HYBRID ACTUATORS FOR LARGE TRAVEL RANGE AND EXTREME HIGH RESOLUTION

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Abstract
Over many years ultra-precision positioning technology was developed primarily for the semiconductor industry. In the 1990’s the opto-electronic telecommunications boom was the starting point for radical new technologies such as very compact multi-axis systems capable of nanometer level resolution and automated alignment tools. 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. But also the roadmap of the semiconductor industry requires novel nanopositioning systems capable of even higher resolution over larger travel ranges because the wafer sizes keep going up.

Traditional motor drives can be used for large movements, but the resolution is far from the requirements for nanotechnology. The paper describes new hybrid systems designs such as the combination of piezoelectric and motorized systems with a long travel range and extremely high resolution.

Keywords: piezo, hybrid, actuator, nanotechnology, controller

Serial stacked Hybrid Systems with separated sensor design

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.

Fig.1: Example of a serial stacked hybrid system:

High-speed coarse positioning over a large range: 25 x 25 mm in x and y

Piezo stage for fine positioning: Up to 6 axes (2 axis stage shown here), down to sub-nm resolution.[2]

<table>
<thead>
<tr>
<th></th>
<th>Piezo Stage</th>
<th>Motorized Stage</th>
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</thead>
<tbody>
<tr>
<td>Actuator resolution</td>
<td>0.00001[µm]</td>
<td>0.1[µm]</td>
</tr>
<tr>
<td>Range</td>
<td>10 to 500[µm]</td>
<td>5 to 1000×10[µm]</td>
</tr>
<tr>
<td>Sensor (typ.)</td>
<td>Capacitive sensor</td>
<td>Incremental optical sensor</td>
</tr>
<tr>
<td>Power dissipation</td>
<td>About zero for static position</td>
<td>Small Motor power Sensors power</td>
</tr>
</tbody>
</table>

Specially designed piezo positioning systems meet the above requirements. Paired with capacitive sensors, they allow for controlled sub-nm motion [1].
Serial Stacked Hybrid Systems with one Common Position Sensor

Hybrid systems consist on the combination of both:
- piezo actuators for extremely high accuracy and
- motorized drives for long travel ranges.

For the maximum absolute positioning accuracy, the controller should rely on only one position sensor for both the coarse and fine positioning ranges. The following sketch shows a variety of hybrid designs with sensors, that measure the complete travel range.

Promising solutions for hybrid actuators are the combination of:
- Leadscrew/nut or ultrasonic piezo drives & PZT linear actuators in the strut
- Leadscrew/ nut & PZT linear actuators in the nut (stack or tube)
- Piezo ultrasonic drives with additional analog mode
- Piezo walk drives

Fig. 2: Hybrid leadscrew (spindle) / nut systems with piezo fine adjustment

Fig. 3: Transfer function of a piezo system

\[ T_p(p) = \frac{K_p}{1 + \frac{2 \cdot D}{\omega_0} p + \left( \frac{p}{\omega_0} \right)^2} \]  

\( T_m(p) \) Transfer function piezo system
\( K_p \) Gain
\( D \) Damping coefficient/ piezo
\( \omega_0 \) Resonant frequency

Fig. 4: Transfer function of a motorized system

\[ T_m(p) = \frac{K_m}{T_i \cdot \left( p + \frac{2 \cdot D}{\omega_m} p^2 + \frac{p^3}{\omega_m^2} \right)} \]  

\( T_m(p) \) Transfer function motorized system
\( T_i \) Integral term
\( K_m \) Gain
\( D_m \) Damping coefficient/ motor, spindle
\( \omega_m \) Resonant frequency

The motor driven unit can be described as a combination of a resonant system and the motor part. Both the motor driven part and the piezo actuators have resonant properties. For fast response these resonant terms should be cancelled by notch filters.

Fig. 5: Hybrid Translation Stage

Controller structure

Figure 4 shows the control structure of the hybrid system.

The control structure consists of two paths: One to control the motor position using the incremental optical sensor; a PID and a notch filter; and a PWM driver to provide power to the motor.

The piezo path consists of the same optical sensor as reference and uses a PI filter and a notch filter.
Some level limits are necessary to stabilize the control function and prevent overflow errors in the D/A or D/PWM parts.

An additional integral – term was added in the motor path, which is designed to drop the piezo voltage, when the system approaches the target position. Because both the motor and the piezo actuator operate on the same position target, it would be possible for the piezo voltage to max out when the stage reaches the target position. The voltage can be reduced by this additional I- term with a lower time constant than the piezo part.

The controller outputs a voltage range of +/- 10V to the piezo in static mode, a few milliseconds after a step.

**Fig. 6: Structure of the hybrid controller**

**Measurement results**

The controller split the frequency response between the piezo actuator and the motorized stage. The piezo actuator is driven at a higher bandwidth than the motorized actuator. Otherwise both actuators would try to compensate for their respective motion.

**Fig. 7: Measured positioning accuracy of a hybrid actuator (40µm steps) / controller system with one incremental sensor for both coarse and fine motion over all sensor controlled function**

The controller is based on a two hardware-synchronized PC cards. One card reads and buffers the encoder pulses for the PC access, the other one works as the D/A and D/PWM output and drives the Piezo and the motor amplifiers. The sample rate for the control function could be changed from 1kHz to 150kHz.

**Fig. 8: Measured positioning accuracy of a hybrid actuator for 100nm steps**

An incremental optical encoder with 4µm pitch and 1000 times interpolation module was used to achieve a resolution of 4nm over a travel range of 100mm. The controller concept shows that the actual position is stable to one encoder count of 4nm.

**Conclusions**

The research & development of nanotechnology systems requires new positioning tools with extremely high resolution combined with a large travel range. New controller and actuator designs show that a hybrid approach with electromagnetic and piezoelectric actuators together with high resolution incremental encoders and capacitive sensors provide the most flexible technology.

**References**


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