MEMS Nanopositioning Mechanisms:
Design and Experimental Characterization

Jason J. Gorman, Sebastien Bergna and Nicholas G. Dagalakis
Intelligent Systems Division
Manufacturing Engineering Laboratory
National Institute of Standards and Technology

MEMS Alliance Symposium

April 19, 2005

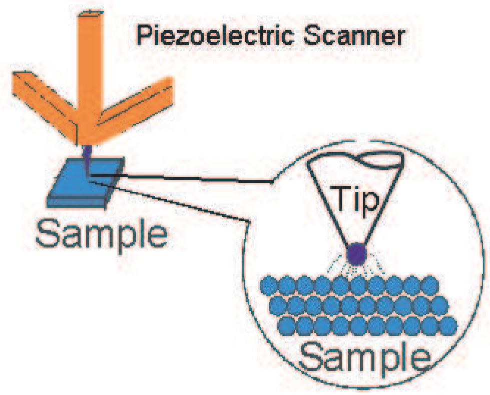
Outline

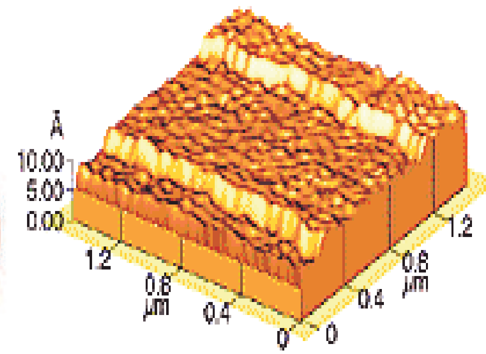
- Background
  - MEMS nanopositioning applications
  - NIST macro-scale nanopositioners
- MEMS Nanopositioner Design
  - Performance specifications
  - Kinematics
  - Electro-thermal actuators
  - 1 DOF and 2 DOF mechanisms
- Mechanism Characterization
  - Methodology: SEM and OM
  - Displacement - voltage calibration
  - Cross-talk error and rotational error measurements
- Conclusion

MEMS Nanopositioning

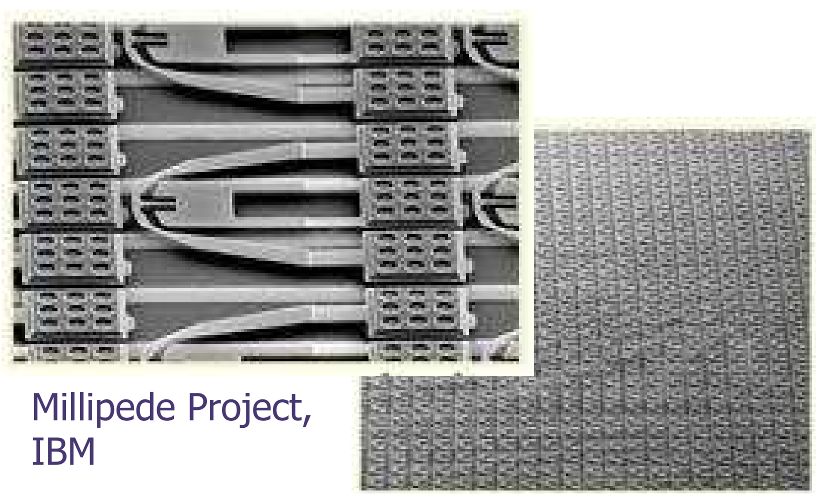
Nanopositioner Applications:

- Atomic Force Microscopy
- Scanning Tunneling Microscopy
- Optical Tweezers
- Nanomanipulation
- Beam Steering





MEMS Nanopositioners:



Millipede Project, IBM

Applications:

- High-density data storage (IBM, Nanochip, etc.)
- Scanning probe arrays
- Parallel nanomanipulation and assembly
- Beam steering (alternative to micromirrors)

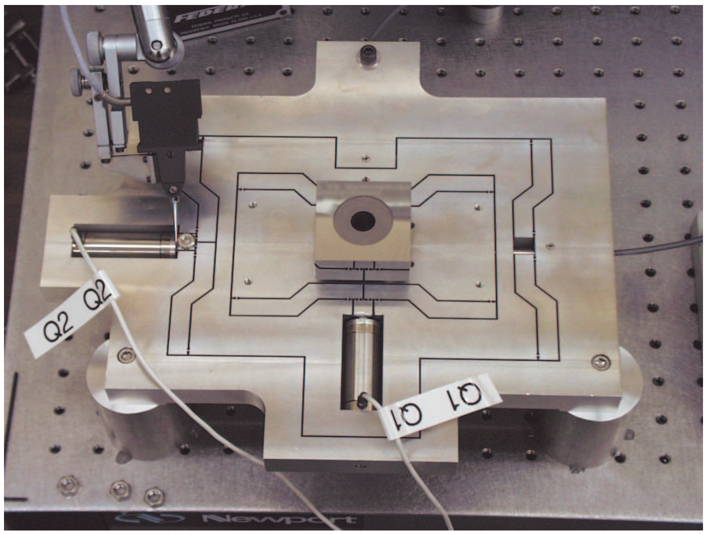
Critical Issues:

- Matching precision of macro-scale devices
- Controlling large arrays of MEMS
- Structural robustness, redundancy, failure

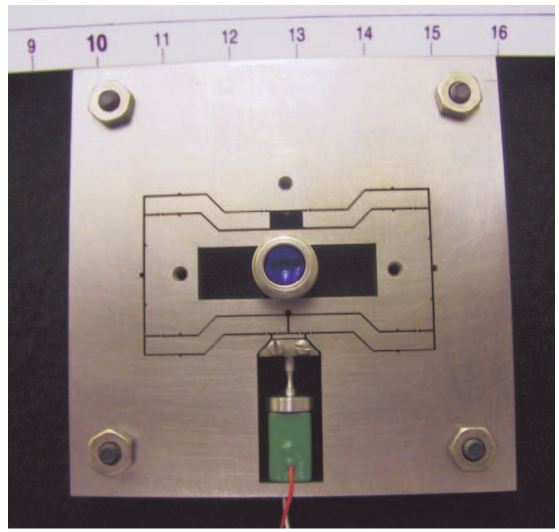
Parallel Dual Lever Nanopositioners

A number of novel macro-scale nanopositioning devices, which combine flexure mechanisms with piezoelectric actuators, have been developed at NIST.

First Prototype: 2 DOF



Compact Stages: 1 and 2 DOF mechanisms



Dimensions: ~ 8 X 8 cm

Materials:
- Aluminum
- Beryllium Copper
- Invar
- Steel
- Titanium Alloy

Range: ~ 100 µm

- The parallel dual lever flexure mechanism uses symmetry for high precision guided motion
- Cross-talk and rotational motion errors have been shown to be very small

Design Objectives and Specifications

Project Objectives:

- Develop devices which meet or exceed the specifications of our macro-scale nanopositioners (range, resolution, accuracy, bandwidth, etc.)
- Apply these devices to critical problems in nanometrology (AFM, STM) and nanomanufacturing (nanoassembly)

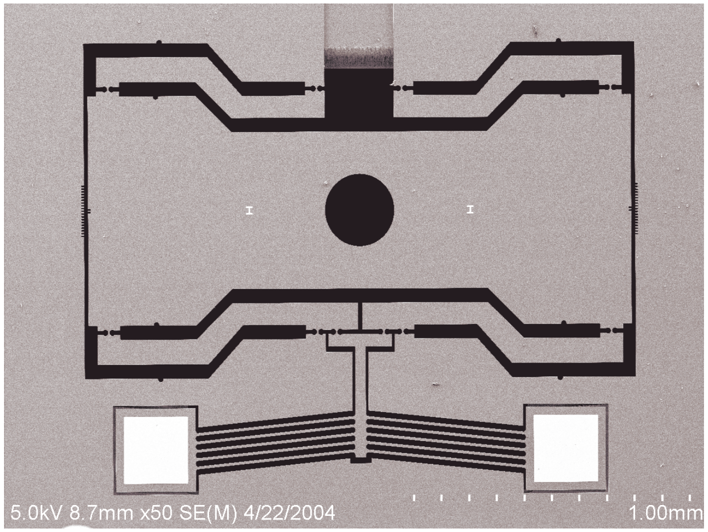
Device Specifications:

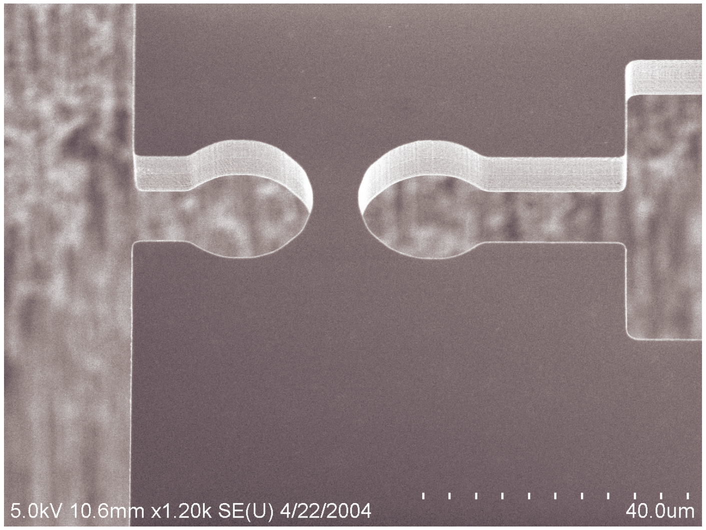
- Motion range ~ > 20 μm
- Motion resolution ~ 5 nm
- Positioning accuracy ~ < 50 nm
- Cross-talk error ~ < 250 nm
- Rotational errors ~ < 10 μrad
- System Bandwidth ~ > 1 kHz

Design Considerations:

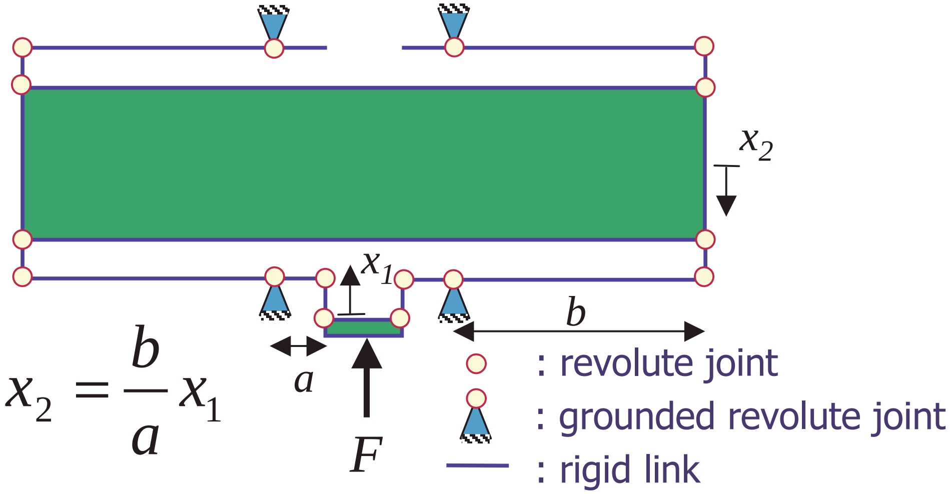
- Mechanisms must be strong enough for the connection of probes, grippers, etc.
- Scalable design, 1 DOF, 2 DOF, etc.

Mechanism Kinematics





Approximate Kinematic Model



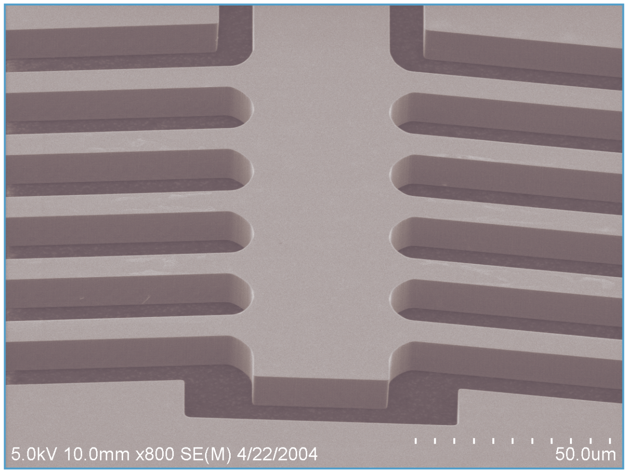
$$x_2 = \frac{b}{a} x_1$$

- Circular notch flexure hinges are used for compliance (5 μm thickness)
- The flexures act as torsional springs or combined torsion/shear springs, depending on their location
- The motion amplification can easily be adjusted for different applications

Electro-Thermal Actuation

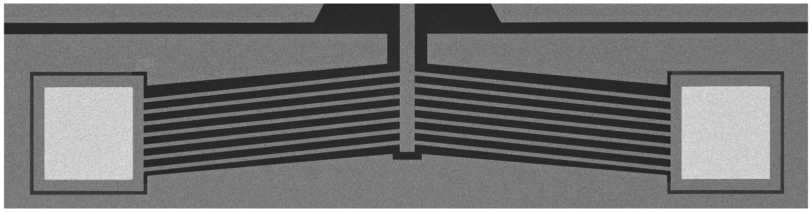
Bent-beam, or 'chevron', electro-thermal actuators have been selected for the nanopositioners due to their:

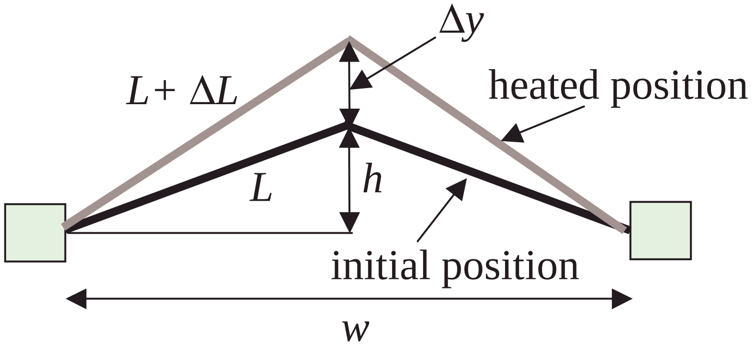
- Straight line motion
- High force output
- Low voltage requirements
- Simple design and fabrication



Working Principle:

Voltage applied across the structure causes Joule heating, resulting in an expansion of the beams and linear motion of the transmission shuttle

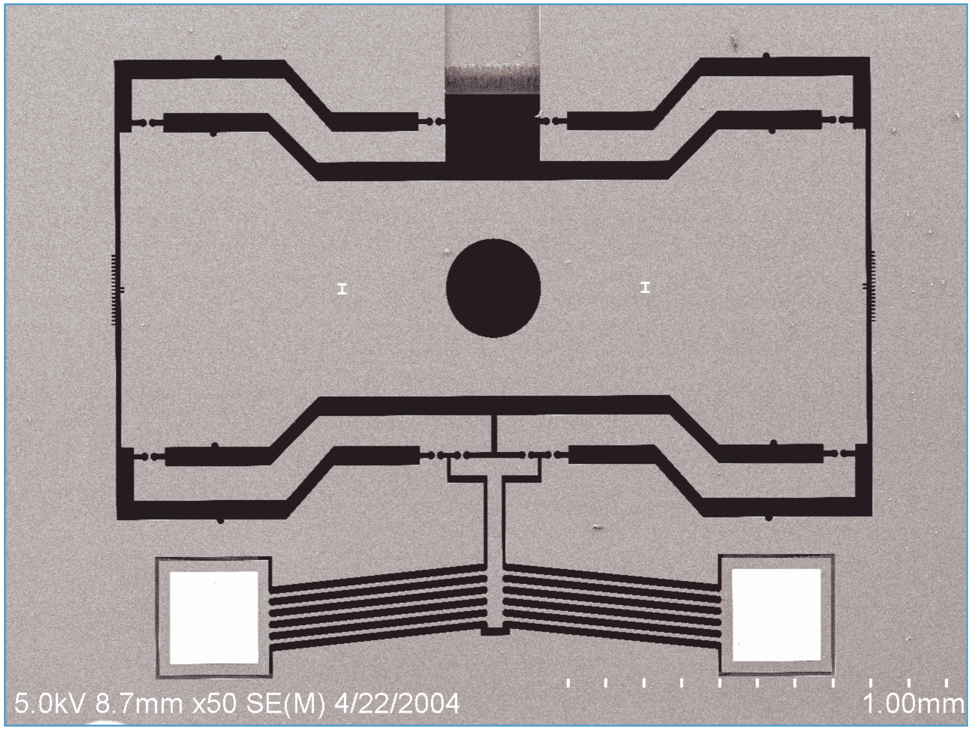


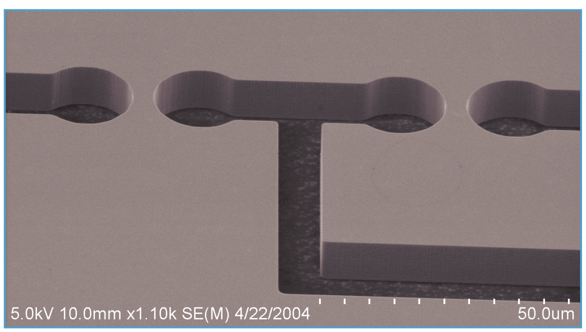


$$\Delta y = \left((L + \Delta L)^2 + \frac{1}{4} w^2 \right)^{1/2} - h$$

$$\Delta L = \alpha \, L \, \Delta T$$

1 DOF Mechanism

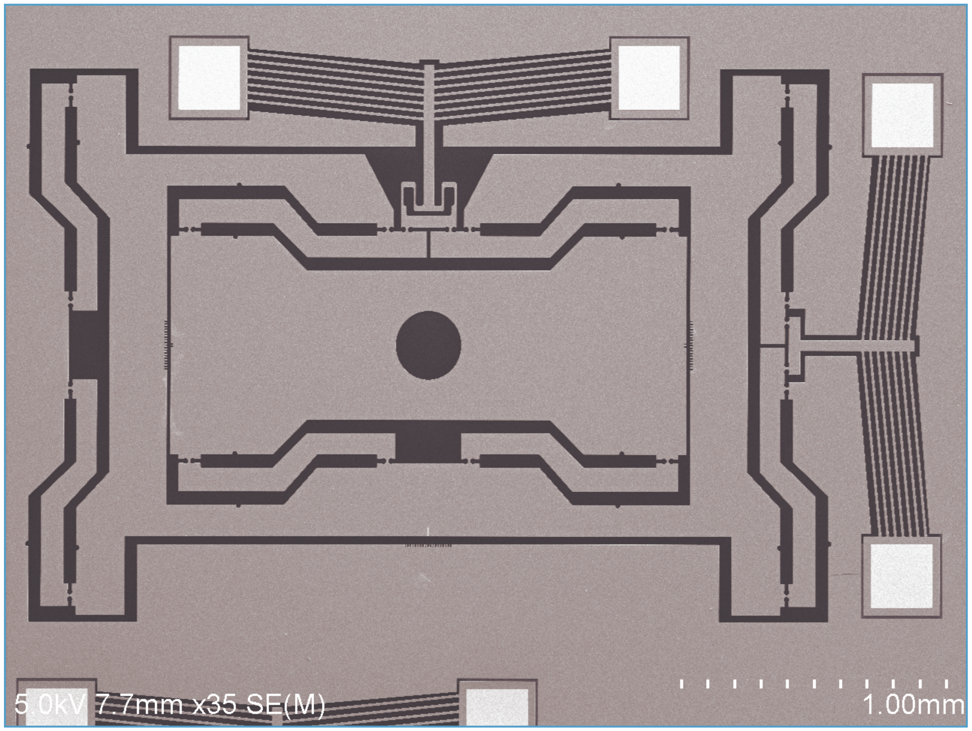


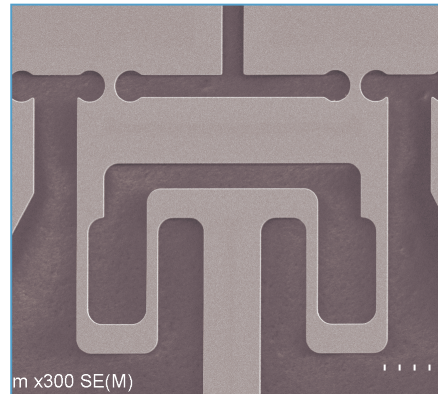


The 1 DOF mechanism incorporates a dual lever flexure mechanism with a bent-beam electro-thermal actuator

- This mechanism is large in comparison to most MEMS (2 mm x 2 mm) due to structural constraints
- Range ~ 15 μm
- Device layer thickness = 10 μm and 25 μm
- Flexure width = 5 μm and 7 μm
- Input voltage ~ 0 V to 15 V
- The bandwidth has not been measured yet, but it is expected to be limited by the thermal actuator rather than structural modes

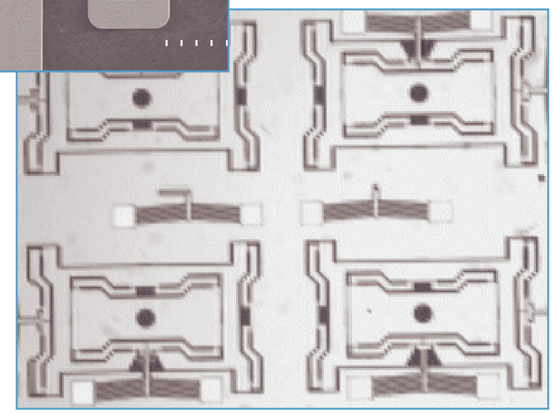
2 DOF Mechanism





Axes decoupler: double parallelogram flexure

2 x 2 array

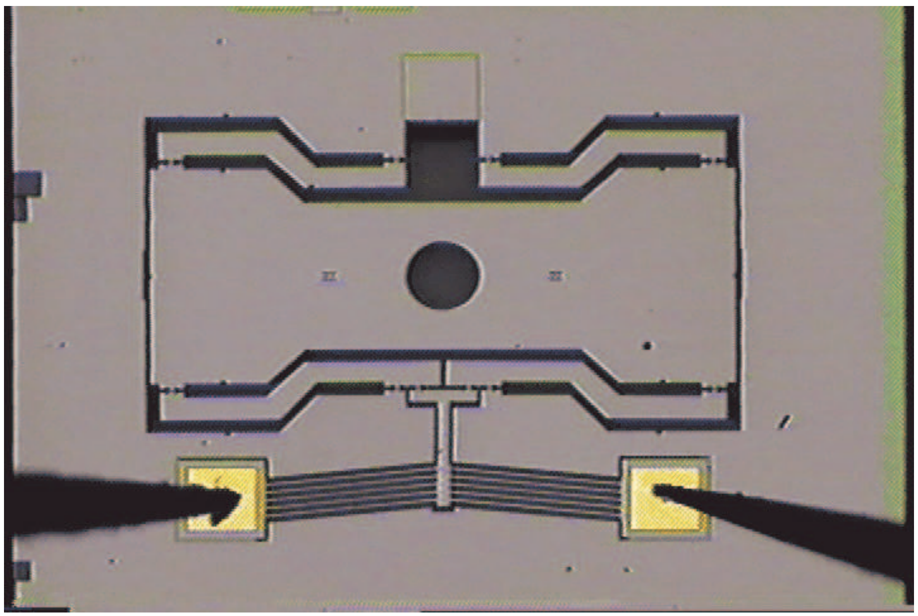


- The 2 DOF mechanism cannot use the nested design utilized in our macro-scale nanopositioners due to constraints on the actuator fabrication
- Therefore, a coupled design has been adopted and a decoupling actuator transmission has been added.
- A prototype nanopositioner array has been fabricated

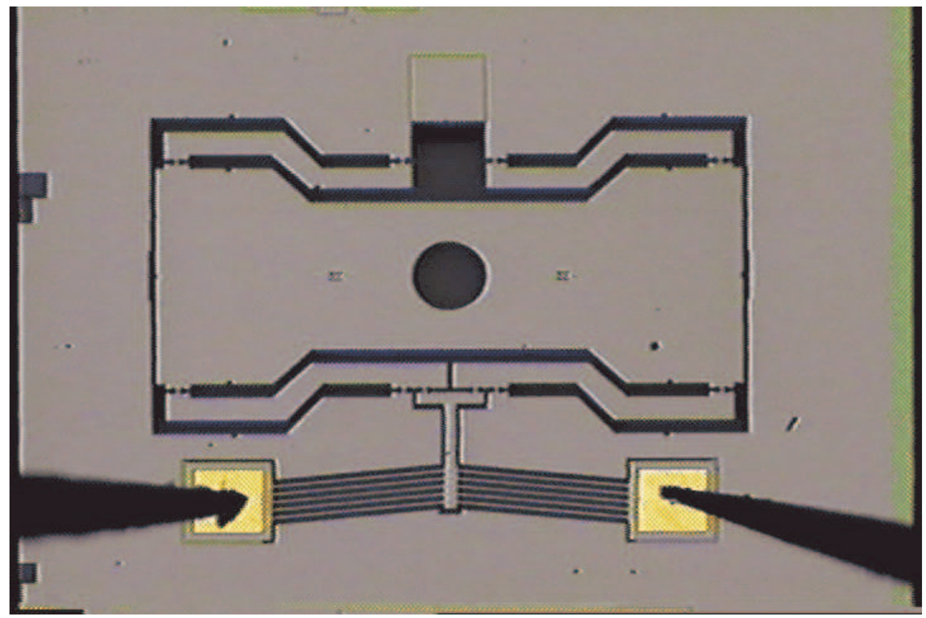
Mechanism Operation

Initial tests performed on a probing station and captured with a standard optical microscope and video camera

Input voltage = 1 Hz square wave



Input voltage = 3 Hz sine wave



Performance Characterization Methodology

Needs

- The mechanisms currently do not have built-in displacement sensors
- Standard sensors will need a calibration approach with the desired resolution (~ 5 nm)
- Several possible metrology tools already exist, based on white light interferometry, laser interferometry and video microscopy (see Veeco, Polytec, Umech)
- These instruments are very expensive and their results are difficult to verify due to proprietary software
- A scanning electron microscope will provide the same level of precision (or better) as any of these instruments when analyzing static performance

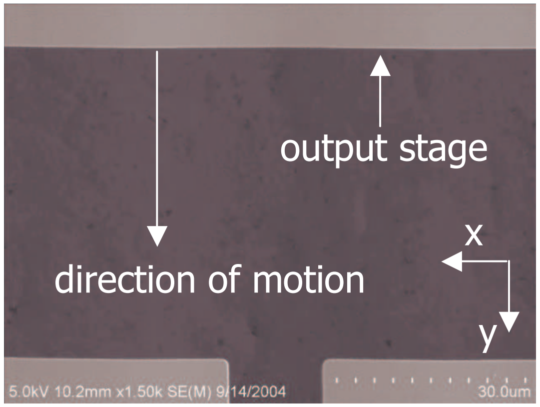
Approach

- Devices were placed in an SEM with a feed-through for providing input voltages
- Input voltages were applied and images were taken successively for the range of interest
- Image processing techniques were applied to extract the motion of the output stage along the y axis (desired linear motion), x axis (cross-talk error), and rotation about the z axis (yaw error)

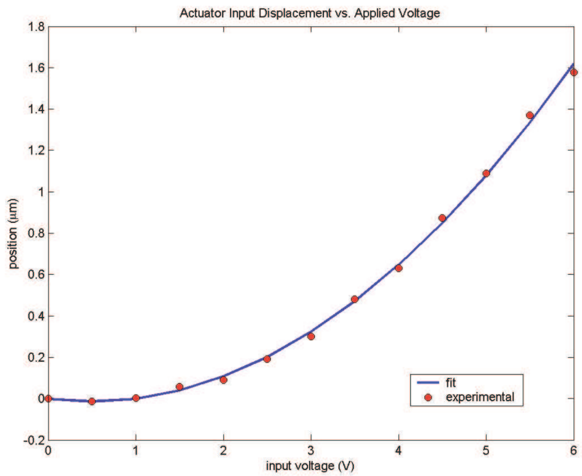
Displacement - Voltage Calibration - SEM

- An SEM is used to take static images of the device – 50 nm pixel resolution
- The edge of the output stage is detected and an average vertical position is calculated
- The relative displacement for each voltage increment is calculated, resulting in a displacement - voltage calibration curve
- The data is strongly quadratic, with the second order term providing the largest weight, as would be expected for a thermal actuator ($y \propto V^2$)

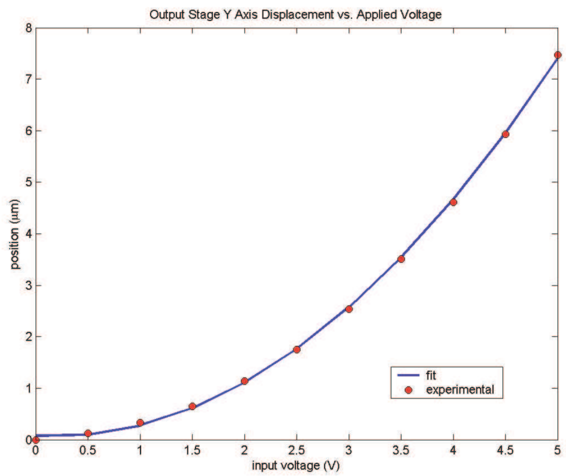
Typical Image



Actuator Motion



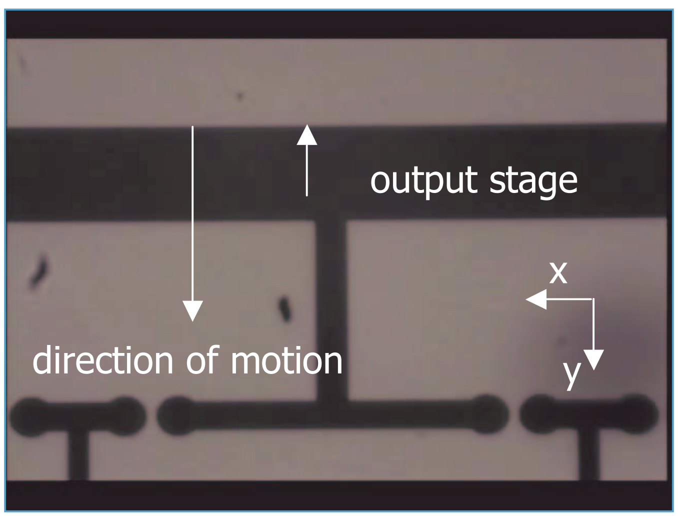
Stage Motion



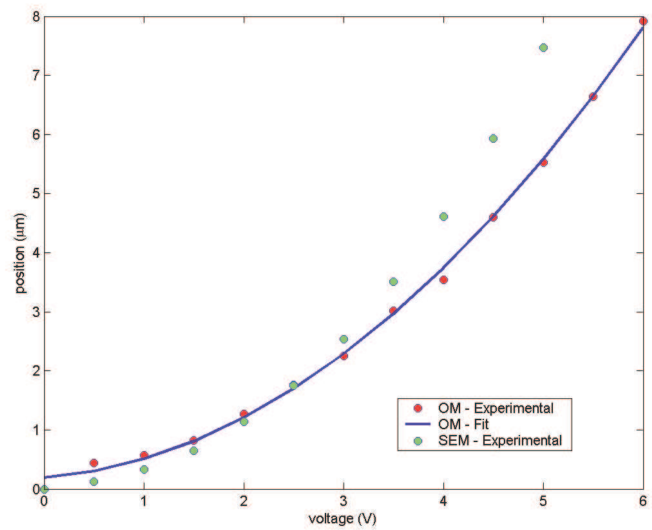
Displacement - Voltage Calibration

- An optical microscope was used to take static images – 500 nm pixel resolution
- The displacements were significantly smaller due to the effects of convection in air
- Calibration in air is necessary for many applications (AFM, beam steering)
- Therefore, the relationship between air and vacuum operation needs to be determined

Typical Image

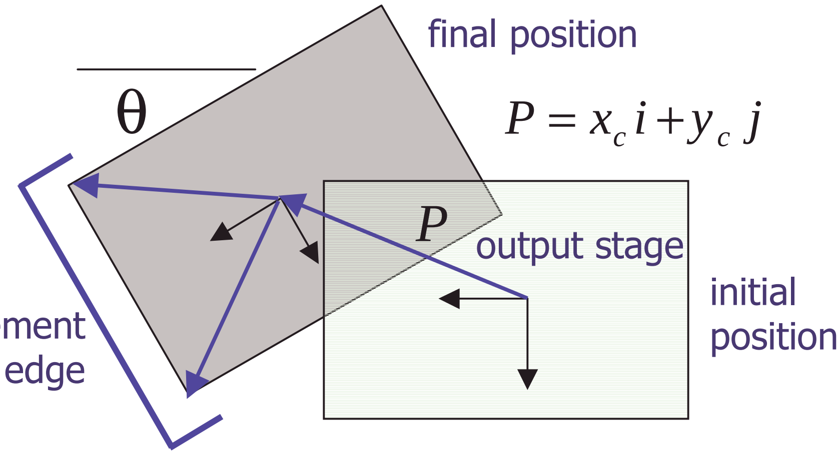


Stage Motion

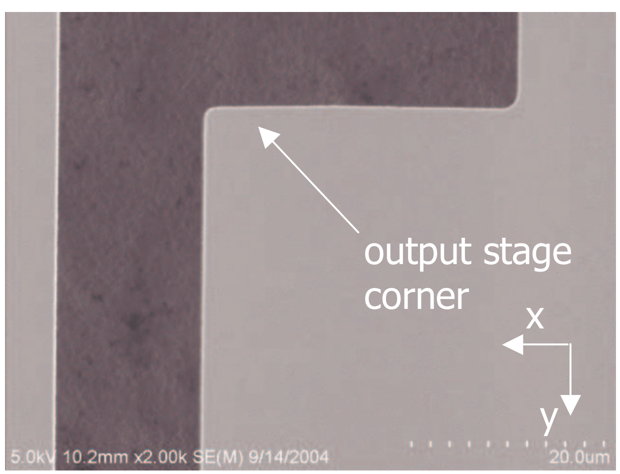


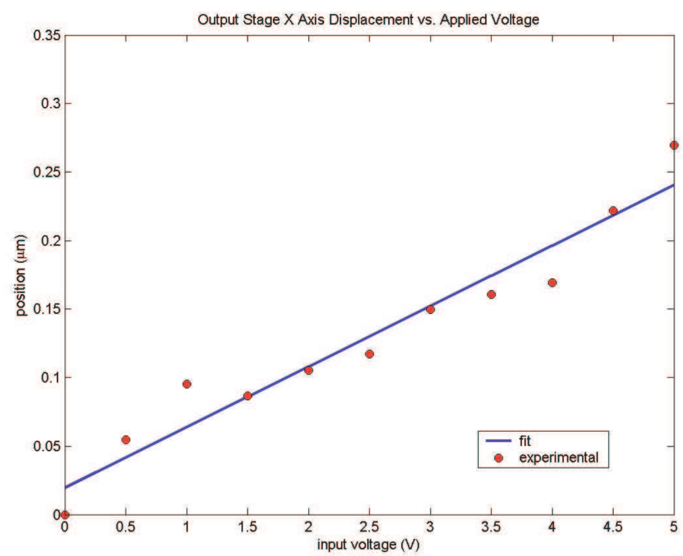
Cross-Talk Error

- Cross-talk and rotational errors are coupled when measuring them at the edge of the output stage
- A simpler metric of the cross-talk is the maximum deviation orthogonal to the desired axis of motion
- The cross-talk is linear, as in the macro-scale mechanism ~ 0.036 μm/ μm



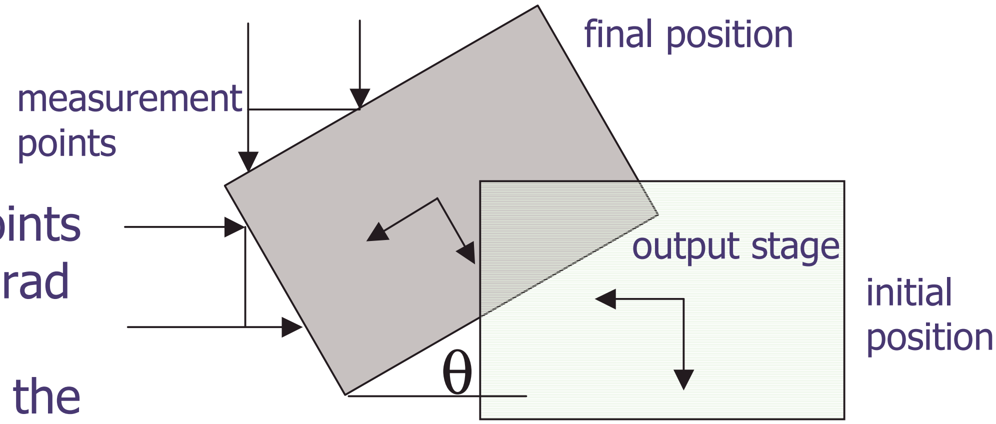
Typical Image



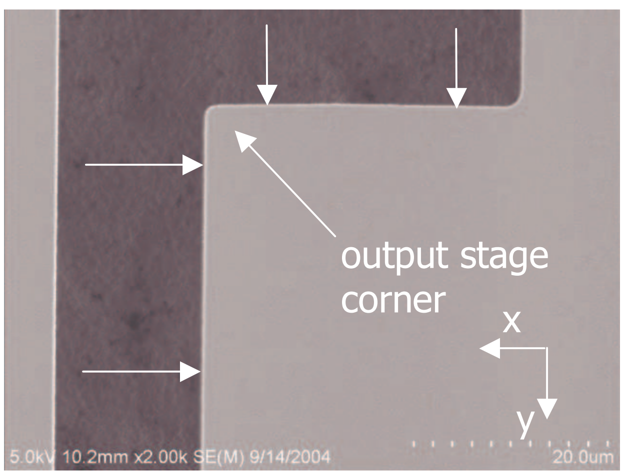


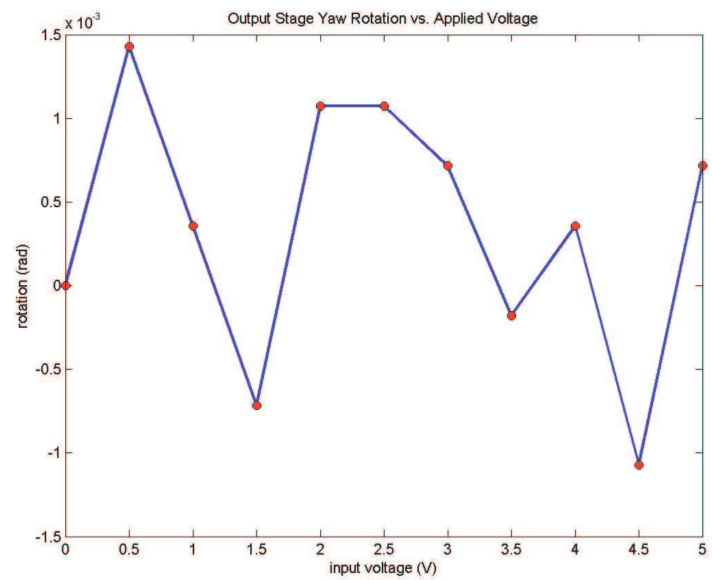
Rotational Errors

- Two points on the vertical and horizontal edges are measured
- The rotation is a function of the differential displacement of these points
- The error was on the order of 1.5 mrad
- However, the measurements are inconsistent, indicating a problem in the methodology



Typical Image





Conclusion

- MEMS nanopositioners based on a novel flexure mechanism have been designed, fabricated, and put through an initial set of performance tests
- The SEM, coupled with image processing, proved to be a straightforward and precise approach for characterizing the static performance of these devices
- The devices do not currently meet our desired specifications, but these results indicate that the specifications should be obtainable through modification of the design and additional testing

Work in Progress

- Redesign for stiffer stage (less cross-talk, rotation, etc.)
- Calibrated open-loop control (nanometer steps, trajectory following)
- Incorporate sensors (piezoresistive, fiber optic interferometers)
- Dynamic testing, frequency response, dynamic modeling
- Closed-loop control