Robotics 1

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)
No Robots !?

International Organization for Standardization

According to the above ISO definition in 2012, these are NOT robots

- software ("bots", AI, Robotic Process Automation - RPA)
- voice assistants
- ATMs (automatic money teller machines)
- cooking machines, smart washing machines, ...

and also

- remote-controlled drones, UAV, UGV, UUV
- autonomous cars

but in the revised standard ISO8373:2021 these are now classified as (autonomous) robotic devices!
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

- computerized numerically controlled (CNC) machines ~ 1950
- robot manipulators 1970
- 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

Robotics 1
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 2023

executive summary for 2023
statistics by IFR
issued yearly in early October
(for back issues since 2007,
check course web site)

- total worldwide stock at end 2022: 3.9 million units of operational industrial robots (+12% w.r.t. 2021; +13% CAGR in 2017-22)
- new robot sales in 2022: 553K (+5%, highest number ever; +7% CAGR)
- second record year in a row, still growing from the high basis of year 2021 –after the strong recovery (+31%) that followed last year to the pandemics
- robot market value in 2022: $15.7 billion (without software and peripherals); robotic systems market value: ~4 times as much
- China is by far the largest market (since 2013): installs every other robot (52%)!
- 79% 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

~4 M robots in operation

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

two years in a row 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

growth in all regions (after strong recovery)
Annual supply
new robots by industrial sectors

electronics is the major customer of robots (automotive is catching up)
Annual supply
shares of new robots in major industrial sectors

### in 2012

Annual installations of industrial robots: automotive and electronics vs. general industry - 2012 - World

- General industries: 69,141 (38%)
- Electrical/electronics: 33,697 (20%)
- Automotive: 66,508 (42%)

### in 2022

Annual installations of industrial robots: automotive and electronics vs. general industry - 2022 - World

- Electrical/electronics: 156,636 (28%)
- General industries: 136,130 (25%)
- Automotive: 189,886 (47%)

**landscape dramatically changed in 10 years** (challenges for general industries)
Annual supply new robots by main application

material handling is the most important application (with 48% share)
Annual supply
new installations in top markets (countries)

**Italy (2\textsuperscript{nd} EU market): >2 times as many new robots installed as in 2015**
China installs more industrial robots per year than the rest of the world taken together (multiplied this figure by more than a factor 12 in a decade)
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 annual installations

![Collaborative and traditional industrial robots](chart)

*000 units

- **2017**: 389 traditional, 11 collaborative
- **2018**: 405 traditional, 19 collaborative
- **2019**: 366 traditional, 21 collaborative
- **2020**: 363 traditional, 26 collaborative
- **2021**: 484 traditional, 42 collaborative
- **2022**: 498 traditional, 55 collaborative

*a revised estimate

Source: World Robotics 2023

a smaller but steadily **growing market share** (10% in industrial setting)
Levels of human-robot collaboration in industrial settings

Types of collaboration with industrial robots

Most collaborative applications are of this type today

- Coexistence
  - No fence but no shared workspace

- Sequential collaboration
  - Robot and worker both active in the workspace but movements are sequential

- Cooperation
  - Robot and worker work on the same part at the same time – both in motion

Responsive collaboration
  - Robot responds in real-time to movement of worker

Requirement for intrinsic safety features vs. external sensors

Level of collaboration

source, IFR 2022
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
new professional service robots in 2022: **158K units** (+48%)

... compare with new personal/domestic service robots: **5M units!!** (-5%)
Professional service robots

Service robots for professional use. Top 5 applications
Unit sales 2021 and 2022

'000 of units

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

Source: World Robotics 2023
Professional service robots

- almost 1000 service robot suppliers worldwide (EU is leading!)
- 81% of service robot suppliers are SMEs (≤500 employees)
Industrial robot and its auxiliary equipment

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
ABB IRB 7600

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)

Video
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)
Reasons to automate with robots in industrial settings

- Higher throughput
- Higher quality of products
- Greater precision and accuracy
- Lower production costs
- Higher quantity of production/upscaling
- Competitive-ness
- Resource & energy efficiency
- Quality and safety at work
- Lack of skilled labour
- Higher standard of living

source, IFR 2022
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)
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!
Cartesian or gantry robots

- **Güdel FP-5 robot**
  - 3P linear/prismatic joints
  - (possibly, with additional rotation around vertical axis)
  - Maximum stroke 14, payload up to 1100 kg

- **Comau Mast robot**
  - 3P linear/prismatic joints with a 3R spherical wrist
  - Payload up to 560 kg

**video**
Delta and Hexa parallel robots

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

**ABB 365 Flexpicker**
- 5-DOF Delta parallel kinematics

**Hexa robot**
- 6-DOF parallel kinematics with DD actuation
- Uchiyama (Tohoku), Pierrot (Montpellier) - 1994

Delta robots are replacing SCARA in planar pick-and-place or assembly
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)
Robot data sheet

### 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)**

| Rotazione asse J1       | 360° (105%)  |
| Rotazione asse J2       | 135° (105%)  |
| Rotazione asse J3       | 361,8° (105%) |
| Rotazione asse J4       | 720° (130%)  |
| Rotazione asse J5       | 250° (130%)  |
| Rotazione asse J6       | 720° (210%)  |

**Carico massimo al polso**

- 165 kg

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

| Asse J4 | 94 kgf cm² | 921 Nm |
| Asse J5 | 94 kgf cm² | 921 Nm |
| Asse J6 | 47 kgf cm² | 461 Nm |

**Momento di inerzia max. al polso**

| Asse J4 | 800 kgf cm² | 78,4 kgm² |
| Asse J5 | 800 kgf cm² | 78,4 kgm² |
| Asse J6 | 410 kgf cm² | 40,12 kgm² |

**Tipo di azionamento**

- Motori elettrici AC

**Ripetibilità**

- ± 0,3 mm

**Peso**

- 1,210 kg

**Ambiente Installazione**

<table>
<thead>
<tr>
<th>Temperatura ambiente</th>
<th>0-45°C C</th>
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</thead>
<tbody>
<tr>
<td>Umidità ambiente</td>
<td>≤ 75%</td>
</tr>
<tr>
<td>Normale:</td>
<td></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

should be ‘embedded’ in 3D (by the rotation of the first joint)
Mobility and workspace visualization

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

CoppeliaSim simulation of the 7-dof KUKA LWR4+ robot (all revolute joints)
Robot end-effector sensors and tools
Simple (rigid to soft) grippers

OnRobot RG6 and Soft Grippers

video

qbrobotics Soft Claw

https://youtu.be/FOM5Pl6Yb4U
Calibration of robot kinematics
Man-machine interface
most traditional ones

- 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)
  - 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/FLSDIdtIHR0
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
(+ my addition ...
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>
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<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 consumer needs is driving the importance of **standardization** & 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 industrial 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

video

www.franka.de