INDUSTRIAL ROBOTICS
Robotics and Automation

Claudio Melchiorri

Dipartimento di Ingegneria dell’Energia Elettrica e dell’Informazione (DEI)
Università di Bologna
Email: claudio.melchiorri@unibo.it
Industrial Automation and Robotics

In the 60’s:
Automation processes are introduced in different sectors of industrial production.

Industrial Automation:
Use of mechanical, electronic and information technologies for control, management and production in the industrial environment.

Examples of industrial automation systems:
• Process control
• Numerical control machines (CNC)
• Assembly machines
• Robots
• Automatic warehouses
• Automatic systems for supervision
• CAD tools
• …

Robots are an example of industrial automation systems!
Industrial Automation and Robotics

**Industrial Automation processes**

- Rigid automation systems
- Flexible automation systems
- Programmable automation systems

![Graph showing Industrial Automation processes](image-url)
Industrial Automation and Robotics

**Rigid automation systems**
- High production volumes of single products
- High production speed (# / hour)
- Specialized productions, with dedicated machines

**Main characteristics of rigid automation machineries:**
- Mechanical architectures optimized for the execution of a single task (time reduction)
- Dedicated control systems e.g. PLC, with low flexibility (non necessary)

**Examples**
- Continuous production processes (chemicals, textile, …)
- High numbers of products (tiles, cigarettes, beverages, …)
- Pharmaceutical
- Food
- …
Flexible automation

• Starts in the ‘80s, due to the growth of consumerism with diversification and personalization of products
• Need of machinery able to be adapted easily (both mechanically and electronically) to “different” products
• Design of machines whose cost is justified by the “flexibility” of tasks they can perform

• FMS: Flexible Manufacturing System

• CIM: Computer Integrated Manufacturing
Programmable automation

- Characterized by many products, each of them with relatively small production volumes.

- Needs:
  - Differentiation of the production/work capabilities
  - Possibility of easy re-programming
  - Reduced periods for changing products
Robots:
The International Organization for Standardization gives a definition of a manipulating industrial robot in IOS 8373:

“An automatically controlled, reprogrammable, multipurpose, manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications.”

This definition is used by the International Federation of Robotics, the European Robotics Research Network (EURON) and many national standards committees.

Robotics:
• Mainly used in flexible and programmable automation
Sales down in 2009
In 2009, the worldwide economic and financial crisis caused a significant slump in the sales of industrial robots. Compared to 2008, considered one of the most successful years, 2009 had a decline of 47% (60,000 units). This is the lowest level reported since 1994.
Diffusion of industrial robots

- In 2009, the **automotive industry** accounted for 36% of the total year’s supply.
- In the **electrical/electronics industry** Worldwide in 2009, the robot investments were down by 34% to 10,855 units accounting for a share of 18%.
- The **rubber and plastics industry** reduced robot investments in 2008 and 2009 from the peak level of about 15,000 units to 5,800 units, accounting for a share of 10% of the total supply in 2009. Robot supplies to the pharmaceuticals and cosmetics industry were growing up to 2008. In 2009, the robot sales only slightly decreased to 1,044 units.
- The **food and beverage industry** decreased robot orders by 10% to almost 3,300 units, accounting for a share of 5% of the total supply. About 60% of the worldwide sales to this industry were made in Europe.
- Sales to the **metal and machinery industry** dropped by 64% to 5,253 units and a share of 9% of the total supply in 2009. Until 2008, robots supplies to the metal and machinery industry as well as to the food and beverage industry were continuously growing.
Diffusion of industrial robots

Operational stock of industrial robots decreased in 2009

Total accumulated yearly sales, measured since the introduction of industrial robots in industry at the end of the 1960s, amounted to more than 2,230,000 units at the end of 2009. This includes, as mentioned before, the dedicated industrial robots installed in Japan up to and including 2000. Many of the early robots, however, have by now been taken out of service. The stock of industrial robots in actual operation is therefore lower. IFR estimates:

the total worldwide stock of operational industrial robots at the end of 2009 was in the range of 1,021,000 and 1,300,000 units.

The minimum figure above is based on the assumption that the average length of service life is 12 years. A UNECE/IFR pilot study has indicated that the average service life might in fact be as long as 15 years, which would then result in a worldwide stock of 1,300,000 units.

After the substantial rise of robot sales in 2010, a further increase will resume in the period between 2011 and 2013 about 10% per year on average attaining a level of more than 100,000 units.

In the Americas sales will be up by 33% in 2010, in Asia/Australia by 34% and in Europe by 12%. Between 2011 and 2013, robot shipments will increase by about 9% per year on average in the Americas, about 12% in Asia/Australia and by 8% in Europe.

Source: 2010 World Robotics Executive Summary
## Diffusion of industrial robots

<table>
<thead>
<tr>
<th>Country</th>
<th>Yearly installations</th>
<th>Operational stock at year-end</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>America</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North America</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Canada, Mexico, USA)</td>
<td>8,417</td>
<td>11,000</td>
</tr>
<tr>
<td>Central and South America</td>
<td>500</td>
<td>900</td>
</tr>
<tr>
<td>Asia/Australia</td>
<td>30,117</td>
<td>40,500</td>
</tr>
<tr>
<td>China</td>
<td>5,525</td>
<td>8,500</td>
</tr>
<tr>
<td>India</td>
<td>363</td>
<td>600</td>
</tr>
<tr>
<td>Japan</td>
<td>12,767</td>
<td>17,000</td>
</tr>
<tr>
<td>Republic of Korea</td>
<td>7,839</td>
<td>9,800</td>
</tr>
<tr>
<td>Taiwan</td>
<td>1,474</td>
<td>2,000</td>
</tr>
<tr>
<td>Thailand</td>
<td>774</td>
<td>1,000</td>
</tr>
<tr>
<td>Other Asia</td>
<td>866</td>
<td>1,600</td>
</tr>
<tr>
<td>Australia/New Zealand</td>
<td>509</td>
<td></td>
</tr>
<tr>
<td><strong>Europe</strong></td>
<td>20,483</td>
<td>23,000</td>
</tr>
<tr>
<td>Benelux</td>
<td>1,286</td>
<td></td>
</tr>
<tr>
<td>France</td>
<td>1,450</td>
<td>1,700</td>
</tr>
<tr>
<td>Germany</td>
<td>8,507</td>
<td>10,000</td>
</tr>
<tr>
<td>Italy</td>
<td>2,883</td>
<td>2,900</td>
</tr>
<tr>
<td>Spain</td>
<td>1,348</td>
<td>1,500</td>
</tr>
<tr>
<td>Sweden</td>
<td>587</td>
<td></td>
</tr>
<tr>
<td>United Kingdom</td>
<td>635</td>
<td>650</td>
</tr>
<tr>
<td>Central/Eastern European countries</td>
<td>1,448</td>
<td></td>
</tr>
<tr>
<td>other Europe</td>
<td>2,339</td>
<td>6,250</td>
</tr>
<tr>
<td>Africa</td>
<td>196</td>
<td>300</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>60,018</td>
<td>76,000</td>
</tr>
</tbody>
</table>

Source: IFR, national robot associations
Diffusion of industrial robots

- Production of robots:
  - *Increasing number* of robots
  - *Decreasing number* of robot producers

- From the ‘80s to the ’90s -> reduction to 1/3 of the robot producers (worldwide)

- Robotics: *a difficult technology*
  - Integration of several competencies
  - Installation in VERY diversified environments
  - Often lack of local technical competencies to use the robots

- Very common: industries specialized in design/realization of *production plants* (workcells)
Workcells:
A robot is always used in cooperation with other machinery. These machines together form a workcell. A workcell must be designed in order to be efficient and to maximize the production.

1 - Workcells with a central robot
The robot is placed centrally, and its main task is to load/unload the surrounding machines.

2 - Production line
Robots are placed along a production line. Products are transported by the line and robots execute the programmed tasks (assembly, direct operations, …).

3 - Workcells with a mobile robot
The robot is placed on a mobile platform; it is moved in different positions of the workcell to execute the programmed activities. The robot can operate with many machineries.
Robot workcells

Workcells with a central robot:
The robot is placed centrally, and its main task is to load/unload the surrounding machines.
Robot workcells

**Production line:**
Robots are placed along a production line. Products are transported by the line and robots execute the programmed tasks (assembly, direct operations, …)
Robot workcells

**Workcells with a mobile robot:**
The robot is placed on a mobile platform, and is moved in different positions of the workcell to execute the programmed activities. The robot can operate with many machineries.
ROBOT – Device composed by:

- A mechanical part, the manipulator, with different complexity and kinematic configurations
- A system for programming and control the manipulator and other devices
Structure and components of an industrial robot

Control System

Context:

- Complex mechanical part
- Requested high performance
- Different typology of applications.

The control system of an industrial robot is a quite complex device, in general composed by a multi-processor system, connected to other local devices for controlling, monitoring and data storage purposes.

The main functions of a robot controller are:

- User interface,
- Data storage,
- Motion planning,
- Real-time control of joints’ motion,
- Sensor data acquisition,
- Interaction and synchronization with other machines,
- Interaction with other computational resources.
**The manipulation system**

Manipulator:
- Chain of rigid bodies: *links*
- Actuated connections: *joints*

An extremity of the manipulator, the **BASE**, can be either fixed in the work environment or placed on a mobile platform.

On the other extremity, the manipulator is equipped with a tool used to execute the desired operations, the **END-EFFECTOR**:  
- gripper,  
- specific tool.

The end-effector is placed in the work space by the manipulator. It is mechanically coupled to the **WRIST**, a mechanical device able to assign an arbitrarily orientation to the end-effector.
Structure and components of an industrial robot

Joints

Two kinds of joints are considered:

- **Prismatic joint**: translation (linear) motion ("T" joint)
- **Rotational joint**: rotational motion ("R" joint)

More complex joints, such as spherical or helicoidal joints, can be considered as proper combination of prismatic and rotational joints.
Structure and components of an industrial robot

Main geometrical configurations of industrial robots

• Different types of geometric configurations can be adopted in an industrial robot. Among the most common ones:
  • Polar configuration,
  • Cylindrical configuration,
  • Cartesian configuration,
  • Anthropomorphic configuration,
  • SCARA.
Geometric structure of a robot

- Polar
- Cartesian
- Cylindrical
- Anthropomorphic

SCARA:
Selective Compliance Arm for Robotic Assembly
Geometric structure of a robot

- These configurations refer to robots with open-chain structures.
- Other kinematic solutions exist, based on closed kinematic chains (parallel robots).

+ higher velocities
+ higher precision
+ higher “force”

- reduced workspace
- increased space occupation (footprint)

Example: ABB Picker: 150 cycles/min => 0.4 sec per cycle!
Comparison criteria for robots

Comparison of robots

Each configuration has peculiar advantages/disadvantages:

• A Cartesian structure is both intrinsically robust (suitable for applications with high payloads) and with good repeatability properties (capability of repositioning).

• Also the cylindrical configuration is quite “robust” and suitable for high payloads.

• Polar and cylindrical configurations can be used for loading/unloading operations, where it may be important for the gripper to enter in restricted areas without generating mechanical interferences.

• The anthropomorphic and polar configurations are able to reach objects located “far” from their basis.
### Comparison of robots

#### Some criteria

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Robustness</th>
<th>Repeatability</th>
<th>Encumbrance</th>
<th>Dexterity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polar Configuration</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Cylindrical Configuration</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Cartesian Configuration</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anthropomorphic Configuration</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
Comparison criteria for robots

Other criteria

• **Workspace:**
  - Volume (set of points) reachable by the manipulator.
  - It depends on: the kinematic configuration, the links’ dimension, the joints’ range of motion
  - Sometimes, the workspace is defined as the set of points reachable by the manipulator without loosing the capability of assuming any orientation in space.
Comparison criteria for robots

Other criteria

• Workspace:

<table>
<thead>
<tr>
<th></th>
<th>IRB 4400</th>
<th>IRB 4400L</th>
<th>IRB 4400FS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load (kg)</td>
<td>IRB 4400/45/60: 45/60</td>
<td>IRB 4400L/10/30: 10/30</td>
<td>IRB 4400FS: 30</td>
</tr>
<tr>
<td>Reach (m)</td>
<td>1.95</td>
<td>2.55/2.43</td>
<td>2.43</td>
</tr>
<tr>
<td>Repeatability (mm)*</td>
<td>0.07</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Foundry Plus version available of IRB 4400L/30

<table>
<thead>
<tr>
<th></th>
<th>IRB 640</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load (kg)</td>
<td>160</td>
</tr>
<tr>
<td>Reach (m)</td>
<td>2.9</td>
</tr>
<tr>
<td>Repeatability (mm)*</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Comparison criteria for robots

Other criteria

• **Payload:**
  Total weight (i.e. end-effector AND carried object) that can be moved by the manipulator without relevant effects on performance (precision)

• From few to many hundreds of kilos (5 – 500 and more)....
Comparison criteria for robots

Other criteria

Precision and Repeatability

- **Precision**: capability of reaching a predefined point in space with a negligible error

- **Repeatability**: capability of repeating many times the same movement (i.e. reaching the same point) with a minimum error

- These quantities are defined with respect to the worst case (in terms of configuration)

- Repeatability is more important: precision errors can be easily compensated for during the programming phase.
Comparison criteria for robots

- Low precision, low repeatability
- Low precision, high repeatability
- High precision, low repeatability
- High precision, high repeatability
Comparison criteria for robots

Resolution

Amplitude $r$ of the minimum possible displacement, very important in precision tasks such as assembly or manipulation.

Precision: $p = r/2$
Joints

Different joints

Two kinds of joints are considered:

- **Prismatic joint**: translation (linear) motion (“T” joint)
- **Rotational joint**: rotational motion (“R” joint)

More complex joints, such as spherical or helicoidal joints, can be considered as proper combination of prismatic and rotational joints.
Joints

(a) RRT

(b) RTT

(c) TTT

(d) RRR
Degrees of Freedom

Degrees of Freedom of a manipulator

- **Degrees of Freedom (dof):** number of actuated joints in an manipulator. If a manipulator has \( n \) actuated joints, it has \( n \) dof.

- The number \( n \) of joint variables is not fixed; the dimension \( m \) of the workspace is in any case less or equal to 6.

- Frequently \( m = n \), i.e. the manipulator has as many dof as the dimension of the workspace. For industrial manipulators, often \( m = n = 6 \).

- **Defective manipulators:** \( n < m \), e.g. \( n = 4, 5 \) and \( m = 6 \). It is not possible to execute all the possible tasks in the workspace, but only those defined in a proper subspace (e.g. SCARA).

- **Redundant manipulators:** \( n > m \), for example \( n = 7, 8 \), and \( m = 6 \). A given task can be executed in infinite different manners.
Degrees of Freedom

Degrees of Freedom of a manipulator

- **Defective manipulators:** $n < m$, e.g. $n = 4, 5$ and $m = 6$. It is not possible to execute all the possible tasks in the workspace, but only those defined in a proper subspace (e.g. SCARA).

- **Redundant manipulators:** $n > m$, for example $n = 7, 8$, and $m = 6$. A given task can be executed in infinite different manners.
End-Effectors

• Manipulators interact with the environment through the end-effector. Some examples:
  • Grasp objects
  • Welding
  • Painting
  • Part assembly.

• The end-effector is one of the most important and complex parts of industrial robots, limiting its diffusion in many applications in industrial and social applications.

• The great flexibility of a robot arm is not present in the end-effectors, usually a very specialized device able to execute only few tasks, with limited sensoriality and with simple kinematic configuration.
End-Effectors

• Since the EE is a specialized device, it must be possible to change it in a simple manner if it is needed by the application. Sometimes, more EEs are available in a repository reachable by the robot, which automatically changes EE to execute different phases of a given task.

• Even restricting the interest to grippers, devices used to grasp objects, many different configurations and systems are available since these are usually designed on the basis of the objects to be grasped
  • 2/3-fingered grippers
  • Inner/outer grasps
  • Gripper for little/large/cylindrical/flat/... objects
  • Sucking grippers
  • Magnetic grippers
  • ...
Wrist

- The wrist is connected to the extremity of the arm to orient the end-effector in the workspace.

- It has at least three rotational dof.

- Many kinds of wrists are commercially available: different in terms of number of dof and their kinematic configuration.

  - **Singular configurations.** Configurations in which it is not possible to orient the EE along a particular direction.

    - In a singular configuration, it is not possible to move the EE along (at least) a particular direction.

    - This problem may be solved by using a wrist with more dof, and exploiting the redundancy to avoid the singular configurations.

    - In this manner the singularities may be avoided and it is possible to execute any task.
Actuators

• Three types of actuators are used in robotics:
  • Electric (DC motors, step, brushless, ... > 50%),
  • Hydraulic (~ 35%),
  • Pneumatic (also in grippers and end effectors, ~ 15%).

• Electric actuators:
  ✦ High speed and precision;
  ✦ Easy to be controlled;
  ✦ High diffusion, relatively low cost;
  ✦ Simple to be used;
  ✦ Small dimensions;

  – Reduction gears (increased cost & size);
  – Non linear effects (backslash, dead zones, ...) due to reduction gears
  – Not enough power for particular applications
Actuators

• **Hydraulic actuators:**
  ✤ High power
  ✤ High speeds
  ✤ Once in position, the configuration is maintained thanks to the oil
  ✤ Quite easy to be controlled
  
  - Relatively high costs for small dimensions
  - Noise and oil leakages
  - More space needed.

• **Pneumatic actuators:**
  ✤ Relatively low cost
  ✤ High velocity
  
  - Low accuracy (air is compressed)
  - Noisy
  - Leakages
  - Need of special filters for air
  - Additional maintenance required.
Sensors

• Important and technologically complex part of a robot.

• Main types of sensors:
  • **Proprioceptive sensors:** measure data “internal” to the robot (joint positions or velocities, joint torques).
    • resolver,
    • encoder,
    • syncros,
    • three- or six-axes force sensors (forces and forces/torques).
  
  • **Exteroceptive sensors:** measure/characterize robot interaction with the environment, enhancing its autonomy (forces/torques, proximity, vision, but also sensors for sound, smoke, humidity...)
Exteroceptive sensors

- Four main families
  - Tactile sensors,
  - Proximity/distance sensors,
  - Vision,
  - Other.....
Selection of robots

• Two phases:
  • Choice of the application,
  • Choice of the robot typology.

• Choice of application:
  • Technical feasibility,
  • Economic considerations.

• Some possible criteria (in general):
  • Simple and repetitive operation,
  • Cycle time compatible with robots (e.g. > 5 sec),
  • Parts to be manipulated can be disposed in a proper order,
  • Limited weight,
  • No inspection is required during task execution.