THIN FILM PZT PIEZO MEMS FOR MICRO-ROBOTIC ANGULAR RATE SENSING AND ROTARY ACTUATION

Gabriel Smith, Ryan Rudy, Don DeVoe, Sarah Bedair, William Nothwang, Jeffrey Pulskamp, Luz Sanchez, Rob Proie, Vishnu Ganesan, Joe Conroy, and Ron Polcawich

July 31, 2012

U.S. Army Research Laboratory

Report Documentation Page

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Prescribed by ANSI Std Z39-18

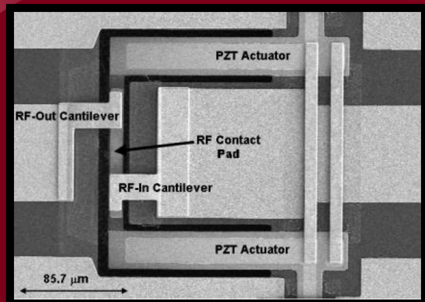
US ARMY RDECOM

PiezoMEMS Technology

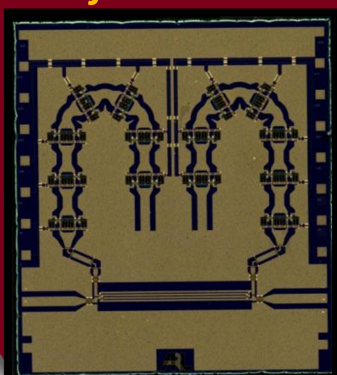
ARL

RF MEMS

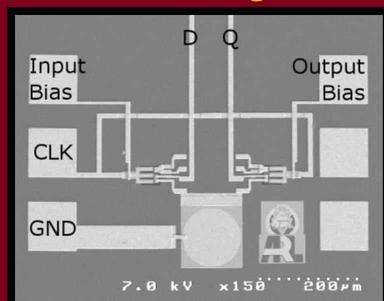
Switches



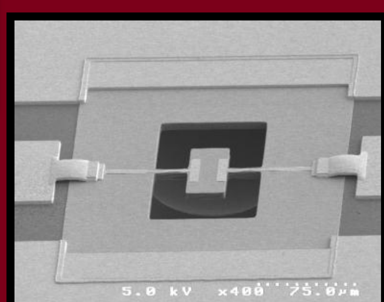
MEMS Phase Shifters



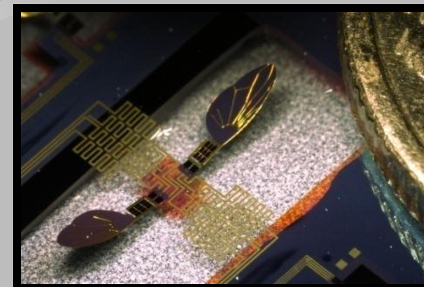
Mechanical Logic



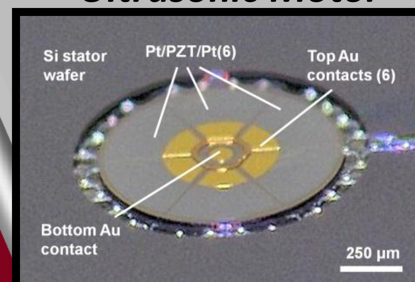
Resonators, Filters, & Transformers



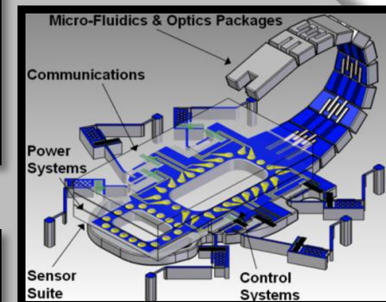
Micro-flight



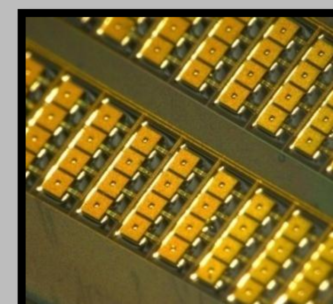
Ultrasonic Motor



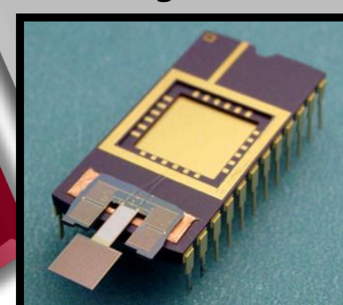
Terrestrial



Bio-Inspired Adhesives



Piezoelectric Energy Harvesting

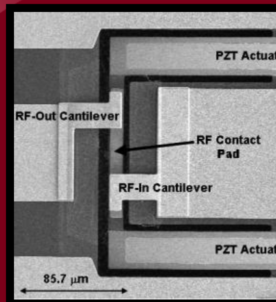


MM-SCALE ROBOTICS

PiezoMEMS Technology

RF MEMS

Switches



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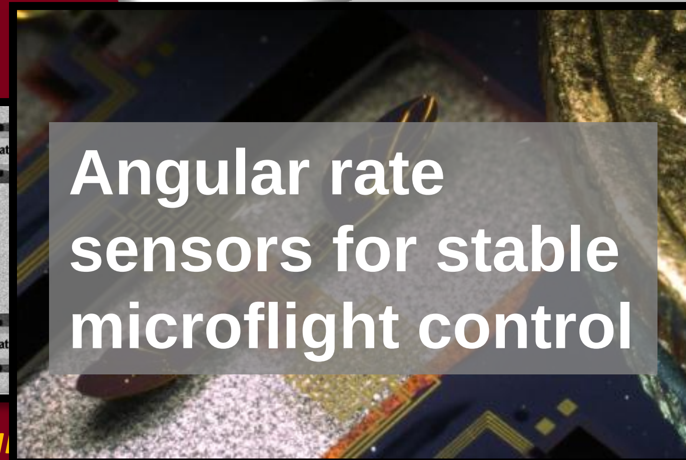

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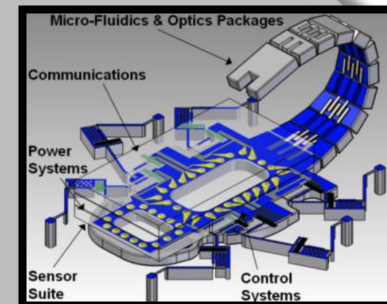
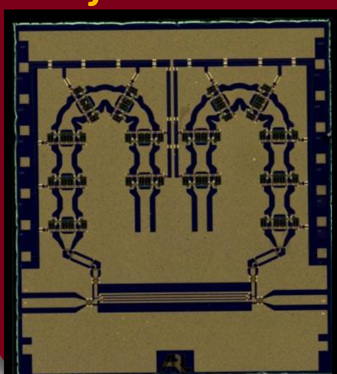
Terrestrial

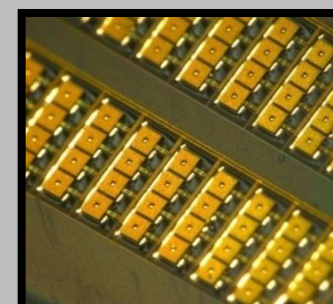


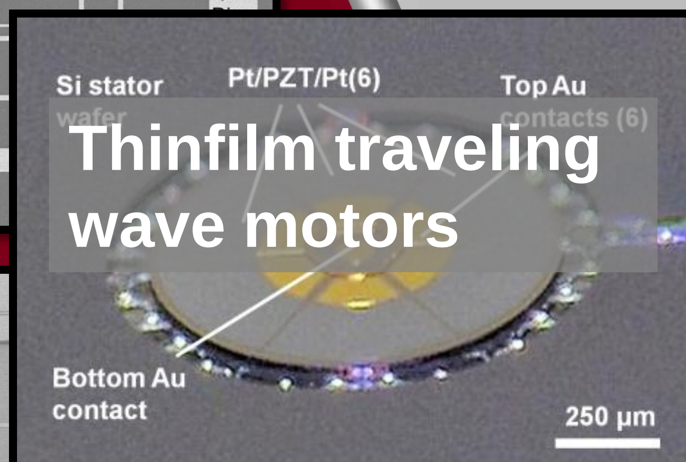
MEMS Phase Shifters



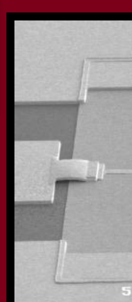
Mecha

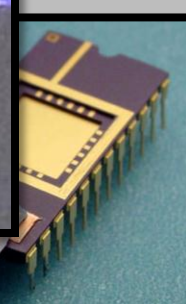
Bio-Inspired Adhesives





ic Energy





MM-SCALE ROBOTICS

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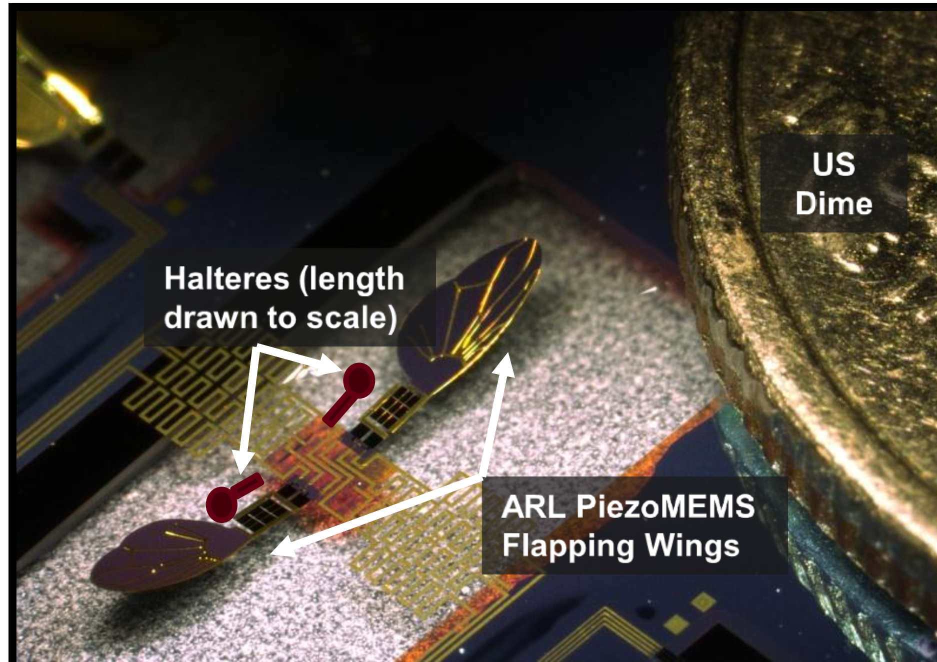
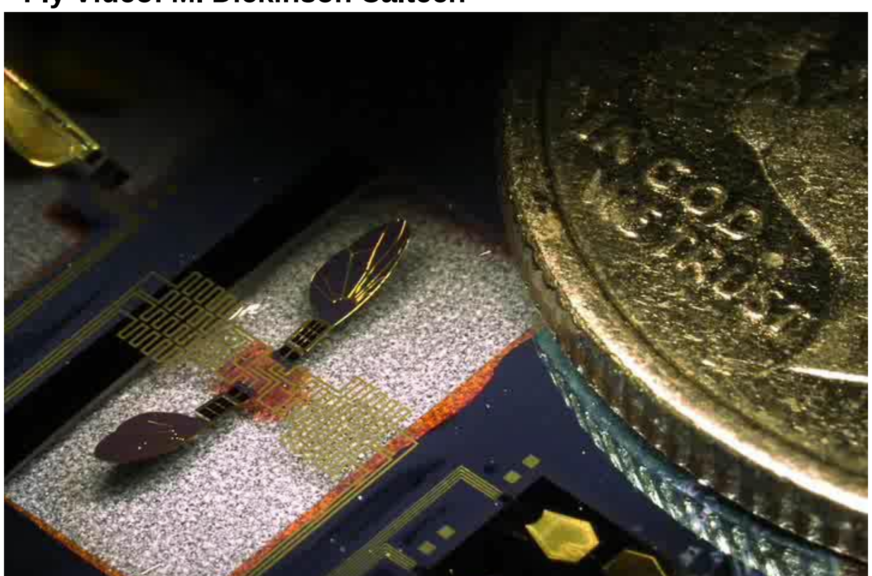
Angular Rate Sensing for mm-scale Robots

Fly Video: M. Dickinson Caltech

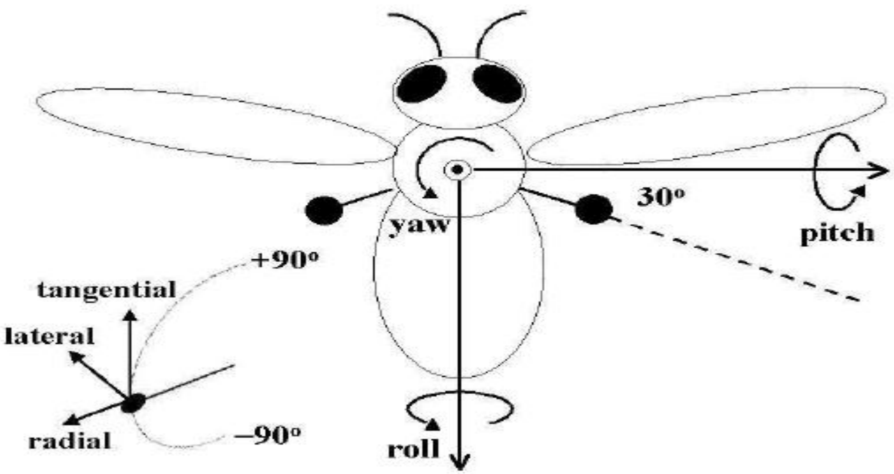


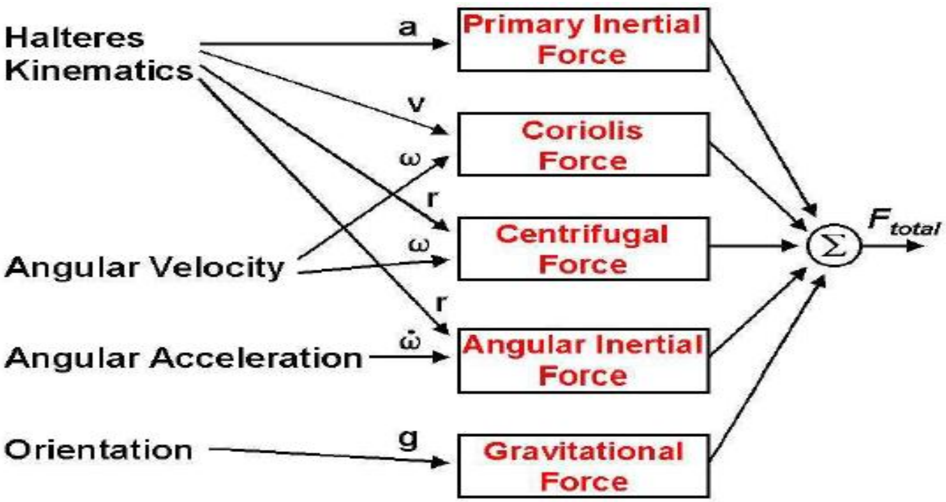


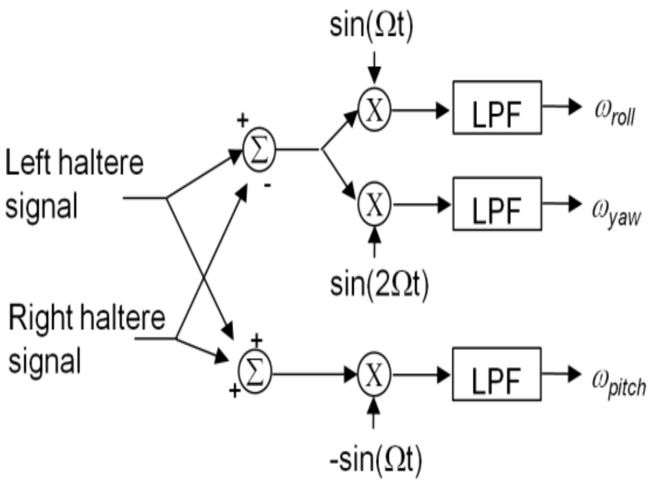
Angular rate sensing on 1-30 mg platform

- **2 orders smaller than packaged state of the art gyroscope.**
- **Integrated biomimetic PZT actuator/sensor approach.**
- **Haltere-like sensor**

Haltere Mechanics





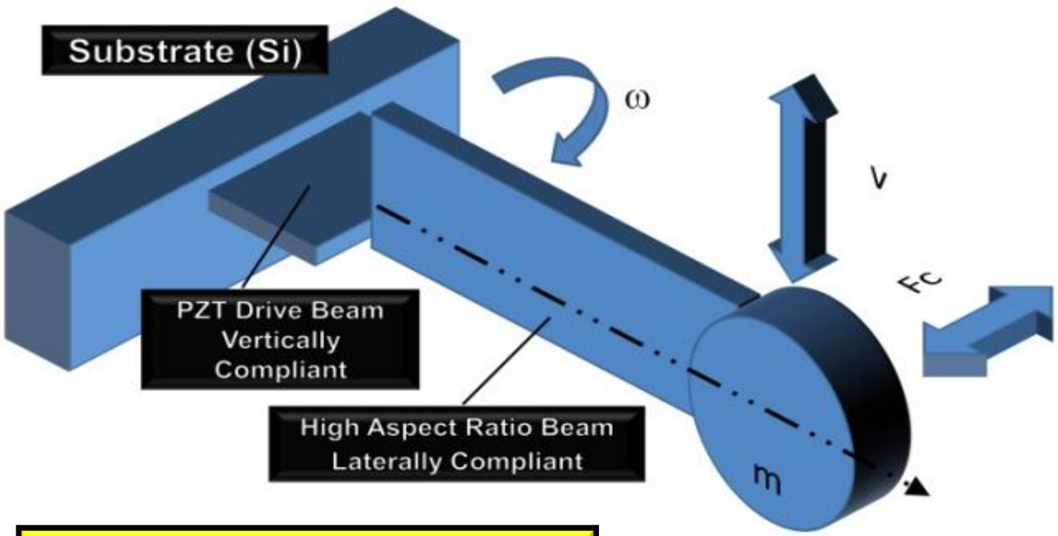


Equation of Motion for macro haltere by Wu et al.

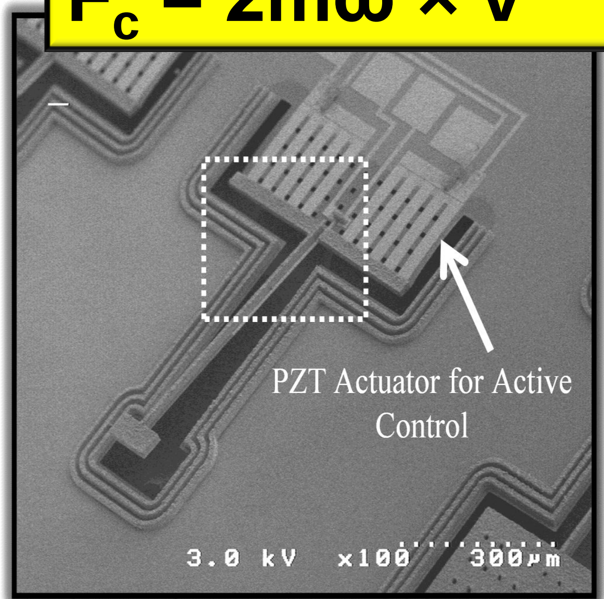
$$\ddot{\theta} + 2\zeta\omega_n\dot{\theta} + \omega_n^2\theta = \dot{\Omega}_3\sin(\gamma) - \dot{\Omega}_1\cos(\gamma) - \dot{\gamma}^2\cos(\theta)\sin(\theta)$$
$$+ 2\dot{\gamma}[(\Omega_3\cos(\gamma) + \Omega_1\sin(\gamma))\cos^2(\theta) \quad - \Omega_2\cos(\theta)\sin(\theta)]$$
$$+ (\Omega_3^2\cos^2(\gamma) + \Omega_1^2\sin^2(\gamma) \ - \Omega_2^2)\cos(\theta)\sin(\theta)$$
$$+ (\Omega_2\Omega_3\cos(\gamma) + \Omega_1\Omega_2\sin(\gamma))\cos(2\theta) \ + 2\Omega_1\Omega_3\cos(\theta)\sin(\theta)\cos(\gamma)\sin(\gamma)$$

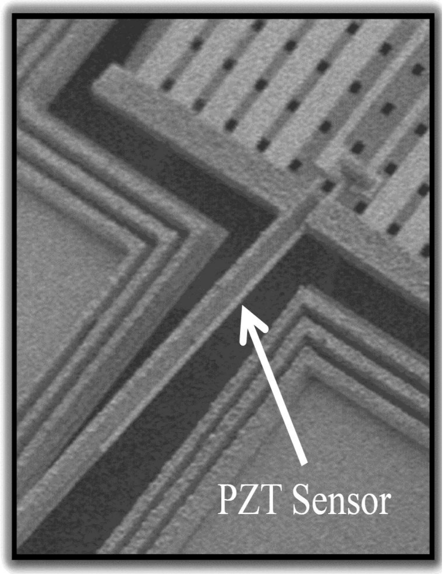
Wu, W. C.; Schenato, L.; Wood, R. J.; Fearing, R. S. Biomimetic Sensor Suite for Flight Control of a Micromechanical Flying Insect: Design and Experimental Results**.** ***IEEE Int. Conf. on Robotics and Automation*****, Taipei, Taiwan, May 2003.**

Orthogonal Actuation and Sensing



$$F_c = 2m\omega \times v$$



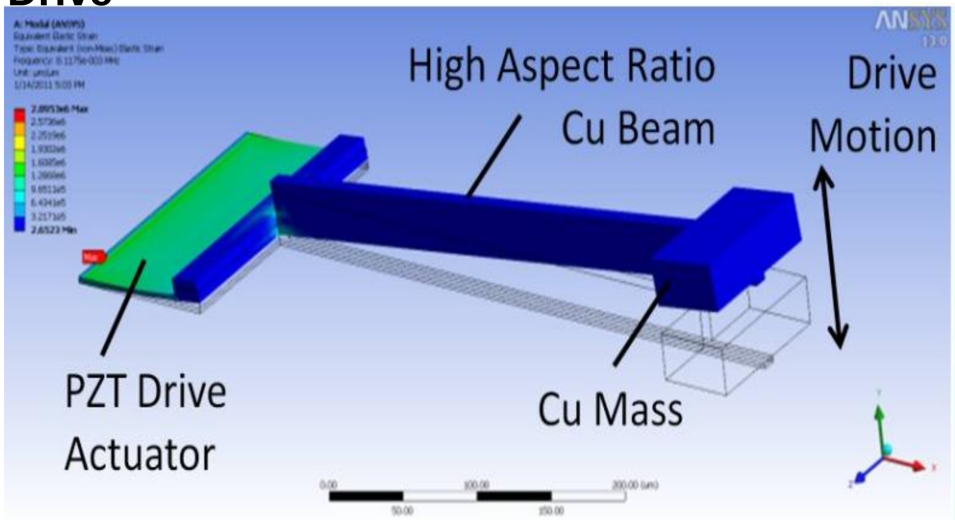


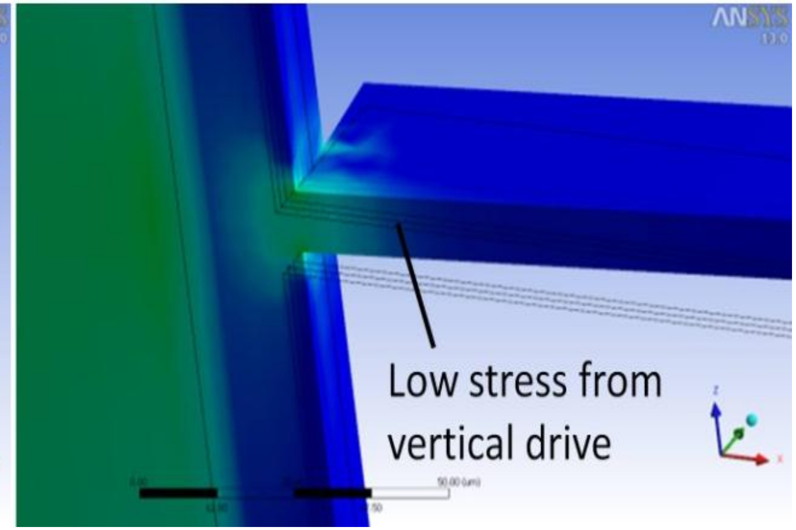
Fundamental Challenges:

- **Body Vibrations**
  - Raise Frequency of sensor structure above wing beat
- **Complex Forces on 3 axes**
  - Oscillate the Haltere to extract the ang. rate components
- **Axis Isolation**
  - Couple the 2 Haltere electrical signals
  - Decouple the rate information for 3 axis
- **Low Q**
  - Trade size, weight, power for sensitivity

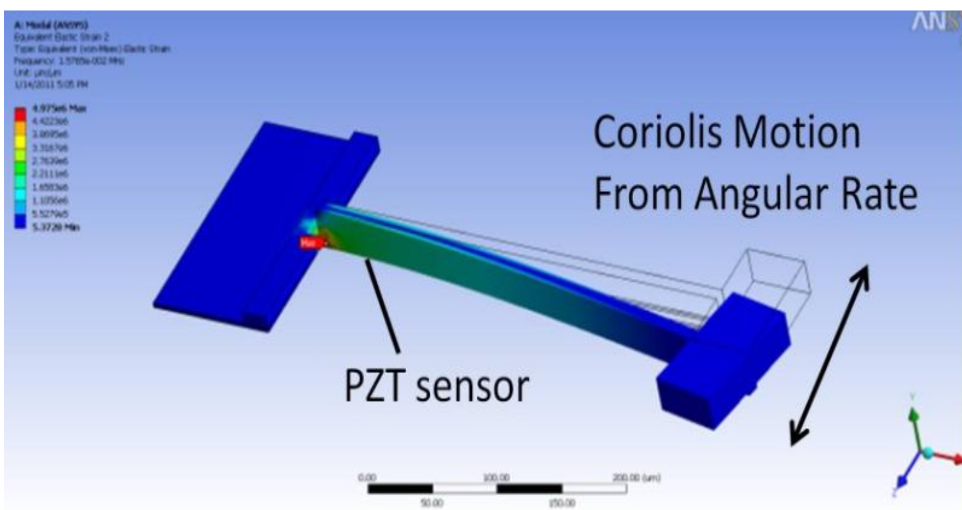
ANSYS Modal Analysis

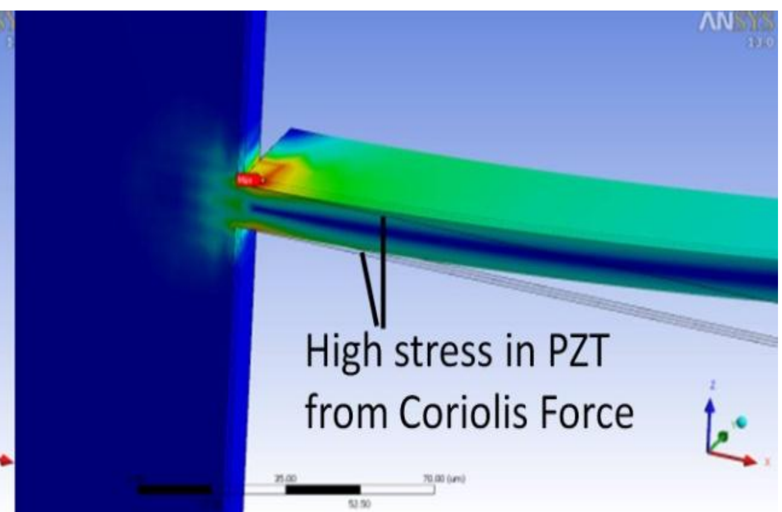
Drive



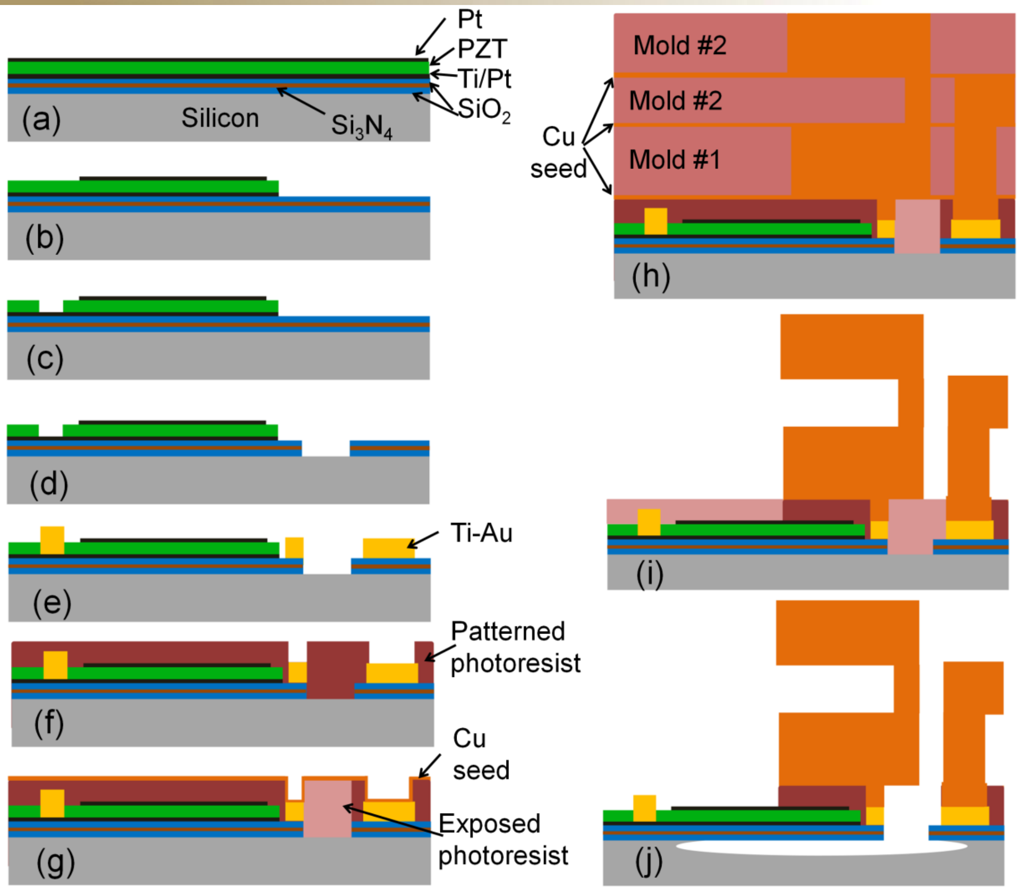


Sense

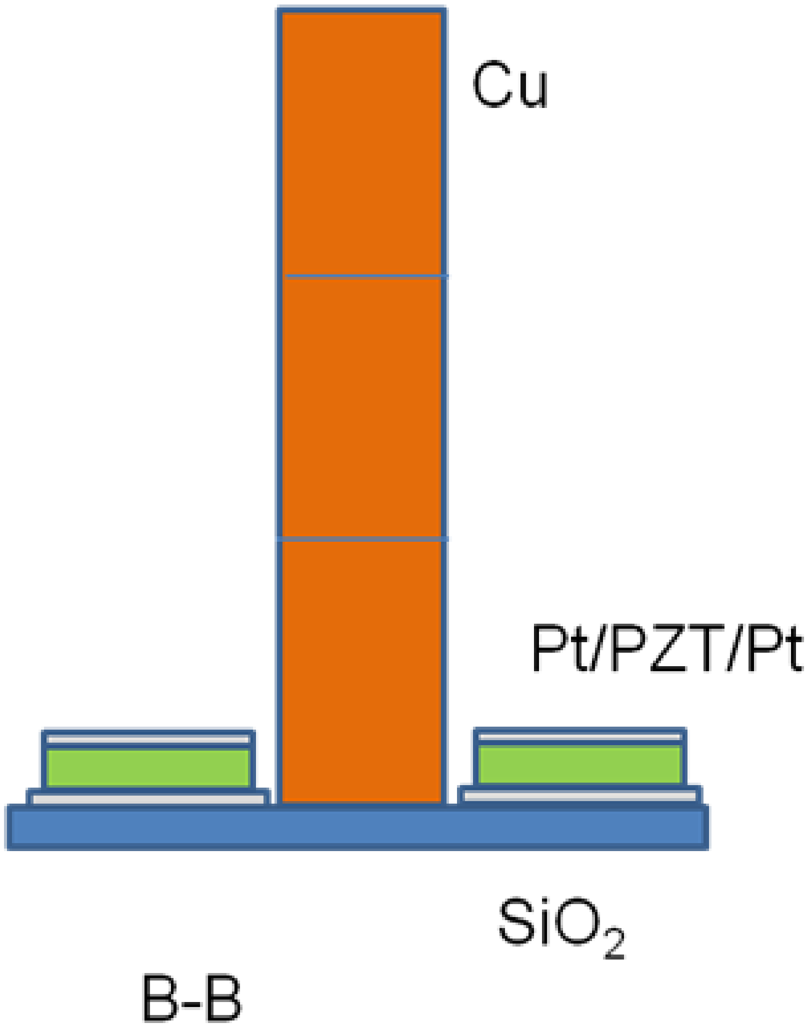




Cu PZT MEMS Fabrication Process



Material	Nominal Thickness
Cu	10-30 µm
Top Pt	1000A
PZT	1 µm
Bottom Pt	1000A
SiO_2	2 µm



Collaboration with Chris Meyer (ARL)

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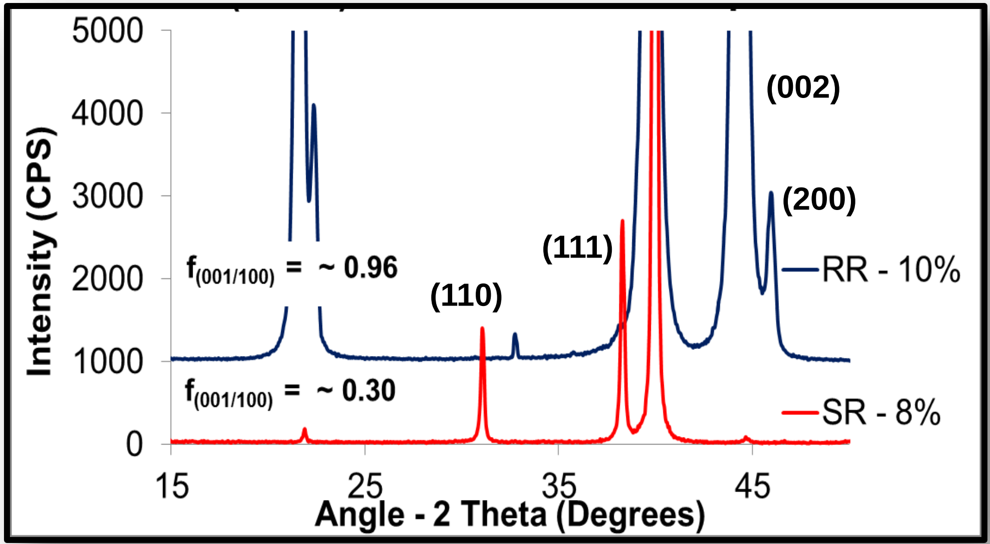
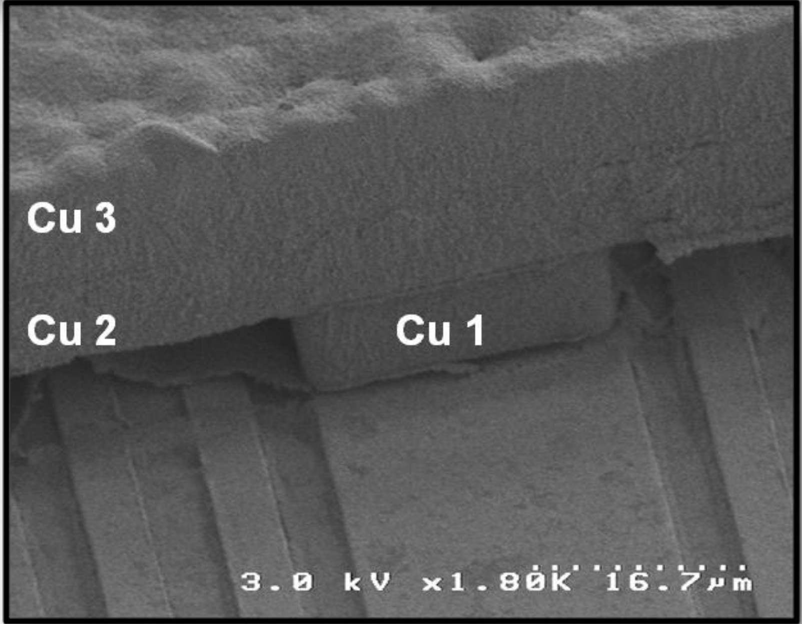
Fabrication Specifics

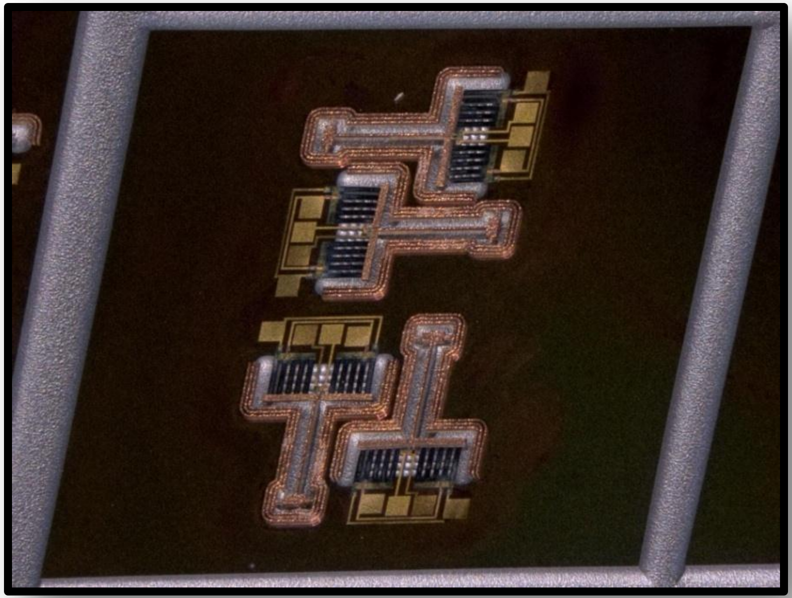
- PZT (52/48) thin films
  - Deposited by chemical solution deposition with 10% Pb excess
  - Pt template (111) with a FWHM of 2 deg
  - (001) PZT with a Lotgering Factor > 0.95
- Pt & PZT Patterning → Ion-mill configured with SIMS endpoint detection
- Multilayer Cu Process → 3 layers
  - Electroplated Cu
  - Photoresist Molds
  - Wet release process for molds
- Final Release
  - Isotropic XeF_2 etch of exposed Si

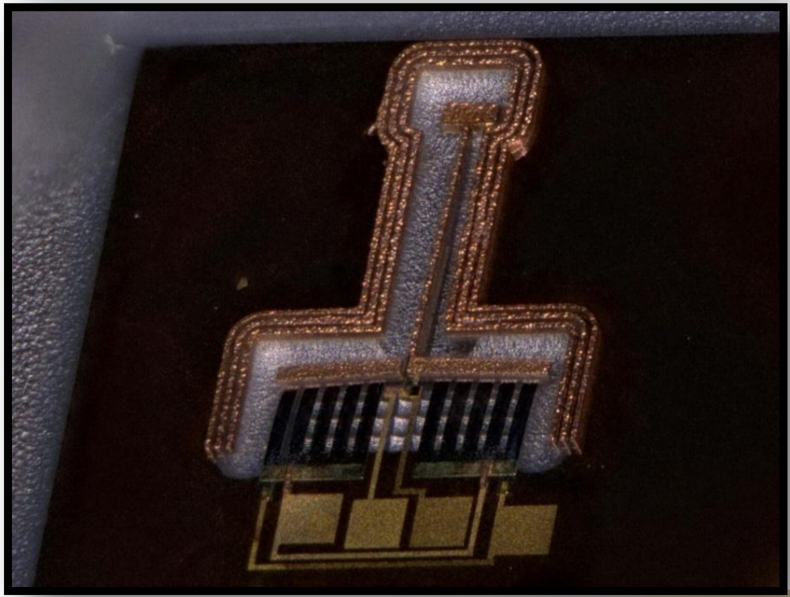




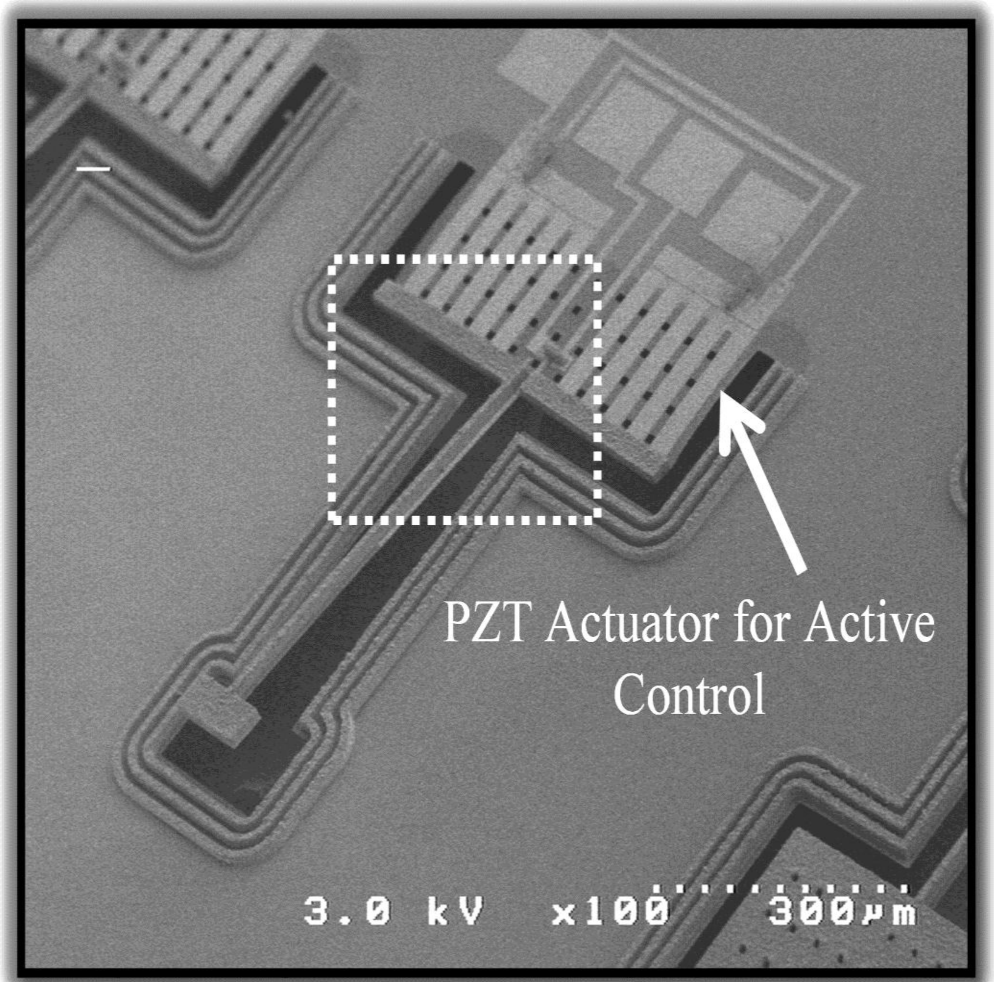
Results: MEMS Fabrication

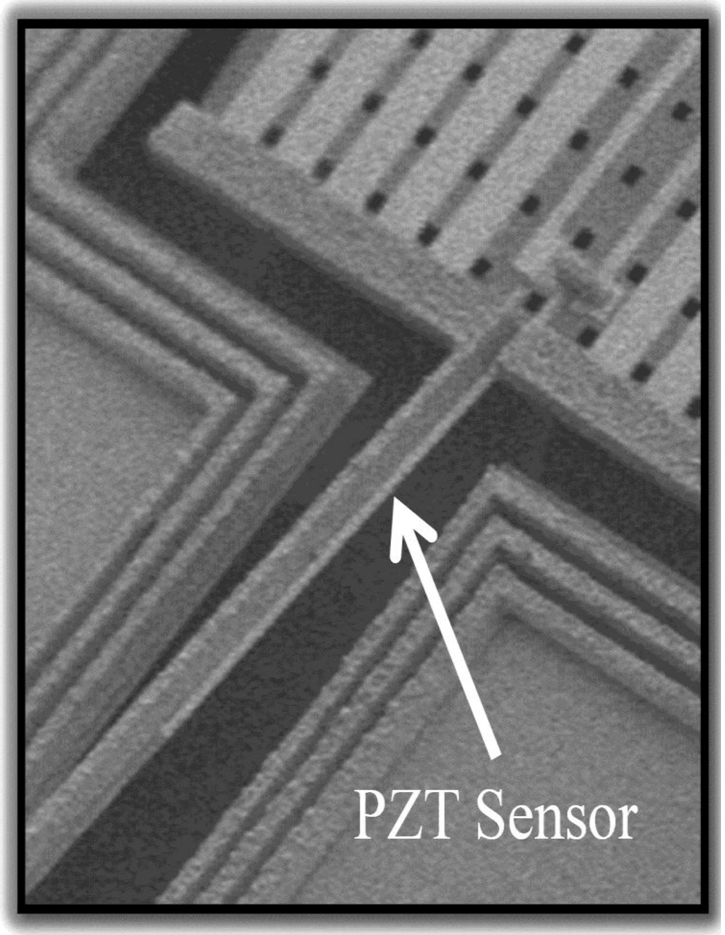
- Length & Size Variances
- Individual Devices
- 2-axis sensing





Actuation and Sensing





SEM of a PZT-based MEMS haltere actuator and sensor

MEMS Device Testing

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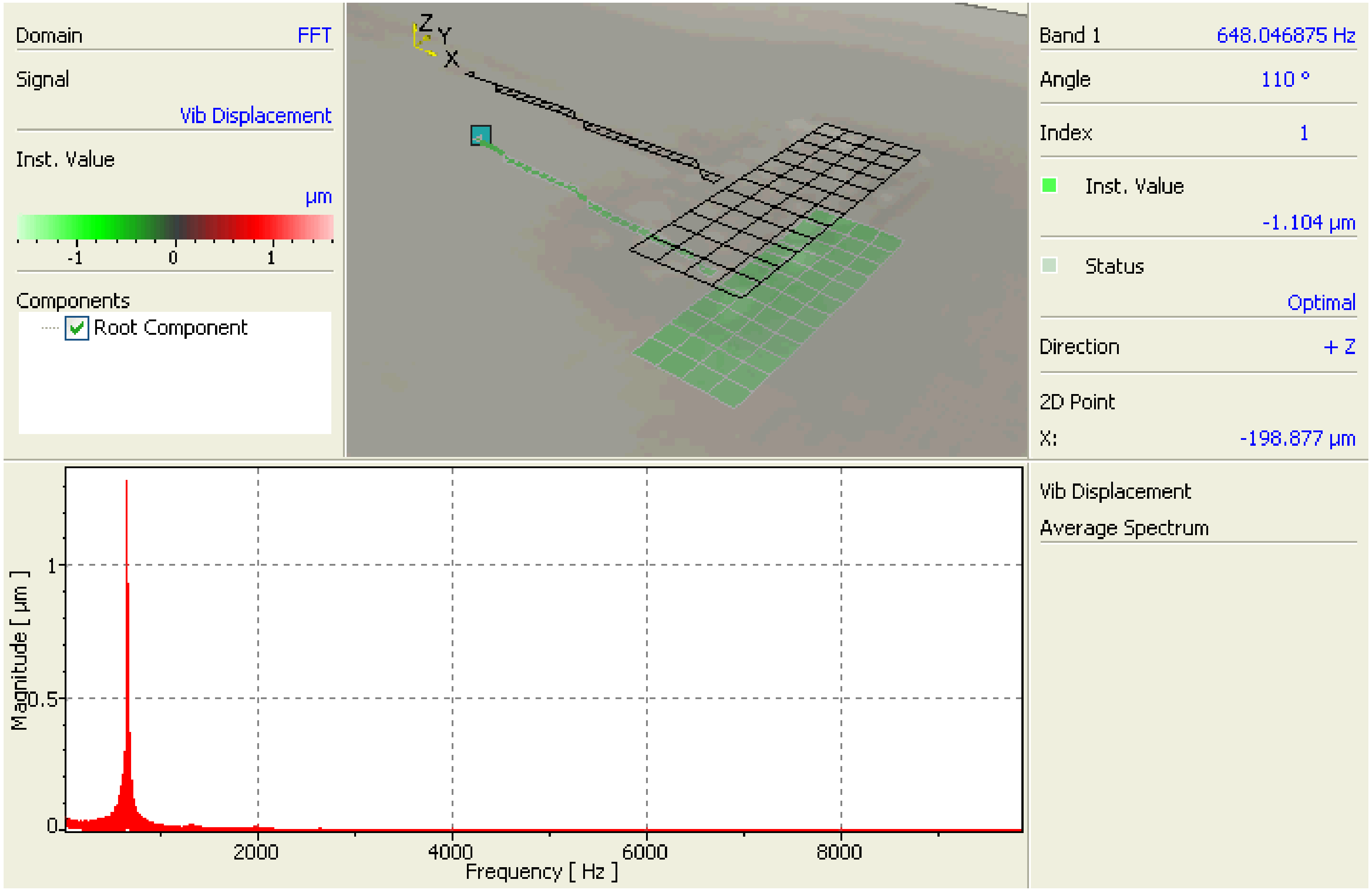
Laser Doppler Vibrometer Testing



LDV Data

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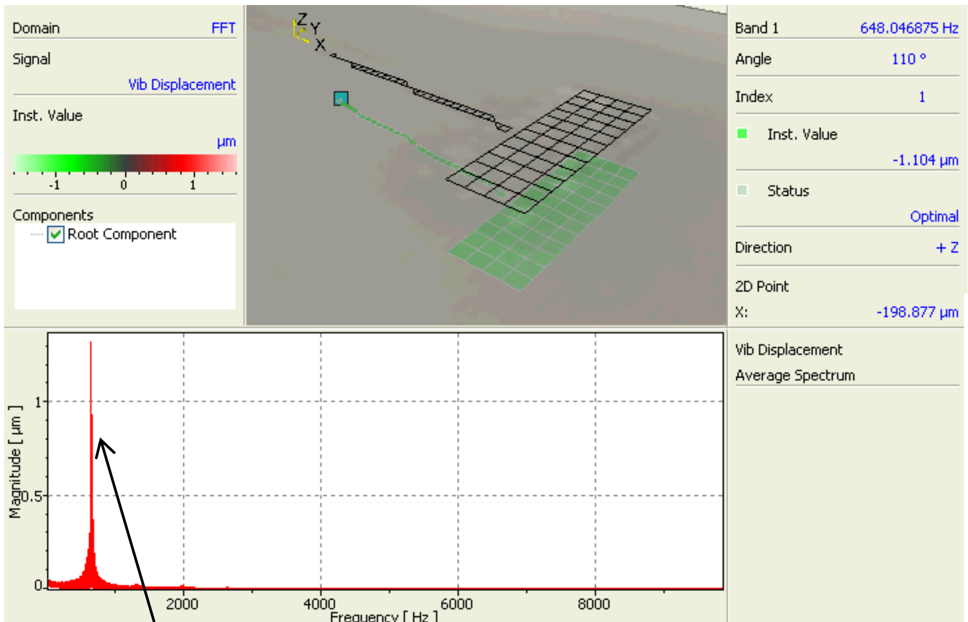
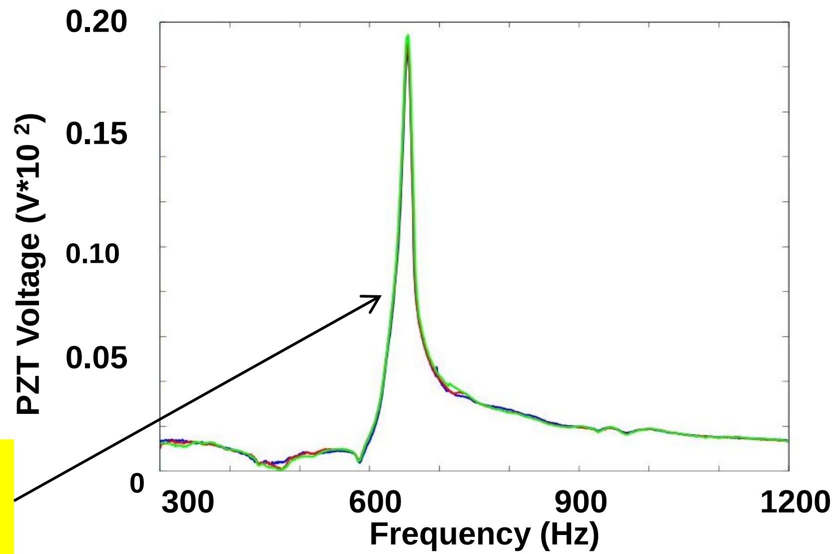
LDV and Shaker Testing

Frequency response of the beams was measured on both Laser Doppler Vibrometer and a shaker table.



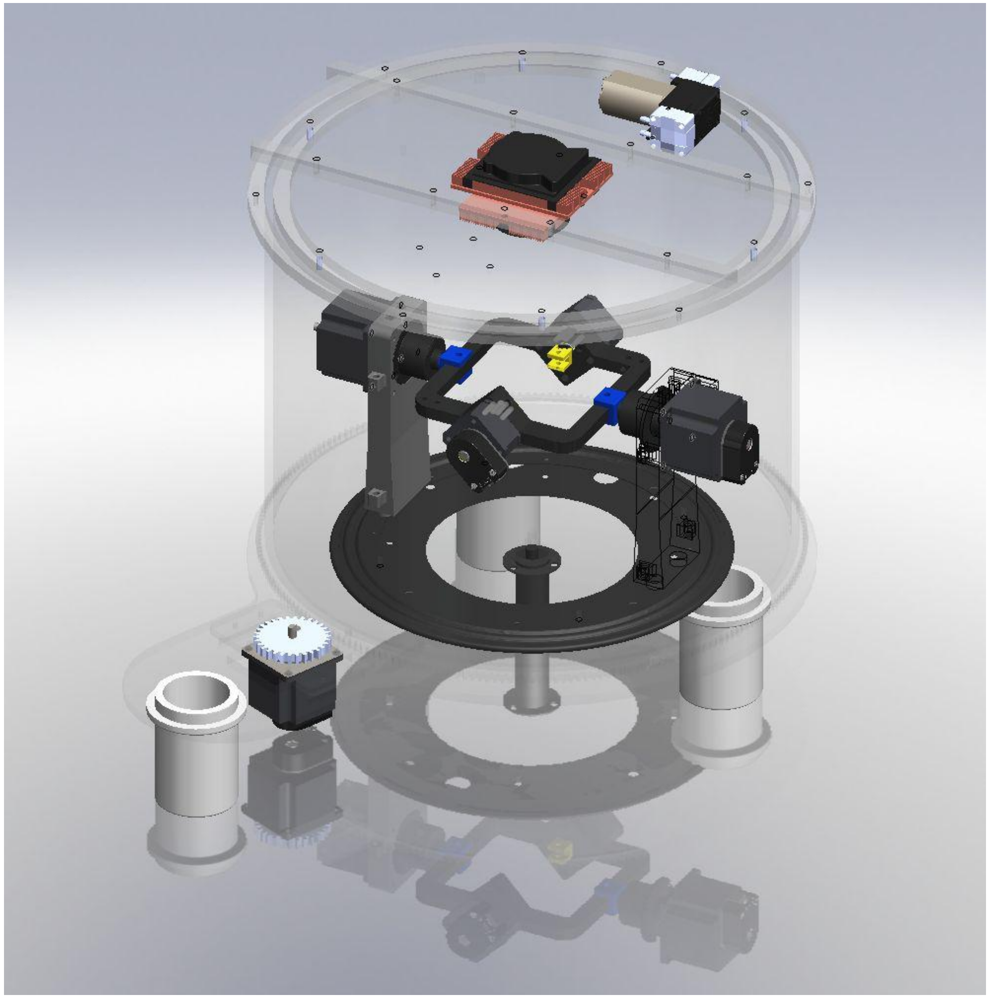
LDV Data

Amplified (100x) signal on drive PZT actuator when excited by external shaker



Both show the same fundamental resonance at 648Hz

Angular Rate Testing



- 3-Axis angular rate table, design and fabrication by J. Shumaker (ARL -VTD)
- Haltere circuit is sensitive to
  - Drive Motor Noise
  - Slip Rings
  - Unshielded Wiring
- Initial qualitative results indicate that the sensor element detects rotation
- New circuit pending to quantify rate sensitivity.

PiezoMEMS Thinfilm Ultrasonic Traveling Wave Motors

University of Maryland

Approved for Public Release

Traveling Wave Ultrasonic Motors

Macro Traveling Wave USM Advantages:

- High torque at low speed
- Low power
- No gearing required
- Zero backlash
- Holding torque with zero standby power
- Compact & few moving parts
- Unaffected by electromagnetic interference

– Commercially in DSLR camera auto focus lenses

– Shinsei, K. Uchino, A.V. Carazo et al.

MEMS Thin-Film USM

•Reduced size (<1mm³)

•Traveling wave style USM previously shown only at >1cm scale

•Flat profile-surface mount

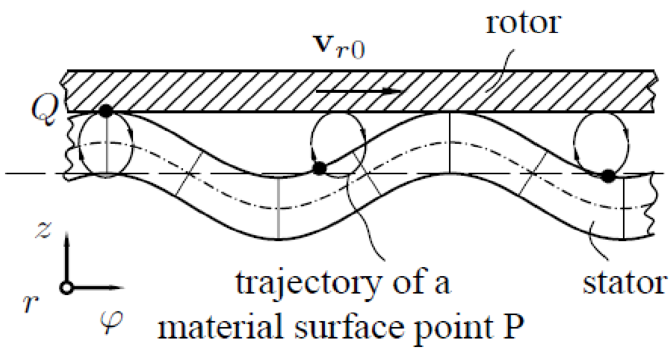
•Low voltage operation (0-10V)

•Wafer level fabrication and packaging

•No assembly required

•Batch production

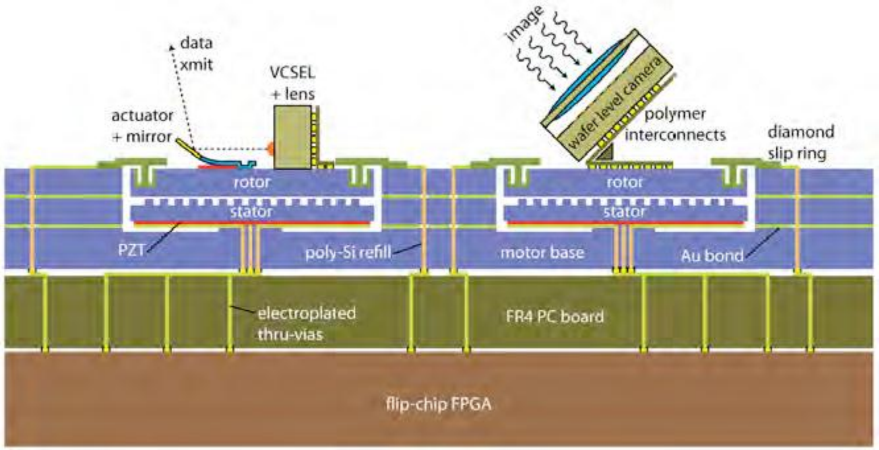
•Lower cost with volume

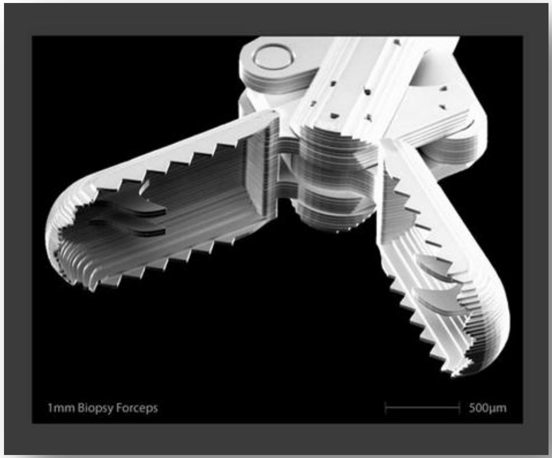


T. Sattel, "Dynamics of Ultrasonic Motors", Doctoral Thesis, Technische Universität Darmstadt, Germany, 2002.

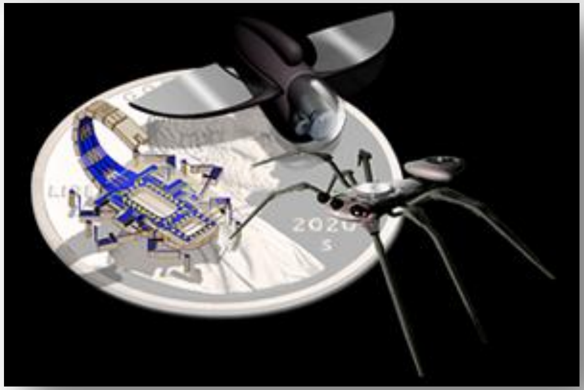
Applications

- Small scale robotics
- Steering directional sensors and optical devices
- Information Tethered Micro Automated Rotating Stages (DARPA)
- Medical MEMS





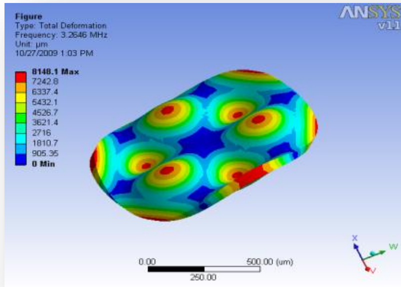
“Microfabrica SEM Image Gallery”, *Microfabrica – MICA Freeform,* http://www.microfabrica.com/gallery.html, accessed on 7/22/11



“Micro Autonomous Systems and Technology (MAST)”, *Micro Autonomous Systems and Technology (MAST) US Army Research Laboratory,* http://www.arl.army.mil/www/default.cfm?page=332, accessed on 5/26/11

How It Works

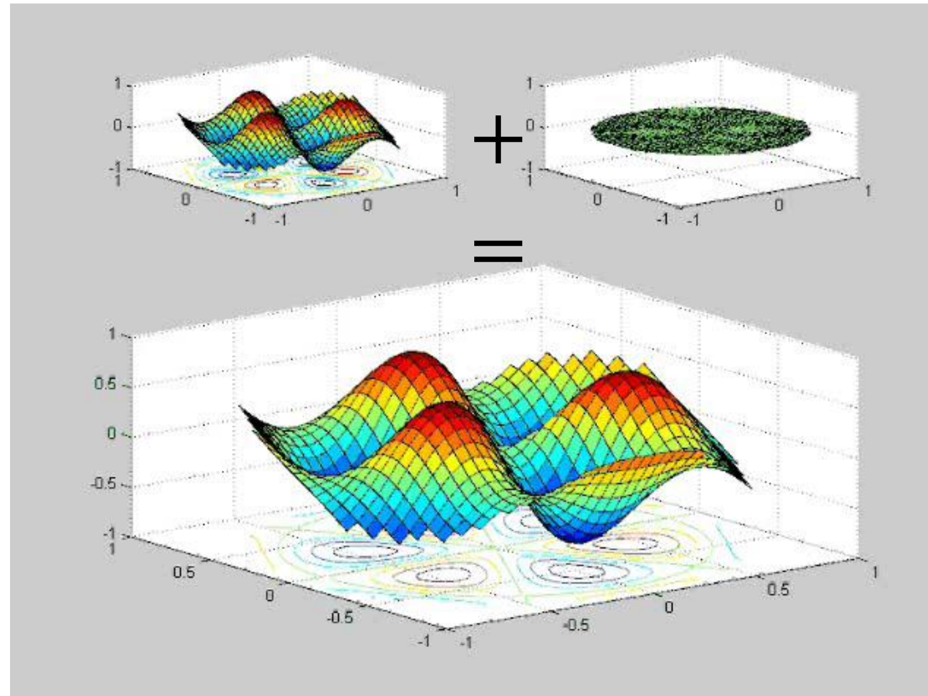
B_{13} mode at 250kHz in 3mm stator

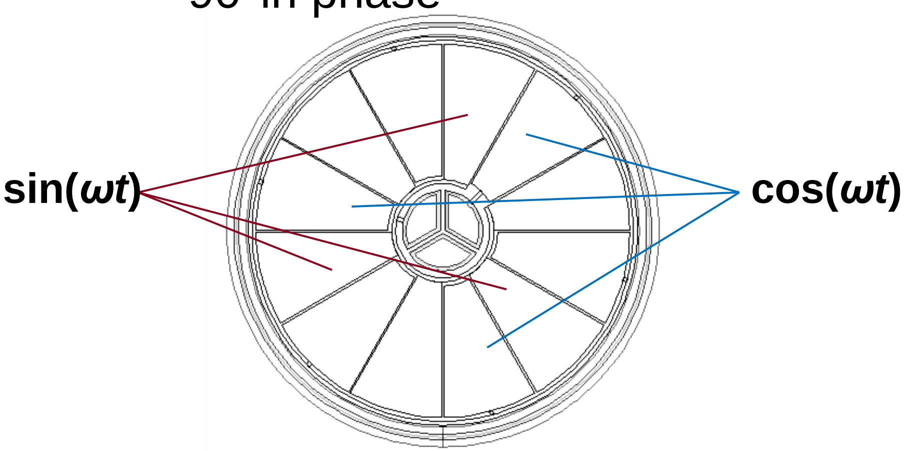


- Combining standing waves apart in space and offset in phase:

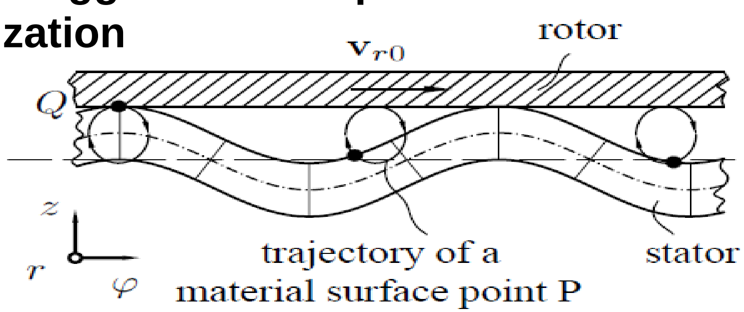
$$\cos(n\theta)\cos(\omega t)+\sin(n\theta)\sin(\omega t)=\cos(n\theta-\omega t)$$

- Electrodes separated by:
  - ¼ wavelength in space
  - 90°in phase





Note: Exaggerated z displacements for visualization



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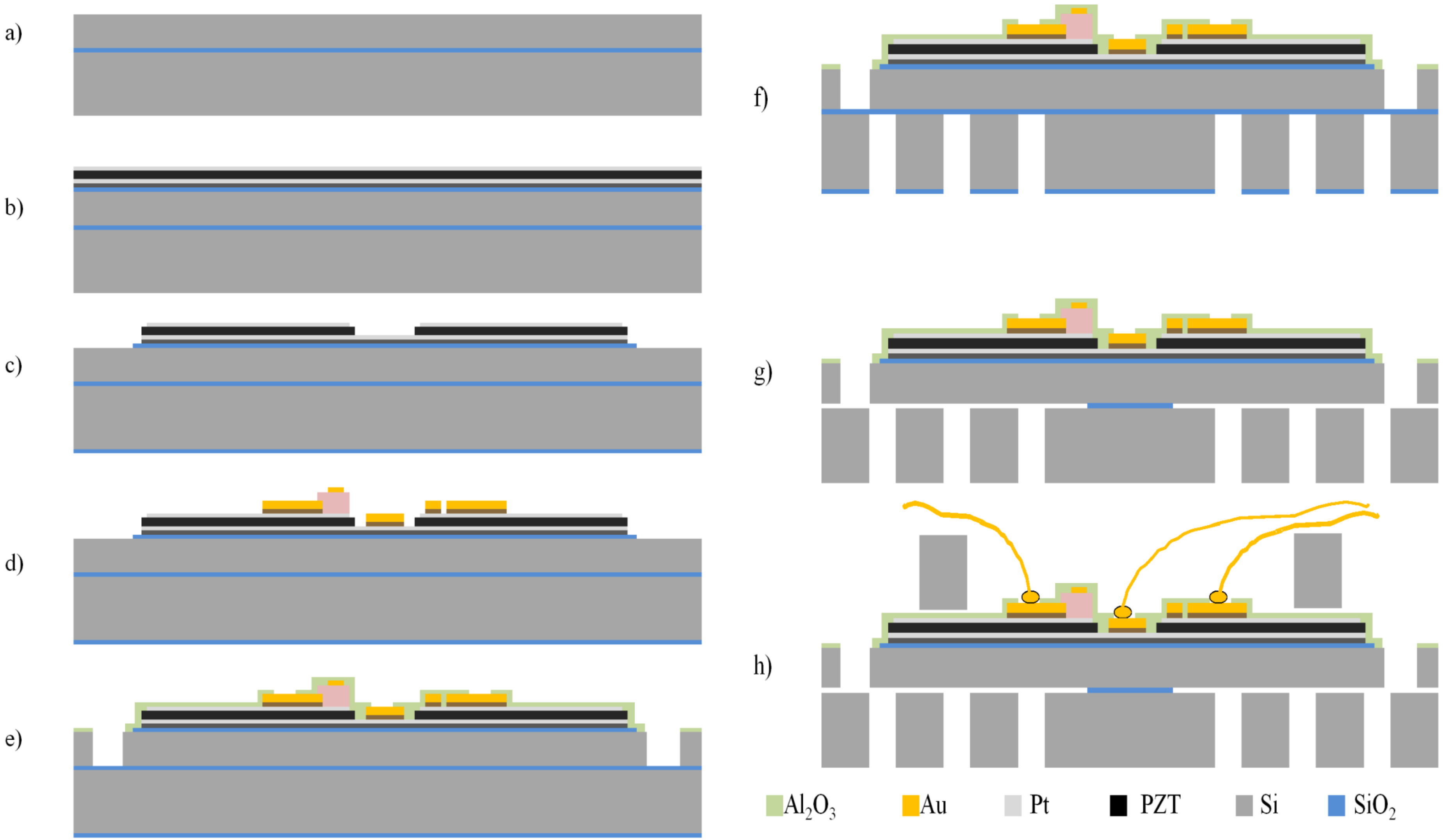
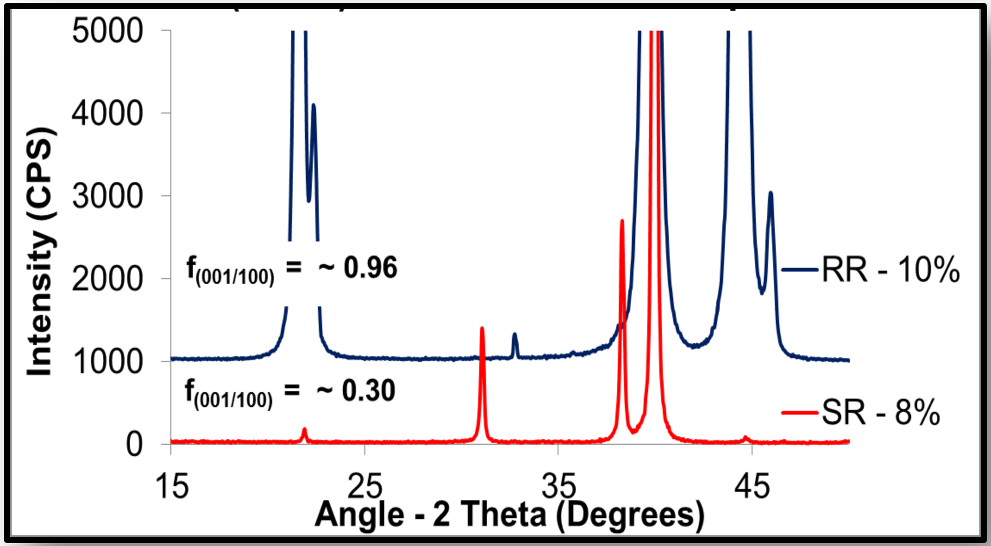
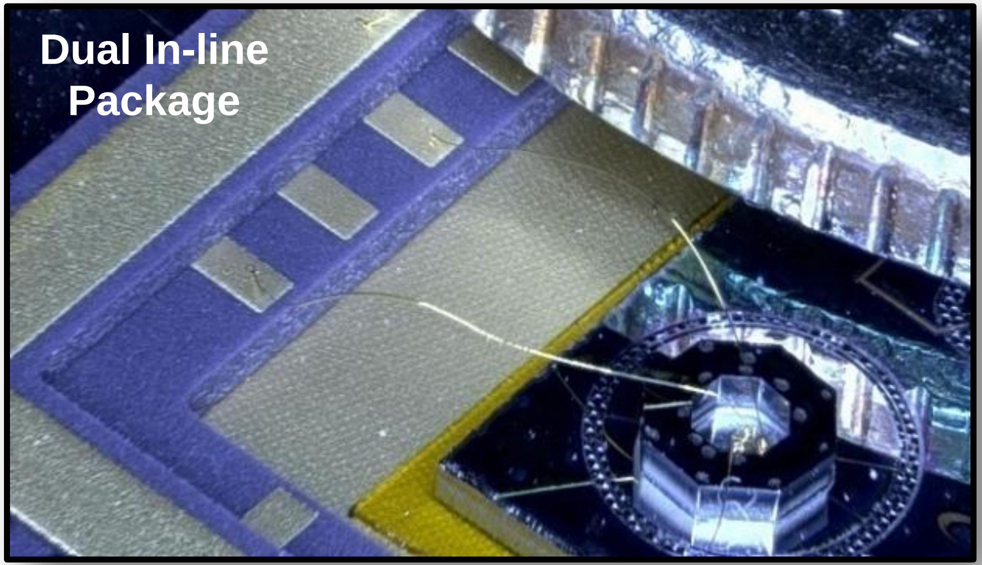
Fabrication Process



Fabrication Specifics

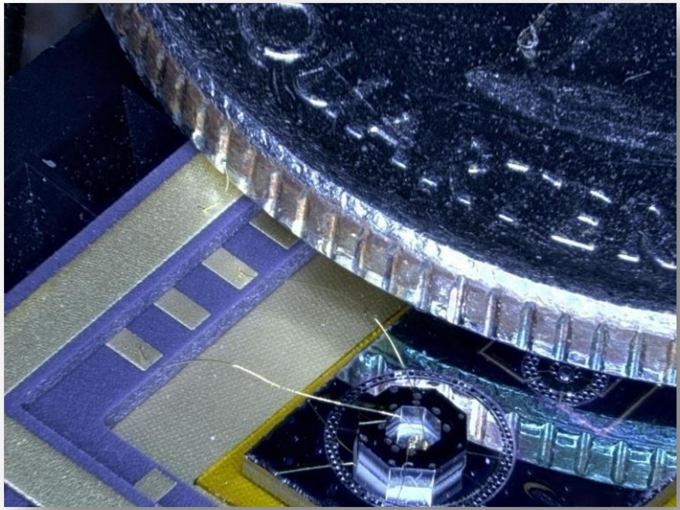
- PZT (52/48) thin films
  - Deposited by chemical solution deposition with 10% Pb excess
  - Pt template (111) with a FWHM of 2 deg
  - (001) PZT with a Lotgering Factor > 0.95
- Pt & PZT Patterning → Ion-mill configured with SIMS endpoint detection
- ALD Al_2O_3 added to provide etch barrier for Vapor HF
- Final Release
  - Backside DRIE of Si
  - Die separation
  - Wirebonding in DIP
  - Vapor HF release of Buried Ox



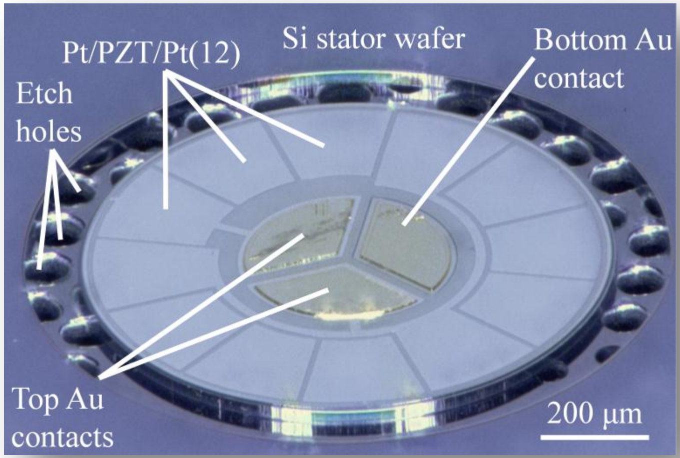


USM

Modeled/Experimental Motor Parameters	
Parameter	**Value**
Voltage input	0-10V
Stator diameter	0.5 - 3 mm
Stator height	30 µm
PZT thickness	1 µm
Eigenfrequency (B13 mode) 3mm	240 kHz
Max output speed	2400 RPM
Maximum output (stall) torque	3.5 N mm
Input power @ 1 Hz	8 mW

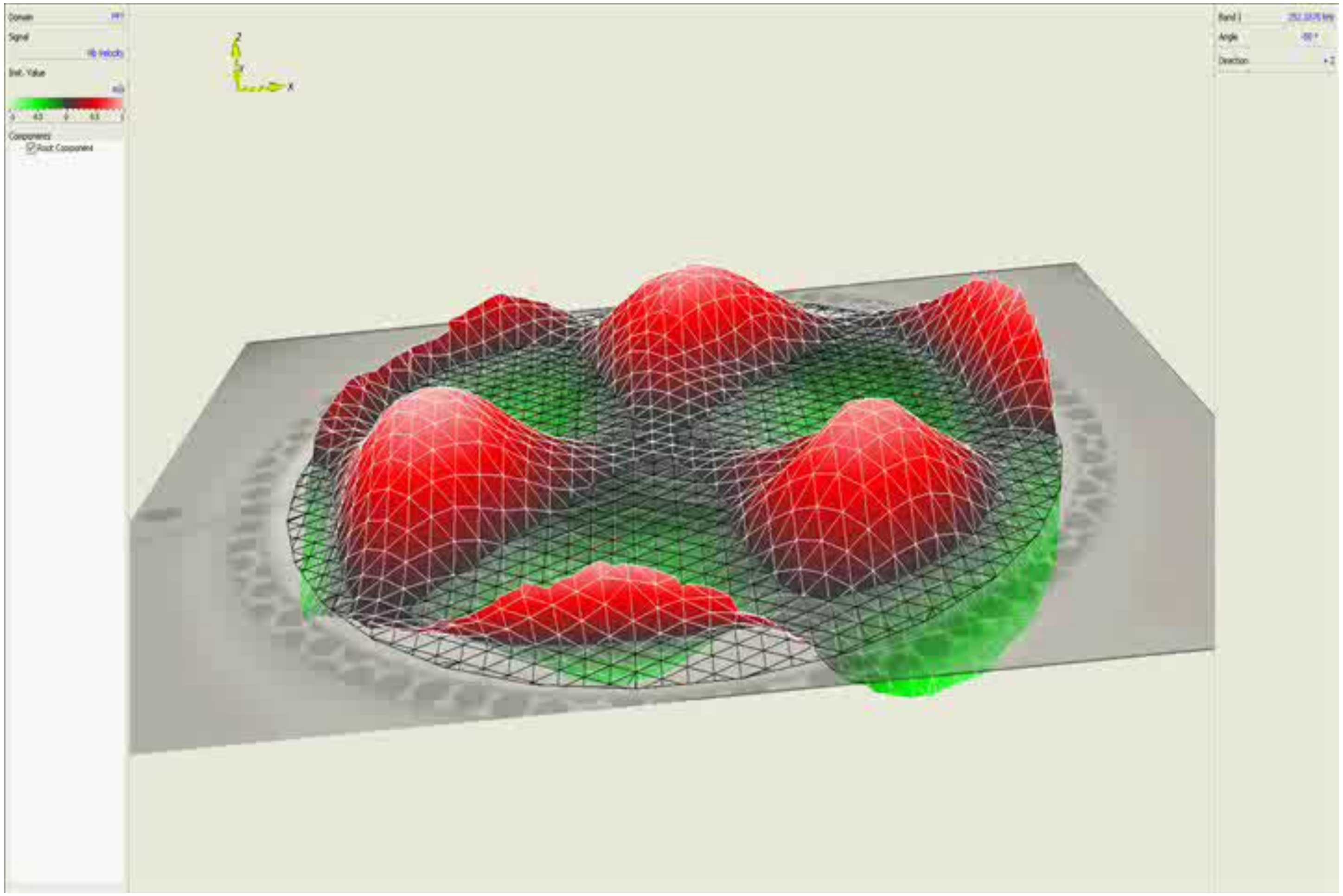


Proof-of-concept motor



Center fixed stator disc

Laser Doppler Vibrometer



Characterized on a Polytec LDV
Traveling wave peaks travel 80kHz for 3mm stator @ 240kHz resonant excitation

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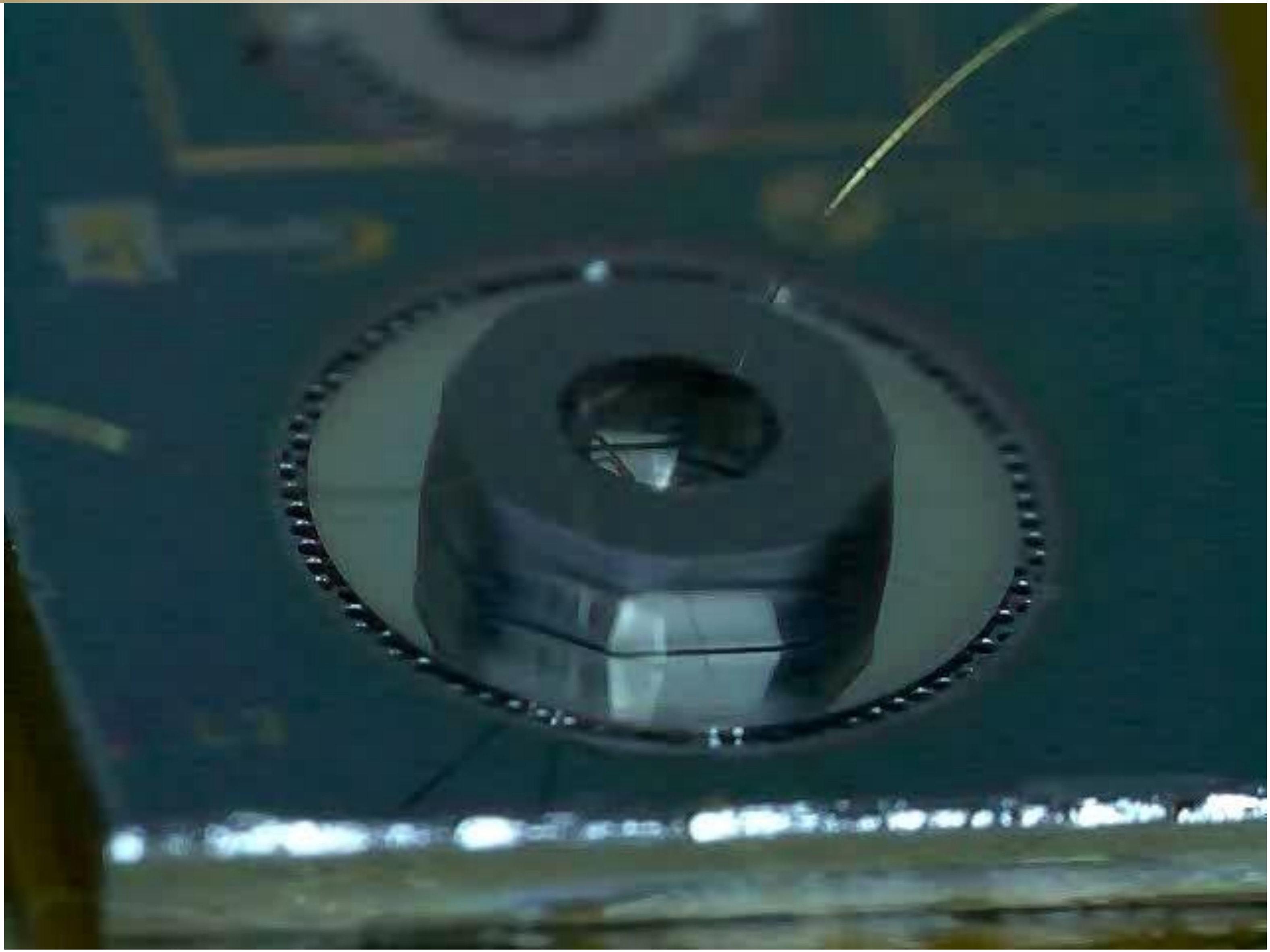
2mm Rotor on 3mm Stator
1000 FPS



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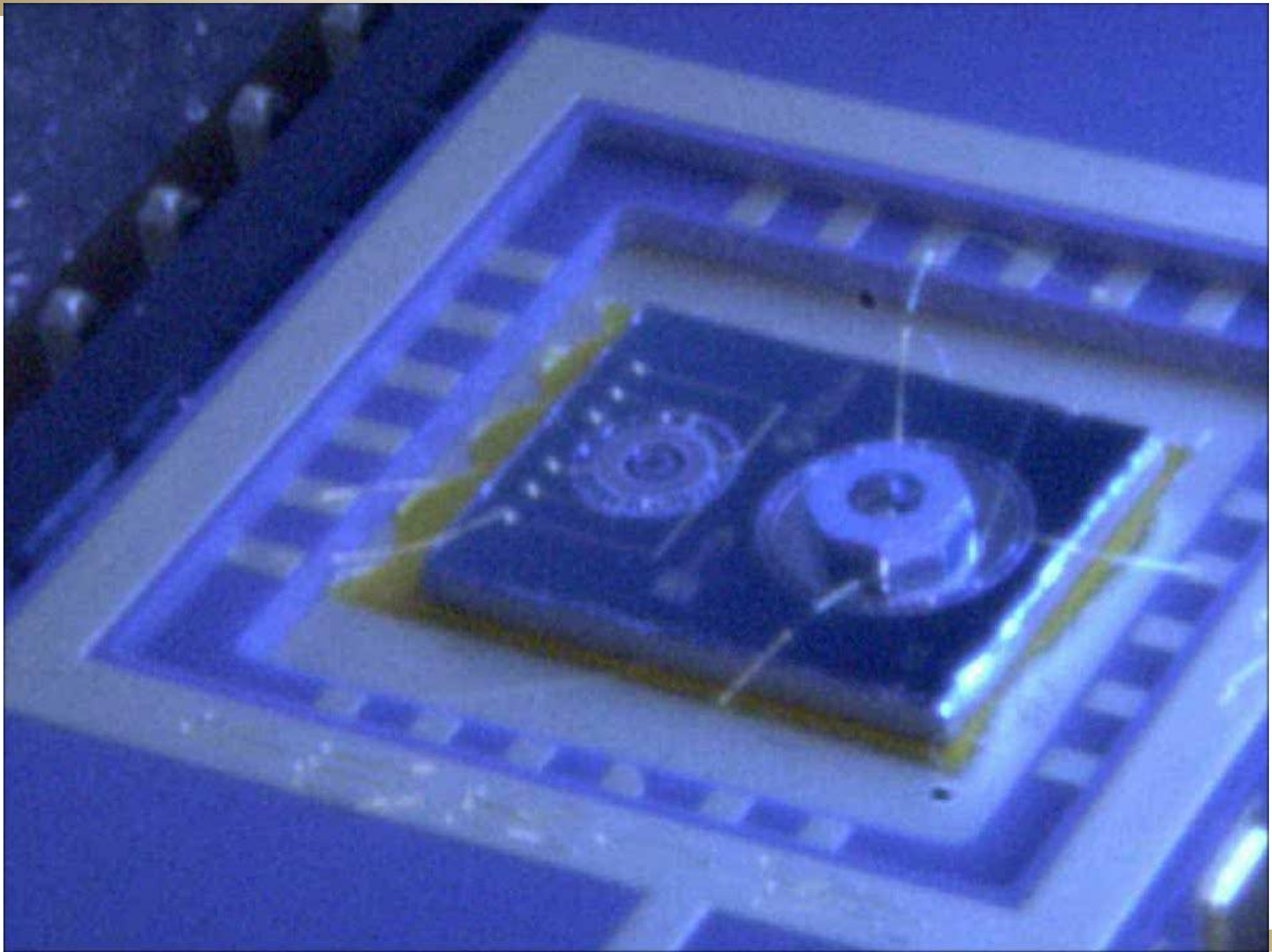
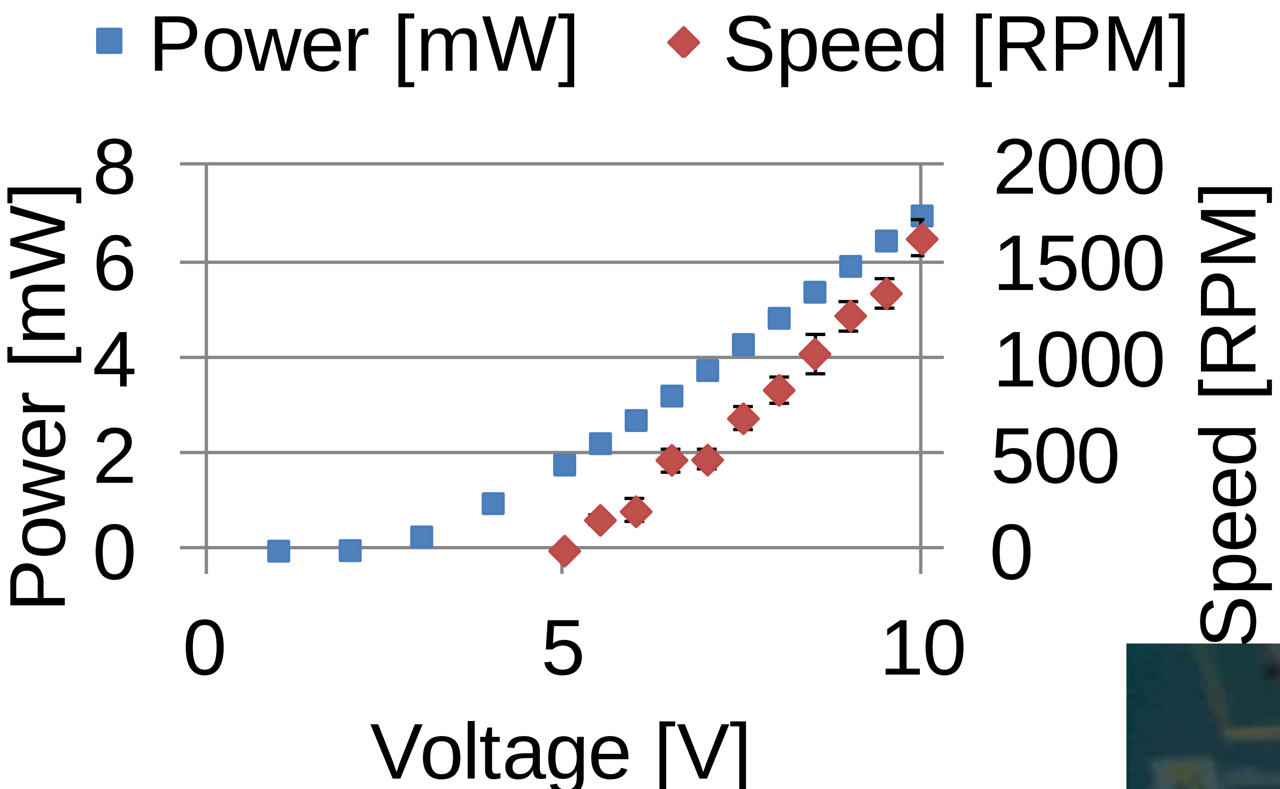
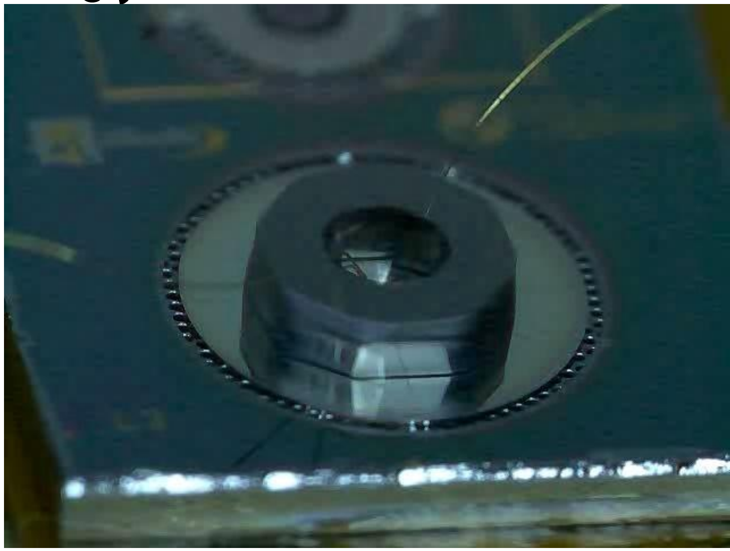
Same Motor in Real-time



Motor Performance



- Rotor motion captured using high speed camera
- 2mm rotor on 3 mm stator
- Speed is linear with voltage
- Bi-directional motion with phase change



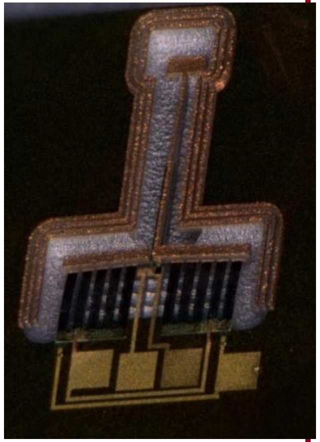
Conclusions & Future Work

PiezoMEMS Haltere

- PiezoMEMS Haltere was designed to detect angular rate.
- Individual, coupled, and arrayed halteres were fabricated in the MEMS cleanroom at ARL-ALC.
- Drive motion demonstrated.
- Initial materials, composite, and dynamic testing is underway on the completed sensors.

Future work:

- Reduce amplifier noise
- Quantify rate sensitivity on rotating platform.
- Iterate design for greater rate sensitivity.



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Traveling Wave Motor

•Proof-of-concept motor demonstrated and characterized

•Traveling wave stator motion measured and characterized

•Motor performance model developed.

Future Work:

•Stator Tooth Integration

- Electroplating
- Aerosol jet deposition

- Wafer scale rotor integration and clamping mechanism
- Frictional material characterization
- FPGA control or ASIC