Physical coupling

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References for this chapter

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Alan Burns and Andy Wellings
Real-Time Systems and Programming Languages
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[Edler01]
F. Edler, M. Kühne, E. Tegeler
Noise temperature measurements for the determination of the thermodynamic temperature of the melting point of Palladium
21. CCT-Meeting, Paris, Sep. 12-14, 2001, France

[Peacock97]
G.R. Peacock
Standards for temperature sensors
web guide: www.temperatures.com/stds.html

all references and some links are available on the course page

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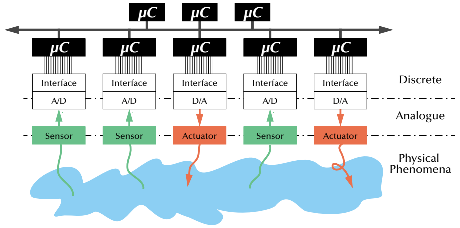
Real-Time Systems Components: Physical coupling



Physical coupling

First step to embed a system into the real world:

Transform all kinds of physical phenomena into analogue voltages

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

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Physical coupling

Measuring temperature

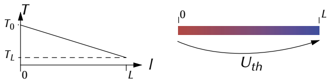
Some observable effects of temperature changes:

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

Physical coupling: Measuring temperature (thermoelements)

Thermoelements

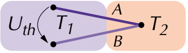
$E_{th} = K \cdot grad(T)$ with K: Seebeck coefficient (depends on material)



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

Physical coupling: Measuring temperature (thermoelements)

Temperature measurement

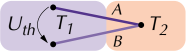


- Take two wires (A & B) with different Seebeck coefficients K_A & K_B
- Connect them on one side
- Place the connected side in one temperature zone, and the open ends in another

☞ Measure the voltage difference U_{th}

Physical coupling: Measuring temperature (thermoelements)

Temperature measurement

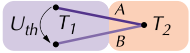


☞ Measure the voltage difference U_{th}

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

Physical coupling: Measuring temperature (thermoelements)

Temperature measurement



some standard combinations: (typical shape:)

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}

Physical coupling: Measuring temperature (thermoelements)

Thermocouples

Pro:

- accepts high temperatures
- small
- relatively cheap

Contra:

- requires stable amplifier
- temperature differences only
- cables to the sensor need to have the same Seebeck coefficient

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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.

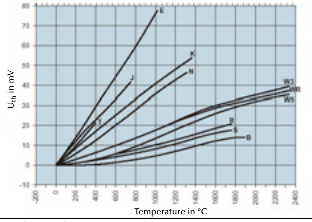
Physical coupling: Measuring temperature (thermoelements)

Applications of standard thermocouples (cont.)

- (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.

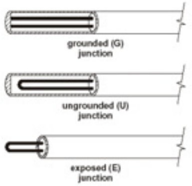
Physical coupling: Measuring temperature (thermoelements)

Linearity of standard thermocouples



Physical coupling: Measuring temperature (thermoelements)

Three standard forms

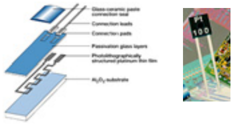


source: Alltemp Sensors

Physical coupling: Measuring temperature (resistors)

Thermoresistors: Pt_{100} sensor

- e.g. in thinfilm technology:



source: sensor-nite

- also common as a Platinum wire around a glass or ceramics tube

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Physical coupling: Measuring temperature (resistors)

Some characteristics of the Pt_{100} sensor:

- general: $R_T = R_0[1 + A(T - T_0) + B(T - T_0)^2 + C(T - T_0)^3 + \dots]$
- Platinum: $A \approx 3.27\times10^{-3}\frac{1}{K}$ (550°C) .. $4.2\times10^{-3}\frac{1}{K}$ (-150°C)
- Pt_{100}: 0°C ☞ $R_T = 100\,\Omega \pm 0.1\,\Omega$ ☞ ≈± 0.26 K
- correction required to compensate for non-linearity
- range approx. -200°C .. +650°C
- speed: 0.1s in flowing water .. multiple seconds in still air

Physical coupling: Measuring temperature (resistors)

Application of the Pt_{100} sensor:

The problem of heating the sensor itself

- Pt_{100} in a TO18 enclosure:

☞ $R_{th} = \frac{T_{Pt_{100}} - T_E}{P_V} = 480°\,C/W$ in non-moving air

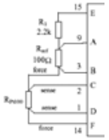
- limiting the sensor error to 0.5°C around 0°C ($R_T = 100\,\Omega$)

☞ $R_{th} = \frac{T_{Pt_{100}} - T_E}{P_V} \rightarrow P_V = \frac{\Delta T}{R_{th}} = \frac{U^2}{R} \rightarrow U_{max} = \sqrt{\frac{\Delta T \cdot R_T}{R_{th}}} \approx 0.323\,V$

Physical coupling: Measuring temperature (resistors)

More things to consider for the Pt_{100} sensor:

- compensate for the non-linearity of sensor itself
- choose an adequate (bridge) circuit, e.g. a 'four wire' setup:
- limit the cable length
- keep the cables on the same temperature
- limit the influence of the sensor to the environment



Physical coupling: Measuring temperature (resistors)

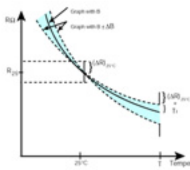
In relation to thermocouples:

Pro:	Contra:
higher accuracy (if all side-effects have been taken care of)	smaller temperature range -200°C .. +650°C (some thermocouples exceed +2000°C)
non-linearity less worse than with thermocouples	more expensive
long term stability	less robust (can be compensated by probe construction)
measures absolute temperatures	usually bigger

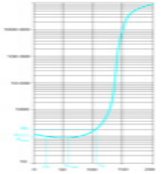
Physical coupling: Measuring temperature (thermistors)

Temperature sensitive semi-conductors (Thermistors):

NTC



PTC



source: AVX

Physical coupling: Measuring temperature (thermistors)

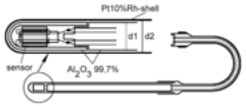
In relation to thermocouples and Pt_{100}:

Pro:	Contra:
very high accuracy (with special models, if extensive compensation is applied)	even smaller temperature range -40°C .. +350°C
usually cheaper than Pt_{100}	terrible non-linearities
high long term stability (with special models)	standard components are very inaccurate and instable
large changes with temperature	larger than thermocouples and Pt_{100}

Physical coupling: Measuring temperature (noise)

Noise temperature measurement

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



combined thermocouple-noise sensor
(source: Physikalisch-Technische Bundesanstalt, Berlin)

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

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Physical coupling: Measuring temperature (noise)

Noise temperature measurement

Pro:	Contra:
wide range	expensive
high accuracy	sophisticated amplifier setups
long term stability	

an actual device: range: 1..2500°K, accuracy: ±0.1% (over the full range)

Physical coupling: Measuring temperature

More ways to measure temperature:

- Spreading resistors
- Piezos and other temperature sensitive quarz elements
- Temperature controlled current sources (e.g. AD590)
- Mercury filled thermometers
- …

Physical coupling

Basic conclusions

☞ we just 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 output is a linear translation of a physical value.

Physical coupling *is not the only loss afflicted stage of conversion*, *but it is usually the most complex one*

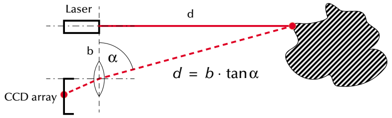
Physical coupling

Range and relative speed measurements

- **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)

Physical coupling

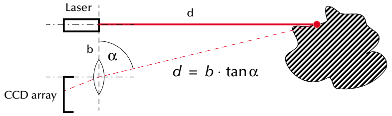
Range measurements – Triangulation



- non-linear, very poor resolution, if $d \gg b$
- highly focused light-beam required ☞ laser ☞ safety considerations
- distances are measured along the optical axis only.

Physical coupling

Range measurements – Triangulation



- projected point might be hidden ☞ no measurement

☞ method is frequently used for measuring liquid levels.

Physical coupling

Range measurements – Time of flight - Phase correlation

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 (> 1GHz)

- Method is perfectly 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.

Physical coupling

Range measurements: Ultrasound & Infrared

☞ in the special case of one ultrasound transducer for sending *and* receiving (like above), there is a short time delay before the transducer is ready to receive a signal (oscillations need to die away first).

Physical coupling

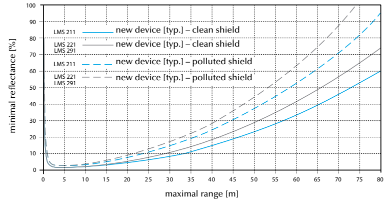
Range measurements: Laser

a common laser range finder (SICK):

- range: max. 80m
- angular resolution: 0.25°
- response time: max. 53ms
- resolution: 10mm
- accuracy: typ. 5-10mm

Physical coupling

Minimal reflectance versus maximal range



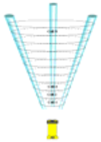
Speed measurements: Doppler current profilers

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

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

a common current profiler (SonTek):

- ping signal: 250 kHz - 3 MHz
- range: up to 160 m; velocity: ±10 m/s
- resolution: 0.15 - 2 m; 1 mm/s
- accuracy: ±1%
- blanking zone: 0.2 - 2.0 m



Physical coupling

- **Physical phenomena**
- **Measuring temperature**
  - thermoelements, thermocouples
  - thermoresistors
  - thermistors
  - noise temperature measurement) and others
- **Measuring range and relative speed**
  - triangulation
  - time of flight
  - intensity
  - Doppler methods
  - interferometry
- **Examples: time-of flight ultrasound & laser, Doppler current profiler**