

## PZN BASED NANO-POSITIONING SYSTEMS

Shane Woody  
InsituTec Inc., Charlotte, NC 28210

Stuart Smith, Pavan Jain and Daisuke Iida  
Center for Precision Metrology, UNC Charlotte, NC 28223

### Summary

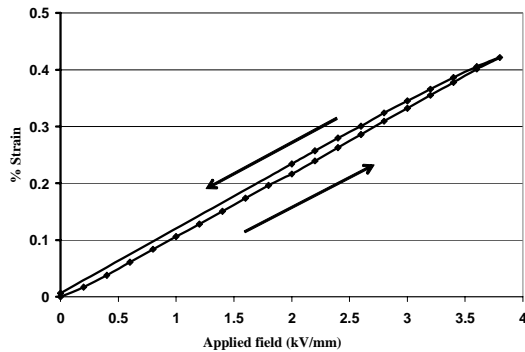
Nano-positioning systems employed with mesoscale performances are often considerably large with respect to the work volume and as a result are slow in bandwidth, precision and accuracy limited, and settling times are marginally acceptable. One example is hydrostatic oil bearing slideways on some diamond turning machines. These often exceed 100 mm traverse range whilst maintaining 10 nm resolution or better under closed-loop control. However, due to their low velocity and acceleration, considerable fabrication costs, and large design footprints, these macro-scale machines are not suitable for routine mesoscale applications. Considering that mesoscale is generally considered to incorporate operating ranges between 10  $\mu\text{m}$  – 10 mm, one limiting factor to obtaining ‘tabletop’ mesoscale machines is the ability to engineer multiple degree of freedom nano-positioning systems in a compact manner. Scaling down systems for mesoscale applications enables shorter measurement loops and stiffer machines, while requiring better resolutions if precision is to be maintained. We report methodologies to enhance the areas of mesoscale positioning systems using relaxor ferroelectrics (PZN-PT), innovative flexure-based lever mechanisms, capacitive sensing for absolute displacement measurement, and digital signal processing (DSP) to provide a ‘smart’ analog interface and data connectivity.

### PZN-PT Mesoscale Actuators

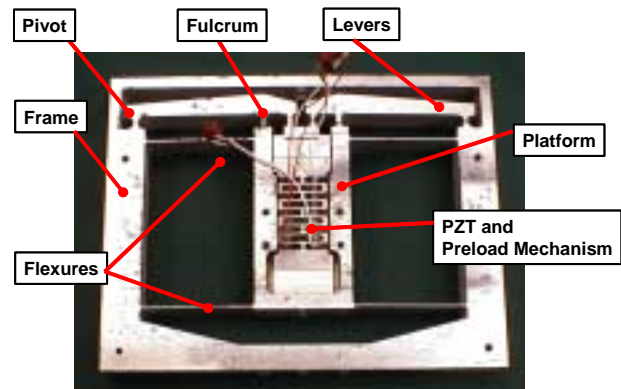
Actuator based systems such as piezoelectric (often referred to as PZT) that can provide high power densities have been employed in positioning devices over the decades. These actuators exhibit compactness, high bandwidth and favorably scale for small-volume application but are typically limited to around 0.1% strain of the stack length. Designs for longer range translations often result in unwieldy long PZT actuators ( $\sim 100$  mm to produce displacements of  $\sim 100$   $\mu\text{m}$ ). For such a large range, the long stacks result in a proportionate decrease in stiffness. Alternatively, voice coils have demonstrated significant output forces to displace a platform over millimeter distances but tend to produce significant heat and are large in volume.

Recently, developments in relaxor-based ferroelectrics single crystals (PZN-PT) have exhibited ultra-high strains exceeding 1.0% in controlled laboratory settings with high piezoelectric coefficients of  $d_{33}$  equal to 2500 pC/N, and exhibit lower hysteresis compared to PZTs<sup>1</sup>. Considering PZT actuators are capable of generating strains up to

0.1%, the PZN-PT are poised to displace an order of magnitude greater than PZT actuators. Investigations are underway within our group to explore applications of this single crystal material for mesoscale positioners, figure 1. In the investigations presented in this paper, a single crystal plate with dimensions  $5.0 \times 5.0 \times 0.5 \text{ mm}^3$  is tested with an applied field up to 1900 volts. A strain of 0.4 % corresponding to a displacement of  $2 \mu\text{m}$  are measured in this experiment, see figure 1.



**Figure 1:** PZN-4.5% PT ( $5.0 \times 5.0 \times 0.5 \text{ mm}^3$ ) Extension with Applied Field



**Figure 2:** PZT based levered mechanism

We are currently investigating use of PZN-4.5% PT stacked actuators with total dimensions  $5.0 \text{ mm} \times 5.0 \text{ mm} \times 5.0 \text{ mm}$  in size<sup>a</sup>. The actuators consist of 10 single crystal plates which are 0.5 mm thick. Currently, these PZN ceramics require a field of 60 kV/cm for 1.1% strain and have 18 nF capacitance across the stack. Consequently, 0.5% strain will require an applied voltage of about 1.5 kV and 1.1% strain will require 3 kV. Although the potential for high strain has been demonstrated the high voltage requirement causes considerable practical problems and thinner plates will be necessary to obtain higher strains with lower voltage and higher bandwidths. At this time, thinner plates may be purchased but these are not readily available at costs that are considered economically viable for our applications. Furthermore, because of the brittle nature of these single crystalline materials, pre-stress conditions are currently being evaluated to determine if the single crystals may be used for the ultra-high strains in the flexure-based systems. An additional benefit is the single crystals have shown to generate less hysteresis compared to PZT ceramics. The energy dissipated (i.e. heat) due to hysteretic (i.e. structural) damping is predicted to be less compared to PZT materials currently used.

<sup>a</sup> purchased from TRS Ceramics, Inc, State College, PA 16801

## Precision High Voltage Power Supplies

Until significantly thinner single crystal plates are economically manufactured, precision power supplies and amplifiers will be necessary. Presently, our group has developed high bandwidth 1100 V precision amplifiers with up to six channels to drive multiple actuator systems. Significant power is essential to drive the high capacitive (i.e. 18 nF) loads of the actuators while rapidly sourcing and sinking current. Obtaining a symmetric source and sink circuit presents considerable problems to HV circuit design, some of which will be addressed during the presentation.

## A Symmetrical lever Mechanism for Mesoscale Systems

Meso-scale applications will require stages to move over millimeter ranges. To achieve this we have developed a unique lever mechanism employing an actuator based platform, shown in figure 2. The particular stage uses three 5.0 x 5.0 x 18.0 mm PZTs<sup>b</sup> which are, in turn, bonded in series resulting in a 54 mm long stack. Additionally, a mechanism is used to provide longitudinal preload to the actuator. The total length of the assembled preload mechanism is approximately 65.0 mm and the three stacks combined will produce about 54  $\mu\text{m}$  of displacement. One end of the preload mechanism is mounted to the moving platform and other end is rigidly attached to two symmetrical levers, figure 2. Each lever also attaches to the platform by way of a fulcrum and the end of the lever is designed with a rotating hinge located on a fixed frame. Upon expansion, the PZT stacks generate a rotation of each lever about the fulcrum points and also about the fixed pivots which are attached to frame. Theoretically, the carriage is then displaced an amplified amount depending upon the lever ratio defined by the lever geometry, 5:1 in this particular design. The platform is also designed with four leaf flexures which are orthogonal to the principle axis of motion. The flexures' stiffness increase the natural frequency of the platform and constrain the platform's motion to a linear translation. The footprint of the flexure is 15.0 x 150.0 x 125.0 mm<sup>3</sup>.

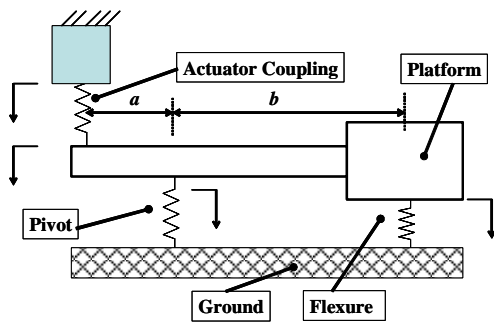
A second advantage to this lever mechanism design is reduction of 'lost motion'. Generally, lever mechanisms are inherently prone to significant fractional loss of motion as the lever ratio is increased<sup>ii</sup>. Figure 3 represents a mathematical model of a single lever driven flexure mechanism. The objective of the lever is to provide some form of amplification or attenuation between the force or displacement at the actuator and that produced at the moving stage of the flexure. In *Flexures* by Smith, the fractional loss of this lever mechanism is given by

$$f = \frac{\frac{k_3}{k_1} + \frac{k_3}{k_2} \left(1 + \frac{1}{n}\right)^2}{\left(\frac{k_3}{k_1} + \frac{k_3}{k_2} \left(1 + \frac{1}{n}\right)^2 + \frac{1}{n^2}\right)} = \frac{\alpha + \beta \left(1 + \frac{1}{n}\right)^2}{\left(\alpha + \beta \left(1 + \frac{1}{n}\right)^2 + \frac{1}{n^2}\right)} \quad (1)$$

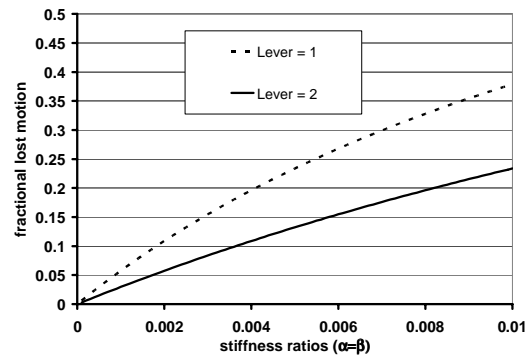
---

<sup>b</sup> purchased from Tokin™

where  $n$  is the lever ratio,  $\alpha$  is the stiffness ratio between the carriage flexure and actuator coupling, and  $\beta$  is the stiffness ratio between the carriage flexure and the fulcrum's longitudinal stiffness. Assuming  $\alpha = \beta$  and a lever ratio of 5:1, the fractional loss of motion will increase as the stiffness ratios are increased, figure 4. Using 2 levers in a symmetrical design as in figure 3 will further reduce the fractional lost motion in the system. The relaxor ferroelectric, such as the PZN-PT, will provide the same amount of displacement but in a smaller volume. Consequently, changing to this material will enable similar range of motion with a smaller footprint, higher bandwidth, and reduced fractional loss of motion. We are currently exploring a  $5.0 \times 5.0 \times 5.0 \text{ mm}^3$  PZN-PT stacks in conjunction with a 5:1 lever mechanism. The mechanism with the PZN-PT actuator is expected to exceed  $100 \text{ }\mu\text{m}$  in displacements and the footprint will be  $50.0 \text{ mm} \times 60.0 \text{ mm} \times 10.0 \text{ mm}$  and results of early test will be presented. Longer PZN stacks in conjunction with the levered mechanism to provide the capability of  $1.0 \text{ mm}$  translations are currently being explored.



**Figure 3:** Model of a lever driven flexure mechanism



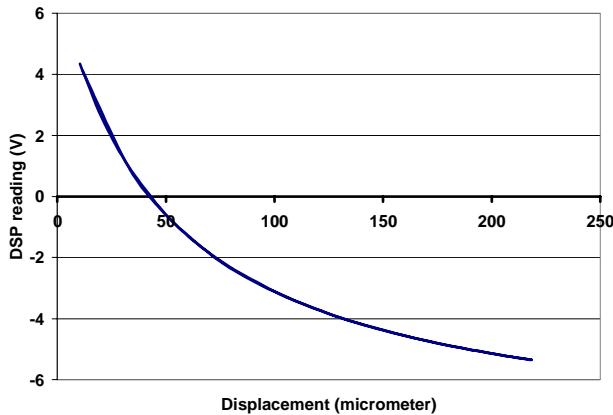
**Figure 4:** Fractional lost motion vs. stiffness ratios for single 5:1 lever and two symmetrical 5:1 levers

## Digital Closed Loop Control for Mesoscale Positioners

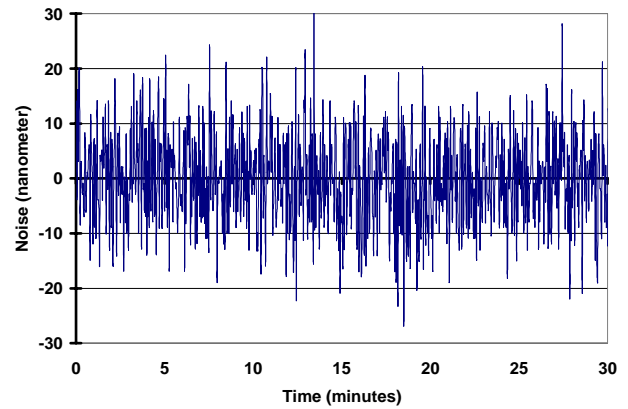
The absolute displacement measurement for the positioners of these studies use capacitive sensing monitored using a digital lock-in amplifier platform developed at UNC Charlotte. Generally, noise sources for capacitive sensors involve carrier signal, oscillator, and amplifier noise. The oscillator noise is a function of the oscillators chosen and will manifest as combinations of amplitude and phase components. Typically, in analog oscillators it is the amplitude that is most difficult to control. However, investigators have implemented digital signal processing (DSP) for both PID control and as a lock-in amplifier for capacitive sensing. The DSP platform is developed with 16 bit AD and DA converters while supporting 40 kps sampling rates and a 100 kps system is currently being evaluated. Nonetheless, fast DA and AD converters supporting 18 bit or higher precision will be necessary to achieve better than 1 part in  $10^5$  accuracy. While

such resolution is possible using sigma delta converters, we have not been able to identify commercially available converters capable of providing the required performance at sufficient bandwidth.

In conjunction with the digital control system, capacitive sensors for the lever mechanism (see figure 2) have been developed. An AC bridge design using one variable capacitance and one referenced capacitor is implemented. The variable capacitor comprises two 16.0 mm diameter electrodes where one electrode is mounted to the fixed frame and the second electrode is mounted to the movable platform. The plates have a nominal gap of 230  $\mu\text{m}$  and produce a capacitance variation between 20-50 pF over a displacement range of 225  $\mu\text{m}$ , figure 5. The displacement is measured with a Michelson interferometer and the capacitance is measuring using the DSP lock-in amplifier. The lever mechanism's actuators and the capacitance sensor are closed loop controlled digitally. To assess the system noise the mechanism was positioned to approximately 100  $\mu\text{m}$  and held stationary for 30 minutes. The gage output at a 1 kHz bandwidth is measured to be approximately 9 nm RMS, figure 6.



**Figure 5:** DSP voltage vs. platform displacement



**Figure 6:** noise over 30 minutes, rms deviation = 8.6 nm for 1 kHz bandwidth

## Conclusion

The PZN-PT represents a likely candidate for nano-positioning and mesoscale applications. However, continued research is necessary to fully understand issues and implementation associated with stack pre-stress requirements and methods for economic manufacture of thinner single crystal sheets. Secondly, flexure systems appear to provide reasonable methods for frictionless motion and precision. However, many flexures are over-constrained for relatively long motions and large deformation models may be required for future designs. Assuming flexure systems are an optimal approach for nano-positioning systems with meso-scale performance, these designs will require additional modifications and perhaps new innovations in order to substantially exceed 1.0 mm ranges. Finally, we believe that alternative sensing methods may be required above 1.0

mm ranges if nanometer accuracy is to be maintained. Furthermore, while the DSP platforms developed at UNCC for software correction (i.e. PID control and Lock-in electronics) have demonstrated significant promise for digitally controlling the positioners. Nonetheless, the DA and AD converters providing DC measurements will need to be increased above 16 bit at tens to hundreds of kilo samples per second to enhance precision measurement.

## **Acknowledgments**

The authors would like to express their thanks to Richard Seugling and Bob Hocken, UNC Charlotte, Paul Rehrig and Dean Anderson of TRS Ceramics for many useful discussions on these developments. We would also like to thank Jeffrey Luner of Boeing, St. Louis, and NSF ( contract #DMI 2975020172) for partial support of this work.

---

<sup>i</sup> Seung-Eek Par and Thomas R. Shrout, Ultrahigh strain and piezoelectric behavior in relaxor based ferroelectric single crystals, J. Appl. Phys. 82 (4), 15 August 1997, pg. 1804-1811

<sup>ii</sup> Stuart T. Smith, Flexures, Gordon and Breach Science Publishers, 2000, pg. 345-352