### Learning Outcomes

- **Sensors**
- Resolution, Sensitivity, Operating Range
- Displacement Sensors
  - Potentiometers
  - Strain Gauges
  - Capacitive Sensors
  - Inductive Sensors
- Temperature Sensors
  - Thermistors
  - Thermocouples
**Sensor:** device which detects changes in quantities of interest and provides a readable output

**Examples**

- Thermocouple converts temperature to voltage.
- Mercury thermometer converts temperature to a reading on a calibrated glass tube.
Resolution

- Smallest change measurable

Sensitivity

\[ \text{Sensitivity} = \frac{\Delta \text{signal}}{\Delta \text{measurand}} \]
Many sensors have a linear operating range.

Outside this range we have the maximum operating range (that doesn’t damage the instrument)

**Thermometer**

Reading on thermometer (output)

Temperature (input)

**Linear Range**

**Maximum Range**

Melting
Sensor Types:

- **Displacement Sensors:**
  - Resistive
  - Inductive
  - Capacitive
- **Temperature Measurement**
  - Thermistors
  - Thermocouples
- **Also:** time, light, chemical, electromagnetic ...
Potentiometers

Construction
- Wire wound
- Carbon film
- Ceramic
- Conducting plastic

(a) Translational
(b) Single-turn
(c) Multi-turn
If we apply 10V across a single turn potentiometer with 50 wire turns covering 250°.

- What is sensitivity (in volts/degree)?
- What is resolution?

(b) Single-turn

110°
Strain gauge measures strain (deformation) by a change in resistance.

- Measurement circuits typically use Wheatstone bridge

**Gauge Factor:** measure of gauge sensitivity

\[ GF = \frac{\Delta R}{R} / \text{strain} \]

- \( R \): undeformed resistance
- \( \Delta R \): change in \( R \) due to strain
- \text{strain: fractional change in length (}\Delta L/L\text{)}
Strain Gauge: analysis

Gauge Factor

\[ G = \frac{\partial R/R}{\partial L/L} = 1 + 2\mu + \frac{\partial \rho/\rho}{\partial L/L} \]

- **Dimensional Effect**
- **Piezoresistive Effect**
  - Metals \( \approx 0 \)
  - Ceramics / Semiconductors have large effect

Examples:
- Metals \( G = 1 + 2(0.3) = 1.6 \)
- n-Si \( G \approx 100 \)
- p-Si \( G \approx -100 \)
  (large temperature drift in semis)
Mercury plethysmograph measures change in leg blood volume after pressure cuff applied (venous occlusion)

- $\mu$ for Hg is 0.5
- Calculate $\Delta R/R$ if blood makes 10% increase in diameter
  
  $$G = 1 + 2 \times 0.5 = 2$$
  
  $$\Delta R/R = G \times (\Delta R/R) = 0.2$$

Note: Hg no longer used.
Quarter-bridge strain gauge circuit with temperature compensation

Source: https://www.allaboutcircuits.com/textbook/direct-current/chpt-9/strain-gauges/
Initially $R_1 = R_2 = R_3 = R_4 = 1k$

Source $V = 10V$

Strain makes $R_4$ increase to 1.1k

Strain makes $R_2$ increase to 1.01k

What is $V$?
- $V_A = 5V$
- $V_B = 10V \times \frac{R_4}{R_2 + R_4} = 5.21V$
- $V = V_A - V_B = -0.21V$

Temperature increase makes both $R_4$ and $R_2$ decrease by 5%. What is $V$?
Strain Gauges + Bridge Circuits

Source: https://www.allaboutcircuits.com/textbook/direct-current/chpt-9/strain-gauges/
Analysis of SG

\[ R = \frac{\rho L}{A} \]

\[ \frac{\partial R}{R} = \frac{\partial \rho}{\rho} + \frac{\partial L}{L} - \frac{\partial A}{A} \]

\[ \frac{\partial R}{R} = \frac{\partial \rho}{\rho} + (1 + 2 \mu) \frac{\partial L}{L} \]

\[ G = \frac{\partial R/R}{\partial L/L} = 1 + 2 \mu + \frac{\partial \rho/\rho}{\partial L/L} \]

Poisson’s Ratio (\(\mu\))

\[ \frac{\partial A}{2A} = -\mu \frac{\partial L}{L} \]

For incompressible media \(\mu=0.5\).

Calculate from

Vol = \(D^2L\) is const
Capacitive sensors

- Low cost, small, mechanically strong
- Quite non-linear, better to indicate contact

Source: Salpavaara, et al., 2008.
Capacitive sensors

Electromagnetic analysis

\[ C = \varepsilon_0 \varepsilon_r \frac{A}{x} , \quad \varepsilon_0 = 8.86 \times 10^{-12} \frac{F}{m} \]

Permittivity of free space

Relative Permittivity

\[ K = \frac{dC}{dx} = -\varepsilon_0 \varepsilon_r \frac{A}{x^2} \]

Non-linear Sensitivity

Electronic Circuit
Inductive Sensors

- Inductance sensor measures displacement by changes in geometry.
- Tend to be non-linear, since geometry to inductance relationship is non-linear.
- Many applications: metal detectors, proximity detector, traffic light car presence detector.
Questions

- What is the Gauge factor? What kinds of materials have large G? When is this useful?
- Why is temperature variation in R of a strain gauge a problem? What strategies can be used to help deal with it?
- Name some applications for inductive sensors?
- Since capacitive sensors are highly non-linear, what kinds of applications are they useful for?
Why measure temperature

- Body is a heat engine. We burn food + oxygen to get energy for life. Temperature monitors the functioning of the engine.
- Temperature increase – hyperthermia
  - typical cause: infection
- Temperature decrease – hypothermia
  - typical cause: shock

Instruments

- Thermistors
- Thermocouples
- Radiation (hot objects emit IR radiation – not included)
**thermistor** is a type of resistor with resistance varying according to its temperature.

*thermal* and *resistor* = thermistor

- Biomedical applications: thermometers, flow sensing, breathing (nasal thermistor)
- All resistors have some temperature variation. Thermistors have large tempco (%change/°C)
- Material is generally a ceramic or polymer
As temperature increases, the thermistor resistance decreases, yielding more current that flows through $R_f$, thus $V_o$ increases.

Many different sizes:
- Small Thermistors are more fragile, faster (2s)
- Larger Thermistors respond slowly (10s)
1B. (5 points) A thermistor, $R_T$ is used in the circuit below. At 35°C, $R_T = 100\Omega$ and at 36°C, $R_T = 101\Omega$. **What is $V_O$ for** at 35°C and 36°C?

1C. (5 points) **What is the sensitivity** of at the output of the sensor, $V_O$, in V/°C over the range from 35°C to 36°C?

The circuit is a summing inverting amplifier, whose output we can therefore write as

$$V_O = -10\ k\Omega \cdot \frac{10V}{100\Omega} - \frac{10V}{R_T}$$

At 35°C, $R_T = 100\Omega$ and so $V_O = 0V$, while at 36°C, $R_T = 101\Omega$ and so

$$V_O = -\frac{10\ k\Omega}{100\ \Omega} \cdot 1 - \frac{1}{1.01} \cdot (10V) = -9.90V$$

from which the sensitivity is seen to be $-9.90$ V/°C.
Typical thermistor temperature characteristics for various materials.

Linear model:

\[ \Delta R = k \Delta T \]

where

- \( \Delta R \) = change in resistance
- \( \Delta T \) = change in temperature
- \( k \) = first-order temperature coefficient of resistance

Linear model only works over small range.
Based on Seebeck effect: when a conductor (such as a metal) is subjected to a thermal gradient, it will generate a voltage.

Thermocouples measure the temperature difference, not absolute temperature.

Traditionally, one of the junctions—the cold junction—was maintained at a known (reference) temperature, while the other end was attached to a probe.

Thermocouples are faster, smaller, more robust, more linear than thermistors.
Thermocouples: Usage

The hot junction is at the thermocouple. The LT1025 electronic cold junction compensates for ambient temperature changes. The noninverting amplifier provides a high input impedance and high gain.

Type K (chromel–alumel) commonly used general purpose thermocouple. Inexpensive. Available in the −200°C to +1350°C range.
Sensitivity ≈ 41 µV/°C.
Thermocouple or thermistor?

- Cheap
- Mechanically strong
- Simplest electrical circuit
- Capable of high temperatures
- Fastest response
How does a thermistor differ from a thermocouple? Which is more linear? Which is less brittle? Which can have the fastest response?

What would you build the temperature cut-off switch in a computer from?

Why does a thermocouple need a reference circuit?

What strategies are used to help reduce drift in radiation thermal detectors?