Large Stroke Cryogenic Single Crystal Piezoactuators for Space Applications

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TRS Technologies, Inc.

Acknowledgement:

NASA Phase II Contract No: NNM07AA24C,

Phil Stahl, Bill Jones (MSFC)

NASA Phase I Contract No: NNL07AA94P, Phase II Contract No: NNL06AA09C

William B. Cook (LaRC)

NASA Phase I Contract no: NNC07QA63P

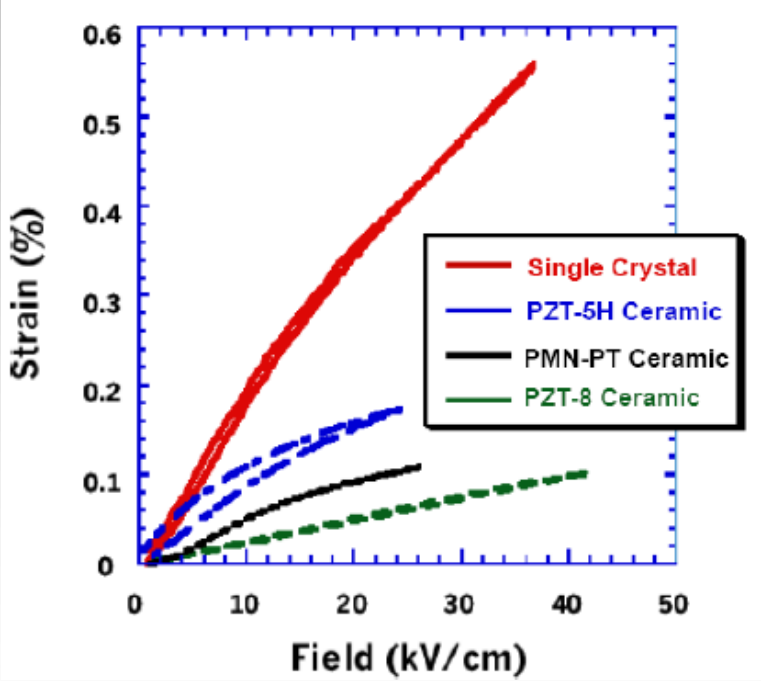
Stewart Sherrit (JPL)

Outline

- Hybrid Electrostatic/Flextensional Deformable Membrane Mirror for Lightweight, Large Aperture and Cryogenic Space Telescopes (Phase II Contract No: NNM07AA24C)
- Cryogenic Stepping Piezomotor for Large Torque, Precise Rotary Motion Control in Passive Optics (Phase I Contract No: NNL07AA94P)
- Cryogenic Piezo Actuators for Lightweight, Large Aperture, Deployable Membrane Mirrors (Phase I Contract No: NNC07QA63P)
- Advanced Electroactive Single Crystal and Polymer Actuators for Passive Optics (Phase II Contract No: NNL06AA09C)

Single Crystal Piezoelectrics

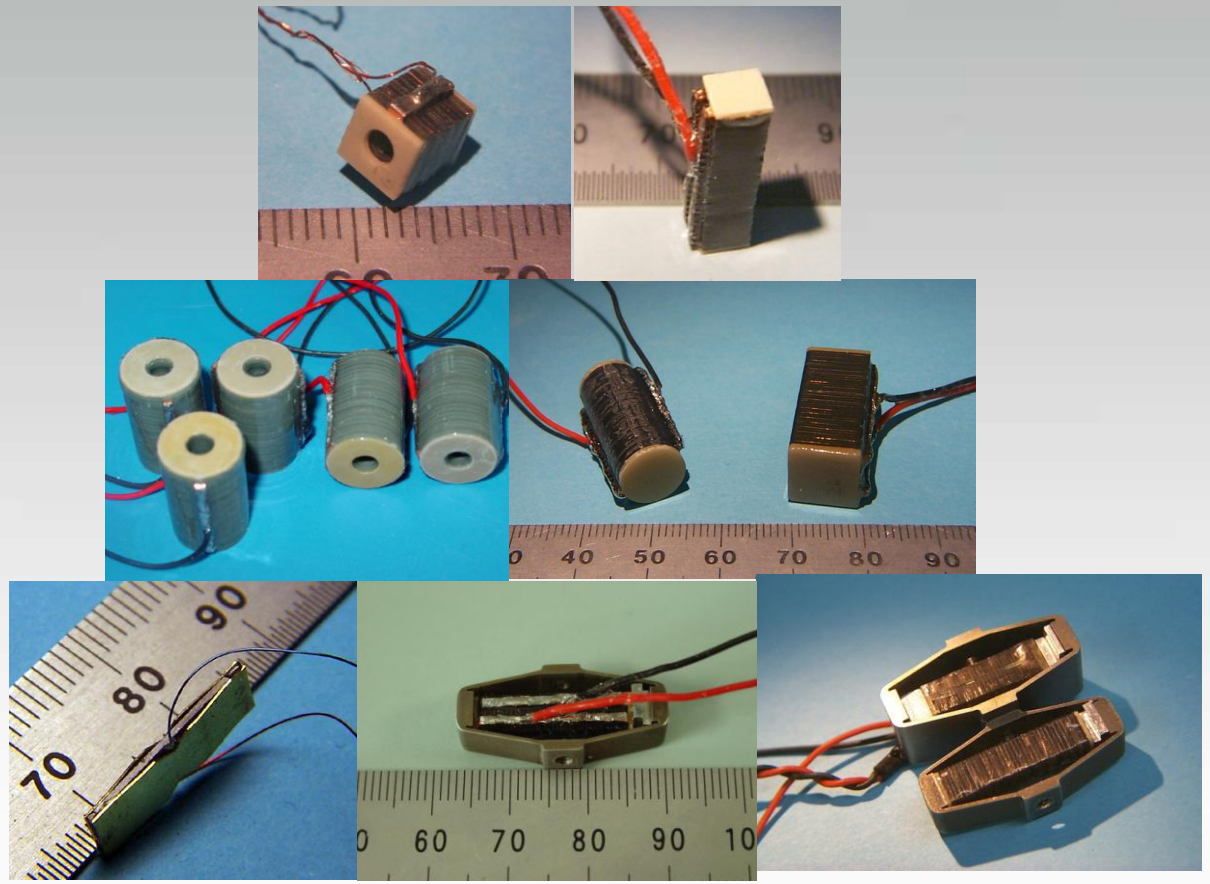
- High electromechanical coupling
- Large piezoelectric coefficient (d_{33}~2000 pC/N)
- Low hysteresis
- Excellent cryogenic properties



Piezoelectric Actuators

- Stack Actuator
- In-plane actuator ("31", IDE, Shear)
- Unimorph/Bimorph
- Flextensional (moonie, cymbal, Thunder, etc.)
- HYBAS
- Polymer
- Piezomotors (ultrasonic and inertial)
- Others (compliant amplification mechanism, etc.)

TRS Single Crystal Actuators



Hybrid Electrostatic/Flextensional Deformable Membrane Mirror for Lightweight, Large Aperture and Cryogenic Space Telescopes

(Phase II Contract No: NNM07AA24C)

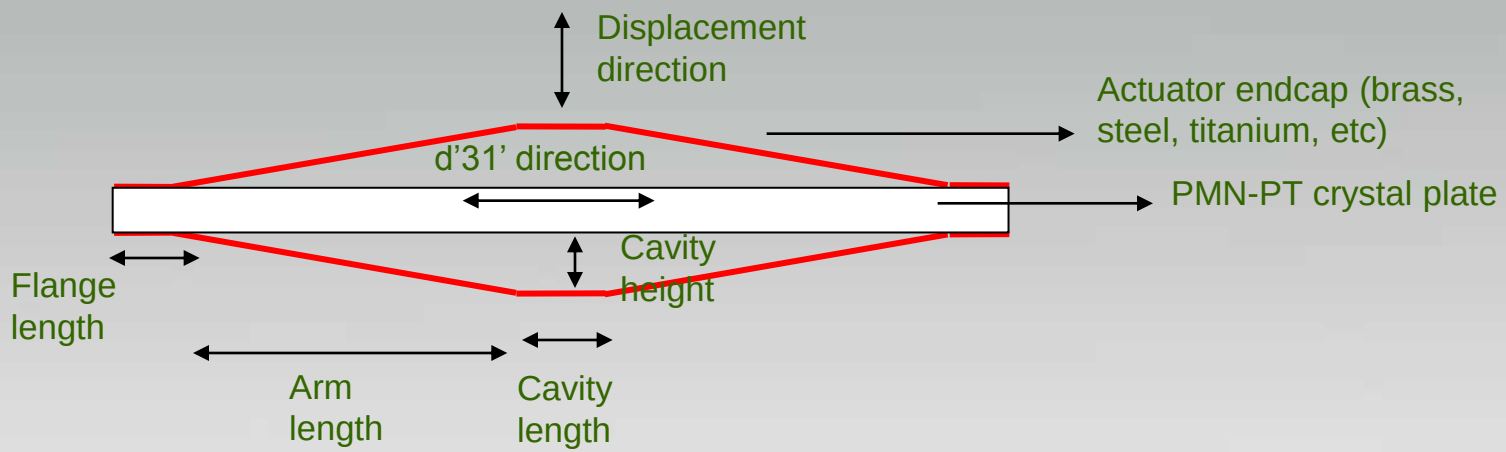
Program Managers: Bill Jones, Phil Stahl (MSFC)

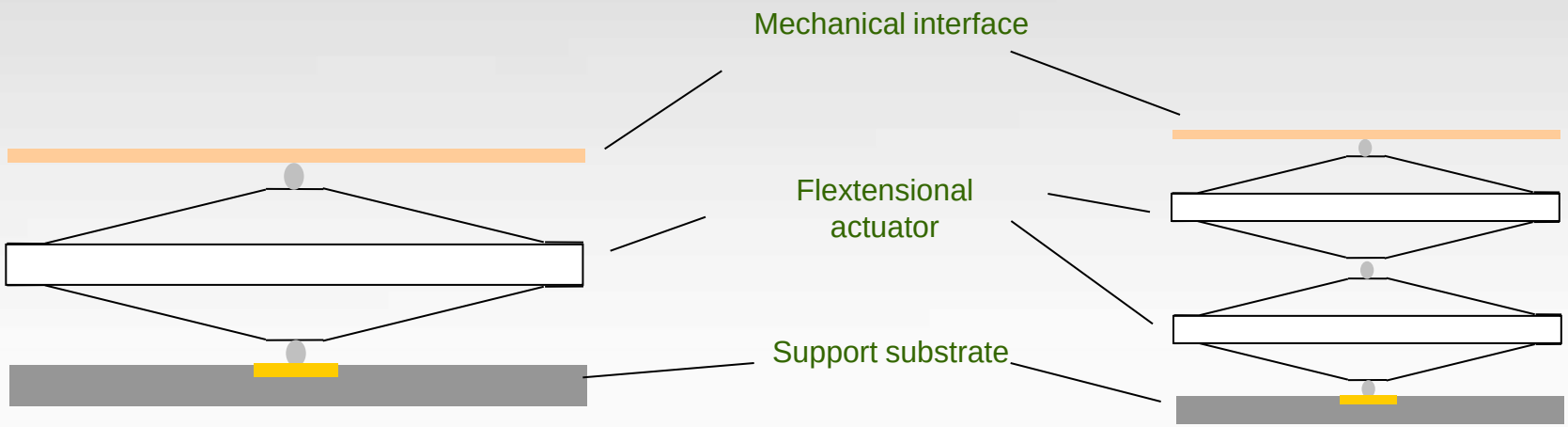
Phase II Goals

- Develop large stroke, large aperture, lightweight, low cost, scalable cryogenic deformable membrane mirror technology using advanced hybrid electrostatic/flextensional actuation;
- Space qualification tests for single crystal piezoelectric actuator;
- Demonstrate the hybrid electrostatic/flextensional membrane DM technology with a 0.25 meter diameter aperture with up to 61 channels of active figure control,
- Demonstrate the ability of the DM prototype to correct large wavefront errors.

Flextensional Actuator Prototyping

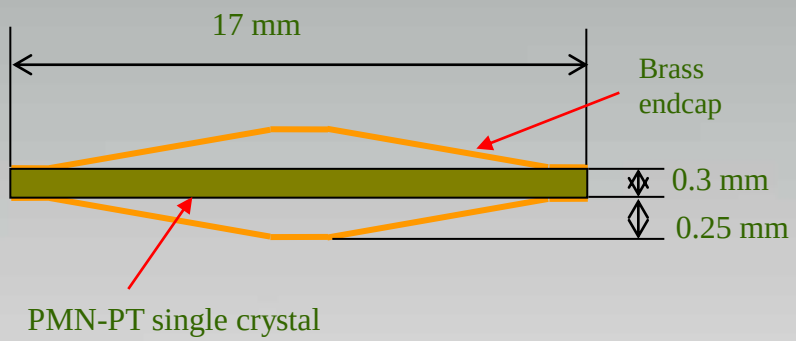
Single crystal flextensional actuator: Design variables

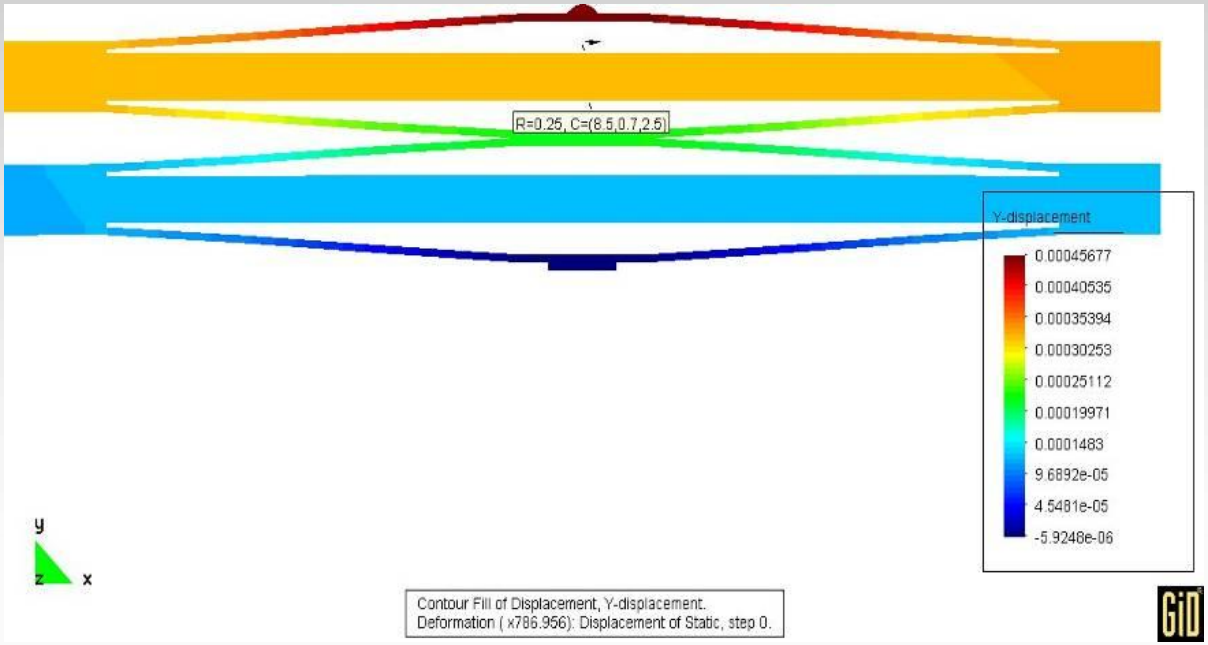




Single crystal flextensional actuator: Single stack and double stack design

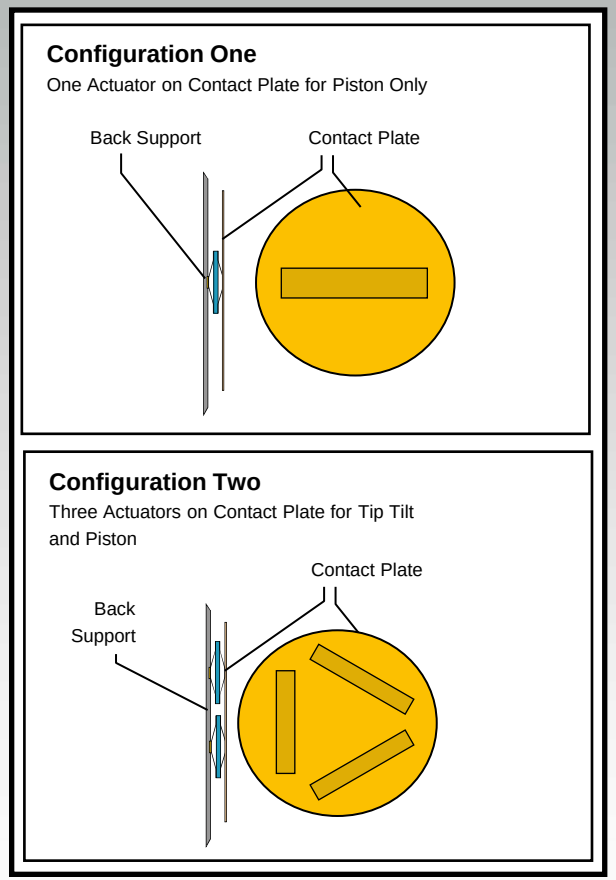
Atila FEM Modeling for Flextensional Actuator Design



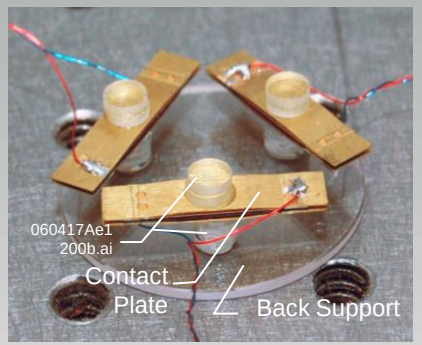


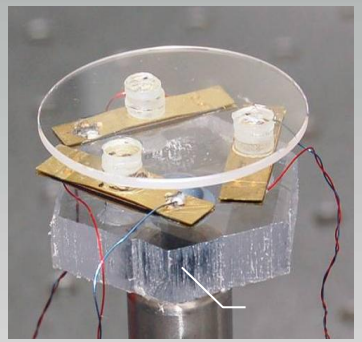
ATILA modeling of single crystal double stack flextensional actuator showing 456.77 micron displacement at 300 V (10 kV/cm)

Flextensional Actuators in Membrane Mirror Demonstration



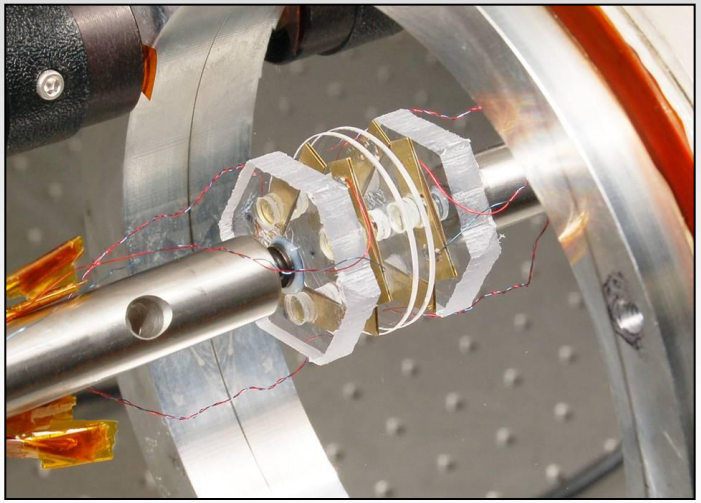
Two different configuration for integration of actuators





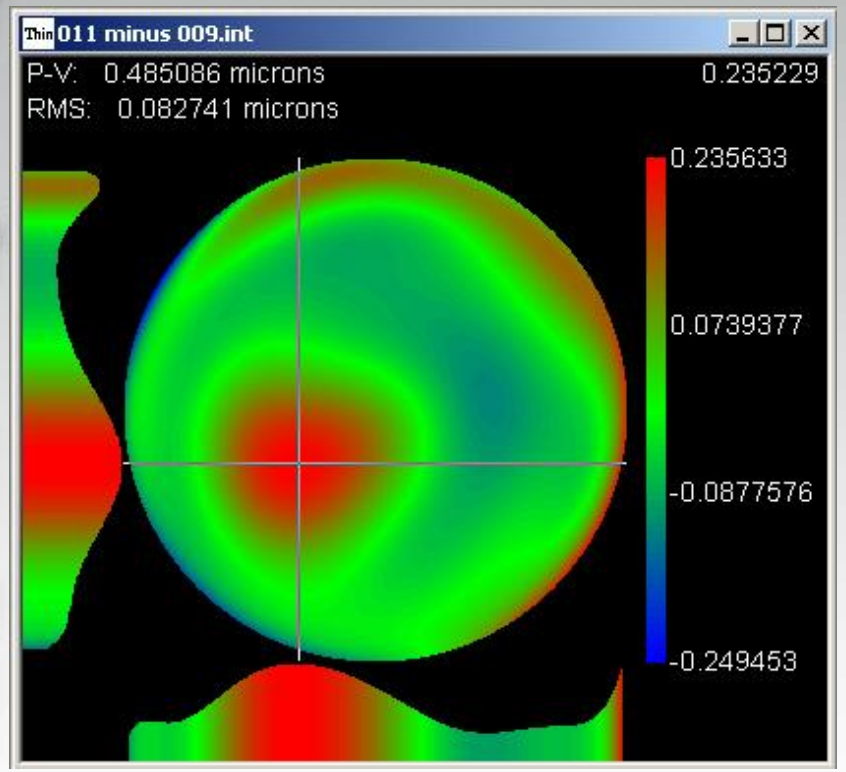
Three Actuator Configuration Prototype

Three Actuators on Contact Plate for Tip Tilt and Piston

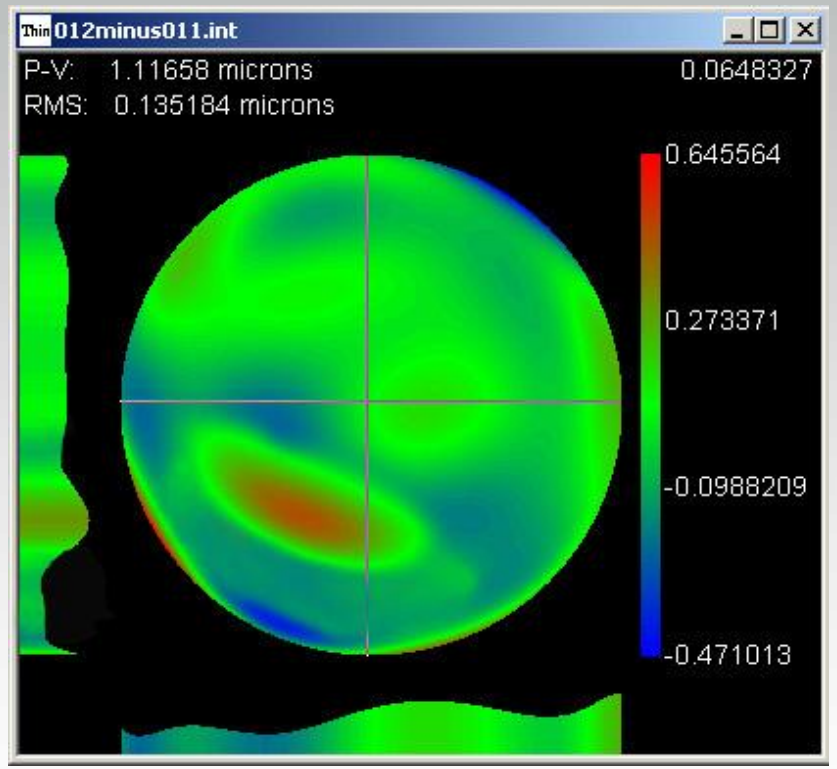


Three actuator configured contact plate in close proximity to membrane electrode

Actuator Displacement Influence Function



All 3 Flextensional Actuators @ 500V



2 Actuators @ 0V
1 Actuator @ 500V

Cryogenic Stepping Piezomotor for Large Torque, Precise Rotary Motion Control in Passive Optics

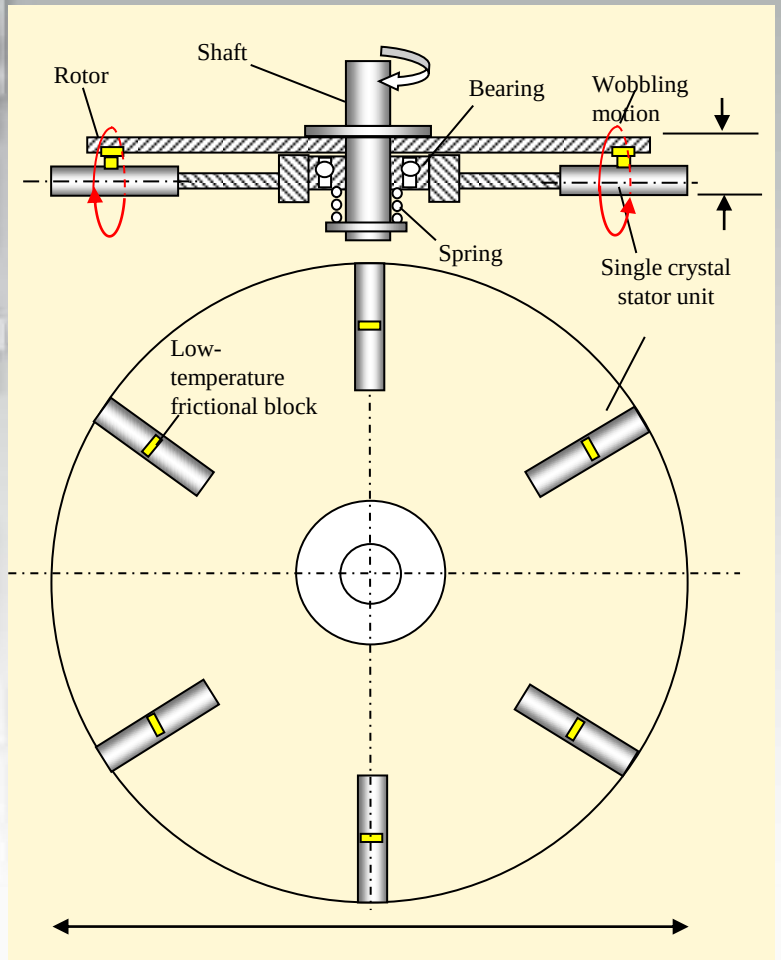
(Phase I Contract No: NNL07AA94P)

Program Manager: William B Cook, LaRC

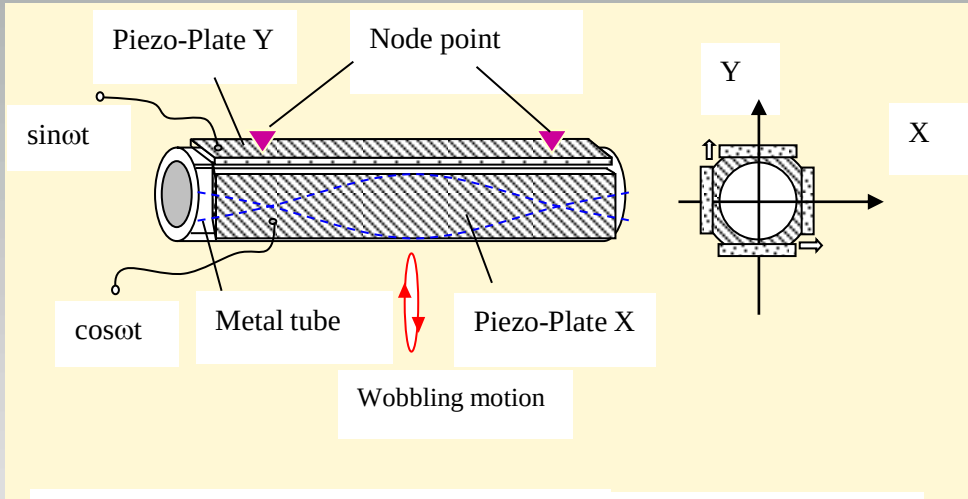
Phase I Goals

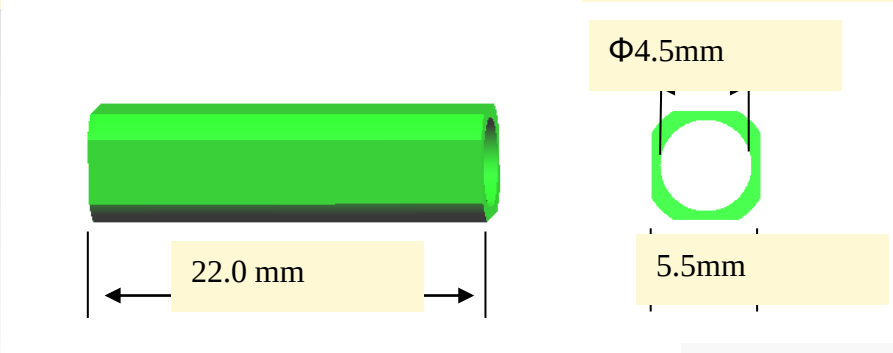
- To develop a low profile, lightweight stepping motor with high electromechanical coupling, high-torque output, and wide temperatures operation
- The major specifications of this motor were proposed as:
  - Maximum running torque: >1.44 kg-cm
  - Steps per revolution: 500
  - Operational speed: < 100 rpm;
  - Operating temperature range: 70-300 K
  - Total mass: < 250 gram;
  - Power consumption in stepping operation: <3-5W
- Both traveling wave piezomotors and wobbling mode motor designs were proposed to achieve the above goals.

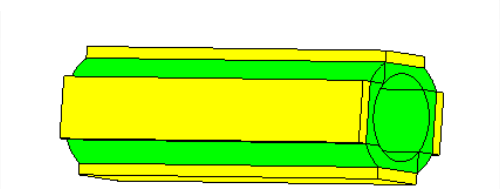
Single Crystal Wobbling Motor – Working Principle



Working principle of a 6-stator wobbling motor



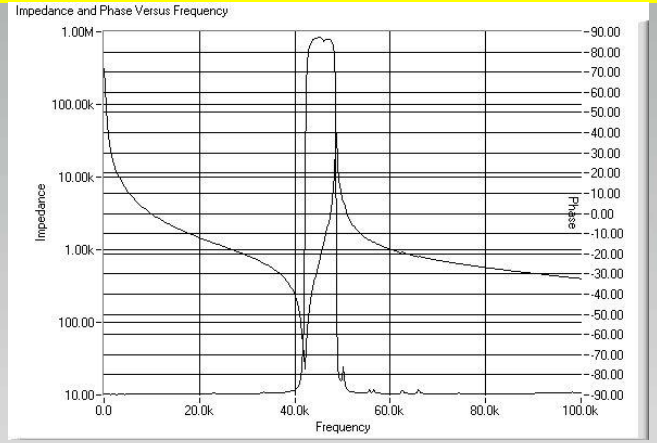




3D model of PMN-PT single crystal stator

Single Crystal Wobbling Motor

(a)



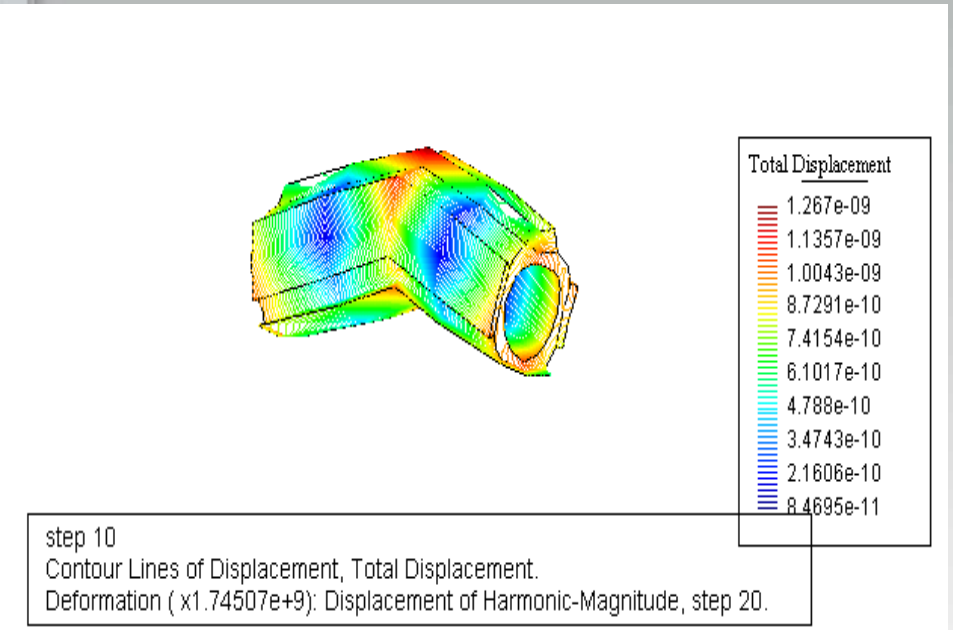
(b)

(c)

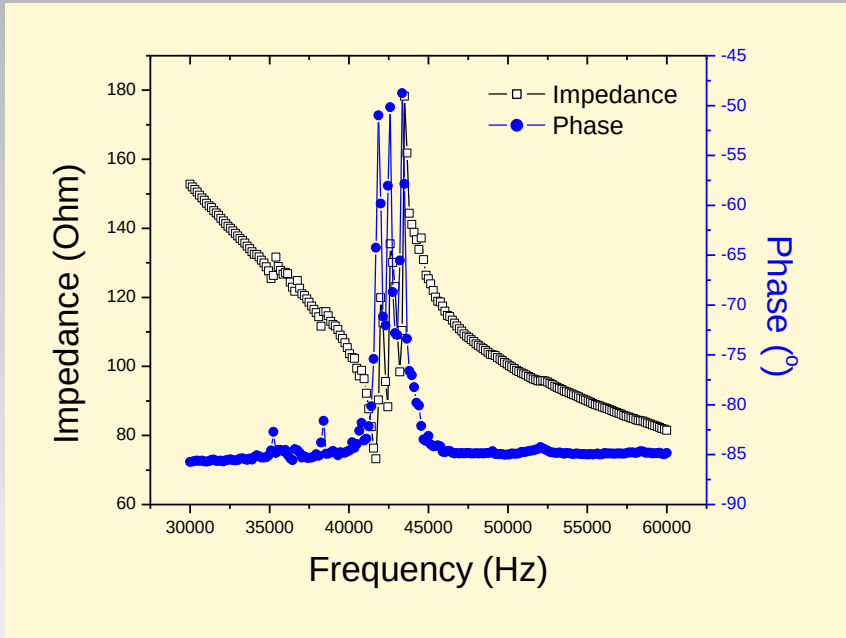
(d)

Single crystal wobbling motor: (a) PMN-PT crystal plates (b) Impedance spectrum of the crystal plate (c) Individual parts of the motor (d) Assembled motor

Single Crystal Wobbling Motor

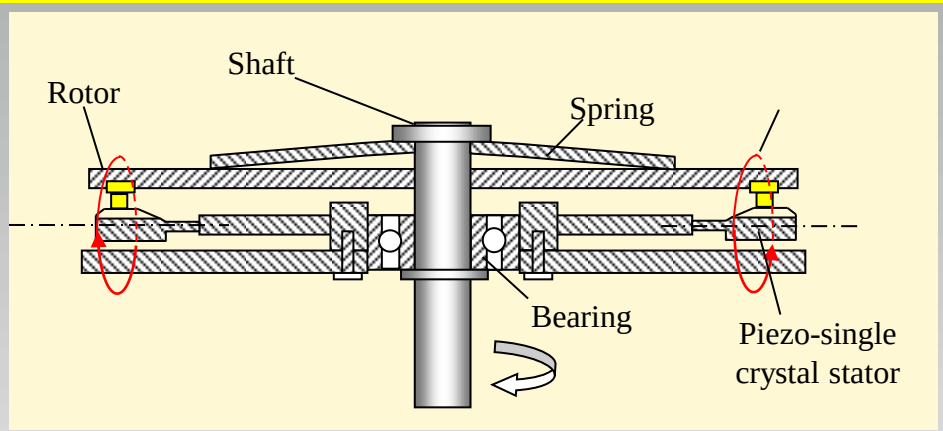


Finite element model of single crystal stator using ATILA software and displacement profile

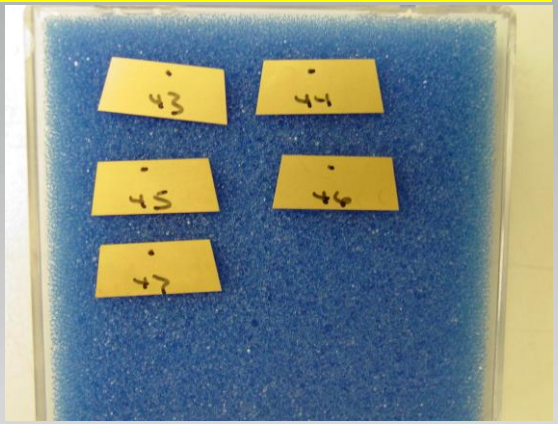


Impedance spectrum of the 6-stator single crystal wobbling motor

Single Crystal Traveling Wave Motor



(a)



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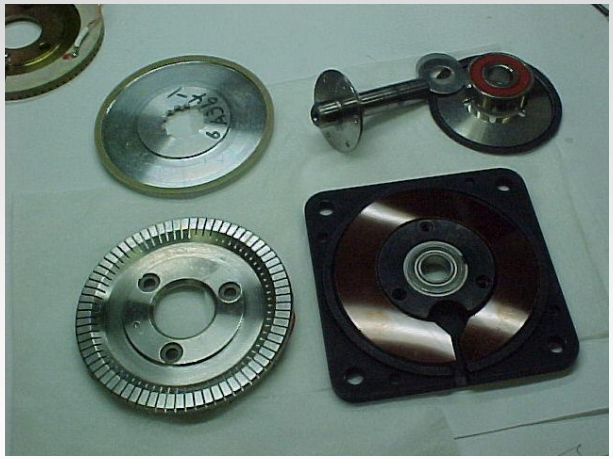

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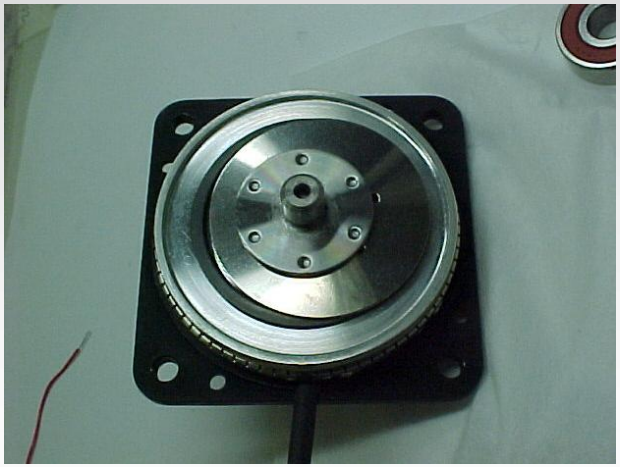
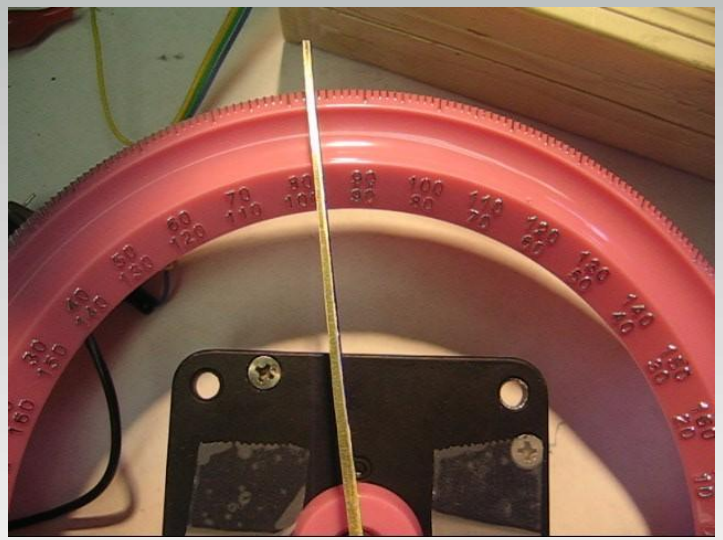


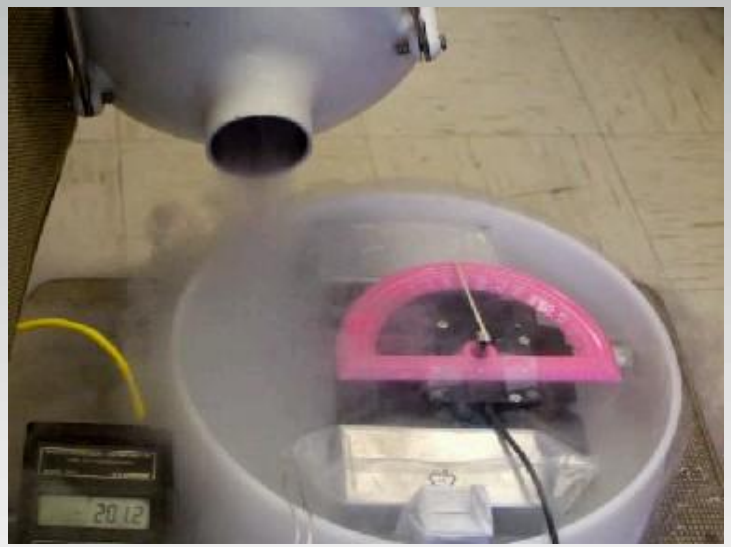
(d)

Single Crystal Traveling Wave Motor: (a) Working principle, (b) Trapezoidal plates, (c) Individual parts of the motor, (d) Assembled motor

Single Crystal Traveling Wave Motor

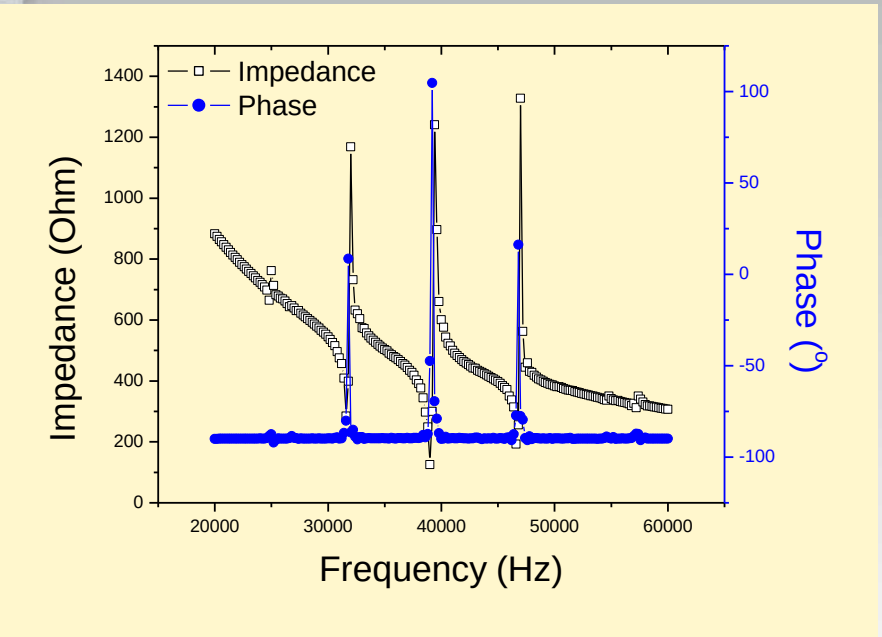


Angular stepping measurement set-up

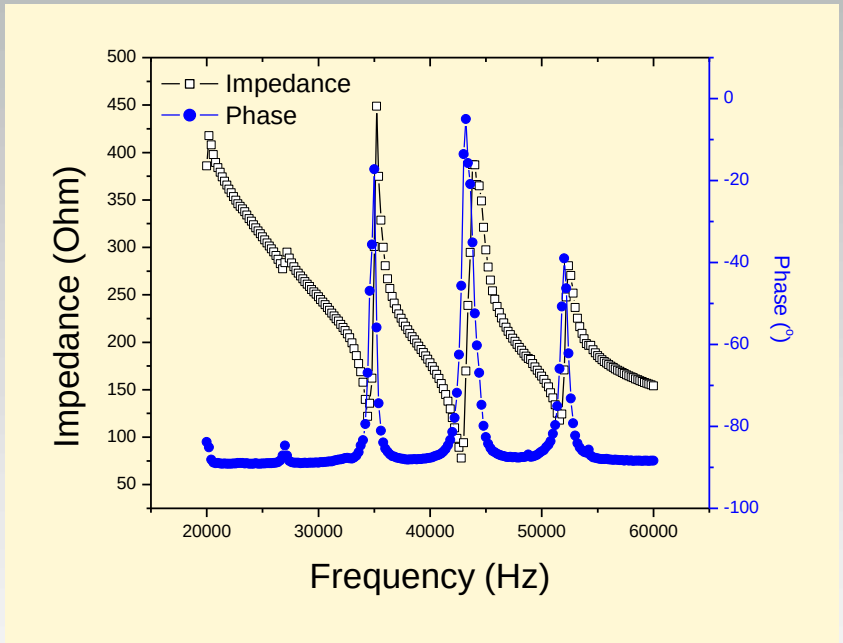


Cryogenic test of a PMN-PT traveling wave motor in liquid nitrogen

Single Crystal Traveling Wave Motor - Performance



Impedance and phase spectrum of a PZT based stator for traveling wave motor



Impedance and phase spectrum of a PMN-PT single crystal based stator for traveling wave motor

Summary of Single Crystal Traveling Wave Motor

	Resonance frequency (kHz)	Freq-band width (Hz)	Starting voltage (V_{p-p})	Working voltage (V_{p-p})	Torque (kg-cm)	Power *(W)	Working temperature range (°C)
PZT	41.5	177	200	400	~5 @400V_{p-p}	7.5 @400V_{p-p}	-30 —70
PMN-PT	43	929	50	100-200	~3 @200V_{p-p}	2.1 @110V_{p-p}	-200—50

- A single crystal traveling wave motor was developed for the first time showing large torque (> 1.5 Kg-cm) and high stepping resolution (0.25°) under relatively low voltage (100 Vp-p pulse with a 12 V DC power supply) and low power consumption (~ 2 W for a 25% duty cycle). The mass of this motor is < 250 g.
- The traveling wave motor operated successfully in liquid nitrogen (77K) with a mass load of 300 gram (~ 0.2 Kg-cm torque) and the stepping resolution of 0.2 .
- The single crystal wobbling mode motor showed torque > 1.0 Kg-cm at driving pulse of 100 Vp-p, > 800 steps per revolution of the axis, and power consumption of ~ 4 W for a 25% duty cycle.
- A broad rotation speed range of <10-100 rpm was demonstrated, which can eliminate gear transmission, a major source of backlash in large torque motion control

Cryogenic Piezo Actuators for Lightweight, Large Aperture, Deployable Membrane Mirrors

(Phase I Contract No: NNC07QA63P)

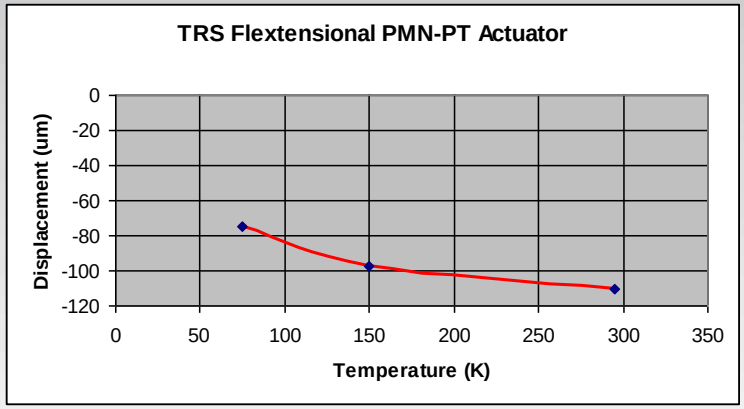
Program Manager: Stewart Sherrit, JPL

Phase I Goals

- Investigation of piezoelectric properties of PMN-PT single crystal as a function of crystal composition down to cryogenic temperatures (~40 K)
- Integration of a compact non-resonant linear piezomotor utilizing a PMN-PT single crystal driver and characterization at temperatures ranging from 4 K-300K
- Specific goals for the cryomotor are: maximum stroke >100 mm, maximum driving force ~10 N, response time ~ ms, positioning resolution ~50 nm, operating temperature of 4K-400 K, total mass <50 g, and power consumption <1 W
- Design of the deployment structure and measurement of stroke and force required for deployment
- Concept demonstration of a 25 mm aperture membrane mirror deployment

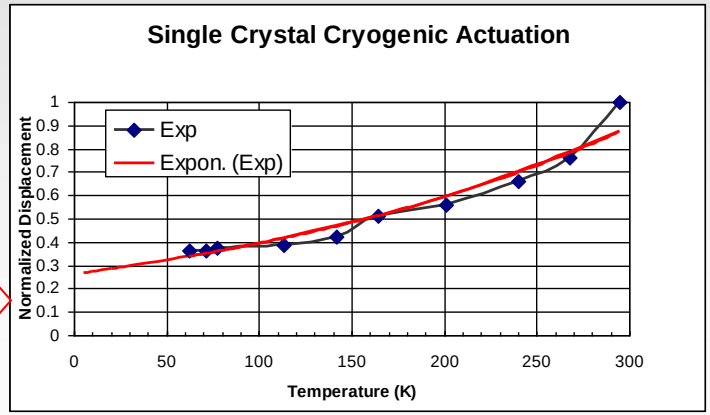
Currently Available Cryogenic Actuations

- Superconducting coil based electromagnetic actuations, e.g. magnetostrictive, EM motor, etc. Temperature range: <77K.
- Compositionally modified piezoelectric and electrostrictive ceramics for electrostrictive and piezoelectric actuations. Temperature range: < 65K.
- Single crystal piezoelectrics. Temperature range: 20K->300K.

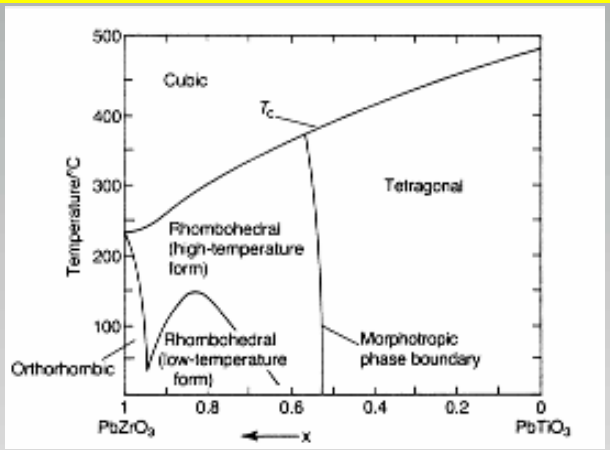


Cryogenic strain test for "33" mode PMN-PT flextensional actuator, stroke >74 um at 75K.

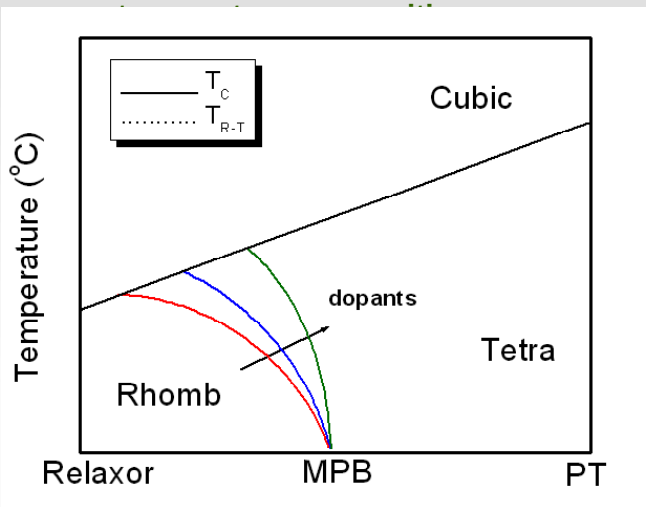
Cryogenic strain test for PMN-PT stack actuator. Predicted stroke ratio (stroke at cryo-temperature/stroke at room temperature) is 27% at 10K.



Single Crystal Compositions



PZT Phase Diagram: The vertical line in the center is the MPB which corresponds to the optimum room



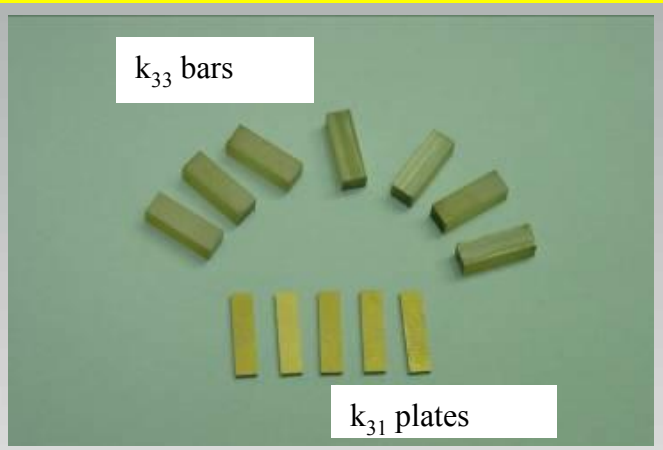
PMN-PT Phase Diagram: Room temperature properties are optimized to the right of the boundary

Single Crystal Specifications (PMN-PT)

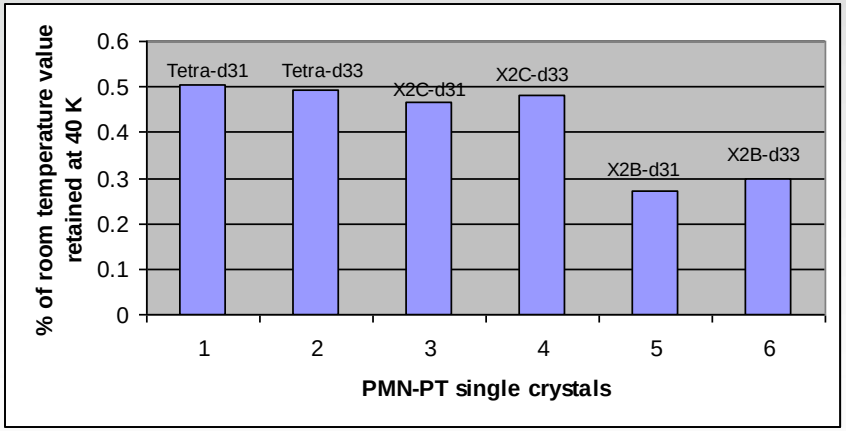
Property	TRS-X2A	TRS-X2B	TRS-X2C
Composition	27-29%PT	29-31%PT	PMN-32%PT
Dielectric, K_3^T	4000-5500	5000-7000	6500-8500
Loss (tanδ)	<0.005	<0.008	<0.01
T_{RT} (1kHz,°C)	>95	>85	75
T_C (1kHz,°C)	>132	>142	160
E_c (kV/cm)		3.2	
d_{33} (pC/N)	1300-1800	1700-2300	2200-2700
d_{31} (pC/N)	-600	-1000	
d_{15} (pC/N)		2500-4000*	
k_{33}	0.88	0.90	0.92
k_{31}	0.40	0.51	
k_t	>0.54	>0.55	>0.56
N_{33} (Hz-m)		599	
N_{31} (Hz-m)	772	721	
N_t (Hz-m)	2270	2002	
Density(g/cm³)	8.0	8.0	8.0

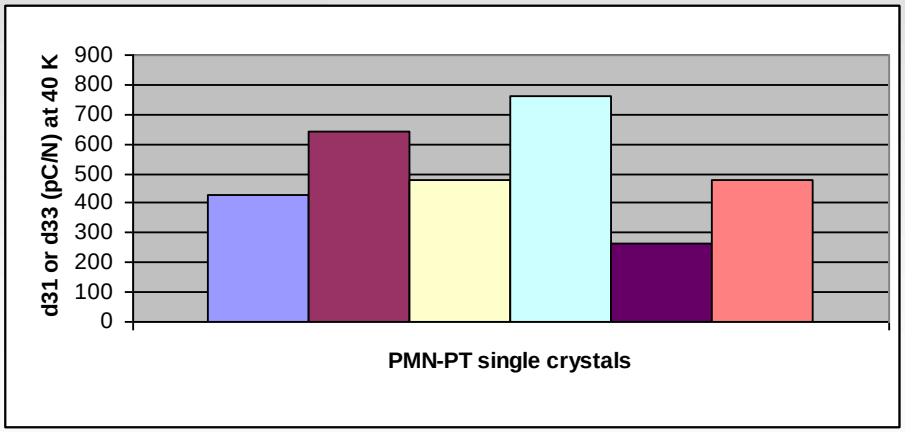
* Denotes optimized property, poled along <111>, as shown under "Orientations"

Single Crystal Properties



PMN-PT single crystal bars and plates with high PT (rhombohedral phase close to MPB and tetragonal) for resonance measurements

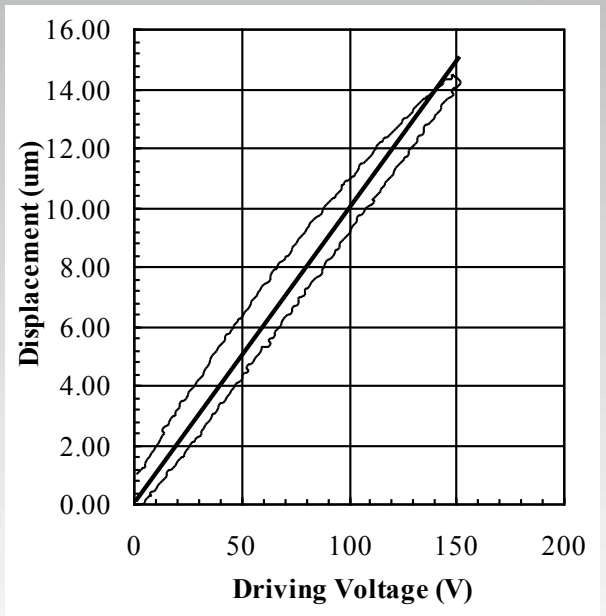




Cryogenic properties of PMN-PT single crystals with various compositions. (a) the ratio of d_{31} and d_{33} at 40 K to those at room temperature ; (b) d_{31} and d_{33} values of various PMN-PT single crystals at 40 K

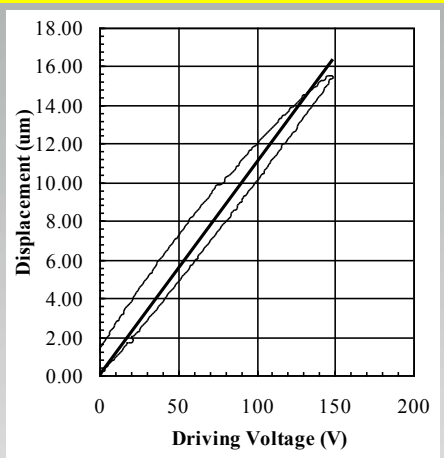
Single Crystal Properties

A PMN-PT stack actuator with dimension of 5 x 5 x 9 mm (layer thickness is 0.1 mm) fabricated for linear motor demonstration



Displacement vs. voltage performance of the 5 x 5 x 9 mm actuator at room temperature

Single Crystal Properties



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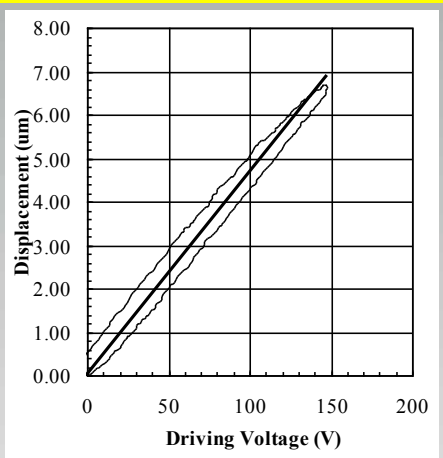

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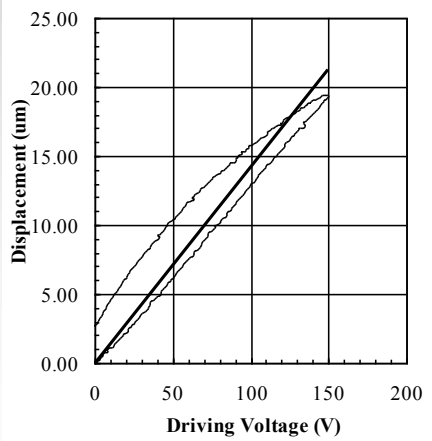

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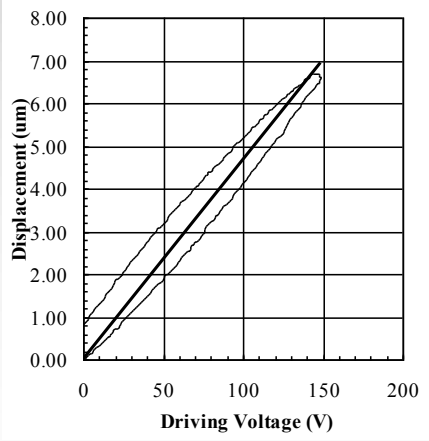
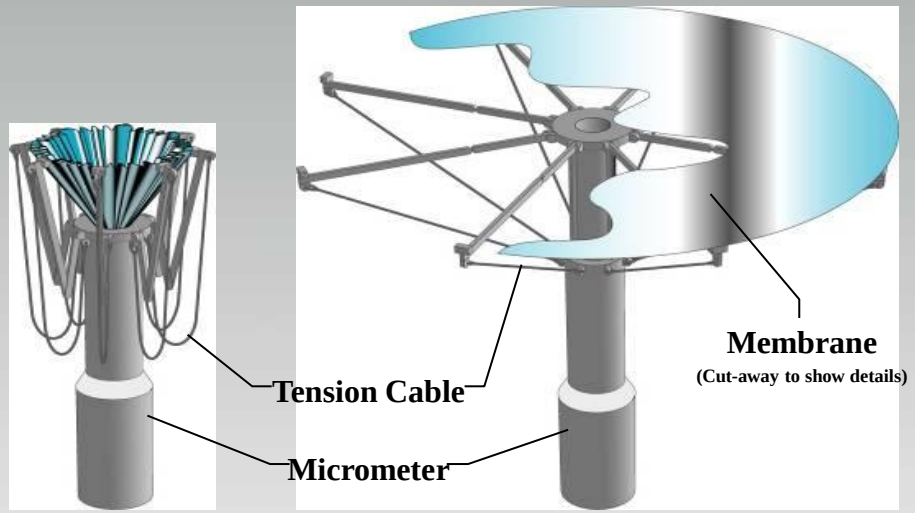


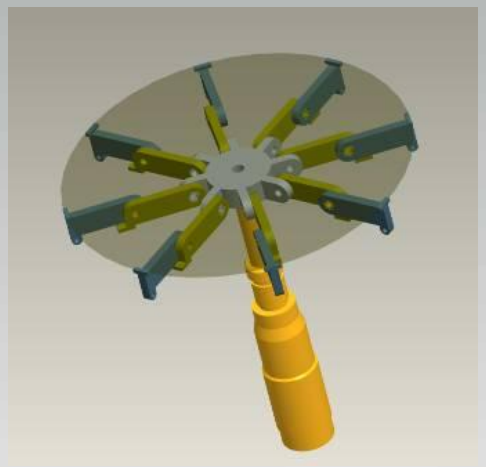
(d)

Displacement vs. voltage measurements for 70 layer single crystal stack actuators with 5 x 5 x 0.1 mm plates: (a) TRS-X2B showing 15.54 microns at RT; (b) TRS-X2B showing 6.9 microns at 59 K; (c) TRS-X2C showing 19.44 microns at RT and (d) TRS-X2C showing 6.68 micron at 56 K

Deployable Structure Concept

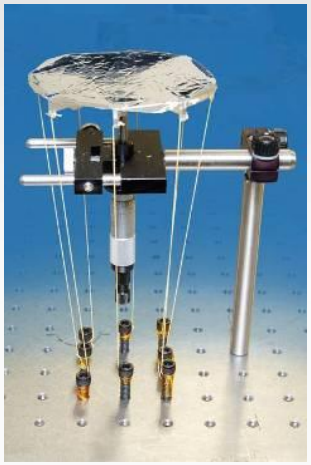


Folded (a) Deployed



(b)

(c)



(d)

(a) Conceptual design for prototype deployable membrane
(b) 3D CAD drawing of prototype mount
(c) Stowed state of the prototype membrane mirror
(d) Deployed state of the prototype membrane mirror

Summary of Single Crystal Cryogenic Actuators

- PMN-PT single crystal samples for k_{31} and k_{33} resonance measurements were prepared and tested at room temperature. A 5 x 5 x 9 mm PMN-PT stack actuator (0.1 m layer thickness) was prototyped with an effective d33 of ~1500 pm/V.
- Cryogenic tests with both resonant samples and the stack were performed using a cryostat up to 40 K
- Cryogenic tests showed that TRS-X2C composition showed higher d31 and d_{33} at cryogenic temperatures (about 45-50% of their room temperature values.) compared to previously investigated TRS-X2B crystals.
- Prototype TRS-X2C stack actuators were fabricated and their strain characteristics were tested at cryogenic temperatures up to 40 K.
- A TRS-X2C actuator was incorporated into a commercial non-resonant inertial (slip-stick) linear motor and successfully operated at 5.2 K

Advanced Electroactive Single Crystal and Polymer Actuators for Passive Optics

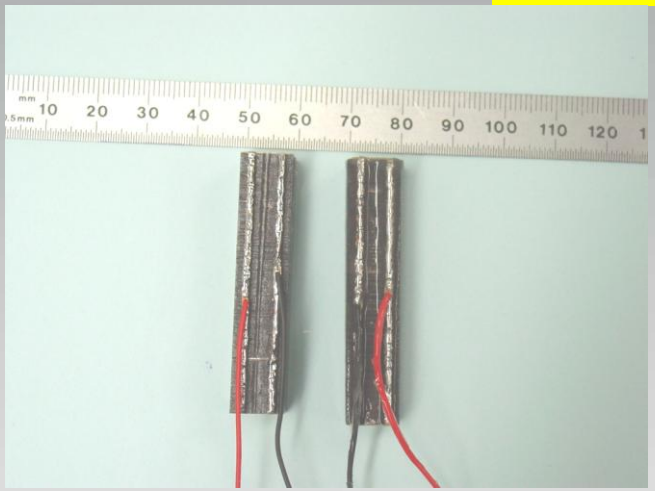
(Phase II Contract No: NNL06AA09C)

Program Manager: William B Cook, LaRC

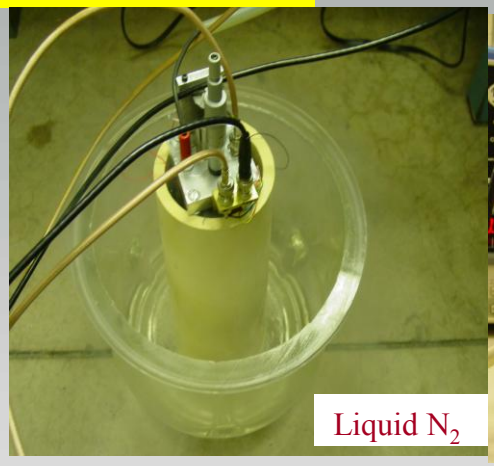
Phase II Goals

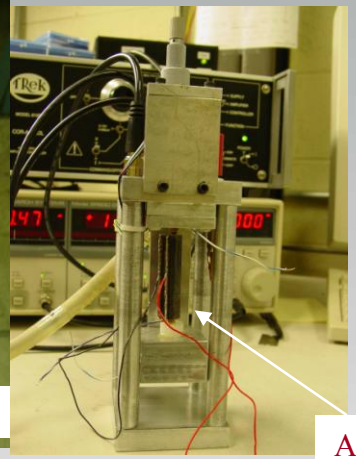
- The primary objective of the Phase II program is to develop electroactive single crystal and polymer actuators for NASA passive optics applications.
- Single crystal stack actuators, flextensional actuators and Hybrid Actuator Systems (HYBAS) actuators will be developed to meet:
  - Current Fabry-Perot Interferometer (FPI) and Fourier Transform Spectrometer (FPS) requirements such as > 25 µm scanning range at 77K,
  - Near future mission requiring 100-200 µm, and
  - Future missions requiring 1-2 mm scanning range for passive optics.
- Single crystal stack actuators (length <50 mm) with stroke of > 25 µm at 77 K will be developed for the current NASA tunable FPI applications.
- Single crystal flextensional actuators with low profile will be developed to generate 100-200 µm stroke at 77K
- Actuators will be integrated into a simple etalon structure for precise scanning control. Stack actuators will be characterized at temperature varied from 77K to 300K

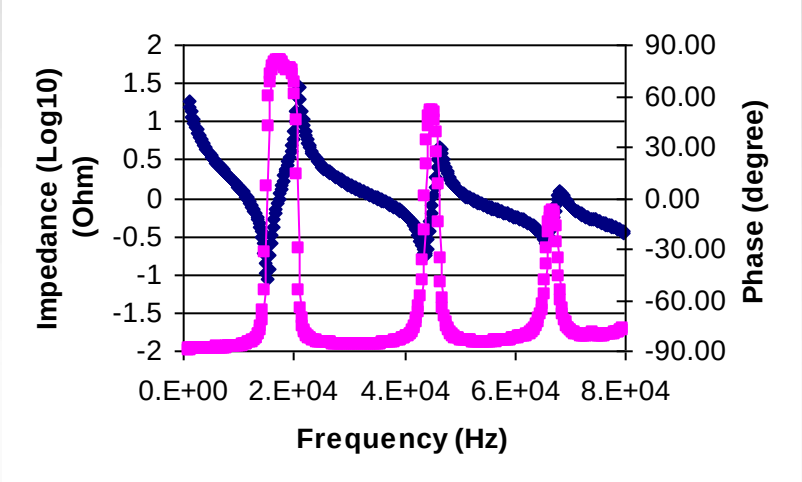
TRS Stack Actuators



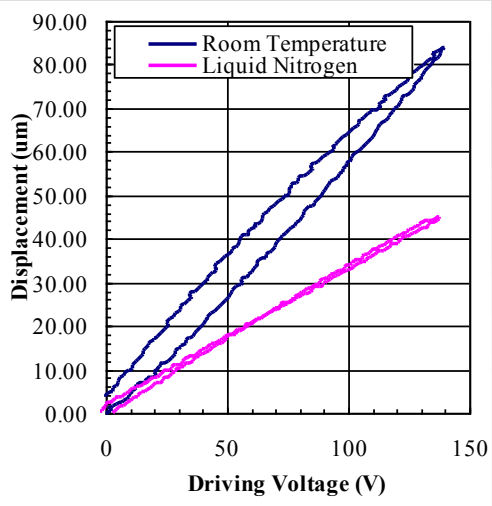
10 x 10 x 50 mm PMN-PT single crystal stack actuators





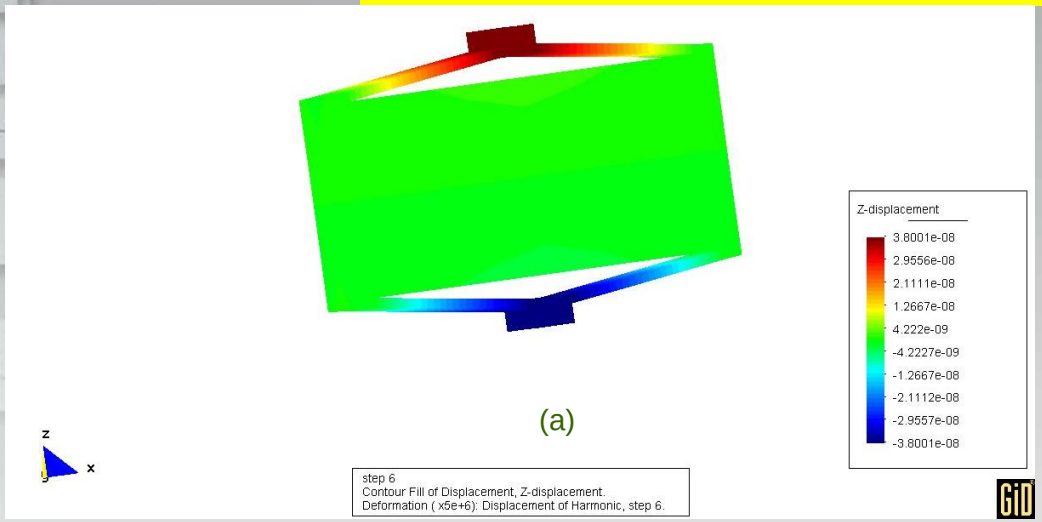


Resonant modes of a 10 x 10 x 50 mm PMN-PT single crystal stack actuator

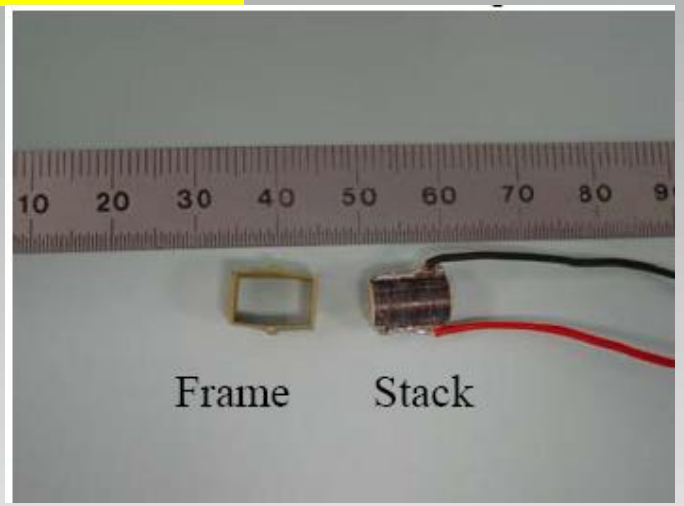


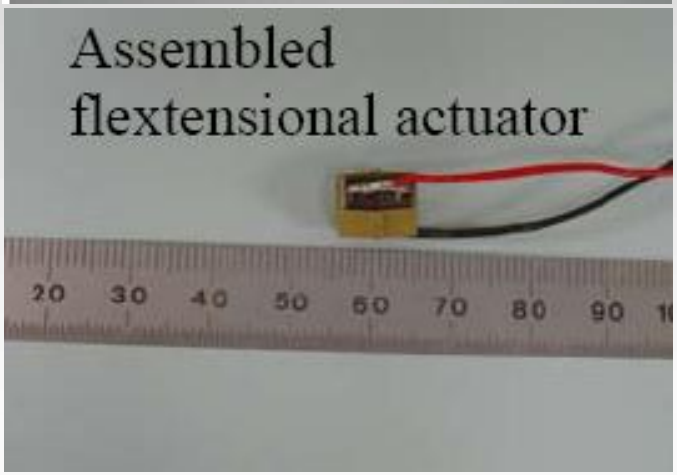
Stroke performance of a 10 x 10 x 50mm PMN-PT single crystal stack at room temperature and at liquid nitrogen environment

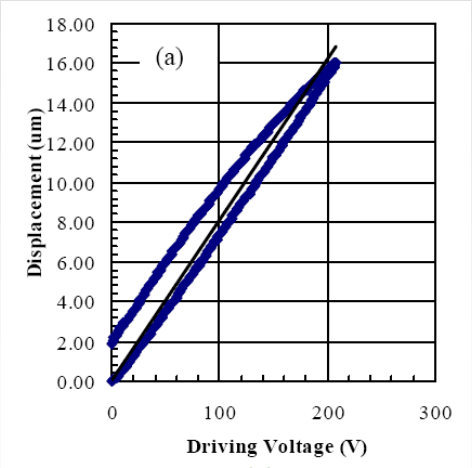
TRS Flextensional Actuators



(a)







(c)

(b)

10 x 5 x 7.6 mm PMN-PT single crystal flextensional stack actuator: (a) ATILA model (b) Frame, stack and assembled actuator (c) Stroke vs. voltage performance

Thank You!!

Questions?