Transducers: Actuators
Overview

- Transducers
- Basic Mechanics
- Actuators
  - Electrostatic
  - Electro-Thermal
  - Bimorph Electro-Thermal
  - Residual Stress
  - Mechanical Components

Transducers

- Transducer: a device that transfers power from one form to another
- Transducers can be divided into two categories
  - Sensors – reacts to environment
  - Actuators – acts on environment

- Can you think of common examples of sensors and actuators?
Transducers

• Transducer Schemes
  • One or more of the below components may or may not be utilized
  • A transducer can perform a dual role as sensor and actuator

Transducers: Examples from the Human Body

Signal Classification

- Measurand
- Sensor
- Processor
- Actuator

Signal Classification

- Measurand
- Sensor
- Processor
- Actuator

Example Components:

- Retina
- Choclea
- Nerves
- Olfactory Receptor Cells
- Taste Buds

Example Senses:

- Sensory
- Mechanical
- Chemical
- Biological

Example Actuators:

- Muscles
- Glands
- Mind
### Transducers

#### Sensor Classification

**Signal Classification** | **Measurands**
--- | ---
Thermal | Temperature, heat, heat flow, entropy, heat capacity, and etc.
Radiation | Gamma rays, X-rays, ultra-violet, visible, infra-red, micro-waves, radio waves, phase, and etc.
Mechanical | Position, displacement, velocity, acceleration, force, torque, pressure, mass, flow, acoustic wavelength and amplitude, and etc.
Magnetic | Magnetic field, flux, magnetic moment, magnetization, magnetic permeability, and etc.
Chemical | Humidity, pH level and ions, concentration of gases, vapors and odors, toxic and flammable materials, pollutants, and etc.
Biological | Sugars, proteins, hormones, antigens, and etc.
Electrical | Charge, current, voltage, resistance, conductance, capacitance, inductance, dielectric permittivity, phase, frequency, and etc.

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#### Actuator Classification

**Signal Classification** | **Action**
--- | ---
Thermal | heat, cool, radiate, and etc.
Radiation | emit light and other radiation
Mechanical | Provide displacement, velocity, acceleration, force, torque, pressure, mass, flow, and etc.
Magnetic | Provide magnetic field, flux, magnetic moment, magnetization, magnetic permeability, etc.
Chemical | Change/Provide humidity, pH level and ions, concentration of gases, vapors and odors, muscle stimulation, and etc.
Biological | Provide mechanical actuation, computing, etc.
Electrical | Provide charge, current, voltage, and etc.
Transducers

- Ideal Sensor Characteristics
  - Linear Operation
  - Noise Free Response
  - Zero Baseline
  - Fast Response Time
  - Large Frequency Bandwidth
  - No Saturation
  - High Sensitivity
  - High Resolution
  - Reliable and Rugged
  - No Performance Drift
  - Intolerant to Interference
  - No Hysteresis, Repeatable
  - Low Power Consumption
  - Simple Construction

- Ideal Actuator Characteristics
  - Aforementioned, plus ….
    - High Force Per Unit Volume
    - Large Deflections
    - Simplicity of Drive and Control
    - Simple Interface

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Axial Stress & Strain

- Strain, $\varepsilon$, is the deformation of a solid ($\Delta L/L$) due to stress
- Stress, $\sigma$, is the force acting on a unit area of a solid (F/A)
- The Young’s Modulus, $E$, is the ratio of stress over strain
  - describes the “firmness” of a material (hard, $E$ large, soft, $E$ small)

$$E = \frac{\text{stress}}{\text{strain}} = \frac{\sigma}{\varepsilon} \quad \text{(typically in N/m}^2\text{)}$$

Shear Stress & Strain

- Shear stress is force applied to an object in the plane of an opposing force
  - Such as an anchor point
  - The shear modulus of elasticity, $G$, represents the degree of displacement an object will allow under shear stress.
- Shear strain, $\gamma$, is related to the angle that a deformed element’s sides make with respect to its original shape

$$G = \frac{\text{shear stress}}{\text{shear displacement angle (rad)}} = \frac{F}{\Delta X} = \frac{A}{\Delta X} \gamma \quad \text{(typically in N/m}^2\text{)}$$
Shear Stress & Strain Cont.

For isotropic materials (those having identical properties in every direction, generally not the case for most single-crystal materials), shear modulus, \( G \), is related to the elastic modulus, \( E \), by

\[
E = 2G(1 + \mu) = 3K(1 - 2\mu)
\]

\( \mu \) is Poisson’s ratio

\( K \) is the bulk modulus

The bulk modulus is defined as the ratio of hydrostatic stress to volume compression

\[
K = \frac{\text{hydrostatic stress}}{\text{volume compression}} = \frac{F}{\frac{4}{3} \Delta V/V}
\]

The bulk modulus of a material represents its volume change under uniform pressure. In general, solids are less compressible than liquids due to their rigid atomic lattices.

For Ex. Water – \( K = 2.0 \times 10^9 \) N/m\(^2\)

Aluminum – \( K = 7 \times 10^{10} \) N/m\(^2\)

Steel – \( K = 14 \times 10^{10} \) N/m\(^2\)

Poisson’s Strain

Typical values are 0.2 to 0.5 for most materials

For most metals, Poisson’s ratio is \( \sim 0.3 \)

Rubber’s have a Poisson’s ratio closer to 0

Cork has a Poisson’s ratio close to 0

Poisson’s ratio \( \nu \) or \( \mu \) always defined as a positive value
Actuators: Electrostatic

- Advantages
  - Simple Designs
  - Simple Fabrication
  - High Frequency Operation
  - Low Power
- Disadvantages
  - Low Force Per Unit Volume
  - High Drive Voltages
  - Nonlinear Operation

Actuators: Electrostatic

- Parallel Plate
  - Two plate like structures facing each other, with a potential difference between them, will be drawn together due to the force of electrostatic attraction.
Actuators: Electrostatic

• Parallel Plate Examples

[Images of parallel plate examples]

Actuators: Electrostatic

• Parallel Plate Examples: Texas Instruments Digital Micromirror Device™

[SXGA device with black aperture: 1280x1024; 1,310,720 mirrors]
Actuators: Electrostatic

- Notes:
  - Displacement vs. Actuation Voltage
  - Spring Constants
  - Damping Coefficient
  - Lumped Element Dynamic Model
Actuators: Electrostatic

- Comb Drive
  - Sandia Example

- Comb Drive
  - Stationary Comb
  - Moveable Comb
  - Anchor
  - Folded Spring Suspension Truss
  - Stationary Comb
  - Drive Line
  - Sense Line
  - Bumper/Limiter
  - Ground

EE 480/680, Summer 2006, WSU, L. Starman
MicroElectroMechanical Systems (MEMS)
Actuators: Electrostatic

• Comb Drive Notes:
  • Displacement vs. Actuation Voltage
  • Spring Constants

Actuators: Electrostatic

• Scratch Drive
  • First demonstrated by:

\[ \Delta x \sim \text{few nm} \]

\[ \text{strong force} \]
Actuators: Electrostatic

• Scratch Drive
Actuators: Electrostatic

• When driving with a zero-bias input signal, the frequency of operation is twice the input signal frequency!

\[
\frac{1}{f_{\text{Drive}}} \quad \frac{1}{2f_{\text{Drive}}}
\]

Actuator Displacement

Drive Voltage

Actuators: Electrostatic

• Cantilever
  • Simpler Structure
  • Modeling Voltage vs. Deflection more complicated.

**Actuators: Resonant Frequency**

- Best and Easiest: By Eye
- 2nd Best: Electrically (Network/Spectrum Analyzer/Impedance Analyzer)

**Comb Setup**

![Comb Setup Diagram]

**Cantilever Setup**

![Cantilever Setup Diagram]

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**Actuators**

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  - Mechanical Components
Actuators: Electro-Thermal

- Advantages
  - Simple Designs
  - Simple Fabrication
  - High Force Per Unit Volume
  - Low Voltage

- Disadvantages
  - Temperature Dependent
  - High Electric Power Consumption
  - Low Frequency Operation

Material expands due to Ohmic or Joule Heating causing motion of actuator structure.

\[ q = \text{Power} = I^2 R = \frac{I^2 L \rho}{A} \quad \text{or} \quad \frac{V^2}{R} = \frac{V^2 A}{L \rho} \quad \hat{q} = \frac{\text{Power}}{\text{Volume}} = \frac{I^2 \rho}{A^2} \quad \text{or} \quad \frac{V^2}{L^2 \rho} \]

Heat Transfer

\[ k \frac{\partial^2 T}{\partial x^2} + \hat{q} = 0 \]

Thermal Expansion

\[ T(x) = \frac{1}{2} k \left( Lx - x^2 \right) + \frac{1}{L} (T_2 - T_1)x + T_1 \quad L_{new} (x) = \left[ 1 + \alpha (T(x) - T_0) \right] dX \]
Actuators: Electro-Thermal

• Laterally/Horizontally Deflecting
  • Motion that is parallel to the plane of the substrate

Example properties needed for modeling an electro-thermal actuator:
- \( \rho \) = electrical resistivity = \( 2.3 \times 10^{-5} \) \( \Omega \) m
- \( \alpha \) = coefficient of thermal expansion = \( 29 \times 10^{-7} \) K\(^{-1}\)
- \( \alpha_r \) = temperature coefficient of resistance = \( 1.25 \times 10^{-3} \) K\(^{-1}\)
- \( k \) = thermal conductivity = 32 W/mK
- \( E \) = Young’s modulus = 169 GPa
- \( v \) = Poisson’s ratio = 0.22

Optimum Dimensions:
1. \( g \) = as small as possible
2. \( h \) = as tall as possible
3. \( W_c/W_h = 7 \)
4. \( W_h \) = as small as possible
5. \( L_f \approx L_h/4 \)
6. Increasing the temp. difference between the cold and hot arm increases deflection.

Comtois et al., 1995

Optimum Dimensions (Continued):
- \( W_c = 14 \mu m \)
- \( W_f = g = 2 \mu m \)
- \( L_c = 35 \mu m \)
- \( L_f = 35 \mu m \)
- \( L_h = 200 \mu m \)
- \( R = 1558 \Omega \)
- Force \( \approx 20 \mu N \)

Comtois et al., 1995

V. Bright et al., AFIT, 1996

Actuators: Electro-Thermal

• Laterally (Horizontally) Deflecting
Actuators: Electro-Thermal

- Low resistance wiring and Si/Au eutectic

“Burned out” electro-thermal actuator hot arm

Eutectic Compound 18.6%Si/81.4%Au with melting temperature of 363 °C

Actuators: Electro-Thermal

- Temperature Distribution (Relative Magnitude)

Temperature (K/μm)

$T_{\text{hot arm}} = 293$ K

$T_{\text{cold arm}} = 293$ K

Conduction through air

Air

adiabatic top and vertical sides

Hot Arm

Cold Arm

Temperature vs. x (μm)
Actuators: Electro-Thermal

V. Bright, AFIT
Actuators: Electro-Thermal

D. Burns et al., AFIT

Design measurements for thermal actuators

<table>
<thead>
<tr>
<th></th>
<th>1-H actuator</th>
<th>2-H actuator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold arm length</td>
<td>182 μm</td>
<td>182 μm</td>
</tr>
<tr>
<td>Cold arm width</td>
<td>14 μm</td>
<td>14 μm</td>
</tr>
<tr>
<td>Flexure length</td>
<td>38 μm</td>
<td>38 μm</td>
</tr>
<tr>
<td>Flexure width</td>
<td>2.5 μm</td>
<td>2.0 μm</td>
</tr>
<tr>
<td>Inner hot arm length</td>
<td>200 μm</td>
<td>222 μm</td>
</tr>
<tr>
<td>Outer hot arm length</td>
<td>not applicable</td>
<td>252 μm</td>
</tr>
<tr>
<td>Hot arm width</td>
<td>2.5 μm</td>
<td>2.0 μm</td>
</tr>
<tr>
<td>Separation between inner hot arm and cold arm</td>
<td>3 μm</td>
<td>3 μm</td>
</tr>
<tr>
<td>Separation between hot arms</td>
<td>not applicable</td>
<td>3 μm</td>
</tr>
</tbody>
</table>

Comparison of single hot-arm (1-H) and double hot-arm (2-H) actuator operating properties

Actuators: Electro-Thermal

- Vertically Deflecting

- Piston Mirrors

W. D. Cowan, AFIT
**Actuators: Electro-Thermal**

- Assembled Devices: Micro-Robot Leg

![Micro-Robot Leg Image](image)

- Low resistance wire necessary for electro-thermal actuation

![Low Resistance Wire Image](image)

Chains are very high resistance, but will provide potential for electrostatic actuators.

*Does not work for electro-thermal*

![Chains Image](image)
**Actuators: Electro-Thermal**

- Assembled Devices: Mirror & Micro-Grippers

W. D. Cowan, AFIT  
J. Comtois, AFIT

**Actuators: Electro-Thermal**

- Back bending
  - The permanent plastic deformation of a “hot arm”.
  - Performed once before beginning normal operation.

W. D. Cowan, AFIT

R. Reid, AFIT, 1996
Actuators: Electro-Thermal

- The design of an electro-thermal actuator is a compromise between thermal and mechanical efficiency!
  - Design domain size
  - Location of electrodes
  - Location of work point
  - Electrical resistance
  - Amount of material used
  - Available voltage
  - Optional:
    - Analytical modeling of the temperature distribution of a laterally deflecting electro-thermal actuator.

![Diagram showing electro-thermal actuator design parameters and temperature distribution.]

**Graph:**
- Temperature (°C) vs. Distance along actuator (m)
- Max temperature: $T_{max} = 1523.7436$°C
- Max displacement: $x_{max} = 130.3 \, \mu m$
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Actuators: Bimorph Electro-Thermal

- An actuator made up of a sandwich of at least two layers with different coefficients of thermal expansion and an internal electric heater.
Actuators: Bimorph Electro-Thermal

Actively moves when heated by an internal electric heater.

\[ R = \frac{(t_1 - t_2)}{6(\alpha_1 - \alpha_2)(T - T_0)t_1t_2} \]

- \( R \) = Radius of Curvature
- \( t \) = thickness
- \( \alpha \) = coefficient of thermal expansion
- \( T \) = temperature
- \( T_0 \) = reference temperature

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Actuators: Residual Stress

- A passive actuator, usually in the form of a cantilever, made up of a sandwich of at least two layers with different coefficients of thermal expansion.

 assembled with residual stress cantilevers.

Possibly assisted by unintentional agitation during release, rinse, and/or dry.

Actuators: Residual Stress

- Assembled with intentional agitation during release and rinse.

Assisted by stressed cantilevers.
Actuators: Other

- Most other actuators are further extensions of the basic examples covered in the previous slides.
- Other types of actuation include:
  - Piezoelectric
  - Magnetic / Electro-Magnetic
  - Pneumatic
  - Shape Memory Alloy

Actuators: Piezoelectric

- In a piezoelectric material, an applied voltage induces an internal stress, resulting in an expansion of the material.
- Conversely, for sensor use, the application of an external force induces an electric field across the material.
Actuators: Magnetic / Electro-Magnetic


Actuators: Pneumatic

Actuators: Shape Memory Alloy (SMA)


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Mechanical Components: Substrate or Staple Hinges

\[
l_h \geq t_p \cos(\alpha) + t_p \sin(\alpha)
\]

\[
l_h \geq t_p + t_p \cos(\alpha) + t_t \sin(\alpha)
\]

\[
l_h \geq \text{minimum fabrication spacing (for } \alpha > 90^\circ)\]

Mechanical Components: Scissor Hinges

- “Up - Folding”
  \[
l_h \geq t_p \cot\left(\frac{\alpha}{2}\right)
\]
  \[
l_h \geq \text{minimum fabrication spacing (for } \alpha > 90^\circ)\]
Mechanical Components: Scissor Hinges

- “Down - Folding”

Mechanical Components: Hinges

- Down - Folding
- Up - Folding
- Slider
- Substrate Hinges
Mechanical Components: Pin Joint

Mechanical Components: Linkages
Mechanical Components: Locks

4 μm steps

Locking Mechanism
Mechanical Components: Springs

Mechanical Components: Other

- Gears
- Flexible Hinges
- Corrugation or Stiffening