SENSORS
a.k.a.
Interfacing to the Real World:
Review of Electrical Sensors and Actuators

Andrew Mason
Associate Professor, ECE

Teach: Microelectronics (analog & digital integrated Circ., VLSI)
Biomedical Engineering (instrumentation)
Research: Integrated Microsystems (on-chip sensors & circuits)
Transducers

• **Transducer**
  - a device that converts a primary form of energy into a corresponding signal with a different energy form
    - **Primary Energy Forms**: mechanical, thermal, electromagnetic, optical, chemical, etc.
  - take form of a *sensor* or an *actuator*

• **Sensor** (e.g., thermometer)
  - a device that detects/measures a signal or stimulus
  - acquires information from the “real world”

• **Actuator** (e.g., heater)
  - a device that generates a signal or stimulus
Sensor Systems

Typically interested in **electronic sensor**
- convert desired parameter into electrically measurable signal

- **General Electronic Sensor**
  - **primary transducer**: changes “real world” parameter into electrical signal
  - **secondary transducer**: converts electrical signal into analog or digital values

- **Typical Electronic Sensor System**
Example Electronic Sensor Systems

- Components vary with application
  - digital sensor within an instrument
    - microcontroller
      - signal timing
      - data storage
    - analog sensor analyzed by a PC
  - multiple sensors displayed over internet
Primary Transducers

- **Conventional Transducers**
  *large, but generally reliable, based on older technology*
  - thermocouple: *temperature difference*
  - compass (magnetic): *direction*

- **Microelectronic Sensors**
  *millimeter sized, highly sensitive, less robust*
  - photodiode/phototransistor: *photon energy (light)*
    - infrared detectors, proximity/intrusion alarms
  - piezoresisitve pressure sensor: *air/fluid pressure*
  - microaccelerometers: *vibration, Δ-velocity (car crash)*
  - chemical sensors: $O_2, CO_2, Cl, Nitrates$ (explosives)
  - DNA arrays: match *DNA sequences*
Example Primary Transducers

- **Light Sensor**
  - photoconductor
    - light $\rightarrow$ $\Delta R$
  - photodiode
    - light $\rightarrow$ $\Delta I$

- **membrane pressure sensor**
  - resistive (pressure $\rightarrow$ $\Delta R$)
  - capacitive (pressure $\rightarrow$ $\Delta C$)
Displacement Measurements

• Measurements of size, shape, and position utilize displacement sensors

• Examples
  - diameter of part under stress (direct)
  - movement of a microphone diaphragm to quantify liquid movement through the heart (indirect)

• Primary Transducer Types
  - Resistive Sensors (Potentiometers & Strain Gages)
  - Inductive Sensors
  - Capacitive Sensors
  - Piezoelectric Sensors

• Secondary Transducers
  - Wheatstone Bridge
  - Amplifiers
Strain Gage: Gage Factor

- Remember: for a strained thin wire
  \[ \frac{\Delta R}{R} = \frac{\Delta L}{L} - \frac{\Delta A}{A} + \frac{\Delta \rho}{\rho} \]
  - \[ A = \pi \left(\frac{D}{2}\right)^2, \] for circular wire

- Poisson’s ratio, \( \mu \): relates change in diameter \( D \) to change in length \( L \)
  \[ \frac{\Delta D}{D} = -\mu \frac{\Delta L}{L} \]

- Thus
  \[ \frac{\Delta R}{R} = (1+2\mu) \frac{\Delta L}{L} + \frac{\Delta \rho}{\rho} \]
  - dimensional effect, piezoresistive effect

- Gage Factor, \( G \), used to compare strain-gate materials
  \[ G = \frac{\Delta R}{R} = (1+2\mu) + \frac{\Delta \rho}{\rho} \]
Temperature Sensor Options

- **Resistance Temperature Detectors (RTDs)**
  - Platinum, Nickel, Copper metals are typically used
  - positive temperature coefficients
    \[ R_T = R_0 \left[ 1 + \alpha_1 T + \alpha_2 T^2 + \cdots \alpha_n T^n + \cdots \right] = R_0 \left[ 1 + \alpha T \right] \]

- **Thermistors** ("thermally sensitive resistor")
  - formed from semiconductor materials, not metals
    - often composite of a ceramic and a metallic oxide (Mn, Co, Cu or Fe)
  - typically have negative temperature coefficients
    \[ R_T = R_0 \exp \left( B \left( \frac{1}{T} - \frac{1}{T_0} \right) \right) \]

- **Thermocouples**
  - based on the Seebeck effect: dissimilar metals at diff. temps. \( \rightarrow \) signal

<table>
<thead>
<tr>
<th>THERMOCOUPLES</th>
<th>RTD</th>
<th>IC</th>
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</thead>
<tbody>
<tr>
<td><strong>ACCURACY</strong></td>
<td>Limits of error wider than RTD or IC Sensor</td>
<td>Better accuracy than thermocouple</td>
</tr>
<tr>
<td><strong>RUGGEDNESS</strong></td>
<td>Excellent</td>
<td>Sensitive to strain and shock</td>
</tr>
<tr>
<td><strong>TEMPERATURE</strong></td>
<td>-400 to 4200° F</td>
<td>-200 to 1475° F</td>
</tr>
<tr>
<td><strong>DRIFT</strong></td>
<td>Higher than RTD</td>
<td>Lower than TC</td>
</tr>
<tr>
<td><strong>LINEARITY</strong></td>
<td>Very non-linear</td>
<td>Slightly non-linear</td>
</tr>
<tr>
<td><strong>RESPONSE</strong></td>
<td>Fast dependent on size</td>
<td>Slow due to thermal mass</td>
</tr>
<tr>
<td><strong>COST</strong></td>
<td>Rather inexpensive except for noble metals TCs, which are very expensive</td>
<td>More expensive</td>
</tr>
</tbody>
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Fiber-optic Temperature Sensor

- **Sensor operation**
  - small prism-shaped sample of single-crystal undoped GaAs attached to ends of two optical fibers
  - light energy absorbed by the GaAs crystal depends on temperature
  - percentage of received vs. transmitted energy is a function of temperature

- **Can be made small enough for biological implantation**

![Diagram of GaAs semiconductor temperature probe]
Example MEMS Transducers

- **MEMS** = micro-electro-mechanical system
  - miniature transducers created using IC fabrication processes
- **Microaccelerometer**
  - cantilever beam
  - suspended mass
- **Rotation**
  - gyroscope
- **Pressure**
  - Diaphragm (Upper electrode)
  - Lower electrode

Dimensions: 5-10mm
Passive Sensor Readout Circuit

- **Photodiode Circuits**
  - ![Photodiode Circuit Diagram]
  - Voltage divider
  - One element varies

- **Thermistor Half-Bridge**
  - Voltage divider
  - One element varies

- **Wheatstone Bridge**
  - R3 = resistive sensor
  - R4 is matched to nominal value of R3
  - If R1 = R2, V\text{out-nominal} = 0
  - V\text{out} varies as R3 changes
  - \[ V_{\text{out}} = V_{\text{CC}} \left( \frac{R_3}{R_2 + R_3} - \frac{R_4}{R_1 + R_4} \right) \]
Operational Amplifiers

• Properties
  - open-loop gain: ideally infinite; practical values 20k-200k
    • high open-loop gain \(\rightarrow\) virtual short between + and - inputs
  - input impedance: ideally infinite: CMOS opamps are close to ideal
  - output impedance: ideally zero; practical values 20-100\(\Omega\)
  - zero output offset: ideally zero; practical value <1mV
  - gain-bandwidth product (GB): practical values ~MHz
    • frequency where open-loop gain drops to 1 V/V

• Commercial opamps provide many different properties
  - low noise
  - low input current
  - low power
  - high bandwidth
  - low/high supply voltage
  - special purpose: comparator, instrumentation amplifier
Basic Opamp Configuration

- **Voltage Comparator**
  - digitize input

- **Voltage Follower**
  - buffer

- **Non-Inverting Amp**
  - circuit diagram
  - equation: $V_{out} = \left(1 + \frac{R_2}{R_1}\right)V_{in}$

- **Inverting Amp**
  - circuit diagram
  - equation: $V_{out} = -\frac{R_2}{R_1}V_{in}$
More Opamp Configurations

- **Summing Amp**

- **Differential Amp**

- **Integrating Amp**

- **Differentiating Amp**
Converting Configuration

- **Current-to-Voltage**
  
  ![Current-to-Voltage Diagram]
  
  \[ V_{\text{out}} = -I_{\text{in}}R \]

- **Voltage-to-Current**
  
  ![Voltage-to-Current Diagram]
  
  \[ I_L = \frac{V_{\text{in}}}{R} \]
Instrumentation Amplifier

- Robust differential gain amplifier

- Input stage
  - high input impedance
    - buffers gain stage
  - no common mode gain
  - can have differential gain

- Gain stage
  - differential gain, low input impedance

- Overall amplifier
  - amplifies only the differential component
    - high common mode rejection ratio
  - high input impedance suitable for biopotential electrodes with high output impedance

\[
G_d = \frac{2R_2 + R_1}{R_1} \left( \frac{R_4}{R_3} \right)
\]
With 776 op amps, the circuit was found to have a CMRR of 86 dB at 100 Hz and a noise level of 40 mV peak to peak at the output. The frequency response was 0.04 to 150 Hz for ±3 dB and was flat over 4 to 40 Hz. The total gain is 25 (instrument amp) x 32 (non-inverting amp) = 800.
Connecting Sensors to Microcontrollers

• Analog
  - many microcontrollers have a built-in A/D
    • 8-bit to 12-bit common
    • many have multi-channel A/D inputs

• Digital
  - serial I/O
    • use serial I/O port, store in memory to analyze
    • synchronous (with clock)
      - must match byte format, stop/start bits, parity check, etc.
    • asynchronous (no clock): more common for comm. than data
      - must match baud rate and bit width, transmission protocol, etc.
  - frequency encoded
    • use timing port, measure pulse width or pulse frequency
Connecting Smart Sensors to PC/Network

• “Smart sensor” = sensor with built-in signal processing & communication
  - e.g., combining a “dumb sensor” and a microcontroller

• Data Acquisition Cards (DAQ)
  - PC card with analog and digital I/O
  - interface through LabVIEW or user-generated code

• Communication Links Common for Sensors
  - asynchronous serial comm.
    • universal asynchronous receive and transmit (UART)
      - 1 receive line + 1 transmit line, nodes must match baud rate & protocol
    • RS232 Serial Port on PCs uses UART format (but at +/- 12V)
      - can buy a chip to convert from UART to RS232
  - synchronous serial comm.
    • serial peripheral interface (SPI)
      - 1 clock + 1 bidirectional data + 1 chip select/enable
  - \( \text{I}^2\text{C} = \text{Inter Integrated Circuit bus} \)
    • designed by Philips for comm. inside TVs, used in several commercial sensor systems
    • several different sensor comm. protocols for different applications
Sensor Calibration

- **Sensors can exhibit non-ideal effects**
  - **offset**: nominal output ≠ nominal parameter value
  - **nonlinearity**: output not linear with parameter changes
  - **cross parameter sensitivity**: secondary output variation with, e.g., temperature

- **Calibration** = adjusting output to match parameter
  - analog signal conditioning
  - look-up table
  - digital calibration
    - $T = a + bV + cV^2$,
      - $T =$ temperature; $V =$ sensor voltage;
      - $a, b, c =$ calibration coefficients

- ** Compensation**
  - remove secondary sensitivities
  - must have sensitivities characterized
  - can remove with polynomial evaluation
    - $P = a + bV + cT + dVT + eV^2$, where $P =$ pressure, $T =$ temperature