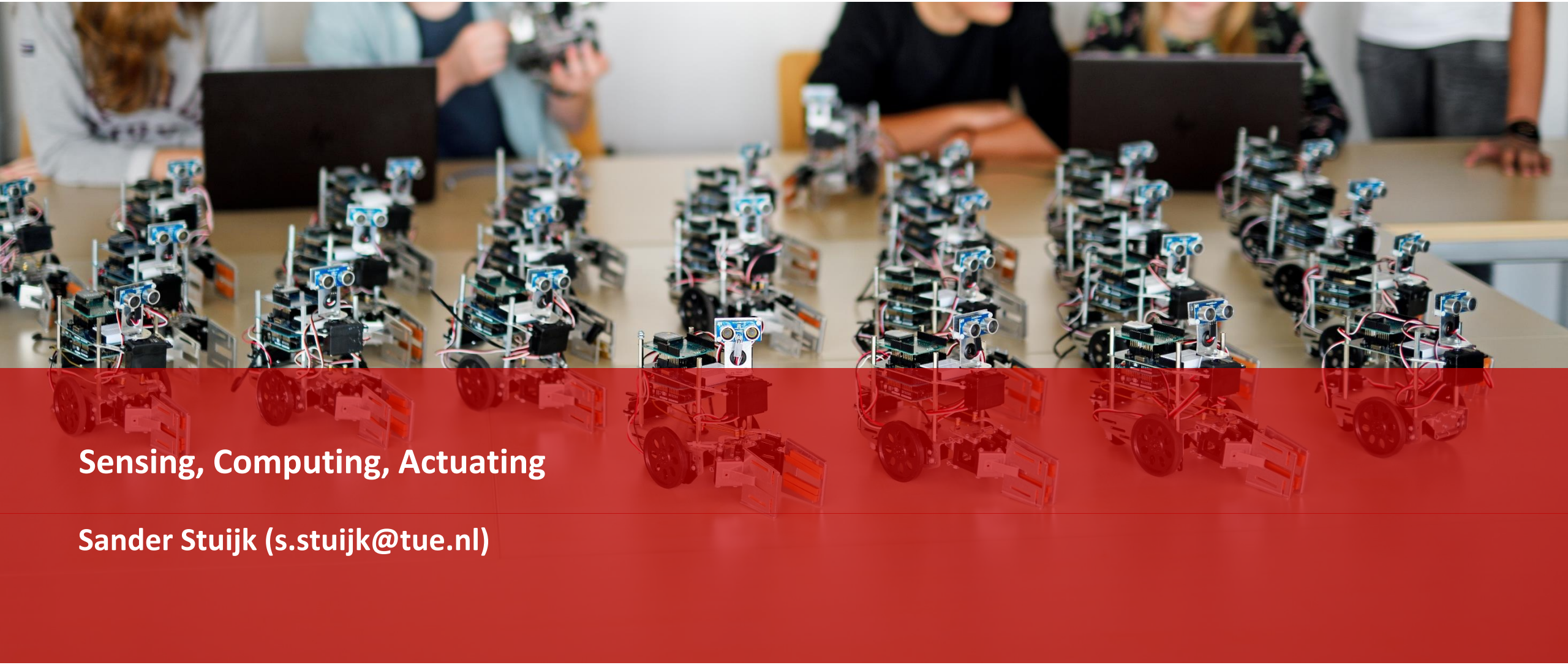
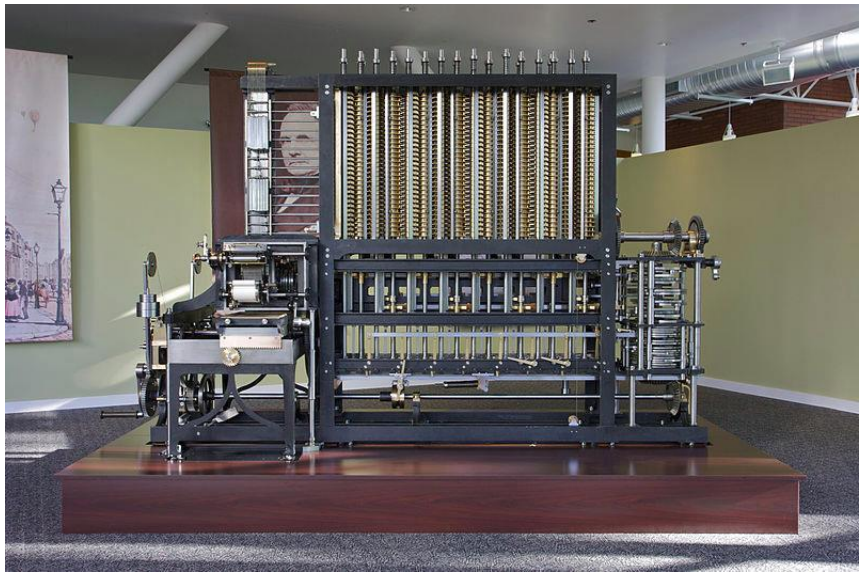
TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

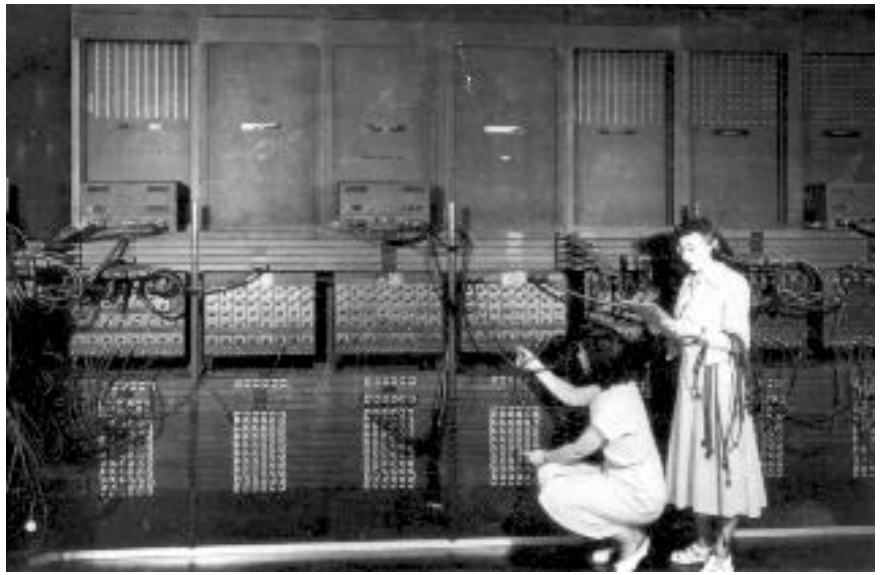


Sensing, Computing, Actuating

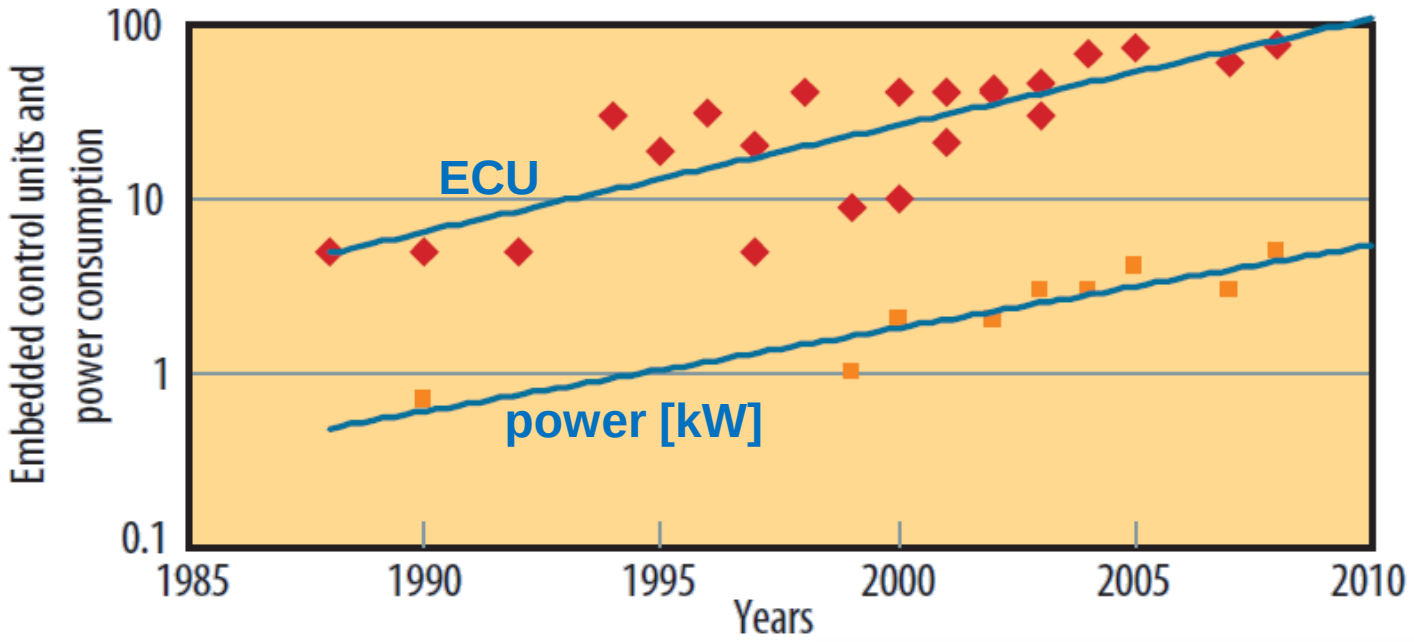
Sander Stuijk (s.stuijk@tue.nl)

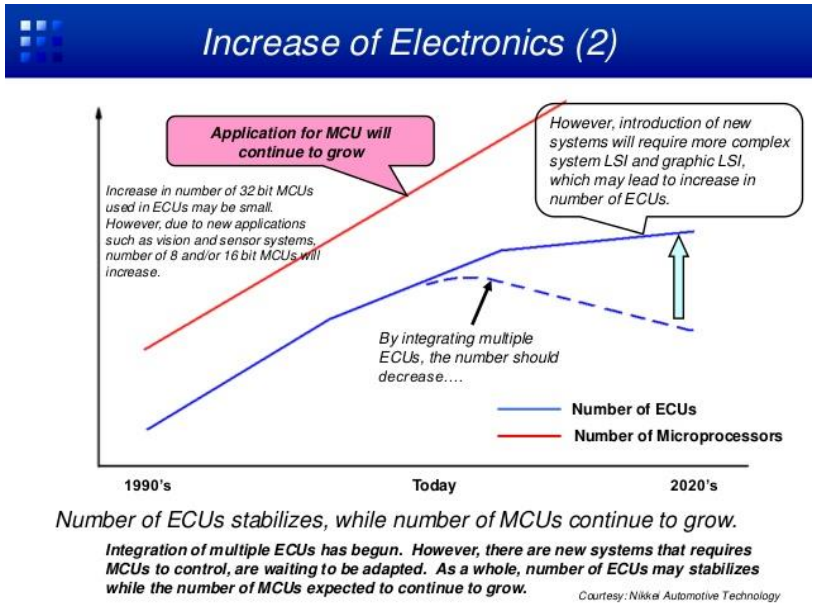
Spot the computer





Spot the computer

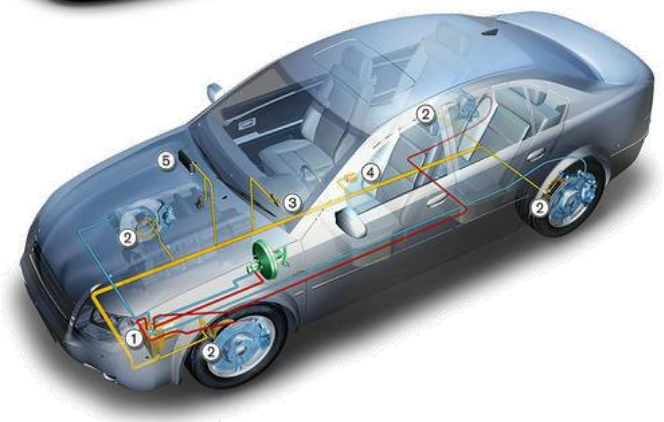




Google driverless car

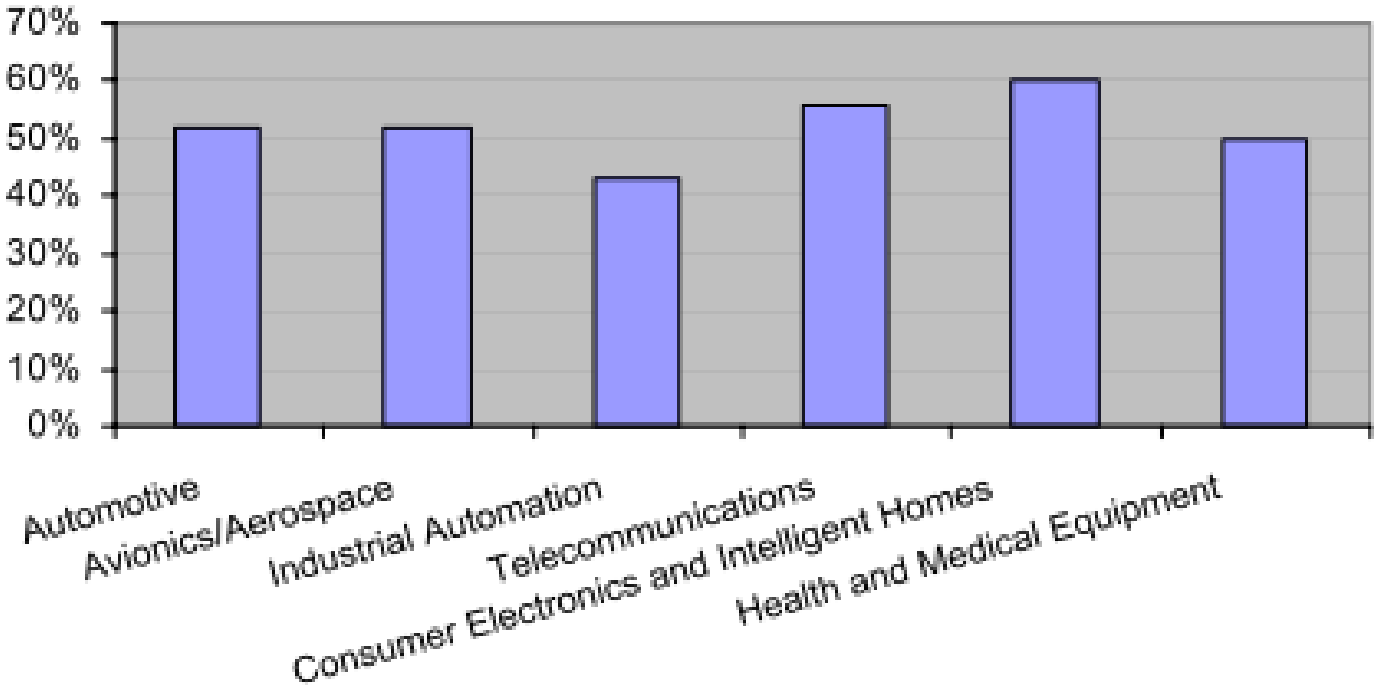
Cyber-physical systems

- 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

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



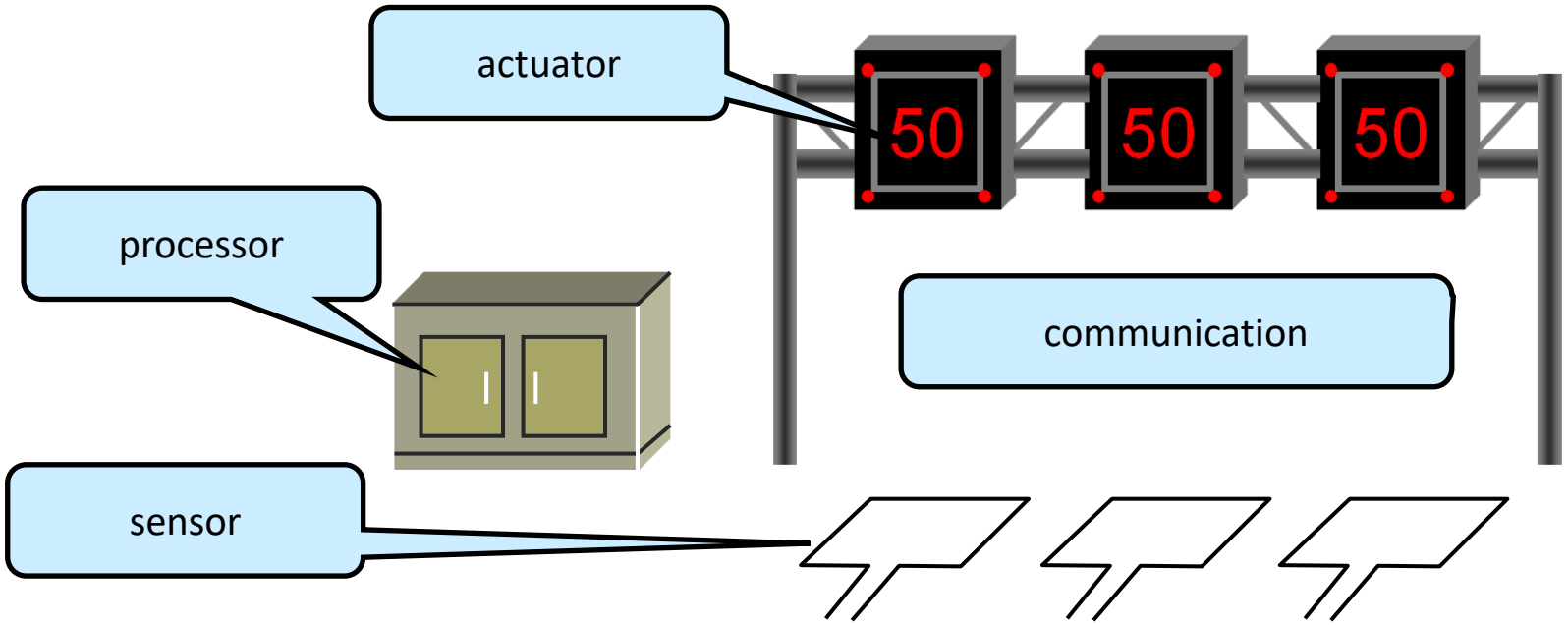
cyber-physical systems are the driving force behind the only silent revolution the world has ever seen

Cyber-physical systems

- cyber-physical systems are different from personal computers
- cyber-physical systems are
  - closely integrated with mechanics
  - reliable
  - consider many demands (energy, code size, ...)
  - designed for a specific application
  - often real-time
  - often reactive

Cyber-physical systems

- an cyber-physical system consists of
  - an actuator
  - a sensor
  - an embedded processor
  - and often a communication network

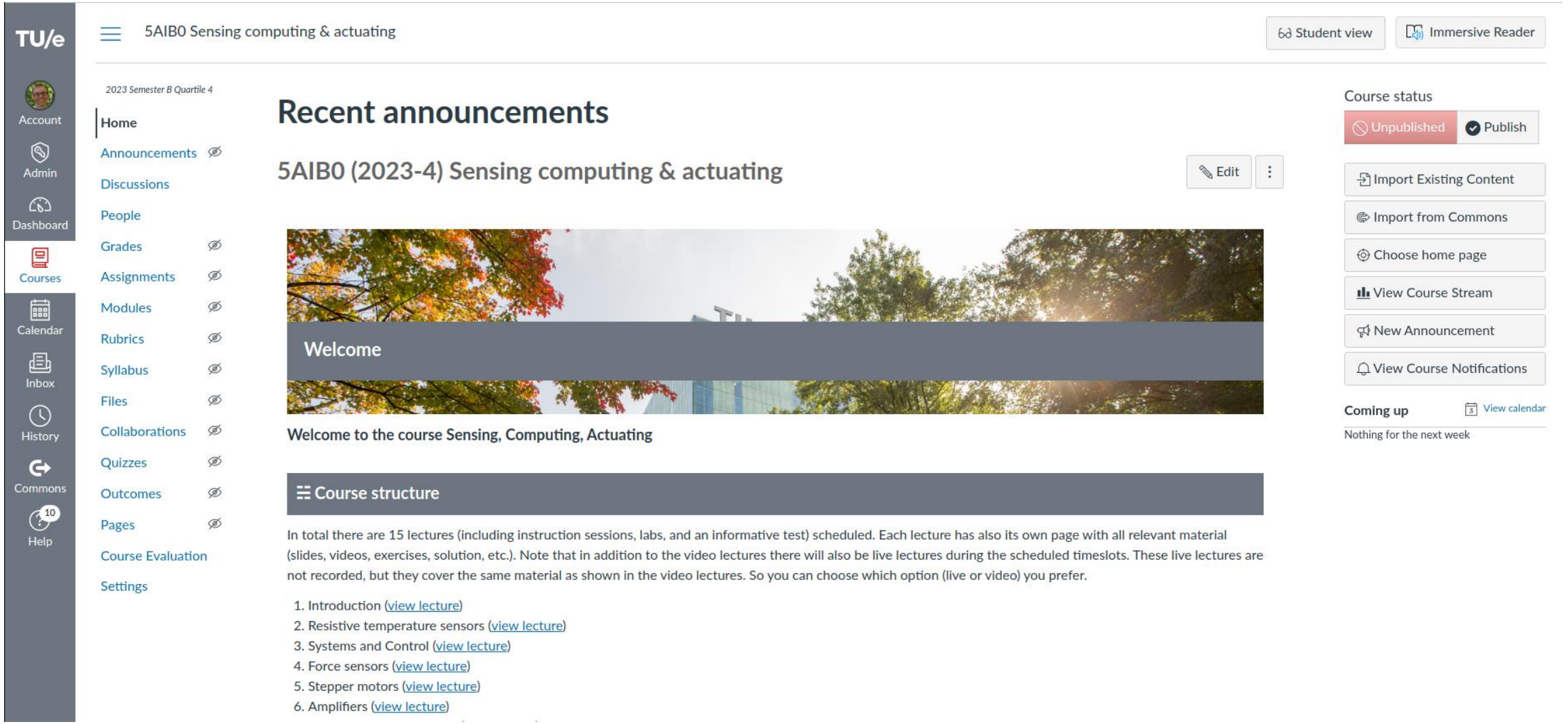


PRACTICAL NOTES

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


TU/e
5AIB0 Sensing computing & actuating
Student view
Immersive Reader
Account
Admin
Dashboard
Courses
Calendar
Inbox
History
Commons
Help
10
2023 Semester B Quartile 4
Home
Announcements
Discussions
People
Grades
Assignments
Modules
Rubrics
Syllabus
Files
Collaborations
Quizzes
Outcomes
Pages
Course Evaluation
Settings
Recent announcements
5AIB0 (2023-4) Sensing computing & actuating
Edit
Welcome
Welcome to the course Sensing, Computing, Actuating
Course structure
In total there are 15 lectures (including instruction sessions, labs, and an informative test) scheduled. Each lecture has also its own page with all relevant material (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)
5. Stepper motors (view lecture)
6. Amplifiers (view lecture)
Course status
Unpublished
Publish
Import Existing Content
Import from Commons
Choose home page
View Course Stream
New Announcement
View Course Notifications
Coming up
View calendar
Nothing for the next week

Course schedule

- Suggested schedule

	23-25 April	30 April – 2 May	7-9 May	14-16 May	21-23 May
Tu 13.30 – 16.15	Introduction to course Sensing displacement	Systems and Control	Stepper motors	Signal amplification	Non-linear sensors
	Arduino lab 1	Thermo-resistive	Strain / Bridges	Arduino lab 2	AD-comverters
Th 8.45 – 12.30	Resistive displacement	Systems and Control	TU/e closed	Signal amplification	No class
	Thermo-resistive	Strain / Bridges		AD Converters Model-based design	Informative test (non graded)

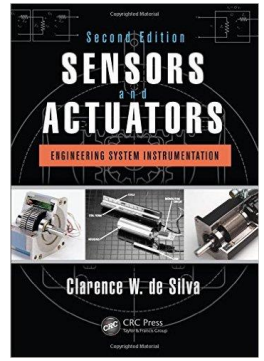
	28-30 May	4-6 June	11-13 June	18-20 June
Tu 13.30 – 16.15	Inductive sensors	Acoustic sensors	Thermocouple	Q&A (old exams)
	Non-linear sensors	Arduino lab 3	LED / Display	Arduino lab 4
Th 8.45 – 12.30	Inductive circuit	Inductive circuit	Thermocouple	No class
	Demodulation	LED / Display	Summary	

lecture / exercises
discuss homework
lab
Informative test (non graded)

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

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

Grading

- 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

Study guide

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

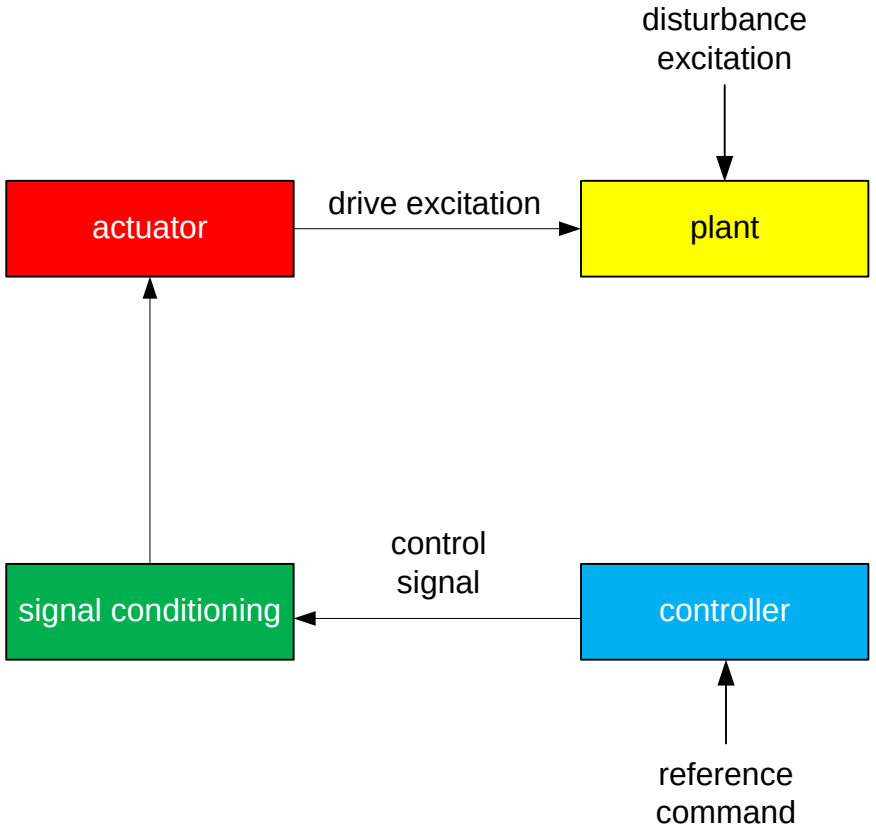
Lecture	Reading	Topic
1. Introduction to course	Ch 1	Control system architecture
1. Sensing displacement	Ch 3.4	Sensor characteristics
1. Sensitivity	Ch 5.3	Transfer function, sensitivity
1. Loading effect	Ch 5.3	Linearity, loading effect, absolute/relative error
2. Sensing temperature	Ch 2.1, 2.2, 5.11	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

- file names of slides, exercises start with corresponding class
  - 01-introduction.pdf
  - 02-resistive-temperature.pdf

CONTROL SYSTEM ARCHITECTURE

(Chapter 1)

Open-loop control



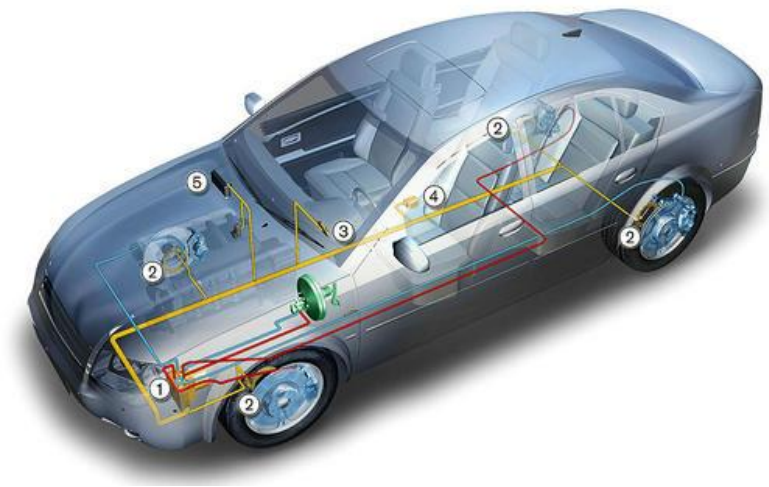
- response not measured
- plant must be stable and accurately known
- inputs must be precisely generated

Sensors

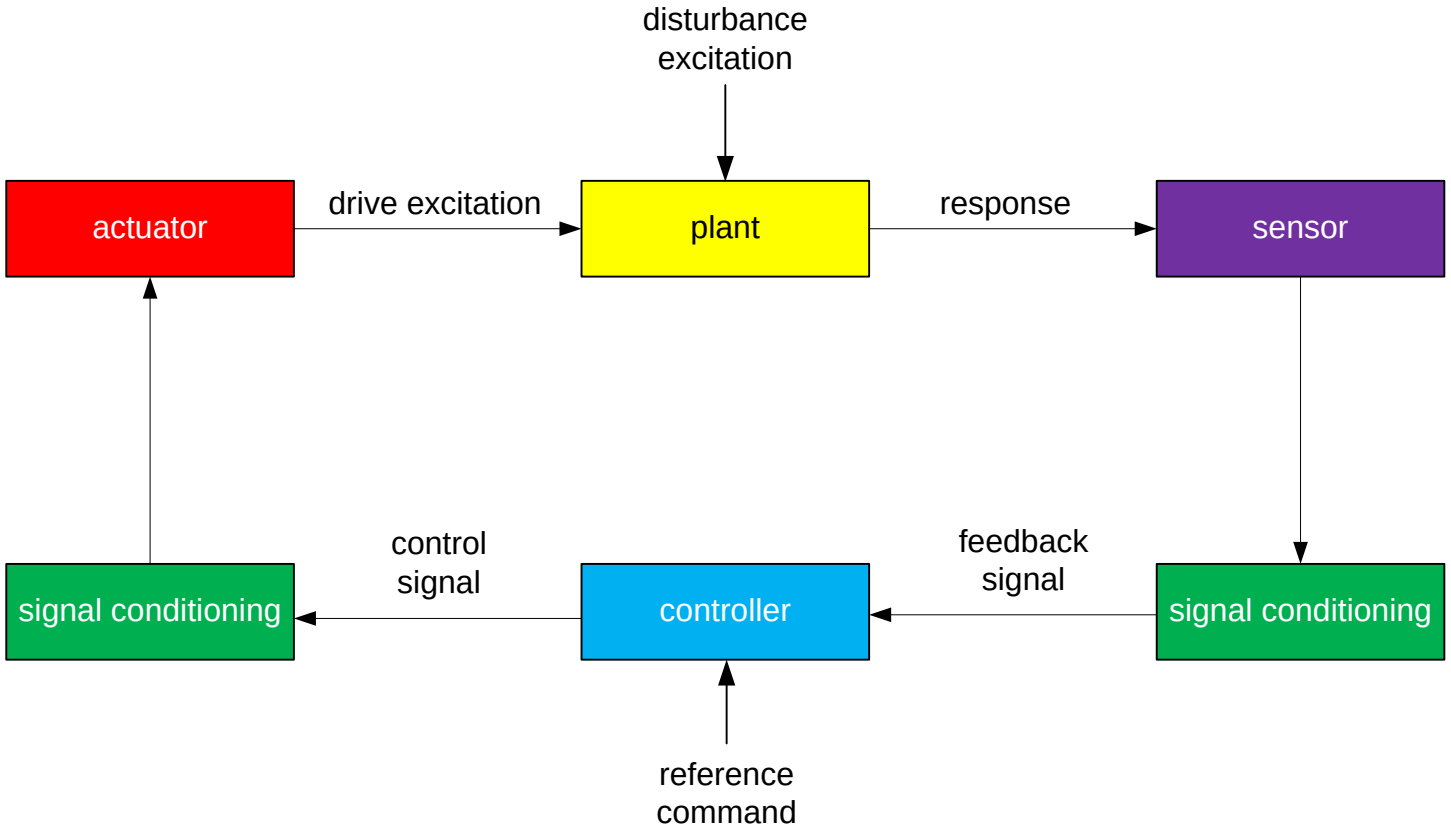
- sensors are common devices
- a system of any complexity cannot be designed without them

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

Control systems are everywhere...

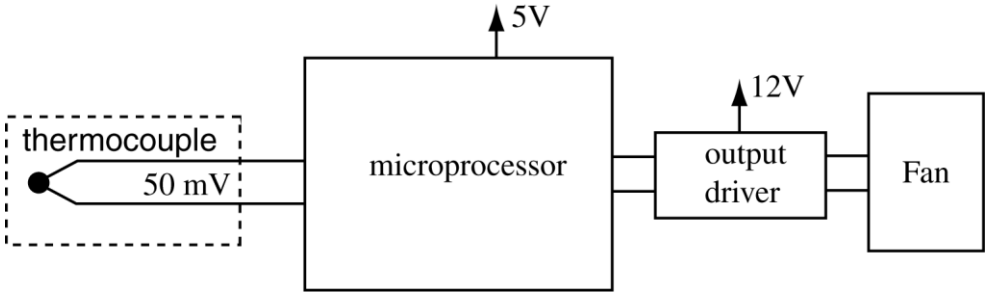


Feedback (closed-loop) control

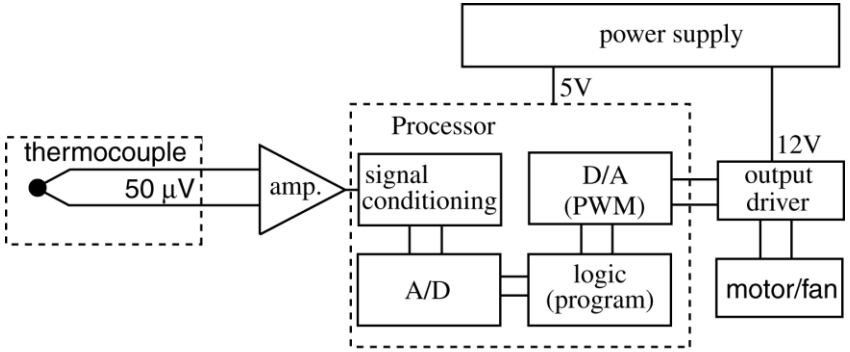


- measure response and compare with reference to minimize error
- several common feedback control strategies exist
  - on-off control
  - proportional (P) control
  - proportional control with integral (I) and derivative (D) action

Example – Temperature control



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



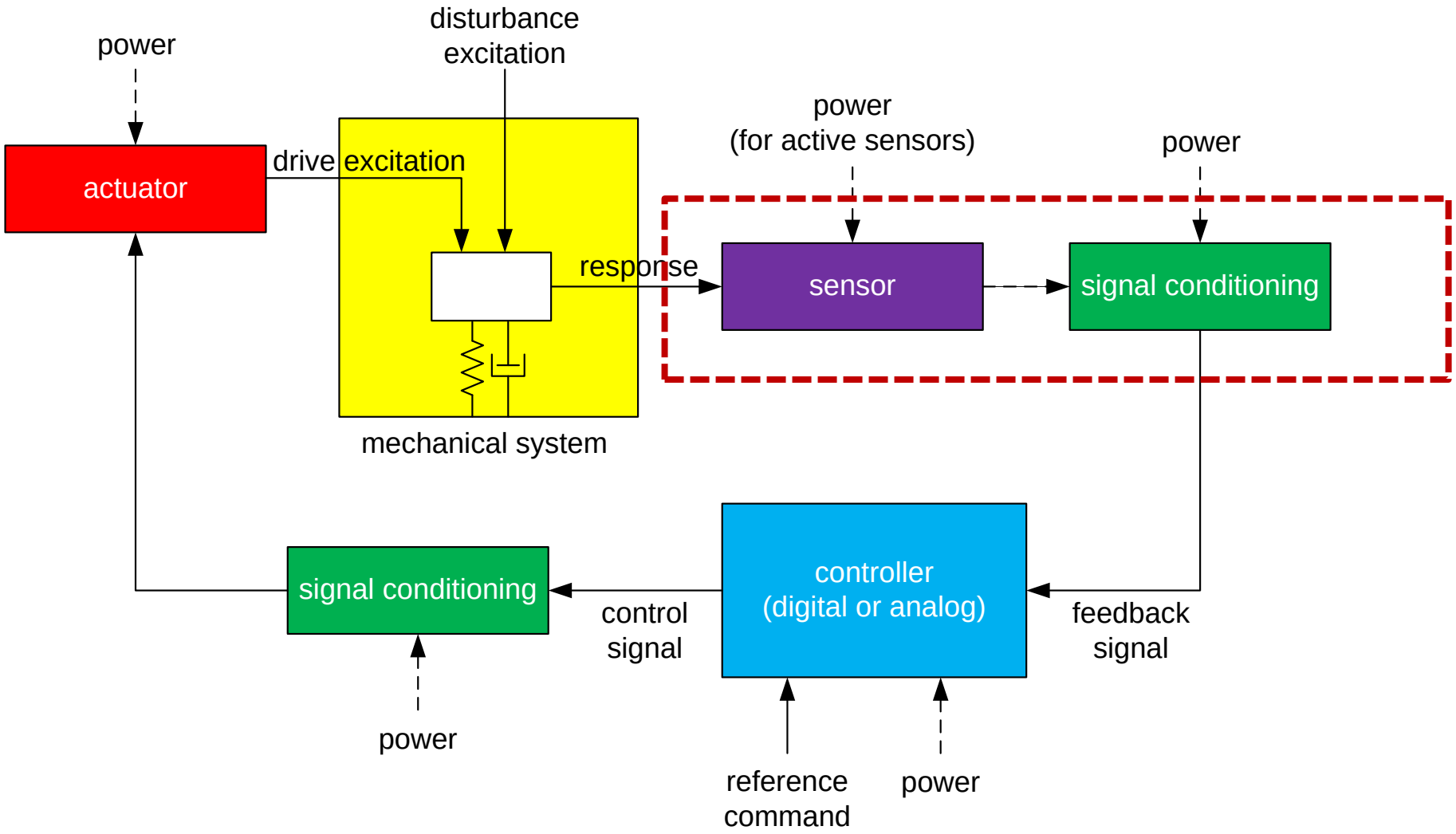
- A/D and signal conditioner can be separated from the processor
- circuitry may be integrated into a “smart sensor”

SENSING DISPLACEMENT

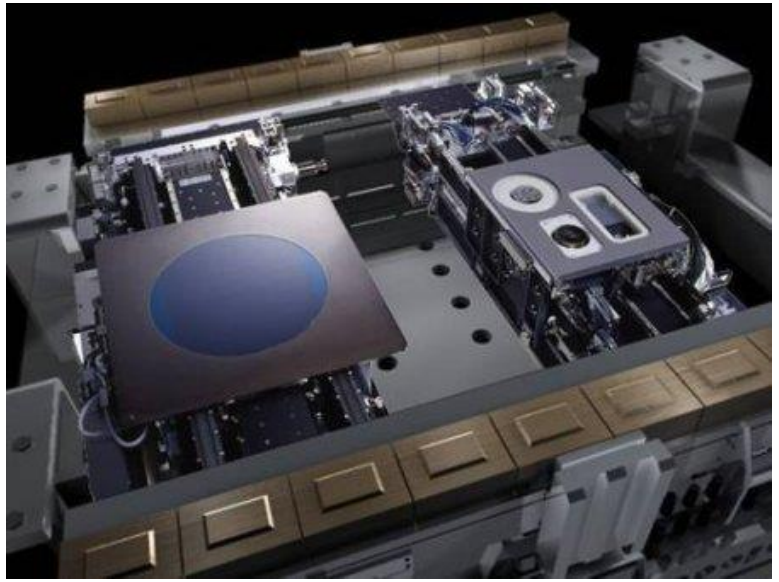
potentiometer, sensitivity, loading effect

(Chapter 5.3)

Control system



Applications



Motion transducers

- 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

Motion transducers

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

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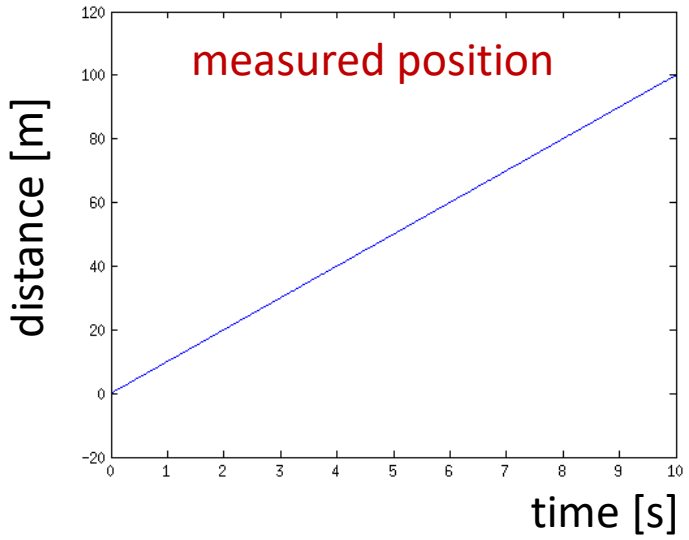
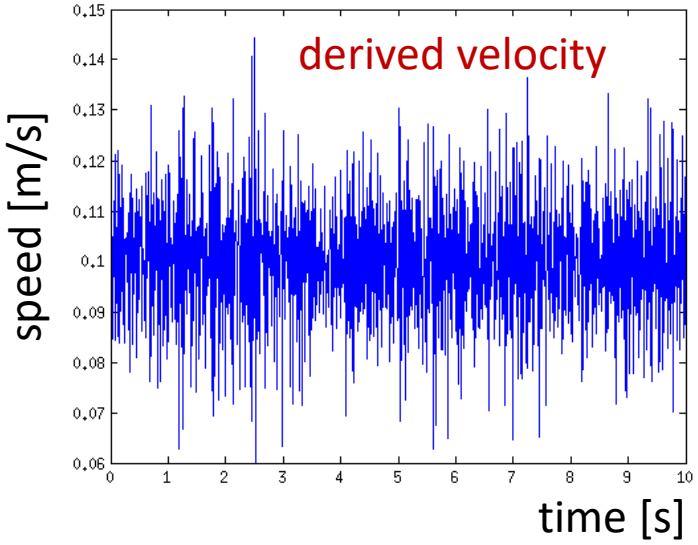
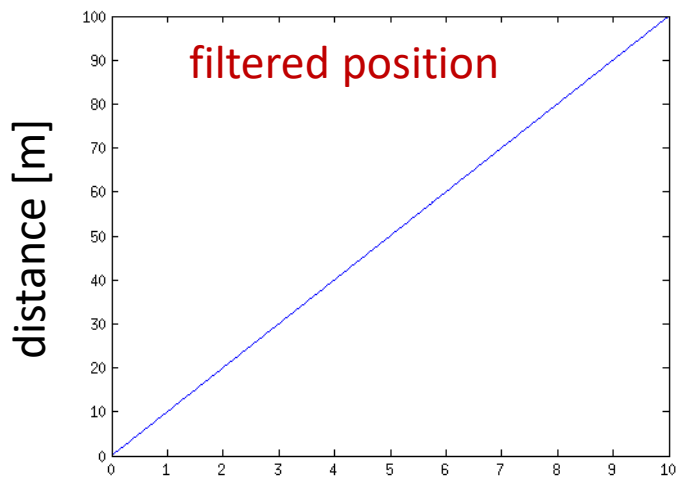


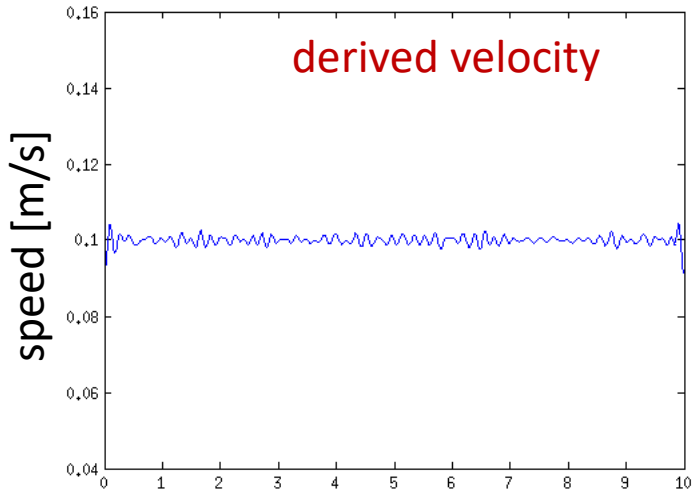


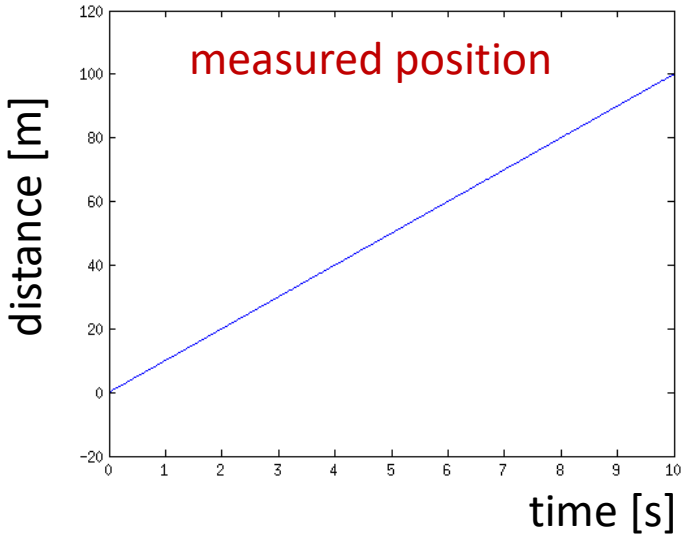
- noise limits accuracy of measurement (i.e. usability of sensor)

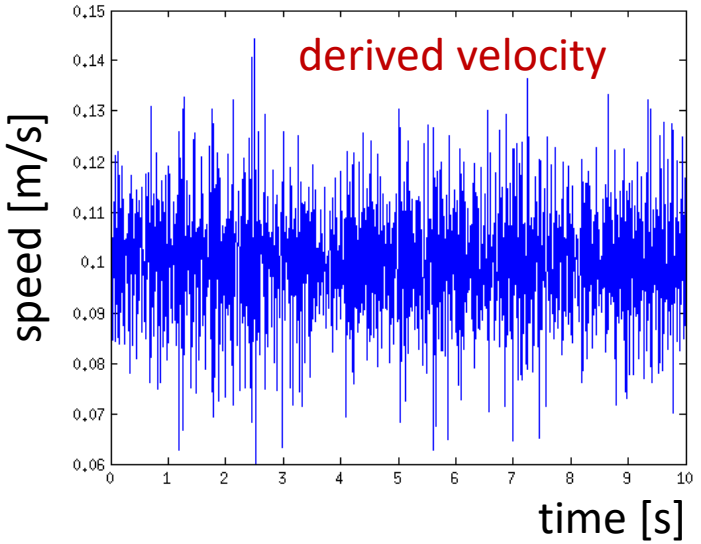
Motion transducers

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









Motion transducers

- 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

Potentiometer

- resistance of a material given by $R = \rho \frac{l}{A}$
  - ρ – resistivity of material
  - l – 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

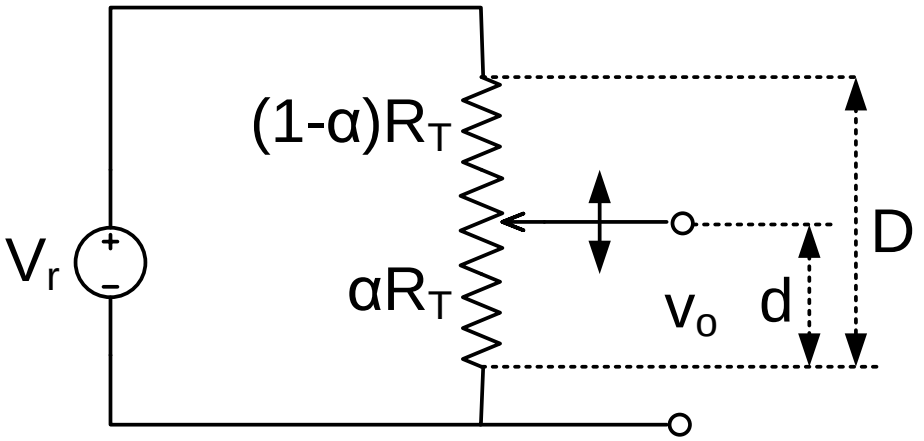
Potentiometer

- output voltage proportional to displacement

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

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

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



Potentiometer

- 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

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

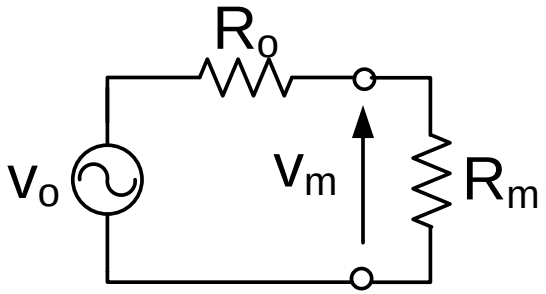
  - output resistance

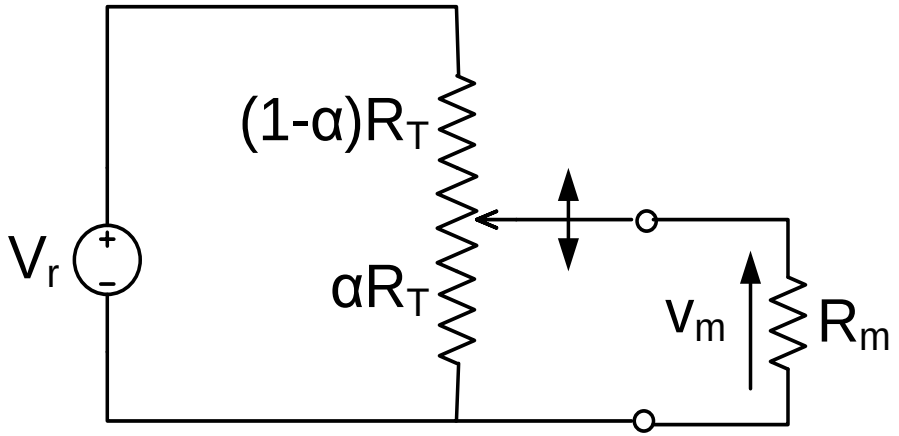
$$R_o = \alpha R_T // (1-\alpha) R_T$$

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

- voltage across load

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





Potentiometer

- 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

$$\left.\begin{aligned} v_m &= \frac{R_m}{R_m + \alpha(1-\alpha)R_T}\alpha V_r \\ k &= R_m/R_T \end{aligned}\right\} \Rightarrow v_m = \frac{1}{1 + \frac{\alpha(1-\alpha)}{k}}\alpha V_r$$

- 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

Potentiometer

- **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

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

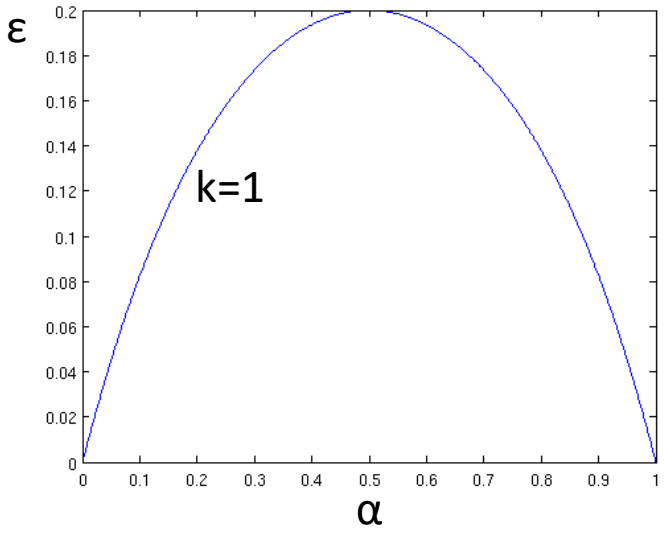
- maximal error

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

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

recall that

$$\frac{d}{d\alpha}\left(\frac{u}{v}\right) = \frac{v\frac{du}{d\alpha} - u\frac{dv}{d\alpha}}{v^2}$$



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

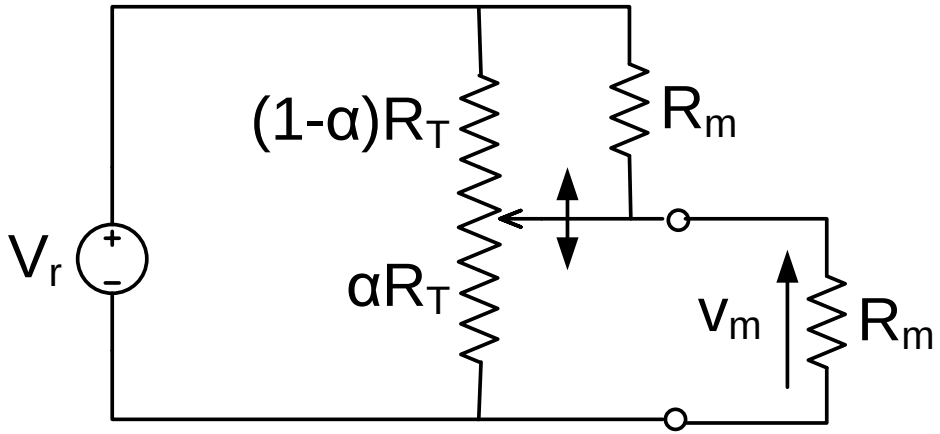
- **what is the output voltage of the sensor?**
- two options to compute output voltage
  - use Thévenin equivalent circuit
  - output voltage is voltage divider of two pair of parallel resistors

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

  - with

$$R_x = (1-\alpha)R_T // R_m = \frac{(1-\alpha)R_T R_m}{(1-\alpha)R_T + R_m}$$

$$R_y = \alpha R_T // R_m = \frac{\alpha R_T R_m}{\alpha R_T + R_m}$$



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?**

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

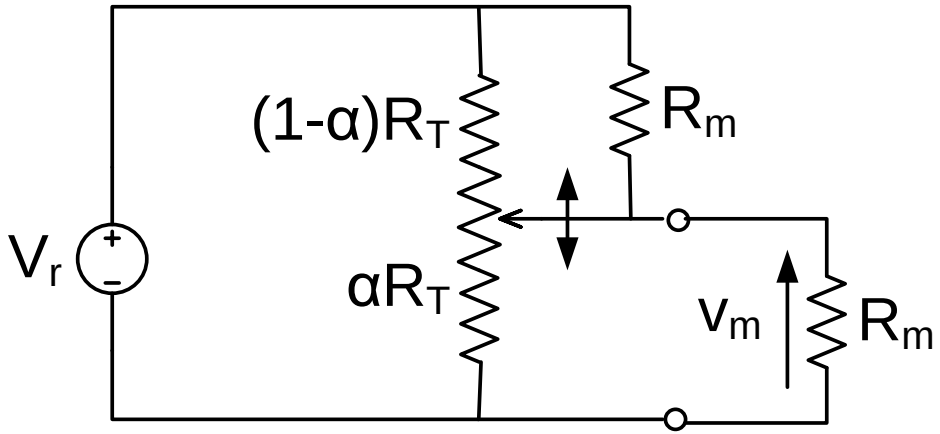
$$k = \frac{R_m}{R_T}$$

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

- 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



Potentiometer – loading error

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?

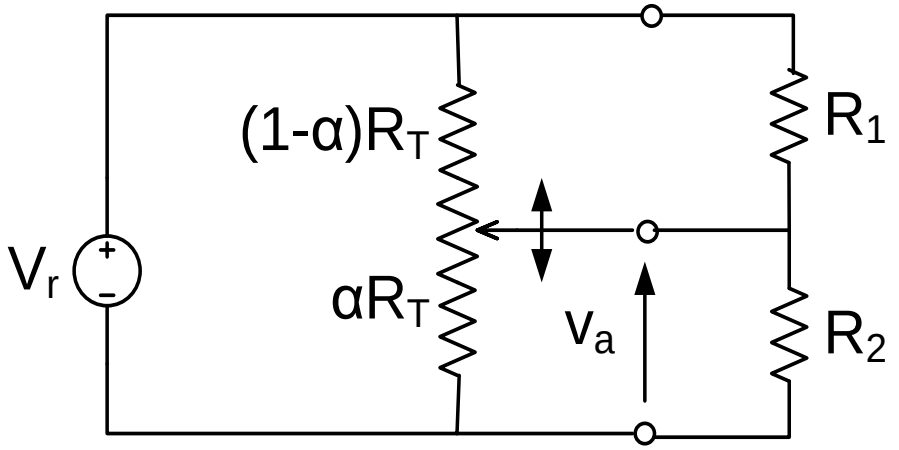
$$v_a = \frac{R_2 // \alpha R_T}{R_2 // \alpha R_T + R_1 // (1-\alpha) R_T} V_r \qquad = \frac{\frac{R_2 \alpha R_T}{R_2 + \alpha R_T}}{\frac{R_2 \alpha R_T}{R_2 + \alpha R_T} + \frac{R_1 (1-\alpha) R_T}{R_1 + (1-\alpha) R_T}} V_r$$

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

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

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

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



Potentiometer – loading error

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

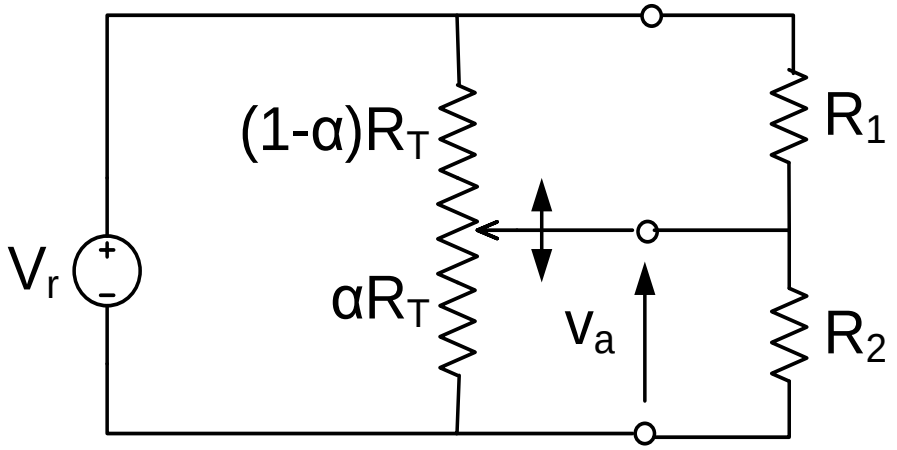
$$0.3 = \frac{6a + 10}{25 + 6(a + b)} \qquad 0.2 = \frac{9a + 10}{90 + 9(a + b)}$$

solving constraints yields

$$a = 3.5 \qquad b = 9.6$$

this implies

$$R_1 = 0.29R_T \qquad R_2 = 0.10R_T$$



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

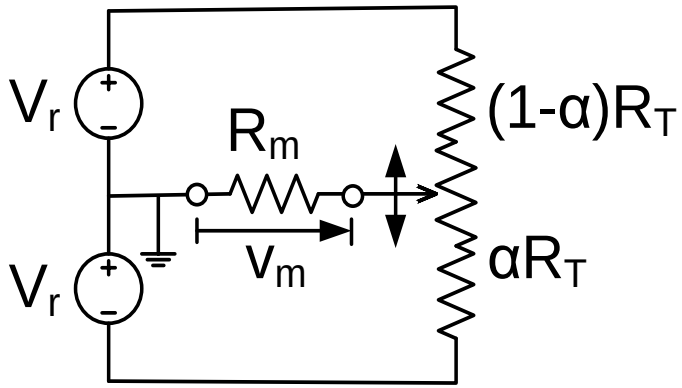
- **what is the output voltage of this sensor?**
- use Kirchhoff current law

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

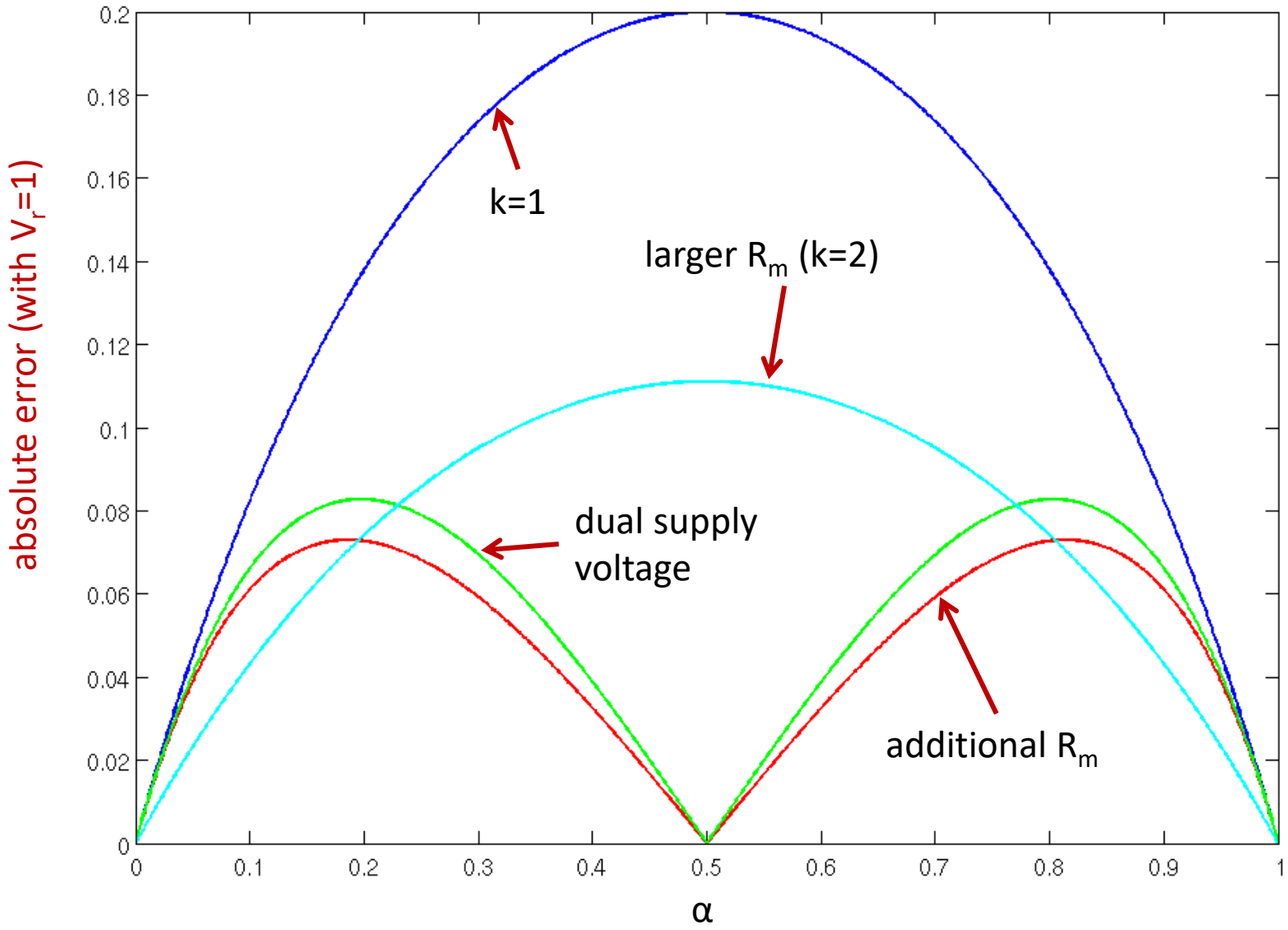
- solving this yields

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

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



Potentiometer – loading error



Potentiometer – lead-wire resistance

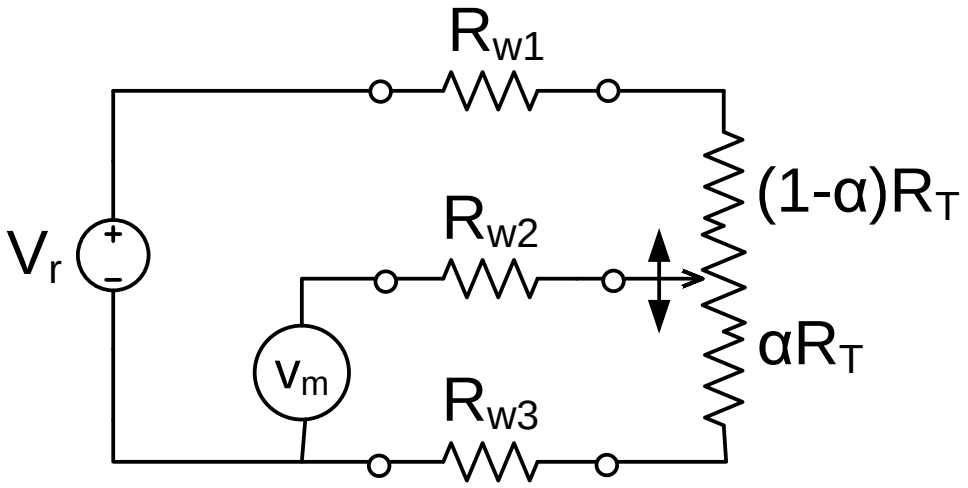
- 3-wire circuit output voltage
  - assume k >> 1, hence loading error is negligible
  - output at α = 0

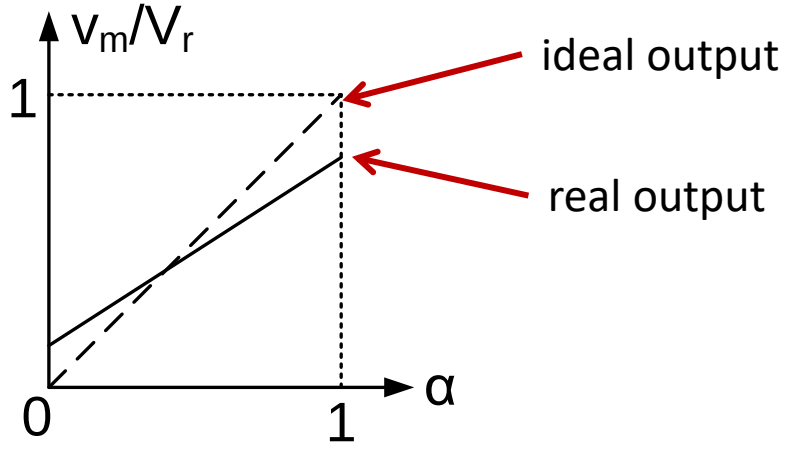
$$v_m(0) = \frac{R_{w3}}{R_T + R_{w1} + R_{w3}} V_r$$

  - 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}





Potentiometer – lead-wire resistance

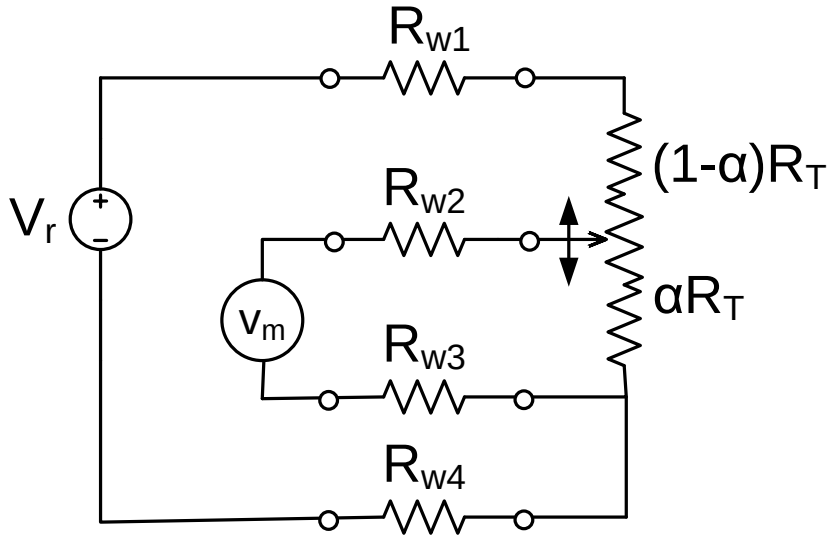
- 4-wire circuit output voltage
  - assume k >> 1, hence loading error is negligible
  - output at α = 0

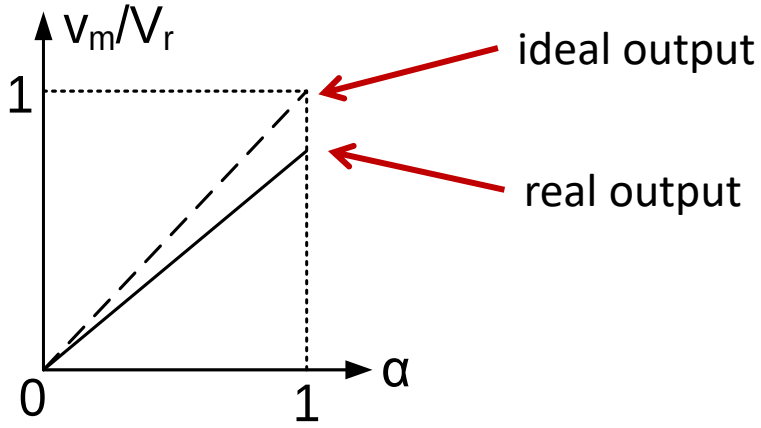
$$v_m(0) = 0$$

  - output at α = 1

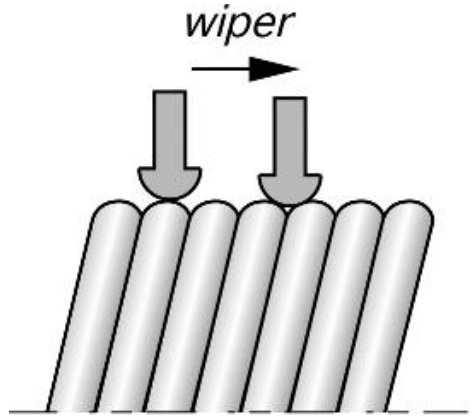
$$v_m(1) = \frac{R_T}{R_T + R_{w1} + R_{w4}} V_r$$

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

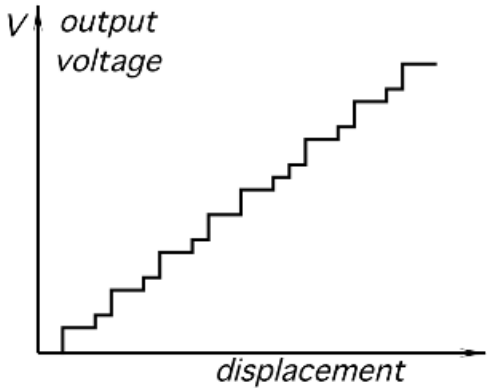




Potentiometer – construction



- 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



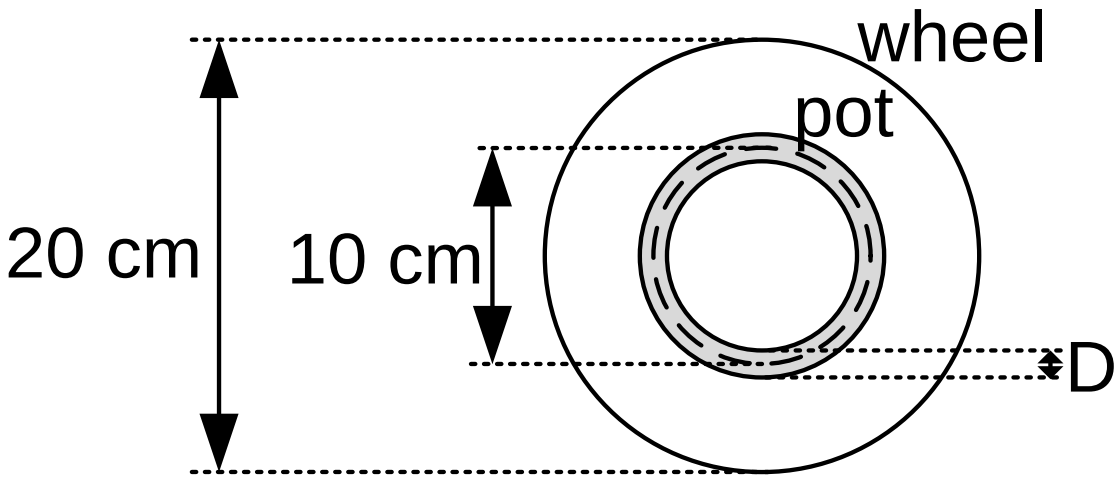
- construction: high-quality resistive film
  - theoretically an infinitesimal resolution
  - resolution limited by
    - noise in circuit
    - non-uniformity of material

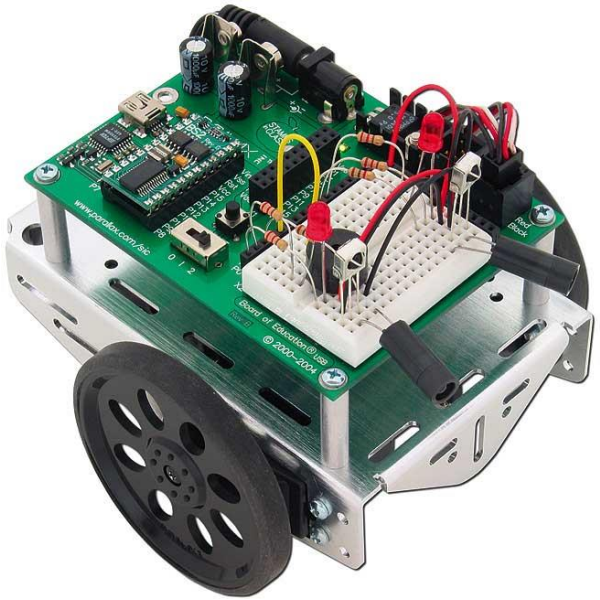
Potentiometer – resolution

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 μΩ cm

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





Potentiometer – resolution

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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)

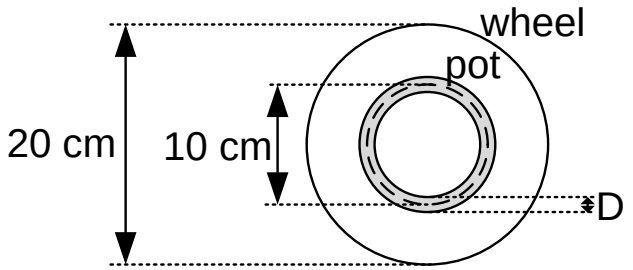
$$r = \frac{100}{N}\%$$

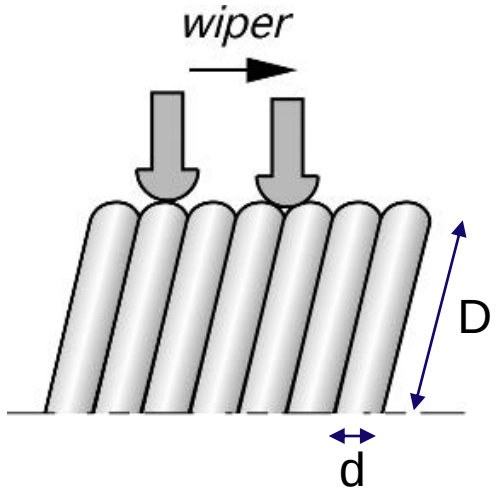
- required resolution

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

- 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 μΩ cm

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

- diameter of wire

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

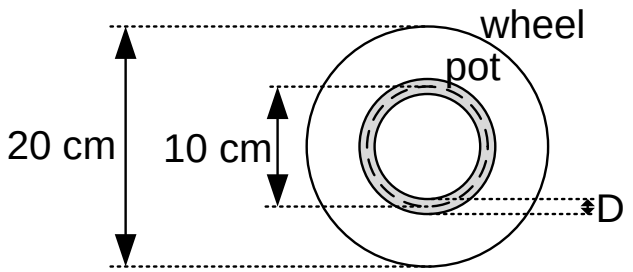
$$\Rightarrow d = 0.5mm$$

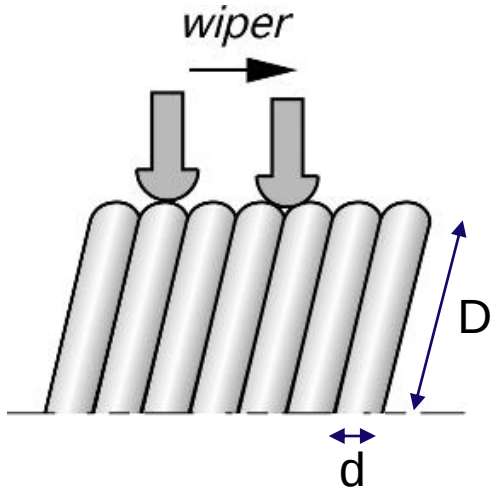
- resistance of a wire

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

- diameter of coil

$$\Rightarrow D = 1.0cm$$





Potentiometer - Summary

- resistance of a material given by $R = \rho \frac{l}{A}$
  - ρ – resistivity of material
  - l – 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

Potentiometer - Summary

- 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

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

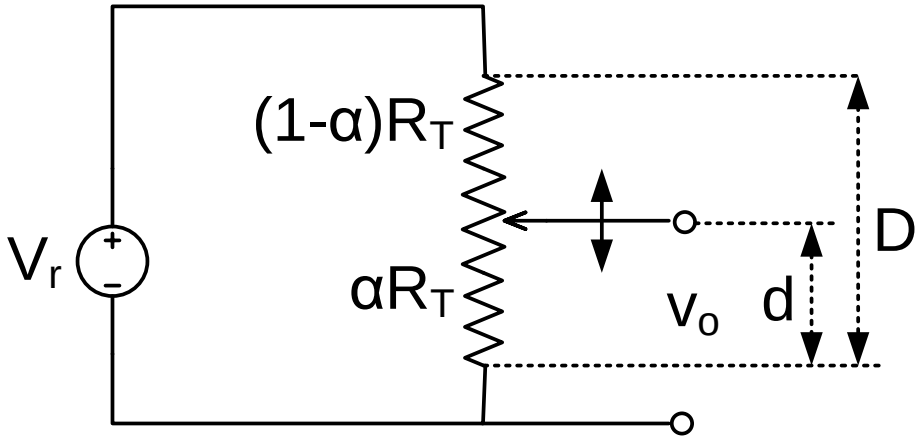
with

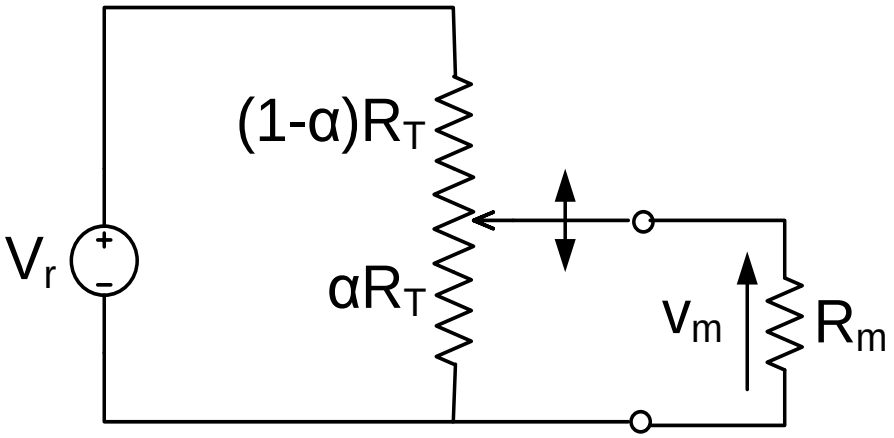
$$k = R_m / R_T$$

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

absolute error

relative error





Potentiometer - Summary

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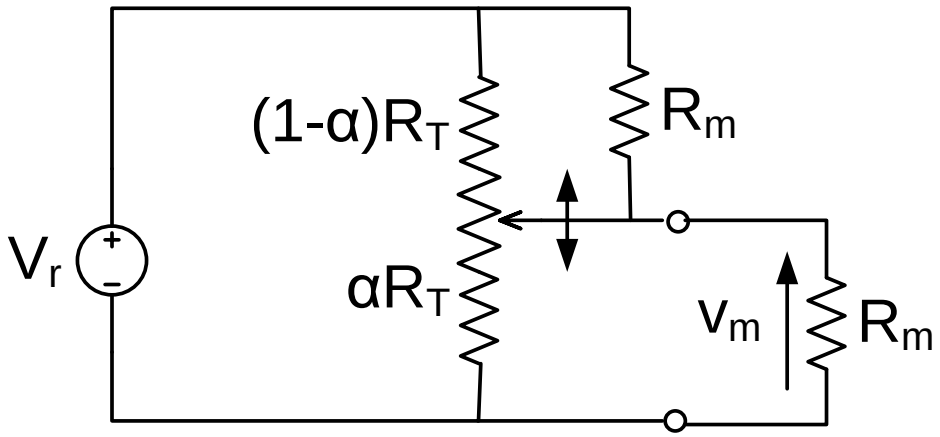

output voltage $$v_m = \frac{\alpha(k+1-\alpha)}{2\alpha(1-\alpha)+k} V_r$$

relative error $$\varepsilon = \left| \frac{2\alpha^2 - 3\alpha + 1}{2\alpha(1-\alpha)+k} \right|$$

Potentiometer - Summary

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