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 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 general definition ("visionary")

  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 machines (CNC)

1970
Unimation PUMA

1970
robot manipulators

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 2017

executive summary for 2017
statistics by IFR
issued yearly in early October
(available on the course web site
since the 2008 edition)

- robotics market value in 2016: $13.1 billion (+18% over 2015); robot systems: $40 billion
- total worldwide stock at end 2016: 1.8 million units of operational industrial robots (+12%)
- highest ever robot sales worldwide in 2016 (~295K, +16%), for the fourth year in a row
- China expanded further as the largest market since 2013, now with a 30% share (+3%)
- 75% of sales goes to 5 countries: first is China (87K, close to Europe + Americas = 97K),
  then Korea (41K, +10%/year average since 2011), Japan (38K, +10%), USA (31K, +14%),
  and Germany (20K, steady); Italy (6.7K, steady) is the 2nd market in Europe (7th worldwide)
- main industrial drivers: automotive (35% of new robots, with moderate rate increase) and
  electrical/electronics (31%, catching up very fast; now first in Asia), followed by metal and
  machinery, rubber and plastics, food industry, ...

a continued accelerated growth!
Diffusion
industrial robots in operation worldwide

(as reference: industrial robots in stock in 1973 = 3K, in 1983 = 66K)
length of robot service life is estimated in 12-15 years
Diffusion
industrial robots in operation by world area

Estimated worldwide operational stock of industrial robots 2015-2016 and forecast for 2017*-2020*

2020*: ~1.9M robots in Asian factories ...

... out of which almost 1M operating in China!
almost 70% of robots are in three main industries
Annual supply
new industrial robots worldwide

Estimated annual worldwide supply of industrial robots
2008-2016 and 2017*-2020*

highest level ever:
294K new units

double-digit average annual increase

+15% on average per year

2017*-2020*: forecast of 1.7M new industrial robots

Source: IFR World Robotics 2017
Annual supply
new robots by industrial sectors

Estimated annual supply of industrial robots at year-end
by industries worldwide 2014-2016

- Chemical, rubber and plastics: 2016: 20, 2015: 20, 2014: 17, -4%

Source: IFR World Robotics 2017

continued increase in major industries
Annual supply
new industrial robots by world area

Estimated worldwide annual supply of
industrial robots 2015-2016 and forecast for 2017*-2020*

*000 of units

<table>
<thead>
<tr>
<th>Year</th>
<th>Asia/Australia</th>
<th>Europe</th>
<th>America</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>161</td>
<td>50</td>
<td>38</td>
</tr>
<tr>
<td>2016</td>
<td>191</td>
<td>56</td>
<td>41</td>
</tr>
<tr>
<td>2017*</td>
<td>230</td>
<td>61</td>
<td>48</td>
</tr>
<tr>
<td>2018*</td>
<td>257</td>
<td>64</td>
<td>51</td>
</tr>
<tr>
<td>2019*</td>
<td>296</td>
<td>71</td>
<td>58</td>
</tr>
<tr>
<td>2020*</td>
<td>354</td>
<td>83</td>
<td>73</td>
</tr>
</tbody>
</table>

*forecast

Source: IFR World Robotics 2017

2020*: 40% of the global supply of new robots will go to China
Annual supply
new installations in top markets (countries)

Estimated worldwide annual supply of industrial robots
15 largest markets 2016

- China: 87,0
- Republic of Korea: 41,4
- Japan: 38,6
- United States: 31,4
- Germany: 20,0
- Taiwan: 7,6
- Italy: 6,5
- Mexico: 5,9
- France: 4,2
- Spain: 3,9
- Thailand: 2,6
- India: 2,6
- Singapore: 2,6
- Canada: 2,3
- Czech Republic: 2,0

in 2016: 5 markets account for 75% of total supply

Source: IFR World Robotics 2017
Annual supply
market comparison of new industrial robots

China:
• **largest** market since 2013
• **40%** of global supply in 2019*
• now also producing robots for their internal market...

**Western EU:**
Germany, Italy, France, Spain, and UK have a slow but steady **increase**
Annual supply market comparison of new industrial robots

USA: considerable increase since 2010

Germany: moderate increase at record levels in Europe

Source: IFR World Robotics 2017
Italy: degree of automation still relatively high, but **not** increasing in comparison to other countries

Number of robots per 10000 employees in the manufacturing industry in 2015 (and 2016)

Average robot density in USA: 184, Europe: 99, Americas: 84, Asia: 63

Average robot density world: 69

Number of robots per 10000 employees in the **manufacuring** industry in 2015 (and 2016)
Density of robots

Number of multipurpose industrial robots (all types)
per 10,000 employees in the automotive and in all other industries 2015

Italy was at 2\textsuperscript{nd} place in 2011!

Comparatively still low density in general industry

Number of robots per 10000 employees
in the automotive and in all other industries in 2015 (and 2016)
A long-range trend in robot prices

An articulated industrial robot with six degrees of freedom of medium size costs about 80-100 KEuro
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
ABB IRB 7600

commercial video by ABB
Industrial applications

- manipulation (pick-and-place)
- assembly
- spray painting and coating
- arc welding
- spot welding with pneumatic or servo-controlled gun
- laser cutting and welding
- gluing and sealing
- mechanical finishing operations (deburring, grinding)
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 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 yet

- 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 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

debugging 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 cell monitoring system (no fences!)
Robot manipulator kinematics

- **Kuka 150_2** (series 2000)
  - **open kinematic chain**
  - (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!

video
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

- *articulated*: 63%
- *cartesian/gantry*: 15%
- *cylindric*: 10%
- *SCARA*: 12%

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

Fanuc
R-2000i/165F

<table>
<thead>
<tr>
<th>Specifiche tecniche</th>
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</thead>
<tbody>
<tr>
<td><strong>Voce</strong></td>
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<tr>
<td><strong>Tipo</strong></td>
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<tr>
<td><strong>Assi controllati</strong></td>
</tr>
<tr>
<td><strong>Installazione</strong></td>
</tr>
<tr>
<td><strong>Area di lavoro</strong> (Velocità massima)</td>
</tr>
<tr>
<td>Rotazione asse J1</td>
</tr>
<tr>
<td>Rotazione asse J2</td>
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<tr>
<td>Rotazione asse J3</td>
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<tr>
<td>Rotazione asse J4</td>
</tr>
<tr>
<td>Rotazione asse J5</td>
</tr>
<tr>
<td>Rotazione asse J6</td>
</tr>
<tr>
<td><strong>Carico massimo al polso</strong></td>
</tr>
<tr>
<td>Momento di carico max. al polso (Nota 1)</td>
</tr>
<tr>
<td>Asse J4</td>
</tr>
<tr>
<td>Asse J5</td>
</tr>
<tr>
<td>Asse J6</td>
</tr>
<tr>
<td>Momento di inerzia max. al polso</td>
</tr>
<tr>
<td>Asse J4</td>
</tr>
<tr>
<td>Asse J5</td>
</tr>
<tr>
<td>Asse J6</td>
</tr>
<tr>
<td><strong>Tipo di azionamento</strong></td>
</tr>
<tr>
<td><strong>Ripetibilità</strong></td>
</tr>
<tr>
<td><strong>Peso</strong></td>
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<tr>
<td><strong>Ambiente e installazione</strong></td>
</tr>
<tr>
<td>Temperatura ambiente</td>
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<tr>
<td>Umidità ambiente</td>
</tr>
<tr>
<td>Normale</td>
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<tr>
<td>Breve (in un mese)</td>
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<tr>
<td>Vibrazioni</td>
</tr>
</tbody>
</table>
Workspace

Side View

Area di lavoro
Operating Space

Top View

+180°
-180°
0°
R265

Robotics 1
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
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

### 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</td>
<td>Lack of robot integration and programming expertise</td>
<td>Easier to use robots with more intuitive programming</td>
</tr>
<tr>
<td>scalability in SMEs</td>
<td></td>
<td></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</td>
<td>Lost productivity to maintain safety</td>
<td>Collaborative automation to maintain safety and productivity</td>
</tr>
<tr>
<td>intervention</td>
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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
  - 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)