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

1970
- 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 2020

executive summary for 2020 statistics by IFR issued yearly in late September (for back issues since 2007, check course web site)

- total worldwide stock at end 2019: 2.7 million units of operational industrial robots (+12% w.r.t. 2018, +13% CAGR since 2014)
- new robot sales in 2019: ~373K (-12%, 3rd highest ever, +11% CAGR since 2014)
- robot market value in 2019: $13.8 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 38% share
- 73% of new robot installations in 5 countries: China, Japan, USA, Korea, Germany

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

Operational stock of industrial robots - World

preview in 2020: ~3M robots in operation

length of robot service life is estimated in 12-15 years
Diffusion
industrial robots in operation by world area

Operational stock of industrial robots
('000 of units)

Asia/Australia: 521 577 629 689 780 887 1,034 1,253 1,478 1,688
Europe: 352 370 381 392 411 433 460 498 543 580
The Americas: 180 193 207 226 248 274 300 324 361 389

Source: World Robotics 2020

preview in 2020: almost 1M robots operating in China!
# Diffusion of robots in industrial sectors

**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>248</td>
<td>216</td>
<td></td>
</tr>
<tr>
<td>Plastic and chemical products</td>
<td>182</td>
<td>176</td>
<td>171</td>
</tr>
<tr>
<td>Food</td>
<td>81</td>
<td>74</td>
<td>64</td>
</tr>
<tr>
<td>All others</td>
<td>149</td>
<td></td>
<td>282</td>
</tr>
<tr>
<td>Unspecified</td>
<td>410</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: World Robotics 2020

70% of robots are deployed in three main industries
almost 70% of robots are used for material handling or welding
Annual supply of new industrial robots worldwide

Stop of growth rate in 2019: automotive transition, trade & political headwinds

Preview in 2020: deferred investments, plummeted consumer demand, travel restrictions, disrupted supply chains (due also to Covid-19)

Medium term preview: crisis will be a digitalization booster creating growth opportunities for robotics industry worldwide
The two major industries struggled in 2019 (especially in Asia)
Annual supply
new installations in top markets (countries)

China well ahead, with 5 markets accounting for 73% of total supply
Italy (2\textsuperscript{nd} EU market): double as many new robots installed as in 2015
Density of robots

Robot density in the manufacturing industry 2019

Almost doubled in last 5 years!

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

Source: International Federation of Robotics
Collaborative robots

Collaborative and traditional industrial robots

2019

355 18

2018*

406 16

2017

389 11

'000 units

Traditional Industrial Robots

Collaborative Robots

*a revised

Source: International Federation of Robotics

a small but steady growing market in the 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

different customers, pricing, machinery, distribution channels, suppliers

... but separation line is blurring: same unit can act as both, depending on the application
Personal/domestic service robots data (2018-19) and forecast*

Service robots for personal/domestic use. Unit sales 2018 and 2019, potential development 2020-2023

<table>
<thead>
<tr>
<th></th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robots for domestic tasks</td>
<td>13.2</td>
<td>18.6</td>
<td>21.6</td>
<td>31.2</td>
<td>39.0</td>
<td>48.6</td>
</tr>
<tr>
<td>Entertainment robots</td>
<td>4.6</td>
<td>4.6</td>
<td>5.1</td>
<td>5.6</td>
<td>6.1</td>
<td>6.7</td>
</tr>
</tbody>
</table>

millions of units

vacuuming and floor cleaning: true tasks for robots
steady growth of turnover expected

Source: World Robotics 2020
Professional service robots
data (2018-19) and forecast*

<table>
<thead>
<tr>
<th></th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logistic robots</td>
<td>52</td>
<td>75</td>
<td>114</td>
<td>207</td>
<td>259</td>
<td></td>
</tr>
<tr>
<td>Robots for public environments</td>
<td>14</td>
<td>20</td>
<td>28</td>
<td>39</td>
<td>54</td>
<td>76</td>
</tr>
<tr>
<td>Defense applications</td>
<td>17</td>
<td>19</td>
<td>22</td>
<td>25</td>
<td>28</td>
<td>33</td>
</tr>
</tbody>
</table>

Source: World Robotics 2020

robots (AGV, AMR) in logistics are still the growth drivers
Europe is the main supplier of service robots (with many young start-ups!)

Robots (AGV, AMR) in logistics are still the growth drivers
Europe is the main supplier of service robots (with many young start-ups!)
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

video

video
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

- Video
- Video

- Glue deposit (on fancy paths!)
- Cooperation of multiple robots for handling and inspecting/sealing a car body
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 is 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)

www.adamisrl.com

video
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

Mitsubishi RP
(repeatability 5 micron, payload 5 kg)

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

Bosch Turbo

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
Adept Cobra i600

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

Comau Mast
gantry robot
(payload up to 560 kg)

ABB Flexpicker
(150 pick-and-place operations/minute)
Chocolate packaging with lightweight parallel robots

test video with ABB Flexpicker

video with Adept Quatro s650
Distribution by robot type

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)
Robot data sheet

<table>
<thead>
<tr>
<th>Specifiche tecniche</th>
<th>R-2000i/165F</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Voce</strong></td>
<td>Articolato</td>
</tr>
<tr>
<td><strong>Tipo</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Assi controllati</strong></td>
<td>6 assi (J1, J2, J3, J4, J5, J6)</td>
</tr>
<tr>
<td><strong>Installazione</strong></td>
<td>A pavimento</td>
</tr>
<tr>
<td><strong>Area di lavoro (Velocità massima)</strong></td>
<td></td>
</tr>
<tr>
<td>Rotazione asse J1</td>
<td>360° (105%)</td>
</tr>
<tr>
<td>Rotazione asse J2</td>
<td>135° (105%)</td>
</tr>
<tr>
<td>Rotazione asse J3</td>
<td>361,8° (105%)</td>
</tr>
<tr>
<td>Rotazione asse J4</td>
<td>720° (130%)</td>
</tr>
<tr>
<td>Rotazione asse J5</td>
<td>250° (130%)</td>
</tr>
<tr>
<td>Rotazione asse J6</td>
<td>720° (210%)</td>
</tr>
<tr>
<td><strong>Carico massimo al polso</strong></td>
<td>165 kg</td>
</tr>
<tr>
<td>Momento di carico max. al polso (Nota 1)</td>
<td></td>
</tr>
<tr>
<td>Asse J4</td>
<td>94 kgf.m</td>
</tr>
<tr>
<td>Asse J5</td>
<td>94 kgf.m</td>
</tr>
<tr>
<td>Asse J6</td>
<td>47 kgf.m</td>
</tr>
<tr>
<td>Momento di inerzia max. al polso</td>
<td></td>
</tr>
<tr>
<td>Asse J4</td>
<td>800 kgf.cm²</td>
</tr>
<tr>
<td>Asse J5</td>
<td>800 kgf.cm²</td>
</tr>
<tr>
<td>Asse J6</td>
<td>410 kgf.cm²</td>
</tr>
<tr>
<td><strong>Tipo di azionamento</strong></td>
<td>Motori elettrici AC</td>
</tr>
<tr>
<td><strong>Ripetibilità</strong></td>
<td>± 0,3 mm</td>
</tr>
<tr>
<td><strong>Peso</strong></td>
<td>1,210 kg</td>
</tr>
<tr>
<td><strong>Ambiente Installazione</strong></td>
<td>Temperatura ambiente: 0-45°C</td>
</tr>
<tr>
<td></td>
<td>Umidità ambiente Normale: ≤ 75%</td>
</tr>
<tr>
<td></td>
<td>Breve (in un mese): ≤ 95%</td>
</tr>
<tr>
<td></td>
<td>vibrazioni: 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)

video
Visualization of workspace and mobility

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

- shift from high volume/low mix to low volume/high mix is having a profound 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 labour arbitrage
- increased focus is being placed on workplace safety

Source: Steven Wyatt (IFR). “Today’s trends, tomorrow’s robots!” Frankfurt, 27 September 2017
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, Digitalisation, 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

**Digitalisation** (Big Data allows taking better decisions on factory operations)
- “Industry 4.0”, linking the real-life factory with a **virtual/digital** one, 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 robots are shifting the traditional limits of “what can be automated?”
- **collaborative** robots 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
- self-programming robots

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

[Image of Franka Emika robot]

www.franka.de

video