Sensors – generalities
Deformation sensors
Temperature sensors

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Slides are supplementary material and are NOT a replacement for textbooks and/or lecture notes.
Outline

• Sensor generalities
• Deformation sensors
• Temperature sensors
Sensors

• Convert an input physical property (the *stimulus*) to a different one (usually an electrical signal). Sensors are «energy converters»

• You can find many disquisitions on the difference between *sensors* and *transducers*, which I gladly leave to your rainy day reading
Sensor classification

• Measurand
  – Temperature, pressure, velocity, current,…

• Detection mean
  – Biological, chemical, electrical, mechanical,…

• Sensor material
  – Semiconductor, organic, liquid,…

• Field of application
  – Scientific, industrial, medical,…

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Sensor characteristics

• Static parameters
  – Transfer function, accuracy, resolution,...

• Dynamic parameters
  – Frequency response, settling time,...

• Other parameters
  – Operating and storage conditions, reliability,...
When used as detectors, the inverse function is needed
I-O ranges

Full-scale output

Full-scale input

From [4]
Sensitivity

- Defined as the ratio between output and input variations
  \[ S = \frac{dS_o}{dS_i} \]
- Linear sensors have constant sensitivity
- Linear approximations can be used in other cases, over a limited input range. Otherwise, data processing is required
(Non)Linearity error

Maximum difference between the real transfer function and its linear approximation
Which linear characteristic?

Different straight lines can be defined (end points, least squares,…), giving different NL errors

From [5]
Independent nonlinearity

Adopts the straight line that minimizes the maximum (absolute) NL error

From [4]
Resolution

- Is the smallest increment in stimulus that can be sensed, specified in absolute quantity or percentage of FS input
- Resolution is ultimately determined by the noise of the sensor itself
- Other factors (noise of electronics front-end, digitization,...) can further degrade it
Precision

• Is the ability of the sensor to reproduce the same result after repetitive experiments

• Precision is *not* resolution
  – A digital clock may have ms resolution but worse precision
  – The terms are often (mis)used interchangeably
Accuracy

- Accuracy is the maximum deviation from the ideal value measured for many (nominally identical) sensors.
- The average value should be considered for each sensor in presence of a strong random component.

From [4]
Accuracy vs. precision

- Poor Precision, Good Accuracy
- Good Precision, Good Accuracy

From [6], modified

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Dynamic parameters

- Frequency response
- Response time
- Bandwidth
- ...
References

2. sales.hamamatsu.com/assets/applications/SSD/nmos_kmpd9001e04.pdf
3. iopscience.iop.org/00223727/45/22/225305/article
Outline

• Sensor generalities
• Deformation sensors
• Temperature sensors
Stress and strain

• For the uniform case under normal load we define the stress as

\[ \sigma = \frac{F}{S} \]

• Strain is the deformation per unit length

\[ \varepsilon = \frac{\Delta L}{L} \]

typical values are a few \(10^{-3}\); the value is usually expressed in \(\mu\text{strain}\)
Materials behavior

In the elastic region, the material will return to its original shape when the stress is removed.

- **A brittle material.** This material is also strong because there is little strain for a high stress. The fracture of a brittle material is sudden with little or no plastic deformation. Glass is brittle.

- **A strong material which is not ductile.** Steel wires stretch very little and break suddenly.

- **A ductile material - after the elastic region there is a strange section where ‘necking’ occurs - permanent deformation occurs in this ‘plastic region’**

- **A plastic material - very small elastic region.**

From [1]

From [2]
Hookes’ law

• In the elastic region
  \[ \sigma = E \varepsilon \]
  where \( E \) = Young (or elasticity) modulus

• Axial strain is always accompanied by lateral strains of opposite sign in the two directions perpendicular to the axial strain

• Their ratio is called Poisson ratio
  \[ \nu = - \frac{\varepsilon_{\text{lateral}}}{\varepsilon_{\text{axial}}} \]
Poisson ratio and volume change

\[ V' = L^3 (1 + \varepsilon)(1 - \nu \varepsilon)^2 \]
≈ \[ L^3 (1 + \varepsilon(1 - 2\nu)) \]
\[ \frac{\Delta V}{V} = \varepsilon(1 - 2\nu) \]

- If there is no volume change, \( \nu = 0.5 \)
- Theoretical limits are \(-1 < \nu \leq 0.5\)

From [3]
Typical values

- For compact, weakly compressible materials such as liquids and rubbers, where stress primarily results in shape change, \( \nu \to 0.5 \)
- For most well-known solids such as metals, polymers and ceramics, \( 0.25 < \nu < 0.35 \)
- Glasses and minerals are more compressible, and for these \( \nu \to 0 \)
- For gases, \( \nu = 0 \)
- Materials with negative Poisson’s ratio are called “auxetic” (e.g., Gore-Tex)
Strain gages (gauges)

- Convert strain into a resistance change:
  \[ R = \rho \frac{L}{S} \]
  \[ \frac{\Delta R}{R} = \frac{\Delta \rho}{\rho} + \frac{\Delta L}{L} - \frac{\Delta S}{S} = \frac{\Delta \rho}{\rho} + \varepsilon(1 + 2\nu) \]

- The gauge factor (GF) is defined as
  \[ GF = \frac{\Delta R/R}{\varepsilon} = 1 + 2\nu + \frac{\Delta \rho/\rho}{\varepsilon} \]
## Typical values

<table>
<thead>
<tr>
<th>Material</th>
<th>$GF$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constantans (Ni-Cu alloys)</td>
<td>1.8 − 2.2</td>
</tr>
<tr>
<td>Ni-Cr alloys</td>
<td>~1.9</td>
</tr>
<tr>
<td>Ni</td>
<td>−12</td>
</tr>
<tr>
<td>Pt-Ir</td>
<td>~5</td>
</tr>
<tr>
<td>Si (with various impurities)</td>
<td>±100 − ±200</td>
</tr>
<tr>
<td>Poly-Si</td>
<td>±30</td>
</tr>
</tbody>
</table>
Metal-foil strain gages

From [4] and [5]

The gage consists of a grid of very fine metallic wire or foil bonded to the strained surface or carrier matrix by a thin layer of epoxy (which must transmit the mechanical strain and be an electrical insulator)
Thin film strain gages

An insulation layer (typically a ceramic) is deposited onto the stressed metal surface, and the strain gage is then deposited onto this layer. Vacuum deposition or sputtering techniques are used to bond the materials molecularly.
Semiconductors strain gages

Larger GF based on piezoresistance, but non-linear and more temperature-dependent. Can be bonded with the same epoxy used for foil gages or directly diffused into the substrate with the technology used for IC manufacturing.

From [7] and [8]
Transverse sensitivity

• SG are also sensitive to strain perpendicular to the longitudinal axis
• In plane wire SG, this is due to the portions in the end loops lying in the transverse directions
• In foil SG many factors contribute (thicknesses and elastic moduli of the backing and foil, width-to-thickness ratio of the foil gridlines,...)
• The transverse sensitivity factor is defined as
  \[ K = \frac{GF_T}{GF_L} \] (usually 0 to 10%)
Temperature effects

- SG resistance and GF depend on T
- T-compensated gages are available, depending on the substrate material
- Correction curves are also available

From [9]
Dummy gage compensation

- The compensation gage must be unstrained or suitably mounted to increase the output signal.
- The temperature should be the same and the two SGs identical.

From [9]
References

1. www.cyberphysics.pwp.blueyonder.co.uk/topics/forces/young_modulus.htm
2. www.tutorvista.com/content/physics/physics-iii/solids-and-fluids/elasticity-modulus.php#
3. en.wikipedia.org/wiki/Poisson's_ratio
4. www.npl.co.uk/reference/faqs/how-many-different-types-of-force-transducer-are-there-(faq-force)
Outline

• Sensor generalities
• Deformation sensors
• Temperature sensors
Contact sensors

Goal is to make $T_s$ as close to $T_x$ as possible
<table>
<thead>
<tr>
<th>Thermal</th>
<th>Electrical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature [K]</td>
<td>Voltage</td>
</tr>
<tr>
<td>Heat flow [W]</td>
<td>Current</td>
</tr>
<tr>
<td>Thermal resistance [K/W]</td>
<td>Resistance</td>
</tr>
<tr>
<td>Heat capacity [J/K]</td>
<td>Capacitance</td>
</tr>
</tbody>
</table>

\[
Q = \frac{\Delta T}{R_T} \quad \quad I = \frac{\Delta V}{R}
\]

\[
Q = C_T \frac{dT}{dt} \quad \quad I = C \frac{dV}{dt}
\]
Isolated system + sensor

\[
\tau = \frac{R_{sx}}{1/C_s + 1/C_x}
\]

\[
T_F = \frac{C_sT_s(0) + C_xT_x(0)}{C_s + C_x}
\]

A small \( C_s \) minimizes both static and dynamic errors
Environment

$$\tau = C_s (R_{sx} \parallel R_{sa})$$

$$T_F = T_x + (T_a - T_x) \frac{R_{sx}}{R_{sx} + R_{sa}}$$

A large $R_{sa}/R_{sx}$ is required to improve the sensor accuracy
Requirements

• Small $C_s$
  – Small sensor

• Small $R_{sx}$
  – Good thermal contact $\Rightarrow$ maximize contact area and (for solids) use good thermal grease

• Large $R_{sa}$
  – «Right» sensor connections $\Rightarrow$ use long, narrow connections with low thermal (and good electrical) conductivity
RTDs

- Resistance Temperature Detectors (RTDs) exploit the resistance change with temperature in certain metals.
- They can provide highly accurate results (from 0.1 to 0.0001°C) and are used to assign the TP temperatures between about 14 and 1200 K.
Resistance of metals

\[ R = R_0 \left( 1 + a_1 T + a_2 T^2 + \cdots + a_n T^n \right) \]

From [1]
The RTD sensitivity is related to the $TCR$ (temperature coeff. of resistance):

$$\alpha = TCR = \frac{1}{R_0} \frac{\Delta R}{\Delta T}$$  (usually computed between 100 and 0°C)

<table>
<thead>
<tr>
<th>Metal</th>
<th>$T$ range [°C]</th>
<th>$TCR$ [°C⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt</td>
<td>−200, +850</td>
<td>3.9 × 10⁻³</td>
</tr>
<tr>
<td>Ni</td>
<td>−100, +200</td>
<td>6.72 × 10⁻³</td>
</tr>
<tr>
<td>Cu</td>
<td>−100, +250</td>
<td>4.27 × 10⁻³</td>
</tr>
</tbody>
</table>
Pt RTD

• Platinum is mostly used for RTDs
  – Chemical inertness
  – Large enough TCR
  – Strain-free fabrication and weak dependence of R on strain
  – Almost linear R-T relationship

• Resistance at 0°C is usually 100 or 1000 Ω (PT100 or PT1000 RTDs)
Wirewound RTDs

From [2] and [3]

A small Pt sensing wire (usually within 7 to 50 μm diameter) is noninductively wound around a cylindrical ceramic mandrel, and covered with a thin layer of material that provides electrical insulation and mechanical protection.
Coil suspension RTDs

A coil of fine Pt wire is assembled into small holes in a cylindrical ceramic mandrel. The coils are supported by ceramic powder, and sealed at both ends. Ceramic powder allows expansion and contraction, reducing the effects of strain.

From [4] and [5]
Thin-film RTDs

From [2] and [6]

A thin film of Pt is deposited onto a ceramic substrate, then etched, leaving the element pattern. Then, the element’s surfaces are covered with glass material to protect the elements from humidity and contaminants.
Thermistors

• Made with transition metal (Cr, Co, Cu, Mn, Ni,...) oxides and showing a semiconductor-like behavior

• Strongly non-linear R-T characteristic, but with high TCR, either positive (PTC) or negative (NTC)

• NTCs only are useful as sensors
R-T characteristics

- The $R$-$T$ characteristics of NTC thermistors follow the intrinsic semiconductor behavior:

$$R(T) = R(T_0) e^{B\left(\frac{1}{T} - \frac{1}{T_0}\right)}$$

- Resistance value is usually referenced at 25°C and varies between 100 Ω and 100 kΩ

From [7]
TCR of NTC thermistors

• The TCR can be expressed as

\[ TCR = \alpha = -\frac{B}{T^2} \]

• Typical values are \(-3 - 5 \times 10^{-2}/°C\), i.e. about one order of magnitude larger than RTDs

• NTC thermistors are generally used between -50 and +150°C (up to 300°C for some glass-encapsulated units)
Bead thermistors

Metal oxide + binder are placed onto parallel Pt leadwires, forming beads. The strand is then sintered, allowing contacts to form intimate bonds with the thermistor. Beads are then cut and coated
Surface contact thermistors

Fabricated by tape-casting (chip) or by compressed metal powders (disk). Metallized contacts are then applied by spraying, painting or sputtering and fired onto the ceramic body.

Also leadless for hybrid- or surface-mount types.

From [10] and [11]
PTC thermistors

- Polycrystalline ceramic materials made semiconductive by the addition of dopants
- Manufactured using compositions of Ba, Pb, and Sr titanates with additives (Y, Mn, Ta,...)
- Used as overcurrent protection, heaters,...

From [12]
Sensor self-heating

\[ T_F \approx T_x + P_s R_{sx} \]

- Ex. \( I = 1 \text{ mA}, R_{sx} = 1^\circ \text{C/mW} \). For a PT100 RTD, \( P_s = 100 \mu \text{W} \), i.e., \( \Delta T = 0.1^\circ \text{C} \)
- If lower currents cannot be used, pulsed or AC measurements (with synchronous detection) must be employed
References

7. www.designinfo.com/cornerstone/ref/negtemp.html
11. www.ussensor.com/surface-mount-end-banded-chip-thermistors-0402