Microfabricated Actuators for Space Applications

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Topics that are covered in this talk

- **Linear Microactuator**
  For active wavefront correction for space telescopes

- **Piezoelectric Microvalve**
  For micropropulsion for microspacecrafts
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- **Linear Microactuator**
  For active wavefront correction for space telescopes

- **Piezoelectric Microvalve**
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A linear actuator is a type of electric actuator or motor that produces overall force and motion linearly.

Typical linear (inchworm) actuation sequence
Why Linear “Micro” actuator

- Extremely large (> 30 m), lightweight (< 1 kg/m²) space telescopes will enable substantial performance gains for future space-based imaging.
- Practical ultra-large, ultra-lightweight aperture systems will more likely be either segmented or flexible monolithic primary mirrors.
- Their large surface errors have to be corrected by active and adaptive wavefront controls.
- Using ultra-lightweight microactuators, the ultra-large mirror system can be designed to have very low areal density.
Applications of Linear Microactuators

Formation Flying Telescope With Highly Segmented Primary

Si Wafer Segments

MEMS Actuators

For segmented mirrors

Space Telescopes as Large as This...
Ultra-large, ultra-lightweight, nanolaminate-based space telescope mirror concept.

The flexures are bonded at the points \( Q_i \) and \( R_i \), and the angles between the tangents to flexures at the points remain constant.

A possible actuated beam concept:

Top layer (nanolaminate)  Passive or active face sheet  Hinged truss (flexure hinges) with beams with actuators

Face-sheet, passive or active

For Monolithic mirrors

## Actuator Target Performance

<table>
<thead>
<tr>
<th>Trait</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Freq.</td>
<td>~1 kHz</td>
</tr>
<tr>
<td>Stroke</td>
<td>&gt; 1 mm</td>
</tr>
<tr>
<td>Resolution</td>
<td>&lt; 30 nm</td>
</tr>
<tr>
<td>Force</td>
<td>&gt; 30 mN</td>
</tr>
<tr>
<td>Power</td>
<td>100 µW → 0</td>
</tr>
<tr>
<td>Mass</td>
<td>~ 100 mg</td>
</tr>
</tbody>
</table>

- The actuator is for correcting the surface figure of a segmented or thin-monolithic mirror (*mass density* < 1 kg/m²) after deployment in space.

- If microactuators weighing a 100-mg are available, a hundred such microactuators per square meter will add only about 0.01 kg/m².
Actuator Target Performance

<table>
<thead>
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</tr>
<tr>
<td>Power</td>
<td>100 $\mu$W $\Rightarrow$ 0</td>
</tr>
<tr>
<td>Mass</td>
<td>What if 100 g</td>
</tr>
</tbody>
</table>

- mass density goal < 1 kg/m$^2$

If actuators weighing 100-g are used, a hundred such actuators per square meter will add about 10 kg/m$^2$. 
Existing Linear “Micro” Actuators

- MEMS linear actuators [1~3]: 50~500μN max push force. No self-latching.
- Macro linear actuators [4]: 100g (mass)

New Linear Microactuators

2-Point Clamping to 4-Point Clamping

2-point clamp actuator is prone to slider tilt

Undesirable drag possible

4-point clamp actuator is more stable

(a) Unit A released.  Unit B clutched.
(b) Unit B laterally moved.
(c) Unit A clutched.  Unit B released.

R. Toda and E. H Yang, “Four Point Latching Microactuator,” (NPO-42041)
Self-Latched Linear Microactuator

- Increase electrostatic force / clamping force
  - Thick structures
  - Post-engagement
  - Pre-stressing tethers for self-latching

Schematics of Silicon Components

Top view

Unit “A”  Unit “B”  A

A’

Driver_front_RIE

Driver_back_RIE

Cross-section

A

A’

Clutch

Comb Drive

Tether

A Drive Unit
Forces applied by slider


Assuming the static friction coefficient is 0.24, the estimated push force when actuating is approximately 24 mN. In power-off mode, the estimated clamping force is approximately 48 mN.

\[ F_s > 25 \text{ mN} \]

\[ F_e > 35 \text{ mN} \]

Fabricated Silicon Components


Assembly Sequence

1. Fabricate rail guides.
2. Attach driver.
3. Insert slider.
4. Bond Au wires.
5. Attach the lid.
6. Attach the PMN-PT to driver and rail.

- Driver fabrication
- Rail fabrication
- Slider fabrication
- Slider insertion
- Individual comb drive actuation test
- Epoxy attachment with PMN-PT
- Wire bonding to Rail
- Mount on PCB, wiring with Ag-epoxy
- Actuation test
Wiring Scheme

- Stopper
- Slider
- PMN-PT
- CH1
- CH2
- GND
- CH3
- GNDCH1
- CH2
- GND
Fabricated and Assembled Actuator - 1st generation
Actuator Test Setup
Actuation speed: 1 cycle / 2 second

After the 500-cycle actuation, the slider was moved by approximately 450 μm. PZT voltage was 20V. There is no conceivable limit to the maximum stroke of our actuator other than constraints imposed by the slider length and external load.
Fabricated and Assembled Actuator - 2nd generation
Slider Motion (2$^{nd}$ Batch Actuator)
Image Processing Using Matlab

Actuator images taken before and after 100-cycle actuation:

Image processing was performed to accurately calculate the slider movement, by comparing two different images taken before and after the actuation. The resolution from the calculation is approximately 50 nm.
Slider Motion

Actuated @ 20-cycle per second with 100 V to PMN-PT
Pathfinder Mirror Modeling

Node displacement and actuator force

1-m diameter
The response of the structure to applied stimulus was calculated by minimizing the total structure energy with respect to the rest of the parameters.

For a 1 μm step, the maximum required force on all actuators is around 1 mN (rod stiffness of $10^4$ N/m).

General "bulk element" model for an arbitrary actuated lattice structure
Pathfinder Mirror Modeling

Effect of one actuator; A 1 nm node displacement and actuator displacement (top) and actuator force (bottom) in dynes.
Response of the structure to a set of minimum energy commands using many actuators, calculated for the same prescribed shape; The average force on the actuators has been reduced by 7 orders of magnitude.
Structure control to the Zernike* modes 2 and 4. Actuator displacement commands were calculated and were subsequently applied. The structure response to the commands was computed.

* In optics, the aberrations are often represented as a sum of special polynomials, called Zernike polynomials. Atmospheric random aberrations can be considered in the same way; however, the coefficients of these aberrations (defocus, astigmatism, etc.) are now random functions changing in time. A Zernike polynomial is defined in polar coordinates on a circle of unit radius.
Actuator Performance Summary

<table>
<thead>
<tr>
<th>Target</th>
<th>Demonstrated</th>
</tr>
</thead>
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</tr>
<tr>
<td>Power</td>
<td>100 µW</td>
</tr>
<tr>
<td>Size</td>
<td>~ 10 mm³</td>
</tr>
<tr>
<td>Mass</td>
<td>100 mg</td>
</tr>
<tr>
<td>20-cycle/s</td>
<td>0.5 mm @ 130-cycle</td>
</tr>
<tr>
<td>50 nm</td>
<td>48 mN</td>
</tr>
<tr>
<td>0 W when latched</td>
<td>14x7x0.6</td>
</tr>
<tr>
<td>100 mg</td>
<td></td>
</tr>
</tbody>
</table>

(1) The higher-speed actuation (>20Hz/cycle) could not be demonstrated due to the frequency limit of the mechanical relay used for supplying electrical AC signal to actuators. In principle, the actuator structure with PZT and comb units can move at frequencies exceeding 1kHz.

(2) The stroke of our actuator is limited only by the slider length and imposed force.

(3) The measured resolution was limited by the image quality for image processing. Actual resolution (minimum step size) is expected to be better.

(4) The clamping force was modeled using ANSYS.
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- **Piezoelectric Microvalve**
  For micropropulsion for microspacecrafts
Small Spacecrafts Requiring Microvalves

Microspacecraft typical envelope:
1~ 10 kg mass, ~10 cm³ volume, ~1 W power

→ Requiring microvalves capable of fast-actuation, low-leak, high-pressure and low-power operation

NASA’s future Earth Science Mission
10s - 100s of S/C

For Xenon-based Micropropulsion (High pressure)
Generic Microvalve Requirements

- **Leak Rate** - 0.005 sccm He
Generic Microvalve Requirements

- **Leak Rate** - 0.005 sccm He
- **Inlet Pressure** - ~ 1000 psi
Generic Microvalve Requirements

- **Leak Rate** - 0.005 sccm He
- **Inlet Pressure** - ~ 1000 psi
- **Actuation Speed** - << 1 ms
Generic Microvalve Requirements

- **Leak Rate** - 0.005 sccm He
- **Inlet Pressure** - ~ 1000 psi
- **Actuation Speed** - << 1 ms
- **Power** - << 1 W
- **Package Weight** - < 10 g
- **Temperature** - 0 ~ 75 °C
Typical Normally-Closed Valves

Closed

Open

Spring
Seal Rings
Piston
Plunger

Actuation Pressure
(50—100 psig)

Typical ratings:
Back pressure < 4,000 psig
Air flow rate < $10^4$ cm$^3$/s
Temp = −40°C to 200°C
Leak = $10^{-2} - 10^{-9}$ cm$^3$/s

Mass, size, power
Solenoid-based Microvalve for Micropropulsion

Moog Micro Valve prototype


**S/C Power** - 1 W

---

**Table 2: Performance Parameters of the MMV Prototype**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MMV Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (gram)</td>
<td>7</td>
</tr>
<tr>
<td>Size (cm³)</td>
<td>1 (approx. 1 x 1 x 1 cm)</td>
</tr>
<tr>
<td>Power (W)</td>
<td>0.7 (continuous)</td>
</tr>
<tr>
<td>Voltages (Vdc)</td>
<td>5</td>
</tr>
<tr>
<td>Response (ms)</td>
<td>1.5 (open), 0.5 (close)</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>300 (nom), 1000 (max)</td>
</tr>
<tr>
<td>Operating Temp(°C)</td>
<td>0-70</td>
</tr>
<tr>
<td>Life</td>
<td>1,000,000 cycles*</td>
</tr>
<tr>
<td>Leakage</td>
<td>&lt; 10⁻⁴ secs GN₂ (after 1M cycles)</td>
</tr>
</tbody>
</table>

*Test terminated voluntarily*
MEMS-based Valves

Thermopneumatic Valve

- Pyrex
- Heaters
- Actuator Cavity
- Poppet

- Silicon
- Fulcrum
- Pyrex

Bimorph Valve

- Flow Inlet
- Ni Heater
- Ni
- Flow Inlet

- Seat
- Flow Outlet
- Boss

Electrostatic Valve

- Seat
- Upper Flange
- Valve Stem

- Insulation
- Membrane
- Sealed Cavity

Electromagnetic Valve

- Permanent Magnet
- Electrode
- Inlet

- Gold Leads
- Valve Motion
- Outlet (past cantilevers)
Limitations of Existing Microvalves

• Conventional microvalve technologies: mass/volume, power consumption
  ➔ e.g. 3-8 W to operate

• Typical MEMS-based valves: leak and/or narrow pressure range
  ➔ e.g. 400 ms, 0.2 sccm (20 psi), 2 W
# Microvalve Actuation Choices

<table>
<thead>
<tr>
<th></th>
<th>Thermo-pneumatic</th>
<th>Bi-metalic</th>
<th>SMA</th>
<th>Electrostatic (w/spring)</th>
<th>Piezoelectric</th>
</tr>
</thead>
</table>
| **Governing Equations**| F = APA \( T_1 / T_2 \)  
P = pressure  
A = area  
T = temperature  
F = \( wt^3 (\Sigma E) d / l^3 \)  
w = beam width  
t = beam thickness  
\( \Sigma E \) = sum of moduli  
l = beam length  
d = deflection  
F = \( KA \delta \)  
A = actuator area  
\( \delta \) = strain  
K = constant, based on Flexinol™ data  
F = \( \varepsilon_0 AV^2 / 2g^2 \)  
g = gap,  
V = voltage,  
A = area  
F = \( EPA \delta \)  
E = piezo modulus  
A = area,  
\( \delta \) = strain |
| **Geometry**           | Gas Capsule  
10 mm diameter  
5 mm high  
8 \( \times \) 2 mm  
Beams  
100 \( \mu \)m thick,  
(50/50 Ni, Si)  
SMA disk  
10 mm diameter  
5 mm high  
Capacitor disk  
10 mm diameter  
w/ spring  
Piezo disk  
10 mm diameter  
5 mm high |
| **Force**              | \(~ 1N \)  
\(~ 2 mN \)  
\(~ 14 kN \)  
\(~ 2 \mu N \)  
\(~ 5 kN \) |
| **Max Deflection**     | -  
10 \( \mu \)m  
20 \( \mu \)m  
5 \( \mu \)m  
5 \( \mu \)m |
| **Power**              | high  
high  
high  
low  
low |
| **Actuation Time**     | long  
long  
long  
short  
short |
Microvalve Design

- Estimated maximum stresses in the tethers (ANSYS): 80 MPa (on-state).
- Seating pressure from pre-stressed PZT: 50 GPa (reducing leak rates).

Narrow valve seat rings: a. Immune to particles, b. Enhance seating pressure.

- PECVD SiO$_2$: 2 $\mu$m
- Thermal SiO$_2$: 0.5 $\mu$m

After Au-Au bonding.
Custom-Designed PZT-Stack

- Thin layers of PZT (100 μm),
- Each layer sandwiched between +/- electrodes
- d33 mode actuation

Seating pressure from pre-stressed PZT: 50 GPa
Fabrication Process

- Seat process

Etching: inlet & outlet holes
Fabrication Process

- Boss process

Etching: boss & tethers
Assembly Sequence
Fabricated Microvalve
Fabricated Microvalve

Microvalve Housing for High-Pressure Test

Test Bench
Leak Performance

"Helium leak detector scale"
leak rates at high-pressures

Leak rate [sccm] vs. Pressure [psi]
Flow Characteristics

![Graph showing flow characteristics](image)

- Flow rate [sccm]
- Displacement [μm]
- Applied voltage [V]
- Frequency [Hz]
- V_{p-p} = 16 V
- GND

- 300 psi
- 200 psi
- 100 psi
Flow Characteristics

- 50 Hz at 100 psi
- $V_{p-p} = 16 \text{ V}$

- Fluctuation [%] vs. Time [min]
- Flow rate [sccm] vs. Duty ratio [%]

- Pulse wave
- $V_{p-p} = 10 \text{ V}$

- @100 psi
Microvalve for Liquid Flow Control

For Butane-based Micropropulsion (Medium pressure)
# Valve Performance Summary

<table>
<thead>
<tr>
<th>Generic Micropropulsion requirements</th>
<th>Commercially available MEMS valves</th>
<th>Miniaturized Solenoid valve</th>
<th>Our Piezoelectric Microvalve (Demonstrated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company A (Fluistor™ Microvalve)</td>
<td>Company B (High Pressure Shuttle, .187&quot; Spring Biased)</td>
<td>Moog MMV</td>
<td></td>
</tr>
<tr>
<td>Leak Rate</td>
<td>&lt; 5x10^{-3} sccm He</td>
<td>5 drops/hr</td>
<td>5x10^{-3} sccm He @ 800 psi (after 1 M cycles)</td>
</tr>
<tr>
<td>Inlet Pressure Tolerance</td>
<td>~ 1000 psi</td>
<td>100 psi max</td>
<td>0 ~ 1000 psi</td>
</tr>
<tr>
<td>Actuation Speed</td>
<td>&lt; 1 ms</td>
<td>1 s</td>
<td>30 µs (calculation)</td>
</tr>
<tr>
<td>Power (on-state)</td>
<td>&lt;&lt; 1 W</td>
<td>1.5 W</td>
<td>3 mW @ DC</td>
</tr>
<tr>
<td>Life Time</td>
<td>&gt; 10^6 cycles</td>
<td>-</td>
<td>10^6 cycles (Test terminated voluntarily)</td>
</tr>
</tbody>
</table>

- **Leak Rate**: Fluxor™ Microvalve with 50 µl/min at 100 psi, 30°C, 5 drops/hr; Moog MMV with 6x10^{-3} sccm N₂ (after 1 M cycles); Our Piezoelectric Microvalve with 5x10^{-3} sccm He @ 800 psi (after 1 M cycles).
- **Inlet Pressure Tolerance**: ~1000 psi, 100 psi max, 0 ~ 1000 psi.
- **Actuation Speed**: <1 ms, 1 s, 2 ms, 30 µs (calculation).
- **Power (on-state)**: <<1 W, 1.5 W, 4 W to open, 3 mW @ DC.
- **Life Time**: >10^6 cycles, - , 10^6 cycles (Test terminated voluntarily).
Summary

• MEMS/NEMS is ideally suited for Space applications since it offers the possibility of having highly capable devices with low mass, size and power consumption.

• Microactuator technologies have been developed for future space applications.
  - Linear microactuator technology: demonstrated the slider motion and modeled a pathfinder mirror structure.
  - Piezoelectric microvalves for high-pressure flow control: demonstrated fast, low power, leak-tight operation under high-upstream pressure.
Acknowledgments

Collaborators and Team Members: Kirill Shcheglov, Risaku Toda, Zensheu Chang, B. M. Levine, R. M. Morgan, Y. Bar-Cohen (NASA/JPL); J. Su (NASA/LaRC); J. Khodadadi (Auburn); S. Trolier-McKinstry (PSU); X. Jiang (TRS);

Sponsors: NASA Code R Micro/Nano Sciencecraft, NASA Gossamer S/T NRA, JPL RTD05-06, JPL DRDF02-05, NRO, NRO-DII04-05
Comb Drive Design

Capacitance at comb drive:
\[ C = \left( C_{\text{tip}} + C_{\text{side}} \right) \frac{W}{2(w+g)} = \varepsilon_0 \left( \frac{w}{s-x} + \frac{l-s+x}{g} \right) \frac{hW}{w+g} \approx \varepsilon_0 \frac{(l-s+x)hW}{g(w+g)} \]

Electrostatic force at comb drive \( F_e \):
\[ F_e = \frac{1}{2} \frac{\partial C}{\partial x} V^2 = \frac{1}{2} \frac{\varepsilon_0 hW}{g(w+g)} \]

\( F_s \): Tether beam restoring force
\( \mu \): friction coefficient
\( F_{e} \): Electrostatic force

For unclamping, \( F_e > F_s \)
Maximum clamp load = \( \mu F_s \)