Drives and Design Criteria for Positioning with Nanometer Resolution and Stability

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To achieve precision and stability down to the nm level over periods of many minutes is one of the key requirements for many biophysical single molecule applications. To achieve both the required positioning range for adjusting the sample in reference to a microscope as well as the sub nm resolution, typically stacked combinations of classical XY stages for microscopes and a multi axis sub nm piezo stage are used. This poster decribes the effects of integration of two suitable drive technologies: Ultrasonic piezo motors for stable long travel range and piezo actuator driven fine positioners. Recently published experimental data generated by an advanced optical trapping application are referenced to support the theoretical statements.

The Experiment: Optical Tweezer

The experiment as described below was conducted by P.C. Anthony during his time at the Block Labs, Stanford University, US and first described in an article by Jordan et al. [1]

All data shown below is courtesy of P.C. Anthony and the Block Labs.

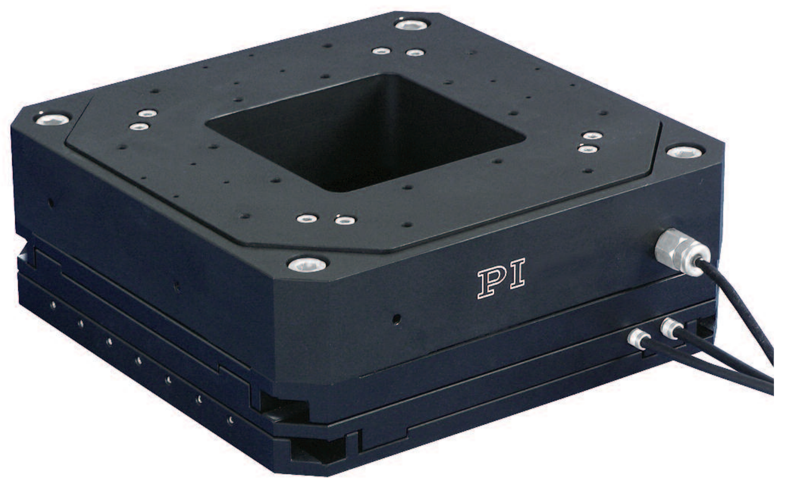
For the experiment an optical trap was used to measure long term (30 min) instrumentation drift by letting it monitor a fixed sample bead. For a detailed description of the setup refer to [1].

Stability is a key requirement in optical trapping experiments as the experiments can take many minutes – and on the other hand optical trap setups provide nm resolution.

If the stacked system drifts during the measurement time there is no way to separate real motion of the observed sample from artifacts caused by system drift.

System Overview

- Dual trap optical tweezer [2]
- Sample cell: coverslip and slide joined by double sided tape
- Modified commercial microscope
- Samples: Latex beads
- Stacked positioner configurations used:
  - P-517 3-axis piezo stage, cap sensor (PI) and M-686 ultrasonic drive substage (PI),
  - P-517 3-axis piezo stage, cap sensor (PI) and Rolyn 750 MS manual substage with screw drive

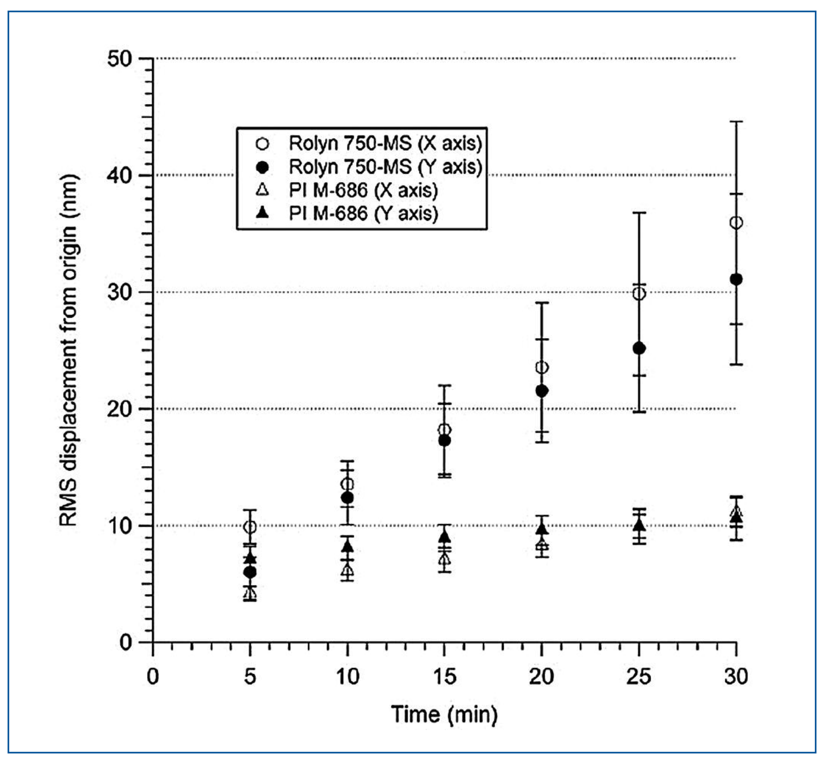


Experimental Procedure

- 0.6 µm polystyrene beads (Bangs Laboratories) suspended in high salt buffer are pipetted into sample cell
- Beads stick to coverslip and cannot move
- Positions of beads are measured with back focal plane reflection [3]
- A stuck bead is positioned into the focus of the trap – this defines the reference position
- Drift over time is recorded, after 5 minutes the bead is recentered in the trap and the position differential is extracted from the results to be able to stitch six 5 min intervals

Test Data: Stability of a Hybrid System

Data courtesy of Block Labs, P.C. Anthony



Results

The upper curve in the figure above shows the observed drift of the stacked configuration using the manual screw stage, the lower curve shows the drift with the ultrasonic stage configuration. The ultrasonic drive stacked configuration shows a significant reduction in drift

Conclusion

Replacing the screw-driven substage with the piezomotor-driven substage significantly reduced the long-term drift of the system. It is believed that this is due to the elimination of lubricant flow in the screw/nut interface. It is important to note that the data is now a sensitive measure of not only the ultrasonic coarse positioning stage's long-term stability but also that of all other mechanical elements of the system including the PZT nanopositioning stage and the microscope's supporting structure.

References:

[1] S.C. Jordan and P.C. Anthony: Design Considerations for Micro- and Nanopositioning: Leveraging the Latest for Biophysical Applications, Current Pharmaceutical Biotechnology, 2009, 10, 515-521

[2] Greenleaf, W.g., W.J.; Woodside, M.T.; Abbondanzieri, E.A. and Block S.M. (2005) Passive all-optical force clamp for highresolution laser trapping. Phys. Rev. Lett., 95 (20), 208102.

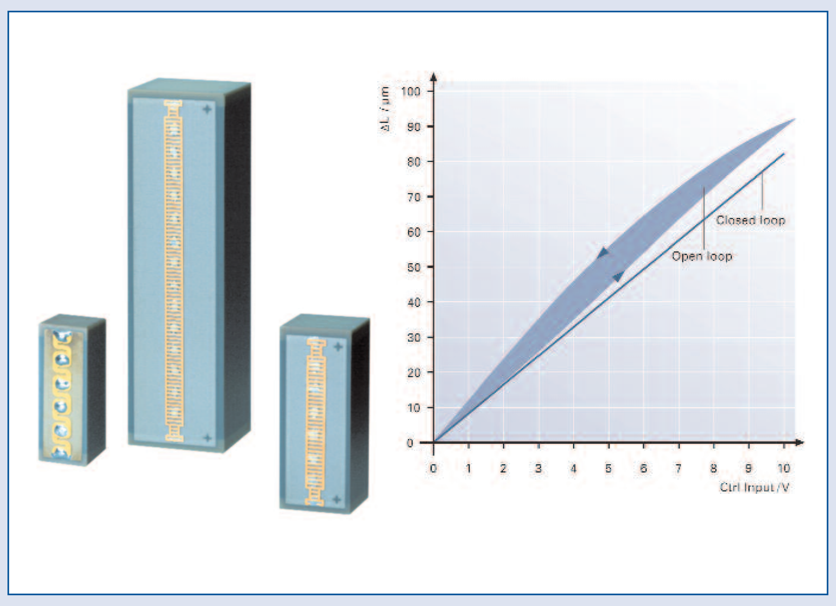
[3] Neuman, K.C. and Block S.M. (2004) Optical trapping. Rev Sci Instrum., 75 (9), 2787-2809.

Nanopositioning Tool: Piezo Stage

Novel methods in Single Molecule Biology often require resolution of motion in the nm range. This is typically achieved by using nanopositioners with PZT ceramic piezo actuators as drive elements.

Properties of PZT Actuators (e.g. PICMA®)

- Sub nm resolution
- Nonlinear expansion and hysteresis over applied electrical field
- Drift over time
- Parasitic tip tilt
- Stroke limited to 0.1% of actuator length

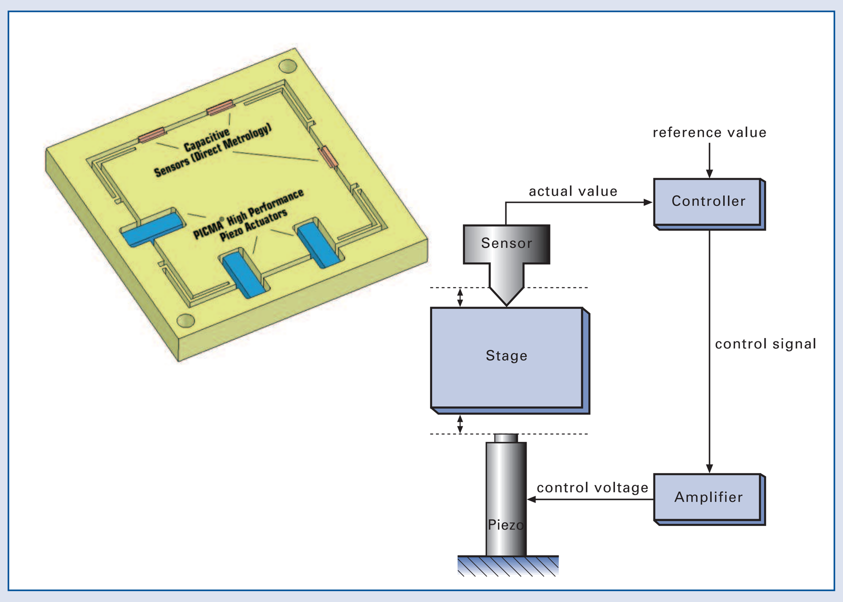


For applications requiring precise positioning the expansion of the PZT actuator needs to be linearized.

Challenges and Solutions for Precise Positioning with PZT

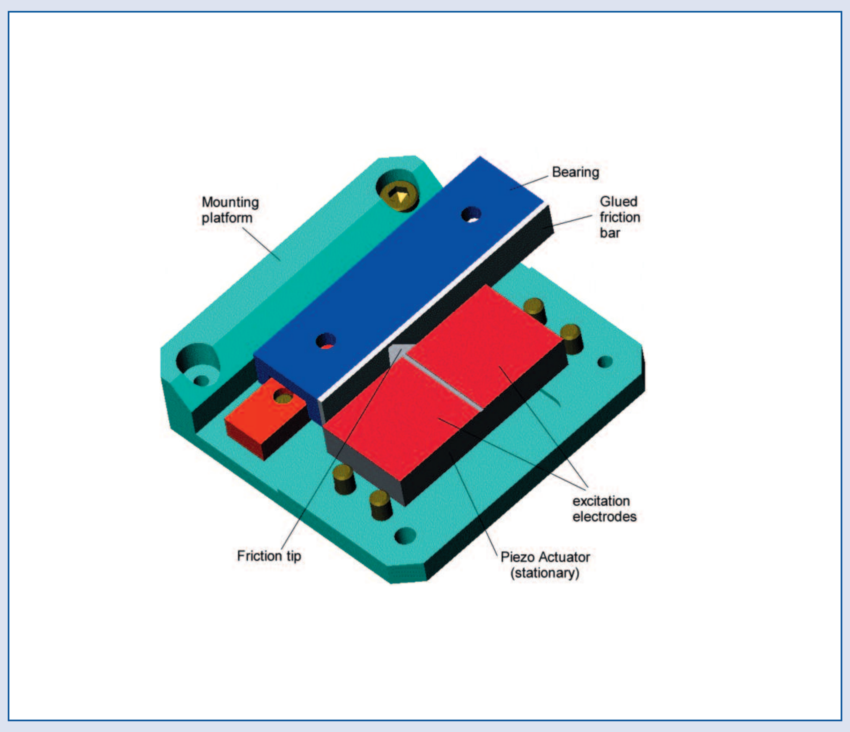
- Parasitic tip tilt: integrate PZT actuators in guiding flexures
- Drift, hysteresis and nonlinearity: use high precision sensors e.g. piezo resistive or capacitive sensors
- Short stroke: use lever amplification for travel range expansion (Feasible up to approx. 500 µm stroke)

Sub nm resolution and nm stability is achieved with cap sensors and suitable control electronics



Ultrasonic Drive Principle

The classical piezoelectrical actuator expands on application of an electrical field. Even with mechanical lever amplification travel range is limited to a few 100 µm. But there is a fundamentally different method of generating motion from PZT ceramics – the so called Ultrasonic Drives.

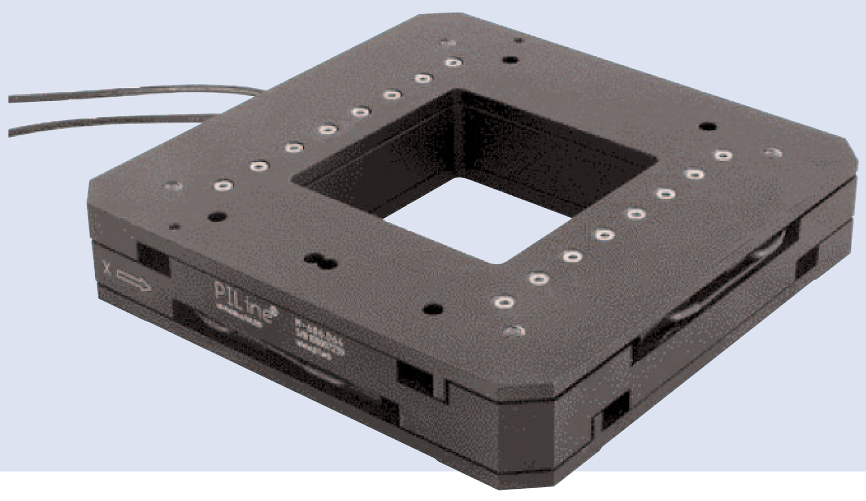


- Piezo ceramic is driven at res. frequency of elliptical vibration mode
- Friction tip is located at point of maximum elliptical motion amplitude
- Friction tip transfers motion to friction bar
- Resulting travel range is only limited by bearing and length of friction bar

- **Resolution:** 50 nm step size

- **Low** overall position drift due to:
  - Self locking when powered down
  - Low thermal load in operation
  - Zero thermal load when holding position
  - Direct linear drive: no gear, no spindle/nut required

- **Low backlash** due to:
  - No gear
  - Direct linear motion, no spindle/nut



Coarse Positioning Substage: Requirements and Drive Type Selection

Travel ranges of nanopositioning systems are typically limited to a few hundred µm. This in turn means that for the majority of applications in Biology a coarse positioning alignment system - typically a two axis microscopy substage is required. This results in a stacked system where the piezo nanopositioning stage is carried by the substage. Though performance specifications in terms of resolution for the coarse stages per se are rather lax compared to the nanopositioning piezo stage selection of a suitable coarse stage is important. **Any substage drift will directly cross talk into position of the nanopositioning stage.**

Key Performance Specifications for Coarse XY Stage

- Resolution: not critical: 0.1 to 1 µm
- Backlash: backlash free
- Stability: nm over minutes
- Form factor: typically flat with free aperture

Design Requirements	Linear Scale	Stepper Motor	Ultrasonic Drive
Defines sensor resolution + min. motor step size	0.1 µm possible	Possible with gear box and microstepping	0.05 µm step size
Direct drive + Direct sensor metrology	Direct metrology	High resolution if geared, but drifty	Direct high stability drive
Direct linear drive + motor with low thermal load	–	Rotary motor, high thermal load in rest	Self locking, low thermal load
Compact + flat motor + sensor	Compact sensor	Bulky motor	Compact motor

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