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INDUSTRIAL EXPERT

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INDEX: Industrial Expert

Sensors and Automation - Intermediate Module

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About This Course

The Sensors and Automation course covers information about various principles and technologies implemented on the most commonly used types of sensors and actuators/transducers. It will provide students with necessary knowledge regarding operation, application and integration of sensors and actuators (including signal processing and interfacing) to enable the design and realization of complete systems.

Format

The form of education is e-learning with approx. 20 hours of lessons and 20 hours of self-studying. Weekly lessons include lectures, thematic videos and performing test tasks. An important part of this course is performing final exam in the form of multiple choices quiz, which contains answers based on study material. The course is set up in compliance with the ECVET System with possibility to obtain the Certificate of attendance.

Who can take this course

This course does not require any specific knowledge on Industry 4.0 and is designed for an audience, who want to learn about 4th Industrial revolution and smart technologies. This means, first of all, students (bachelors, masters), whose curricula include disciplines related to the industry 4.0 as well as specialists and mangers in the various application areas of smart technologies. The course will be of particular interest to:

- senior executives or a development department managers of your enterprise interested in learning about innovation and technology transfer

- professionals interested in commercialisation of Industry 4.0-based solutions in his area of expertise

- founders of high-technology start-ups

- young engineers of the company who is already working on development of specific components of Industry 4.0 and their application or is interested in expanding the base of customers that develop smart technologies for new fields of application

- educators teaching graduate and postgraduate courses focusing on commercialisation and technology transfer

- students or postgraduates interested in commercialisation and technology transfer

Programme of the course

1. Different types of sensors
1.1 Classification of sensors

1.2 Thermal sensors
1.3 Humidity sensors
1.4 Optical sensors
2. Sensor characteristics
2.1 How to select the right sensor
2.2 Transfer functions
2.3 Accuracy, resolution
2.4 Selectivity and sensitivity
3. Sensors made by micro- and nanotechnology
3.1 Introduction to micro- and nanotechnology
3.2 MEMS devices
3.3 Integrated photonic devices
4. Chemical and biological sensors
4.1 Introduction to chemical and biological sensors
4.2 Electrochemical sensors
4.3 Gas sensors
4.4 Electronic noses
5. Industrial automation
5.1 What is industrial automation
5.2 Automation architecture

Course Staff

Dr. Martin Bennink

Saxion University of Applied Sciences, Professor

Dr. Aurel Ymeti

Saxion University of Applied Sciences, Senior Researcher

BASc. Maarten van Rossum

Saxion University of Applied Sciences, Researcher

Results

As the result of completing the Sensors and Automation intermediate level course, learners will know about:
- classification of sensors and actuators based on their operation principle;
- most commonly used types of sensors (mechanical, thermal, electro-magnetic and bio-chemical) and actuators;
- features/functionalities needed to achieve a complete working system;
- analysis of systems and selection of proper types of sensors and actuators that are needed to realize such systems based on required applications

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Competences

By completing the Sensors and Automation intermediate level course, learners will develop the ability to:

- properly apply a certain type of sensor for a given application
- select suitable sensors based on their characteristics
- select and apply sensors based on micro- and nanotechnology
- apply chemical and biological sensors in daily life applications
- manage basic sensors and automation projects

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Sensors and Automation - Intermediate Module

Different types of sensors

Classification of sensors

There are a large number of sensors available that differ in many aspects. Have a look at this collection:

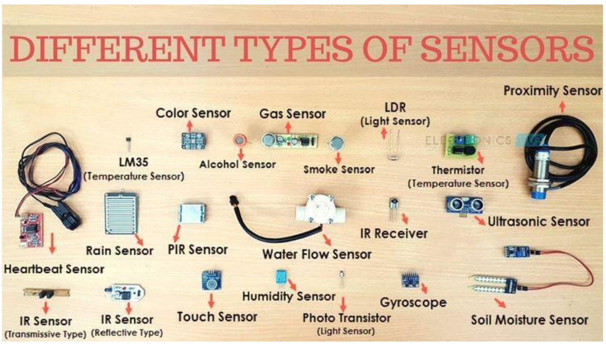

Figure 1: Overview of different types of sensors. © electronicshub.org

All these sensors are different, and it is interesting to note that most of these sensors are classified according to the property, or stimulus they measure. Others are categorised based on their mode of operation (such as the gyroscope).

They differ in:

- complexity
- active/passive
- relative/absolute sensors
- application in which they are used
- specifications
- sensing element material
- conversion phenomena
- stimulus to which they respond

This makes it rather complex to create any logical structure as there is not a single way to organise or classify them.

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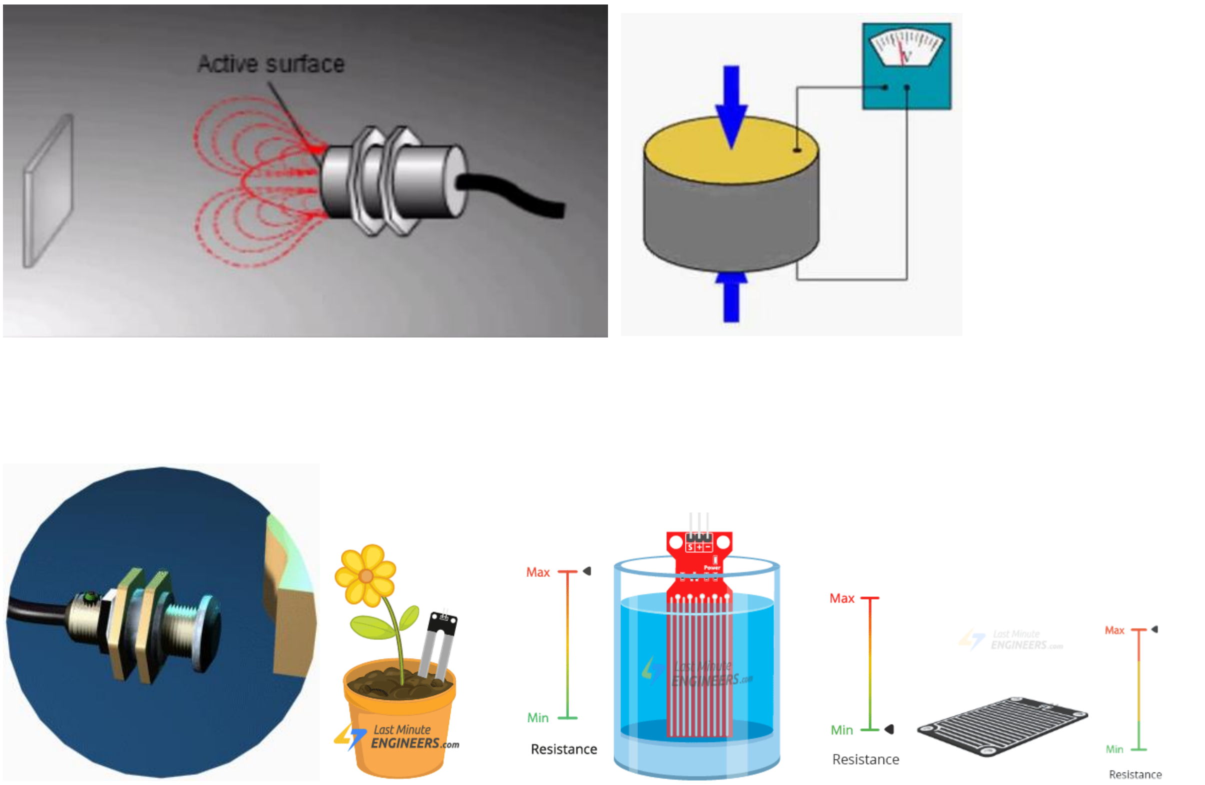

Figure 2: examples of sensors; inductive proximity sensor, pressure sensor, spring loaded proximity sensor, humidity sensor, water level sensor, rain sensor. © Last minute Engineers.com

Digital and analog sensors

In the following video the difference between digital and analog sensors is explained.

Watch the videl [Types of Sensors]

Exercise

In the video different examples of digital and analog sensors have been mentioned.
Which of the sensors mentioned below are digital sensors (multiple answers possible)?

☐Proximity sensor.
☐ Humidity sensor.
☐ Gas fuel sensor.
☐ Limit switches.

Active and passive sensors

Sensors are either active or passive.

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Passive sensors do not require any additional energy source. The electrical signal is generated in response to an external stimulus.

Examples of passive sensors are a thermocouple, a photodiode and piezoelectric sensor.

Check out the video below explaining the basic principle of a thermocouple. The signal of the thermocouple is generated because of the Seebeck effect. As there is a temperature difference between two contact points of a metal wire, a potential difference will appear. When two different metals are used this potential will be different as this is a property of the metal.

It is clear that there is no external power or signal needed to generate the output electrical signal.

Watch the video [What is a Thermocouple and how does it work? Explained].

Active sensors on the other hand do require external power for their operation. This signal is called the excitation signal, and is modified (or modulated) by the sensor to produce the output signal.

Schematically:

Figure 1: schematic of an active sensor. © Index consortium license: CC-BY-NC-SA

The output of the sensor is "changed" or modulated as a function of the stimulus, and this modulation "carries" the information on the measured value.

An example of this is the thermistor, which effectively is a temperature sensitive resistor.

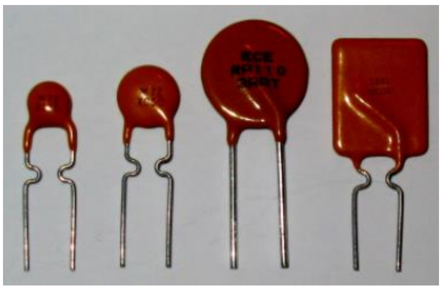

Figure 2: different types of thermistors. © Wikipedia (Shaddack): Public Domain

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Here are some examples of thermistors, which effectively do not generate an electrical signal, but when you connect this to an external current source, the voltage across the thermistor is a measure of the temperature.

Another example of sensors is strain gauges, which are made of a material of which the resistance changes as the strain on the material is changing.

Absolute and relative sensors

Another way to classify sensors is whether they measure the stimulus in absolute or relative values.

An **absolute sensor** that produces a signal is a reference to an absolute physical scale (which is independent of the measurement conditions). The thermistor, which we have discussed in the previous unit is an example of an absolute sensor, because the electrical resistance is directly related to the absolute temperature scale of Kelvin.

Another example of an absolute sensor is, for example, a pressure sensor that produces a signal in reference to vacuum. Vacuum represents an absolute zero point on the pressure scale.

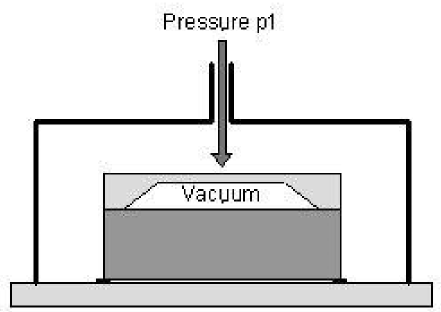

Figure 1: a pressure sensor. © MeasureX

As you can see the sensor has a sealed container in which there is a vacuum. The pressure to be measured (p1) can then always be referenced to this absolute vacuum.

A **relative** sensor produces an output signal that is related to a selected baseline. Take the thermocouple discussed in the previous unit as an example. This sensor needs a temperature (Tc) that is known (or referenced in another way) to determine the temperature of an unknown sample (Th). It effectively measures differences between two different conditions, and in order to get this working you need to have to use one condition as a reference point.

Sorted on stimulus

By far most of the sensors are categorised based on what they measure. In other words, the stimulus of the sensor. In the scheme below the measurand (i.e. stimulus) is first divided in subcategories and per category different examples of properties are mentioned.

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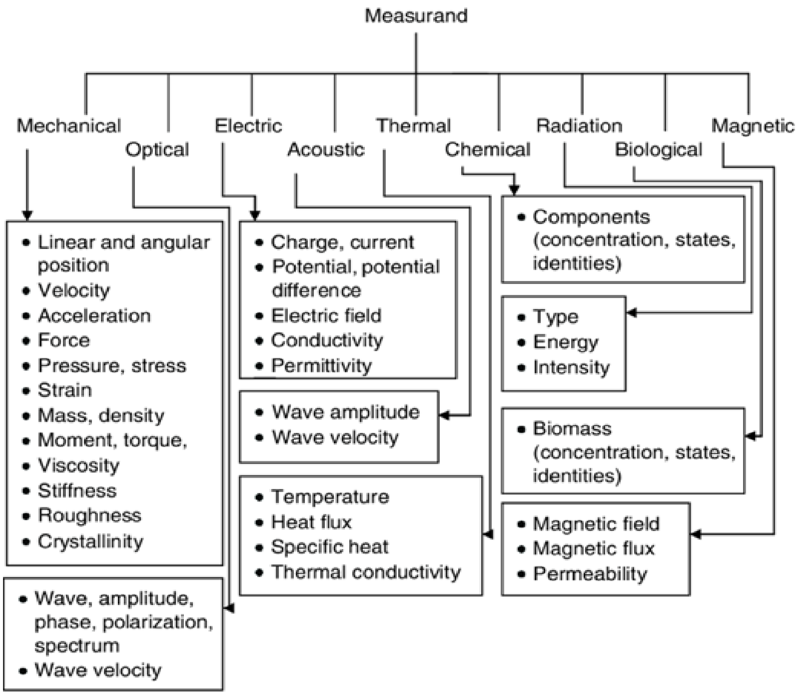

Figure 1: Sensors and measurand. © Reproduced from White, R. M. A Sensor Classification Scheme. IEEE Trans. Ultrason., Ferroelectr., Freq. Control 1987, UFFC-34 (2), 124-126

Other classifications

As mentioned by far most sensors are categoris ed on what they measure, but there are a few other ways to classify them. You can classify, sort or categorise them based on their sensor specification, sensing element material, conversion phenomenon, or field of application.

When classifying **sensor specifications** you can do this based on properties of the sensor such as sensitivity, stability, accuracy, speed of response, hysteresis, resolution, dynamic range, linearity, etc.

Another way is to classify them is on the **material of the sensing element**, being inorganic, conductor, semiconductor, organic, biological substance.

A more technical way to classify sensors is based on the **conversion phenomenon** that is used by the sensors. If you consider the working principle of a photodiode, you see that light intensity is converted to an electrical signal, which means this is a photoelectric device. Another example is a piezoelectric sensor, which is based on the piezoelectric effect (strain change as a result of a voltage applied to a material).

Examples of different conversion phenomena are: thermoelectric, photoelectric, photomagnetic, magnetoelectric, thermoelastic, thermomagnetic, photoelastic, chemical transformation, electrochemical, spectroscopic, biochemical transformation.

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Units of measurement

We have been discussing sensors that produce quantitative data. What is important to realise is that different standards of units are used around the world.

Figure 1: pressure dial, units in kPa and psi. © Wikipedia (leapingllamas): CC-BY 2.0

Here is a pressure meter that has two different scales of different unit systems. In black you can see the values expressed in kPa, which is a part of the **SI unit** set. In red, this pressure scale is expressed in psi, pounds per square inch. This scale is part of the **US Customary System**.

Also for length and distance measurements different units are used in different parts of the world. A person's height is typically expressed in metres in Europe (1.80 metre, which is 1 1 metre and 80 cm tall). In the US this same person is 5 feet and 9 inches tall. And when it comes to distances, in Europe distances are expressed in kilometres, and in the US in miles.

When looking at sensors and particularly their operating range it is important to be aware of this, and do the conversion to ensure you have what you need. Nowadays simply use Google to convert any number into other units.

The most common standard is SI, which is short for "Le systeme International d'Unites". This standard is a base set of 7 basic units, from which all other units are derived.

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Dimension	Unit	Symbol
Length	meter	L
Mass	kilogram	M
Time	second	T
Electric Current	ampere	I
Luminous Intensity	candela	J
Temperature	kelvin	θ
Amount of Substance	mole	N

Table 1: the 7 basic units of the SI system standard. © Cohl, H. , Schubotz, M. and Veenhuis, D. (2016), Getting the units right, Conference on Intelligent Computer Mathematics 2016, Bialystok

This system also has a defined number of letters that are used as prefixes for factors of 1000.

- 1 mA current is equal to 10^-3 A or (1/1000) A.
- 100 km is equal to 100 10^3 meter or 100,000 metre.
- 2 nm is equal to 2 10^-9 meter, or 0.000000002 metre

See the table below for all prefixes that are used:

Prefix	Abbreviation	Meaning	Example
Giga	G	10^9	1 gigameter (Gm) $= 1 \times 10^9$ m
Mega	M	10^6	1 megameter (Mm) $= 1 \times 10^6$ m
Kilo	k	10^3	1 kilometer (km) $= 1 \times 10^3$ m
Deci	d	10^{-1}	1 decimeter (dm) = 0.1 m
Centi	c	10^{-2}	1 centimeter (cm) = 0.01 m
Milli	m	10^{-3}	1 millimeter (mm) = 0.001 m
Micro	μ[a]	10^{-6}	1 micrometer (μm) $= 1 \times 10^{-6}$ m
Nano	n	10^{-9}	1 nanometer (nm) $= 1 \times 10^{-9}$ m
Pico	p	10^{-12}	1 picometer (pm) $= 1 \times 10^{-12}$ m
Femto	f	10^{-15}	1 femtometer (fm) $= 1 \times 10^{-15}$ m

[a]This is the Greek letter mu (pronounced "mew").

Table 2: Prefixes used with the SI system. © Pearson Prentice Hall

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Sometimes other systems of units are used. These are the **Gaussian system** and the **British system**. In the US a variant of the latter is used, known as the US Customary System.

This means it is sometimes necessary to convert values from one unit system into another. Below is an example of a conversion table to recalculate pressure in 5 different unit systems.

Unit	Pascal (Pa)	Bar (bar)	Technical atmosphere (at)	Standard atmosphere (atm)	Torr (Torr)	Pounds per square inch (psi)
1 Pa	**1 N/m²**	10^{-5}	1.0197×10^{-5}	9.8692×10^{-6}	7.5006×10^{-3}	1.450377×10^{-4}
1 bar	105	**100 kPa** **10^{6} dyn/cm²**	1.0197	0.98692	750.06	14.50377
1 at	0.980665×10^{5}	0.980665	**1 kp/cm²**	0.9678411	735.5592	14.22334
1 atm	1.01325×10^{5}	1.01325	1.0332	1	**760**	14.69595
1 Torr	133.3224	1.333224×10^{-3}	1.359551×10^{-3}	1.315789×10^{-3}	**1/760 atm** ≈ 1 mmHg	1.933678×10^{-2}
1 psi	6.8948×10^{3}	6.8948×10^{-2}	7.03069×10^{-2}	6.8046×10^{-2}	51.71493	**1 lb_F /in²**

Table 3: conversion table for different measurement systems. © Precision Labware

Thermal sensors
Introduction

The temperature sensor (also known as the thermal sensor) refers to a sensor that can sense/measure the temperature and convert it into a usable/readable output signal. The temperature sensor is one of the most frequently used sensors, which is widely used/applied in computers, automobiles, kitchen appliances, air conditioners and household thermostats.

The five common types of temperature sensors include:

- Thermocouples.
- Thermistors.
- RTDs (Resistance Temperature Detectors).
- Analog thermometer.
- Digital thermometer.

Watch the video [What is a temperature sensor?]

Thermocouples

Introduction to thermocouples

The combination of two different conductors or semiconductors is called a thermocouple. The thermoelectric potential EAB (T, T0) is composed of the contact potential and the temperature difference potential. Contact potential is generated by two different conductors or semiconductors at the contact point, which is related to the property of the two and the temperature at the contact point.

When two different conductors or semiconductors A and B are connected to each other to form a loop (see Figure 1), as long as the temperature at the two nodes is different, there will be current in the circuit. The temperature at one end is T, which is called the working end, while that at the other end is TO, which is a free end, and the electromotive force at this moment is called thermal electromotive force. The electromotive force is generated due to different temperatures.

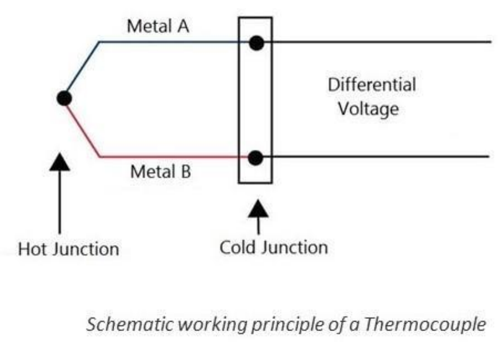

Figure 1: Schematic working principle of a Thermocouple. © maximintegrated.com

Watch the video Temperature Sensor

Thermometers

A thermometer is a sensor that senses and converts temperature into a readable output. The output can be direct or indirect. For example, a mercury thermometer which uses a level of mercury against a fixed scale is a direct output. Whereas a digital readout thermometer is an indirect output (see images below). For a digital readout thermometer, a converter is used to convert the output of the temperature transducer to an input for the digital display. The measured temperature is displayed on a monitor. The thermometer can be considered to be both a transducer (usually a thermocouple that transfers heat energy to voltage) and a sensor (quantifies the transducer output with a readable format).

The mercury thermometer utilises the mercury’s property of expanding or contracting when heated or cooled, respectively. In a mercury thermometer, a temperature increase is sensed by the mercury contained in a small glass tube. The thermal energy resulting from the temperature increase is

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transferred into the mercury causing it to expand. The expansion of mercury is scaled to numbers on the tube indicating the temperature.

Figure 1: Mercury thermometer, digital readout and infra-red (contactless) thermometers © scme-nm.org

RTDs: Resistance Temperature Detectors

Watch the video [RTDs]

Humidity sensors
Introduction

Humidity is related to the presence of water in air. The amount/quantity of water vapour in air can affect human comfort and many different manufacturing processes in industries. The presence of water vapour can also influence various physical, chemical and biological processes.

Humidity sensors work/operate by detecting changes that alter electrical currents or temperature in the air. Three basic types of humidity sensors can be defined: capacitive, resistive and thermal. All three types will monitor rapid (minute) changes in the atmosphere to calculate the humidity in the air.

Watch the video [Introduction to humidity sensors]

Capacitive humidity sensors

Watch the video [Principle of capacitive humidity sensors]

Optical sensors
Introduction to optical sensors
Introduction

Optical sensors are devices that convert light signals into electrical/electronic signals.

The purpose of an optical sensor is to measure a physical quantity of light, e.g. light intensity, and, depending on the type of sensor, then translates/transforms it into a form that is readable by an integrated measuring device. Optical sensors are used for contact-less detection, counting or positioning of parts. Optical sensors can be either internal or external. External sensors gather and transmit a required quantity of light, while internal sensors are most often used to measure the bends and other small changes in direction.

The measurands that are possible from different optical sensors are Temperature, Velocity Liquid level, Pressure, Displacement (position), Vibrations, Chemical species, Force radiation, pH- value, Strain, Acoustic field and Electric field.

Integrated optical sensors

In an integrated optical (IO) sensor, many components of the sensor are implemented in a single chip/device. There are various types of (integrated) optical sensors. Well-known types are the waveguide-based sensors such as interferometric sensors, grating couplers, resonant mirrors, integrated microcavity based sensor; surface plasmon resonance (SPR)-based sensor and reflectance-based sensors like reflectance interference device, etc. One of the main advantages of the optical-based sensors is their high resolution and sensitivity.

Integrated optical sensors, especially the interferometric ones that have been developed in recent years, such as the Mach-Zehnder interferometer (MZI) and the Young interferometer (YI), show an extremely high refractive index resolution, being in the range of 10-7-10-8 RIU, which is equivalent to detection of a protein mass coverage of ~ 20 - 30 fg/mm2. Furthermore, the IO readout systems are robust and small, allowing for a miniaturis ation where many elements of the device can be integrated into a single chip, which on the other hand occupies a relatively small area. These features offer the prospect for development of multi-sensing/multiplexing systems. Furthermore, this implies an increase of the analysis throughput, a reduction in the consumption of biomaterials, and cost reduction. Moreover, the optical-based sensors are label free sensing techniques, which require less complex sample preparation, do not need special laboratories and skilled personnel, and costs of a test are lower. In addition, usually a simpler and faster signal analysis can be performed.

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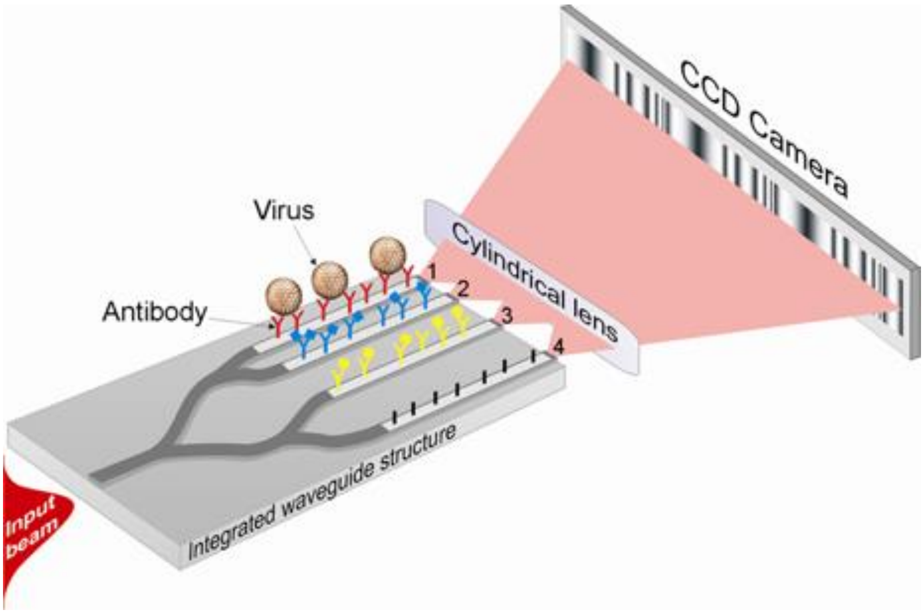

Figure 1: Schematic presentation of a multichannel integrated optical sensor based on Young interferometer principle. Ymeti, A. (2014). Multimode Interference Biosensor Working With Multiple Wavelengths And Two Polarizations. International Journal of Scientific & Technology Research, 3, 314-320.

Photonic biosensors

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Zinoviev, Kirill & Carrascosa, Laura & Sánchez del Río, José & Sepulveda, Borja & Domínguez, Carlos & Lechuga, Laura. (2008). Silicon Photonic Biosensors for Lab-on-a-Chip Applications. Advances in Optical Technologies. 383927. 10.1155/2008/383927.

Silicon Photonic Biosensors for Lab-on-a-Chip Applications

[A Fast, Sensitive Virus Detector]

Quiz

Multiple Choice

Humidity sensors operate by detecting:

☐ changes in the refractive index, e.g. in integrated waveguide strucures

☐ changes that alter electrical currents or temperature in the air

☐ the temperature and convert it into a usable/readable output signal

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☐ the presence/concentration of gases or gas mixtures in the atmosphere

Multiple Choice

Which of the sensors mentioned below are digital sensors (multiple answers possible)?

☐ proximity sensor

☐ humidity sensor

☐ gas fuel sensor

☐ limit switches

Matching specs

In constructing a control system, it is important to select the right sensor. It is tempting to go for a sensor that has the best performance in, for example, terms of response speed, resolution and repeatability, but this is not always needed. In most cases better sensors are more expensive, and you might end up in a situation where you pay for overkill. Your sensor has a performance that you simply do not need. This is not a very good engineering practice.

So where to start?

Start with **outlining the requirements** for a particular situation. Define what characteristics your sensor must have in order to be suited for your application.

Once this is done, you look for sensors, and **carefully evaluate their characteristics**. These characteristics can be found in the specification sheet of a sensor, that the manufacturer of the sensor can provide you with. If you do not have it, ask for it. These "specification sheets" or "technical data sheets" tell you all the details about the sensor.

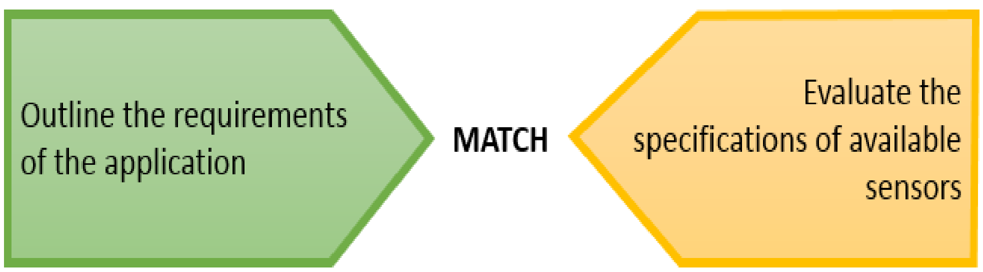

Figure 1: Matching requirements and specifications. Index consortium license: CC-BY-NC-SA

Then the challenge is to "match" the required characteristics (coming from the application) to the characteristics of the sensors that are available.

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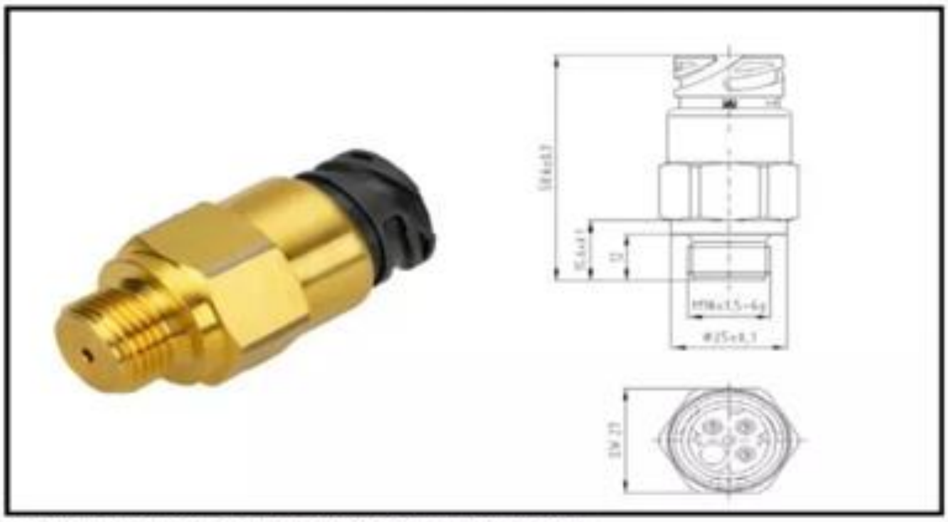
Technical data sheets

Specification of the sensor's characteristics is typically given in so-called "Technical data sheets" or "Specification sheets", that are in many cases available on the website of the company that sells the sensors.

Have a look at this following example, which is the specification sheet of an oil pressure sensor (a cheap one):



ELECTRICAL AND MOUNTING SPECIFICATIONS

Pressure Range	0-6 bar *
Temperature Range	-40°C to +125°C
Output Signal	0.5-4.5V Ratiometric
Thread	M18x1.5*
Connector	DIN 72585
Protection Range	IP6K9K
Product Code	96 760

Figure 1: Specification sheet of an oil pressure sensor © https://nl.farnell.com/avx/96760-10-930/sensor-pressure-6bar-1-m18/dp/2455467

This specifies the characteristics that are most important for you to know. Please realise that many sensor producers fabricate sensors for a specific market, which might mean that they do not directly show all the specifications you would like to know. If this is the case, ask for it. In many cases more data is available.

Check out the next example, which is a bit more extended. You will notice that it contains a lot of information and needs to be studied carefully to make sure that this fits what you are looking for.

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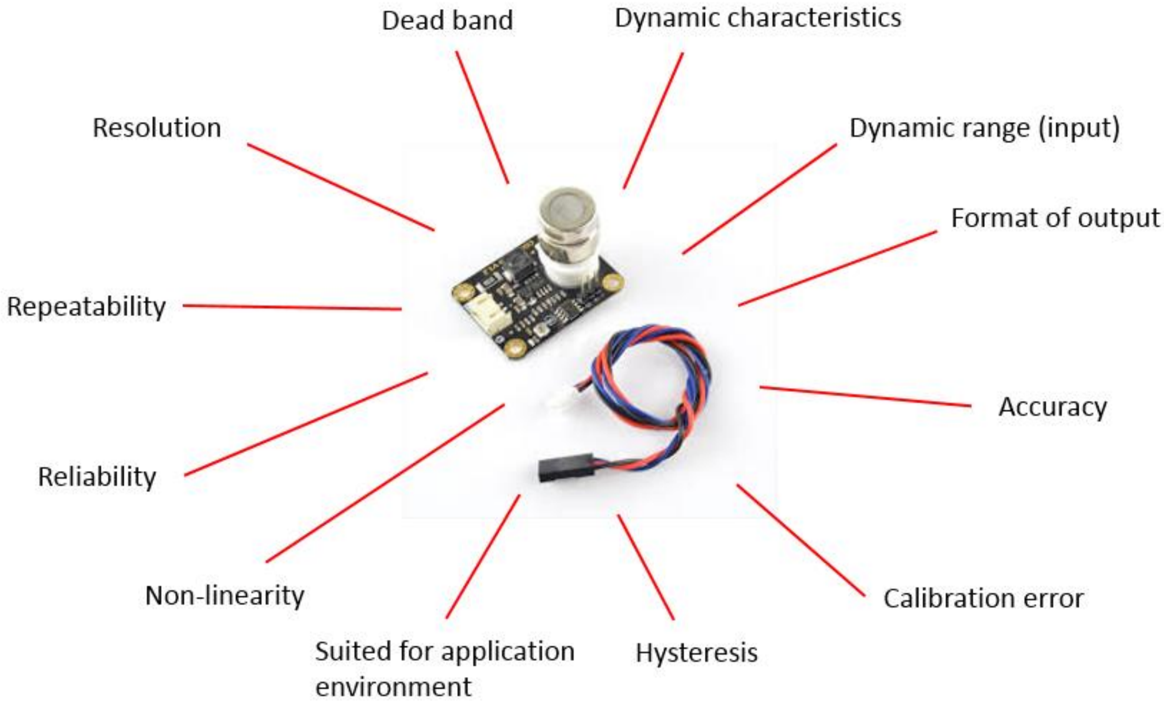
This sheet contains a lot of information and you will also notice that it takes a bit of training to decipher all the terminology used in these sheets.

How to select the right sensor

What specs

As you have seen in the previous units, a lot of detailed information on the sensor can be given. Below is an overview of the different characteristics of the sensor that need to be considered to see if they fit your purpose:



But next to these, the specifications also include, for example, dimensions of the sensor, how to fix it in a larger system, colour, material, etc.

In the next units we will discuss most of the specifications mentioned in the figure. We will explain to you what they mean and what you need to pay attention to.

Ideal stimulus-response relationship

We have defined a sensor as a device that converts a physical parameter into an electrical parameter. Many sensors do this conversion in a number of steps, making this relationship between the input stimulus and output response in most cases non-linear.

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Here we will consider the sensor as a so-called "black box". We basically do not know (or describe) what goes on in the sensor, but we are only concerned with the relationship between the input stimulus and the output electrical signal.
This is important, as eventually you want to be able to calculate the value of the physical quantity you measure from the electrical signal that you measure.

Ideal input-output relation
Every sensor has an *ideal* input-output relation, which, if the sensor is *ideally* designed and fabricated with *ideal* materials by *ideal* workers working in an *ideal* environment using *ideal* tools, allows the calculation of the *true* value of the stimulus from the output of the sensor.
This relationship is referred to as the **transfer function** of the sensor. In some cases the word "static" is put in front of it to indicate that it is independent of time (i.e. time-invariant, which is also an ideal situation).

E=f(s)

'E' represents the electrical signal, either in volts (when a potential difference) or amperes (when a current). 'f' is a (mathematical) function and 's' is the value of the stimulus.
Let's have a look at an example for a thermocouple:

mV	4.37	8.74	13.11	17.48
°C	250	500	750	1000

Table 1: output of a thermocouple vs temperature. © Index consortium license: CC-BY-NC-SA

The top row presents the mV response that is given when the sensor is put in an environment with a certain temperature. And these temperatures are given in the bottom row.
If we plot this graphically, this is what you get:

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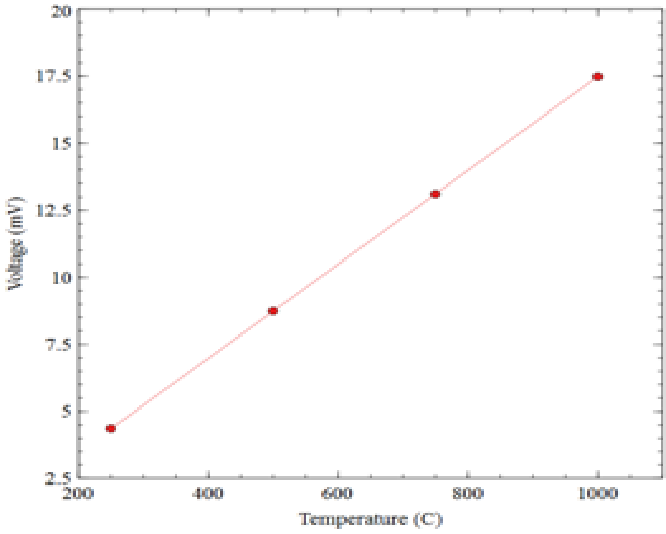

Figure 1: Temperature vs Voltage. © Index consortium license: CC-BY-NC-SA

It clearly reveals a linear relationship between temperature and the voltage.

Exercise - Multiple Choice

The voltage of the thermocouple has only been determined for 4 individual temperatures, but the stimulus-response curve gives a nearly perfect linear relationship. This means you can interpolate for other values of temperature.

What voltage would the thermocouple give at a temperature of 900 degrees?

☐ 5 mV.

☐ 10 mV.

☐ 15 mV.

☐ 20 mV.

Inverse function

The challenge for a measuring system is to "break the code E". What you measure is an electrical signal (a voltage in the previous example), but what you really want to know is the value of stimulus (the temperature in this example) that it represents.

Let's have another look at the transfer function E=f(s) for the thermocouple.

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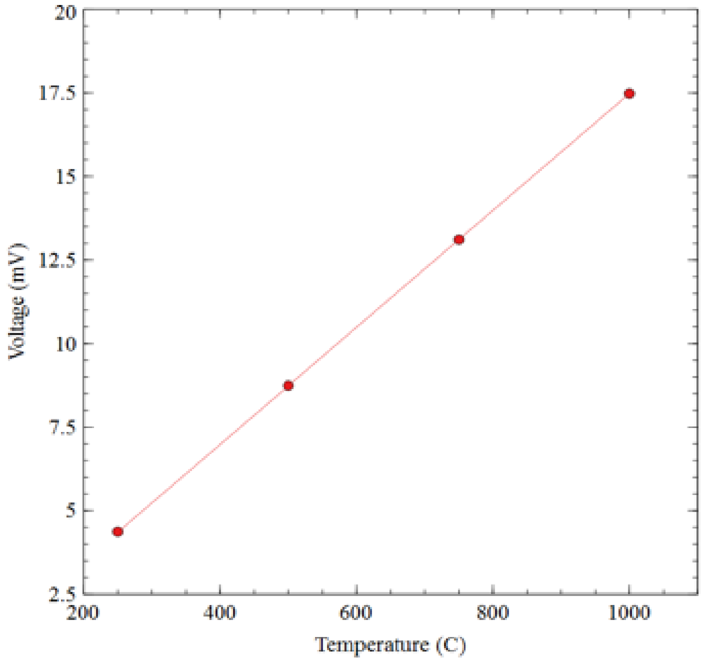

Figure 1: Thermocouple transfer function. © Index consortium license: CC-BY-NC-SA

Graphs are always plotted in a way that the x-axis is the value that is given, and the y-axis is showing what is measured. So, when the sensor is put in an oven at 500 degrees Celsius, it produces an output of 8.?? mV.

But graphs can be read the other way around as well. You can also look at the output of your sensor in mV. Imagine the sensor you are using is giving a 10 mV output. When you now look for '10 mV' at the y axis, move horizontally to the curve, and from there down to the x axis, and simply read-off the value. This gets to about 560 degrees Celsius.

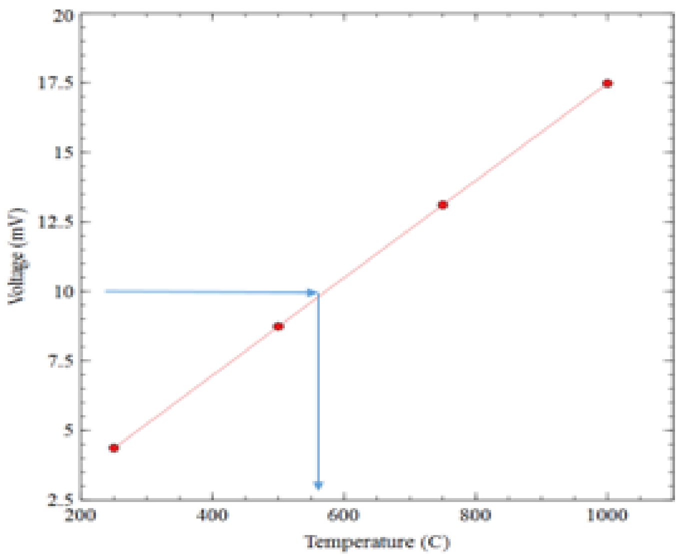

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Figure 2: Thermocouple transfer function. © Index consortium license: CC-BY-NC-SA

Exercise - Multiple Choice

Try this yourself for another voltage.

What is the temperature when your sensor is giving a 15 mV voltage?

☐ 400 degrees Celsius.

☐ 870 degrees Celsius.

☐ 1020 degrees Celsius.

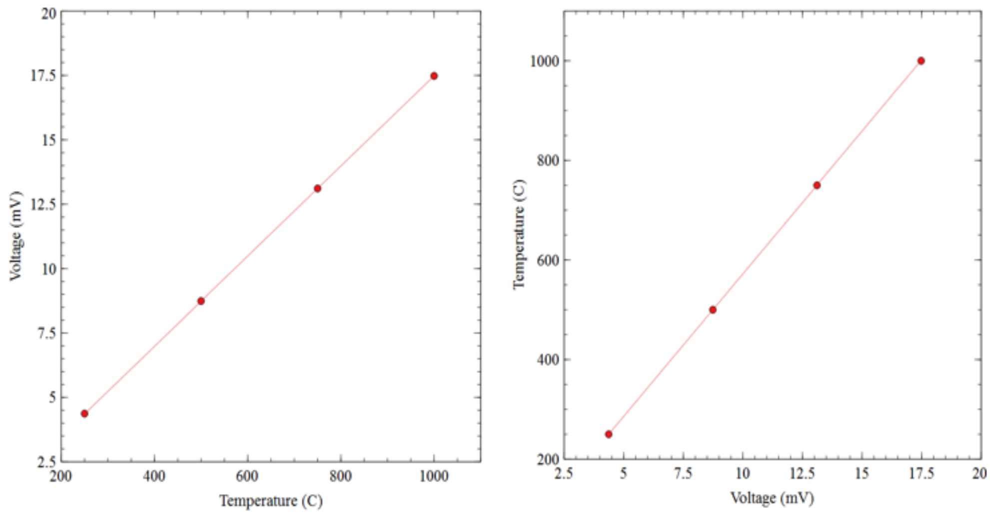
STAFF DEBUG INFO SUBMISSION HISTORY

A more formal way to do this is to determine the inverse transfer function.

The transfer function is E=f(s), relating s to E

The inverse transverse function s=f^-1(E), relates E to s

Graphically this looks as follows:



Both graphs show the same data points, but the axes are swapped. The left graph shows the transfer function, with temperature on the x axis, and voltage of the y axis. The right graph shows the inverse transfer function, showing voltage on the x axis, and temperature of the y-axis.

Non-linear transfer functions

So, in the previous unit we have shown you a stimulus-response curve of a thermocouple, that shows to be linear.

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Most sensors do not have a linear relationship, or do have this only in a rather limited range. Let's consider a more realistic example of a flow sensor that measures the amount of liquid volume that flows through a sensor. The output is given as a voltage between 0 and 1 V.

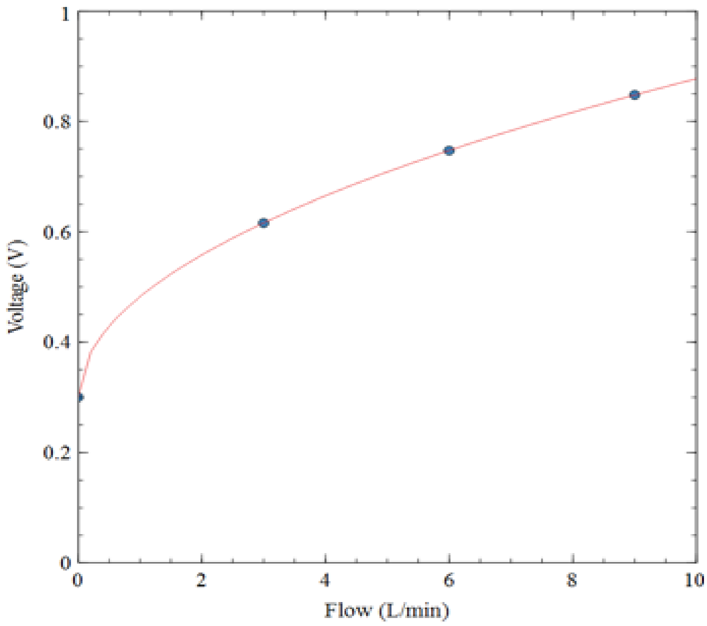

Figure 1: Non linear relation stimulus-response curve. © Index consortium license: CC-BY-NC-SA

In the graph here, the input-output relationship is graphically presented. As you can see on the graph, this relationship is non-linear. At a flow rate of 0 L/min the output value is 0.3 V, and as the flow rate increases, the voltage initially increases rather fast, but levels off as the flow rate increases to get to just over 0.8 V at 10 L/min.

Just as we did for the linear function, we can also graph the inverse function of this non-linear curve. This can be obtained by a mirror reflection of the curve with respect to the bisector of the right angle formed by the x and y axis.

For the above curve this looks like:

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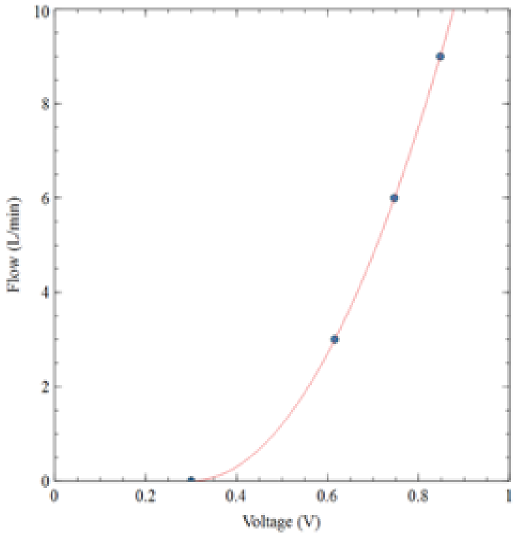

Figure 2: Inverse Non-linear relation stimulus-response curve. © Index consortium license: CC-BY-NC-SA

So, with this graph you can simply determine what flow rate matches with a certain voltage that the sensor is giving.

Transfer functions

Linear approximations

In determining the relationship between the input and the output of the sensor you typically expose it to a number of values of the input and you measure the corresponding output. Just take the example shown here:

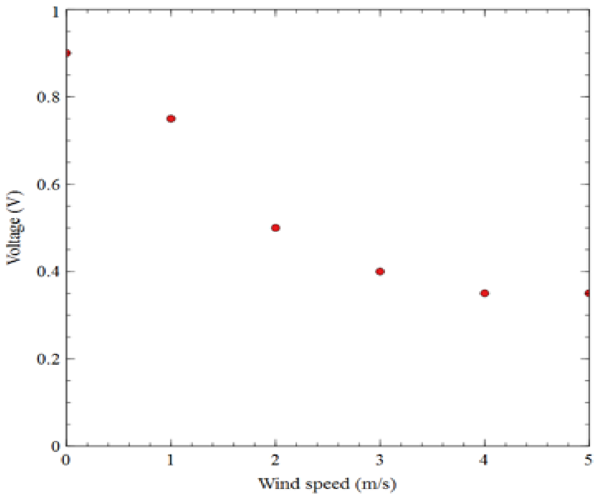

Figure 1: Example input-output values. © Index consortium license: CC-BY-NC-SA

You have bought an electronic wind speed sensor, and have calibrated this in a wind tunnel using 6 different wind speeds: 0, 1, 2, 3, 4, 5 and 6 m/s. At each of these conditions you have accurately determined the voltage the sensor gave as an output, in the range 0.3 to 0.9 V.

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Exercise - Multiple Choice

Now you take your sensor outside and measure the wind speed in your garden. The sensor gives a value of 0.6 V.

What is the approximate wind speed it is measuring?

☐ 0.5 m/s.

☐ 1.2 m/s.

☐ 1.5 m/s.

☐ 2.0 m/s.

☐ 2.5 m/s.

You most likely discarded the 0.5 and 2.5 V option right away, and eventually choose the 1.5 mV out of the 2 remaining options. What you most likely did is, imagine a continuous curve that crossed all the measured data points, and see which one fits best. But this is an approximation. What you actually need is a fast and efficient way to allow you to determine each point in between the measured points.

Linear curve-fitting

One way to do this is curve-fitting. You use a mathematical expression to fit your data points as accurately as possible. The first question that comes up then, is **what function** to use? Important here is to find a function that is as simple as possible, but that still describes the results rather accurately. The easiest function you can use is a **linear function**, which has the following form:

$E = A + Bs$

A in the equation is the offset, the point at which the curve is cutting the y-axis, and B is the slope of the curve.

Let's try to do this with the dataset that we have:

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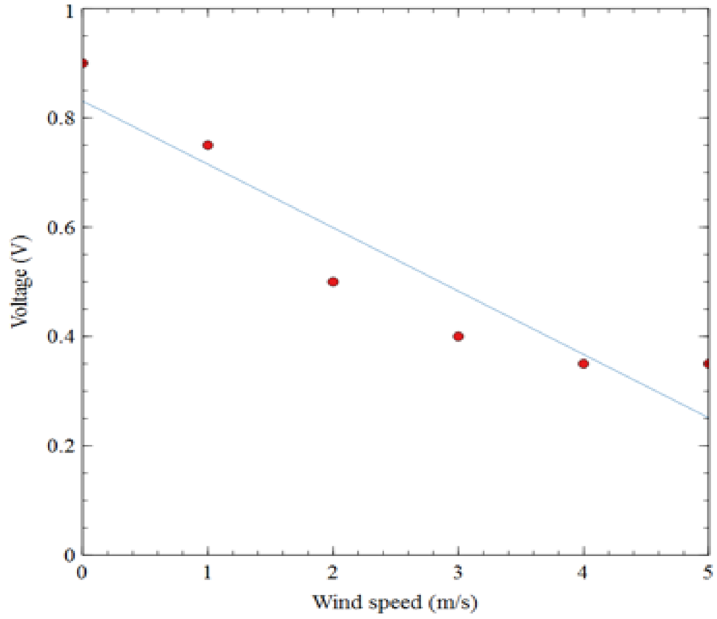

Figure 1: Linear curve fit. © Index consortium license: CC-BY-NC-SA

The mathematical function that is used to fit the data points is:

E = 0.831 - 0.116*s

The 0.831 is the offset, the point where the line cuts the y-axis, and 0.116 is the slope. Notice the minus sign in front of it, which indicates a negative slope, as can be seen in the graph.
This line most accurately describes all the data points, but you can also see that in many parts there is quite some deviation of the curve from the actual data points.

Exercise - Multiple Choice

Now let's do this final exercise again. Your sensor gives an output of 0.6 V.
What is the wind speed when you use this linear approximation?

☐ 0.5 m/s.
☐ 1.2 m/s.
☐ 1.5 m/s.
☐ 2.0 m/s.
☐ 2.5 m/s.

Now, the correct answer is 2.0 m/s, as in your own approximation you did get to a value of 1.5 m/s. That is a 25% difference, which is quite substantial.
Maybe the linear approximation, although mathematically speaking simple and easy to implement, is just not accurate enough to describe the input-output characteristic of this sensor.

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Piecewise linear approximation

Watch the video [Piecewise Linear Functions]

Accuracy and precision

Accuracy can be defined as the amount of uncertainty in a measurement of a signal with respect to the true/absolute value of that signal. Accuracy indicates how close the performed measurement is to the true/absolute value being measured. The measured signal values do not have to be the true/absolute values. Taking the average of the signal measurements, then the difference between the measurement average and the true/absolute value can give us the accuracy.
Precision describes the reproducibility of the measurement of a signal performed by a sensor.
For example, when a signal in steady state is measured repeatedly several times and the measured values are close to each other, this measured signal has a high degree of precision or reproducibility/repeatability.

Accuracy versus Precision

Accuracy and precision are frequently used interchangeably, especially in promotional literature for sensor products. The two figures below identify the obvious differences between the two specifications. Figure 1 shows the statistical distribution for precision versus the proximity to an actual, target or reference value for accuracy. A more precise sensor has a narrower distribution and a more accurate sensor is closer to the actual value. Alternatively, Figure 2 shows how precision and accuracy can increase or decrease independently.

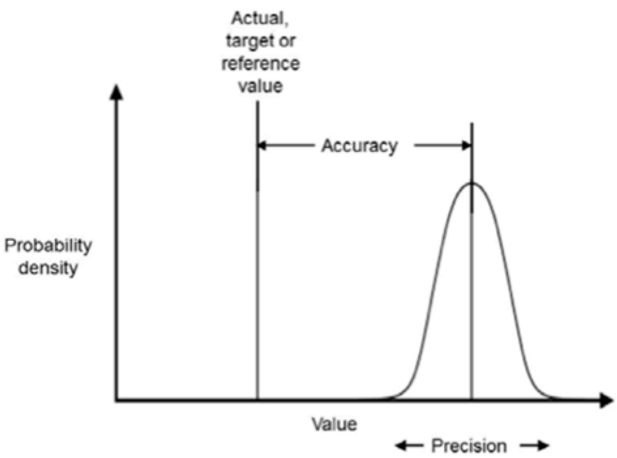

Figure 1. Relationship between accuracy and precision. © Index consortium license: CC-BY-NC-SA

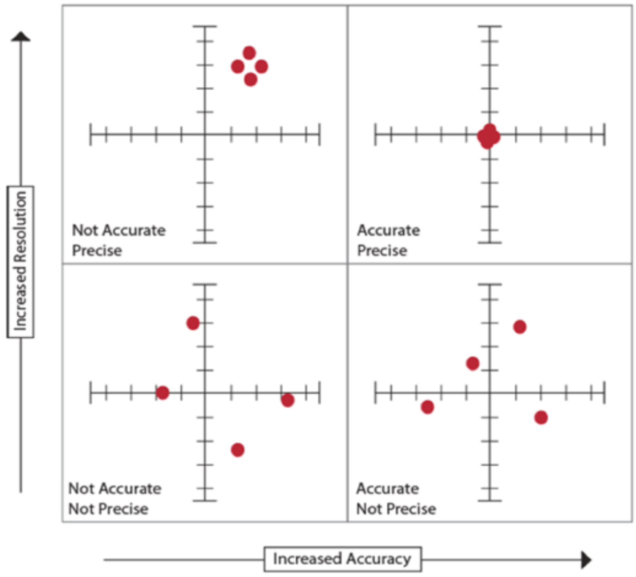

Figure 2. Difference between accuracy and precision.

Accuracy, resolution

Resolution

Resolution of a sensor can be defined as the smallest signal part/unit that can be resolved/indicated/measured by the sensor. For example, in an imaging system (optical) resolution describes the ability of that system to resolve details in an object that is being imaged.

Selectivity and sensitivity

Selectivity

Selectivity of a sensor is the ability of the sensor to determine/measure the value of a given parameter by suppressing/reducing the interference/disturbance of other parameters. Selectivity (often referred to as specificity) is an important aspect if we want to achieve a high accuracy of a measurement performed by the sensor.

Sensitivity

Sensitivity of a sensor can be defined as the ratio between output sensor signal and the smallest absolute amount of change of a given input parameter/signal that can be detected/measured by the sensor. Sensitivity and resolution are usually related to each other: a high sensor resolution can result in a high sensitivity, i.e. ability to measure very small signal changes.

Quiz

Multiple Choice

The voltage of the thermocouple has only been determined for 4 individual temperatures, but the stimulus-response curve gives a nearly perfect linear relationship. This means you can interpolate for other values of temperature.

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What voltage would the thermocouple give at a temperature of 900 degrees?

☐ 5 mV

☐ 10 mV

☐ 15 mV

☐ 20 mV

Multiple Choice

Let us suppose that the mathematical function that is used to fit the datapoints of a sensor measuring the wind speed is:

E = 0.831 - 0.116*s (E is the output of the sensor in V and s is the wind speed in m/s)

If your sensor gives an output of 0.6 V, what is the wind speed when you use this linear approximation?

☐ 0.5 m/s

☐ 1.2 m/s

☐ 1.5 m/s

☐ 2.0 m/s

☐ 2.5 m/s

Introduction to micro- and nanotechnology

Miniaturization

Do you keep track of the latest developments regarding smartphone technology? Even if you don't, you cannot help noticing that the electronic device we check up to 200 times a day has gone through an impressive development in the last decade(s). They were getting smaller and thinner, but the performance and the versatility of the mobile phones have increased tremendously. Watch the video and see the figure below to get a sense of the most common types of sensors in a modern smartphone.

Figure 1: Sensors in a typical smartphone. © Majumder, S; Deen, M.J. Smartphone sensors for health monitoring and diagnosis. Sensors 19, 2164 (2019)

Watch the video [What sensors are in a smartphone]

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How is it possible to embed more and more sensors in our smartphones, not to mention the other countless components that have to be fit in the housing? For decades we are working on miniaturizing these components and, at the same time, enhancing their performance. This is enabled using the techniques of micro- and nanotechnology.

Introduction to micro- and nanotechnology
History of micro- and nanotechnology

Microtechnology era
The microtechnology era began around 1920. Specific concepts and inventions have provided the necessary basis for micro-technology. These significant inventions include: the microscope, electricity, computers, and lasers. For example, microscopes allow technicians to view small regions of microdevices and that enable a more precise device production.

Figure 1: Traditional microscope ca 1920. © Wikipedia (Tamorlan) CC-BY-SA-3.0

Starting point of nanotechnology
1959 is considered the starting point of nanotechnology when Richard Feynman held his famous talk: "There's plenty of room at the bottom." In his lecture he argued that one would be able to do amazing things by decreasing the size. He challenged the audience with two tasks that needed to be solved and associated both of them with a cash prize of $1000. The challenge to build an electric motor within a cube with an edge length of 0.6 mm was already solved within a year . The second task was to miniaturize a text page by a factor of 25,000. This challenge however remained unsolved until 1985 when Tom Newman etched the opening of Dickens' Tale of Two Cities with an electron beam in a piece of plastic, ten times smaller than the pinhead of a needle (as can be seen on the figure below).

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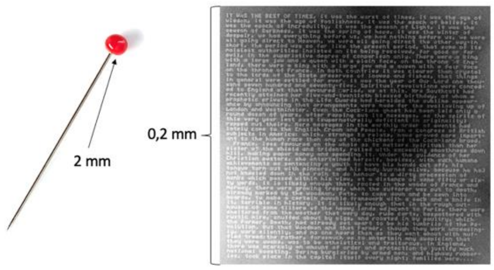

Figure 1: Opening of Dickens' Tale etched onto needle pin head. © Tom Newman

If you are interested in his full lecture, check out this:
http://www.nanoparticles.org/pdf/Feynman.pdf

But Richard Feynman talked about nanotechnology in conceptual terms, and the various examples that were shown are not really nanotechnology, but still in the micrometer domain. But nevertheless, he did start the concept of nanotechnology
It was only in 1974 that Norio Taniguchi mentioned nanotechnology for the first time as a production technology, as a way of making things. So instead of discussing it as an academic conceptual framework, as Feynman did, Taniguchi considered nanotechnology as the next step in ultra-precision machining, allowing the production of nanostructures using different tools. He also considered this to be the end-point of machining as you cannot get smoother than atomic roughness.
See below the first page of the paper in which he describes this.

On the Basic Concept of 'Nano-Technology'

Norio TANIGUCHI
Tokyo Science University
Noda-shi, Chiba-ken, 278 Japan

Abstract

'Nano-technology' is the production technology to get the extra high accuracy and ultra fine dimensions, i.e. the preciseness and fineness of the order of 1 nm (nanometer), 10^{-9}m in length. The name of 'Nano-technology' originates from this nanometer. In the processing of materials, the smallest bit size of stock removal, accretion or flow of materialsis probablyof one atom or one molecule, namely 0.1~0.2 nm in length. Therefore, the expected limit size of fineness would be of the order of 1 nm. Accordingry, 'Nano-technology' mainly consists of the processing of separation, consolidation and deformation of materials by one atom or one molecule. Needless to say, the measurement and control techniques to assure the preciseness and fineness of 1 nm play very important role in this technology.
In the present paper, the basic concept of 'Nano-technology' in materials processing is discussed on the basis of microscopic behaviour of materials andas a result the ion sputter-machining is introduced as the most promissing process for the technology.

From: N. Taniguchi, "On the Basic Concept of 'Nano-Technology'," Proc. Intl. Conf. Prod. Eng. Tokyo, Part II, Japan Society of Precision Engineering, 1974

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What is a nanometer?

The terms micro and nano are derived from the Greek words mikros, which means small, and nanos, which means dwarf. This already suggests that we are dealing with a range of techniques used to fabricate and study systems with dimensions ranging from several micrometres (one micrometer is one millionth of a metre) to a few nanometres (one nanometre is one billionth of a metre).
so:
1 nanometre = 1 billionth of a metre

So, let's look at the following video [How BIG is a nanometer] that is trying to explain this by comparing it to the Empire State Building

Let's do another comparison.
What do you notice when you compare the size of the earth, with the size of a soccer ball, and with the size of a so-called buckyball. A buckyball is a molecule that consists of 60 C-atoms, that are arranged in the shape of a 3-dimension ball. Typical size of this buckyball is about 1 nm.
If you compare the size of our planet (diameter is about 12,800 km) with that of a soccer ball (20-25 cm diameter), this is roughly a factor of 100,000,000 in size. Now if you look at the size of the buckyball, which is about 1 nm, you will find that this is also about the same factor. The ratio between the 25 cm soccer ball and the buckyball is about 100,000,000, the same as the ratio between the soccer ball and the planet Earth.
Mind-boggling !!! Right
So now you know that 1 nanometer is extremely small, which is indeed correct. Now have a look at the next figure in order to get an idea of objects that are typically micrometer or nanometer sized.

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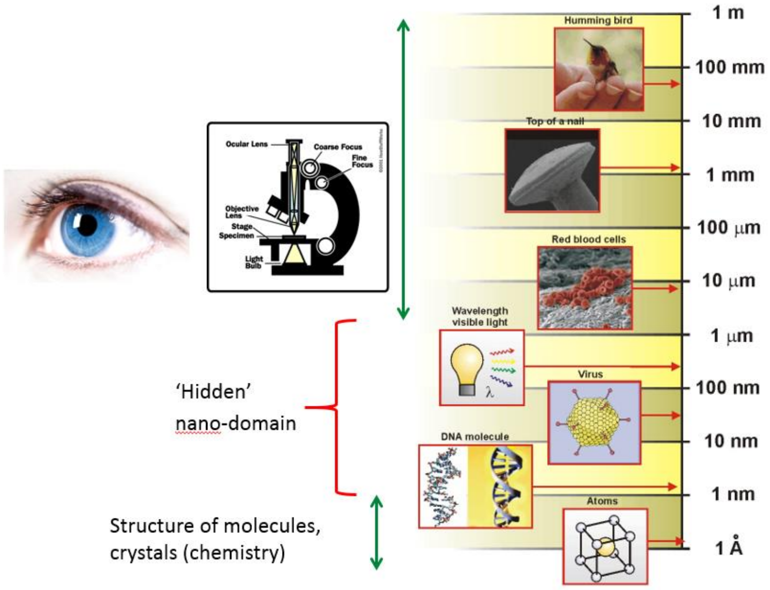

Figure 2: How big is a nanometer. © http://hideyo.blogspot.com/2008/03/teknologi-nano-nanotechnology-sinopsis.html

What you see in this image is a ruler, going from 1 meter (at the top) all the way down to the nanometer, or actually 1/10th of a nanometer, the angstrom. Notice that this is not a linear ruler, but a logarithmic one: As you move down each line you cross is a ten-fold reduction in size. So starting at the top with 1 meter, as you move down one notch, you get to one-tenth of a meter, which is 100 mm = 10 cm = 1 dm. When you move down another notch you again go down in size by a factor of 10, which brings you to the 1 cm. And now, if you keep doing this 9 times, starting at 1 meter, you do get to the nanometer.

To the left, there are a number of examples of images of objects that are typical on that scale. So again, at the top are objects that we as humans are familiar with and that we can observe with our eyes. This works fine up till about 100 ums where you do need a microscope to see objects. Typical objects that we cannot observe with only our eyes, but we can observe using an optical microscope are biological cells, with typical diameters in the 5 to 20 um range. Also bacteria are on this length scale and can be observed using a microscope.

As soon as you do get to about 0.5 um or 500 nm, you will reach the ultimate resolution of the optical microscope. This means that all objects smaller than 500 nm cannot be seen or resolved using an optical microscope. This is indicated in the figure, by the wavelength of visible light. Visible light (for humans) ranges from 400 nm (blue) to about 750 nm (red). As we use visible light as a way to observe objects, the wavelength sets the lower limit.

Interestingly enough, on the lower end of the scale, say from 1 nm to 0.1 nm we actually do have tools to determine structure. This is in the realm of chemistry. Tools such as X-ray diffraction that have been around for multiple decades were used to determine crystal structures of materials and biological

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molecules, such as proteins. These tools were able to resolve structures on the 1/10th of nanometer scale, atomic resolution. But this only worked for crystalline structures. As soon as structures did not form crystals, X-ray diffraction was not able to resolve anything on that length scale.

In between the 1 and 500 nm is the realm of nano, the so-called "hidden nano-domain" as for a long time we did not have access, that is tools to "see" what is going on at the length scale. Nanotechnology focuses exactly on that region, both in terms of characterization, that is observation of structures as well as fabrication of structures on that length scale.
Most biological molecules, such as DNA, proteins, viruses, as well as other nanoparticulates fall within this nano-domain.

Check out the following video which was made by Google, based on an earlier version made by IBM in 1977. This video starts zooming out first, and in the second part continues to zoom in showing the objects you encounter when going to the micro and nanoscale (and even to the picoscale, which is smaller than individual atoms).
Enjoy ...
Watch the video Cosmic Eye

Exercise - Multiple Choice

What is the size of a typical biological cell?

☐ 1 metre.
☐ 5-20 micrometres.
☐ 3 nanometres.
☐ 1 angstrom.

Multiple Choice

What is the size of the SARS-CoV-2 virus (also known as the coronavirus)?

☐ 1 cm
☐ 100 micrometres.
☐ 100 nanometres.
☐ 1 angstrom

Manipulation of individual atoms

It was Richard Feynman who described nanotechnology (although he never used this term) as art for putting atoms in any way we would like to have them. If this can be achieved, we can basically make anything. It took until 1980 before scientists showed how they manipulated individual atoms on a surface using a very sharp tip. By meticulously imaging the surface, to determine where the atoms were located, then manipulating the tip to push atoms across the surface, the scientists Heinrich Rohrer and Gert Binnig both working at IBM, showed that they were able to position a large number

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of individual atoms in a perfect circle. See the image (made by a scanning tunneling microscope). It took them 48 hours to get it done and the surface needed to be kept close to zero Kelvin (the absolute minimum) to ensure the atoms do not move as a result of the temperature.

Not a very practical situation, but a nice demonstration!

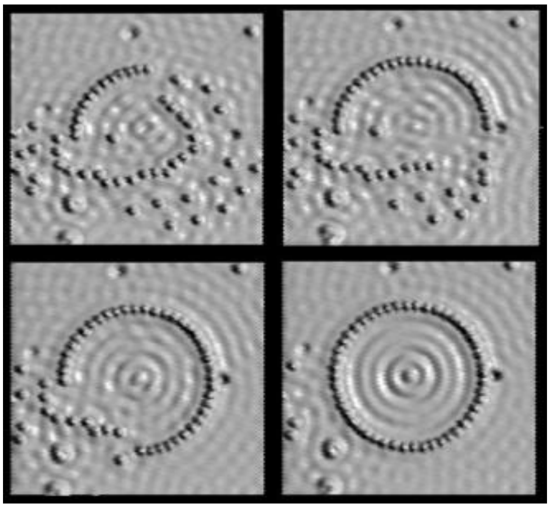

Figure 1: Iron atoms on Copper (111) surface, arranged into a circle. © Crommie , et al., Science 262 ,218 (1993)

Top-down fabrication

Moving individual atoms to create nanometre-sized structures turned out to be academically very interesting, but practically not very feasible if we want to make products out of these. Researchers are still trying to improve this, but it is far from a practical tool to make structures.

In the meantime another revolution was taking place, that actually started just after the second world war (1947). Bell Labs produced their first transistor, which can be seen here. The size of this transistor is enormous. The transistor is basically the building block for electronic circuits, as we still have them in all our electronic devices, but fortunately much smaller.

Figure 1: First transistor. © Nokia Bell Labs

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It was clear for companies such as IBM that for electronics to be powerful and cost-effective, there was a need to scale down this elementary building block. After a number of new versions of the transistor, still having the size of about a centimetre, IBM started to create planar transistors in silicon. And this started what is now known as the microelectronics revolution. The technology used was photolithography.
In the next video the technique of photolithography, or optical lithography is explained in more detail.

Watch the video [Photolithography: Step by step]

Advantages of photolithography in combination with chemical etching of materials allowed the fabrication of small transistors on a silicon wafer surface. This started the micro-electronics revolution. Gordon Moore, co-founder of Intel, predicted in 1965 that the number of transistors on microprocessors would double every year. 10 years later, in 1975, he revised his prediction to a doubling every two years. Ever since 1975 his prediction holds to be true.

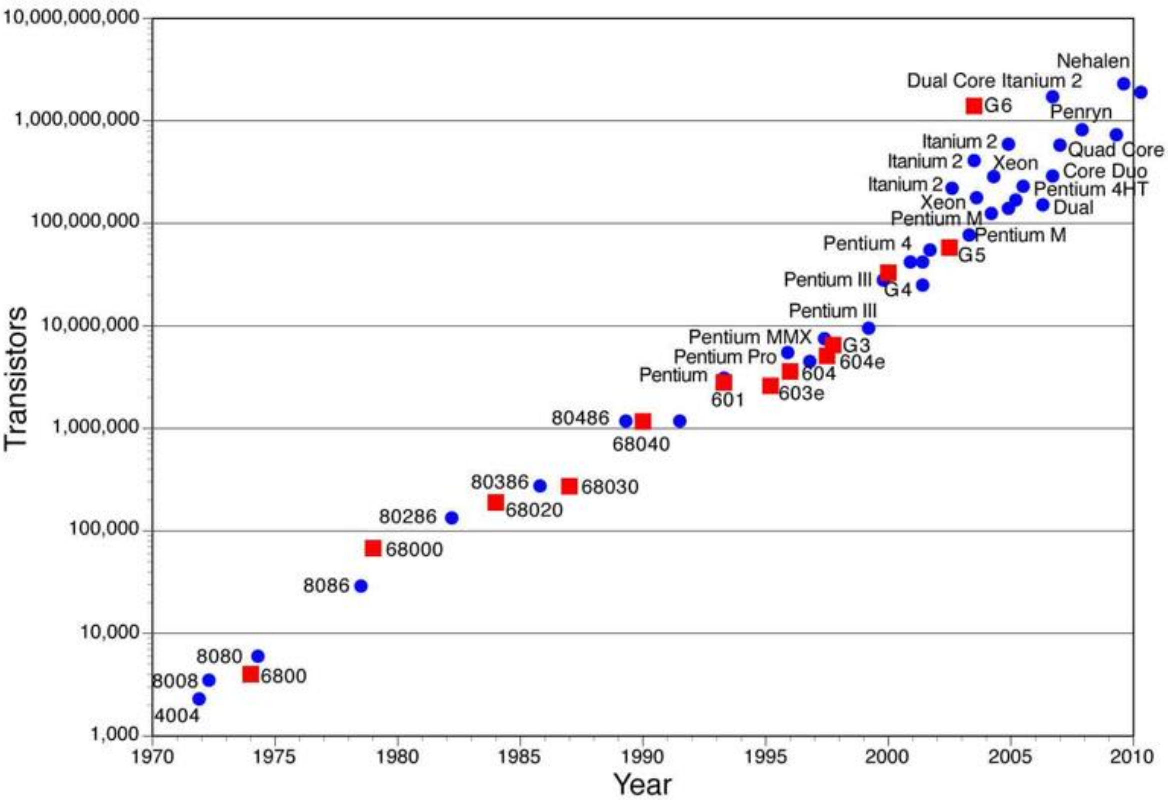

Figure 2: Graphical representation of Moore's law

In the graph above you can see the number of transistors that were present on a microprocessor chip of a certain year. And as you start in 1972, there we only about 2000 transistors in the microprocessor, that was the building unit of the 4004 computer, one of the very first microprocessors of IBM. Every

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1.5 to 2 years the number of transistors doubled, which lead to having several billion transistors on chips in 2010.

Interestingly, the fabrication technique does not only allow to make electronics components such as transistors, but can also be used to create other structures, for a wide variety of applications, one of these applications is sensors.

Here is another figure showing the basic steps of creating structures in a silicon wafer. And a shot of the cleanroom where these structures are nowadays made. Cleanrooms are essential as these structures need to be made in dust-free environments, because the size of a dust particle is many times larger than the sizes of the individual transistors. If a dust particle attaches to this surface it will cause a defect in the electronic circuitry, which needs to be prevented.

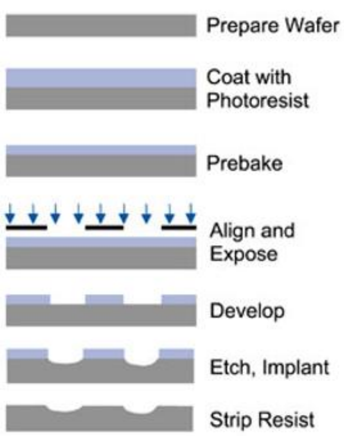

Figure 3: Imec cleanroom at Leuven (BE). © De Gelderlander

Bottom-up fabrication (copyright images)

Top-down fabrication, as the name suggests, starts with a wafer (large structure) and uses photolithography and material etching to fabricate smaller structures, down to nanometre scale. It goes from LARGE to SMALL. As shown, this approach is very much driven by the microelectronics industry and emerged from the disciplines such as electrical engineering, physics and material science. At the same time, from the disciplines of chemistry and biology another approach to creating nanostructures emerged, which was referred to as bottom-up nanofabrication. This approach starts at the very small end and by assembling these are able to create larger structures. So, this is from SMALL to LARGE.

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An important phenomenon in this approach is that of self-assembly and self-organisation.
Let's start with a lipid as an example to illustrate this a bit more.

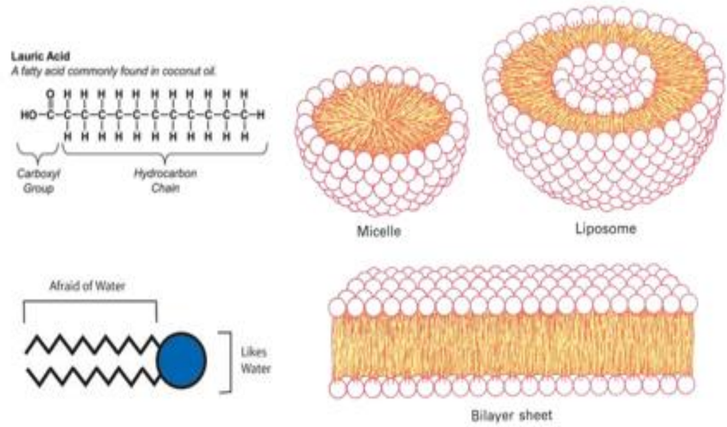

Figure 1: Lipids as a micelle, liposome or bilayer sheet.

If you look at a lipid molecule, here the lauric acid, as an example, consists of a carboxyl group, and a carbohydrate tail. The carboxyl group is relatively polar and for that reason can easily interact with water molecules. In other words, this part of the lipid actually "likes" water. In technical terms it is hydrophilic. The other part of the lauric acid, the carbohydrate tail, is non-polar, and does not easily interact with water molecules. When put into an aqueous environment, it tends to stay away from water as much as possible. Here it "dislikes" or "is afraid of" water. The technical term for this is hydrophobic.

When you now put many of these lipid molecules in water, they will, as a result of the special properties that they have (hydrophilic head and hydrophobic tail) automatically form certain structures. Examples of these are depicted in the figure. In all these structures you can see that the hydrophobic carbohydrate tails tend to stick together, not having to interact with water, and the hydrophilic head groups are the ones that are on the surface of the structure as they "like" to be in contact with water.

This is a very good example of self-organisation. The properties of the individual molecules determine via intermolecular interactions the larger structures that they form. This is bottom-up nanotechnology.

More complicated examples can be found in nature. The above example of a liposome and bilayer sheet are both structures found in the living world. Another example is the formation of a virus. Putting together all the components of a virus, that is some proteins and a DNA or RNA molecule, it will automatically fold into a virus particle by the process of self-assembly.

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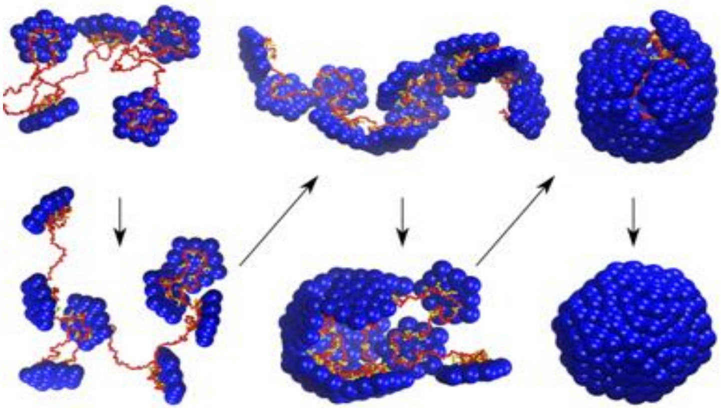

And even more complicated structures such as molecular motors are formed that are present within the living cell. Check out the following video where different proteins come together in order to duplicate DNA, which is an essential process in cell division as each cell needs its own set of DNA. Here, very specific interactions between different components form transient structures that perform specific functions.

Watch the video Mechanism of DNA replication

Introduction to micro- and nanotechnology

Micro- and nanotechnology sensors

So now you know about micro and nanotechnology, and the top-down and bottom-up approach fabrication methods, but how does this relate to sensors?

The top-down approach using photolithography was able to create structures, initially mainly for micro- and nano-electronic components, but the technology also allows the production of other structures such as sensors.

Just one example, as more will be given in the subsequent sections:

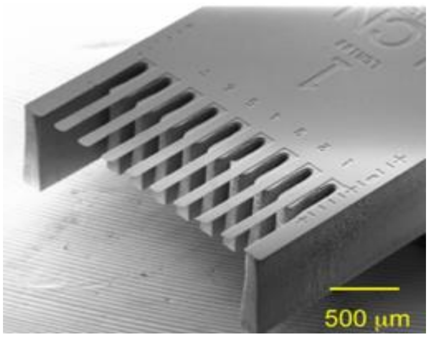

Figure 1: Scanning Electron Microscope (SEM) image of cantilever sensor array. Paxman R., © Sensors. 2012; 12(5):6497-6507. https://doi.org/10.3390/s120506497

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This is a mechanical sensor that is able to sense gasses. What you see is an array of freestanding cantilevers (these are the diving boards you see extending to the lower left). Each cantilever has a specific resonance frequency at which it prefers to vibrate. This frequency is determined by the mass of the cantilever (the diving board) and the elastic parameters of the material it is made of. As soon as the material binds or absorbs a gas that is present, this resonance frequency changes and can be accurately determined, making this a very sensitive sensor. The small size of the cantilever means that small changes (due to a low concentration of gas that is present) are already measurable.

The bottom-up approach is about creating specific interactions on a small scale (mostly the molecular scale) such that molecules interact. In sensors this is essential in order to create specificity. In biology this is referred to as molecular recognition. If you want to create a sensor that is specific for a protein, you need to find another molecule that strongly binds to the protein that you wish to detect, and it should not bind to any other molecule. Antibodies that are used by our immune system are often used in sensor applications to make a sensor specific for a certain compound.
In the next sections we delve more deeply into MEMS sensors and integrated optical sensors.

MEMS devices

Introduction to MEMS

Micro-Electro-Mechanical Systems (MEMS) are defined as miniature devices and systems fabricated by micromachining processes. MEMS devices have critical dimensions in the range of 100 nm to 1000 µm. MEMS technology is a forerunner to nanotechnology, which refers to science, engineering and technology below 100 nm down to the atomic scale. MEMS devices with dimensions in the millimeter-range are referred to as meso-scale MEMS devices.

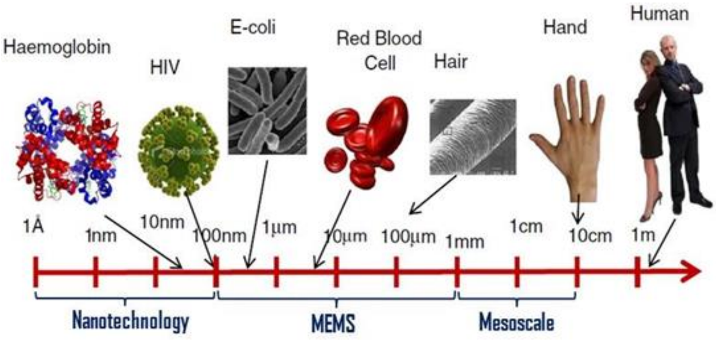

Figure 1: Dimensional scale alongside biological matter © J. Chem Rev, 2019, 1, 3, 243-251

MEMS devices can vary from relatively simple structures having no moving elements to extremely complex electromechanical systems with multiple moving elements under the control of integrated microelectronics. The functional elements of MEMS are miniaturised structures, sensors, actuators, and microelectronics.

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Microsensors and microactuators are the most interesting MEMS elements.

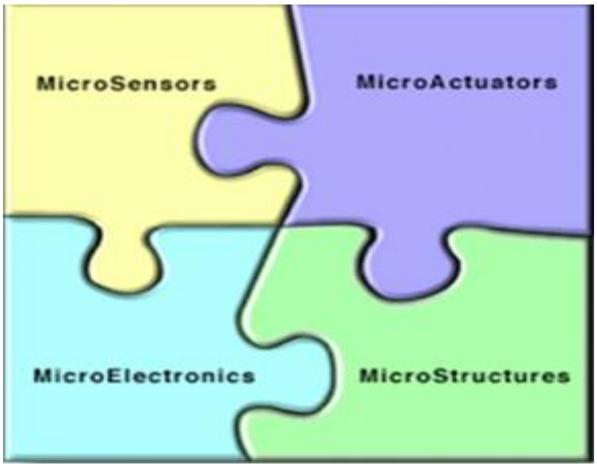

Figure 2: Functional elements of MEMS Devices. © Basu (2019). Fabrication Processes for Sensors for Automotive Applications: A Review. 10.1007/978-981-13-3290-6.

Watch the video [Introduction to MEMS]

MEMS Applications (copyright picture)

MEMS has proved to be a revolutionary technology in various fields of the physical domain such as mechanical, e.g. pressure sensors, accelerometers and gyroscopes; microfluidics, e.g. inkjet nozzles; acoustics, e.g. microphone; RF MEMS, e.g. switches and resonators, and optical MEMS, e.g. micromirrors.

MEMS technology has demonstrated unique solutions and delivered innovative products in the chemical, biological and medical domains as well. MEMS have penetrated into consumer electronics, home appliances, automotive industry, aerospace industry, biomedical industry, recreation and sports.

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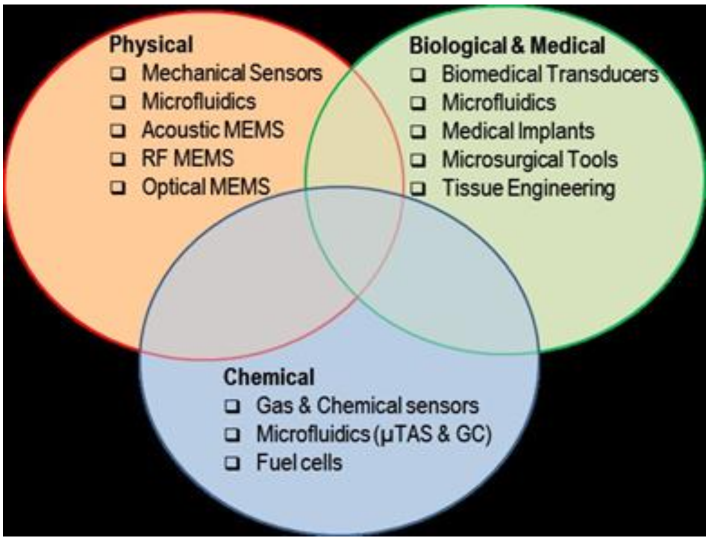

Figure 1: Various MEMS applications. ©

The real potential of MEMS devices could be realised when miniaturised sensors, actuators and structures will be merged onto a common Silicon substrate along with integrated circuits, i.e. microelectronics. While microelectronics are fabricated using integrated circuit (IC) process sequences such as CMOS, the micromechanical components are fabricated using either compatible "micromachining" processes that selectively etch away parts of the Silicon substrate or add new structural layers to form the mechanical and electromechanical devices. Merging of MEMS with microelectronics and other technologies such as (nano-) photonics and nanotechnology (known also as “heterogeneous integration”) can be the most interesting approach with many commercial market opportunities that will be explored in the future.

BioMEMS

BioMEMS refers to the science and technology of micro-devices fabricated by micromachining for biological and medical applications. BioMEMS application areas include biomedical transducers, microfluidics, medical implants, microsurgical tools and tissue engineering.

Examples of BioMEMS include:

- MEMS Pressure Sensors.
- MEMS Inertial Sensors.
- Microfluidics for diagnostics & drug delivery.
- Micromachined needles.
- Microsurgical tools.

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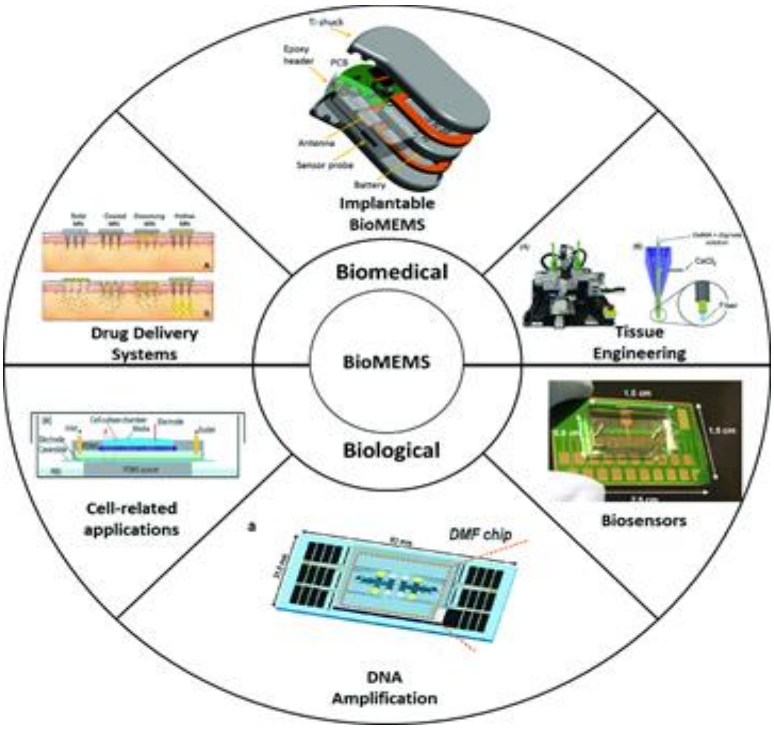

Figure 1: Overview of BioMEMS devices. © Garcia-Ramirez, History of Bio-microelectromechanical Systems

Micromachined needles:
Micromachining enables fabrication of needles smaller than 300 µm. Microneedles have been fabricated out of various materials, e.g. Silicon, glass, metals and polymers using micromachining processes. Usually, microneedles are integrated and used in combination with microfluidic systems. Microneedles have been used for various applications: drug delivery, blood extraction, fluid sampling, cancer therapy and microdialysis.

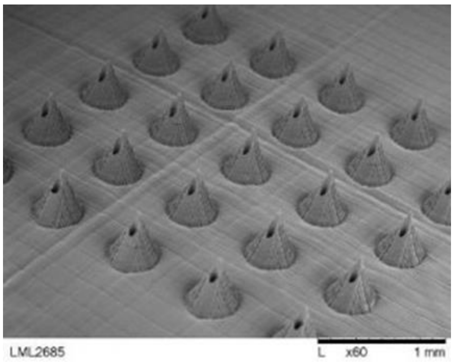

Figure 2: Micromachined polymer based hollow needles. © lasermicromachining.com

MEMS devices

Future development

Future vision of MEMS Devices, whereby microsensors, microactuators and microelectronics can be integrated onto a single microchip, is expected to be one of the most important technological

breakthroughs in the future. This will enable the development of smart products by enhancing the computational ability of microelectronics with the perception and control capabilities of micro sensors and microactuators.
MEMS technology is extremely diverse and fertile, both in its expected application areas as well as in how the devices are designed and manufactured.
MEMS Devices will revolutionise many product categories by enabling realisation of complete Systems-on-a-Chip.

Photonics

Photonics is the science of creating, moving and detecting photons. It brings together physics, electrical engineering and materials science knowledge about photons and electrons. Photonics technology surrounds us in the modern world: CT scans, barcodes, LED lights, flatscreens, CD and DVD players, driverless cars, laser-guided missiles, fiber-optic communications, cellular phone networks, solar power and many more. Light-based technologies are efficient, reliable and fast.
Photonics technology includes many devices such as sources of light, e.g. lasers and LEDs, waveguides to guide light such as fiber optics and a variety of opto-electronic devices that encode digital information onto optical signals and further convert optical signals to electrical signals.

Watch the video [What is photonics? And why should you care?]

Integrated photonic devices

Integrated photonics

Integrated photonics is an emerging branch of photonics in which waveguides and devices are fabricated as an integrated structure onto the surface of a flat substrate, e.g. in an optical chip. Due to integration, complex photonic circuits can process and transmit light in similar ways to how electronic integrated circuits process and transmit electronic signals.
Key technology manufacturing areas for integrated photonics include:
Data Centres: Today Facebook, Amazon and Google alone run massive cloud computing data centre s consuming the equivalent of 34 (500-MW) coal-fired power plants. Using integrated photonics, the centre s will be able to handle greater Terabit-scale data rates of traffic while consuming only half as much power, resulting in a dramatic cost savings.
Sensors: Sensors can identify (bio-)chemical gases from air pollution and contaminants in the water. They can also be used to detect abnormalities in our blood, such as low glucose levels and variations in concentrations of (health) biomarkers. Photonic integrated circuits can be designed as comprehensive and ubiquitous sensors with glass/silicon/plastic and embedded via high-volume production in various handheld devices. Handheld sensors will enable us to more directly engage with practices that improve our health, protect our environment and monitor our food supply.

Watch the video [Photonics Powering the 21st Century with Integrated Photonics]

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Quiz

Multiple Choice

What is the size of a typical biological cell?

☐ 1 meter

☐ 5-20 micrometer

☐ 3 nanometer

☐ 1 angstrom

Multiple Choice

Micro-Electro-Mechanical Systems (MEMS) are defined as:

☐ the science of creating, moving and detecting photons

☐ the science and technology of micro-devices fabricated by micromachining for biological and medical applications

☐ miniature devices and systems fabricated by micromachining processes

☐ a sensor that senses and converts temperature into a readable output

Test: Sensors made by micro- and nanotechnology (empty)

Chemical sensors

Chemical sensors detect/measure the presence of certain chemicals or classes of chemicals and quantify the type and/or amount of chemicals detected. Chemical sensing is an application that clearly benefits from recent development in micro /nanotechnology. MEMS chemical sensors can detect a wide variety of different gases. The advantage of the MEMS sensors is that they can be incorporated into objects/systems for continuous sensing of a gas or selection/mixes of gases. These devices have numerous medical, industrial and commercial applications such as environmental, quality control, food processing and medical diagnosis.

Chemical sensor devices are sometimes referred to as an ENose or electronic nose. Well-known chemical sensors are:

- *Oxygen sensor*: measures the percentage of oxygen in a gas or liquid being analysed
- *Carbon dioxide detector*: detects the presence of CO2

Watch the video **Greentest - Food Chemical Detector**

Biochemical sensors

Biochemical sensors are devices that convert a biochemical response into an electrical signal [1]. Biochemical sensors can be used for determination/measurement of an analyte (such as biomarkers and micro-organisms) concentration in a given sample solution. The biochemical transduction layer,

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or the biochemical interface, is an important component of the biochemical sensors that selectively reads the information from the biochemical domain. That type of sensor that uses a biological receptor interface is called a biosensor. In that case the bio-interface layer performs the biochemical selectivity, as a preliminary step for measuring the component of interest in a given sample solution. There are multiple biological compounds that can be used as a receptor such as [2]:

- Antibodies
- Proteins/antigens
- Aptamers
- Enzymes
- Nucleic acids
- Cells
- Tissue, etc.

[1] C. Nylander, Chemical and biological sensors, J. Phys. E. 18, 736-750 (1985).
[2] Sharma, S.; Byrne, H.; O'Kennedy, R. J. Antibodies and Antibody-Derived Analytical Biosensors. Essays Biochem. 2016, 60 (1), 9–18.

Watch the video Introduction to Chemical Sensors and Biosensors

Biosensors

Watch the video What is a biosensor?

Immunosensors

When an antibody or an antigen layer is used as a transducer layer in a biosensor, that type of biosensor is called an immunosensor. There are different types of immunosensors available. These biosensors differ in various aspects such as working/operation principle, complexity of the equipment needed to implement a given principle, use of labeling, operating conditions, monitoring time, etc. In addition, features such as sensitivity, resolution, accuracy, reproducibility, selectivity, stability, robustness, multiplexing ability, reusability, etc., are some other important aspects that differ from one type of biosensor to another. All these parameters combined with each other give an indication about sensing techniques that can be easily developed, validated and effectively used/applied for a given type of application.

DIASENS: the DIAbetes SENSor

Watch the video Label free detection of insulin with Photonic Biosensors

PHOBIOSENS

PHOBIO SENS

Rapid detection of antibiotics in milk products using photonic sensors

The dairy industry is very interested in the development of a rapid, easy and cost-effective method to detect contamination such as antibiotics and bacteria in milk products and baby food. Current methods are expensive, time and labour-consuming, and it takes hours to days before a reliable result is obtained. In collaboration with a number of SMEs and other partners, the objective of this project is to develop a portable demonstrator that enables rapid, easy, multiplexed detection of antibiotics, such as tetracycline in milk, based on a multi-channel photonic sensor principle. This will be achieved by the integration of existing innovative technologies such as lab-on-a-chip, microfluidics, inkjet printing and integrated photonics sensors.

This demonstrator will be a first step towards a handheld device that can be used for detection on site, such as on the farm and the milk factories.

Partners:

SAXION UNIVERSITY OF APPLIED SCIENCES

micronit microtechnologies, FrieslandCampina, Nanoalmyona, TWENSPEC, Qlip, LipoCoat, LioniX International, rivm, InterFluidics, MinacNed, Melkveebedrijf Kromhof

Electrochemical sensors

Introduction to electrochemical sensors

The electrochemical sensor is a device based on transducing the biochemical events to electrical signals. Electrochemical sensors are made up of three essential components:

1) a receptor that binds to the sample/analyte;

2) the sample or analyte, and

3) a transducer to convert the reaction into a measurable/detectable electrical signal.

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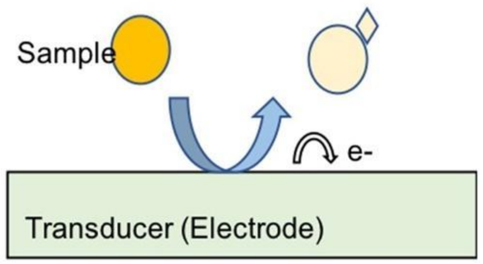
In electrochemical sensors, the electrode (being a key component) acts as the transducer that is used as a solid support for immobilization of biomolecules. Electrochemical sensors are typically used for detection of oxygen and toxic gases. More specifically, they can measure the concentration of a specific gas (or gas mixture). This is done by method of oxidation or reduction reactions. In most electrochemical sensors, an electrode surface is used as the site of the reaction. The electrode will either oxidize or reduce the analyte of interest. The current that is generated from the reaction is monitored and used to calculate concentrations of the sample/analyte. Typically, an electrochemical sensor device is made up of a "working" electrode, a "counter" electrode, and usually a "reference" electrode. All these components are integrated inside of a sensor prototype housing along with a liquid electrolyte.

Some examples of electrochemical sensors are:
- Breathalyzers
- Blood Glucose sensors
- Carbon Dioxide/Monoxide sensors
- Oxygen sensors



Schematic representation of an electrochemical sensor

Reference

Harper, A., & Anderson, M. R. (2010). Electrochemical glucose sensors developments using electrostatic assembly and carbon nanotubes for biosensor construction. Sensors,10(9), 8248-8274.

Gas sensors

Introduction to gas sensors

A gas sensor is a device which detects/measures the presence/concentration of gases of gas mixtures in the atmosphere. Based on the concentration of the gas, the sensor produces a corresponding potential difference by changing the resistance of the material inside the sensor, which can be measured e.g. as output voltage. The type and concentration of the gas can be estimated/derived based on the voltage value.

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There are various gas sensors used to detect/measure gases like Oxygen, Carbon Dioxide, Nitrogen, methane, etc. They can be commonly found in devices that are used to detect the leakage of the harmful gases, monitor the air quality, etc.
The type of the gas that the sensor could detect depends on the sensing material present inside the sensor. Here is a classification of the various types of gas sensors based on the sensing element that is used/applied in various applications:
- Metal Oxide based gas sensor
- Optical gas sensor
- Electrochemical gas sensor
- Capacitance based gas sensor
- Calorimetric gas sensor
- Acoustic based gas sensor

Watch the video [How can gas sensor response be measured ?]

Electrochemical gas sensors
Watch the video [Operating Principles of Electrochemical Gas Sensors]

Semiconductor gas sensors
Watch the video [Semiconductor gas sensors used in various applications]

Introduction to electronic noses
Watch the video [How does an electronic nose work?]

CYBERNOSE
Watch the video [CYBERNOSE: What's a bio-electronic nose?]

Health-E-Nose
Watch the video [Health-E-Nose]

Quiz

Multiple Choice

A gas sensor is a device (multiple answers possible)?

☐ based on transducing the biochemical events to electrical signals
☐ which detects the presence of gases in the atmosphere
☐ that converts a bio-chemical response into an electrical signal
☐ which detects the presence of gas mixtures in the atmosphere.

Multiple Choice

Which of the sensors mentioned below are chemical sensors (multiple answers possible)?

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☐ electronic noses
☐ carbon dioxide detectors oxygen sensors
☐ capacitive humidity sensors
☐ carbon dioxide detectors

Industrial automation
What is industrial automation
Definitions

Video: [What is industrial Automation?]

Automation

Already since the very start of industry and industrial manufacturing in the period 1760 to 1840, people have continuously looked for ways to "increase productivity at lower cost". Automation was the answer to do this.

Automation is defined as the automatically controlled operation of an apparatus, process or system by mechanical or electronic devices that take the place of human labor. It is derived from the words "auto", meaning "self", and "matos", which in Greek means "moving". So in simple terms it means "self-moving".

Maybe the best example is the car, that we are all quite familiar with. Interesting fact here is to note that in many languages car is referred to as "auto", which is directly connected to this "self-moving" mentioned earlier. The car is a machine or apparatus that operates without significant human intervention (as the definition of automation states). Obviously, we are still not completely in the era of self-driving cars, and you could argue that it is still controlled by humans. But, your input is only a small part of this. Within you car there are numerous systems (that you most probably are not aware of), that ensure that your care is running as it should, making it very automated.
So in general terms, automation refers nowadays to a set of technologies that results the operation of machines and systems that require limited human intervention and achieves a performance superior to manual operation.

Mechanization

Another term that is often used is **mechanization**, but this is a bit more limited. Mechanization only refers to the simple replacement if human labor by machines. Examples here are the tools that farmers use to work on their land, such as plowing or seeding. In the past all this heavy work was done by a person, and currently a farmer uses a tractor with a plow machine. This is mechanization.

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Automation goes further and implies the integration of machines into a self-governing system.

Industrial automation

So, we have discussed automation, and industial automation is simply put the application of automation within industry. But it is important to realize that industry is an **economic activity** related to manufacture, service or trade. This implies that the application or use of automation will only be effective when it is profitable. And that makes it dependent on the industry that you are discussing. We will come back to this later in this module.

Exercise

Automated systems are able to achieve superior performance in product manufacturing compared to a manual one. Why?

☐Automated systems have a higher precision.

☐ Automated systems can use more energy.

☐ Automated systems can have more speed of operation.

☐ Automated systems are controlled by humans.

What is industrial automation?

Industrial Information Technology

Industrial automation makes extensive use of information technology (IT), and can nowadays not go without it.

At the beginning of the Industrial Revolution up to the middle of the 20th century, production units/machines were rather isolated, requiring a person to control it and provide input parameters. The machine was then able to produce based on this input. If anything needed to be changed, because different products needed to be made, input parameters needed to be changed by the controller (a person) directly on the machine itself. In a larger factory this also meant that the alignment of different machines needed to be done manually, and this is a potential cause for delays, accidents and failures. With the advent of computers and information technologies, machines were no longer completely isolated from one another. This started with having ethernet-based communication protocols that were able to communicate data from one machine to another, to provide a proper alignment of the

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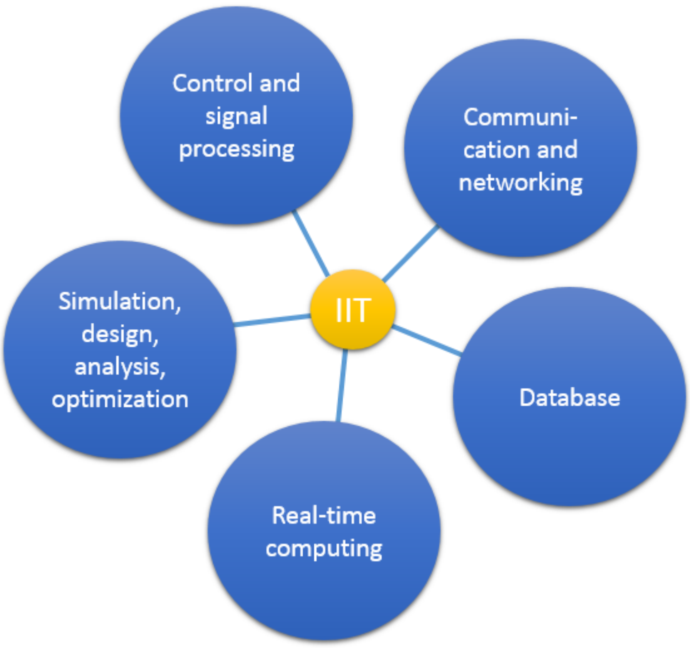
output of one machine to the input of a next one. Later, enabled by the enormous development in information technology, this was expanded enormously. Nowadays machines in a factory are integrated within a larger system that includes a lot of information technology.

But it does not stop there. Information technologies enable the connection of multiple factories to optimise the production process, or can even integrate manufacturing with other areas of business, such as sales, customer care, finance, HR.

IIT's main areas



This scheme shows the main areas of IT that are used in the context of industrial automation.

Industrial automation versus Industrial IT

As mentioned, industrial automation nowadays does not go without Industrial IT, but it is distinct from it. Industrial automation involves (also) a significant amount of hardware technologies, such as sensors and actuators that we discussed earlier. This also includes electronics for signal conditioning and displays for communication (to display process parameters to the human operator, as an example).

As industrial automation systems grow more sophisticated, the usage of IT increases dramatically. IT here serves as an enabler to connect the different manufacturing units within one factory, or units in different factories or even units in other business areas. With the addition of better integration of IIT into industrial automation, systems are reactive to a large number of stimuli from their environment. Environment here is defined as the relevant environment for a system to extract its data from. This can be other machines in the plant, information from, for example, finance, or even the worldwide open information resources.

We are all familiar with information systems, and we work with them in our work, our lives, etc. But it is important that IIT does differ on specific aspects from the IT we work with.

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One aspect of industrial IT is that they need to be **real-time**. This might sound like an open-door to you, but what it implies is that the computation does not have to be correct, but it does need to be delivered in time. In some cases, it is preferable to have a less accurate result but produced on time, as opposed to having a very accurate answer, but not on time.
Another aspect to consider is that the information is **mission-critical**. This means that in case of malfunction, they can lead to catastrophic situations in terms of loss of human life or property. They need therefore to be flawless.

Role of automation in industry

As mentioned earlier: industry is an economic activity, and this requires that it is profitable. This defines a clear role that automation has in industry.
So what defines profit? In simple terms:

$$\text{Profit} = \left(\frac{\text{Price}}{\text{Unit}} - \frac{\text{Cost}}{\text{Unit}} \right) \text{x Production volume}$$

Profit can be increased by:
- reduction of the production costs.
- increase of the price for the product.
- increase of the production volume.
- producing good quality products (you need to sell them).

Automation can have an effect on the **costs/unit** and the **production volume**.

Effect on costs and production volume

Automation can have an effect on the profitability through reduction of the costs per unit and the increase of the production volume.
If we consider in more details the **costs** involved, we can distinguish a number of components, such as costs involved in **materials, energy, manpower and infrastructure**. The use of automation does allow you to reduce the amount of people needed for the production. This saves payment of salaries and thus direct costs. Automation also allows you to better and more efficiently use materials and energy. Less is wasted, and is therefore a reduction in costs.
Production volume is determined by time needed for manufacturing a product which includes the **production time, material handling time, idle time, and time needed for quality assurance**. Larger production volumes can be achieved through automation, as the production is faster, and more precise compared with manual productions. By doing this the production time per unit goes down and production volume can go up.

Automation in the full product life cycle

Up till now we have been considering industrial automation within the production phase, and maybe including quality control. But specifically with the integration of IT in industrial automation, it is possible to include the other areas of the industrial product life cycle as well.

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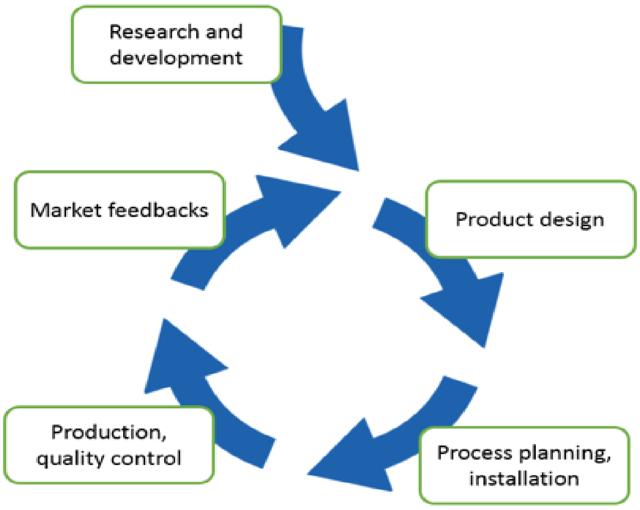

Information technologies allow information to flow from one phase to another phase. For example, it means that the design of a product is not independent from the process planning and the actual production. Information from the production phase can be fed back (real-time) to the design phase, to ensure that what is designed can indeed be produced. A connection with finance for example would enable the designer to directly have insight into costs incurred in choosing different options. When all this is connected the entire product cycle can be automated.

Economy of scale / Economy of scope

Automation can increase productivity and profitability in two different ways: economy of scale and economy of scope.

Economy of scale refers to achieving a reduction of cost per unit, resulting from an increased production, which is a result of operational efficiencies. Automation can enable this, and this leads to large-scale production. This economy benefits from the characteristic of scale. Assembly lines in which one component of a product is produced is a typical example of this.

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Although still applicable for many industrial sectors, we do see a clear shift to another model, which is the economy of scope.

Economy of scope refers to a situation in which the production of one product or service reduces the cost of producing another related product or service. They occur when a wider variety of products/services are produced in tandem and are, as such, more cost effective for a company than producing each one independently. This economic form is characterized by variety. This requires rapid programmability and reconfigurability of machines and processes, which is exactly what automation can provide.
This industrial automation enables the industry to exploit a much larger market and protect itself against fluctuations in demand.

Watch the video Economy of scope

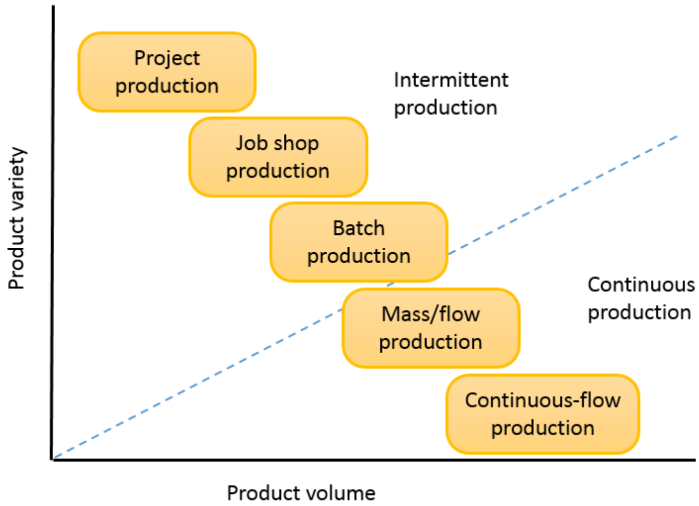
Type of production systems

When you want to consider industrial information in your specific business, it is essential to determine the characteristics of the particular branch you are in, or what type of production process you are using now. Based on this, you can make the right choice on what automation would be profitable for your specific case.
So, let's first look at different industrial production processes.

Types of production systems and processes
Based on their scale and scope industrial processes can be categorized in the following classes
1. Process/Continuous flow production is one in which the product is produced in continuous quantities and in a continuous manner (24/7). Examples are products coming out of chemical plants, oil refineries, steel plants, where the product is not a discrete object, but more of a continuous material. In such factories the volume of production is generally high, while variation in different products is low (mostly one).
2. Mass/flow production. Also, here product variation is very limited. Examples are automobiles and appliances, which are discrete, countable objects that are manufactured in large volumes. Includes more humans than continuous production.
3. Batch production (intermittent, non-continuous). In this setting the same set of equipment is used to produce a variety of product types (each by changing the settings of the equipment or materials a bit). It is not produced continuously, but a limited number at a time. Examples for this industry are pharmaceuticals, plastic moulding products, printing.
4. Job shop production. This is for manufacturing small quantities of discrete products, which in most cases are custom-built. Customers in this form usually provide drawing and /or requirements, after which the product can be made. Any variation in the product can be made. Machine shops, Fablabs, and other prototyping facilities are examples of this.

5. Project production. This is product or service based, where a company accepts a single, complex and large contract (in the form of project). Construction of infrastructural works or making movies is an example of this.

As we go from the production process number 1 to number 4, we see a **decreasing trend in quantity** of production and an **increasing trend in variety** of products.



Type of automation systems

Automation systems can be categorised based on **flexibility** and **level of integration** in manufacturing processes.

Fixed automation which is used most in large volume production that is done with dedicated equipment. Continuous flow and mass production systems use this type of automation. This means that the automation is optimised for one type of production which is efficient for only producing that one product. It is not flexible or easy to adjust.

Programmable automation. This can be used when the sequence of operations, or configurations (settings) of machines need to be adapted. This is typically used in batch processes. It is important to find the right balance between the ease of programmability and number of times that the production process is changed.

Flexible automation. This is computer controlled and is used in Flexible Manufacturing Systems (FMS). Humans are only involved in providing high-level code, which are then further translated (by software) to instructions for settings for each production machine. Multipurpose CNC machines, 3D printers, automated guided vehicles are examples of this

Integrated automation refers to full automation of a manufacturing plant. All processes are computer controlled and are coordinated through digital information processes. This is a full integration of process and management operations using information and communication technologies.

As you go down the above list, you see an increase in scope and complexity of the systems. Which level is needed for your individual manufacturing facility depends on the specifications for

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manufacturing, labour conditions and costs, competitive pressure. What is important to consider is that any investment in automation must be earned back by an increase in profitability.

Exercise - Multiple Choice

Flexible automation is most suited for an industry producing:

☐ Light bulbs.
☐ Soap.
☐ Pharmaceuticals.
☐ Textiles.

Programmable automation is most suited for a factory producing:

☐ Bricks.
☐ Toys.
☐ Textiles.
☐ Electronic appliances.

Fully integrated automation is most suited for a factory producing:

☐ Bricks.
☐ Toys.
☐ Textiles.
☐ Electronic appliances.

Automation architecture

Different elements of industrial automation

When we discuss industrial automation, we need to be aware that there are many elements that perform a wide variety of functions. These functions relate to:

- Instrumentation
- Control
- Supervision
- Operation management

All these elements exchange information with one another to enable overall coordination.

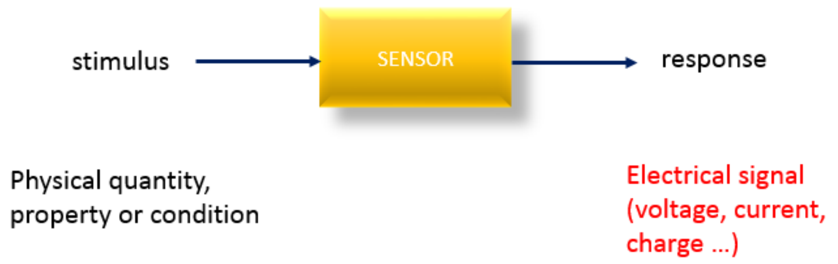
Sensors and actuators

Sensors and **actuators** are the elements that interface in a direct and physical manner with the actual industrial process. These senses and actuate different properties of parts of equipment, or machines used.

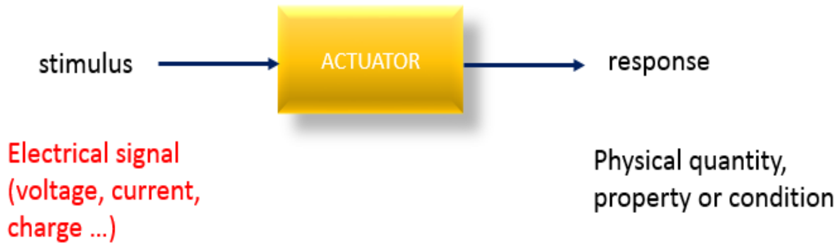
In the previous sections we have discussed a wide variety of sensors that measure different properties. Just a quick recap:

Sensors are a specific type of transducer that converts a physical property into an electrical signal.

Physical properties such as pressure, temperature, displacement, are converted into electrical signals (voltage, current or charge).



The above yellow box is a somewhat simplified version, and in many sensors this does include the actual sensing element, some signal-conditioning and processing elements and depending on the application the signal is displayed, stored or fed back into a control system.
Actuators do the opposite and convert an electrical signal into forms that can be applied to the actual process. These forms are physical quantities such as power, displacement, heat, etc.



Also, here the yellow box does contain multiple elements that have different tasks that are generic for actuators, such as signal processing, power amplification, conversion of the signal from a non-electrical to electrical form, possibly a second amplification of conversion element.

Industrial control systems

Before going in more depth on industrial control systems, let's start with an easy every-day example of a control system.

Watch the video [Feedback control]

Industrial control systems

Control elements, or controllers are those that interface between sensors and actuators. They receive electrical signals from sensors, and with this input, create electrical signals that are send to actuators that in turn affect the process. Control systems also accept command signals from either human operators or supervisory systems.

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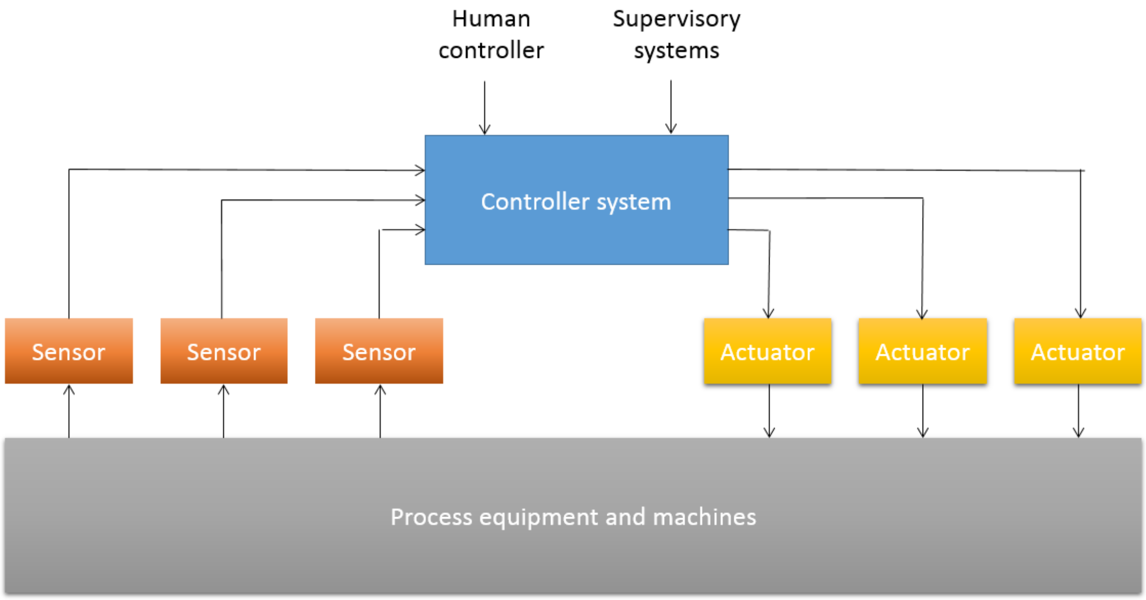
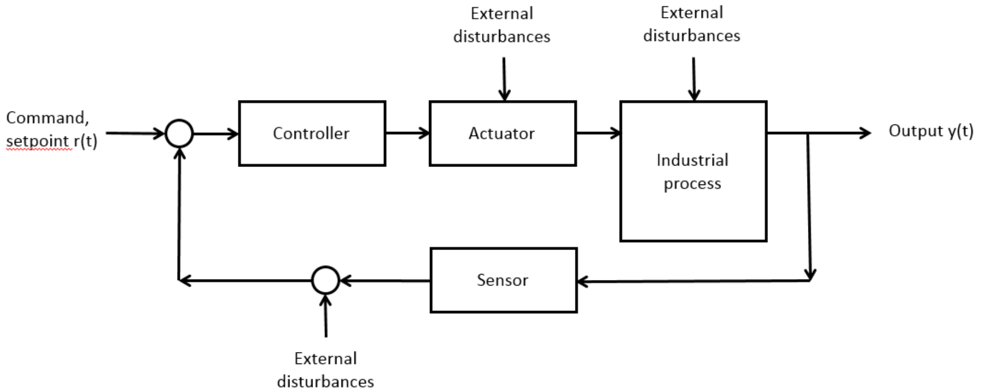


There are 2 types of control: continuous control and sequence control

Continuous control is also known as automatic control process control, or feedback control. In most cases the command signals are constant (for a considerable amount of time). These are also referred to as set points. The setpoints are basically levels of pressure, temperature, flow and level that are desired, or that are needed to ensure the quality of the product that is being produced. The task of the continuous control system is to maintain these values at the desired level, by adjusting different process properties (via the actuators)

In other cases the setpoint (or command) may be continuously varying, for example in case of motion control in machining applications. Also in this case the task of the control system is to follow the command (set-point) as closely as possible.

Below here is a simple version of a control loop having one sensor and one actuator.



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Again, on the left there is a command r(t), which can be either constant or varying in time. The command for example states that the temperature needs to be 151 degrees Celsius. At the first node this command is compared with the actual temperature, which is measured by a sensor (at the bottom) which is present in the industrial process. Based on a discrepancy between what is desired and the actual value (is effectively the difference between the actual temperature and the setpoint) the controller drives an actuator. If this difference is zero, the actual temperature is equal to the setpoint, and no actuation is needed. However, when the temperature drops below 151 degrees, the controller needs to drive an actuator which in turn will increase the temperature in the process. As the temperature is continuously measured and fed back into the system, it will do so, until the actual temperature is again on the desired level. This is a feedback system.
Above is an example of a single-loop controller, but in practice one single device can control multiple loops, using different algorithms (P, PI, PID, fuzzy logic)

Sequence or logic control
Feedback control as described above is useful in the case that continuously varying variables are use, such as pressure, temperature or displacement. Continuously varying means that they can adopt a wide range of values. Instead of using continuous variables it is also possible to use discrete variables. These are variables that one have a limited number of values. The best example of this are binary variables which are either 1 or 0, ON or OFF, open or closed. Control systems that work with discrete variables operate by turning on and off switches, motors, valves, flows in response to operating conditions and as a function of time. This is known as sequence or logic control. This also means that for example for the actuation of a motor, the control system is not providing an variable signal that controls the speed at which the motor is running. It only tells it to be ON or OFF. Having only a limited set of command simplifies the control significantly. Also, the sensors do not provide continuously varying variables but discrete ones. The pressure is ABOVE or BELOW a threshold value, being either 0 or 1.
Modern sequence controlling is mostly done with PLC, which stands for Programmable Logic Controll. It is a special purpose industrial microprocessor based real-time computing system.

Supervisory control

In the previous sections we have discussed the sensors, actuators and control systems. Directly above these controllers, we have supervisory control systems.
They typically have the following functions.

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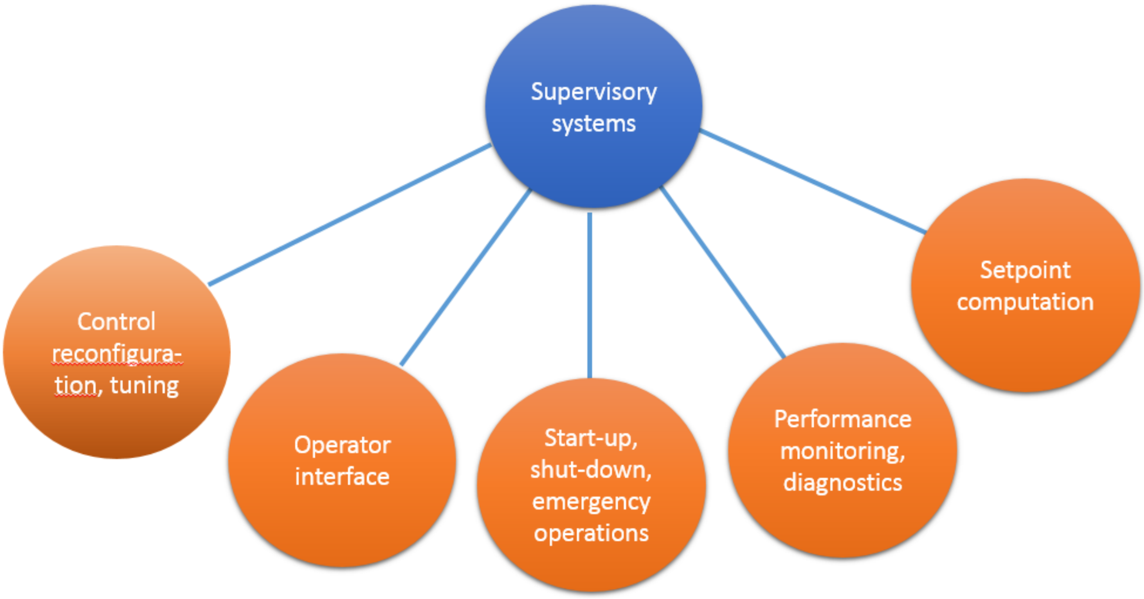

The supervisory systems actually controls multiple automatic controller systems that are controlling the processes. Depending on the nature of the process they are providing the setpoints (or commands), but are also taking care of start-up, shut-up or operations that are needed in an emergency situation.

A well-known system for this is SCADA, Supervisory Control and Data Acquisition system. As well as controlling the automatic controllers, these systems can also be simply monitoring (and not influencing), acquiring and collecting data to have information on the performance and to perform diagnostics.

Watch the video What is SCADA?

Production control

On top of the supervisory control system(s) or SCADA are the production control systems. These systems typically have a number of managing tasks, such as:

- process scheduling
- maintenance management
- inventory management
- quality management

In contrast to the other control systems, production control is not real-time.

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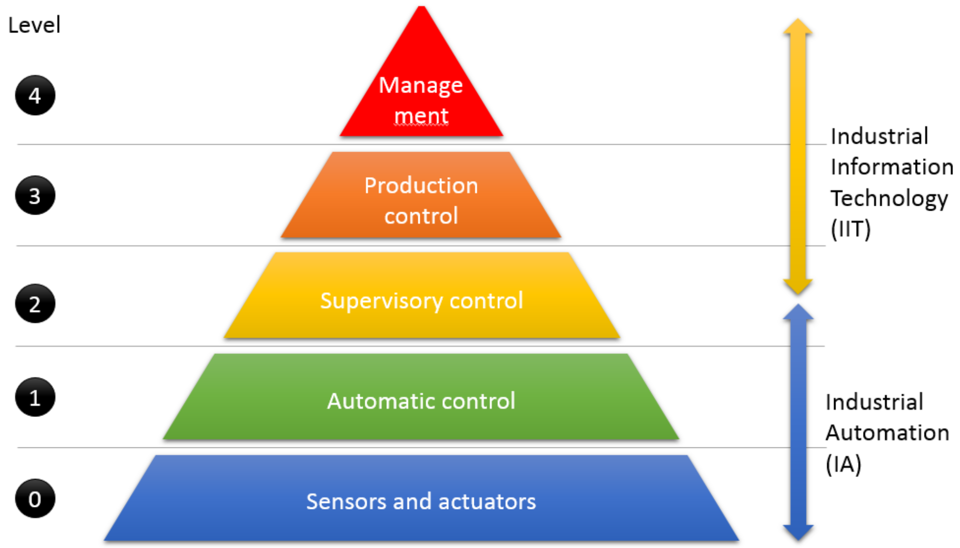
The automation pyramid

Any industrial information system consists of many different elements that perform a huge variety of functions, which are all essential and related to the industrial process. All these elements need to communicate with one another to exchange information.

The various elements in an industrial automation system can be explained using the automation pyramid:



In this pyramid 5 different layers can be discerned. The width of each layer represents the number of devices involved, indicating that the lower layer, that is the sensors and actuators, is the largest one in a number of devices. As you move up in the pyramid the number of devices reduces. The hierarchical order also represents the speed of reaction to changes. The lowest level sensors and actuators are responding with high speed as they are close to the processes and machines and need to react fast upon changes. Again, as you move up the pyramid, systems become slower and slower.

Watch the video [What is automation pyramid]

Quiz

Multiple Choice

Automated systems are able to achieve superior performance in product manufacturing compared to a manual one. Why?

☐ Automated systems have a higher precision

☐ Automated systems can use more energy

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☐ Automated systems can have more speed of operation

☐ Automated systems are controlled by humans

Multiple Choice

Programmable automation is most suited for a factory producing...

☐ Bricks

☐ Toys

☐ Textiles

☐ Electronic appliances

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