Industrial Robotics

Prof. Alessandro De Luca
What is a robot?

- **Industrial definition (RIA = Robotic Institute of America)**
  
  re-programmable multi-functional manipulator
  designed to move materials, parts, tools, or specialized devices through
  variable programmed motions for the performance of a variety of tasks,
  which also **acquire information from the environment**
  and move intelligently in response

- **ISO 8373:2012 definition**
  
  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

- more **“visionary”** definition
  
  **intelligent** connection between **perception** and **action**
Robots!!

Comau H4 (1995)

Waseda WAM-8 (1984)

Spirit Rover (2002)
A bit of history

- **Robota** (= “work” in slavic languages) are artificial human-like creatures built for being inexpensive workers in the theater play *Rossum’s Universal Robots (R.U.R.)* written by Karel Capek in 1920

- **Laws of Robotics** by Isaac Asimov in *I, Robot* (1950)
  1. **A robot may not injure a human being** or, through inaction, allow a human being to come to harm
  2. **A robot must obey orders given to it by human beings**, except where such orders would conflict with the First Law
  3. **A robot must protect its own existence** as long as such protection does not conflict with the First or Second Law
Evolution toward industrial robots

- with respect to the ancestors
  - flexibility of use
  - adaptability to a priori unknown conditions
  - accuracy in positioning
  - repeatability of operation

~ 1950

computer numerically controlled (CNC) machines

~ 1970

robot manipulators

Unimation PUMA

mechanical telemanipulators
The first industrial robot

US Patent

General Motor plant, 1961

G. Devol and J. Engelberger (Unimation)
Historical pictures and clips

- Bimanual remote manipulation at Oak Ridge Nat’l Labs
- Unimate 6-dof robots

Video
Robot manipulators

ASEA IRB-6 (1973) first robot all-electric-drives

Hirata AR-300 (1978) first SCARA robot

Cincinnati Milacron T3 (1974) first micro-computer controlled robot

Unimation PUMA 560 (1979) 6R with human-like dexterity
robots – a 50-year journey
robotics research up to 2000

Video compiled for the IEEE ICRA 2000 conference, S. Francisco
World Robotics 2022

executive summary for **2022**
statistics by IFR
issued yearly in early October
(for back issues since 2007, check course web site)

- total worldwide stock at end 2021: **3.5 million units** of operational industrial robots (+15% w.r.t. 2020, +14% CAGR in 2016-21)
- new robot sales in 2021: **517K** (+31%, highest number ever, +11% CAGR)
- strong recovery after two pandemic years, expected to leverage in next future
- robot market value in 2021: **$15.7 billion** (without software and peripherals); robotic systems market value: ~4 times as much
- **China** expanded further as the largest market since 2013, now with a **52%** share
- **78%** of new robot installations in **5 countries**: China, Japan, USA, Korea, Germany

Compound Annual Growth Rate: \( \text{CAGR} = \left( \frac{V_{\text{end}}}{V_{\text{begin}}} \right)^{1/\text{years}} - 1 \)
Diffusion
industrial robots in operation worldwide

Operational stock of industrial robots - World
1,000 units

~3.5 M robots in operation

length of robot service life is estimated in 12-15 years
Annual supply
new industrial robots worldwide

Annual installations of industrial robots - World
1,000 units

year of highest ever selling of new robots

stop of growth rate in 2019: automotive transition, trade & political headwinds
... and in 2020: deferred investments, plummeted consumer demand, travel restrictions, disrupted supply chains (due also to Covid-19)
Annual supply of industrial robots by world area

**Strong recovery in all regions**

*Source: International Federation of Robotics*
Diffusion of robots in industrial sectors [as of 2019]

### Operational stock of industrial robots by customer industry - World

<table>
<thead>
<tr>
<th>Industry</th>
<th>2019</th>
<th>2018</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automotive</td>
<td>923</td>
<td>847</td>
<td>762</td>
</tr>
<tr>
<td>Electrical/electronics</td>
<td>672</td>
<td>597</td>
<td>509</td>
</tr>
<tr>
<td>Metal and machinery</td>
<td>281</td>
<td>248</td>
<td>216</td>
</tr>
<tr>
<td>Plastic and chemical products</td>
<td>182</td>
<td>176</td>
<td>171</td>
</tr>
<tr>
<td>Food</td>
<td>174</td>
<td>149</td>
<td>121</td>
</tr>
<tr>
<td>All others</td>
<td>410</td>
<td>349</td>
<td>282</td>
</tr>
<tr>
<td>Unspecified</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: World Robotics 2020

70% of robots were deployed in three main industries
Annual supply
new robots by industrial sectors

Electrical/electronics: 137 (110 in 2020, 89 in 2019), +24%
Automotive: 119 (84 in 2020, 102 in 2019), +42%
Metal and machinery: 102 (64 in 2020, 52 in 2019), +45%
Plastic and chemical products: 52 (24 in 2020, 19 in 2019), +29%
Food: 52 (18 in 2020, 11 in 2019), +18%
All others: 37 (30 in 2020, 87 in 2019)
Unspecified: 87 (87 in 2020, 87 in 2019)

Source: World Robotics 2022

electronics is now the major of customer of robots (surpassing automotive)
almost 70% of robots were used for material handling or welding
Annual supply
new robots by main application

Material handling is the most important with a 44% share
Annual supply
new installations in China/Rest of World

China now installs more industrial robots per year than the rest of the world taken together

Annual installations of industrial robots
(‘000 of units)

Source: International Federation of Robotics

- China
- Rest of World

<table>
<thead>
<tr>
<th>Year</th>
<th>China</th>
<th>Rest of World</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>97</td>
<td>207</td>
</tr>
<tr>
<td>2017</td>
<td>156</td>
<td>243</td>
</tr>
<tr>
<td>2018</td>
<td>155</td>
<td>268</td>
</tr>
<tr>
<td>2019</td>
<td>148</td>
<td>243</td>
</tr>
<tr>
<td>2020</td>
<td>178</td>
<td>216</td>
</tr>
<tr>
<td>2021</td>
<td>249</td>
<td>268</td>
</tr>
</tbody>
</table>
Annual supply
new installations in top markets (countries)

### Annual installations of industrial robots
15 largest markets 2021

<table>
<thead>
<tr>
<th>Country</th>
<th>Number</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>268.2</td>
<td>+51%</td>
</tr>
<tr>
<td>Japan</td>
<td>47.2</td>
<td>+22%</td>
</tr>
<tr>
<td>United States</td>
<td>35.0</td>
<td>+14%</td>
</tr>
<tr>
<td>Rep. of Korea</td>
<td>31.1</td>
<td>+2%</td>
</tr>
<tr>
<td>Germany</td>
<td>23.8</td>
<td>+6%</td>
</tr>
<tr>
<td>Italy</td>
<td>14.1</td>
<td>+65%</td>
</tr>
<tr>
<td>Chinese Taipei</td>
<td>9.6</td>
<td>+31%</td>
</tr>
<tr>
<td>France</td>
<td>5.9</td>
<td>+11%</td>
</tr>
<tr>
<td>Mexico</td>
<td>5.4</td>
<td>+61%</td>
</tr>
<tr>
<td>India</td>
<td>4.9</td>
<td>+54%</td>
</tr>
<tr>
<td>Canada</td>
<td>4.3</td>
<td>+66%</td>
</tr>
<tr>
<td>Thailand</td>
<td>3.9</td>
<td>+36%</td>
</tr>
<tr>
<td>Singapore</td>
<td>3.5</td>
<td>-35%</td>
</tr>
<tr>
<td>Spain</td>
<td>3.4</td>
<td>+1%</td>
</tr>
<tr>
<td>Poland</td>
<td>3.3</td>
<td>+56%</td>
</tr>
</tbody>
</table>

Source: World Robotics 2022

**Italy (2nd EU market): three times as many new robots installed as in 2015**
Density of robots [as of 2019]

Almost doubled w.r.t. the previous 5 years in 2021, an average of 126 robots

Number of robots per 10,000 employees in the manufacturing industry

Source: International Federation of Robotics
Collaborative robots

Collaborative and traditional industrial robots (annual installations)

- 2017: 389,000 (Traditional) + 11,000 (Collaborative)
- 2018: 405,000 (Traditional) + 19,000 (Collaborative)
- 2019: 370,000 (Traditional) + 21,000 (Collaborative)
- 2020*: 368,000 (Traditional) + 26,000 (Collaborative)
- 2021: 478,000 (Traditional) + 39,000 (Collaborative)

* projected

Source: World Robotics 2022

a smaller but steadily growing market share in industrial setting
Industrial & service robots

**Industrial robots**
- automatically controlled, programmable, multipurpose, 3+ axes
- for use in industrial automation applications
- equipped with application-specific end-effectors

**Service robots**
- perform tasks excluding industrial automation
- usually application-specific design, often fewer than 3 axes
- sometimes not fully autonomous but remote-controlled

... but separation line is blurring: same unit can act as both, depending on the application

different customers, pricing, machinery, distribution channels, suppliers
Professional service robots

new professional service robots in 2021: **121K units** (+37%)

... compare with new personal/domestic service robots: **19M units!!** (+9%)
Professional service robots

Service robots for professional use. Top 5 applications
Unit sales 2020 and 2021
000 of units

Transportation and logistics AP5
Hospitality AP8
Medical robotics AP6
Professional cleaning AP2
Agriculture AP1

Source: World Robotics 2022
Professional service robots

- more than 1000 service robot suppliers worldwide
- 80% of service robot suppliers are SMEs
- start-ups becoming mature
Industrial robot and its auxiliary equipments

1. Comau SMART H robot
2. C3G Plus controller
3. Welding control box
4. Application software
5. Air/water supply
6. SWIM Board
7. Integrated cables
8. Welding gun
9. Auxiliary devices in the robotic cell (servo-controlled axes)

SWIM = Spot Welding Integrated Module
commercial video by ABB
Industrial applications

- manipulation (pick-and-place, handling, machine feeding)
- assembly and packaging
- spray painting and coating (nozzles)
- arc welding or spot welding (with pneumatic or servo-controlled guns)
- laser cutting and welding
- gluing and sealing
- mechanical machining operations (milling, drilling, deburring, grinding, ...)

video
A day in the life of an industrial robot

• At BMW car production line with ABB robots

pick-and-place with end-effector to reorient part

pick-and-place with support to reorient part
A day in the life of an industrial robot

pick-and-place heavy parts and human intervention

metal cutting on a supporting machine with dofs
(video speeded up at some point)
A day in the life of an industrial robot

- glue deposit (on fancy paths!)

- cooperation of multiple robots for handling and inspecting/sealing a car body

video

video
A day in the life of an industrial robot

coating parts for rust and corrosion protection

spray painting
A day in the life of an industrial robot

- hood deburring with a suspended tool
- test measurements with assembly on a AGV
What a robot should do and what cannot do

- spray painting very unhealthy for human operators
- assembly of flexible or complex parts (here a car dashboard)

⇒ human-robot collaboration (co-bots or co-workers)
Plasma cutting

small KUKA robot used for plasma cutting of a stainless steel toilet
(courtesy of Engenious Solutions Pty)
Robotized workcells
3D simulation of robotic tasks

- analysis of operative cycle times
- off-line programming and optimization
- layout design and collision checking
- 3D graphic simulation
Welding - 1

- spot with servo-controlled gun
- stud welding
Welding - 2

- spot (discrete) or arc (continuous)
Two cooperating robots in arc welding

ABB video at Laxa, Sweden
Palletizing

pallet = a portable platform on which goods can be moved, stacked, and stored
Palletizing of cheese forms using Kawasaki robots (courtesy of Effedue Engineering)
Folding

with loading of sheets under the press
Deburring

- car windshields may have large manufacturing tolerances and a sharp contour profile
- the robot follows a given predefined Cartesian path
- the contact force between cutting blade and glass must be feedback controlled
- deburring robot head mounts a force load cell and is pneumatically actuated
Deburring center

deburring center for steel parts using Comau SMART NJ 110-3.0/foundry robot (courtesy of Adami srl)

video

www.adamisrl.com
Off-line robot workstation

articulated robot in metal surface finishing operation
Safety in robotic cells

commercial video from ABB
SafeMove (2008) cell monitoring system: no fences!
Robot manipulator kinematics

- **Kuka 150_2 S2000**
  - Open kinematic chain
  - (series of rigid bodies connected by joints)

- **Comau Smart H4**
  - Closed kinematic chain

- **Fanuc F-200iB**
  - Parallel kinematics
SCARA-type robots

SCARA (Selective Compliant Arm for Robotic Assembly)

- 4 degrees of freedom (= joints): 3 revolute + 1 prismatic (vertical) axes
- compliant in horizontal plane for micro-assembly and pick-and-place

Mitsubishi RP
(repeatability 5 micron, payload 5 kg)

Mitsubishi RH
(workspace 850 mm, velocity 5 m/s)

Bosch Turbo

Robotic 1
Adept Cobra i600

fastest SCARA robot for pick-and-place tasks!
Other types of robots

Comau Mast gantry robot
3P linear/prismatic joints with 3R spherical wrist payload up to 560 kg

ABB 340 Flexpicker
4 DOFs Delta parallel kinematics
1-2 kg payload, max speed 19 m/s
150 pick-and-place ops/minute

Delta in motion (https://link to web)

Delta robots are replacing SCARA-type robots for planar pick-and-place and assembly tasks
Chocolate packaging with lightweight parallel robots

test video with ABB Flexpicker

video with Adept Quatro s650
Distribution by robot type [in 2004]

of kinematic configuration

for 59600 articulated robots installed back in 2004
(90% of all robots installed in America, 74% in Europe, only 49% in Asia)
**Fanuc R-2000i/165F**

### Specifiche tecniche

<table>
<thead>
<tr>
<th>Voce</th>
<th>R-2000i/165F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tipo</td>
<td>Articolato</td>
</tr>
<tr>
<td>Assi controllati</td>
<td>6 assi (J1, J2, J3, J4, J5, J6)</td>
</tr>
<tr>
<td>Installazione</td>
<td>A pavimento</td>
</tr>
</tbody>
</table>

#### Area di lavoro (Velocità massima)

<table>
<thead>
<tr>
<th>Asse</th>
<th>Rotazione</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>360° (105°%)</td>
</tr>
<tr>
<td>J2</td>
<td>135° (105°%)</td>
</tr>
<tr>
<td>J3</td>
<td>361,8° (105°%)</td>
</tr>
<tr>
<td>J4</td>
<td>720° (130°%)</td>
</tr>
<tr>
<td>J5</td>
<td>250° (130°%)</td>
</tr>
<tr>
<td>J6</td>
<td>720° (210°%)</td>
</tr>
</tbody>
</table>

#### Carico massimo al polso

- Valore: 165 kg

#### Momento di carico max. al polso (Nota 1)

<table>
<thead>
<tr>
<th>Asse</th>
<th>94 kgf·m</th>
<th>92 Nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>J4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Momento di inerzia max. al polso

<table>
<thead>
<tr>
<th>Asse</th>
<th>800 kgf·m²</th>
<th>78,4 kg·m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>J4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Tipo di azionamento

- Motori elettrici AC

#### Ripetibilità

- ± 0,3 mm

#### Peso

- 1,210 kg

#### Ambiente Installazione

<table>
<thead>
<tr>
<th>Parametro</th>
<th>Valore</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperatura ambiente</td>
<td>0-45°C</td>
</tr>
<tr>
<td>Umidità ambiente</td>
<td>≤ 75%</td>
</tr>
<tr>
<td>Breve (in un mese)</td>
<td>≤ 95%</td>
</tr>
<tr>
<td>Vibrazioni</td>
<td>0,5 G max.</td>
</tr>
</tbody>
</table>
Workspace
Visualization of workspace and mobility

kinematic simulation of a 6-dof Comau robot (all revolute joints)
Visualization of workspace and mobility

V-REP simulation of the 7-dof KUKA LWR4+ robot (all revolute joints)
Robot end-effector sensors and tools

Robot
Force/torque sensor
Pneumatic tool-changer
Camera
3-Finger robotic hand
Calibration of robot kinematics
Man-machine interface

- teach-box pendant used as robot programming interface
- cabinet with power electronics for robot supervision and control
Programming and control environment

control modules and interfaces (Reis Robotics)
Motion programming and scaling

commercial video from ABB
TrueMove & QuickMove fast motion control performance

**ABB RAPID** programming language: sequence of coordinated Cartesian commands
MoveL (linear, point-to-point) and MoveC (center & radius, by an arc)
Robot programming from CAD

3D laser cutting for metal sheets and tubes, using a 6R robot (FANUC) commercial video by Golden Laser: https://youtu.be/FLSDIIdtIHR0
Mobile base robots in industry

- **AGV** (Automated Guidance Vehicles) for material and parts transfer on the factory floor: wire- or laser-driven along predefined paths
Lifting AGV for warehouses

video by Elettric80
Kiva Systems

company acquired in 2012 for $775 million by Amazon (store automation)
Intelligent AGV in factories

commercial video of ADAM mobile robot (RMT Robotics)
What’s next in industrial robotics?

changing nature of manufacturing and work

- growing shift from high volume/low mix to low volume/high mix is having a deep impact on manufacturing
- many industries are facing acute shortages of skilled labor
- quicker return-of-investment (ROI) of automation and rising wages are eventually discouraging labor arbitrage
- increased focus is being placed on workplace safety
- securing supply chains, increasing resilience and sustainability

Source: Steven Wyatt (IFR). “Today’s trends, tomorrow’s robots!” Frankfurt, 27 September 2017 (with additions..)
What’s next in industrial robotics?

addressing some real facts opens huge opportunities

<table>
<thead>
<tr>
<th>The Trends</th>
<th>The Challenges</th>
<th>The Enablers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low volume high mix</td>
<td>Automation complexity and unpredictability</td>
<td>Collaborative automation for greater flexibility</td>
</tr>
<tr>
<td>Shorter cycles, faster launches</td>
<td>Shop floor disruptions and high engineering costs</td>
<td>Better software for engineering efficiency</td>
</tr>
<tr>
<td>Increased need for automation and scalability in SMEs</td>
<td>Lack of robot integration and programming expertise</td>
<td>Easier to use robots with more intuitive programming</td>
</tr>
<tr>
<td>Rising cost of downtime</td>
<td>Higher lifetime TCO due to increase in planned downtime</td>
<td>Advanced analytics and services for greater reliability</td>
</tr>
<tr>
<td>Increased and sporadic human intervention</td>
<td>Lost productivity to maintain safety</td>
<td>Collaborative automation to maintain safety and productivity</td>
</tr>
</tbody>
</table>

answers to these challenges lie in
Simplification, Digitalization, and Collaboration
What’s next in industrial robotics?

**Simplification** (critical for SME, but also for large global manufacturers)
- robots easier to install, program (with open source) and operate will unlock entry barriers to the large market of small and medium enterprises (SMEs)
- trend towards having production closer to the end consumer is driving the importance of **standardisation** & consistency across global brands

**Digitalization** (Big Data allows taking better decisions on factory operations)
- Industry 4.0 & 5.0, linking the real-life factory with a **virtual/digital** twin, will play an increasingly important role in global manufacturing
- **vision and sensing** devices, coupled with analytics platforms, will pave the way for new industry business models
- IoT/AI/Machine Learning will drive many robotics developments in coming years

**Collaboration**
- **collaborative robotics** is shifting traditional limits of “what can be automated?”
- cobots increase manufacturing flexibility as ‘low-volume, high-mix’ becomes the main standard
- collaboration is also about productivity with increased physical and cognitive **human/robot interaction**
What’s next in industrial robotics?

“connected” future of robotics

self-optimizing production
- robots doing the same task connect across all global locations so performance can be easily compared and improved

self-programming robots
- robots automatically download what they need to get started from a cloud library and then optimize through “self-learning”

connected and collaborative robots will enable SMART Manufacturing for both SMEs & Global Enterprises
Franka Emika robot

... one possible example (dated 2016)