



Sensing, Computing, Actuating

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Spot the computer





Spot the computer





Google driverless car

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- a cyber-physical systems is a device used to control, monitor or assist the operation of equipment, machinery.
- "cyber-physical" reflects the fact information processing (cyber) and mechanics (physics) are closely linked together.





cyber-physical systems make up a large part of the product cost



TU/e

cyber-physical systems are the driving force behind the only silent revolution the world has ever seen

- cyber-physical systems are different from personal computers
- cyber-physical systems are
 - closely integrated with mechanics
 - reliable

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- consider many demands (energy, code size, ...)
- designed for a specific application
- often real-time
- often reactive











- an cyber-physical system consists of
 - an actuator
 - a sensor

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- an embedded processor
- and often a communication network





PRACTICAL NOTES

10 Learning objectives

- at the end of the course, you will be able to
 - describe the basic components (sensor, signal conditioner, controller, actuator) in a control system
 - describe the physical conversion phenomena underlying the operation of transducers (sensors, actuators)
 - apply filtering and DSP techniques on the signals to and from the transducers
 - analyze the static and dynamic characteristics of transducers and the complete system
 - analyze the static errors that limit the accuracy of transducers
 - dimension the interface electronics used in a control system that contains sensors and actuators
 - select control algorithms that meet the performance requirements of the system under design

Canvas

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Settings

Course Evaluation

- (slides, videos, exercises, solution, etc.). Note that in addition to the video lectures there will also be live lectures during the scheduled timeslots. These live lectures are not recorded, but they cover the same material as shown in the video lectures. So you can choose which option (live or video) you prefer.
- 1. Introduction (view lecture)
- 2. Resistive temperature sensors (view lecture)
- 3. Systems and Control (view lecture)
- 4. Force sensors (view lecture)

Suggested schedule

	21-23 April	28-30 April	5-7 May	12-14 May	19-21 May		
Mo 13.30 – 16.15	TU/e closed	Thermo-resistive	TU/e closed	Stepper motors	AD Converters		
					Model-based design		
		Resistive displacement		Strain / Bridges	Signal amplification		
We 8.45 – 12.30	Introduction to course	Thermo resistive	Systems and Control	Stepper motors	AD-converters		
	Sensing displacement	Thermo-resistive					
	Arduino lab	Systems and Control	Strain / Bridges	Signal amplification	Non-linear sensors		
	26-28 May	2-4 June	10-11 June	16-18 June			

	26-28 May	2-4 June	10-11 June	16-18 June	
Mo 13.30 – 16.15		Domodulation	LED / Display	Summary	
	Informative test (non graded)	Demodulation	LED / Display	Thermocouple	
		Inductive sensors	Acoustic sensors	mernocoupie	
We 8.45 – 12.30	Non-linear sensors	Demodulation	LED / Display	No class	
	Inductive sensors	Acoustic sensors	Thermocouple		



• All lectures and material can be found online at http://www.es.ele.tue.nl/education/SensingActuating/lectures

13 Course material

- book
 - Sensors and Actuators: Control System Instrumentation, Clarence W. de Silva, CRC Press (2nd edition)
- slides and instruction exercises
 - www.es.ele.tue.nl/education/SensingActuating
- exercises and short questions embedded in slides
 - marked in **bold** with question mark
 - solutions provided on slides
- instructions
 - exercises available on the website
 - solutions provided on the website (as pdf) and screencast



- final test (see Canvas for schedule)
 - counts for 100% of final grade
 - all material taught in the course
 - paper-based on campus
- Lecture 9 will contain a practice test covering the first 4 lectures
- no material, slides, books allowed on exam and test

15 Study guide

- available at www.es.ele.tue.nl/education/SensingActuating
- contains exact list of material to be studied before each class

Lecture	Reading	Topic	
1. Introduction to course	Ch 1	Control system architecture	
1. Sensing displacement	Ch 3.4	Sensor characteristics	
1. Sensitivity	Ch 5.3	Transfer function, sensitivity	
1. Loading effect	Ch 5.3	Linearity, loading effect, absolute/relative error	
2. Sensing temperature	Ch $2.1, 2.2, 5.11$	Device model, self-heating, lead-wire error	
2. Self-heating	Ch $2.1, 2.2, 5.11$	Trade-off linearity, self-heating, sensitivity	
2. Bridges	Ch 2.8	Wheatstone bridge	
3. Sensing force	Ch 5.8	Strain gages	
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- file names of slides, exercises start with corresponding class
 - 01-introduction.pdf
 - 02-resistive-temperature.pdf

CONTROL SYSTEM ARCHITECTURE

(Chapter 1)

Open-loop control

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- response not measured
- plant must be stable and accurately known
- inputs must be precisely generated

- sensors are common devices
- a system of any complexity cannot be designed without them



- why can a system not perform its tasks without sensors?
 - complexity
 - uncertainty
 - dynamic world
 - detection / correction of errors

19 Control systems are everywhere...











21 Feedback (closed-loop) control



- measure response and compare with reference to minimize error
- several common feedback control strategies exist
 - on-off control
 - proportional (P) control
 - proportional control with integral (I) and derivative (D) action



- sense the temperature of a CPU
- control the speed of the fan to keep the temperature constant



- A/D and signal conditioner can be separated from the processor
- circuitry may be integrated into a "smart sensor"

SENSING DISPLACEMENT

potentiometer, sensitivity, loading effect

(Chapter 5.3)

24 Control system



Applications



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- displacement (position, distance, proximity)
- velocity (rate of change of displacement)
- acceleration (rate of change of velocity)

$$a = \frac{dv}{dt} = \frac{d^2x}{dt^2}$$

- can a displacement (position) sensor be used to measure all these quantities?
 - A) yes, no problem just look at the equation
 - B) yes, depending on the requirements
 - C) no, this will never work

- displacement (position, distance, proximity)
- velocity (rate of change of displacement)
- acceleration (rate of change of velocity)

$$a = \frac{dv}{dt} = \frac{d^2x}{dt^2}$$

can a displacement (position) sensor be used to measure all these quantities?



use (low-pass) filter on signal before deriving velocity



- derivation or integration of signal may introduce additional errors
- use of a sensor suited for a specific quantity

sensor type	quantity	physical effect	sensor
resistive	displacement	resistance	potentiometer
inductive	displacement	reluctance	variable differential transformer
inductive	displacement	Joule effect, Villari effect, Wiedemann effect, Matteucci effect	magnetostrictive
electromagnetic	velocity	Hall effect	Hall effect
electromagnetic	velocity	Faraday's law	linear velocity
capacitive	acceleration	capacitance	variable capacitor
capacitive	acceleration	capacitance	differential capacitor

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- resistance of a material given by $R = \rho \frac{l}{A}$
 - ρ resistivity of material
 - I length
 - A cross-sectional area of material
- change in the length changes the resistance of the material
- potentiometer (pot) is a variable resistor
- pot wiper mechanically coupled to object whose displacement must be measured
- movement (linear or rotation) of object causes change in resistance





output voltage proportional to displacement

$$v_o = \frac{\alpha R_T}{\alpha R_T + (1 - \alpha) R_T} V_r = \frac{\alpha R_T}{R_T} V_r = \alpha V_r$$

$$v_o = \frac{\alpha R_T}{R_T} V_r = \frac{dR_T}{DR_T} V_r = \frac{d}{D} V_r$$

- output voltage does not depend on the resistance R_T
- potentiometer is a ratio metric device



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output voltage proportional to displacement

$$v_o = \frac{\alpha R_T}{\alpha R_T + (1 - \alpha) R_T} V_r = \frac{\alpha R_T}{R_T} V_r = \alpha V_r$$

- what happens when a load R_m is connected to the sensor?
- Thévenin equivalent circuit
 - open circuit voltage

$$v_o = \frac{\alpha R_T}{R_T} V_r = \alpha V_r$$

output resistance

$$R_o = \frac{\alpha R_T}{(1 - \alpha)R_T}$$
$$R_o = \frac{\alpha R_T (1 - \alpha)R_T}{\alpha R_T + (1 - \alpha)R_T} = \alpha (1 - \alpha)R_T$$

voltage across load

$$v_m = \frac{R_m}{R_m + R_o} v_o = \frac{R_m}{R_m + \alpha(1 - \alpha)R_T} \alpha V_r$$





output voltage proportional to displacement

$$v_o = \frac{\alpha R_T}{\alpha R_T + (1 - \alpha) R_T} V_r = \frac{\alpha R_T}{R_T} V_r = \alpha V_r$$

- what happens when a load R_m is connected to the sensor?
- voltage across load

$$v_m = \frac{R_m}{R_m + \alpha (1 - \alpha) R_T} \alpha V_r$$

$$k = R_m / R_T \qquad \Big\} \Rightarrow v_m = \frac{1}{1 + \frac{\alpha (1 - \alpha)}{k}} \alpha V_r$$

- sensor becomes linear when k >> 1(R_m >> R_T)
- relative error of the sensor

$$\varepsilon = \left| \frac{v_m - v_o}{v_o} \right| = \left| \frac{\frac{k}{k + \alpha(1 - \alpha)} \alpha V_r - \alpha V_r}{\alpha V_r} \right| = \left| \frac{k - k - \alpha(1 - \alpha)}{k + \alpha(1 - \alpha)} \right| = \left| \frac{-\alpha(1 - \alpha)}{k + \alpha(1 - \alpha)} \right| = \frac{\alpha(1 - \alpha)}{k + \alpha(1 - \alpha)}$$

- relative error depends on position of the wiper (i.e. it depends on α)
- no error at the ends of the scale

when is the maximal relative error reached?

$$\frac{d\varepsilon}{d\alpha} = 0 \Rightarrow \frac{d\varepsilon}{d\alpha} = \frac{d}{d\alpha} \left(\frac{\alpha(1-\alpha)}{k+\alpha(1-\alpha)} \right) = \frac{[k+\alpha(1-\alpha)](1-2\alpha) - [\alpha(1-\alpha)](1-2\alpha)}{[k+\alpha(1-\alpha)]^2}$$

$$\Leftrightarrow \frac{d\varepsilon}{d\alpha} = \frac{k(1-2\alpha)}{[k+\alpha(1-\alpha)]^2}$$

maximal error reached when

$$1 - 2\alpha = 0 \Rightarrow \alpha = \frac{1}{2}$$

maximal error

$$\varepsilon(0.5) = \frac{\alpha(1-\alpha)}{k+\alpha(1-\alpha)} = \frac{0.25}{k+0.25}_{\max}$$

- increasing load resistor decreases error
- error is symmetrical around the center





³⁵ Potentiometer – loading error

- relative error (loading error) can be decreased by
 - increasing load resistor R_m
 - placing a resistor equal to R_m at the top side of the potentiometer
- what is the output voltage of the sensor?
- two options to compute output voltage
 - use Thévenin equivalent circuit
 - output voltage is voltage divider of two pair of parallel resistors

$$v_m = \frac{R_y}{R_y + R_x} V_r$$

with

$$R_{x} = (1 - \alpha)R_{T} / R_{m} = \frac{(1 - \alpha)R_{T}R_{m}}{(1 - \alpha)R_{T} + R_{m}}$$

$$R_{y} = \alpha R_{T} / / R_{m} = \frac{\alpha R_{T} R_{m}}{\alpha R_{T} + R_{m}}$$



³⁶ Potentiometer – loading error

- relative error (loading error) can be decreased by
 - increasing load resistor R_m
 - placing a resistor equal to R_m at the top side of the potentiometer
- what is the output voltage of the sensor?

$$v_m = \frac{R_y}{R_y + R_x} V_r \implies v_m = \frac{\alpha (R_m + R_T - \alpha R_T)}{2\alpha (1 - \alpha) R_T + R_m} V_r$$
$$k = \frac{R_m}{R_T} \qquad \Big\} \Rightarrow v_m = \frac{\alpha (k + 1 - \alpha)}{2\alpha (1 - \alpha) + k} V_r$$

output voltage at α = 0.5

$$v_m(0.5) = \frac{0.5(k+0.5)}{0.5+k}V_r = \frac{1}{2}V_r$$

- additional resistor R_m enforces $v_m = V_r/2$ at central position
- zero error at this point



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example - set zero error at any desired point

which value must R_1 and R_2 have such that a wiper displacement of ±15% of its stroke around the position corresponding to ¼ of the full-scale value produces a change in voltage of only 10% with respect to the full-scale voltage?

$$v_{a} = \frac{\frac{R_{2}}{\alpha R_{T}}}{\frac{R_{2}}{\alpha R_{T}} + \frac{R_{1}}{(1-\alpha)R_{T}}} V_{r} = \frac{\frac{\frac{R_{2}\alpha R_{T}}{R_{2} + \alpha R_{T}}}{\frac{R_{2}\alpha R_{T}}{R_{2} + \alpha R_{T}} + \frac{R_{1}(1-\alpha)R_{T}}{R_{1} + (1-\alpha)R_{T}}} V_{r}$$

$$= \frac{R_2 \alpha R_T (R_1 + (1 - \alpha) R_T)}{R_2 \alpha R_T (R_1 + (1 - \alpha) R_T) + R_1 (1 - \alpha) R_T (R_2 + \alpha R_T)} V_r$$

use a = R_T/R_1 and b = R_T/R_2

$$v_a = \frac{\alpha (1 + \alpha (1 - \alpha))}{\alpha (1 + \alpha (1 - \alpha)) + (1 - \alpha)(1 + \alpha b)} V_r$$

$$v_a = \frac{\alpha \left(1 + a(1 - \alpha)\right)}{1 + \alpha (1 - \alpha)(a + b)} V_r$$



example – set zero error at any desired point

which value must R_1 and R_2 have such that a wiper displacement of ±15% of its stroke around the position corresponding to ¼ of the full-scale value produces a change in voltage of only 10% with respect to the full-scale voltage?

two constraints

1) at α = 0.25 + 0.15 it must hold that $v_a = (0.25 + 0.05)V_r$ 2) at α = 0.25 - 0.15 it must hold that $v_a = (0.25 - 0.05)V_r$ constraints imply

$$0.3 = \frac{6a+10}{25+6(a+b)} \qquad 0.2 = \frac{9a+10}{90+9(a+b)}$$

solving constraints yields

a = 3.5 b = 9.6 this implies

$$R_1 = 0.29 R_T$$
 $R_2 = 0.10 R_T$



³⁹ Potentiometer – loading error

- relative error (loading error) can be decreased by
 - increasing load resistor R_m
 - placing a resistor equal to R_m at the top side of the potentiometer
 - using a symmetrical voltage supply
- what is the output voltage of this sensor?
- use Kirchhoff current law

$$0 = \frac{v_m}{R_m} - \frac{V_r - v_m}{(1 - \alpha)R_T} - \frac{-V_r - v_m}{\alpha R_T}$$

solving this yields

$$v_m = \frac{V_r(2\alpha - 1)}{1 + \frac{\alpha(1 - \alpha)}{k}}$$

- error is zero at end of the wiper ($\alpha = 0, \alpha = 1$)
- error is zero at central position ($\alpha = 0.5$)





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- 3-wire circuit output voltage
 - assume k >> 1, hence loading error is negligible
 - output at $\alpha = 0$

$$v_m(0) = \frac{R_{w3}}{R_T + R_{w1} + R_{w3}} V_r$$

output at α = 1

$$v_m(1) = \frac{R_T + R_{w3}}{R_T + R_{w1} + R_{w3}} V_r$$

- circuit has two errors
 - reduced sensitivity
 - offset voltage
 - due to current through R_{w3}



42 **Potentiometer – lead-wire resistance**

- 4-wire circuit output voltage
 - assume k >> 1, hence loading error is negligible
 - output at α = 0

 $v_m(0)=0$

output at α = 1

$$v_m(1) = \frac{R_T}{R_T + R_{w1} + R_{w4}} V_r$$

- no offset voltage
- sensitivity equal to 3-wire circuit



Potentiometer – construction

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- construction: wire wound around a coil
- problem: wiper makes contact with 1 or 2 wires
 - results in uneven voltage steps
 - sensor has a variable resolution
 - resolution: smallest change in input stimulus which can be sensed
 - consider average resolution when computing displacement
- construction: high-quality resistive film
 - theoretically an infinitesimal resolution
 - resolution limited by
 - noise in circuit
 - non-uniformity of material







example – high-precision mobile robot

robot has drive wheel with diameter of 20 cm; position measured using potentiometer, average diameter pot: 10 cm, resistance: 5 Ω , specific resistance wire: 4 $\mu\Omega$ cm

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what diameter D must the core of the coil have to achieve a resolution of 1 mm?



Potentiometer – resolution

example – high-precision mobile robot

robot has drive wheel with diameter of 20 cm; position measured using potentiometer, average diameter pot: 10 cm, resistance: 5 Ω , specific resistance wire: 4 $\mu\Omega$ cm

what diameter D must the core of the coil have to achieve a resolution of 1 mm?

coil with N windings has a

resolution r (as % of output range)

$$r = \frac{100}{N}\%$$

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required resolution

$$r = \frac{0.1cm}{\pi \cdot 20cm} \cdot 100\% = 0.16\%$$

number of turns of wire on coil

$$N = \frac{100\%}{0.16\%} = 625 \ turns$$





Potentiometer – resolution

example – high-precision mobile robot

robot has drive wheel with diameter of 20 cm; position measured using potentiometer, average diameter pot: 10 cm, resistance: 5 Ω , specific resistance wire: 4 $\mu\Omega$ cm

what diameter D must the core of the coil have to achieve a resolution of 1 mm?

diameter of wire

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potentiometer circumference = $\pi \cdot 10cm = 625 \cdot d$

- $\Rightarrow d = 0.5mm$
- resistance of a wire

$$R = \rho \frac{l}{A} \Rightarrow 5\Omega = 4 \cdot 10^{-6} \Omega cm \frac{\pi d \times 625}{\pi (D/2)^2}$$

diameter of coil

 $\Rightarrow D = 1.0cm$





- resistance of a material given by $R = \rho \frac{l}{A}$
 - ρ resistivity of material
 - I length
 - A cross-sectional area of material
- change in the length changes the resistance of the material
- potentiometer (pot) is a variable resistor
- pot wiper mechanically coupled to object whose displacement must be measured
- movement (linear or rotation) of object causes change in resistance



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output voltage proportional to displacement

$$v_o = \frac{\alpha R_T}{\alpha R_T + (1 - \alpha) R_T} V_r = \frac{\alpha R_T}{R_T} V_r = \alpha V_r$$

loading resistance causes error

relative loading error

 $v_m = \frac{1}{1 + \frac{\alpha(1 - \alpha)}{k}} \alpha V_r$ with







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- relative loading error can be decreased by
 - increasing load resistor R_m
 - placing a resistor equal to R_m at the top side of the potentiometer
 - using a symmetrical voltage supply



- various error sources present
 - Ioading resistance causes non-linearity error
 - lead-wire resistance causes offset voltage, reduced sensitivity
 - physical construction limits resolution