Sensors-Transducers and Actuators
Fundamental elements of a measuring instrument

- **Process or measurement medium**: Physical variable to be measured
  - Input signal
  - Calibration signal
  - Calibration signal source representing known value of physical variable

- **Primary stage**: Detector-transducer
  - Sensing & conversion
  - Transduced signal
  - Feedback signal for control
  - Modified signal

- **Intermediate stage**: Manipulation & transmission
  - External power

- **Final (output) stage**:
  - Controller
  - Indicator
  - Recorder
  - Final (output) stage

- **Environmental effects**: (noise, temperature etc)

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Electronic versus Mechanical Measuring Instruments

- Electronic devices are versatile and easy to use.
- An electrical quantity can be easily manipulated, displayed and used for feedback control.
- Electronic equipment has a very high speed of response; it can be used to measure both static (constant in time) and dynamic (time-varying) signals.
- With electronic equipment, no physical connection is needed between the sensing element and the observer since electromagnetic waves can be used.
Definitions

• Transducer: a device that converts one form of energy into another.

• Sensor: a device that converts a physical parameter to an electrical output.

• Actuator: a device that converts an electrical signal to a physical output.
What to look for in a Sensor?

• Dynamic range
  – Min and max range of the measured physical quantity
  – Min and max range for electric output
• Input/output relation
• Sensitivity/Resolution
  – Smallest change to be detected
• Power requirements
  – Passive vs active
  – Power consumption/requirements
• Band width and frequency response
• How to calibrate
General Sensors

- Resistive
- Capacitive
- Inductive
Resistive Sensors

(a) Translational  
Translational distance from 2 to 500 mm

(b) Single-turn  
Rotational displacements from 10° to 50° or more

(c) Multi-turn

- Linear and active
  $V_o = I \cdot R$
  $R = \text{constant} \cdot \text{Length/area} \ (\rho \cdot L/A)$
Capacitive sensors

- The capacitance between two parallel plates of area $A$ separated by distance $d$ is

\[ C = \varepsilon \frac{A}{d} \]

- $\varepsilon$ is a constant related to the dielectric material between both plates.

- Change $d$ (distance) $\Rightarrow$ change the capacitance
Example Capacitive sensors

- Elevators button switches, calculator key pads,

- Other applications: Position sensing, small dynamic motion,
- Activity, calculate Vo in terms of d
Inductive Sensors
Linear Variable Differential Transformer (LVDT)

- Used to measure pressure, displacement and force
- Inductance \( L \propto \) Distance and number of turns
- Can vary distance and number of turns mechanically
- Non linear
Strain Gauges

• Definitions
• Stress and Strain
• Measuring force and pressure with strain gauges
• Circuits involving strain gauges
Stress and strain

**Tension:** A bar of metal is subjected to a force \( (T) \) that will elongate its dimension along the long axis that is called the *axial* direction.

**Compression:** the force acts in opposite direction and shortens the length

**Stress:** the force per unit area
\[
\sigma_a = \frac{T}{A} \text{ (N/m}^2)\]

**Strain:** The fractional change in length
\[
\varepsilon_a = \frac{dL}{L} \text{ (\mu m/m)}
\]
Stress and strain

• Stress ➔ Internal resistance to external force
• Strain ➔ displacement and deformation due to external force
• Stress is linearly related to strain for elastic materials
  \[ \varepsilon_a = \sigma_a / E_y = (T/A)/E_y \]
• \( E_y \) : constant, T: external force, A: cross area
Strain Gages

- Mechanical motion $\rightarrow$ Electricity
- $\Delta R, \Delta C, \Delta L \propto \varepsilon_a$
- $\Delta R/R = K \varepsilon_a$
- $K$ (gage factor) is ration of relative change in $R$ to relative change in length $L$

$$K = \frac{\Delta R/R}{\Delta L/L}$$
Example: Strain Gage Resistance

- A strain gage has a gage factor 2 and exposed to an axial strain of $300 \, \mu m/m$. The unstrained resistance is $350 \, \Omega$. Find the percentage and absolute changes in the resistance.
  - $\varepsilon_a = 300 \, \mu m/m = 0.3 \times 10^{-3}$;
  - $\Delta R/R = K\varepsilon_a = 0.6 \times 10^{-3}$
  - %age change = 0.06%
  - $\Delta R = 350 \times 0.6 \times 10^{-3} = 0.21 \, \Omega$. 

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Example 2: Strain Gage Resistance

- A strain gage has an unstrained resistance of 1000 $\Omega$ and gage factor of 80. The change in the resistance is 1$\Omega$ when it is exposed to a strain. Find the percentage change in the resistance, the percentage change in the length and the external strain ($\mu$m/m)
  - $\Delta R/R$ (%) = 0.1 %;
  - $\Delta L/L$ (%) = $[\Delta R/R$ (%)]/$K = 1.25 \times 10^{-3}$%,
  - $\varepsilon_a = [\Delta L/L$ (%)]/100 = $1.25 \times 10^{-5} = 12.5 \mu$m/m
Bonded Strain Gage

- Beam deformation ➔ change in resistance proportional to stress and strain
- Change in resistance ➔ change in voltage
- Calculate stress and strain
Un-Bonded Strain gauge as pressure Sensor

- When Pressure increases, strain pairs B and C is increased, while gage pairs A and D is decreased. Wheatstone bridge with four active elements. \( R1 = A, R2 = B, R3 = D, \) and \( R4 = C \) when the un-bonded strain gage is connected for translation motion.
- Resistor \( R_y \) and potentiometer \( R_x \) are used to initially balance the bridge.
- \( v_i \) is the applied voltage and \( Dv0 \) is the output voltage on a voltmeter with an internal resistance of \( R_i \).
THE WHEATSTONE BRIDGE

• Variation in impedance usually small \( \Rightarrow \) use Wheatstone bridge

• Activity:
  – Calculate \( V_A - V_C \)
  – \( V_A - V_C = \)

\[
E_b \left( \frac{R_4}{R_1 + R_4} - \frac{R_3}{R_2 + R_3} \right) = E_b \frac{R_2 R_4 - R_1 R_3}{(R_1 + R_4)(R_2 + R_3)}
\]

• Balanced Bridge \( \Rightarrow R_2 R_4 = R_1 R_3 \) \( \Rightarrow V_A - V_C = 0 \)
Bridge with a Single Active Element (Quarter Bridge)

- R4 is taken as the strain gage.
- R3 is made variable to balance the bridge when there is no force applied
Quarter Bridge Calculation

• Let
  – \( R_1 = R_2 = R_3 = R \) and
  – \( R_4 = R_x = R + \Delta R = R(1 + \Delta R/R) \)

\[
E_0 = E_b \frac{R_2 R_4 - R_1 R_3}{(R_1 + R_4)(R_2 + R_3)} = E_b \frac{R(R + \Delta R) - R^2}{(R + R + \Delta R)(R + R)} = E_b \frac{\Delta R}{2(2R + \Delta R)}
\]
Definition of Temperature

• An expression for the kinetic energy of vibrating atoms and molecules of matter.

• Can be measured by various secondary phenomena, e.g.,
  – change of volume or pressure,
  – electrical resistance,
  – electromagnetic force,
  – electron surface charge, or
  – emission of electromagnetic radiation.
Temperature Measurement
Temperature Scale

- Celsius, divide the difference between the freezing and boiling points of water into 100°
- Fahrenheit which divide the difference between the freezing and boiling points of water into 180°
- °C = (5 /9) (°F - 32), and °F = (9 /5) °C + 32.
- The thermodynamic scale begins at absolute zero, or 0 Kelvin, the point at which all atoms cease vibrating and no kinetic energy is dissipated.
- 0 K = –273.15° C = –459.67° F.
  - The official Kelvin scale does not carry a degree sign. The units are expressed in “kelvins,” not degrees Kelvin.
Temperature measuring devices

• Temperature can be measured via a diverse array of sensors. All of them infer temperature by sensing some change in a physical characteristic.

• In the chemical process industries, the most commonly used temperature sensors are thermocouples, resistive devices and infrared devices.
Fluid-Expansion Devices

• Types:
  – the mercury type: an environmental hazard, so there are regulations governing the shipment of devices that contain it.
  – the organic-liquid type.
  – gas instead of liquid type

• No electric power, do not pose explosion hazards, and are stable even after repeated cycling.

• On the other hand,
  – they do not generate data that are easily recorded or transmitted, and
  – they cannot make spot or point measurements.
Thermocouples

- Two strips or wires made of different metals and joined at one end.
- Changes in temperature at that junction induce changes in the emf between the other ends.
- As temperature goes up, this output emf of the thermocouple rises, though not necessarily linearly.

\[ V_{AB} = \alpha T, \] where \( \alpha \), the Seebeck coefficient, is the constant of proportionality.
Peltier effect

- If a voltage is applied, then there will be temperature change at the junction. This is called the Peltier effect and can be used for heating and cooling (refrigeration).
Thomson effect

- 2nd effect that generates voltage and it is the temperature gradient along a single conductor.
- The net e.m.f. due to this effect is proportional to the difference between the squares of the absolute junction T’s.
- the voltage is actually generated by the section of wire that contains a T gradient, not necessarily by junction.
Equation of a thermocouple

- The output voltage “V” of a simple thermocouple (with a reference temperature $T_0 = 0^\circ C = 32^\circ F$) is:

$$V = AT + \frac{1}{2} BT^2 + \frac{1}{3} CT^3 \text{ volts,}$$

where $T$ is the temperature of the measuring junction in $^\circ C$, $A$, $B$, and $C$ are constants that depend upon the thermocouple material.
Characteristics of thermocouples

![Graph showing millivolt vs temperature for different types of thermocouples: E, J, K, T, and R.]

<table>
<thead>
<tr>
<th>Type of Metals</th>
<th>+</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>E Chromel vs Constantan</td>
<td></td>
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<tr>
<td>J Iron vs Constantan</td>
<td></td>
<td></td>
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<tr>
<td>K Chromel vs Alumel</td>
<td></td>
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<tr>
<td>R Platinum vs Platinum</td>
<td>13% Rhodium</td>
<td></td>
</tr>
<tr>
<td>S Platinum vs Platinum</td>
<td>10% Rhodium</td>
<td></td>
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<tr>
<td>T Copper vs Constantan</td>
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</table>
Resistance Temperature Devices

- Resistance temperature devices capitalize on the fact that the electrical resistance of a material changes as its temperature changes;
- \( R = R_0[1 + \alpha(T - T_0)] \)
- Where \( R_0 \) is the resistance at \( T = T_0 \) and \( \alpha \) is the temperature coefficient of the device. Ex. Thermistors
- Equation of a thermistor

\[
R = R_0 e^{\beta \frac{T_0 - T}{TT_0}}
\]
If the temperature increases, the thermistor resistance decreases, yielding more current that flows through $R_f$, thus $V_0$ increases.
Light Sensors
Optical Sensors

• Light ➔ Electric Energy

• Radiation sources
  – Tungsten lamps
  – Arc discharges
  – Light-emitting diodes (leds)
  – LASERs
Photo-resistor/Photoconductor

- Resistance depends on light
- Made of cadmium sulfide
Photodiode

• Light $\rightarrow$ current or voltage
• Light Photon $\rightarrow$ Electron

• Photo-multiplier
  – Sensitive detectors of light in the ultraviolet, visible, and near-infrared ranges of the electromagnetic spectrum
  – Multiply the current produced by incident light by as much as 100 million times
  – Used in Geiger counters
Light Emitting Diodes (LED)

- Transmit light at different wavelengths (visible, infrared)
- Photodiodes with matching wavelengths are used to detect the light
- Transmitted information can be decoded through voltage to pulse width techniques
Voltage to pulse width coding

• Coding is sometimes referred to as modulation

- Transmitted light can be infra red or laser
Laser Light

- Why laser?
  - Coherent (narrow beam)
  - Less attenuation with distance due to short wavelength

- Detected via photodiode, photo sensors operating at laser wavelengths
X-Ray detection

• X-Ray detectors convert x-ray photons into electric current
• Electrons generated proportional to photons
• Detectors
  – X-Ray film
  – Image intensifier (mesh of photo-diodes)
  – Solid state detectors
Flow and Speed Measurement
Flow measurement using light

• Using Light
  – Two laser sources along a pipe
  – Two Photo sensors to detect laser
  – Sensor 1 picks up the scatter of laser due to flow
  – Sensor 2 picks up the scatter of laser at a later time
  – The time difference can be used to measure the flow
Flow Measurement using Temperature

- As gas/fluid flows → Temperature decreases
- Flow rate can be detected based on the change in temperatures at sensors
Flow Measurements using Magnetic field

• Apply Magnetic field along a pipe
• The flow of the liquid will act as a variable resistance
• The voltage drop across the pipe will be proportional to the flow rate
Ultrasound: Piezoelectric Crystal

- A piezoelectric disk generates a voltage when deformed
- Used to measure strain, force, or pressure by converting them to electricity
- Also used to generate clocks for computers
Piezoelectric Crystal

• A piezoelectric disk generates a force with a voltage is applied
• Used to generate ultrasound waves
Doppler Effect

- Applied in Ultrasound, laser and Radar applications
- Definition:
  - The change in frequency of a wave for an observer moving relative to the source of the waves is proportional to the relative speed between both objects
- Speed detectors, radars, ultrasound imaging, blood flow in arteries ..etc
Doppler Frequency

Doppler frequency is calculated according to: \( \frac{f_d}{f_o} = \frac{u}{c} \), where

\( f_d \) = Doppler frequency shift
\( f_o \) = source frequency
\( u \) = target velocity
\( c \) = velocity of the sound

Two shifts due to two paths yielding

\[ \frac{f_d}{f_o} = \frac{2u}{c + u} \approx \frac{2u}{c} \]

The approximation is valid since \( c \approx 1500 \text{ m/s} \) and \( u \approx 1.5 \text{ m/s} \).

We have to take the transmission angle \( \theta \) into consideration. Then the Doppler frequency becomes

\[ f_d = \frac{2f_0u \cos \theta}{c} \]
Principle Circuits to measure blood flow

\[ f_d = \frac{2 f_o u \cos \theta}{c} \]

Boost Doppler frequency

Detect freq difference

Detect freq difference

Convert frequency difference to voltage

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Summary on Sensors

- Temperature, flow, speed, acceleration, angle, position, pressure, force, light and many physical quantities can be converted to electrical signals through different techniques.
- The resulting electrical signal carries information contained in the physical quantity sensed.
- Signal processing techniques allow us to understand the environment.
Fundamental elements of a measuring instrument

Process or measurement medium
Physical variable to be measured

Primary stage
Detector-transducer
Sensing & conversion

Intermediate stage
Manipulation & transmission

Final (output) stage
Controller
Indicator
Recorder

Feedback signal for control
External power

Modified signal

Calibration signal

Calibration signal source representing known value of physical variable

Environmental effects (noise, temperature etc)

Observer
Quantity presented to observer

Input signal

Transduced signal

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References

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