical motion of optics for inspection or profiling systems. Simultaneous control of piezo flexure actuators and motorized drives provides inches of travel with nanometer to subnanometer resolution.

PIEZO WALK DRIVES AND STACKED HYBRID SYSTEMS

Piezo walk drive technology provides advantages in systems, where high stiffness, compactness but low speed are required. The new NEXLINE piezowalk drive technology is a piezoelectric hybrid system which combines the d33 longitudinal piezo effect with d15 deformation – the shear effect. These drives require high resolution sensors and a controller for step and analog control of the hybrid piezo stacks.

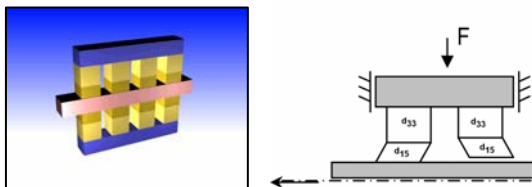


FIGURE 1. NEXLINE piezo walk drive structure, Four stacks with d33 and d15 piezo material are preloaded from both sides onto a moving runner

A different approach to long travel with high resolution is the combination of piezo ultrasonic motors with piezo flexure actuated stages. Piezo ultrasonic systems can achieve high dynamic performance and very smooth motion. Additionally, when the ultrasonic system is switched off, the self-locking effect is very beneficial for long-term stability and a prerequisite for high system accuracy using the fine adjustment range of the piezo flexure stage.

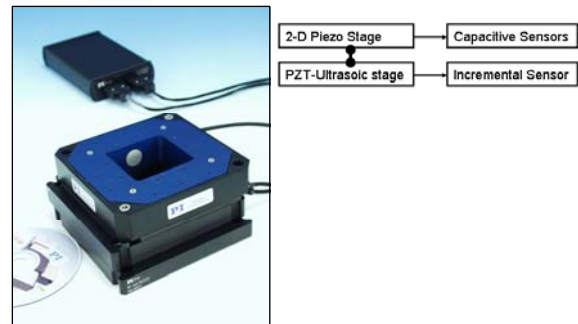


FIGURE 2. Example of a stacked hybrid system: High-speed coarse positioning over large range: 25 x 25 mm in x and y with ultrasonic drives. Piezo flexure stage for fine positioning: Up to 6 axes, down to sub-nm resolution.

This type of stacked (independent) hybrid motion system provides subnanometer resolution but the absolute accuracy at the platform is limited to the accuracy of the coarse (fast) piezo ultrasonic stage. The system requires two sensors and two controllers- one for the piezo ultrasonic system and the second for the multi axis piezo stage.

NEW DESIGN WITH SINGLE SENSOR HYBRID STAGE

The Hybrid Multi Actuator Principle

To overcome the limitations of the independent stacked design, the new hybrid system is the integration of one extremely high resolution incremental sensor into a stage driven by both – a short range piezo stack actuator and a long range servo motor (or piezo-ultrasonic) actuator at the same time.

With the proposed design, the stage motion is measured directly by the incremental sensor. This sensor can be an optical incremental sensor, an interferometer or a magnetic incremental sensor type. Because of the long stroke motion and limited space, an incremental sensor seems to be the best solution.

Which type of main (long travel) actuator is chosen depends on the application. For small volume and high static forces (high loads in vertical direction) servo motor–leadscrew systems provide advantages. For horizontal motion, systems with air bearings, and electromagnetic linear motors could be a good choice. In high vacuum applications piezo ultrasonic drives can be beneficial.

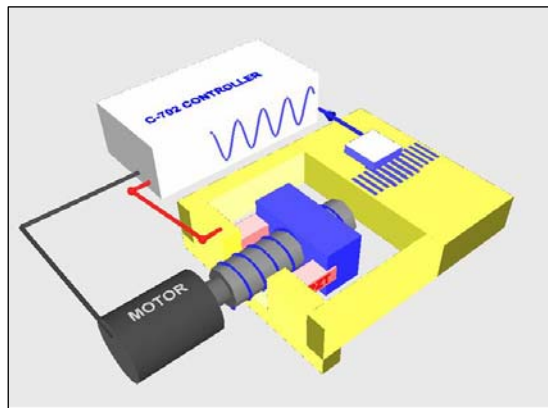
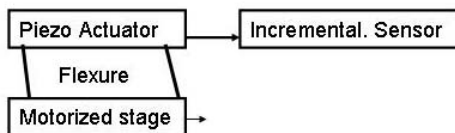


FIGURE 3. Function principle of hybrid system:

A high resolution optical incremental sensor with interpolation unit and controller running both the servo motor–ballscrew drive and the piezo stack actuators.

The integrated piezo stack actuators are used to overcome the friction effects, eliminate the ballscrew hysteresis and to improve the dynamic behavior (somewhat similar to an active damper). They can be implemented in a direct drive or flexure arrangement. This design prevents additional hysteresis effects.

The hybrid controller structure controls both- the coarse, main (electromagnetic or ultrasonic) actuator and the fine drive piezo actuator simultaneously. The loop is closed via the incremental sensor- placed at the carrier platform.

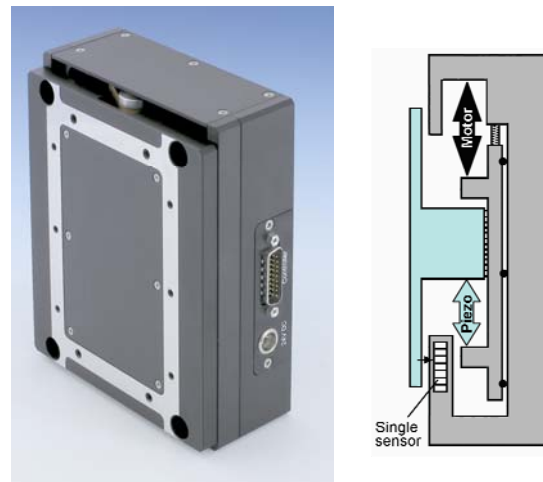
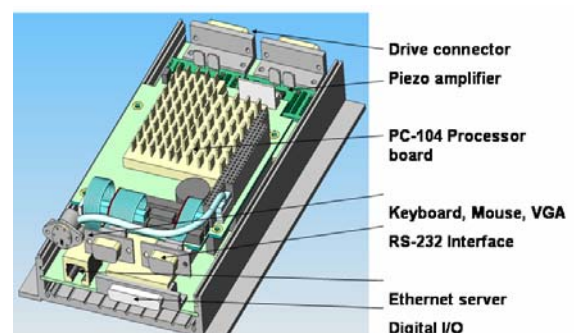


FIGURE 4. M-714 hybrid translation stage optimized for vertical applications

Embedded Controller Design for Hybrid Stages

The hybrid controller runs on an embedded PC based on the OnTime real-time operating system, with hardware-clock-buffered sensor inputs and a synchronized output buffer. The servo motor is driven by a PWM signal and the piezo amplifier is driven by 24bit D/A converter. The sampling rate can be set between 1kHz and 200kHz, with 10kHz used for initial testing.



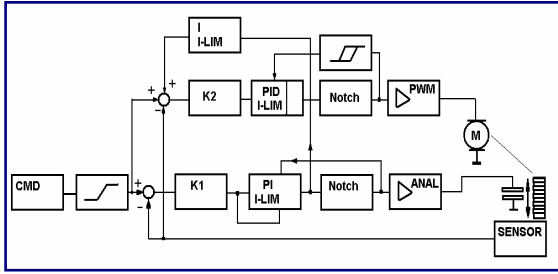


FIGURE 5. Hybrid controller hardware and main control structure

The OnTime real time operating system has a very short interrupt latency time of less than 1.5µs. Since both actuators—piezo and servo motor—are acting on the same moving platform, it is necessary to separate the control frequencies for both drives in the controller. The piezo is operated in a higher bandwidth than the servo motor. 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 minimizes the piezo drive voltage in long term operation to increase the lifetime.

Control Strategy for Hybrid Systems

Figure 5 shows the structure of the digital control algorithm. A PID filter is used for the servo motor. With additional notch filters the resonant frequencies can be canceled. In our controller 2 notch filters for each motor path are used. The basic control function of a piezo actuator is more simple than that of a servo motor, because of the constant transfer function up to the resonance peak. The linearized transfer function of a piezo actuator can be approximated as follows:

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

K_p Gain
 D Damping coefficient
 ω_0 Resonant Frequency

With the Nyquist criterion it can be shown that a simple PI controller function may be stable but can not provide very high bandwidth.. At least a

notch filter should be added into the control path, to cancel the resonant frequency peak and improve the stability. [2]

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

$$T_L(p) = T_C(p) \cdot T_N(p) \cdot T_A(p) \cdot T_Z(p) \cdot T_S(p) \quad (2)$$

To further improve the performance,, various methods were developed at PI to overcome non-linearity (hysteresis) and creep effects of piezo ceramics.

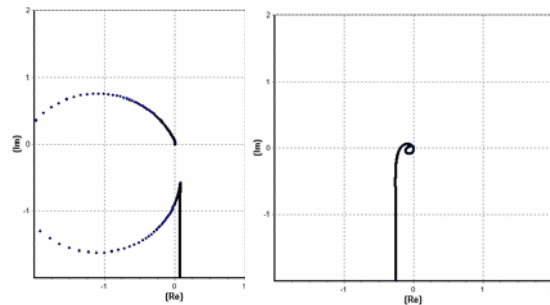


FIGURE 6. Z-plane of the open loop transfer function a) without notch filter b) with notch filter

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

The notch filter frequency in (3) is set to the system resonant frequency to avoid controller instability at this point. $\omega_n = \omega_o$

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

$$T_c(p) = \frac{K_p \cdot (T_i \cdot p + T_i T_g \cdot p^2)}{T_i p + T_i T_g \cdot p^2} \quad (4)$$

T_g Smoothing term time constant

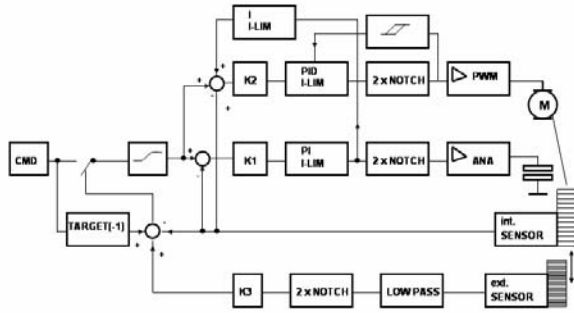


FIGURE 7. Hybrid controller structure with internal and external sensor

The controller can be hardware synchronized via a second interface. The interpolator unit (factor 1000) of the internal sensor is integrated in the stage to reduce the signal noise level. A serial bus is designed to transmit the sensor data in each servo loop cycle.

Figure 7 describes the configuration of the internal and external sensor setup. The external sensor input moves the target position for the trajectory generator so that the main control loop is not destabilized. The design provides stability also under conditions where highly resonant equipment is placed on the stage. Using a programmable interface with an external incremental sensor, the stage can be operated parallax-free without Abbe error misalignment.. The controller firmware is open for implementation of forward looking algorithms.

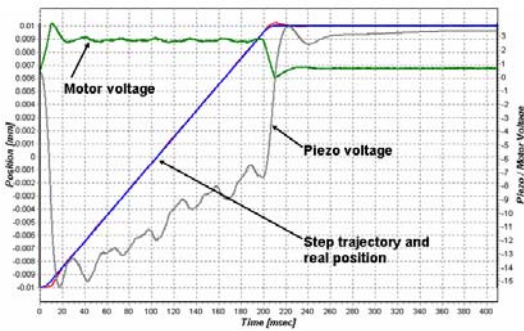


FIGURE 8. Step size of 20µm with small overshoot

Figure 8 shows the hybrid setup with a small overshoot to test the continuously driven mode of both actuators. The servo motor and the piezo are actuated at all time. The piezo voltage is controlled within a range of +/- 10 V for the final position (+/- 36 V maximum).

Test Results of the Hybrid Stage

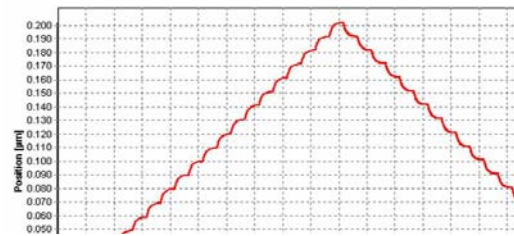


FIGURE 9. Sequence of 10nm steps forward and backward measured with laser interferometer

The hybrid system shows no significant hysteresis at the stage platform.

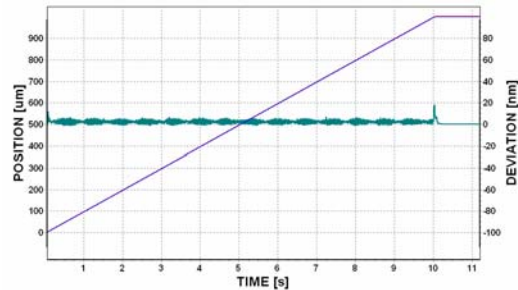


FIGURE 10 Linear travel of 1mm

For longer moves the tracking error can be reduced to less than 10nm deviation from the target trajectory.

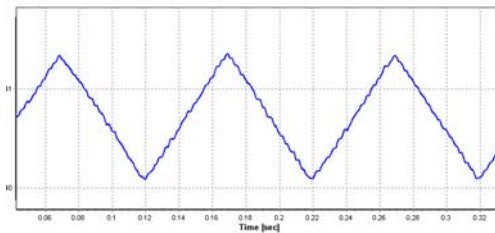


FIGURE 11. 1.2nm(peak to peak) test triangle signal measured with Sony optical linear encoder (4096 interpolation factor)

Internal and external sensors with resolution significantly better than 1 Nanometer can be used in the hybrid system. The 24 bit D/A structure provides piezo resolution in the picometer range.

SUMMARY

New system designs show that hybrid nanopositioning stages based on electromagnetic and piezo electrical actuators together with high resolution incremental sensors provide a very flexible technology. For maximum performance the piezo part should be separated via a flexure guidance and be controlled by the same position sensor used for the coarse drive. A new type of embedded controller and a two path control algorithm shows promising results for extremely small steps, high repeatability and good linearity over long travel ranges.

REFERENCES

- [1] R.Gloess, H.Marth. Adjusting Device with Piezo Drive", US-Patent 5 424 597
- [2] R.Gloess. Systeme zur Nanopositionierung, Teil 2 ,F&M, Jahrg. 108 (2000) Carl Hanser Verlag Muenchen, S.72-78