Chapter 7
Industrial Robots 4.0

Irene Fassi, Simone Pio Negri, Claudia Pagano, Lara Rebaioli and Marcello Valori

7.1 Introduction

The main goal of Industry 4.0 in Robotics is the development of smart industries with increased productivity of high-quality products meeting customer expectation. This requires flexibility, automation and interconnection. In smart factories the products will be handled by autonomous *mobile robots*, human and robot skills will be combined using *collaborative robots* (cobots), the huge amount of collected data will be used to predict maintenance and disruption and take decisions by robots with *artificial intelligence*.

The use of industrial robots in factories is becoming more widespread. They are typically used to perform tasks which are dangerous to humans, to enhance the throughput and quality of production, and reduce production costs. They work in a confined and structured space, are programmed to continuously perform a repetitive sequence of actions which hinders the flexibility and reconfigurability of production lines.

The new generation of robotics, integrating the technologies of Industry 4.0 such as Internet of Things, Big Data, Cloud Computing, Artificial Intelligence, creates the industry of the future able to automatically and efficiently reconfigure itself to fulfil individual customer requests. Machines and facility components are all interconnected so that the entire production process is fully automatic. The incoming order is processed by a machine which defines the production process, orders the materials, which are handled by robots, as well the final product and shipping. In such an interconnected system of the smart factory, robots monitor their own health so that predictive and self-maintenance is possible, reducing the

---

I. Fassi, S.P. Negri, C. Pagano (✉), L. Rebaioli, 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: https://doi.org/10.17639/vjvt-7681

downtime and increasing efficiency and productivity. The role of humans will be to supervise the robots and ensure correct functionality.

This chapter gives a short overview on industrial robots, providing the terminology and the basic concepts helpful for the comprehension of the next sections in the book. Then the main concepts of collaborative and mobile robots are introduced, before being discussed further in the next chapters.

7.2 Industrial Robot

Although several definitions of robot and robotic systems can be found in the literature, hereafter we adopt those provided in the ISO 8373:2012 [1] standard.

- A *robot* is an actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks. Autonomy in this context means the ability to perform intended tasks based on current state and sensing, without human intervention.
- A *service robot* is a robot that performs useful tasks for humans or equipment excluding industrial automation application. Robots that perform useful tasks for humans or equipment in industrial automation applications are referred to as *industrial robots*.
- A *personal service robot* or service robot for personal use is a service robot used for a non-commercial task, usually by the general public. Examples are domestic servant robots, such as robot vacuums, lawn mowers, personal robot assistants, automated wheelchairs, and personal mobility assist robots, such as wearable upper or lower limb exoskeletons.
- A *professional service robot* or a service robot for professional use is a service robot used for a commercial task, usually operated by a properly trained operator. Examples are cleaning robots for public places, delivery robots in offices or hospitals, fire-fighting robots, rehabilitation robots and surgery robots in hospitals. In this context, an operator is a person designated to start, monitor and stop the intended operation of a robot or a robot system.
- A *robot system* is a system comprising robot(s), end-effector(s) and any machinery, equipment, devices, or sensors supporting the robot performing its task.

In addition, a *collaborative industrial robot* is defined by the International Federation of Robotics [2] as an industrial robot that is designed in compliance with ISO 10218-1 “Robots and robotic devices – Safety requirements for industrial robots – Part 1: Robots” [3] and intended for collaborative use. A collaborative operation happens when a purposely designed robot works in direct cooperation with a human.

7.2.1 Robot Terminology

An industrial robot's mechanical apparatus is usually composed by sequences of articulations and rigid segments, respectively called *joints* and *links* (Figure 7.2-1); the resulting *kinematic chain* enables the motion of the *end-effector* according to the trajectories required for the specific task. As a result, the mobility level of the

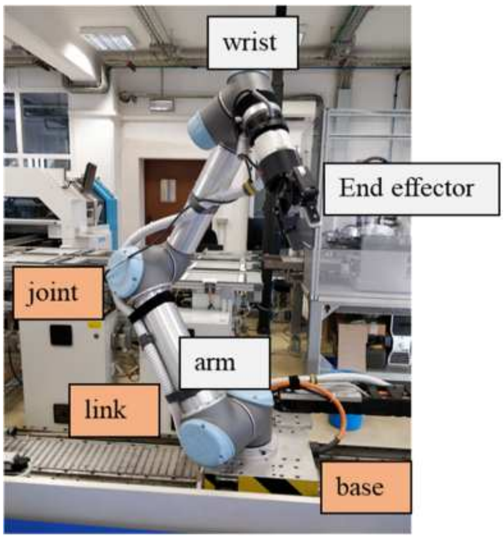


Figure 7.2-1 Robot main components.

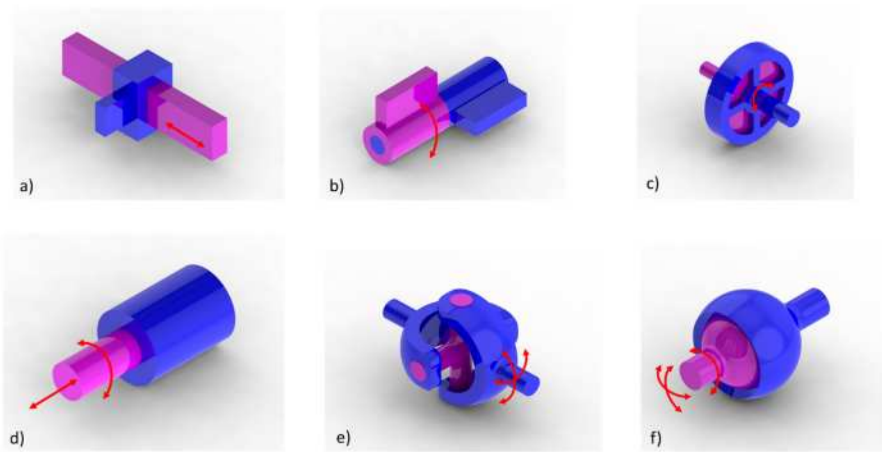


Figure 7.2-2 Typical joints used in robotics: a) prismatic (translation along one direction), b) and c) rotoidal (hinge, rotation about one axis), d) cylindrical (rotation and translation) e) cardanic (rotation about two orthogonal axes), f) spherical (rotation about 3 axes) [4]. Image rights: Authors.

end-effector directly depends on the number of joints (Figure 7.2-2) in the system. In order to represent this concept, the number of *degrees of freedom* (DOFs) of a robotic arm can be defined, on a general basis, as the number of joints making up arobotic arm's kinematic chain. This feature directly affects the possible motion of the end-effector: under appropriate design criteria, an equivalence can be established between the number of DOFs of the arm and the number of DOFs of the end-effector.

Industrial robots are usually classified by their kinematic chain (serial or parallel), the number of degrees of freedom, accuracy and repeatability, payload and workspace. A *serial* kinematic structure is normally realized with rigid links connected in series by means of 1 DOF actuated articulations (able to perform a rotation or translation), while a *parallel* kinematic structure is composed by several convergent kinematical chains, where not all the articulations are actuated, as shown in Figure 7.2-3.

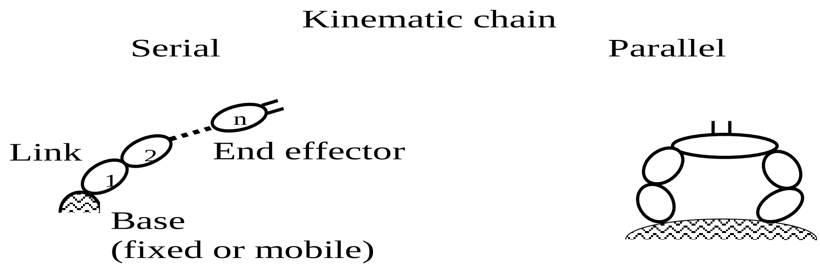


Figure 7.2-3 Example of serial and parallel kinematic chains [4].

The DOFs of the end-effector cannot exceed three translations (x,y,z in the Cartesian space) plus three rotations, which are the six DOFs which can characterize an object in a 3D space. As a result, a number of DOFs higher than six in the joint space has the effect of increasing the overall dexterity of the system, which is the ability to obtain a defined pose of the end-effector with different configurations.

Robots with more than 6 DOFs are defined as being *kinematically redundant*. This redundancy can be usefully applied to improve the dexterity of the end effector.

A robot is then characterized by its *accuracy,* which is defined as the deviation between the obtained and the expected (programmed) position, and its *repeatability*, which is a measure of the manipulator's ability to return to a previously reached position (from the same and from different directions).

The robot repeatability depends not only on the characteristics of its mechanical structure and dimensions but also on the transducers and controller. Typical repeatability values are in the order of few hundred microns, while precision robots have repeatability values up to 5 micrometres.

The *workspace* is generically defined as the 3D space the robot can access (Figure 7.2-4). The *space of movement* is the space achievable by every part of the robot. The *maximum space* is the space of movement and the portion of space achievable by the end effector. The *operating space* is the portion of maximum space reached in a specific task. The *safeguarded space* is the space delimited by physical barriers–to limit potential dangers. The *collaborative workspace* is the workspace within the safeguarded space where the robot and a human can perform tasks simultaneously.

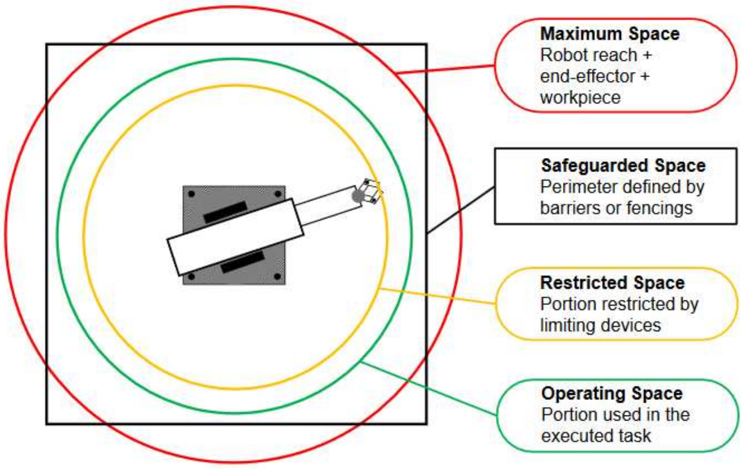


Figure 7.2-4 Working space zones according to the applicable industrial standard for traditional robotics [5]. Image rights: Authors

7.2.2 Mechanical Structures of Industrial Robots

The main categories of mechanical structures of industrial robots are:

- *Cartesian Robots*: Having three prismatic joints (Figure 7.2-2) whose axes are coincident with a Cartesian coordinate system.
- *SCARA (Selective Compliance Assembly Robot Arm) Robots:* Having two parallel rotary joints to provide compliance in a plane.
- *Articulated (or Anthropomorphic) Robots:* Having at least three rotary joints (Figure 7.2-2) placed in series with their interconnecting links.
- *Parallel Robots:* Whose arms have concurrent prismatic or rotary joints.

Each kinematic structure determines the corresponding shape of the workspace. The different industrial robots and their workspaces are illustrated in Figure 7.2-5.

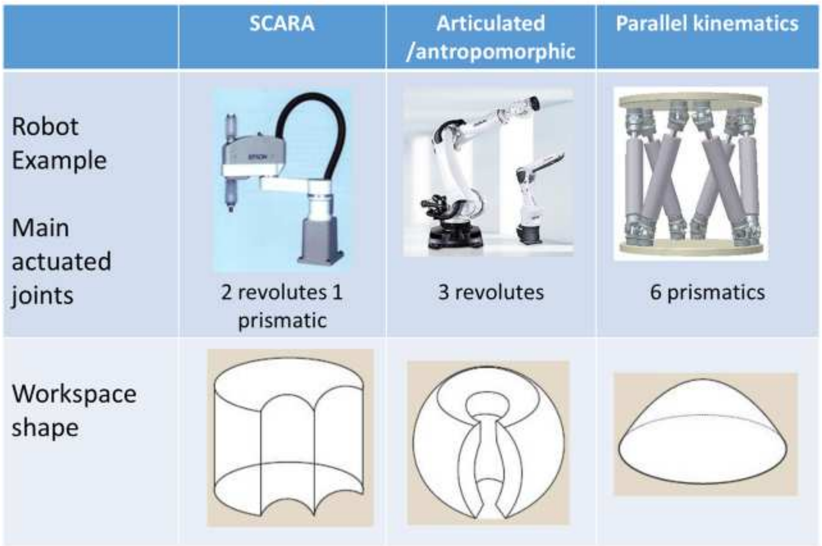


Figure 7.2-5 Main categories of mechanical structures of industrial robots.

The robots of the first three categories (Cartesian, SCARA and articulated) are serial manipulators, because they are realized by connecting several links in series with each one actuated by a rotoidal (revolute) or a prismatic joint. Each joint is actuated by a motor; the term *axis* usually denotes a joint and its actuator (linear or revolute motor). Parallel manipulators are characterized by several links connected in parallel to move the mobile base.

7.2.3 Robot Applications

The different structures of industrial robots are better suited to different tasks:

- *Articulated Robots:* These are used in almost all applications, but they are mostly associated with welding, dispensing and handling applications. Examples of different applications of articulated robots are shown in Figure 7.2-6.
- *Cartesian Robots:* These are mainly employed in plastic moulding, packaging, pick and place operations, and assembly applications. Examples of different applications of Cartesian robots are shown Figure 7.2-7.
- *SCARA Robots:* These are used in assembly and material handling, and also cleanroom applications. Examples of different applications of SCARA robots are shown in Figure 7.2-8.
- *Parallel Robots:* These are typically adopted for handling, packaging, pick and place operations. Examples of different applications of parallel robots are shown in Figure 7.2-8.

Handling for metal casting	**Palletizing**
 [photo courtesy of Global Casting Magazine]	 [photo courtesy of ABB]
Welding	**Painting**
 [photo courtesy of Roboteco S.p.A.]	 [photo courtesy of FANUC]

Figure 7.2-6 Examples of applications of articulated robots. Image rights: Global Casting Magazine, ABB, Roboteco S.p.A., FANUC.

Handling for plastic moulding	Dispensing
	
[photo courtesy of Dürrschmidt GmbH]	[photo courtesy of Steeldot]
Welding	**Pressing**
	
[photo courtesy of R&E Engineering]	[photo courtesy of Güdel Group AG]

Figure 7.2-7 Examples of applications of Cartesian robots. Image rights: Dürrshmidt GmbH, Steel dot, R&E Engineering, Güdel Group AG.

Assembly	Packaging
	
[photo courtesy of Dynamic Automation and Robotics]	[by Hirata Robotics GmbH - Bilder von Hirata Robotics, CC BY-SA 3.0 de]

Figure 7.2-8 Examples of applications of SCARA robots. Image rights: Dynamic Automation and Robotics, Hirata Robotics.

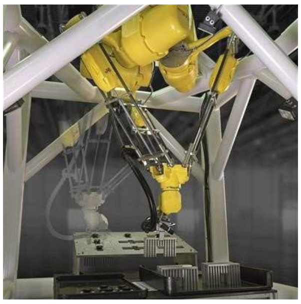
Pick and place operations	Assembly
 [photo by Humanrobo - Own work, CC BY-SA 3.0]	 [photo courtesy of FANUC America]

Figure 7.2-9 Examples of applications of parallel robots. Image rights: Humanrobo, FANUC America.

7.3 Collaborative Robot

The concept of human-centred factories is aimed at combining the new "social expectations on how factories are related to workers and neighbours as a working place and as a dynamic element of the environment" with the idea of a "production system that delivers cost-efficient and flexible manufacturing" [6].

Competences, awareness and individual preferences of the worker are promoted and working environment and equipment accordingly evolve in terms of ergonomics, user-friendliness and integration. On the robotic side, this results in the emergence of *collaborative robots*.

"A collaborative robot is a robot that CAN (capable) be applied for use in a collaborative operation", that is a *"state in which a purposely designed robot system and an operator work within a collaborative workspace"* [7]. By combining the potentialities of human (flexibility, critical thinking) and robots (precision, reliability), new automated production lines can be set up in a wide range of fields. *Human-Robot Collaboration* is driven by some innovative aspects of the smart factories, such as the centrality of human workers and the introduction of the CPPS as more "intelligent" production systems.

Advanced interfaces are enabled by the technological progress in actuators, sensors and control techniques. *Safety* and *ergonomics* are the main issues to consider in the definition of new human-robot interaction models. Analysing these aspects is useful to understand the flexibility introduced in workspace configuration by a "collaborative" approach.

The idea of *cobots* (collaborative robots) was first introduced in the late 1990s into the automotive industry. Nowadays, a wide variety of collaborative robots (Figure 7.3-1) are available on the market, with different features and capabilities, and at affordable prices.

YuMi IRB 14000 (ABB)	Sawyer (HAHN Robotics)
 Multi-purpose end-effector: vacuum and servo grippers, camera. Padded redundant arms. Collaborative assemblies, inspection and packaging. https://new.abb.com/	 Power and force limited compliant arms (elastic actuators, sensors). Force sensors in each joint. Cameras in the wrists and in the head. https://www.rethinkrobotics.com/
E-Series (Universal Robot)	**Aura (Comau)**
 Available in 3 sizes. Touch-screen tablet to set movement options. Programmable by demonstration. Low starting price. https://www.universal-robots.com/	 High payload and fully collaborative. Manual guidance functionality. Collision prevention. https://www.comau.com/
LBR iiwa (KUKA)	**duAro (Kawasaki)**
 Available in 2 sizes. Integrated sensors at each joint for position control and sensitivity. Collision detection control algorithms. Image rights: KUKA AG, https://www.kuka.com/	 Dual-arm SCARA (Articulated Arm in the horizontal plane and end-effector with vertical motion). Easy teaching by demonstration. Extreme repeatability. https://robotics.kawasaki.com/

Figure 7.3-1 Some commercial models of collaborative robots. Image rights: ABB, Rethink Robotics GmbH, University Robots, Comau, Kuka, Kawasaki.

Collaborative robot versatility is achieved thanks to several factors:

- The intrinsic safety facilitates the workcell design and reconfigurability.
- The lightweight robots are characterized by simpler transportation and installation.
- Fast programming methods accelerate task set up.

Collaborative robot flexibility makes them particularly attractive for SME environments, often poorly automatized, to carry out tasks such as fine manipulation and assembly, packaging, manufacturing, pick and place. Due to their easiness of installation and reprogramming, and intrinsic safety, they can be easily moved around the production lines and placed where needed when needed Furthermore, the price of collaborative robots can be conveniently affordable. On the other hand, collaborative robots are often characterized by low repeatability and payloads when compared with traditional industrial robots.

7.3.1 Robotic Devices for Enhancing Workers' Performance

Current developments in the industrial world are characterized by even more synergistic devices: with the innovation introduced by recent industrial trends, exoskeletons for industrial applications have seen a great development in recent years (Figure 7.3-2). They can be classified as follows [9]:

- *Tool Holding Exoskeletons*: These articulated arms are directly supported by a structure that moves with the legs of the wearer, transmitting the weight directly to the ground. In the arms' joints there are springs that make weights lighter to lift and hold, as they are not motorized.
- *Chairless Chairs*: These devices are wearable, compliant with the user's movements. If required, they provide suitable stool-like support.
- *Back Support*: The purpose is to provide a rigid support to the back during the lifting of heavy loads. They can be motorized or not.
- *Powered Gloves*: These gloves are used to enhance the operator grasp by the implementation of auxiliary "muscles".
- *Upper Body Exoskeletons*: Lightweight suites that support the wearer in performing tiresome tasks, sometimes in unnatural positions.
- *Full Body Powered Suits*: The original concept is based on heavy robotic devices. Nowadays, some simplified architectures are available, empowering different part of the body.

Figure 7.3-2 Exoskeletons for industrial use: 1. Fortis by Lockheed Martin Corporation (courtesy of Lockheed Martin), 2. Noonee “Chairless Chair” (courtesy of Noonee), 3. Powered Wear ATOUN MODEL Y (courtesy of ATOUN), 4. BIOSERVO Ironhand powered glove (courtesy of Bioservo Technologies AB), 5. ©EksoVest by Ekso Bionics upper body exoskeleton, 6. MAX© - Modular Agile eXoskeleton by suitX©.

7.3.2 Human-Robot Collaboration Safety

In traditional robotics, the operations of a robot and a human operator can be complementary but not collaborative. A robot working area is limited to a confined workspace with different *working space zones* defined around that workspace, as shown in Figure 7.2-4. On a general basis, a human operator can only access a robot workspace when it is not working.

In cases where human and robot are required to share a working space, the robot has to be in a “safe” mode before the operator accesses the robot working space.

In *collaborative robotic tasks*, the operations of a robot and a human operator are more integrated and they need to become collaborators, moving beyond simple coexistence. The first step towards this goal is the need to share the workspace: the optimal synergy is achieved by working hand in hand. Due to this, *new safety requirements* arise for the design of the production systems, affecting both robotic machines and workspaces.

The ISO TS 15066:2016 “Robots and Robotic Devices – Collaborative Robots” [8] provides a complete and comprehensive guideline for anyone involved in the risk assessments of collaborative robotic operations. The maximum power and speed of collaborative robots are described, as well as the design criteria for the realization of collaborative robots. Although this Technical Specification is not a mandatory standard, the design of collaborative operations is exhaustively detailed, even defining the impact limits for each human body region (Figure 7.3-4).

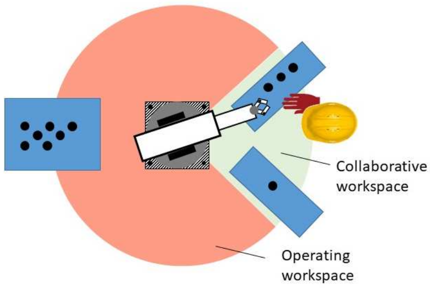


Figure 7.3-3 Workspace sharing in collaborative workcells. The operator can access only the collaborative workspace. Source: Author based on [8].

With reference to the risk assessment described in the standard UNI EN ISO 13849-1 "Safety of Machinery – Safety-related Parts of Control Systems", a simplification of the safety performance level is expected in the design of the safety functions of robot controllers (Figure 7.3-4).

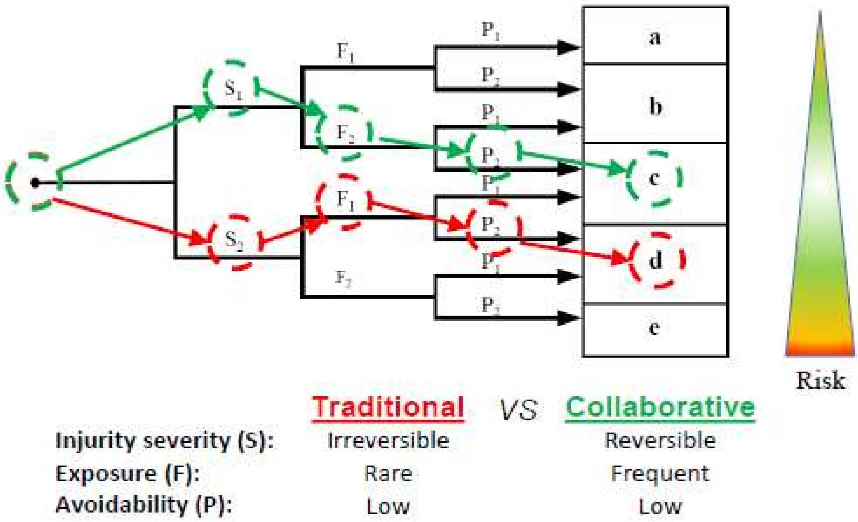


Figure 7.3-4 The Performance Level (PL) of safety functions in control systems is based on the probability of dangerous failure per hour. An example of a comparison between traditional (PL d) and collaborative (PL c) robots from the risk assessment perspective is reported, highlighting the assessment method as per the definition of the applicable standard. *Collaborative robots can be characterized by lower PL, as the intrinsic safety guarantees higher safety levels.*

According to the technical innovations on the robotic side, the role of the human operator changes considering the interaction with the robot and the robot programming. Building on existing standards, ISO TS 15066:2016 “Robots and Robotic Devices – Collaborative Robots” summarizes the types of collaborative robotic operations, defining requirements, safety measures and risk assessment, as illustrated in Figure 7.3-5.

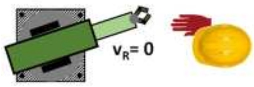
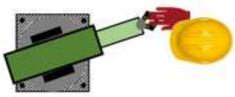
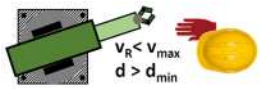
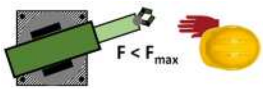
Method	Description	Risk reduction
Safety-rated monitored stop 	The workspace is shared, but simultaneous operation is not allowed.	When the operator is in the work space, the robot stops without interrupting drive power.
Hand guiding 	The end-effector is guided by the operator for collaboration or teaching/programming.	The robot stop and then moves guided in a *safety-rated monitored speed* mode.
Speed and separation monitoring 	The operator and robot can operate simultaneously; the robot is equipped with vision or proximity sensors.	The robot moves with safe dynamics and distance from the operator.
Power and force limiting 	The operator and robot can operate simultaneously; advanced force control strategies are used.	In a collision the robot can transfer a controlled amount of energy or immediately stop.

Figure 7.3-5 Types of collaborative operations.

7.4 Mobile Robots

Logistics in smart factories is usually performed by means of automated guided vehicles (AGVs) that move along predefined paths in the factory plant to transport heavy loads or materials. They are typically equipped with sensors for navigation and collision detection and path planning. The next generation of AGVs is represented by fully autonomous mobile robots, which can autonomously navigate along the production line and interact with machines and operators.

Ideally, it is possible to represent a mobile robot by four subsystems (Figure 7.4-1):

1. *Perception*: This is the ability to measure and perceive either the state of the external environment (by external sensors), or the internal state of the robot (by internal sensors) and to extract information useful to reach the goal.
2. *Information processing*: This is the computation that, using the information acquired by the sensors, determines the operations to be executed. For a mobile robot the most important processes are:
   - *Mapping:* The identification of a map of the environment in which the robot operates.
   - *Localization:* The determination of the robot state.
   - *Navigation:* Definition of the robot path to reach the goal, considering the obstacles in the environment.
   - *Kinematics:* Description of the robot movement, considering any constraints due to the robot's mechanical structure.
   - *Control:* Coordination of the whole process, comprising acquisition, computation and actuation to obtain the goal. The control process can include some input from the operator.
3. *Action*: This is the ability to translate the decisions coming from the control system into operations in the real world. This function is implemented by the actuators installed on the robot itself.
4. *Power Supply*: This system is responsible of energy generation and delivery to the whole system. It is usually supplied by chemical batteries, but other solutions are possible.

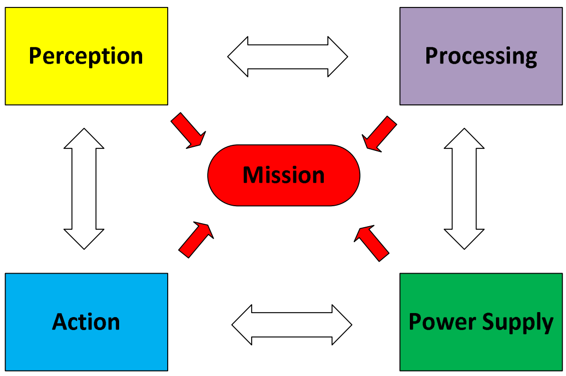


Figure 7.4-1 Conceptual diagram of a mobile robot.

The most ability of a mobile robot is locomotion. Different possibilities arise for how the locomotion [10] is implemented, many of them inspired by the biological world though some of the concepts implemented in nature are difficult to replicate from an engineering point of view.

Figure 7.4-2 divides the mobile robot set in two sub-sets: Wheeled Mobile Robots (WMR) and Not Wheeled Robots.

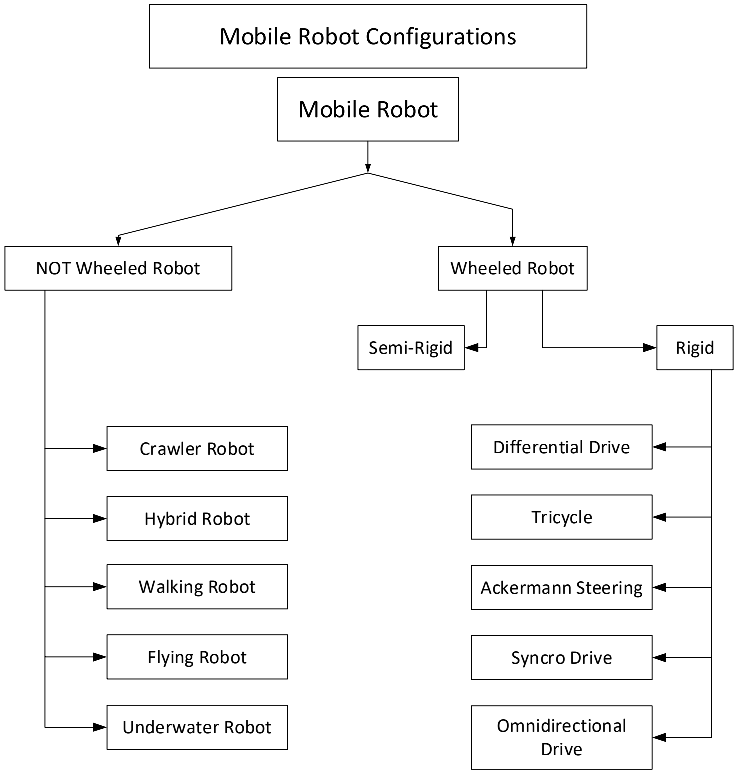


Figure 7.4-2 Classification of Mobile Robots.

7.4.1 Wheeled Mobile Robots (WMR)

Locomotion by wheels is the most used in mobile robotics. Robots equipped with wheels (also called “Rover”) achieve very good power to weight efficiencies. Moreover, their mechanical construction is simple.

WMR are commonly used on flat floors such as found in research laboratories, warehouses, factories, airports, exhibitions and other similar environments (indoor Rover). There are also outdoor applications on rough surfaces with obstacles and subsidence (outdoor Rover).

WRM stability on the ground is assured by using at least three wheels, though there are robots with only two wheels that can be stable under specified conditions.

A WMR is made of a rigid or semi-rigid frame, on which the wheels are installed according specific criteria to make it stable and to guarantee good traction. Each kind of wheel has its specific kinematics (i.e. movement) so the wheel choice influences the WMR whole kinematics.

There are four major wheel classes, as illustrated in Figure 7.4-3**:**

Figure 7.4-3 Wheel classification: (a) standard wheel, (b) Caster wheel, (c) omnidirectional wheel, and (d) spherical (ball) wheel.

- *Standard Wheel:* This can be fixed or steerable. It is the most common wheel used in robotics, and also the simplest from both a mechanical and kinematic point of view. The fixed standard wheel has a rotational axis, through its center and parallel to the ground. The movement of the robot is due to the rotation around this axis (1 degree of freedom). The steerable wheel has the same axis of the fixed wheel for the traction plus a steering axis orthogonal to the first. This steering axis goes through the instantaneous contact point between the wheel and the ground, and to the wheel center. The steerable wheel has a variable orientation with the frame (in total 2 d.o.f.).
- *Caster Wheel*: This is similar to the steerable wheel, the only difference is in the steering axis that does not intersect the horizontal axis, but it passes at a fixed distance. This distance must be considered in the wheel design, because it generates a static torque on the steering axis. In this way the Caster wheel can move in every direction, potentially without sliding. The steering process can be passive or active; in the latter case a steering actuator is needed.
- *Omni-directional Wheel* (also called *Swedish Wheel*): is a particular wheel that can go forward, backward and sideways. It is complex from a mechanical point

of view (so has a high cost), but enables potentially every movement and this is a big advantage in many situations.

- *Spherical Wheel:* This is made using a sphere, without a main rotational axis. The advantage is that it is conceptually simple; the drawbacks are that it has a big volume compared with the payload and the difficulty to actuate it to make a traction wheel.

Different kinds of wheels can be installed on the same robot to exploit the peculiarities of each one of them.

7.4.2 Crawler Mobile Robots (CMR)

WMR have some limitations due to the fact that the ground must be sufficiently flat so that no obstacles prevent the wheels' movement. This is a drawback that does not fit with an increasing number of applications, for example on sandy or rocky ground, big slopes or other planet exploration. For these reasons and in this context CMR are preferred.

Crawlers allow a correct movement of the mobile robot on rough ground, giving better traction and distributing better the pressure due to the weight. On the other hand, crawler mobile robots are slower than WMR and are more energy hungry. Their control is more complex because the point of contact between the crawler and the ground is not well defined and an estimate of their position is necessary to evaluate their movement.

7.4.3 Legged Mobile Robots (LMR)

Legged robots are usually bio-inspired robots. They are used in unstructured environments because they have a great mobility; one typical application is climbing stairs. However, legged robots have a slow speed and relatively high energy consumption. Their mechanical structure is very complex compared with WMR; a legged mobile robot has a high number of links and actuators, so its control is quite difficult.

The number of legs can vary: robots with four legs are called *quadrupeds* and exhibit a very stable and robust locomotion. Using four legs guarantees at least three contact points with the ground at all times; in this way the robot is always in the condition of static equilibrium. The advantage of quadrupeds is that dynamic effects do not affect their gait, so these effects are not considered in the control system, making it simpler with respect to other legged robots with a lower number of legs. To guarantee equilibrium the robot's center of mass has to be inside the projection of the robot on the ground. Moreover, quadrupeds enable dynamic gaits: under certain conditions the number of contact points can be reduced to two or even one. Although more complex, this kind of gait can reach high speed. *Exapods* are legged mobile robots with six legs. Usually the gaits implemented on exapods are only static.

A particular class of legged mobile robot is that of *bipeds*. These robots can implement either static or dynamic gaits[*]. Dynamic gaits are more interesting, because they are more efficient and guarantee higher speed. The advantages of bipeds are:

- The low number of legs imply a lower number of links and actuators.
- They can easily move and work in the same environments designed for humans beings (stairs, lifts, …).
- The interaction can be more friendly due to their humanoid aspect.

Indeed, research on humanoid robots is in progress; and many prototypes have been built, especially from USA (e. g. Boston Dynamics [11]) and Japan (Honda [12]).

7.4.4 Hybrid Mobile Robots

This class of robot is reserved for very special applications, for example planetary exploration or very rough ground, such as steps or surfaces with high slopes. The robots belonging to this class rely on a mixed "wheels-legs" traction system that tries to combine the advantage of both. One of the most famous robots in this class is the NASA All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE,) prototype [13].

The ATHLETE (Figure 7.4-4) vehicle concept is based on six 6 d.o.f. limbs, each with a 1 d.o.f. wheel. ATHLETE uses its wheels for efficient driving over stable, gently rolling terrain, but each limb can also be used as a general purpose leg. In the latter case, wheels can be locked and used as feet to walk out of excessively soft, obstacle laden, steep, or otherwise extreme terrain. ATHLETE is envisioned as a heavy-lift utility vehicle to support human exploration of the lunar surface, useful for unloading bulky cargo from stationary landers and transporting it across long distances.

[*] The word "static gait" is referred to a movement of the robot where the dynamic forces are negligible, so they are not considered into the dynamic model used to control the robot. When these forces are important the movement is classified as "dynamic gait" and these forces must be carefully considered for the motion control of the robot

Figure 7.4-4 The robot ATHLETE, climbing a hill with high slope. Image rights: reproduced courtesy NASA/JPL-Caltech.

Another way to integrate the advantages of legged and wheeled mobile robots are *Whegs* (Wheel + Leg). Wheel+Leg is a mechanism that includes good qualities of both wheels and legs. The result of that is a good passing ability in different terrain including stairs and steps. In the smooth terrain the wheel regime is used. When terrain changes to hardly passable the wheel-leg adjusts itself.

A famous example of robot based on *whegs* is RHex by Boston Dynamics Figure 7.4-5. RHex is an autonomous robot, based on a hexapod with compliant legs and one actuator per leg. It has shown good mobility over a wide range of terrains at speeds of 2.7 m/s, climbs stairs and slopes exceeding 45 degrees and swims [14][15].

Figure 7.4-5 Rhex robot images provided courtesy of Boston Dynamics, Inc. For more information see the video at this link: https://www.bostondynamics.com/rhex. Image rights: Boston Dynamics, Inc.

7.5 Conclusions

The role played by robots in modern manufacturing industry is already essential and forecasted to increase. However, the majority of current industrial robots lack sufficient intelligence and flexibility to accomplish complex tasks. The uncertainties and variables of unstructured environments require sensing and adaptive features not yet fully present in the robots. Industry 4.0 aims at providing the robots with innovative technological features, focusing on safety, flexibility, versatility and collaboration, enabling them to complete tasks intelligently. These innovative concepts will have a huge impact on both processes and business models. Flexibility and reconfigurability will allow the production of small lots, and even single unit, at low price due to the ability to rapidly configure machines and fulfil customer's requests. This will boost innovation since prototypes and several variants can be easily and quickly produced. Innovation will be further promoted by digital integration since modelling and simulation will reduce the time between design and production. Production quality will improve due to the extended sensorization which allows monitoring every product rather than just a few samples. It will not only be errors that can be immediately detected, but also machine malfunctioning, improving also the production efficiency. This new generation of robots is also suitable for smaller companies since the investment is largely repaid thanks to the flexibility and high number of usage options. Overall, thus, Industry 4.0 robotics will increase competitiveness and economic growth.

The next chapter, Chapter 8, will focus on sensors and actuators, providing basic and advanced principles, and introducing the link between physical and cyber world.

Chapter 9 will go deeper into the main concepts of Industry 4.0, considering the software, or cyber, elements, describing the cyber-physical system and some applications. Finally, an overview on Artificial Intelligence and the related ethical issues is presented.

7.6 References

[1] International Organization for Standardization. “ISO 8373: 2012 (en) Robots and robotic devices–Vocabulary”.

[2] IFR World Robotics 2019.

[3] International Organization for Standardization. “EN ISO 10218-1: 2011 Robots and robotic devices — Safety requirements for industrial robots — Part 1: Robots”.

[4] Legnani G. Fassi I. Robotica industriale. Modellazione, pianificazione, controllo, programmazione, componentistica, normativa e sicurezza, Citta Studi edizioni, 2019.

[5] EN ISO 10218-2:2011 - Robots and robotic devices - Safety requirements for industrial robots - Part 2: Robot systems and integration.

[6] J. Lee, S.D. Noh, H.J. Kim, and Y.S. Kang, “Implementation of cyber-physical production systems for quality prediction and operation control in metal casting”, *Sensors*, *18* (5), p.1428, 2018.

[7] https://ec.europa.eu/assets/jrc/ilv/edge/pcs/index-63.html.

[8] ISO/TS 15066:2016 – Robots and robotic devices – Collaborative robots (Technical specification).

[9] https://exoskeletonreport.com/2016/04/exoskeletons-for-industry-and-work/

[10] Roland Siegwart, Illah R. Nourbakhsh, Davide Scaramuzza – Introduction to Autonomous Mobile Robots – Second Edition, The MIT press, ISBN 978-0-262-01535-6, 2011.

[11] https://www.bostondynamics.com/ [Accessed 16 07 2019]

[12] https://it.wikipedia.org/wiki/ASIMO [Accessed 16 07 2019]

[13] https://www-robotics.jpl.nasa.gov/systems/system.cfm?System=11 [Accessed 16 07 2019]

[14] https://en.wikipedia.org/wiki/Rhex [Accessed 16 07 2019]

[15] https://www.bostondynamics.com/rhex [Accessed 16 07 2019]

“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