PIEZOCERAMIC MICROACTUATION
FOR ROBOTIC SPACE EXPLORATION

JPL

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OUTLINE

- OVERVIEW: CURRENT SURFACE MOBILITY FOR PLANETARY EXPLORATION
- INSECT EXPLORERS: NEW PARADIGM FOR MOBILITY
- APPROACH
  - FLEXIBLE MICROACTUATORS
  - ELECTRICAL/OPTICAL ACTIVATION
  - ENHANCED BIMORPH: LOW POWER, HIGH FORCE
- APPLICATIONS
  - ADVANCED MOBILITY
  - OPTICAL SHAPE CONTROL
  - MICROVALVES
  - PRECISION MEDICAL TREATMENT/DIAGNOSTICS
- CONCLUSIONS/SUMMARY
OVERVIEW: CURRENT SURFACE MOBILITY SYSTEMS

- Current approach for realization of small vehicles is evolutionary: through the miniaturization of existing wheeled/legged vehicles based on state of the art in miniature actuators and motors. However, such miniaturization does not lend itself to cost reduction concomitant with the size reduction because cost of the individual mobility components goes up by an order of magnitude or more for such miniature motors etc which often need to be precisely hand assembled.

- An alternate approach with significant potential advantages, especially when traversing unusual and difficult terrain such as loose granular surfaces, is to imitate the mobility attributes of insects. Mimicking biology, such artificial insects may possess varied mobility modes: surface-roving, burrowing, hopping, hovering, or flying, to accomplish surface, subsurface, and atmospheric exploration. They would combine the functions of advanced mobility and sensing with a choice of electronic and/or photonic control. Preprogrammed for a specific function, they could serve as "no-uplink, one-way communicating" beacons, spread over the exploration site, autonomously looking for the object of interest.
OVERVIEW: MOBILITY APPROACHES

● CURRENT APPROACH:
  ENERGY SOURCE (SUN) ----- SOLAR CELLS/BATTERY ------ MOTORS ------- PASSIVE MOBILE COMPONENTS
  EFFECTIVE EFFICIENCY \(\sim 3-5\%\)

● NEW PARADIGM (INSECT EXPLORERS):
  ENERGY SOURCE (SUN) -------- ACTIVE MOBILE COMPONENTS
  EFFECTIVE EFFICIENCY \(\sim 10\%\)
VISION:
ADVANCED MOBILITY . . . . . . the size of small insects
. . . . . . with the same mobility agility

When coupled with dedicated microsensors/microimagers -

INSECT EXPLORERS

They will be ideal for:
• SCOUTING MISSIONS - IN-SITU SENSING
• HAZARDOUS AREA EXPLORATION
• REACH NARROW CREVICES

Such "artificial" insects will enable that couldn't be easily done today
PAY_OFF - WHY INSECT EXPLORERS

• Extremely small size - allows reach to places never reached before for in-situ sensing
• Expendable due to low cost - will be used to explore high risk zones
• Science return /$ would be tremendous, unprecedented.
WHY PIEZOCERAMIC ACTUATION?
(AS WE SCALE DOWN TO THIN FILM PIEZOCERAMICS)

<table>
<thead>
<tr>
<th>MECHANISM</th>
<th>PIEZOELECTRIC &amp; ELECTROSTRICITVE</th>
<th>SHAPE MEMORY ALLOY</th>
<th>POLYMERIC MATERIALS</th>
<th>MAGNETOSTRICTIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRAIN</td>
<td>$10^{-4}$ TO $0.3 \times 10^{-3}$**</td>
<td>$10^{-4}$ TO $10^{-3}$</td>
<td>$10^{-4}$ TO $10^{-3}$</td>
<td>$10^{-4}$ TO $10^{-2}$</td>
</tr>
<tr>
<td>DISPLACEMENT</td>
<td>LOW TO HIGH*</td>
<td>MEDIUM TO HIGH***</td>
<td>LOW TO HIGH</td>
<td>LOW TO MEDIUM</td>
</tr>
<tr>
<td>FORCE</td>
<td>HIGH ~100 kgf FORCE</td>
<td>LOW-MEDIUM ~1 kgf FORCE</td>
<td>SMALL</td>
<td>SMALL</td>
</tr>
<tr>
<td>HYSTERESIS</td>
<td>TAILORABLE BY COMPOSITION</td>
<td>LARGE</td>
<td>SMALL TO MEDIUM</td>
<td>LARGE</td>
</tr>
<tr>
<td>AGING</td>
<td>COMPOSITION DEPENDENT</td>
<td>VERY SMALL</td>
<td>LARGE</td>
<td>LARGE</td>
</tr>
<tr>
<td>TEMPERATURE RANGE</td>
<td>-196°C TO 300°C</td>
<td>-196°C TO 100°C WIDE</td>
<td>-10°C TO 80°C LIMITED</td>
<td>-273°C TO 100°C WIDE</td>
</tr>
<tr>
<td>RESPONSE SPEED</td>
<td>µsec-msec</td>
<td>seconds</td>
<td>msec</td>
<td>µsec-msec</td>
</tr>
<tr>
<td>ACTIVATION MODE</td>
<td>BOTH OPTICAL AND ELECTRICAL</td>
<td>THERMAL AND ELECTRICAL</td>
<td>ELECTRICAL</td>
<td>MAGNETIC</td>
</tr>
<tr>
<td>POWER REQUIREMENT</td>
<td>LOW</td>
<td>LOW</td>
<td>MEDIUM</td>
<td>LOW TO MEDIUM</td>
</tr>
<tr>
<td>RADIATION HARDNESS</td>
<td>YES</td>
<td>TBD</td>
<td>TBD</td>
<td>YES</td>
</tr>
<tr>
<td>CYCLABILITY</td>
<td>EXCELLENT</td>
<td>GOOD</td>
<td>FAIR</td>
<td>FAIR-POOR</td>
</tr>
<tr>
<td>PROSPECT OF</td>
<td>GOOD</td>
<td>GOOD</td>
<td>GOOD</td>
<td>FAIR</td>
</tr>
</tbody>
</table>

PIEZOELECTRICS REPRESENT A LEADING CANDIDATE FOR ADVANCED MICROACTUATION

**With amplification techniques (e.g. optically or electrically activated bimorph, flexensional elements and combination thereof to obtain double amplification)

** Antiferroelectric phase transition materials

** Limited by Thermal Energy Input
ENERGY DENSITY AS FUNCTION OF THICKNESS

- PIEZOELECTRIC
- MAGNETIC
- ELECTROSTATIC

ENERGY DENSITY (MJ/m³)

THICKNESS (µm)
Flexible microactuators are envisioned by depositing tailored thick (~2-10 micron) films of active materials on judiciously chosen, strong flexible (polymeric) substrates. Flexible microactuators would provide a combination of high force and displacement and be operable over a wide temperature range as is required for a variety of advanced mobility applications. Potential advantages of flexible microactuators are:

- low power (low voltage operation, <5 V), low mass, low volume
- low cost, batch production of the components compatible with VLSI processing
- high force/volume even with low voltage operation
- higher deflection
- flexible, miniaturizable microactuator: scaleable for MEMS/MOMS
- excellent cyclability -more than million cycles
- amenable to both electrical or optical activation
Flexible Micro Actuators For Advanced Mobility

[Diagram showing flexible microactuators with piezoceramic films, flexible substrates, and fibers/legs.]
Flexible microactuators would enable a new generation of microelectro-mechanical and micro-opto-mechanical systems where the actuation will not be restricted by the clamping effect due to the rigid substrate as in the current silicon based micromachined structures. Also in the current micromachined structures, the actuation force out of the structure is limited by the thickness to which the micromachined structures could be grown. Deposition of tailored piezoceramic thin films on flexible substrates would substantially eliminate the substrate clamping effect and thicker films can be deposited by high rate deposition processes, leading to mobile elements with substantially higher force to input power ratio with the option of contact-less optical activation.
FLEXIBLE MICROACTUATORS

- Optimization of the Piezoceramic films:
  - Optical quality enhancement
  - Polarization direction & intensity optimization
  - Optimization of the optical penetration effect
ILLUMINATION WAVELENGTH
-350-400 nm

CERAMIC BIMORPH

LEAD LANTHANUM ZIRCONATE TITANATE (PLZT)

DIRECTION OF BIMORPH DEFLECTION

opticallY ELECTRICALLY DRIVEN

FLEXIBLE MICROACTUATOR

PIEZOCERAMIC FILM

FLEXIBLE SUBSTRATE

PIEZOCERAMIC FILM

METAL ELECTRODE

ELECTRICAL LEAD

OPTICALLY DRIVEN ELECTRICALLY DRIVEN

film thickness: 2 micron

(a) (b)

ceramic thickness: 200 micron
PHOTOEFFECT PREDOMINANTLY AT THE EDGES

(HYPOTHESIS: EFFECT WOULD BE MAXIMUM FOR NORMAL INCIDENCE OF PHOTONS WHEN C-AXIS IS PARALLEL TO SUBSTRATE)

Si SUBSTRATE

(b)
TABLE 4: Flexible film microactuators matrix of improvement

<table>
<thead>
<tr>
<th>ELECTRICAL ACTUATION PARAMETERS</th>
<th>Thickness</th>
<th>Operating Voltage</th>
<th>Energy Density</th>
<th>Force/Volume</th>
<th>Current Status</th>
<th>'jected Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic Bimorph</td>
<td>200 microns</td>
<td>100 V</td>
<td>1X</td>
<td>1X</td>
<td></td>
<td>Thickness reduced, material tailored</td>
</tr>
<tr>
<td>Film Bimorph</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5 V : Operational voltage reduced</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25X enhancement for film bimorph</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OPTICAL ACTUATION PARAMETERS</th>
<th>Optical Power</th>
<th>Power Ratio</th>
<th>Photonic to Mechanical Conversion Efficiency</th>
<th>Force./Energy</th>
<th>Force./Power</th>
<th>Current Status</th>
<th>'jected Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80 mW/cm²</td>
<td>10X</td>
<td>0.1 %</td>
<td></td>
<td>1X</td>
<td></td>
<td>8 mW/ cm² : Illumination Intensity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 x</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10/0 - 100/0 : significant enhancement in overall efficiency</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2F to 20F : Multifold enhancement in the film bimorph</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20X to 200X</td>
</tr>
</tbody>
</table>
CHEMICAL STRUCTURE OF POLYBENZOXAZOLE (PBO)

PBO IS A CONJUGATED AROMATIC HETEROCYCLIC LIQUID CRYSTALLINE POLYMER (LCP) WITH OPERABILITY DEMONSTRATED AT 460°C. THE HIGH STRENGTH AND SUPERIOR PHYSICAL PROPERTIES OF PBO ARE DUE TO THE ROD-LIKE NATURE OF THE PBO MOLECULE AND THE ORIENTATION THAT CAN BE BUILT INTO THE POLYMER FILM. PBO FILM’S SELF-REINFORCING MICROSTRUCTURE RESULTS IN A “MOLECULAR FABRIC” WITH PROPERTIES COMPARABLE TO THOSE OF ADVANCED, FIBER-REINFORCED MATERIALS BUT WITHOUT THE DRAWBACKS OF DISTINCT FIBER AND MATRIX COMPONENTS.
# COMPARATIVE DATA FOR FILMS

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>UNIT</th>
<th>KAPTON</th>
<th>ARAMID</th>
<th>PET</th>
<th>PEN</th>
<th>PBO</th>
</tr>
</thead>
<tbody>
<tr>
<td>DENSITY</td>
<td>g/cm³</td>
<td>1.420</td>
<td>1.500</td>
<td>1.395</td>
<td>1.355</td>
<td>1.54</td>
</tr>
<tr>
<td>MELTING TEMP</td>
<td>°C</td>
<td>NONE</td>
<td>NONE</td>
<td>263</td>
<td>272</td>
<td>NONE</td>
</tr>
<tr>
<td>GLASS TRANSITION TEMP</td>
<td>°C</td>
<td>350</td>
<td>280</td>
<td>68</td>
<td>113</td>
<td>NONE</td>
</tr>
<tr>
<td>YOUNG’ S MODULUS</td>
<td>kg/mm²</td>
<td>300</td>
<td>1000-2000</td>
<td>500-850</td>
<td>650-1400</td>
<td>4900</td>
</tr>
<tr>
<td>TENSILE STRENGTH</td>
<td>kg/mm²</td>
<td>18</td>
<td>50</td>
<td>25</td>
<td>30</td>
<td>56-63</td>
</tr>
<tr>
<td>TENSILE ELONGATION</td>
<td>%</td>
<td>70</td>
<td>60</td>
<td>150</td>
<td>95</td>
<td>1-2</td>
</tr>
<tr>
<td>LONG-TERM HEAT STABILITY</td>
<td>°C</td>
<td>230</td>
<td>180</td>
<td>120</td>
<td>155</td>
<td>&gt;300</td>
</tr>
<tr>
<td>HEAT SHRINKAGE (200°C x % min)</td>
<td>%</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>1.5</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>COEFFICIENT OF THEW EXPANSION</td>
<td>ppm/°C</td>
<td>20</td>
<td>15</td>
<td>15</td>
<td>13</td>
<td>-2</td>
</tr>
<tr>
<td>COEFFICIENT OF HYDROSCOPIC EXPANSION</td>
<td>ppm/% RH</td>
<td>20</td>
<td>18</td>
<td>10</td>
<td>10</td>
<td>0.8</td>
</tr>
<tr>
<td>MOISTURE ABSORPTION</td>
<td>%</td>
<td>2.9</td>
<td>1.5</td>
<td>0.4</td>
<td>0.4</td>
<td>0.8</td>
</tr>
</tbody>
</table>
# Properties of High-Performance Fibers

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>PBO</th>
<th>PBO HIGH MODULUS</th>
<th>ARAMID</th>
<th>STEEL</th>
<th>SPECTRA® (HDPE)</th>
<th>CARBON (HI-TENSILE)</th>
<th>GLAS (s-2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TENSILE STRENGTH (ksi)</td>
<td>820</td>
<td>800</td>
<td>400-500</td>
<td>250</td>
<td>435</td>
<td>500-700</td>
<td>665</td>
</tr>
<tr>
<td>TENSILE MODULUS (MsI)</td>
<td>25-30</td>
<td>40-45</td>
<td>10-25</td>
<td>29</td>
<td>25</td>
<td>30-40</td>
<td>12.6</td>
</tr>
<tr>
<td>COMPRESSION STRENGTH (ksi)</td>
<td>40</td>
<td>65</td>
<td>65</td>
<td>250</td>
<td>10</td>
<td>300-400</td>
<td>&gt;150</td>
</tr>
<tr>
<td>ELONGATION, BREAK (%)</td>
<td>3.0</td>
<td>1.5</td>
<td>1.5-4.0</td>
<td>2.0</td>
<td>3.5</td>
<td>1.5 - 2.0</td>
<td>5.4</td>
</tr>
<tr>
<td>DENSITY (g/cc)</td>
<td>1.56</td>
<td>1.56</td>
<td>1.44</td>
<td>7.86</td>
<td>0.97</td>
<td>1.8-1.9</td>
<td>2.4</td>
</tr>
<tr>
<td>SPECIFIC TENSILE STRENGTH (ksi)</td>
<td>525</td>
<td>510</td>
<td>280-350</td>
<td>32</td>
<td>450</td>
<td>270-380</td>
<td>280</td>
</tr>
<tr>
<td>SPECIFIC TENSILE MODULUS</td>
<td>16</td>
<td>26</td>
<td>7-18</td>
<td>4</td>
<td>26</td>
<td>16-22</td>
<td>5</td>
</tr>
<tr>
<td>LIMITING OXYGEN INDEX (LOI: %)</td>
<td>56</td>
<td>56</td>
<td>30</td>
<td>'19</td>
<td>50-65</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TEMPERATURE DEPENDENCE OF FILM TENSILE STRENGTH

FILM TENSILE STRENGTH IN MACHINE DIRECTIONS

FILM TENSILE STRENGTH IN TRANSVERSE DIRECTIONS

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TEMPERATURE DEPENDENCE OF FILM TENSILE MODULUS FOR PBO FILM

FILM TENSILE MODULUS IN MACHINE DIRECTIONS

FILM TENSILE MODULUS IN TRANSVERSE DIRECTIONS

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msf96 25
COEFFICIENT OF THERMAL EXPANSION (CTE) OF PBO FILM

MACHINE DIRECTION (NEGATIVE CTE)

TRANSVERSE DIRECTION (POSITIVE CTE)
CTE OF α-BO FIBER BUNDLE

DIMENSION CHANGE (μm/m)

TEMPERATURE, °C

32.39°C

498.76°C

α = -6.04μm/m°C
THERMAL ANNEXING OF PBO

He FLOW @ 100 CC/min
TEMPERATURE INCREMENT 10° C/min

DIMENSION CHANGE (μm)

TEMPERATURE (°C)

609.90°C
THERMOGRAVIMETRIC ANALYSIS (TGA) OF DRIED 760 FILMS

WEIGHT (%)

TEMPERATURE, °C

98.36%
THERMAL \& NEALING OF PBO

He FLOW @ 100 cc/min
TEMPERATURE INCREMENT 100°C/min
STEADY 550°C for 15 min
COOL DOWN 50°C/min to RT
ADVANCED MOBILITY FOR INSECT EXPLORERS

CILIARY/FLAGELLAR MECHANISMS FOR FLUID NAVIGATION

MULTIPOD CRAWLING MECHANISMS (INSECT ROVERS/CRAWLERS)

FLEXIBLE MICROACTUATORS

FIABRES/LEGS

SHEET

HOVERING MECHANISMS (AERIAL EXPLORATION)

HOPPING MECHANISMS (OPTICAL/ELECTRICAL BURST TECHNIQUE INNOVATIONS)

Sarita Thakur
Mobility #4
CONCLUSION

FLEXIBLE MICROACTUATORS OFFER A COMBINATION OF HIGH FORCE AND DISPLACEMENT WITH POTENTIAL OF OPERABILITY OVER A WIDE TEMPERATURE RANGE AND A CONTACT-LESS OPTICAL ACTIVATION

- PIEZOCERAMIC BASED FLEXIBLE MICROACTUATORS FORM AN ENABLING TECHNOLOGY FOR A VARIETY OF APPLICATIONS:
  - ADVANCED MOBILITY
  - SHAPE CONTROL
  - MICROVALVES
  - MINIMALLY INVASIVE PRECISION MEDICAL TREATMENT/DIAGNOSTICS
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