231

Real-Time & Embedded Systems 2019

2

Physical Coupling

Uwe R. Zimmer - The Australian National University

232

Physical Coupling

References

[Edler2003]
Edler et al.
Noise temperature measurements for the determination of the thermodynamic temperature of the melting point of palladium.
Metrologia (2003) vol. 41 (1) pp. 47-55

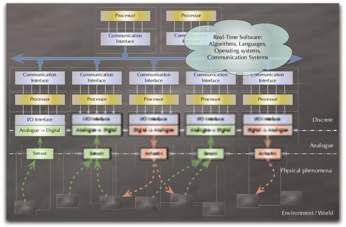
[Peacock97]
G. R. Peacock
Standards for temperature sensors.
http://www.temperatures.com/resources/standards/ (1997)

(additional data-sheets)

233

Physical Coupling

Real-Time Systems Components: Physical coupling



234

Physical Coupling

Definition

First step to embed a system into the real world:

Transform physical phenomena into electrical signals

Usual intention:

*Transform **one** dominant phenomenon into **one** electrical signal*

☞ e.g. speed, pressure, brightness, loudness, colour, force, humidity, distance, salinity, density, radioactivity, spectrograms, reflectivity, acceleration, conduction, power, turbulence, deformation, …, …, …, or: temperature

235

Physical Coupling

Phenomena to voltage

Measuring temperature

Some observable effects of temperature changes:

- Mean square noise voltage changes
- Volume changes (gas, liquids, metals)
- Thermovoltage changes
- Changes in conductors and semiconductors
- State changes: into solid, liquid, or gaseous

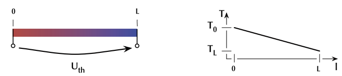
236

Physical Coupling

Measuring temperature (Thermoelements)

Seebeck Coefficient

$E_{th} = K \cdot grad(T)$, with K being the **Seebeck coefficient** (material constant of conductors)



$$U_{th} = \int_0^L E_{th}\, dl = \int_0^L K \cdot grad(T)\, dl = K(T_0 - T_L)$$

This phenomena stems from the characteristics of electrons to transfer electric potentials as well as to react to heat.

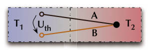
237

Physical Coupling

Measuring temperature (Thermoelements)

Thermocouple

- Connect two conductors A and B (of different Seebeck coefficients K_A and K_B) on one end.
- Place the connected end into the temperature zone T_2 which is to be measured.



- Measure the Voltage over the open ends in temperature zone T_1:

$$U_{th} = K_A(T_1 - T_2) + K_B(T_2 - T_1) = (K_A - K_B)(T_1 - T_2)$$

$$☞ T_2 = T_1 - \frac{U_{th}}{(K_A - K_B)} \text{ with } T_1 \text{ known.}$$

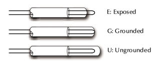
238

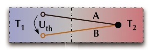
Physical Coupling

Measuring temperature (Thermoelements)

Thermocouple

Standard thermocouples come prefabricated for different applications:





Short name	Material	T_{max}	U_{th} with 0°to T_{max}	$K_A - K_B$
(T)	Cu-Constantan	400°C	21.000 mV	42.5×10^{-6}
(J)	Fe-Constantan	700°C	39.720 mV	53.7×10^{-6}
(K)	NiCr-Ni	1000°C	41.310 mV	41.1×10^{-6}
(S)	PtRh-Pt	1300°C	13.138 mV	6.43×10^{-6}

239

Physical Coupling

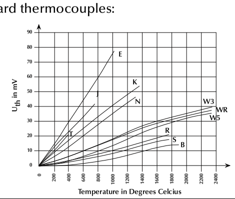
Measuring temperature (Thermoelements)

Thermocouple

Linearity of some standard thermocouples:

J-Type:

K-Type:



240

Physical Coupling

Measuring temperature (Thermoelements)

Applications of standard thermocouples

- **(TYPE N) Nicrosil-Nisil** thermocouples are suitable for use in oxidizing inert or dry reducing atmospheres. Must be protected from sulphurous atmospheres. Very accurate at high temperatures. Virtually the same emf (electromotive force) and range as Type K.
- **(TYPE J) Iron-Constantan** thermocouples are suitable for use in vacuum, oxidizing, reducing or inert atmospheres. Suitable for measuring temperatures up to 760°C for largest wire size.
- **(TYPE K) Chromel-Alumel** thermocouples are suitable for continuous use in oxidizing or inert atmospheres up to 1260°C for largest wire size. Because their oxidation resistance characteristics are better than those of other base metal thermocouples, they find widest use at temperatures above 538°C.
- **(TYPE E) Chromel-Constantan** thermocouples are suitable for use up to 781°C in oxidizing or inert atmospheres for largest gauge wires. Type E thermocouples develop the highest emf per degree of all commonly used thermocouples.

241

Physical Coupling

Measuring temperature (Thermoelements)

Applications of standard thermocouples

- **(TYPE T) Copper-Constantan** thermocouples are suitable for subzero temperatures with an upper temperature limit of 371°C and can be used in vacuum, oxidizing, reducing or inert atmospheres.
- **(TYPE R) Platinum 13% Rhodium - Platinum** thermocouples are suitable for continuous use in oxidizing or inert atmospheres at temperatures up to 1482°C.
- **(TYPE S) Platinum 10% Rhodium - Platinum** thermocouples are suitable for continuous use in oxidizing or inert atmospheres at temperatures up to 1482°C.
- **(TYPE B) Platinum 30% Rhodium - Platinum 6% Rhodium** thermocouples are suitable for continuous use in oxidizing or inert atmospheres and short-term use in vacuum atmospheres at temperatures up to 1705°C.
- **(TYPE W) Tungsten - Rhenium Alloy** thermocouples are used to measure temperatures up to 2760°C. These thermocouples have inherently poor oxidation resistance and should be used in vacuum, hydrogen or inert atmospheres.

242

Physical Coupling

Measuring temperature (Thermoelements)

Thermocouple

Pro:

- Accepts high temperature.
- Small.
- Relatively cheap.

Contra:

- Requires stable amplifier.
- Temperature differences only.
- Cables between the amplifier and the sensor need to be of the same Seebeck coefficient.

243

Physical Coupling

Measuring temperature (Resistors)

Thermoresistors

PT_{100} casings

Thin film resistor arrays

PT_{100} resistors are commonly manufactured as (thin film) Platinum wire on / around glass / ceramic tubes / plates.

244

Physical Coupling

Measuring temperature (Resistors)

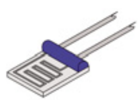
Thermoresistors

General case: $R_T = R_0[1 + A(T - T_0) + B(T - T_0)^2 + C(T - T_0)^3 + \ldots]$

Platinum: $A \approx 3.27 \times 10^{-3}\, {}^1/_K$ (at 550°C) … $4.2 \times 10^{-3}\, {}^1/_K$ (at −150°C)

PT_{100}

- *Calibrated value*: $0° \Rightarrow R_T = 100\Omega \pm 0.1\Omega;\ 0.1\Omega \Rightarrow \pm 0.26K$
- *Range*: $-200°C \ldots +650°C$
- *Response time*: $\approx 0.1s$ in flowing water … multiple seconds in still air.



245

Physical Coupling

Measuring temperature (Resistors)

Thermoresistors: Heating & Measuring

Assume the PT_{100} to be potted in a TO18 enclosure:

Thermal resistance: $R_{th} = \frac{T_{PT_{100}} - T_E}{P_V} = 480\, {}^{°C}/_W$

Assume we want to limit the sensing error to $\pm 0.5°C$ around $0°C$ ($R_T = 100\Omega$):

$$R_{th} = \frac{T_{PT_{100}} - T_E}{P_V} \Rightarrow P_V = \frac{\Delta T}{R_{th}} = \frac{U^2}{R} \Rightarrow U = \sqrt{\frac{\Delta T \cdot R}{R_{th}}}$$

$$\Rightarrow U_{max} = \sqrt{\frac{\Delta T \cdot R_T}{R_{th}}} \approx 0.323V$$

Thus in order to prevent heating the sensor element by more than 0.5°C we need to keep the operating voltage under 0.323V.

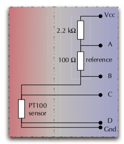
246

Physical Coupling

Measuring temperature (Resistors)

Thermoresistors: Connections

Separating currents from signals ☞ Four wire setup:



Further measures:

- Adding a reference resistor.
- Limit the cable length.
- Keeping all cables on the same temperatures.
- Limit the current.
- Model the non-linearity on the sensor itself.

247

Physical Coupling

Measuring temperature (Thermoelements)

Thermoresistors

Pro:

- Potentially higher accuracy.
- Less non-linearities.
- Long term stability.
- Absolute temperature.

Contra:

- Limited temperature range ($-200°C \ldots +650°C$).
- Slower reaction time.
- More expensive.
- Less robust.
- Usually bigger.

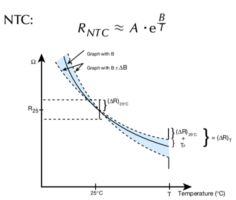
248

Physical Coupling

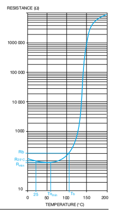
Measuring temperature (Thermistors)

Temperature Sensitive Semi-conductors

NTC: $R_{NTC} \approx A \cdot e^{\frac{B}{T}}$



PTC:



Source: AVX

249

Physical Coupling

Measuring temperature (Thermistors)

Temperature Sensitive Semi-conductors

Pro:

- Cheap.
- Can be accurate if combine with compensation for non-linearities.
- Large effects with temperatures (easy instrumentation).
- Long term stability (some models).

Contra:

- Further limited temperature range ($-40°C \ldots +350°C$).
- "Strongly" non-linear.
- Comparatively large.
- Generally instable and inaccurate.

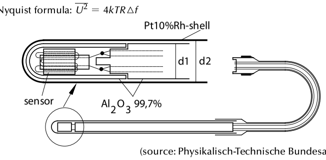
250

Physical Coupling

Measuring temperature (Noise Voltage)

Noise temperature measurement

Based in Nyquist formula: $\overline{U^2} = 4kTR\Delta f$



(source: Physikalisch-Technische Bundesanstalt, Berlin)

with k: Boltzmann constant, T: thermodynamic temperature, R: electric resistance, and Δf: the measurement bandwidth.

251

Physical Coupling

Measuring temperature (Noise Voltage)

Noise temperature measurement

Pro:

- Linear.
- Highly accurate.
- Long term stability.
- Wide temperature range: $1 \ldots 2500°K$, at $\pm 0.1\%$ accuracy over the full range.

Contra:

- Expensive.
- Large.
- Sophisticated amplification required (small effect).

252

Physical Coupling

Phenomena to voltage

Further methods of measuring temperature …

- Spreading resistors.
- Piezos and other temperature sensitive crystals.
- Temperature controlled current sources (e.g. AD590).
- Watch Mercury filled thermometers with cameras.
- Sense blackbody radiation (e.g. infrared-, or more generally: thermal radiation-thermometers)
- …

253

Physical Coupling

Phenomena to voltage

First conclusions

… we only scratched the surface of conversion methods for *one* physical value (temperature).

☞ Converting physical phenomena into analogue voltages seems to be a complex matter.
… in fact a whole industry is dedicated to this field exclusively.

☞ Always ask for the full sensor specifications (and read them).
☞ Never assume that the voltage output is a linear translation of a single physical value.

Physical coupling is not the only loss afflicted stage of conversion, yet it is often the most complex one.

254

Physical Coupling

Phenomena to voltage

Range and relative speed measurements

Some commonly employed principles:

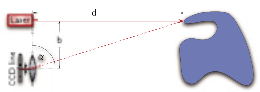
- Triangulation (optical)
- Time of flight (optical, acoustical, electro-magnetic)
- Phase correlation (optical, acoustical, electro-magnetic)
- Intensity (optical, acoustical)
- Doppler methods (acoustical, electro-magnetic)
- Interferometry (optical, electro-magnetic)

255

Physical Coupling

Phenomena to voltage

Range measurements by triangulation



$d = b \cdot \tan\alpha$ ☞ non-linear and poor accuracy for $d \gg b$

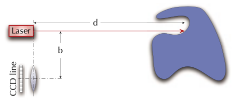
- Laser required.
- otherwise simple setup with slow components, often used for liquid level measurements.
- Measures along the optical axis only ☞ problematic for safety applications.

256

Physical Coupling

Phenomena to voltage

Range measurements by triangulation



$d = b \cdot \tan\alpha$ ☞ non-linear and poor accuracy for $d \gg b$

☞ Occlusion omits readings ☞ not suited for randomly curved surfaces

257

Physical Coupling

Phenomena to voltage

Range measurements by time of flight / phase

Method: measure the time of flight between the outgoing signal and the received, reflected signal.

☞ In case of light, this method requires high resolution timers (> 1 GHz).

- Method is linear.
- The achieved resolution depends on the precision of the signal's rising edge and the resolution of employed timers.
- Signals can be formed and volume measurements are possible.

☞ In order to increase the resolution, the outgoing signals are often modulated and the phase shifts between outgoing and reflected signals are detected.

258

Physical Coupling

Phenomena to voltage

Range and relative speed measurements

2-d Scanning Laser Range Finders

Hokuyo UTM-30:

- 905 nm semiconductor laser.
- Nominal range: 0.1 … 30 m outdoors.
- Maximum range: 60 m
- Accuracy: 10…50 mm depending range and background light.
- Coverage: 270°.
- Weight: 210 g.

259

Physical Coupling

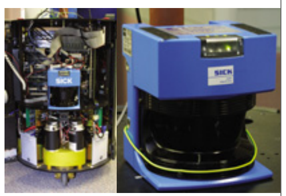
Phenomena to voltage

Range and relative speed measurements

2-d Scanning Laser Range Finders

SICK (indoor):

- 905 nm semiconductor laser.
- Maximum range: 80 m.
- Accuracy: 5-10 mm (typical).
- Coverage: 180°, 0.25° resolution.
- Response time: 53 ms.
- Weight: 4.5 kg.
- MTBF: 80,000 h



260

Physical Coupling

Phenomena to voltage

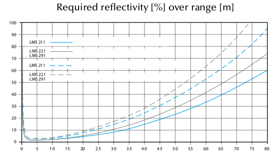
Range and relative speed measurements

2-d Scanning Laser Range Finders

SICK (indoor):

- 905 nm semiconductor laser.
- Maximum range: 80 m.
- Accuracy: 5-10 mm (typical).
- Coverage: 180°, 0.25° resolution.
- Response time: 53 ms.
- Weight: 4.5 kg.
- MTBF: 80,000 h

Required reflectivity [%] over range [m]



(source: SICK AG, Germany)

Black leather: ≈ 2% reflectivity

261

Physical Coupling

Phenomena to voltage

Range and relative speed measurements

Ultrasound time-of-flight & Infrared reflected-intensity

Classical "low end" sensors:

- US signal is transmitted and received on the same membrane.

☞ Minimal range limitations.
☞ Specular reflections lead to potential overestimation.

- IR intensity readings depend on object material.

262

Physical Coupling

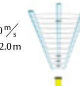
Phenomena to voltage

Speed measurements: Doppler current profilers

Doppler shift frequency: $f_d = -2f_s \frac{v}{c}$

with source frequency f_s, relative velocity v and signal speed c.

- Signal: 250 kHz - 3 MHz
- Range: 160 m, Accuracy: ±1%
- Velocity range: $\pm 10\,\frac{m}{s}$
- Blanking zone: 0.2-2.0 m



Physical Coupling

Summary

Physical coupling

- **Physical phenomena**
- **Measuring temperature**
  - Thermoelements, thermocouples, Thermoresistors, Thermistors, Noise temperature measurement) and many others …
- **Measuring range and relative speed**
  - Triangulation, Time of flight, Intensity, Doppler methods, Interferometry
- Examples: **Common acoustical and optical sensors**