Chapter 8
Robot Components

Gianmauro Fontana, Claudia Pagano and Marcello Valori

8.1 Introduction

The availability of digital technologies, in terms of both hardware (sensors, high computation capabilities, PLC, etc.) and software (big data analytics, artificial intelligence, etc.) tools, enables the development of advanced smart factories, based on the synergistic development and convergence of computer science, Information and Communication Technologies (ICT) and manufacturing science and technology. In a smart factory, huge amounts of information are collected in real time from the different processes and machines on the factory floor from smart sensors. Afterwards, these data are integrated in the information system, where they are analysed in order to improve the quality and efficiency of the production system controlling the actuators. Production and information systems are constantly synchronized so that the response time to unpredicted events can be minimized.

A robot is a complex machine composed–of different elements which have different functions, such as mechanical architecture, actuators, sensors and a control system. Considering the robot as a black box, an input energy, properly modulated by input commands, is translated into coordinated motion of the mechanical parts.

In order to accomplish this task, the action of an actuator is governed by the control system, that can modify in real-time such an action by combining sensor readings with planned tasks.

A diagram of the process is outlined in Figure 8.1-1.

This chapter is focused on basic and advanced principle of sensing and actuation of robots, since they allow the monitoring and control of the physical system that is the foundations of a smart factory.

G. Fontana, C. Pagano(✉), M. Valori
Institute of Intelligent Industrial Technologies and Systems for Advanced Manufacturing, National Research Council, Milan, Italy
e-mail: claudia.pagano@stiima.cnr.it

J.C. Chaplin et al. (eds), *Digital Manufacturing for SMEs*
DOI: 10.17639/J6AM-VP75

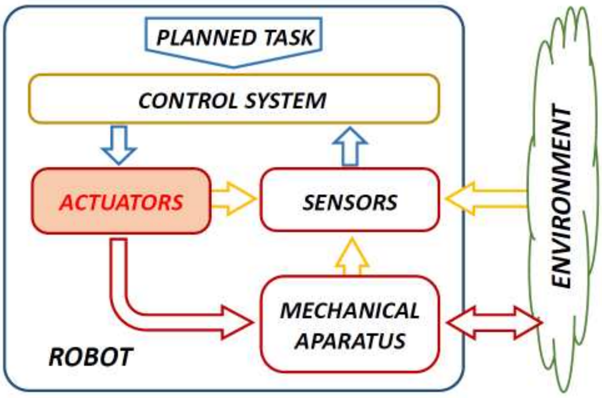

Figure 8.1-1 Block diagram of robot components.

Sensors are also discussed in section 9.2 of Chapter 9 in the context of digital twins of manufacturing sensors. However, they perform an essential role in robotic systems, so a detailed discussion in the context of robotics is provided in the next paragraphs.

8.2 Sensors

Robot sensors are the components of a robotic system in charge of collecting information about its internal state or features of the external environment; the awareness about these aspects is fundamental for the robot to perform its tasks.

Sensors can be thought of as robot senses, as they can provide the robot with different kinds of information depending on the task requirements. In order to achieve this goal, different sensor types are used to measure different physical quantities. Whenever the sensor information is acquired, the robot control system interprets them and acts to execute its task.

Sensors fall into one of two categories:

- *Internal Sensors:* Which measure physical values internal to the system such as the position, velocity, acceleration, forces, torques of robot joints, and inertia of the robot links. Based on these measurements the control system controls the actuators of the robot joints in order to perform the desired motion correctly and accurately.
- *External Sensors:* Which gather information about the environment surrounding of the robot, such as distances to objects, light and temperature measurements, and forces encountered when interacts with the world.

Figure 8.2-1 provides some examples of each of these categories.

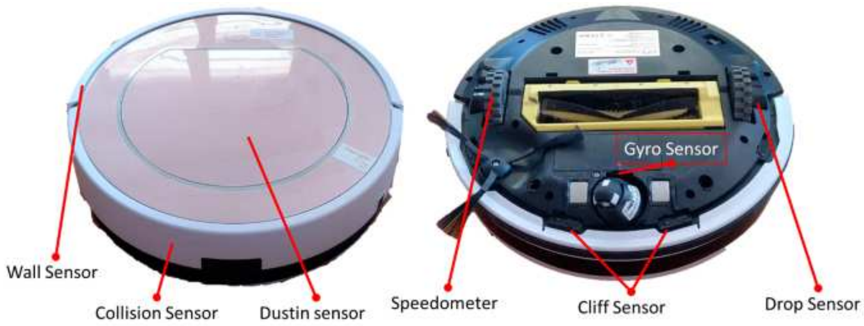

Figure 8.2-1 The top and bottom view of an autonomous vacuum cleaner with internal sensors (gyro sensor, speedometer, suction sensor) and external sensors (dust-in sensor, cliff sensor, infrared sensor receiver, wall sensor, collision sensor, drop sensor).

8.2.1 Sensor transduction principle

Each sensor is based on a *transduction principle*; a conversion of energy from one form to another. Typically, sensors convert to electrical energy to enable the robot to read a signal generated from the measurement of a physical quantity.

Even though sensors might be based on more than one transduction principle, a classification based on the transduction principles [1] can be useful to identify materials, costs and time of response involved and, thus, to choose the most appropriate for the application.

- *Mechanically-based Sensors:* These work as simple switches; the contact closes the circuit inside the sensor and the current is detected. Releasing the contact opens the circuit and no current flows. A minimum force threshold can be set as the requirement for the switching.
- *Resistive-based Sensors:* These detect mechanical changes by detecting resistance changes of the device. In their simplest form they consist of two electrodes separated by a layer of deformable material, whose resistance varies according to the shape it assumes as a reaction to a mechanical stimulus. The simplest resistive sensor is the potentiometer that measure the position or the displacement. Other resistive sensors include strain gauges (to measure the force/torque, strain or acceleration), thermocouples (to measure the temperature), photoresistors (to measure light intensity) and thermistors (to measure the temperature).
- *Capacitive-based Sensors:* These are similar to resistive approaches, where the change of distance between plates or of an area of material due to an external input changes the capacitance of the material. Many types of sensors use capacitive sensing, including sensors to detect and measure proximity, pressure, position and displacement, force, humidity, fluid level, and acceleration.

- *Optical Sensors:* These detect a change in the intensity, phase, or polarization of the transmitted or reflected light and convert it into an electronic signal. They are not affected by electromagnetic interference, are intrinsically safe, and require fewer electrical wires. They are mostly used as position sensors, that activate when an object interrupts a light beam, as photoelectric sensors that detect the distance, absence, or presence of an object, or camera sensors to acquire an image.
- *Optical Fibre-based Sensors:* These use fibres not only as light transmitter but as sensors, as when these fibres deform due to an external stimulus, they produce a variation in the intensity, phase, polarization, wavelength or transit time of light of the transmitted light. Optical fibres are mostly used as sensors to measure strain, temperature, and pressure.
- *Piezoelectric Sensors:* These are based on the property of piezoelectric materials, in that they generate an electrical potential difference when deformed, or vice versa (in this case they are used as actuators). They are used to measure changes in pressure, acceleration, temperature, and strain.

8.2.2 Contact Sensors

External sensors can be classified as either *contact sensors and non-contact sensors*, depending on whether the sensor needs to physically touch the object to function.

Contact sensors are largely used for obstacle avoidance: when a physical contact between the robot and the external environment occurs it triggers the robot to execute a task, such as a movement aimed at avoiding contact.

Force sensors can be *quantitative* where they detect the value of the force, or they can be *qualitative* where the output shows only whether the force overcome a set threshold value.

A common application for these sensors is the need to assess forces or torques that appear during manipulation. This aim can be achieved by directly measuring force/torques on the end-effector wrist (that is the joint holding the end-effector) or sensors within robot joints.

In the first case (see Figure 8.2-2), forces and torques are measured by the use of multi-axes force sensors, mainly consisting of mechanical structures with elastic elements built-in, whose deformation is measured. Since the structural behaviour of these elements is well-known, the applied load can be determined depending on the effective deformation. The deformation can be assessed with different approaches, but the most common relies on the application of *strain gauges;* specific components whose electrical resistance changes depending on the deformation.

Some recent robots equip the gripper joints or directly the gripper tips with force sensor, in order to control the grasping force and compute the contact points. Sensors useful to fulfil this goal include single-axis force sensors as strain gauges, piezoelectric sensors, pressure sensors, or multi-axis force sensors as presented above for the robot wrist.

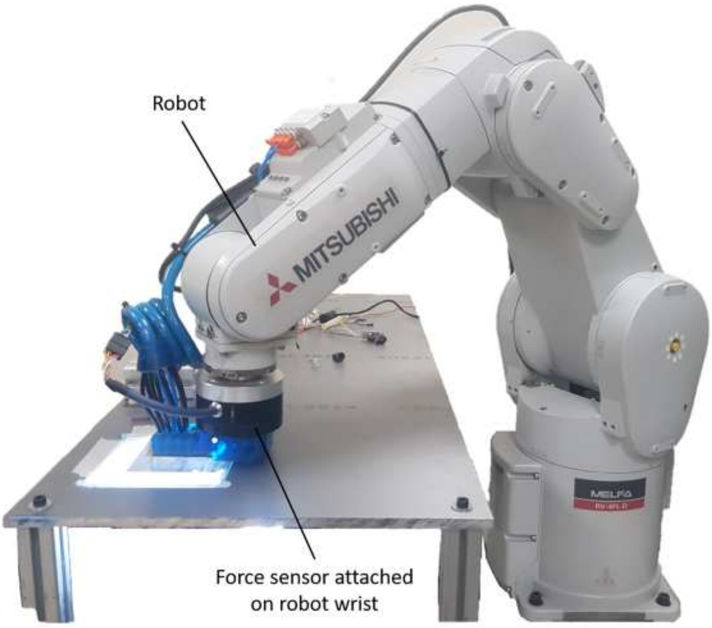

Figure 8.2-2 Anthropomorphic robot with a force/torque sensor attached on wrist.

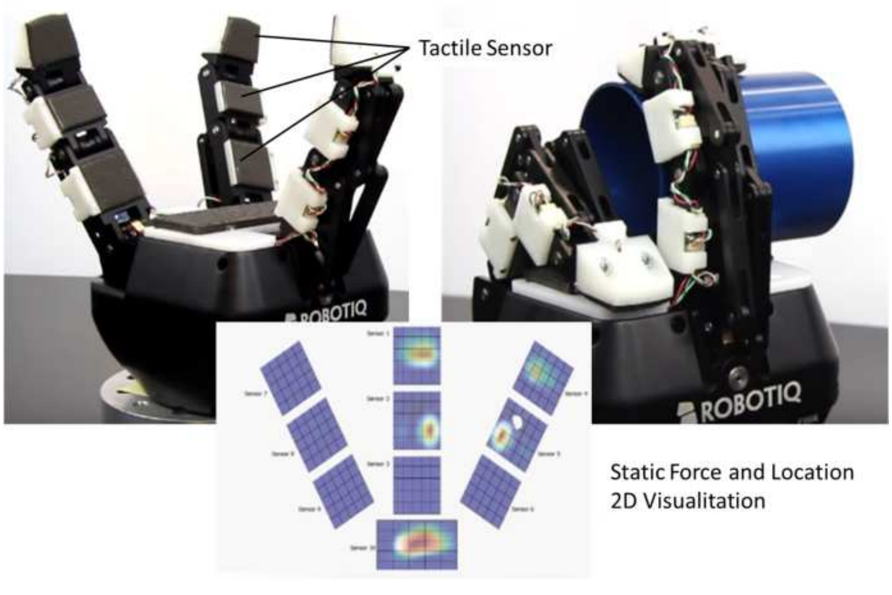

Figure 8.2-3 Tactile sensor on industrial robot gripper – 3-Finger Adaptive Robot Gripper. The array sensor is able to detect force position and intensity, as shown in the 2D visualization. Source: Authors based on Robotiq (www.robotiq.com).

Tactile sensors consist of arrays of sensors (and are hence sometimes called array sensors), whose signals are collected individually to detect the type of physical contact analogous to the human sense of touch.

They can be defined as the continuous sensing of all the various effects originated by contact between the robot (usually the end-effector or the gripper fingertips) and an object. Most significant contact-based effects are contact stresses and forces in the two contacting surfaces. The tactile sensors are able to measure the variable contact forces over an area with a specific spatial resolution.

The tactile sensors on the fingers of the robot gripper allows the robot to detect the presence of the object, the pressure distribution, the object shape, surface texture and roughness, the object pose (i.e. position and orientation), and contact locations, and any slipping information.

The tactile sensors are used on the gripper fingertips, as illustrated in Figure 8.2-3, but they can be assembled on the robot links.

The tactile sensors typically used in robotics are array sensors that measure the pressure of contact using the deformation of an elastic skin/overlay. An example of this type of sensor is presented in [2]; it is an elastic capacitive pressure sensor array based on a thin all-elastomeric platform. In particular, the sensor consists of 16 individual capacitively-coupled pressure sensing cells to detect the external tactile information in a 4x4 arrayed configuration [2]. Each capacitive pressure-sensing cell is composed of a pair of CPDMS (Capacitive PolyDiMethylSiloxane) sensing electrodes facing each other across the elastomeric insulating layer (Ecoflex) to construct a parallel-plate capacitor. The applied pressure causes the local change in distance between the CPDMS pairs (since the Ecoflex layer is more easily deformed than the PDMS) and thus the consequent change of the capacitance, which can be detected to obtain pressure and the normal force.

8.2.3 Non-contact Sensors

Non-contact sensors are used to give the robot information about the external environment without the necessity of physical contact.

Proximity sensors detect the presence of objects that are close to the surface of the sensor but not in contact. In robotics these sensors are used to detect possible collisions between a robotic arm and the environment. This could be desirable if the approaching object is to be acted upon, or may cause an undesirable collision so an avoidance plan should be enacted or the robot halted.

Range sensors are devices that can provide precise measurements of object distances, usually measuring the gap between the sensor and the nearest surface. Moreover, they enable the scan of the three dimensional (3D) structure of the environment from the sensor viewpoint. In the robotics field, range sensors are useful for locating objects within the robot working space and also as a feedback in a closed loop control scheme [3]. They are used for robot navigation, obstacle avoidance, and to reconstruct the third dimension from a 2D vision system like a camera.

Range sensing techniques can be based on one of two principles: *triangulation* or *time-of-flight*.

The *laser-based triangulation* working principle is illustrated in Figure 8.2-4: a laser beam is projected from one position onto the surface. The light spot (that can be also a light stripe to acquire simultaneously more points) is observed by a vision sensor from a second position. With the geometrical information of the relative positions and orientations of the laser source and sensor, it is possible to calculate the 3D position of the illuminated surface point or its distance. In order to capture a 3D image, the laser-based triangulation sensor has to move relative to the environment, performing a scanning process. Alternatively, the laser spot can be reshaped with lenses or mirrors to create multiple spots or stripes allowing the measurement of multiple 3D points simultaneously, without movement.

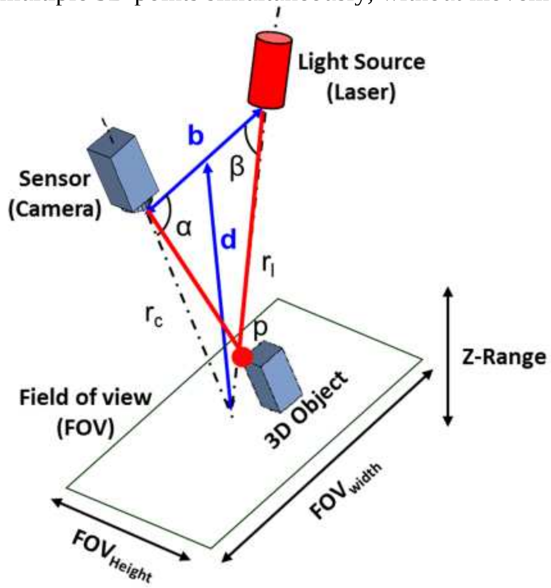

Figure 8.2-4 The physical principle of triangulation sensors: a laser source emits a light, generating a spot on a 3D surface to be measured and the sensor detects the spot on its image plane. Combining this 2D information with the geometrical parameters of the system, it is possible to calculate the 3D position of the projected spot in the environment. A collection of these points (by moving the triangulation system) enables surface reconstruction. The fundamental parameters of the system are the baseline (b) and stand-off distance (d). The former is the distance between the optical centres of the camera and the laser, and it affects to the measurement Z-range, the latter is the distance from the baseline to the focal plane of the camera, and it affects the Z-resolution.

Time-of-flight range sensors compute distance by measuring the travel time of a signal (e.g. light) to cover the path *source - object - detector*; the detector is usually located close to the source. Laser-based and sonar range sensors are the most common time-of-flight sensors. The former can be considered a radar that is based on light emission and detection. A sonar employs acoustic pulses and their echoes to measure the distance of an object and also its 3D position. As light and sound speed are known, it is possible to obtain the distance from the delay time.

Vision Systems also allow information on the environment to be gathered with no contact with the surrounding. The acquisition of data based on computer vision is a complex sensing process consisting of extraction, characterization and interpretation of the information provided by the images in order to identify objects in the environment. A vision system consists of one or a series of lenses, associated with a vision sensor that converts the visual information into electrical signals. These signals are then analysed by an image digitizer, called a frame grabber, to obtain a digital image.

8.3 Actuators

In the human body, movements are generated in the brain's primary motor cortex, translated and transferred to the muscles, which are able to transform available energy in mechanical motion (see Figure 8.3-1). The muscle appears as the principal contributor to the process, the "*motor*" enabling movement occurrence.

But… what is the muscle of a robot?

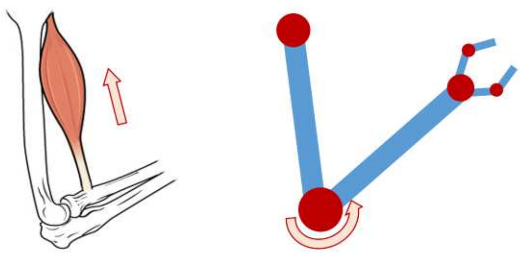

Figure 8.3-1 Human muscles * vs robot actuators. Image rights: OpenStax

In robots this role is played by *actuators*, which are the components responsible of the motion of links, in accordance to desired trajectories. An actuator converts a primary, available form of energy, into mechanical energy to operate the robot.

A robot capable of moving the end-effector in any configuration (limited by its own working volume) is equipped with at least 6 actuators, each one responsible for the motion along/around a single axis. An example is shown in Figure 8.3-2.

---

* https://commons.wikimedia.org/wiki/File:1015_Types_of_Contraction_new.jpg (partially reported), Link to license

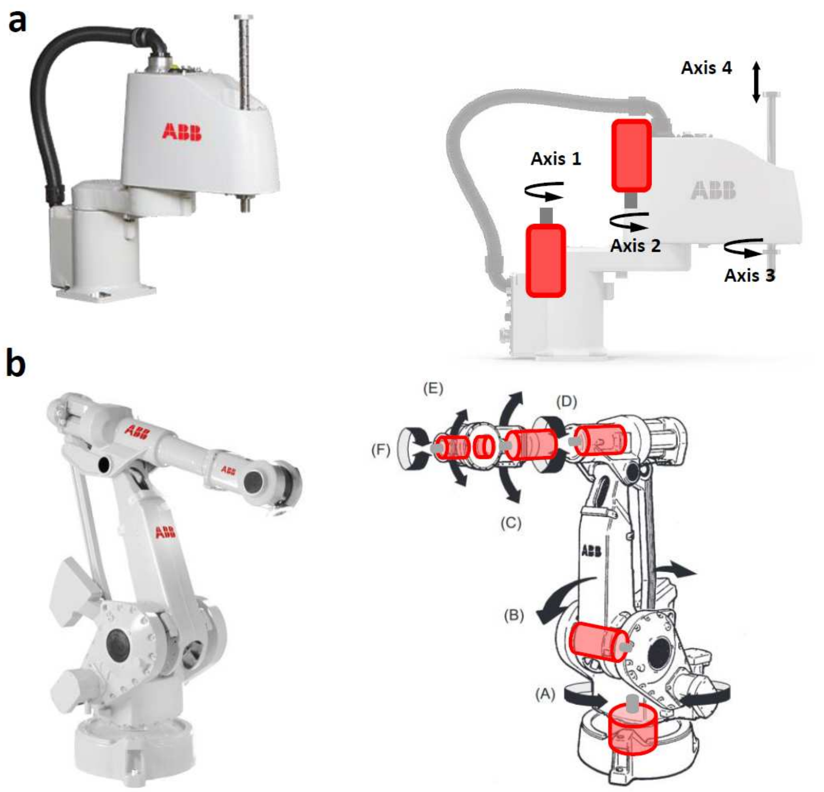

Figure 8.3-2 The four axes of the ABB IRB 910SC (4 axes) VS the six axes of the ABB IRB 4400 (6 axes) with the positions of some actuators highlighted in red*. Image rights: ABB

An actuator must be properly sized to support loads and inertias, as well as to comply with performance requirements: dynamic modelling of robots allows precise assessment of the performance required for each individual actuator, that can be primarily represented as the power it can exert.

Power is a suitable parameter in order to compare different forms of energy: as already explained, actuators convert power, provided as a certain source, providing mechanical power to links and joints. Even if the effective power is the appropriate parameter to identify the size of an actuator, it is not sufficient for the complete definition of an actuation unit. There are, indeed, other features which characterize the performance required to properly move a mechanical architecture, that accurately specify the most appropriate actuation unit.

* https://new.abb.com/products/robotics/industrial-robots

8.3.1 Type of motion

A first classification of actuators can be defined on the basis of the *type of motion* generated by the action of the actuator:

- *Linear Actuators:* Provide motion along a straight direction and their own geometry limits the stroke; an example outside the robotic world is represented by hydraulic actuators of heavy duty machines (Figure 8.3-3a).
- *Rotary Actuators:* Can rotate, usually spanning 360° and performing more rounds; position limits are instead imposed by the robotic architecture. With appropriate differences, an example in our daily experience is represented by the motor driving a washing machine (Figure 8.3-3b).

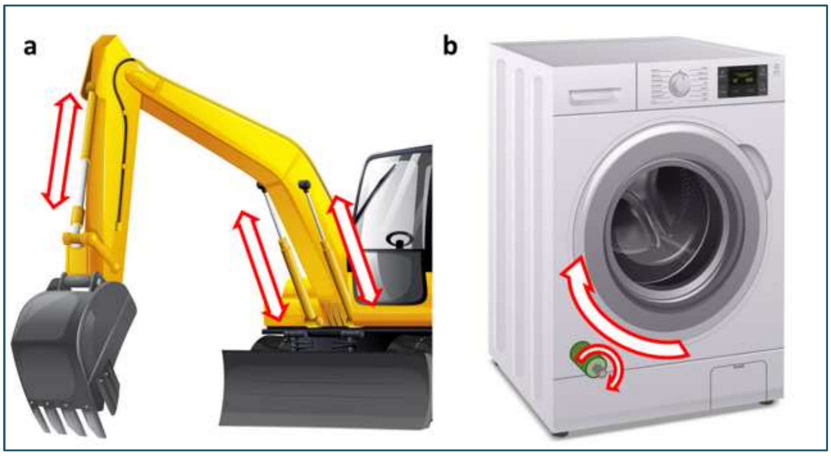

Figure 8.3-3 Examples of actuators in other application fields: a) hydraulic cylinders of overhaul machines (linear) and b) the electrical motor of a washing machine (rotary)*.

Considering the concept of mechanical power, it results as the combination of *force* and *velocity*. This is valid for all mechanical systems, regardless the type of movement. In linear actuators, this is expressed as $P = F \cdot V$, whereas in rotary actuators $P = T \cdot \omega$, with *torque* (T) representing a form of "rotational force", and ω the angular velocity. It follows that a more detailed specification for actuator performance defines not only the power, but also the maximum force (or torque) and velocity (linear or angular). Due to this, specific speed reduction gears are usually installed in a robot downstream of an actuator in order to properly modulate force and velocity and match the requirements of the particular implementation.

* Images designed by Freepik

Industrial robots sometimes have complex architectures, that are defined by taking into account dynamic features such as dexterity in certain zones of the working envelope and load/inertia distribution. Due to this, actuators, that can be heavy and bulky, often cannot be installed in direct proximity of the joints to be controlled. The need arises for systems able to transfer the power from actuators to joints, leading to the implementation of different motion transmission strategies, based on belts, gears and/or other mechanical systems. According to these considerations, a general actuation unit can be defined as composed of an actuator (the motor unit), reduction gears and a mechanical transmission, as represented in Figure 8.3-4.

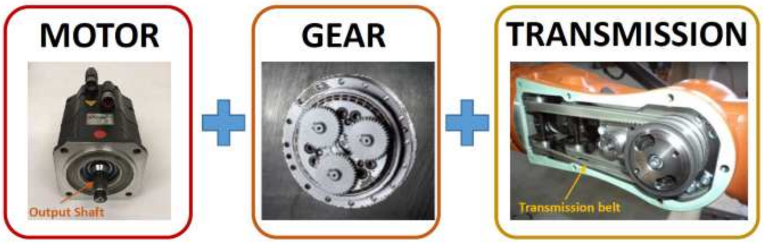

Figure 8.3-4 Examples of robot electrical motor, planetary gearhead and belt transmission*. Image rights: Dr. Arun Dayal Udai.

8.3.2 Power source

A second fundamental classification of actuators is based on the source of power exploited to generate mechanical motion:

- *Electrical actuators*: These represent the most common choice for industrial robots and are mostly based on direct current (DC), though versions based on alternate current (AC) are available. The most popular are rotary actuators but linear models also exist. Electric actuators (or, electrical motors) are characterized by high compactness and reliability. Due to this, and considering the availability of electricity in all plants, they are actually the most widespread form of actuator in the robotics industry. Electric actuators generate extremely high velocities, and as a result they are always coupled with specific reduction gears.
- *Hydraulic actuators:* These use oil as an incompressible fluid, hydraulic actuators usually provide linear motion, though rotary models are available. They are very powerful, but require maintenance and dedicated circuits for oil

* https://www.youtube.com/watch?v=iRKDfknqtbc (Property of Dr. Arun Dayal Udai, arun_udai@yahoo.com)

circulation. Their implementation in robots is also widespread, especially in "legged" designs.

- *Pneumatic actuators*: They represent the air-powered version of hydraulic actuators. The use of pressurized air does not guarantee sufficient stiffness with high payloads; however, pneumatic actuators do enable a number of manufacturing tasks, to be performed with extreme simplicity (push, pull, lift, positioning, tightening, blend, cut, punching, etc.), even if extreme precision control is not possible. They are mostly linear, they are implemented in stop-to-stop trajectories, such as certain pick-and-place tasks.

The main advantages and disadvantages of the different actuator power sources are presented schematically in Figure 8.3-5.

Power sources	Main advantages	Main disadvantages
Electric actuators	Speed and precision Easy control and, thus, possible complex control algorithms Low cost Reduced dimensions and weight	Reduction gears are a source of mechanical losses and imprecision Limited available power
Hydraulic actuators	High performance (force/speed) Intrinsic backdrivability: does not require energy to maintain a pose	Disadvantageous cost/performance ratio Noise and leakage Bulky envelope
Pneumatic actuators	Low cost High velocity No toxicity in case of leakage	Limited accuracy (due to fluid features) Noise (less than hydraulic) Need for air filters and maintenance

Figure 8.3-5 Main advantages and disadvantages of the most common actuators.

Although the actuators listed above represent the main actuators used in industrial robotics, there are some other actuators which exploit particular physical principles and are worth mentioning.

Piezoelectric actuators use certain crystalline materials, like quartz, which modify their configuration and physically deform when a voltage is applied to the material (see Figure 8.3-6). This deformation, proportional to the electrical field, is very small but also very precise, enabling positioning in the order of µm. It follows that their application can be foreseen in the assembly of products at the microscale. It is worth noting that their working principle is reversible and they can be used as positioning sensors by measuring the induced voltage.

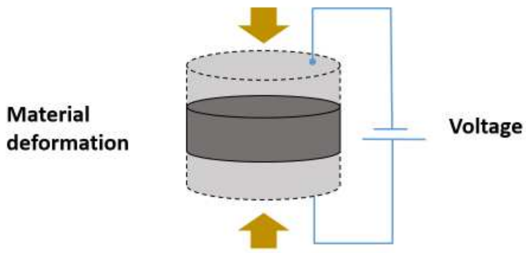

Figure 8.3-6 Working principle of a piezoelectric actuator.

Shape Memory Alloys (SMA) are metallic alloys which are able to “remember” their original position. In order to restore their initial configuration, it is sufficient to heat the material by applying an electrical current (Joule effect). The forces generated are considerable. Currently, their implementation as actuators is still experimental and being investigated in several fields which have demanding geometrical requirements, due to their great advantage of being able to exert a force without the need for bulky actuators.

8.4 Microrobotics

The achievements of miniaturisation are becoming more and more evident in everyday life; miniaturised devices are present in an increasing number of applications, especially electronics devices – such as smart phones, laptops, vehicle sensors and household goods – but also biological probes, medical systems and military devices. In robotics this trend leads to innovative solutions in a large variety of application fields, such as the maintenance and inspection in industry, non-invasive surgery in medicine and micro operation in biology. Due to their reduced dimensions miniaturised robots can perform tasks which are in small spaces that are not accessible to humans. Microrobotics is still a very promising research topic even though several research prototypes have already been developed [4][5][6][7]. Microrobotics is often mentioned as part of the Industry 4.0 technology portfolio - including also sensors, drones, virtual and augmented reality, additive manufacturing – which can address the challenges of the Sustainable Development Goals, set up by the United Nations [8].

In the literature the term *microrobot* refers to a large variety of robotic devices. It is generally applied to *all kind of robots that perform tasks in the microworld*.

However, the term microrobots is more correctly used for *miniature robots whose size is in the order of a few cubic centimetres*. The rationale behind this broad definition of the term is that both categories share some of the main challenges: non-intuitive physics**,** difficult fabrication and observation.

Like conventional robots, microrobots are integrated systems consisting of sensors, actuators and a logic circuit. The most challenging aspect in the development of microrobots is the fabrication of micro-actuators and micro-sensors which can give high efficiency and high stability. Sensors that can be used in small spaces are often not very precise so that the knowledge of the environment is not complete and the control system has to cope with this. Moreover, the *microcontrollers* do not usually have the processing power and memory common at the macroscale. Therefore, simplified control methods are usually preferred at the microscale. Mechanics are intrinsically more robust on the small scale [9]; this is an advantage for microrobots where space can be saved for more critical components.

The assembly of such small components is another relevant issue for microrobots. The scale effects and the consequent predominance of superficial forces affect the operation of a micromanipulator [10]. In particular, the releasing phase of a manipulation is critical and several strategies have been investigated and tested. As for micromanufacturing, each method has advantages and disadvantages which make one method more suitable in some applications than others.

All these issues made not only the fabrication, but also the design of microrobots very complicated. There is a strong dependency between the control and the model and the entire system, cyber and physical parts have to be conceived at the same time and any change in one of them is reflected in a redesign of the other. This makes microrobots complicated cyber-physical systems, more deeply discussed in the next chapter.

8.4.1 Power

One of the main issues related with the miniaturisation of robots is energy; due to the size reduction the space for the power source is reduced and, in addition, leakage currents increase. Therefore, the minimization of power consumption is essential; the operating voltage must be as low as possible and the energy required by all components minimized.

The solutions most commonly used are batteries and supercapacitors. Batteries are suitable in terms of output and durability, but are difficult to miniaturise. Supercapacitors have lower voltage limits and offer lower energy density but higher currents for charging and discharging. Moreover, supercapacitors can be recharged allowing them to be combined with power generators, such as solar cells. Indeed, wireless power sources, such as radio frequency, optical power, and energy harvesting are suitable and often advantageous due to the miniaturisation.

8.4.2 Control

The controller of a robot has to process information and generate suitable actions. Smaller devices tend to deal with less complex and more restricted environments and make smaller and slower movements, thus they might require a simpler and not so fast control system. Nevertheless, due to the very small dimensions of microrobots, onboard processors with enough calculation power are still a challenge.

8.4.3 Sensors

In order to perform its task a robot should be equipped with as many sensors as necessary to perceive the surrounding environment. Mobile robots have to be able to detect obstacles at a great enough distance so they can be avoided; thus, touch sensors, distance sensors and/or proximity sensors are.

Sensors for microrobots have to both be reduced in size, and their power consumption minimized, which can be a major issue. Therefore, passive sensors, which do not supply energy into the environment, or very simple active sensors are the most suitable sensors for microrobots. Cameras and microphones are, thus, very common as passive sensors in microrobots, together with strain gauges which can be easily downsized. Active infrared proximity sensors, which are simple to use, inexpensive and can be found in compact packages, are also very suitable.

8.4.4 Actuators

Actuators are one of the major issues in designing miniature robots. The choice of the actuation principles for the design of a microrobot has to reach a compromise in the range of motion, force, actuation frequency, power consumption, control accuracy, system reliability, robustness, load capacity, etc.

Figure 8.4-1 lists the most common types of actuation and their main characteristics. Each solution offers advantages and disadvantages, but none is perfectly suited to all applications.

Driving principle	Actuator	Driving range	Yield	Response speed	Driving voltage
Static electricity	Electrostatic rotary motor	Large	Small	Medium	High
	Electrostatic linear	Small	Medium	High	High
Electro magnetic induction	Ordinary motor	Large	Small - Medium	Medium - High	Low
Piezo electricity	Bimorph	Small	Medium - High	High	High
Heat	Shape Memory Alloy	Large	Large	Low - Medium	Low

Figure 8.4-1 Typical characteristics of the most common actuator types [11].

Electrostatics, electromagnetics and piezoelectrics are the most commonly used solutions for actuation at small scale.

Electrostatic and electromagnetic fields can be rapidly created and interrupted, allowing very fast actuation. Moreover, electrostatic fields can exert great forces, but in a very short distance, unless high voltage is used. The extremely low current consumption associated with electrostatic devices makes for highly efficient actuation. Electromagnetic fields offer the advantage of converting electrical energy into mechanical work with high efficiency, leading to a low current consumption. The main disadvantage is the poor scalability of the electrical magnets.

Piezoelectric materials (zirconate titanate, PZT, quartz, SiO2, lithium niobite) are also very common. Their molecular crystals show a dimensional change when in an electric field and, vice versa, produce a voltage when deformed. They show a very quick response to the input, great repeatability and high force, but they exhibit very small strokes (under 1%). Thus, they are usually combined in piles or in stick-slip modes to obtain larger strokes.

Other smart materials also become advantageous at the microscale [12]. Shape memory alloys (SMA) are functional materials that have two stable solid crystallographic phases. They can transform reversibly from a crystal structure to the other structure upon heating and generate mechanical work during the phase transformation. They offer large displacement and actuation force within an extremely small volume and a low operating voltage. Some problems, such as low dynamic time response and large hysteresis, limit their use at the macroscale, but these problems are less relevant at the microscale.

Electroactive polymers (EAP) are very promising materials. A very large deformation (10% - 400%) can be achieved when a voltage is applied across the polymeric film, coated with electrodes on both sides. They are lightweight, inexpensive, fracture tolerant and fast, but they usually require a high DC voltage (>150V/µm), which is also very close to the breakdown voltage of the material. Moreover, their applications are limited by low actuation forces.

8.5 Conclusions

Sensors and actuators are the main components of robots and in continuous development in order to improve their performance and meet new challenges. In the context of Industry 4.0 further advancements are required to build smart factories where all the devices are integrated in a network system and the entire production chain is automated. In smart factories, smart sensors serve as the interface between the digital and physical world. They consist of the combination of a sensor, a microprocessor and a communication system so that environmental data is monitored and transmitted, in real time, to the main control system. This data is used to activate the actuators in order to automatically manage the process and maintenance, improving the efficiency and the quality of the manufacturing. A huge amount of data is collected to monitor the production processes, the environment and its modifications. This improves health and safety in the work space, in particular where cooperation between robots and humans occurs.

8.6 References

[1] J. Fraden, Handbook of Modern Sensors: Physics, Designs, and Applications, III Edition, Springer International Publishing, 2016

[2] S-J. Woo et all, "Thin All-Elastomeric Capacitive Pressure Sensor Array Based on Micro Contact Printed Elastic Conductors", *Journal of Materials Chemistry C* vol2, pp. 4415-4422, 2014

[3] R. B. Fisher et al., Range Sensors, Springer Handbook of Robotics, II Edition, Ed. Siciliano et Khatib, Springer Berlin Heidelberg, pp 455-476, 2016.

[4] G. Caprari, T. Estier, and R. Siegwart, “Fascination of down scaling- alice the sugar cube robot”, *Journal of Micro-Mechatronics*, vol. 1, no. 3, pp. 177–189, 2002.

[5] S. Kernbach, R. Thenius, O. Kernbach, and T. Schmickl, “Re-embodiment of Honeybee Aggregation Behavior in an Artificial Micro-Robotic System,” *Adaptive Behavior*, vol. 17, no. 3, pp. 237–259, 2009.

[6] F. Mondada, M. Bonani, X. Raemy, J. Pugh, C. Cianci, A. Klaptocz, S. Magnenat, J.-C. Zufferey, D. Floreano, and A. Martinoli, “The e- puck, a robot designed for education in engineering,” in Proceedings of the 9th conference on autonomous robot systems and competitions, vol. 1, no. 1, pp. 59–65, 2009.

[7] M. Rubenstein, C. Ahler, and R. Nagpal, “Kilobot: A low cost scalable robot system for collective behaviors,” in *IEEE International Conference on Robotics and Automation*, pp. 3293–3298, 2012.

[8] Kumar A, and Nayyar A, “si3-lndustry: A Sustainable, Intelligent, Innovative, Internet of Things Industry. In: Nayyar A., Kumar A., editors. A Roadmap to Industry 4.0: Smart Production, Sharp Business and Sustainable Development. Springer; p. 1-21, 2020.

[9] Zhu, TT, Bushby, A.J. and Dunstan, D.J., “Materials mechanical size effects: a review”, *Materials Technology*, 23(4), p. 193-209, 2008.

[10] A. Ghosh, “Scaling laws”, in Mechanics over micro and nano scales, p. 61-94. Springer, New York, NY 2011.

[11] P. Dario et al., “Microactuators for microrobots: a critical survey”, *Journal of Micromechanics and Microengineering*, 2(3), pp. 141-57, 1992..

[12] C. Pagano, I. Fassi, “Introduction to miniaturisation in Micro-manufacturing technologies and their applications”, in I. Fassi, D. Shipley, editors. Micro-Manufacturing Technologies and Their Applications. Springer Cham; p. 1-22, 2017.

“The European Commission support for the production of this publication does not constitute an endorsement of the contents which reflects the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein”

Digital Manufacturing Training System for SMEs (Digit-T)
Project ref: 2017-1-UK01-KA202-036807