Sensor and Actuator Technology

Agenda:
- Classification
- Transduction Mechanisms
- MEMS System
- MEMS Design Methodology
- MEMS Design Specifications

Reading: Senturia, Ch. 2 pp. 15-28.
Classification

■ Transducer
  ➣ Element that converts one form of energy to another.
  ➣ May include
    – sensors (for measurement)
    – actuators (for doing work)
    – displays

■ Microsensor or microactuator
  ➣ a sensor or actuator that is manufactured using microfabrication and micromachining techniques

■ Other microstructures that neither sense nor actuate.
  ➣ Microchannels, micronozzles, microlenses, etc.
# Transduction Mechanisms

## Table 56.1: Physical and Chemical Transduction Principles

<table>
<thead>
<tr>
<th>Primary Signal</th>
<th>Mechanical</th>
<th>Thermal</th>
<th>Secondary Signal</th>
<th>Magnetic</th>
<th>Radiant</th>
<th>Chemical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>(Fluid) mechanical and acoustic effects (e.g., diaphragm, gravity balance, echo sounder)</td>
<td>Friction effects (e.g., friction carimenter)</td>
<td>Piezoelectricity</td>
<td>Magneto-mechanical effects (e.g., piezo-, magnetic effect)</td>
<td>Photocaloric systems (stress-induced birefringence)</td>
<td>Reaction activation (e.g., thermal dissociation)</td>
</tr>
<tr>
<td>Thermal</td>
<td>Thermal expansion (bimetal strip, liquid-in-glass and gas thermometers, resonant frequency)</td>
<td>Seebeck effect</td>
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<tr>
<td>Radiometer effect (light null)</td>
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<tr>
<td>Electrical</td>
<td>Electrokinetic and electromechanical effects (e.g., piezoelectricity, electrometer, Ampere's law)</td>
<td>Joule (resistive) heating</td>
<td>Charge collectors</td>
<td>Riot-Sart's law</td>
<td>Electro-optical effects (e.g., Kerr effect)</td>
<td>Electrolysis</td>
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<tr>
<td></td>
<td></td>
<td>Pellicer effect</td>
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<td>Electromigration</td>
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<tr>
<td>Magnetic</td>
<td>Magnetomechanical effects (e.g., magnetoresistive), magnetometer</td>
<td>Thermomagnetic effects (e.g., Oersted effect)</td>
<td>Thermomagnetic effects (e.g., Faraday effect)</td>
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<td></td>
<td></td>
<td>Galvanomagnetic effects (e.g., Faraday effect)</td>
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<tr>
<td>Radiant</td>
<td>Radiation pressure</td>
<td>Bolometer thermopile</td>
<td>Photocative effects (e.g., photoelectric, photoconductive)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Chemical</td>
<td>Hygrometer</td>
<td>Calorimeter</td>
<td>Potentiometry</td>
<td></td>
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<tr>
<td></td>
<td>Electrodeposition cell</td>
<td>Thermal conductivity cell</td>
<td>Conductimetry</td>
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<tr>
<td></td>
<td>Photoacoustic effect</td>
<td></td>
<td>Amperometry</td>
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<td></td>
<td></td>
<td></td>
<td>Flame ionization</td>
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<td>Volta effect</td>
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<td></td>
<td></td>
<td></td>
<td>Gas-sensitive field effect</td>
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### Transduction Mechanisms

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<th>Primary Signal</th>
<th>Mechanical</th>
<th>Electrical</th>
</tr>
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<tbody>
<tr>
<td>Primary Signal</td>
<td>Frictional and inertia, gravity, balance, etc.</td>
<td>Torsional, bending, etc.</td>
</tr>
<tr>
<td>Thermal</td>
<td>Frictional effect, thermal expansion</td>
<td>Calorimeters, thermal effects, etc.</td>
</tr>
<tr>
<td>Electrical</td>
<td>Electrokinetic and electro mechanical effects, etc.</td>
<td>Charge collectors, Langmuir probe, etc.</td>
</tr>
<tr>
<td>Magnetic</td>
<td>Magnetic effects, e.g., Biot-Savart's law</td>
<td>Electrooptical effects, electrolysis, electromigration</td>
</tr>
</tbody>
</table>

**Motorola’s integrated pressure sensor**

- **Piezoelectricity**
- **Piezoresistivity**
- **Resistive, capacitive, and inductive effects**
Transduction Mechanisms

**Mechanical**
- Friction effects (e.g., friction gages)
- Inductance (e.g., inductive proximity sensors, reed relays, balanced electro-mechanical, and thermal flow meters)

**Optical**
- Photoelastic systems (stress-induced birefringence)
- Interferometers
- Tunable VCSELs
- Sagnac effect
- Doppler effect

**Electrical**
- Thermal expansion
- Chemical transduction

**Chemical**
- Electrolysis
- Photochemical effects

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JAMES S. HARRIS GROUP at Stanford University

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TABLE 5.1 Physical and Chemical Transduction Principles

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<th>Chemical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction</td>
<td>Friction gages</td>
<td>Thermoelectricity</td>
<td>Magneto-mechanical effects</td>
<td>Photoelectricity</td>
</tr>
<tr>
<td>Inductance</td>
<td>Inductive proximity sensors</td>
<td>Inductive effects</td>
<td>Inductive effects</td>
<td>Photochemical effects</td>
</tr>
</tbody>
</table>

Transduction Mechanisms

Thermal expansion:
(bimetal strip, liquid- and gas thermometers, resonant frequency)
Radiometer effect (light mill)

Mechanical:
• Xie’s group at University of Florida
MEMS Transducer Systems

- Modular MEMS system design
  - Sensor design
  - Actuator design
  - Interface design
  - Packaging design
MEMS Transducer Systems

- Separate components
  - Signal attenuation
  - Noise
  - Packaging

OUTSIDE WORLD

USER
MEMS Transducer Systems

- Integrated sensors
MEMS Transducer Systems

- Integrated microsystems
MEMS Design Strategy

- Technology-driven or market-driven?
- High-Level Design Issues
  - Market, Impact, Competition, Technology, Manufacturing

Relative Importance of High-Level Design Issues

<table>
<thead>
<tr>
<th>Category</th>
<th>Markets</th>
<th>Impact</th>
<th>Competition</th>
<th>Technology</th>
<th>Manufacturing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology Demonstration</td>
<td></td>
<td>++</td>
<td></td>
<td>+++</td>
<td></td>
</tr>
<tr>
<td>Research Tools</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+++</td>
<td>++</td>
</tr>
<tr>
<td>Commercial Products</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
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</tr>
</tbody>
</table>

MEMS Design Process

MEMS Design Methodology

- Top-down design
  - System level
  - Device: macromodels
  - Physical: numerical modeling, finite-element methods
  - Process: TCAD or Technology CAD

- Bottom-up verification
MEMS Design Methodology

Definitions:

\( P(t) = \text{physical variable (input)} \)

\( x(t) = \text{sensor excitation} \)

\( y(t) = \text{sensor response (output)} \)

- **Calibration**
  
  \( P_{\text{meas.}}(t) = P(t) \)

  determines the function that relates \( y(t) \) to known physical input, \( P(t) \)
MEMS Design Specifications (2)

- **Full Scale Output**
  - algebraic difference between upper and lower endpoints of output

- **Linearity**
  - closeness of calibration curve to a specified straight line (maximum deviation of calibration point from straight line as percentage of *Full Scale Output* )

- **Offset**
  - *y(t)* under normal excitation and zero applied input, *P(t)=0*
MEMS Design Specifications (3)

- Hysteresis
  - maximum difference in $y(t)$ when the value is approached first with increasing input and second with decreasing input, expressed in percent *Full Scale Output*

- Error
  - difference between measured $P(t)$ and true value of $P(t)$ (usually indicated as percentage of *Full Scale Output*)
MEMS Design Specifications (4)

- **Sensitivity**
  - magnitude of change of $y(t)$ with respect to change in $P(t)$, $S = \frac{\Delta y(t)}{\Delta P(t)}$

- **Accuracy**
  - ratio of *Error* to *Full Scale Output* expressed in percentage

- **Repeatability**
  - agreement between independent measurements made under the identical conditions (maximum difference in output readings given as % of *Full Scale Output*)

- **Resolution**
  - smallest change in $P(t)$ that results in a detectable change in $y(t)$ (called *Threshold* if increment is from zero)

- **Frequency Response**
  - change with frequency, $\omega = 2\pi f$, of output/input magnitude ratio and phase difference for sinusoidally varying input
MEMS Design Specifications (5)

- **Cross-axis sensitivity**
  - Sensitivity of sensor to transverse acceleration or other transverse input (also known as transverse sensitivity)

- **Signal-to-Noise**
  - $S/N = y/n_{\text{rms}}$ where $y$ is the output magnitude and $n_{\text{rms}}$ is the root-mean-square noise

- **Selectivity**
  - Ability to measure one input (measurand) in the presence of other inputs

- **Overload characteristics**
  - Maximum magnitude of input that can be applied to the sensor without changing the sensor response

- **Stability**
  - Ability of sensor to reproduce output for identical input and conditions over time (expressed as percent of *Full Scale Output*)
Homework 1

Due: Wednesday, September 1

Problem 1.1 (Textbook)
A Library Treasure Hunt: By consulting recent issues of at least two of the following MEMS-oriented journals, locate articles that illustrate (a) accelerometers for human activity monitoring or civil infrastructure security, (b) MEMS optical imaging, (c) MEMS optical switching, (d) MEMS biosensors, (e) RF MEMS, and (f) MEMS microphones. The journals are: IEEE/ASME Journal of Microelectromechanical Systems, Journal of Micromechanics and Microengineering, Sensors and Actuators, Sensors and Materials, IEEE Sensors Journal, and Biomedical Microdevices. Give full citations of at least two articles for each of the above topics. List the top 2 topics that are most interesting to you.


Problem 1.2 (Textbook)
An On-Line Treasure Hunt: By consulting the events calendar at the web site http://www.memsnet.org (or some other MEMS-oriented web site), identify conferences scheduled for the coming year that cover some combination of (a) accelerometers for human activity monitoring or civil infrastructure security, (b) MEMS optical imaging, (c) MEMS optical switching, (d) MEMS biosensors, (e) RF MEMS, and (f) MEMS microphones.