Robotics 1

Industrial Robotics

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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

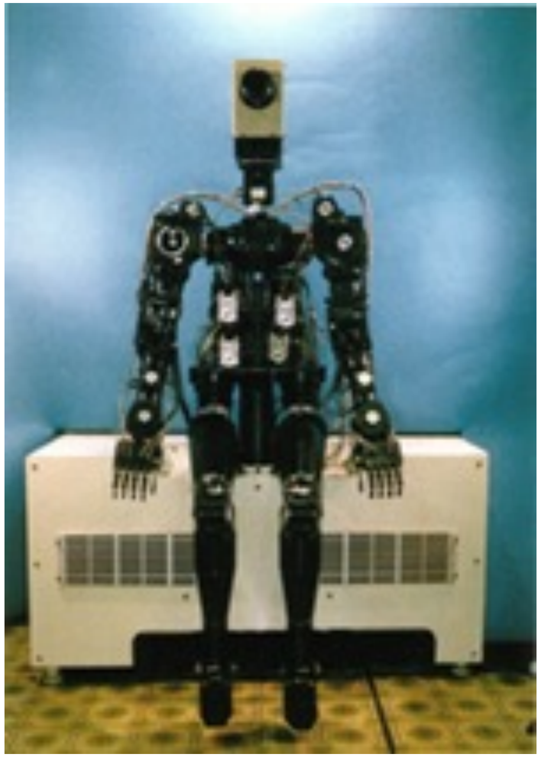
an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications

- 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

accent (for Italian students only): we say "ròbot" and **never** "robòt" !!

Evolution toward industrial robots

computerized numerically controlled (CNC) machines

~ 1950

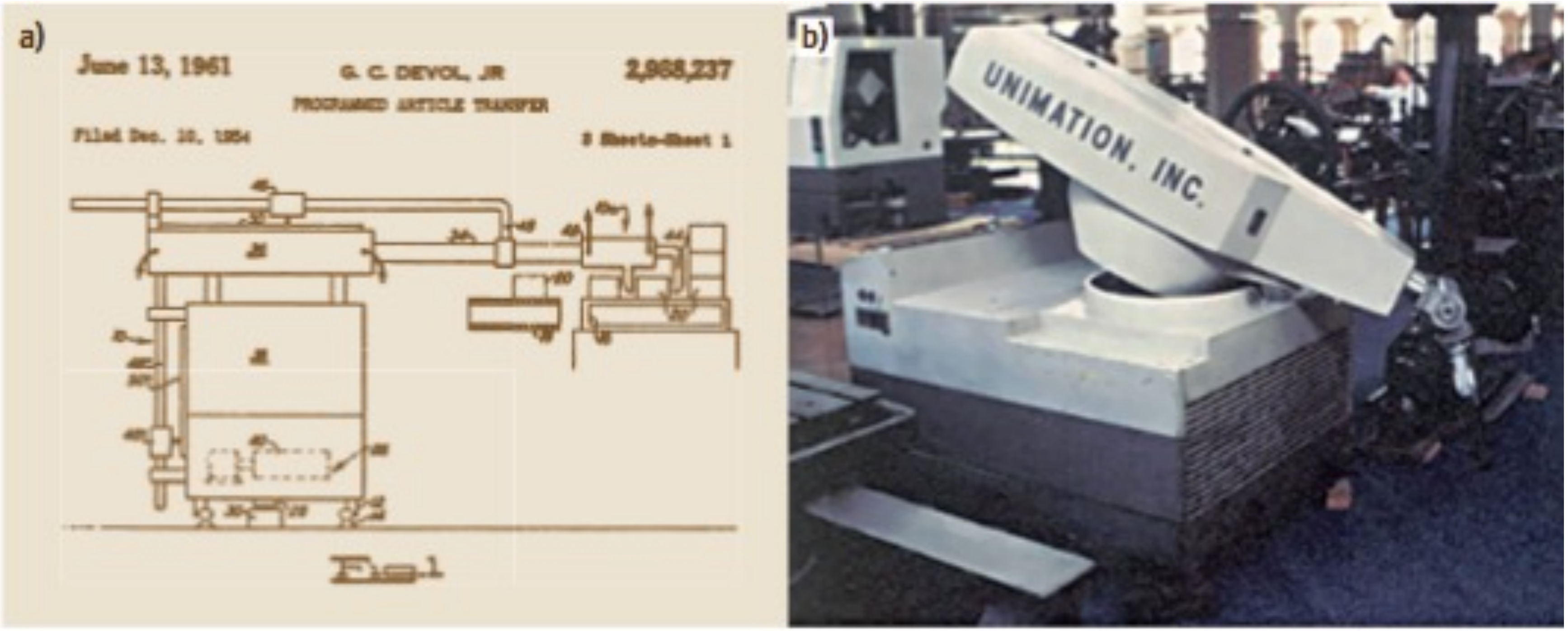
mechanical telemanipulators

robot manipulators

1970
Unimation PUMA

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

The first industrial robot

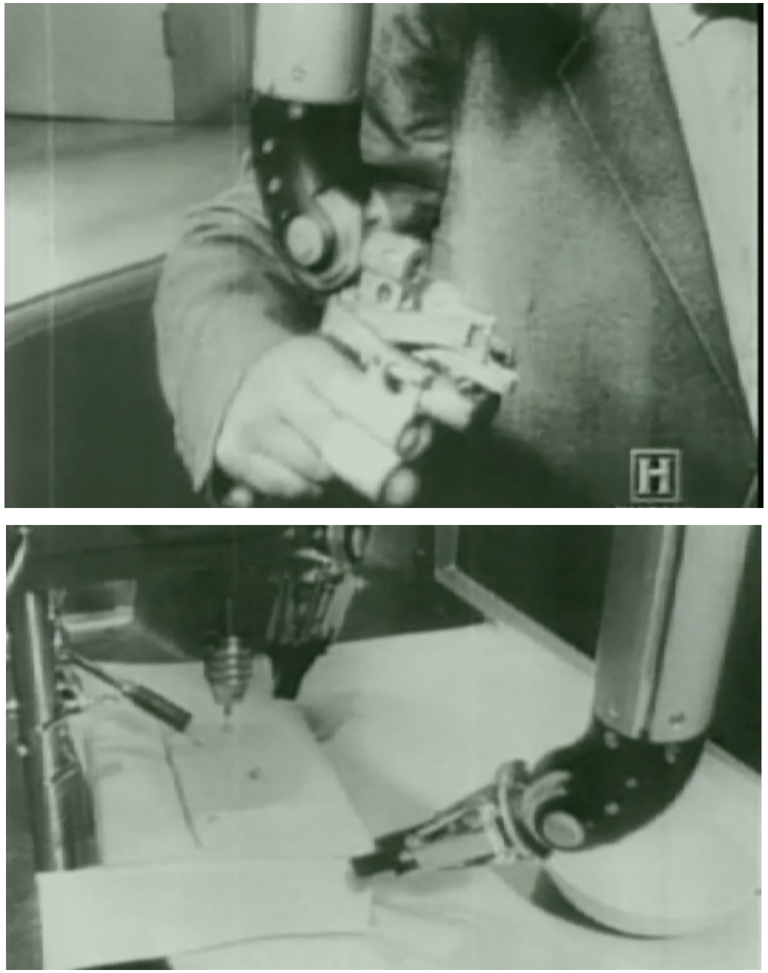


US Patent

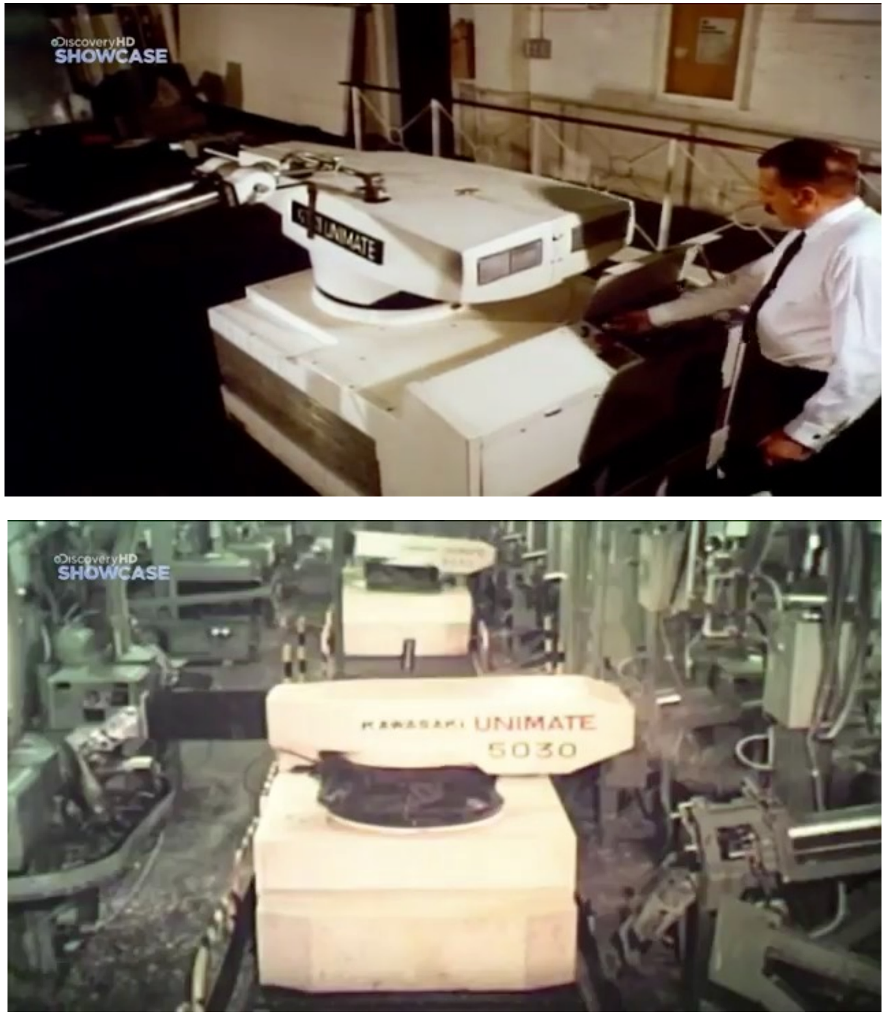
General Motor plant, 1961

G. Devol and J. Engelberger (Unimation)

Historical pictures and clips



bimanual remote manipulation
at Oak Ridge Nat'l Labs



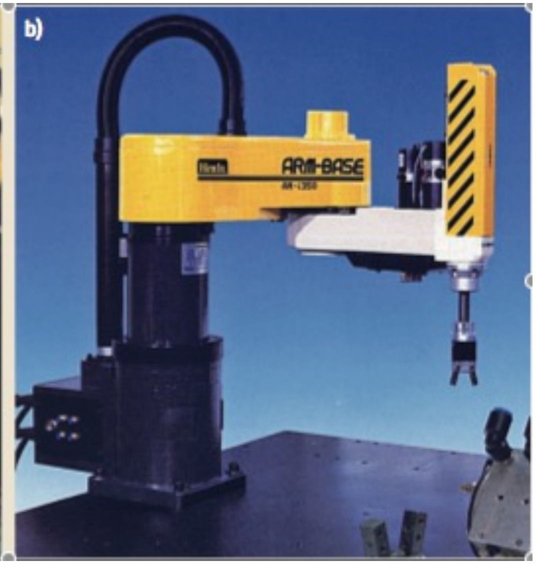
video

video

Unimate 6-dof robots

Robot manipulators

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

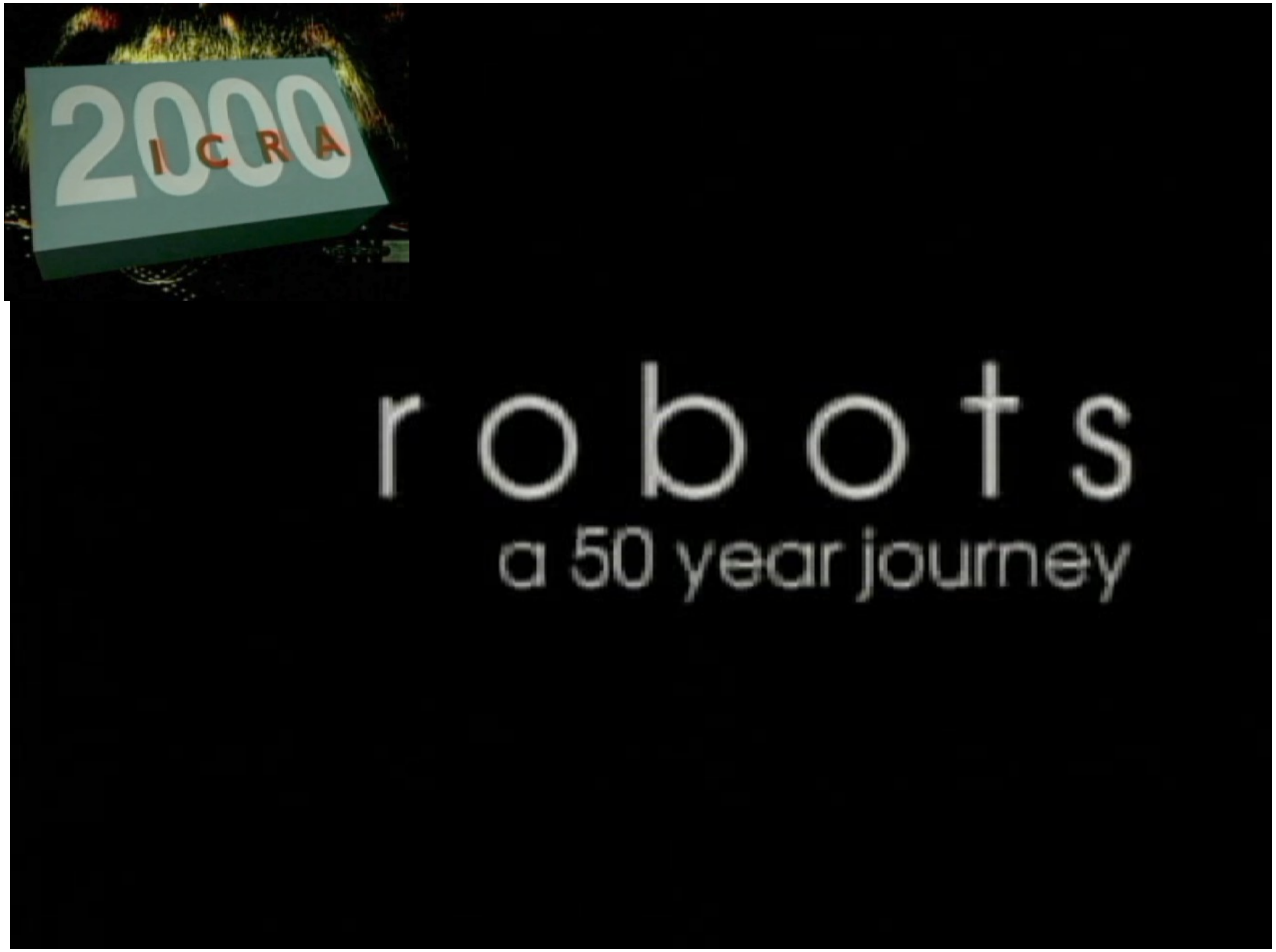


Hirata AR-300
(1978)
first SCARA
robot

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

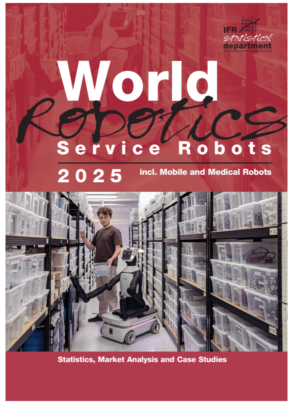


Video compiled for the IEEE ICRA 2000 conference, S. Francisco

World Robotics 2025

executive summary for 2025
statistics by IFR
issued yearly in late September

(for back issues since 2007,
check course web site)

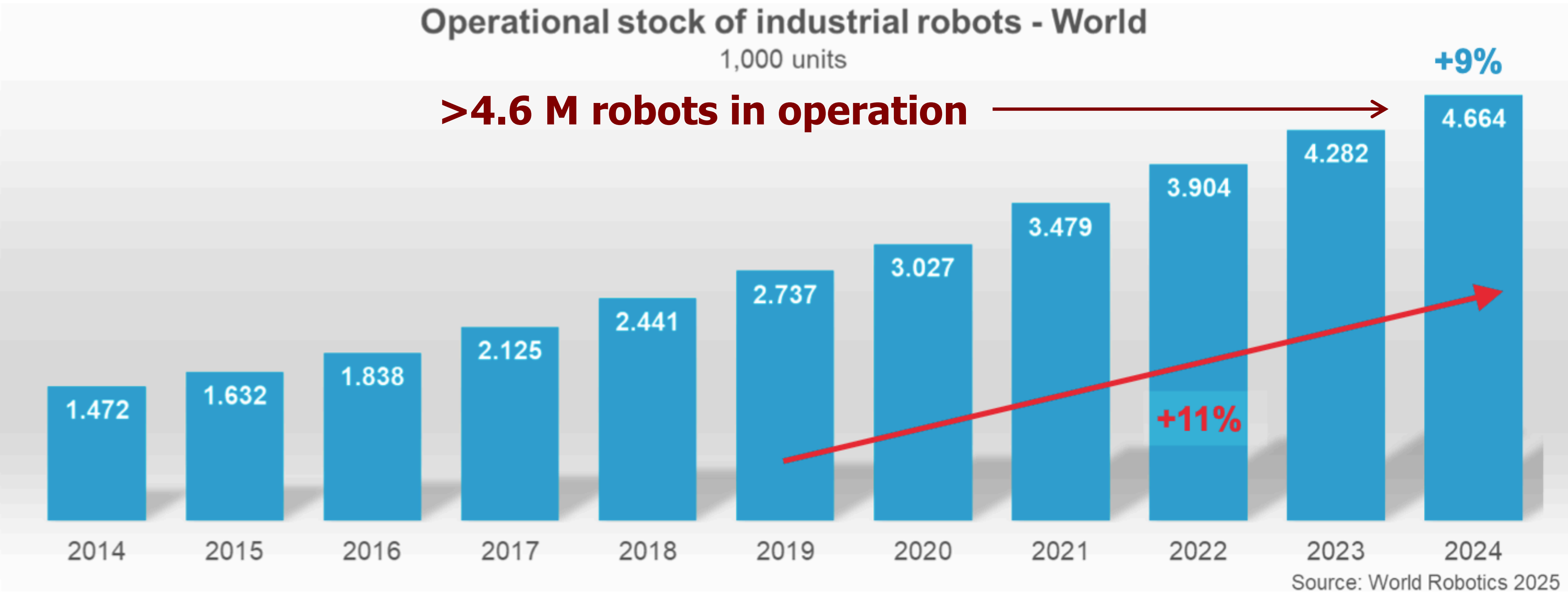


- total worldwide stock at end 2024: 4.6 million units of operational industrial robots (+9% w.r.t. 2023; +11% CAGR in five-year period 2019-24)
- new robot sales in 2024: 542K (±0% w.r.t. 2023; +7% CAGR 2019-24)
- for the fourth consecutive year annual new installations exceeded 500K
- robot market value in 2022: $15.7 billion (without software and peripherals)
  - robotic systems market value: ~4 times as much
- electronics & automotive industries decline; market growth for collaborative robots
- China is by far the largest market (since 2013): installs **every other robot** (54%)!
- 80% of new robot installations in 5 countries: China, Japan, USA, Korea, Germany

Compound Annual Growth Rate: $\mathrm{CAGR} = \left(\frac{V_{end}}{V_{begin}}\right)^{1/years} - 1$

Diffusion

industrial robots in operation worldwide

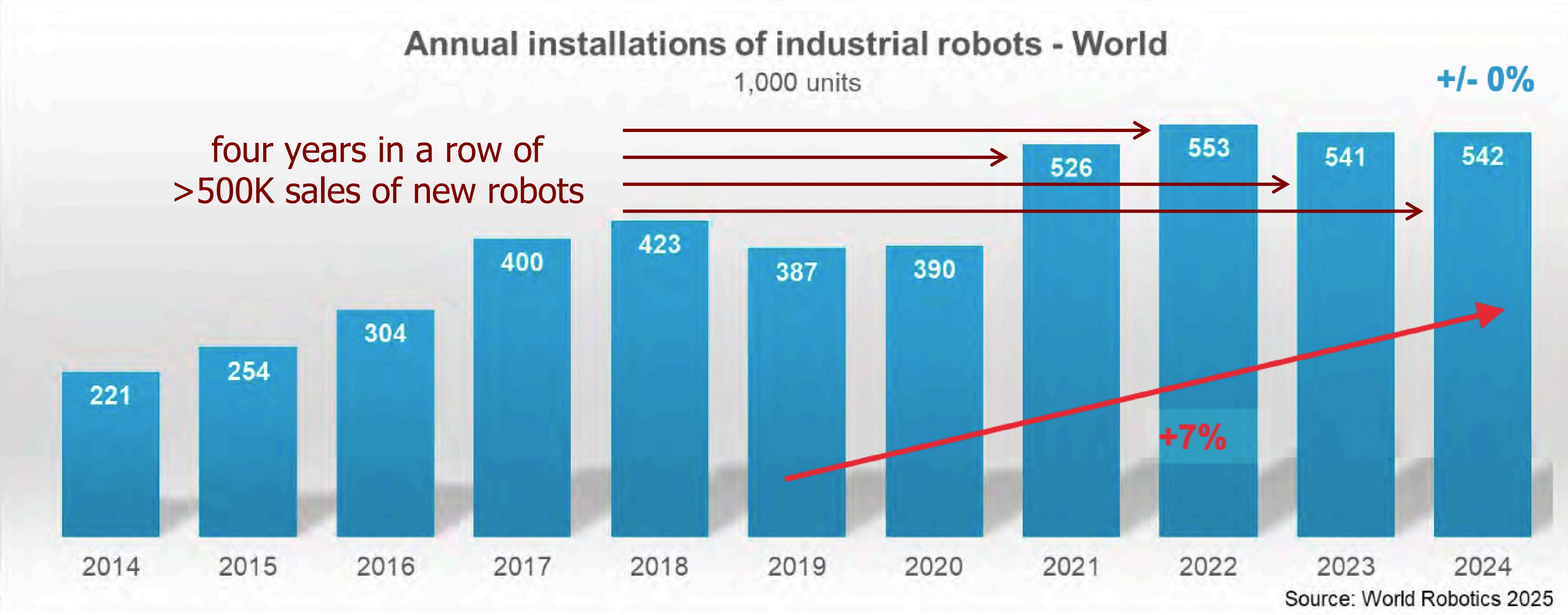


(reference: **industrial robots in 1973 = 3K**, 1983 = 66K, 1993 = 575K, 2003 = 800K)

length of **robot service life** is estimated in **12-15 years**

Annual installations

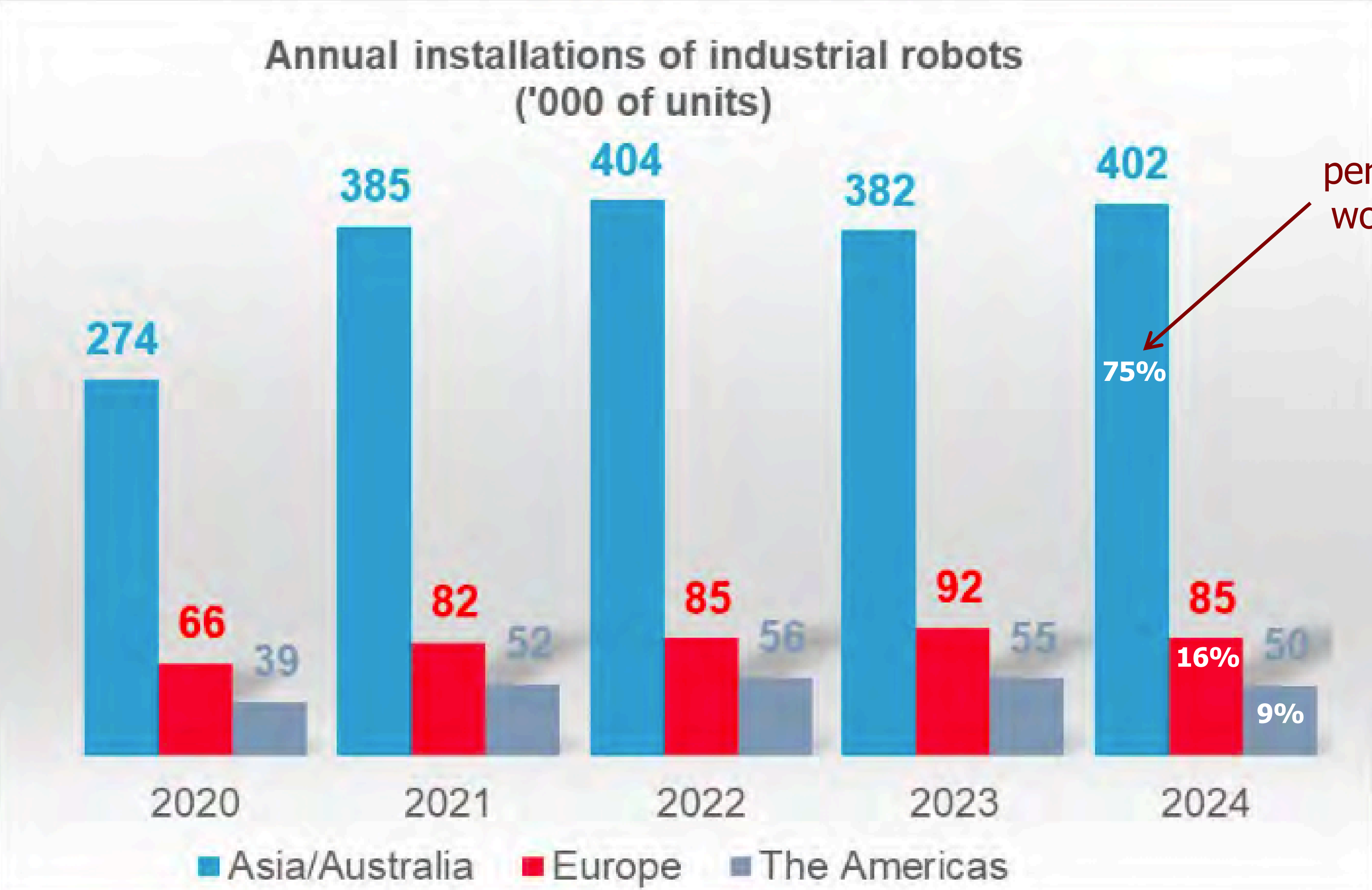
new industrial robots worldwide



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 installations
of industrial robots by world area

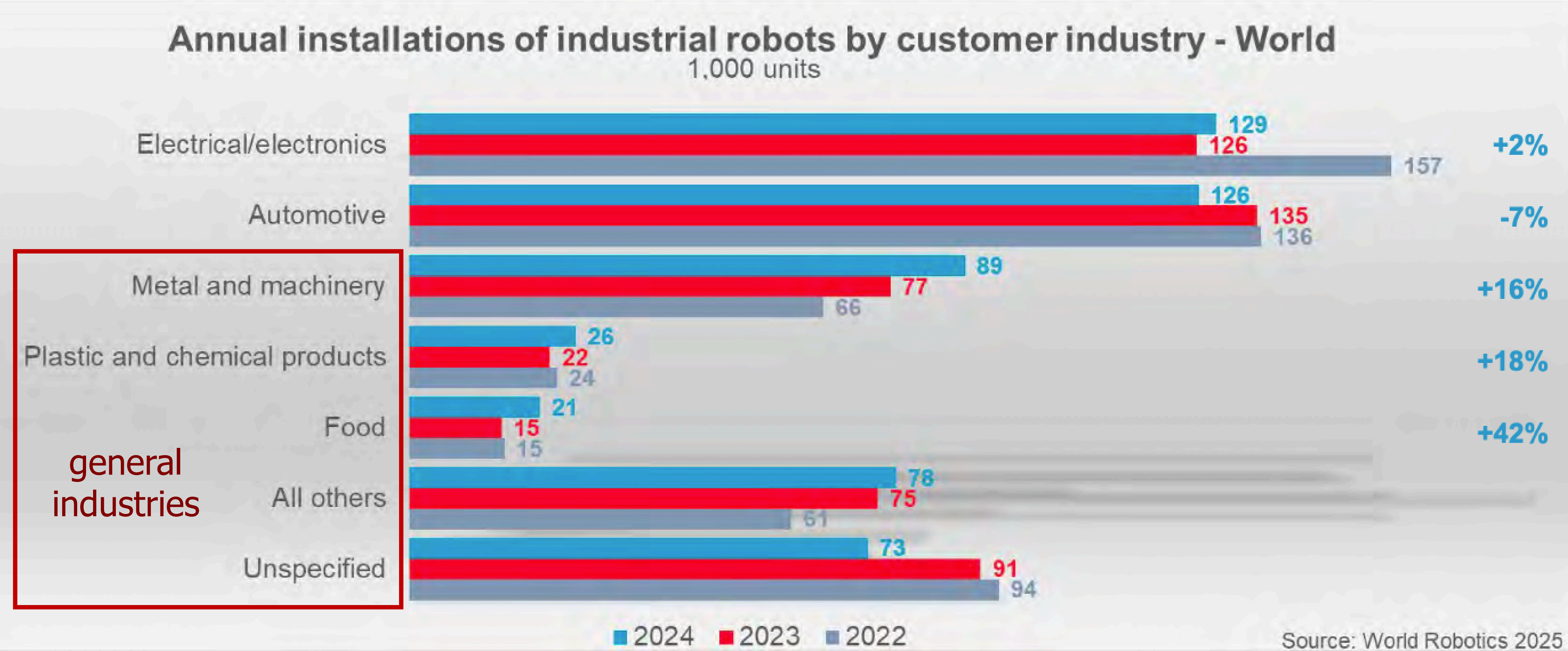


percentage worldwide

growth in Asia!

Annual installations

new robots by industrial sectors



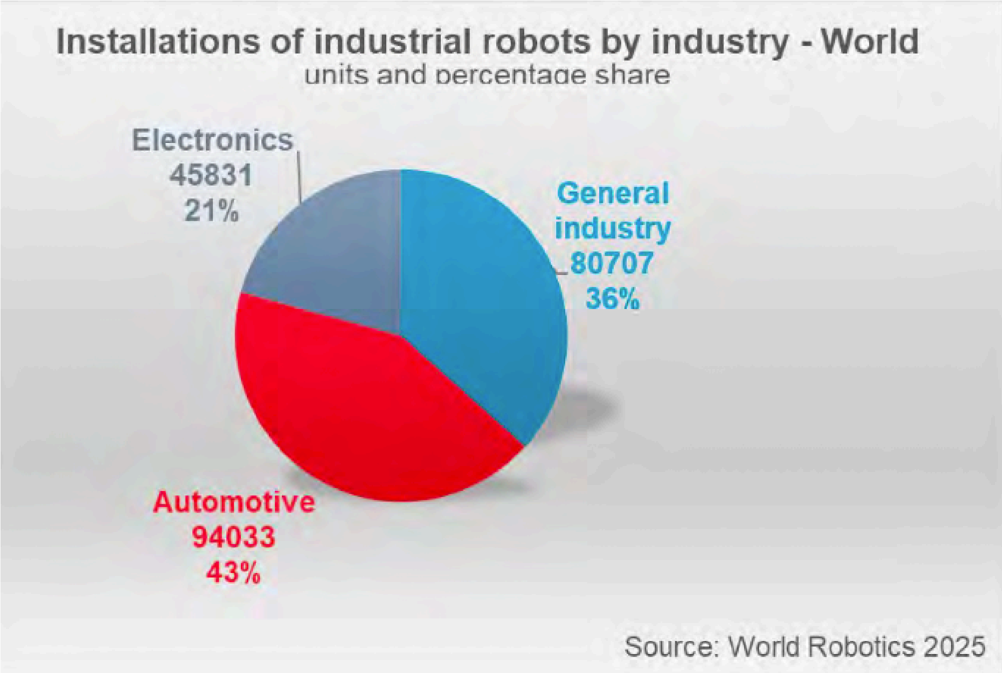
electronics back to **main** customer, due to **weaker** demand for **automotive**

general industries compensate for the weaker or stagnant two main sectors

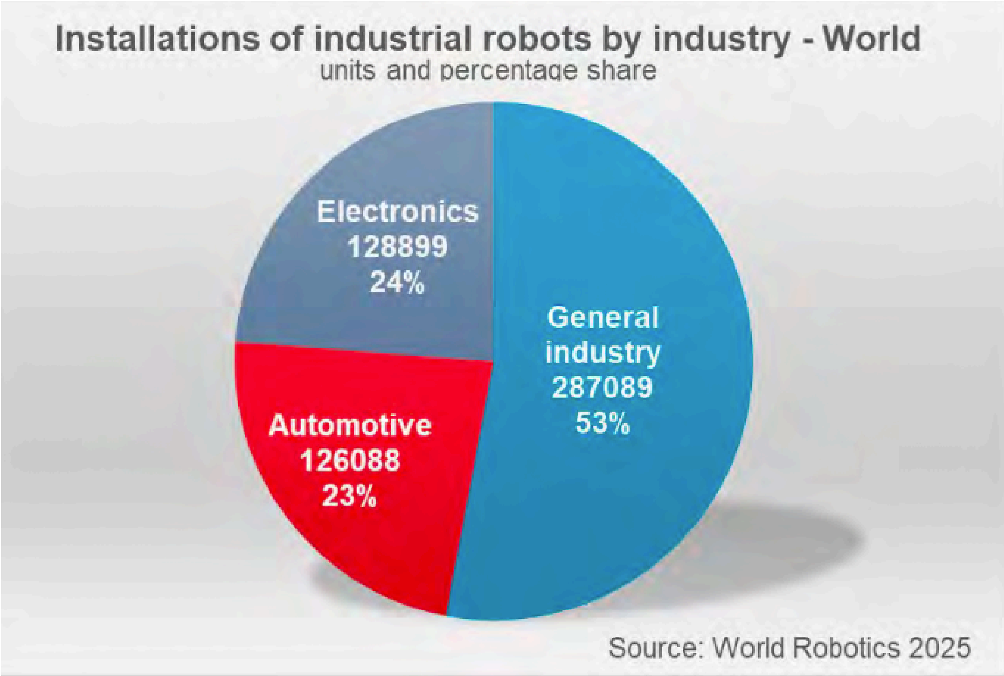
Annual installations

market shares of major industrial sectors

in 2014



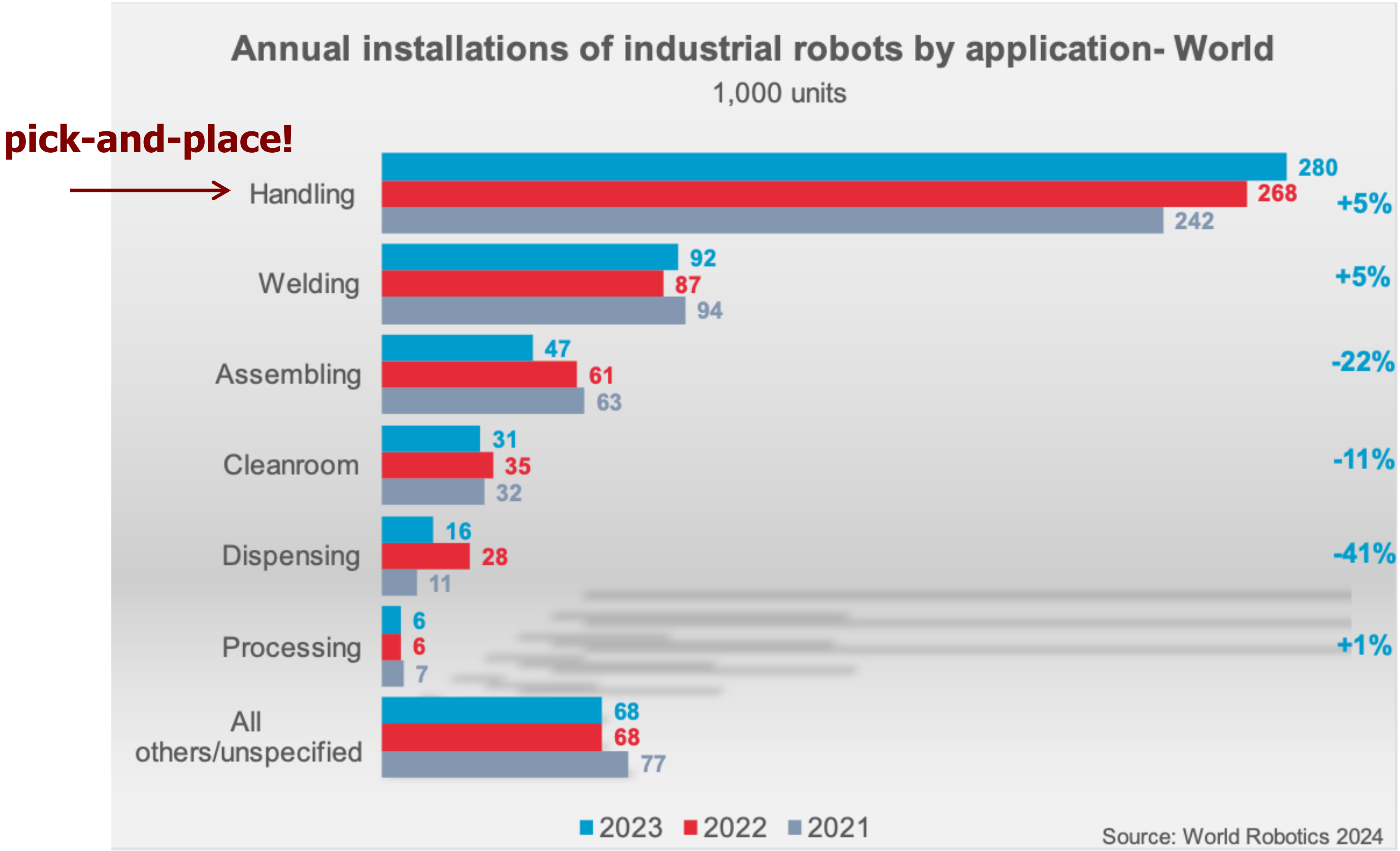
in 2024



landscape dramatically changed in 10 years (with growth of general industries)

Annual installations

new robots by main application [from WR 2024]



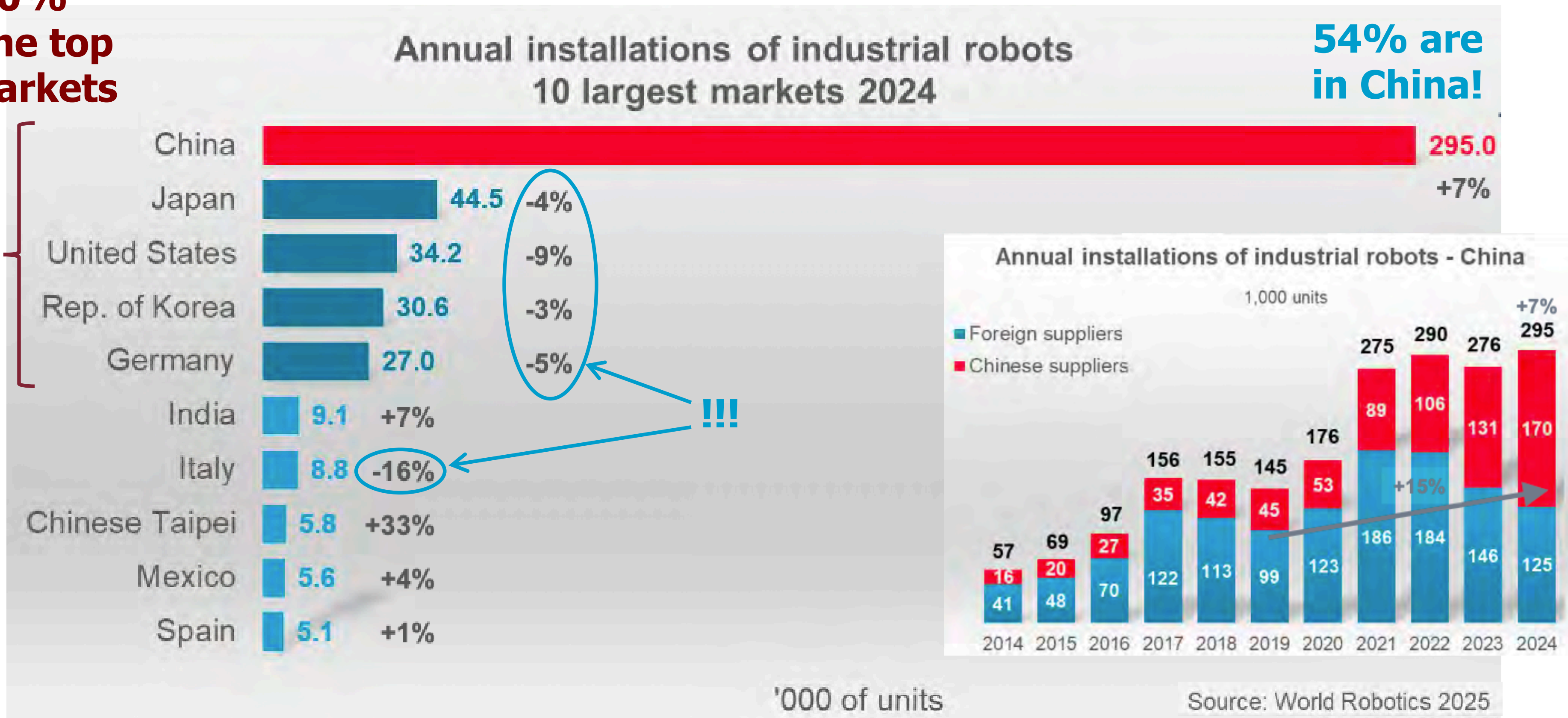
material handling by far the most important application (with 52% share)

Annual installations

new installations in top markets (countries)

80% in the top 5 markets

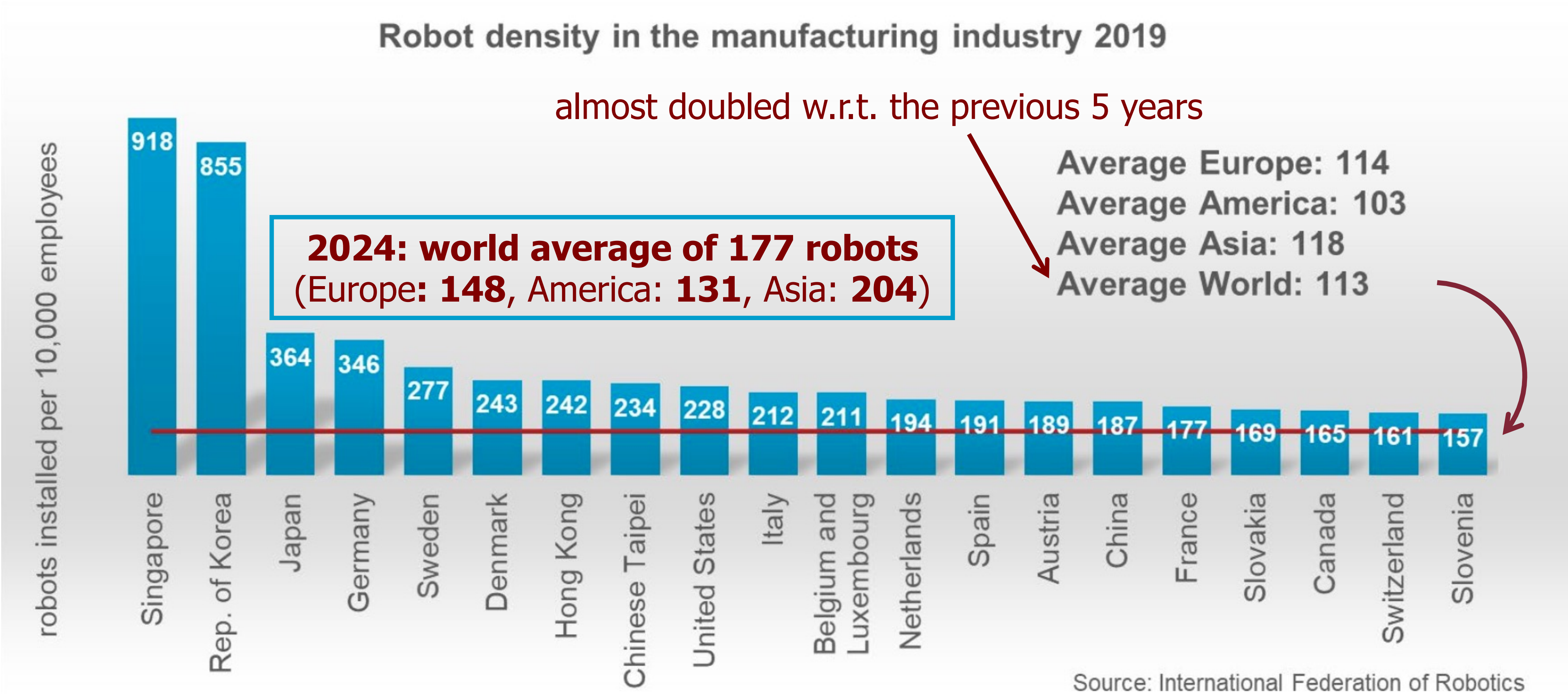
54% are in China!



market share in China by **Chinese robot suppliers** at **57%**

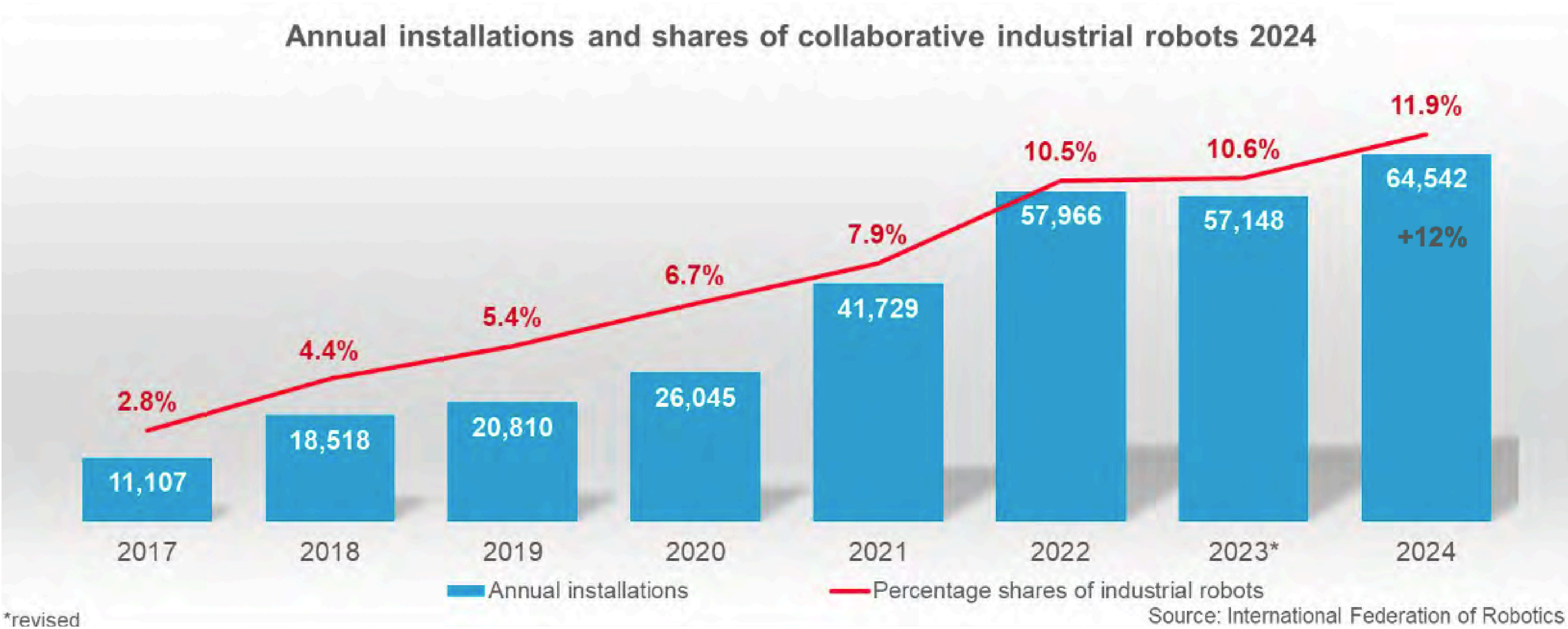
Italy (2nd EU market)**: 70% more new robots installed than in 2015**

Density of robots
[as of 2019]



number of **robots per 10000 employees**
in the **manufacturing** industry

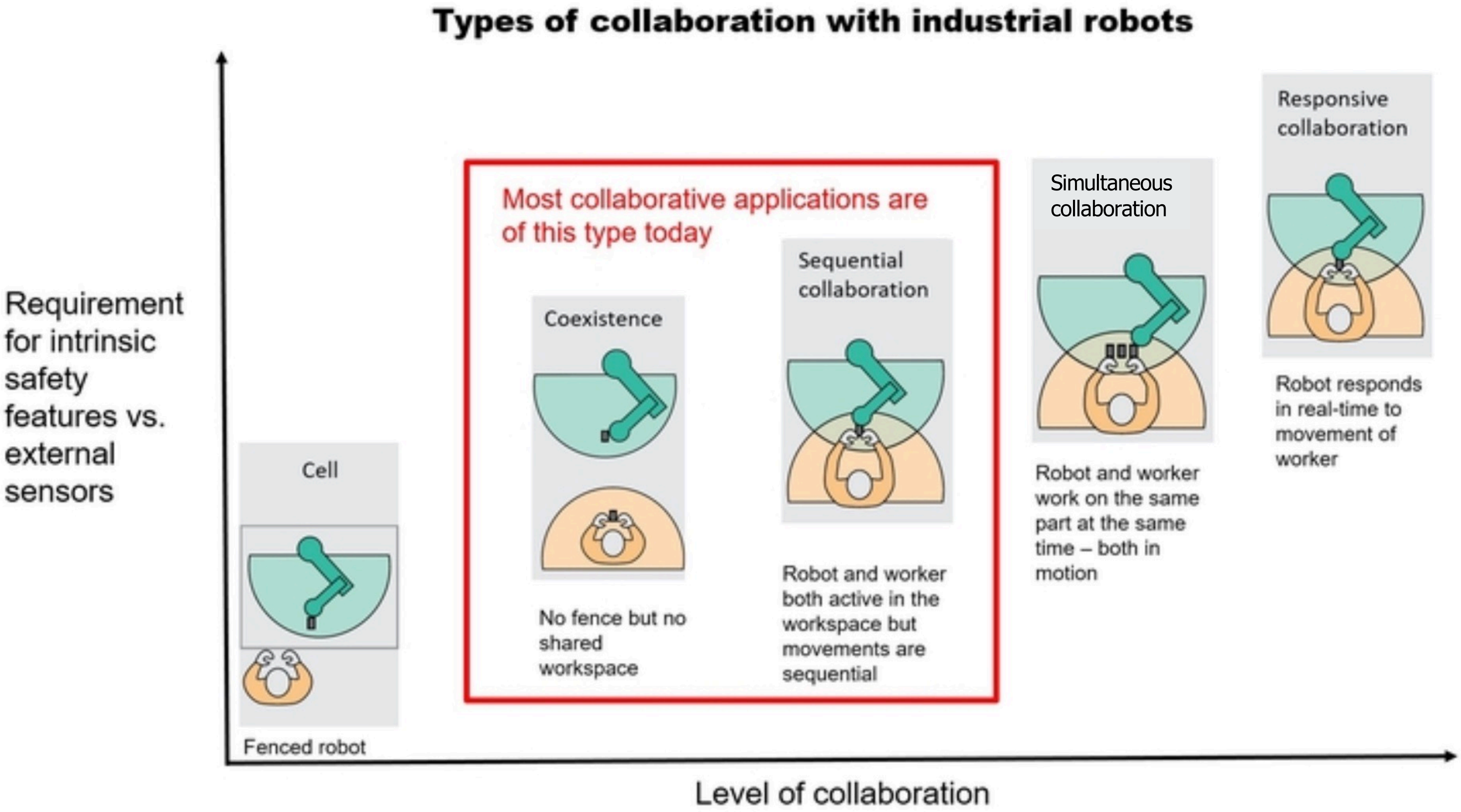
Collaborative robots
annual installations and shares in industry



market share in industrial settings **at 11.9%**

growth in double digit rate (**at 12%**)

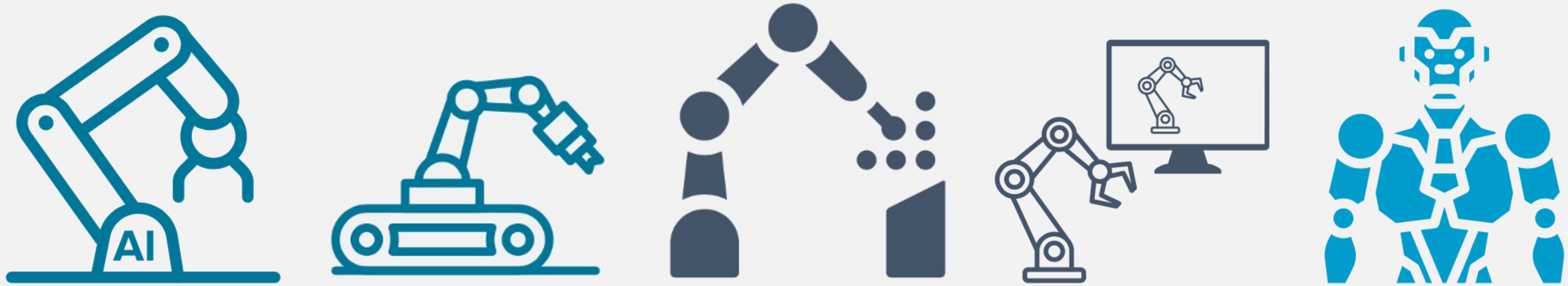
Levels of human-robot collaboration
in industrial settings



source, IFR 2022

Top trends in industrial robotics - 2024

AI and Machine Learning	Mobile manipulators	Cobots in new applications	Digital Twin	Humanoids



improved **AI** solutions at incredible pace: "physical" AI & generative AI in new applications

transportation & handling tasks to be **jointly automated** end-to-end in one device

two enabling technologies for **Industry 4.0** and **5.0** (sustainable, resilient, human-centric & energy-efficient)

R&D of humanoid robots has boosted, **but** still
i) few commercial deployments
ii) mainly single purpose

Industrial & service robots

Industrial robots

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

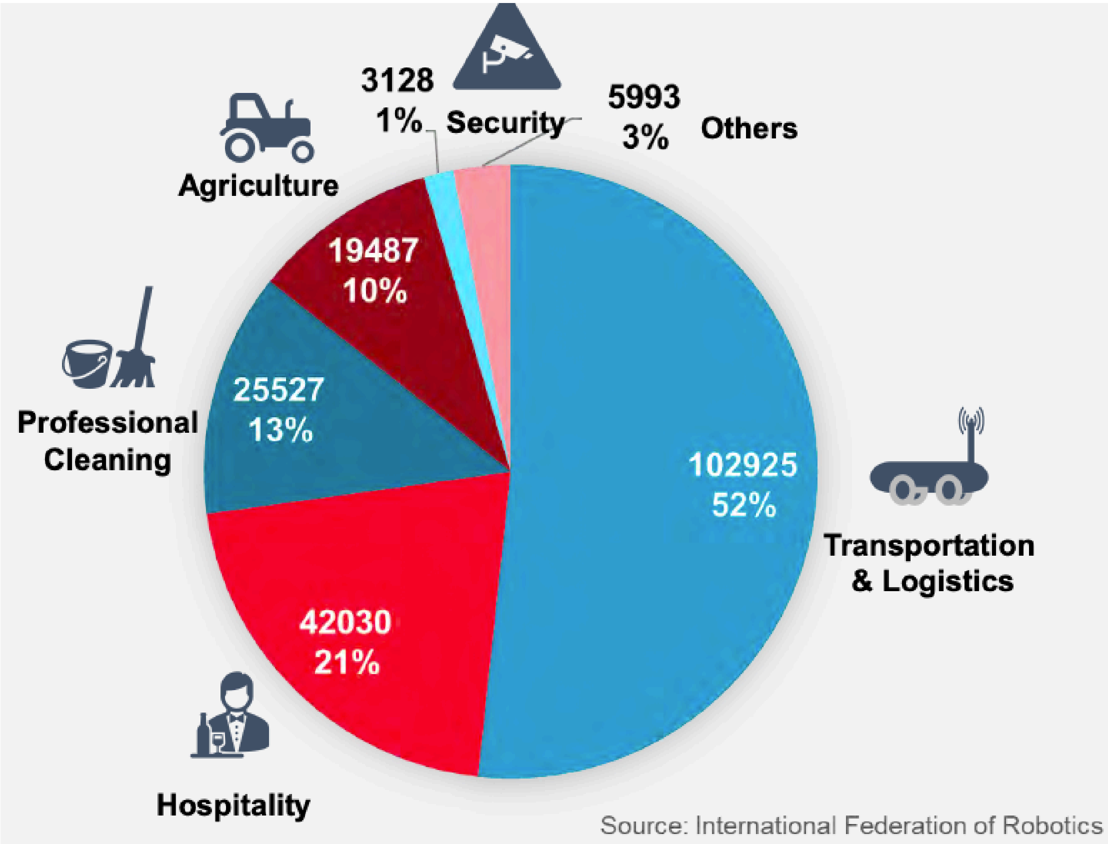
Service robots

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

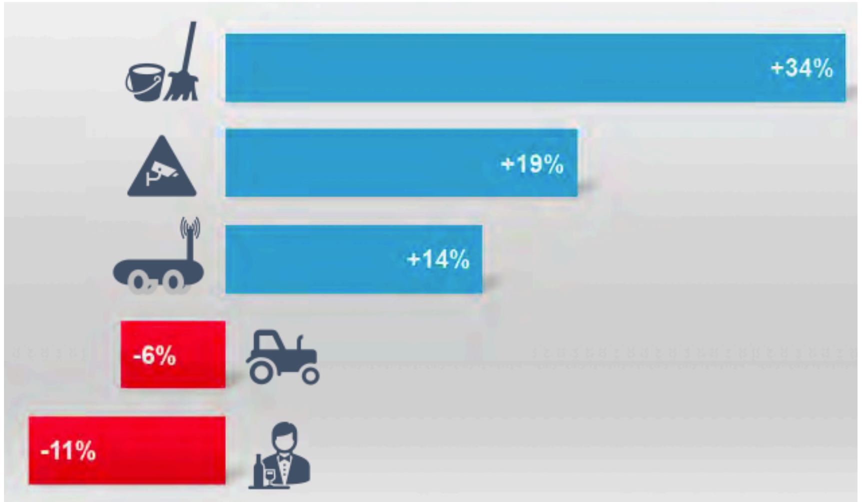
different customers, pricing, machinery, distribution channels, suppliers

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

Professional service robots
excluding medical robots (since WR 2025)



growth rates of top 5 applications of professional service robots (2023 to 2024)



new professional service robots in 2024: ~200K units (+9%)

… compare with new personal/domestic service robots: 20.1M units!!

Medical robots

Surgery

Image: Kawasaki

+41%

Rehabilitation & non-invasive therapy

Image: Life Science Robotics

+106%

Diagnostics & Medical laboratory analysis

Image: ABB Robotics

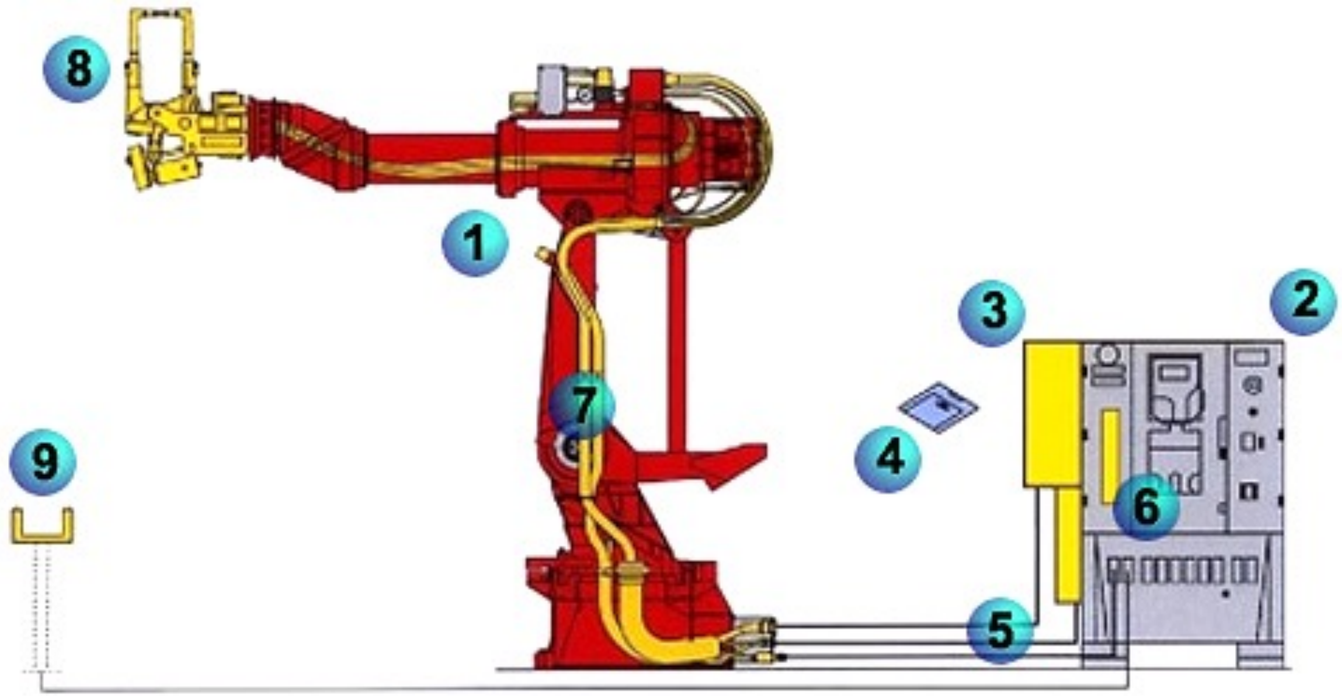
+610%

medical robots growing strongly:
16700 new units in 2024 (+91%)

daVinci 5 surgical robot
by **Intuitive**
(cost ≈ **1.5M$** in 2024)

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



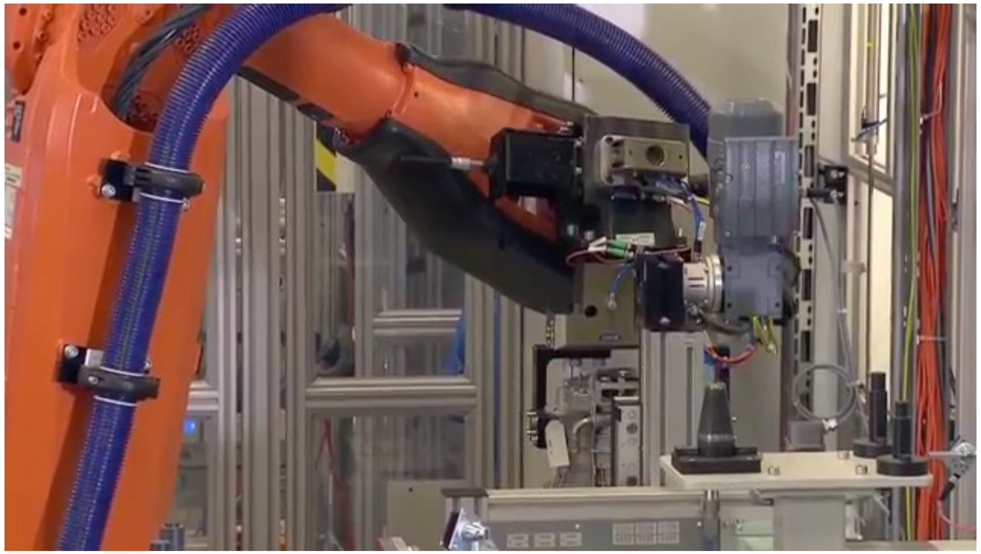

A day in the life of an industrial robot

- At BMW car production line with ABB robots

video

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

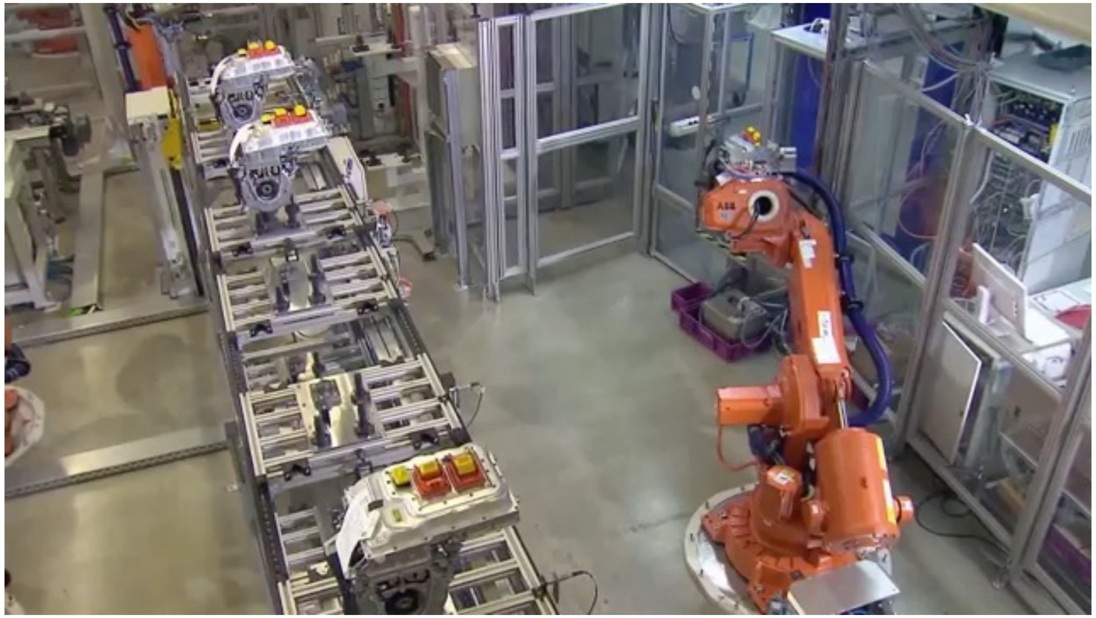
video



pick-and-place
with support
to reorient part

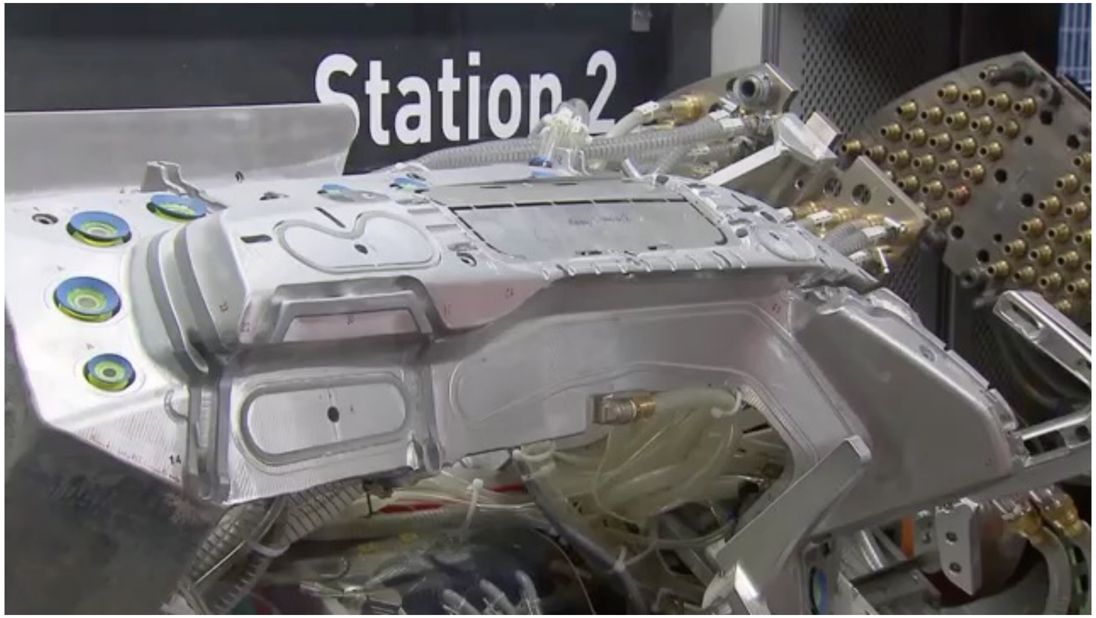
A day in the life of an industrial robot

video



pick-and-place
heavy parts and
human intervention

video



metal cutting
on a supporting
machine with dofs

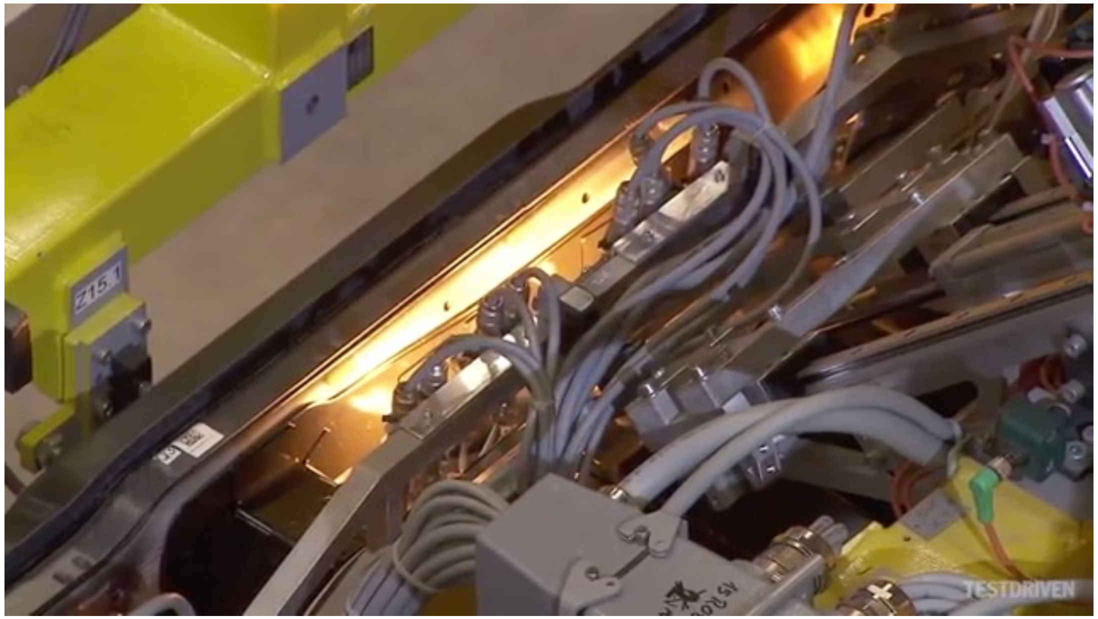
(video speeded up
at some point)

A day in the life of an industrial robot

video

glue deposit
(on fancy paths!)

video



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

A day in the life of an industrial robot

video

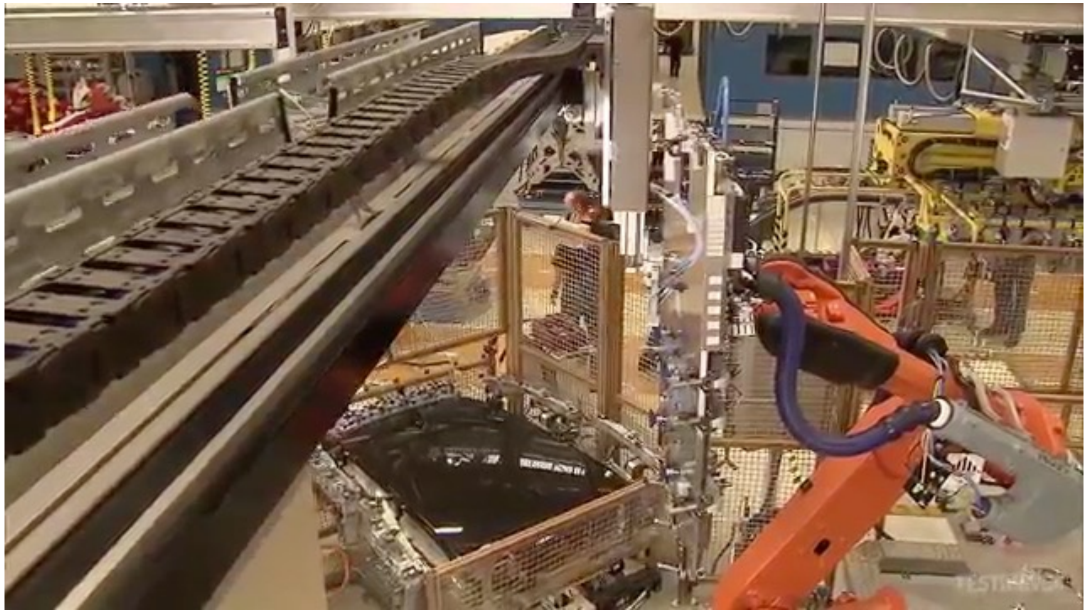
coating parts
for rust and corrosion protection

video

spray painting

A day in the life of an industrial robot

video



hood deburring
with a suspended tool

video

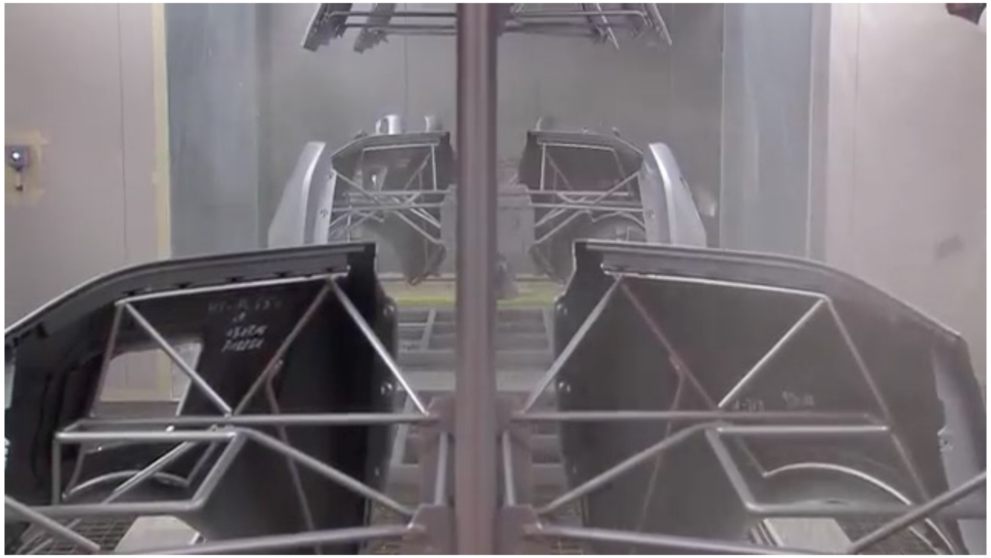
test measurements
with assembly on a AGV

What a robot should do and what cannot do

yet

video

video



spray painting
very unhealthy
for human operators

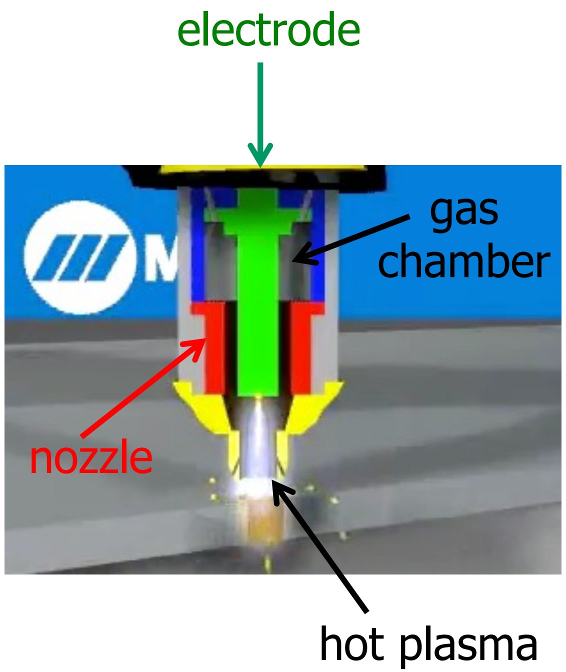
assembly of flexible
or complex parts
(here a car dashboard)

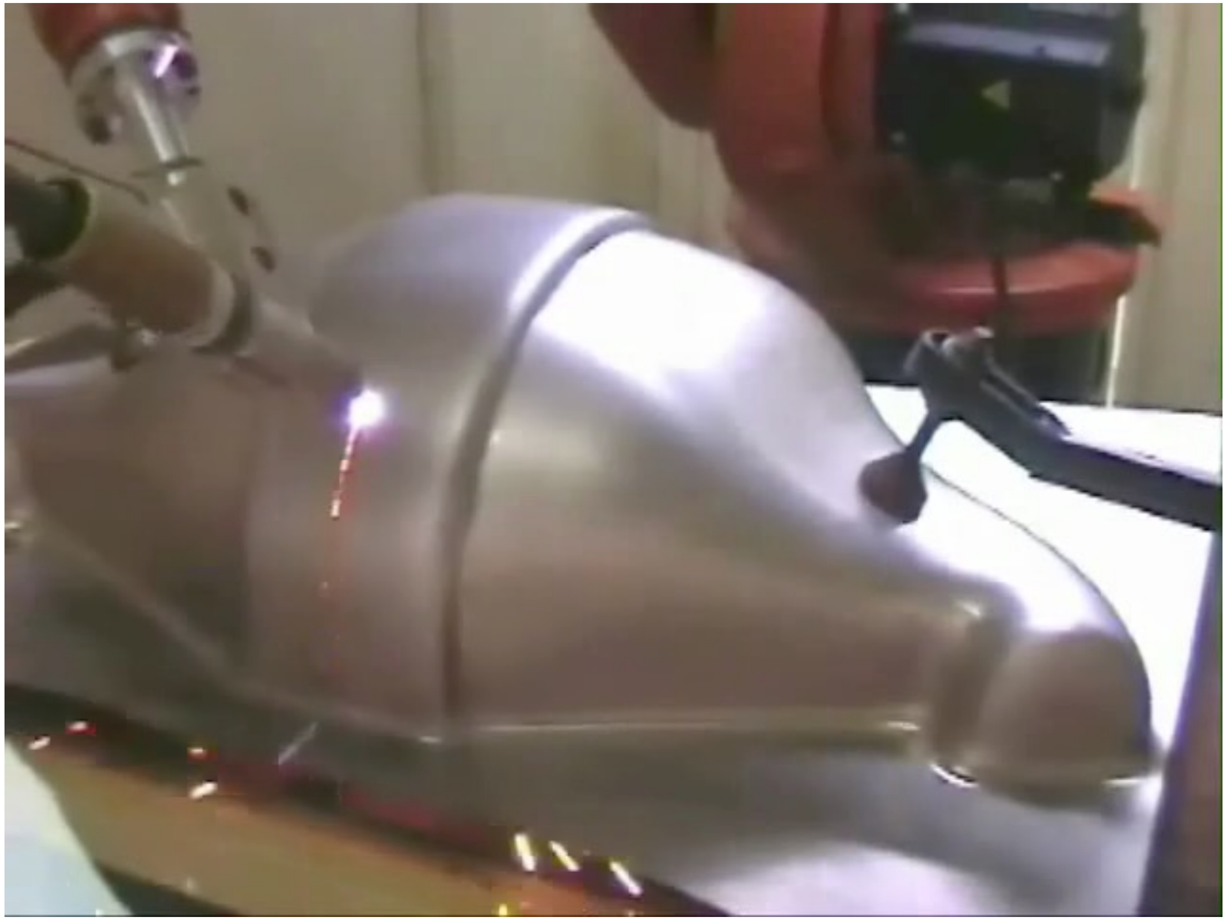
⇒ human-robot **collaboration**
(co-bots or co-workers)

Reasons to automate with robots
in industrial settings

source, IFR 2022

Plasma cutting

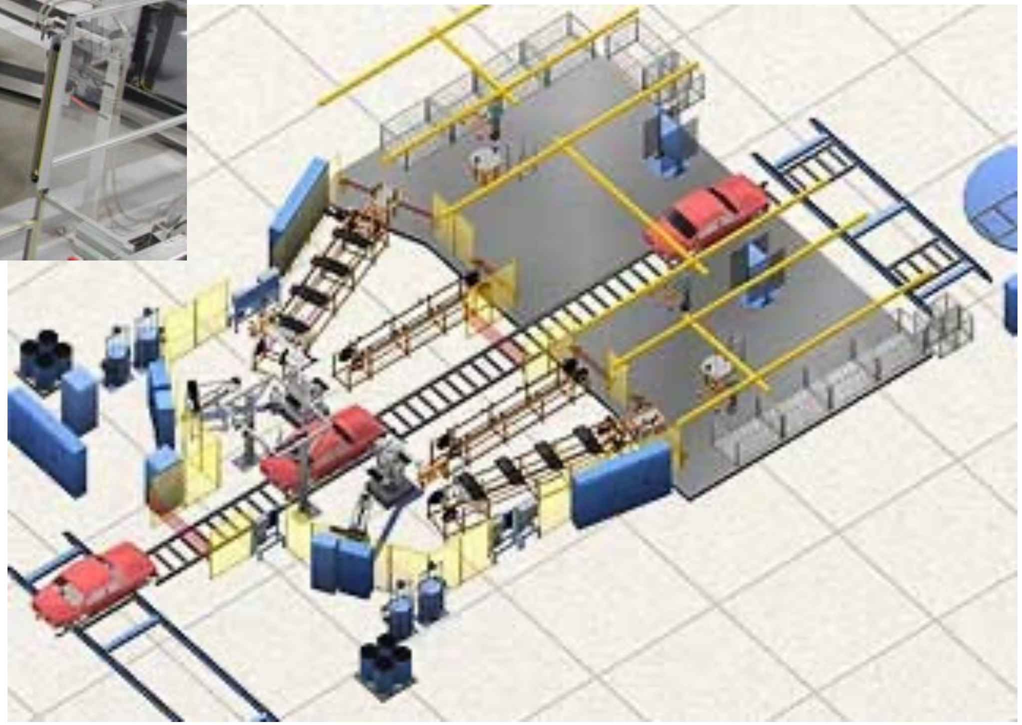




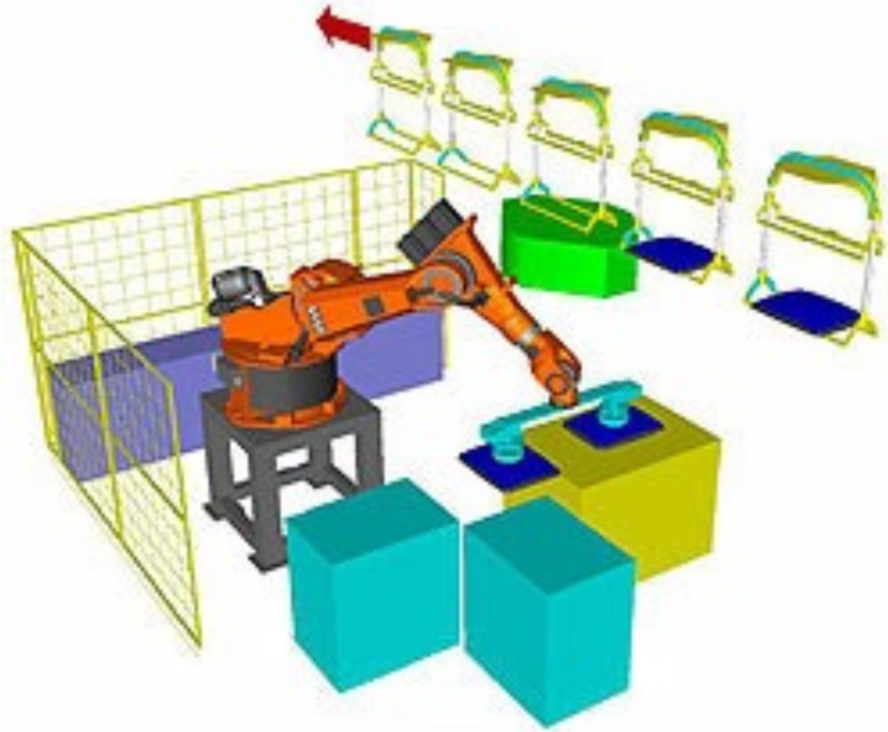
video

small KUKA robot used for plasma cutting of a stainless steel toilet
(courtesy of Engenious Solutions Pty)

Robotized workcells

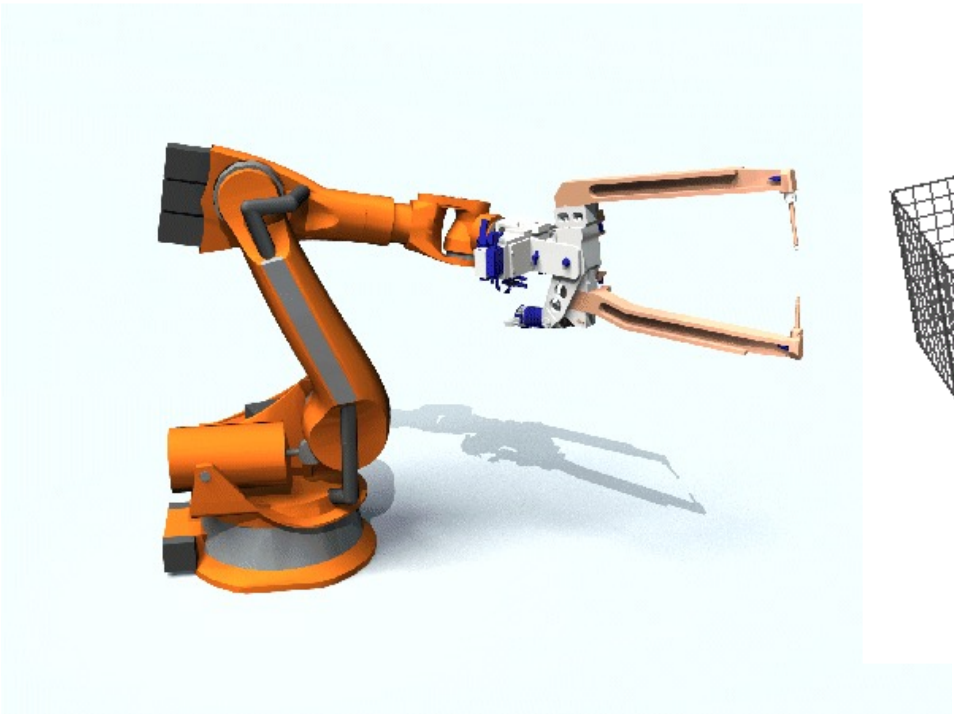


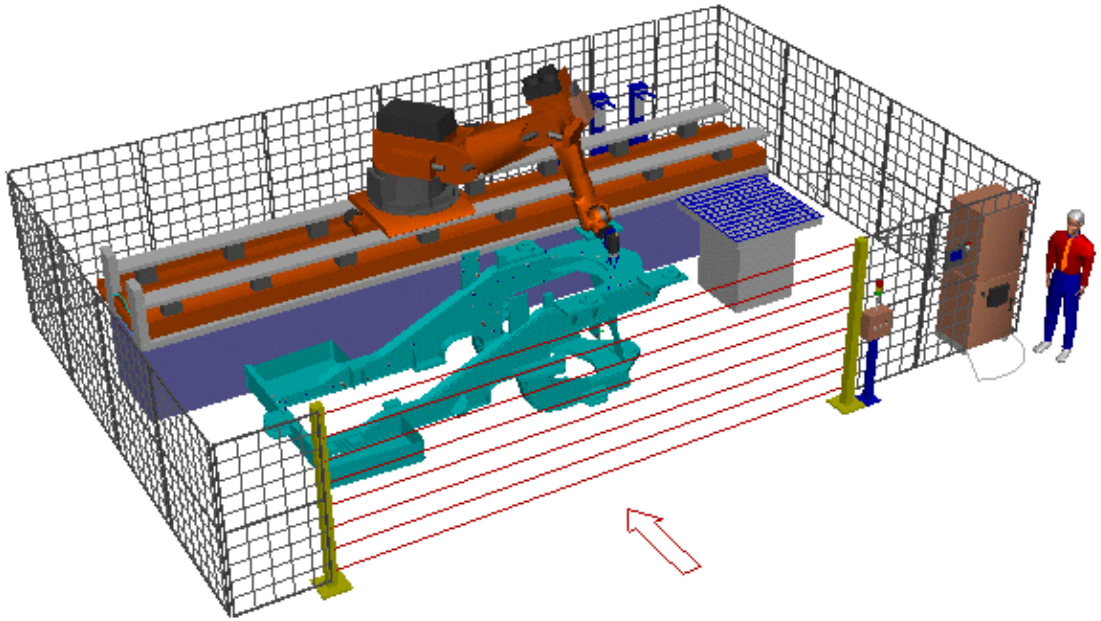
3D simulation of robotic tasks



- 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

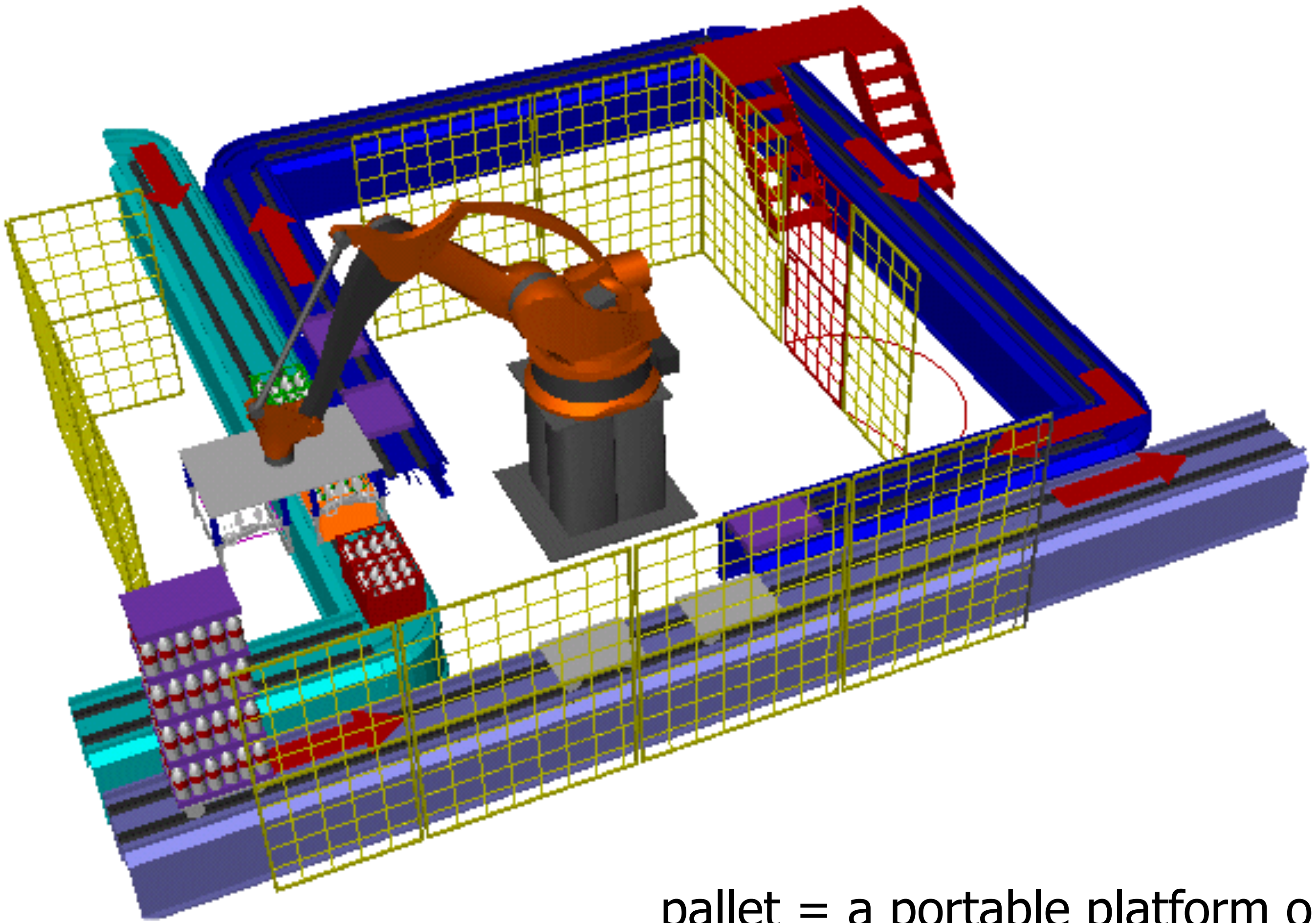
Welding - 2

- spot (discrete) or arc (continuous)

Two cooperating robots in arc welding

ABB video at Laxa, Sweden

Palletizing



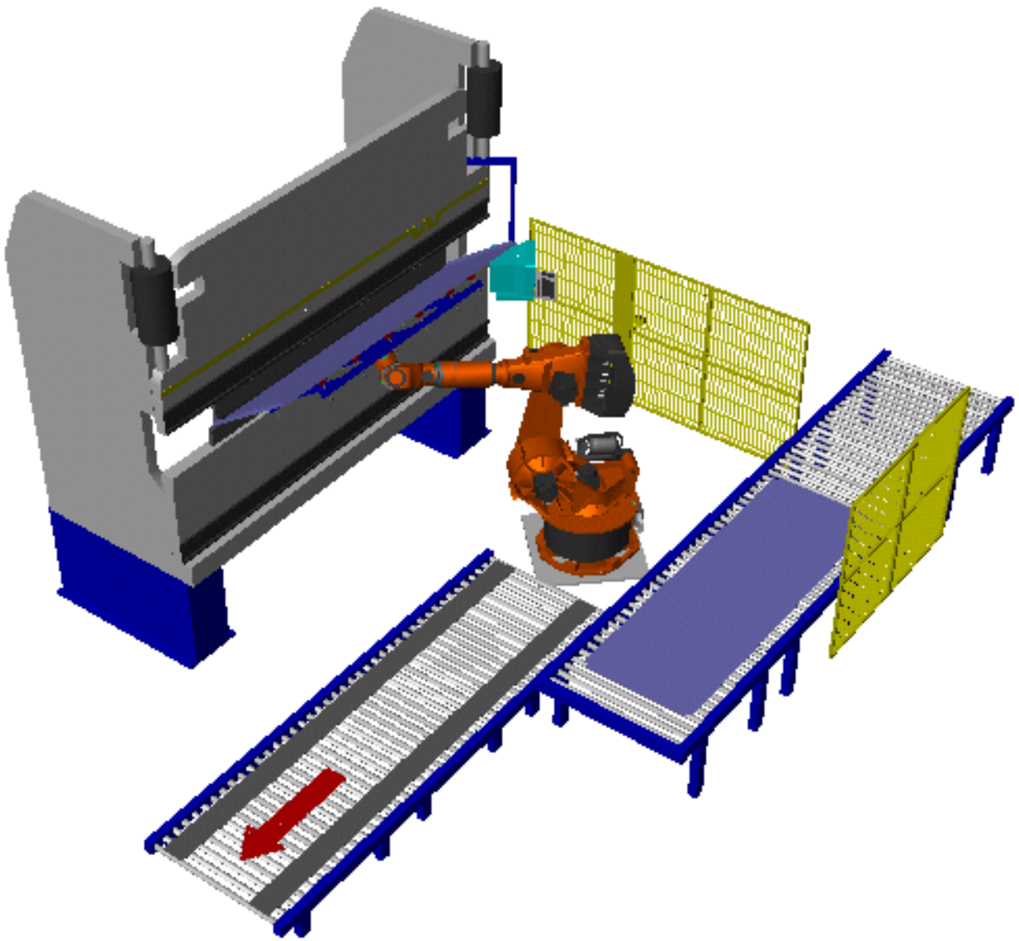
pallet = a portable platform on which goods can be moved, stacked, and stored

Palletizing of cheese forms

video

using Kawasaki robots (courtesy of Effedue Engineering)

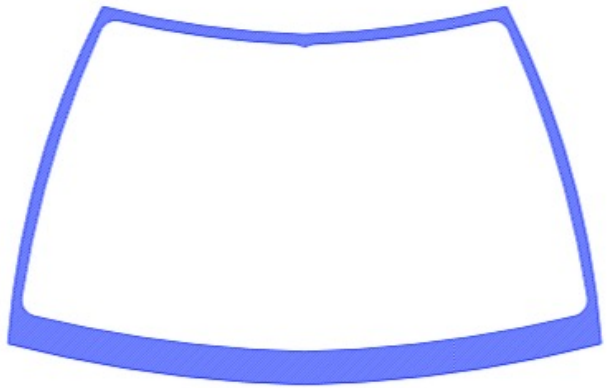
Folding

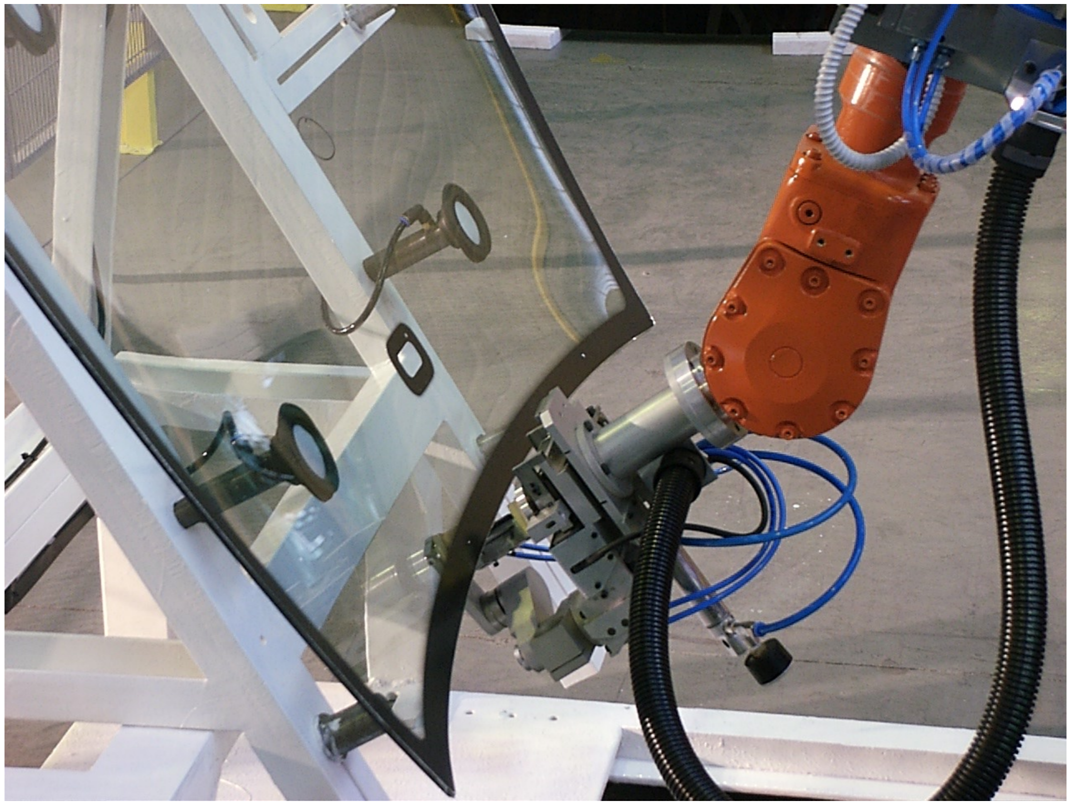


with loading of sheets under the press

Deburring

- car windshields may have large manufacturing tolerances and a sharp contour profile





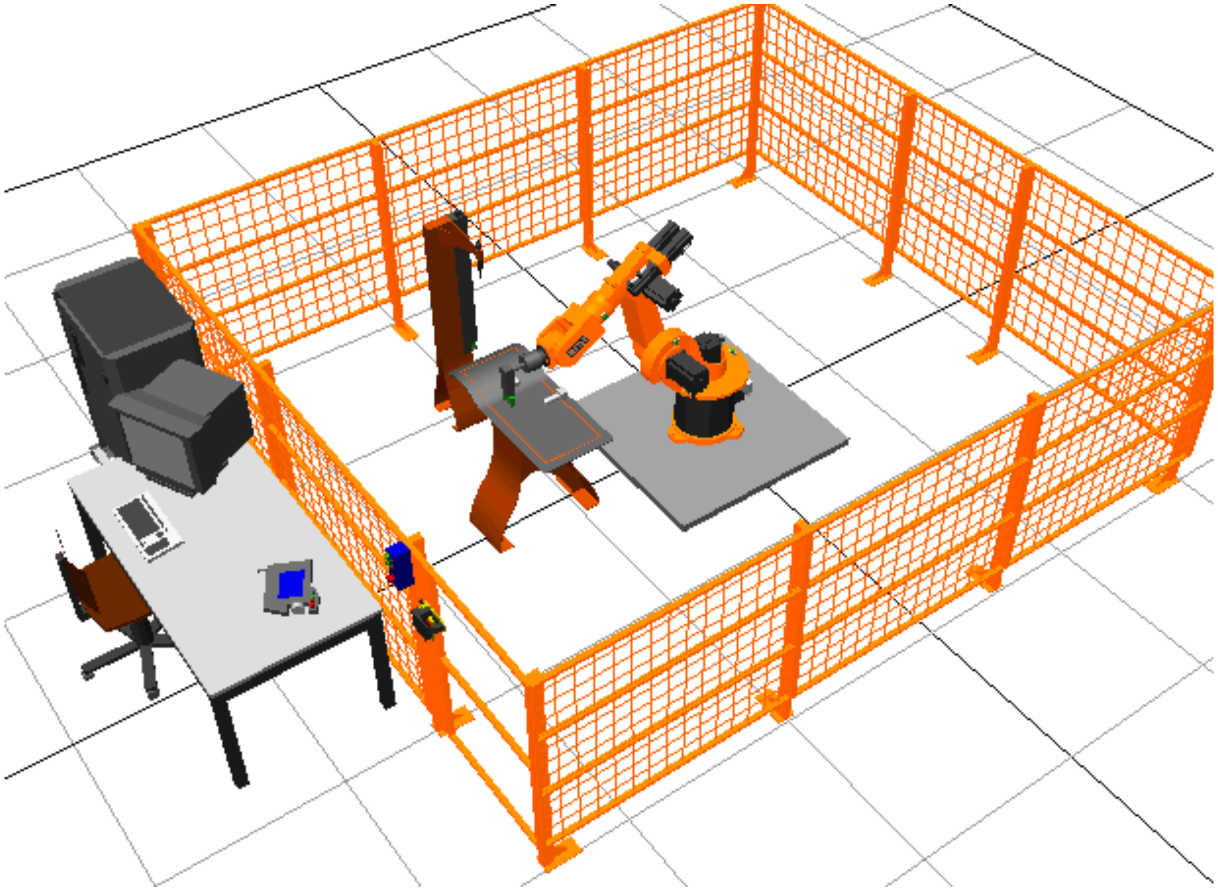
- the robot follows a given predefined Cartesian path
- the contact force between cutting blade and glass must be feedback controlled
- deburring robot head mounts a force load cell and is pneumatically actuated

Deburring center

video

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

video

fastest SCARA robot for pick-and-place tasks!

Cartesian or gantry robots

video

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

Delta and Hexa parallel robots

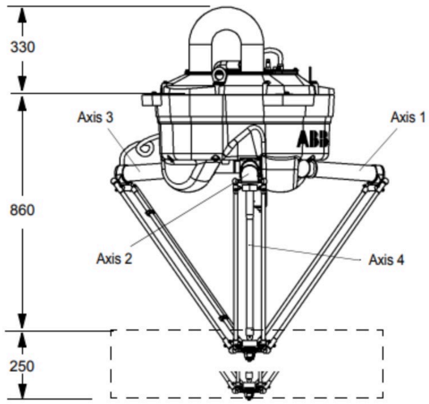


ABB 365
Flexpicker
5-DOF Delta
parallel
kinematics

video

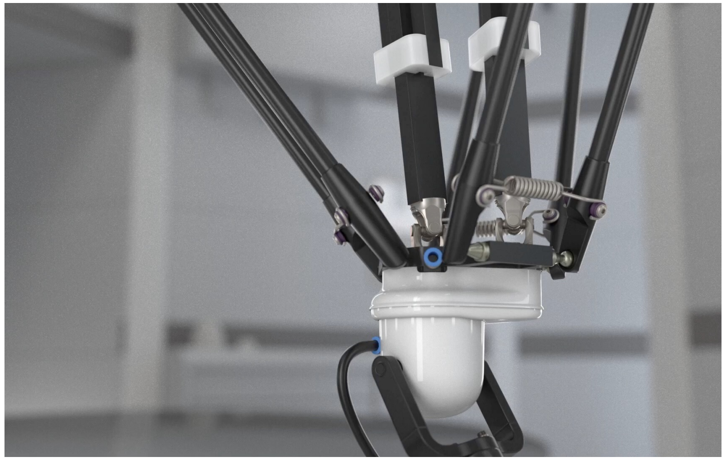
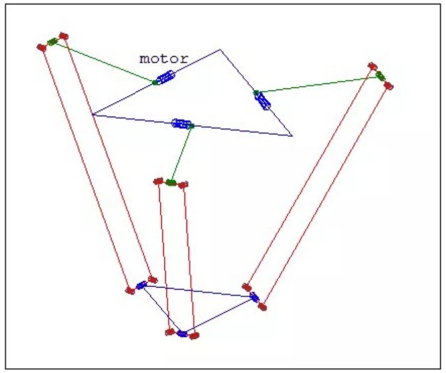
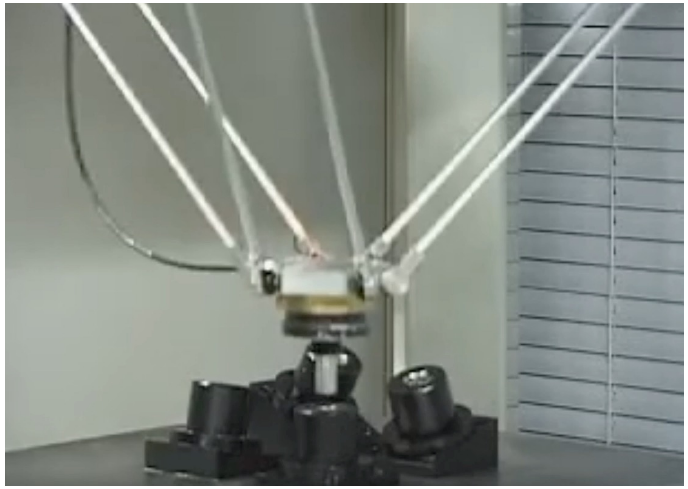


ABB 340 Flexpicker
4-DOF Delta parallel kinematics
1-2 kg payload, max speed 19 m/s
150 pick-and-place ops/minute



3-DOF Delta
in motion
(https://link to web)



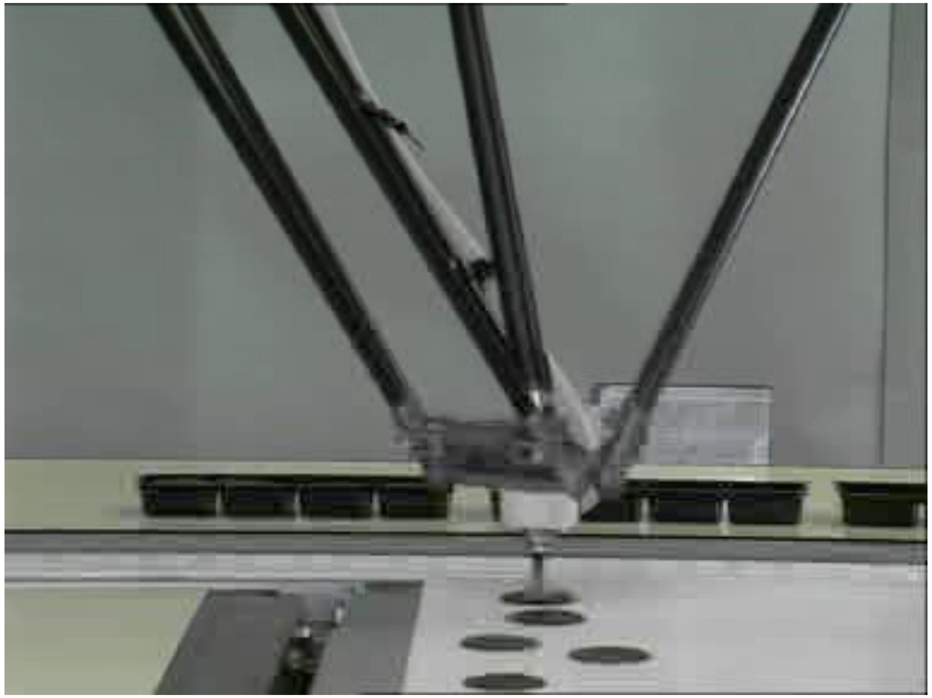
Hexa robot

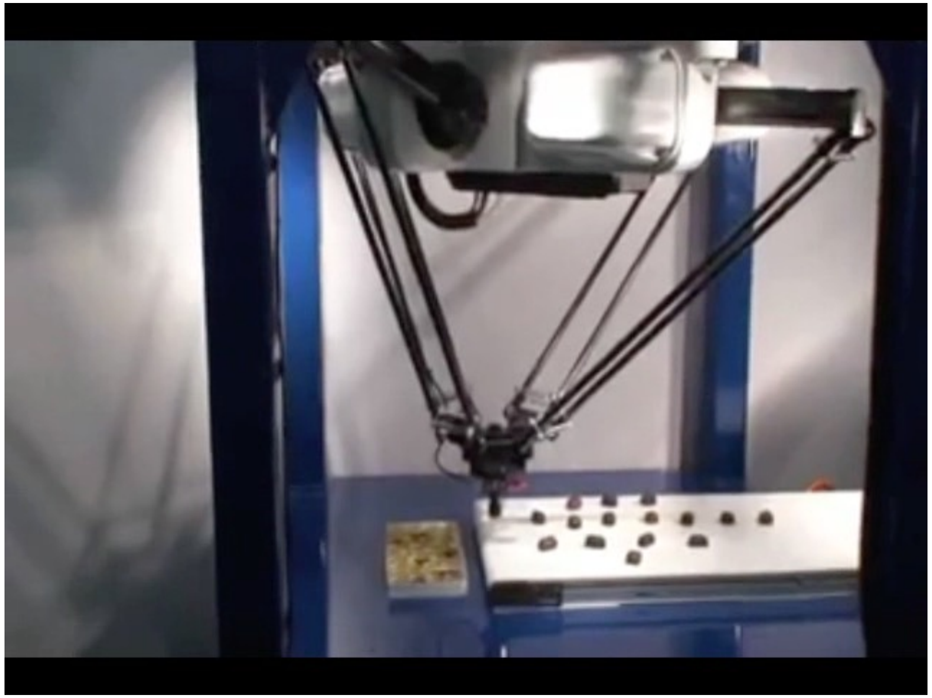
video

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



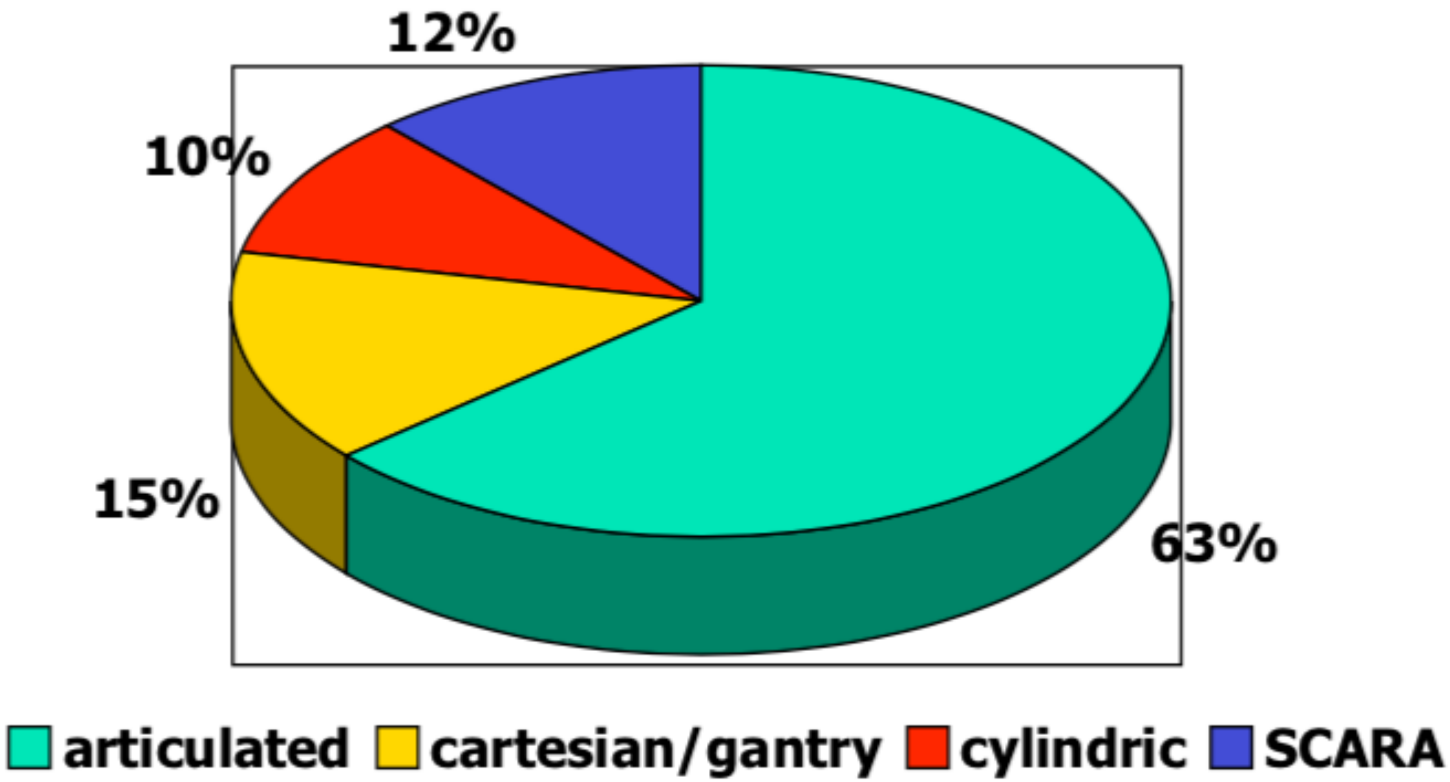


test video with
ABB Flexpicker

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)

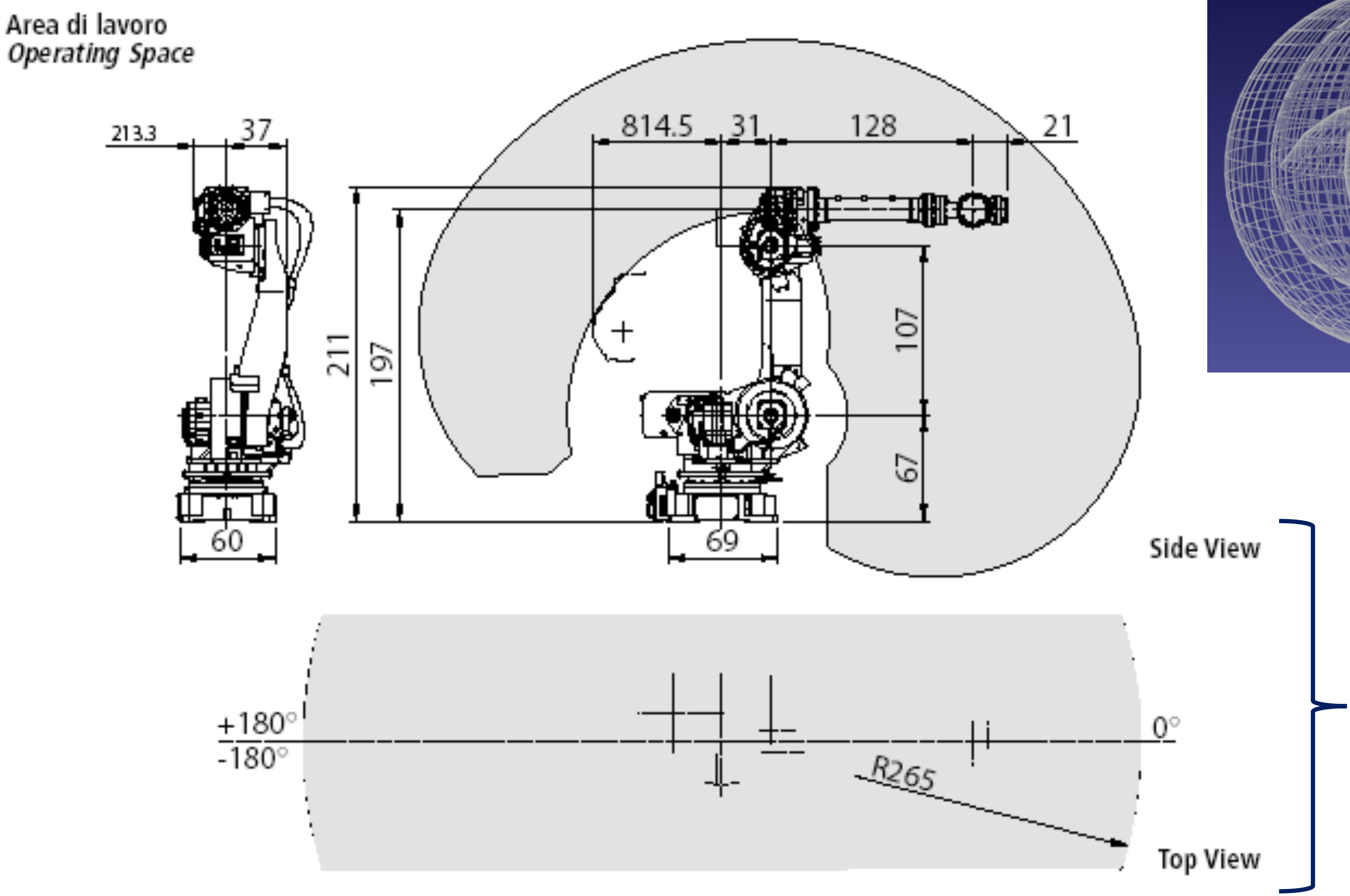
Robot data sheet

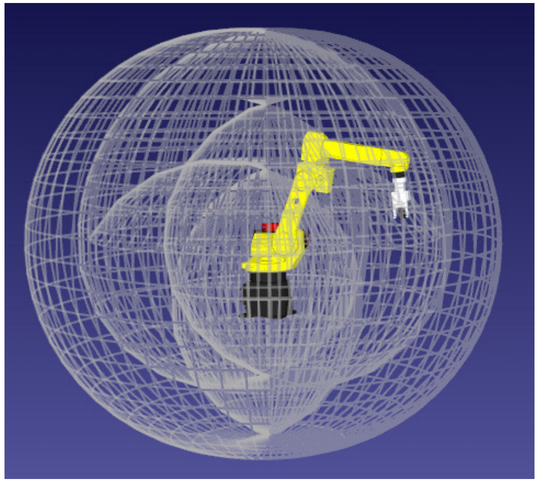
Fanuc
R-2000i/165F

Specifiche tecniche

Voce		R-2000i/165F	
Tipo		Articolato	
Assi controllati		6 assi (J1, J2, J3, J4, J5, J6)	
Installazione		A pavimento	
Area di lavoro (Velocità massima)	Rotazione asse J1	360° (105°/s)	
	Rotazione asse J2	135° (105°/s)	
	Rotazione asse J3	361,8° (105°/s)	
	Rotazione asse J4	720° (130°/s)	
	Rotazione asse J5	250° (130°/s)	
	Rotazione asse J6	720° (210°/s)	
Carico massimo al polso		165 kg	
Momento di carico max. al polso (Nota 1)	Asse J4	94kgfm	921Nm
	Asse J5	94kgfm	921Nm
	Asse J6	47kgfm	461Nm
Momento di inerzia max. al polso	Asse J4	800kgfcms^2	78,4kgm^2
	Asse J5	800kgfcms^2	78,4kgm^2
	Asse J6	410kgfcms^2	40,12kgm^2
Tipo di azionamento		Motori elettrici AC	
Ripetibilità		± 0,3 mm	
Peso		1.210 kg	
Ambiente installazione		Temperatura ambiente: Umidità ambiente Normale: Breve (in un mese) Vibrazioni	0-45° C ≤ 75% ≤ 95% 0,5 G max.

Workspace





should be 'embedded' in 3D (by the rotation of the first joint)

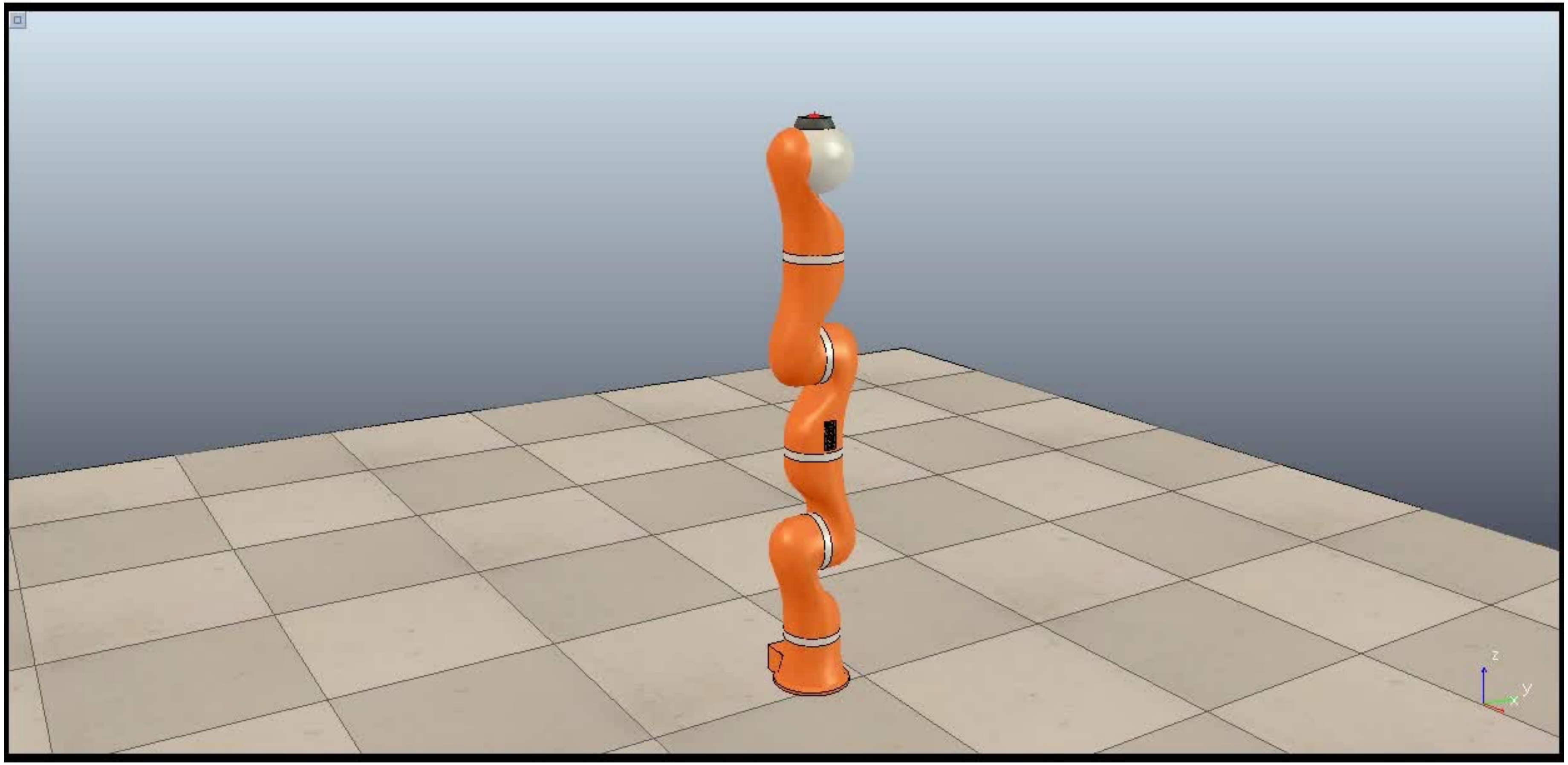
Mobility and workspace
visualization

video

kinematic simulation of a 6-dof Comau robot (all revolute joints)

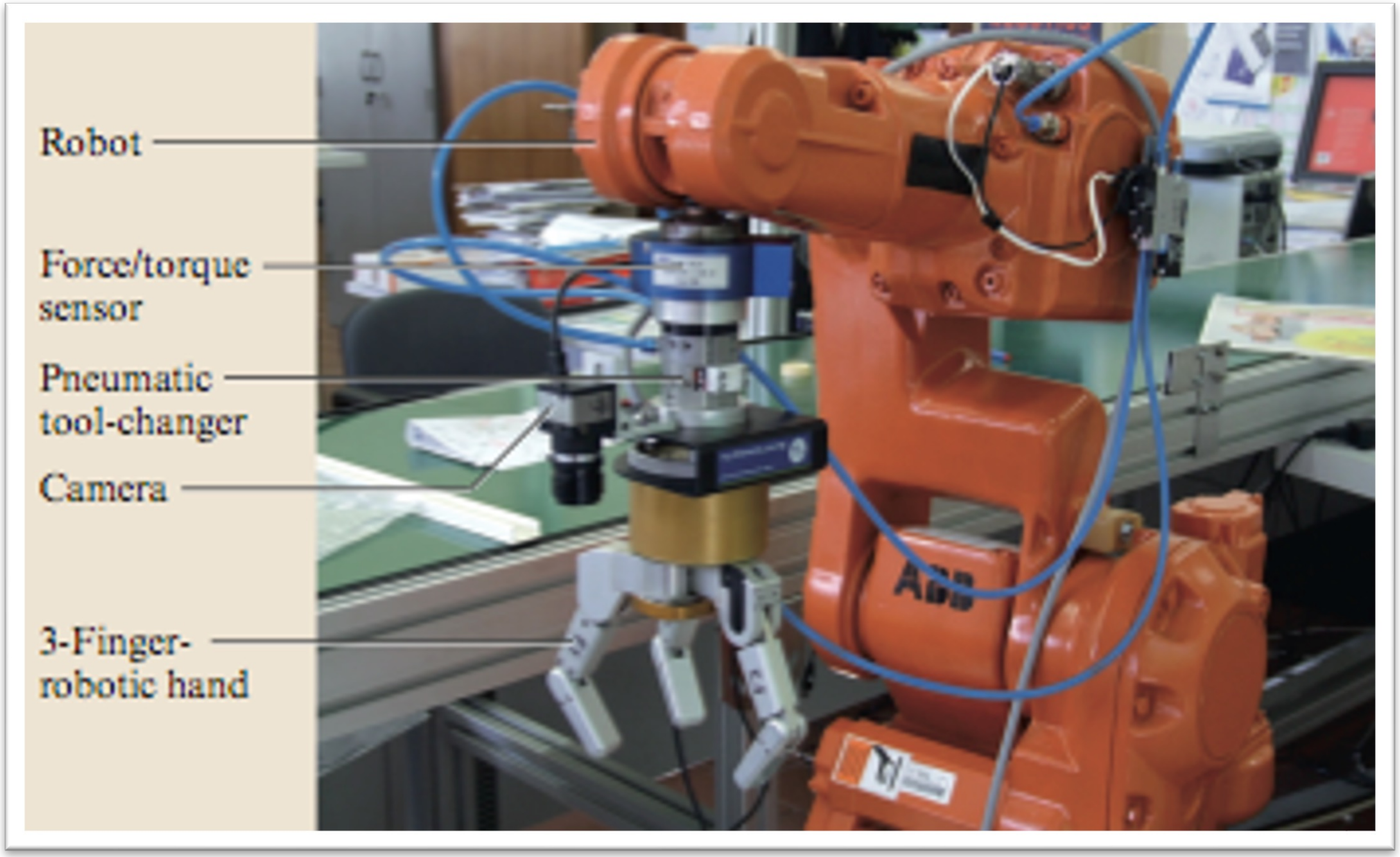
Mobility and workspace
visualization

video

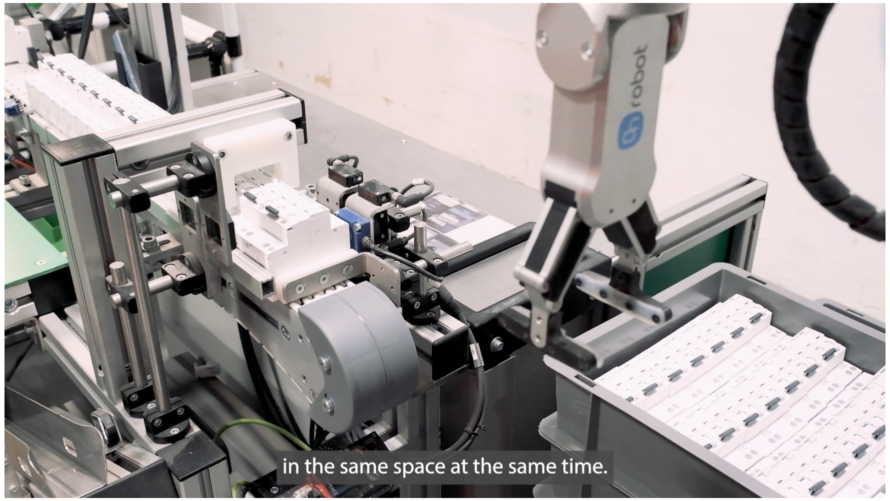


CoppeliaSim simulation of the 7-dof KUKA LWR4+ robot (all revolute joints)

Robot end-effector sensors and tools



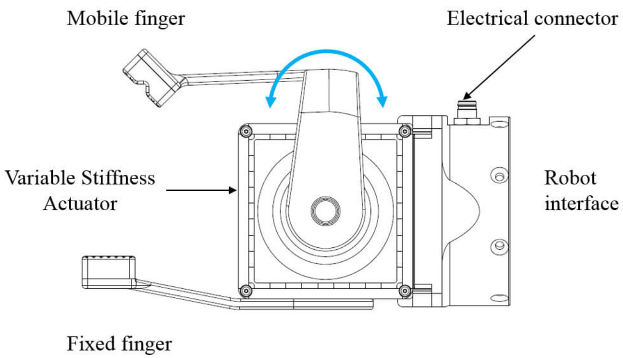
Simple (rigid to soft) grippers



video

OnRobot RG6 and Soft Grippers

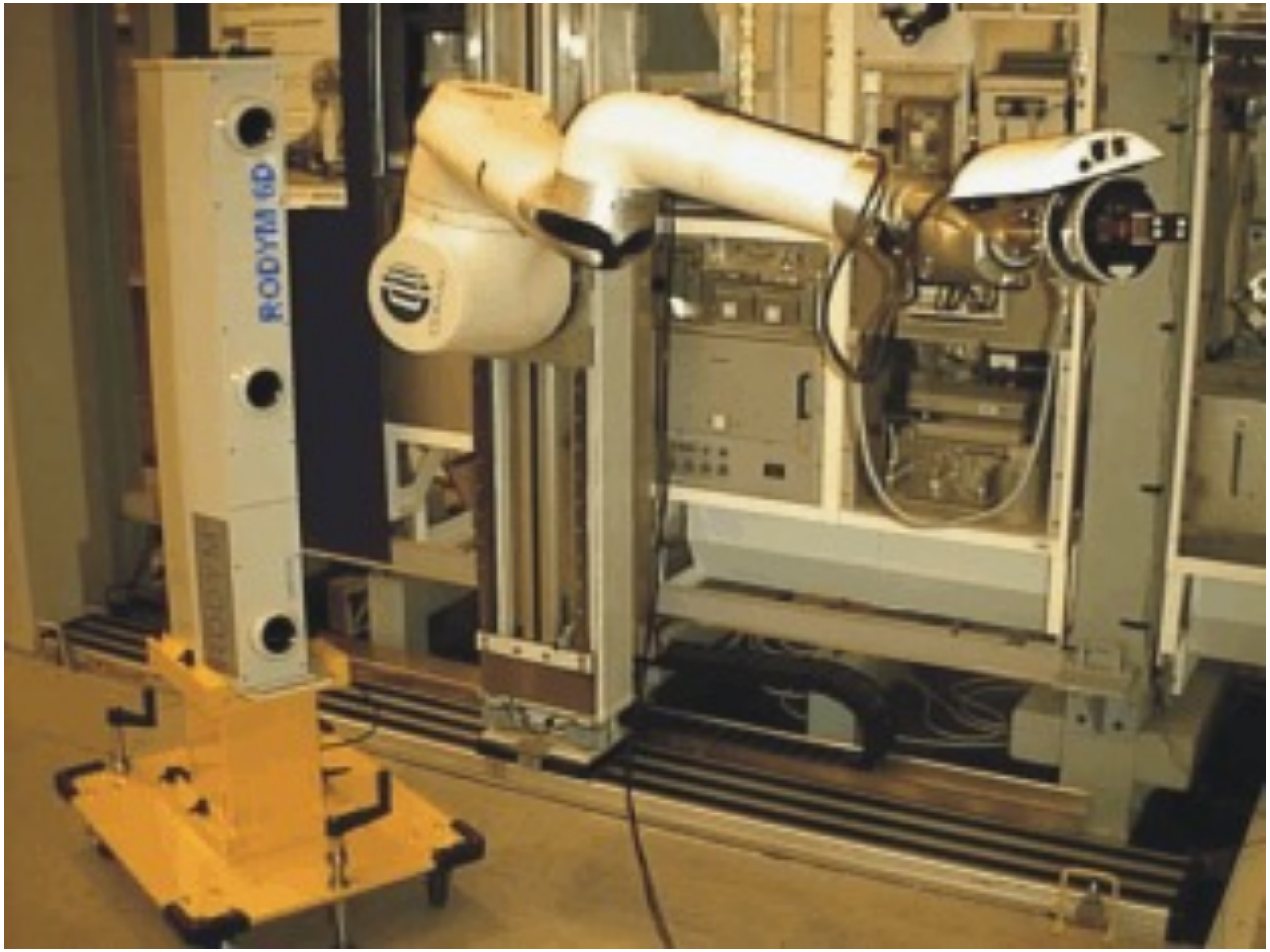
video



qbrobotics SoftClaw

https://youtu.be/FOM5Pl6Yb4U

Calibration of robot kinematics

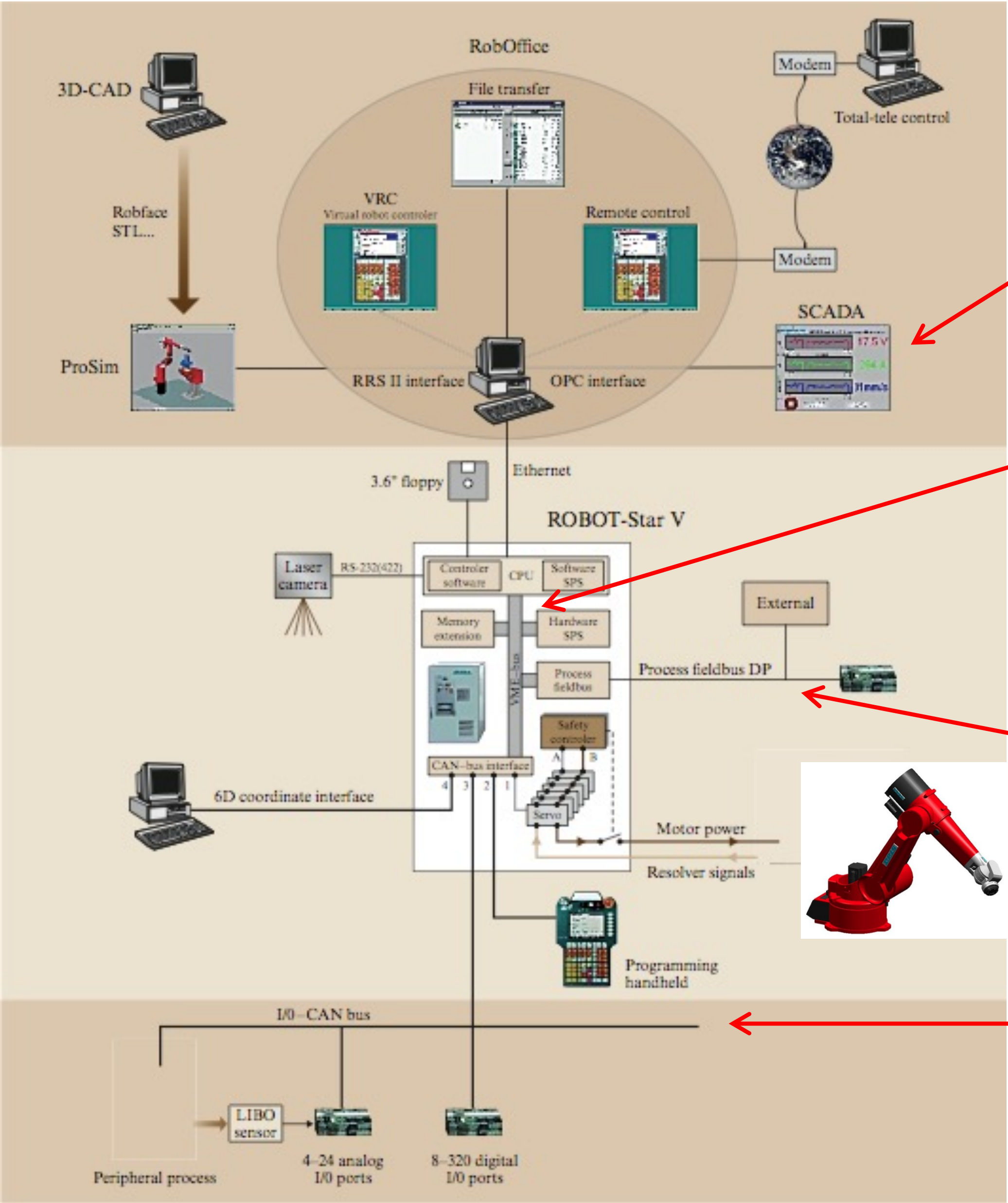


Man-machine interface
most traditional ones

- teach-box pendants used as robot programming interface (now also with 3D view)
- cabinet with power electronics for robot supervision and control

Programming and control environment

control modules and interfaces (Reis Robotics)



communication keywords

SCADA = Supervisory Control And Data Acquisition

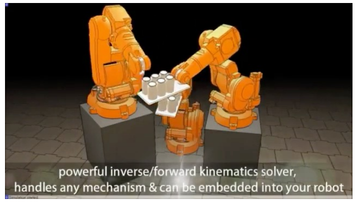
VME = internal protocol with separated data and address lines

Fieldbus = family of industrial computer network protocols for real-time distributed control

CAN [Bosch] = Controller Area Network serial bus standard (IEEE RS-485)

Motion programming and scaling

also simulated in CoppeliaSim



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/FLSDldtlHR0

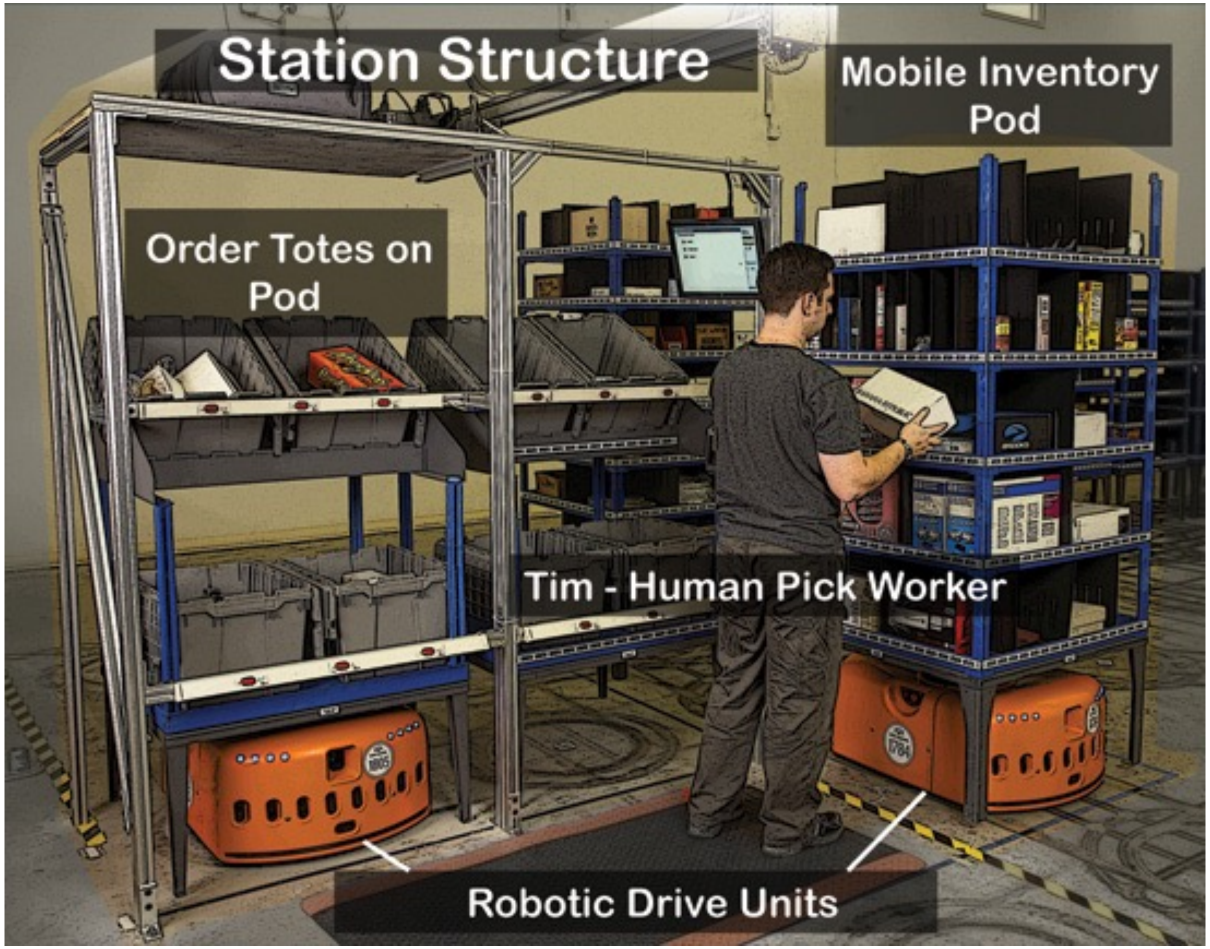
Mobile base robots in industry

- 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

IFR International Federation of Robotics

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

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

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

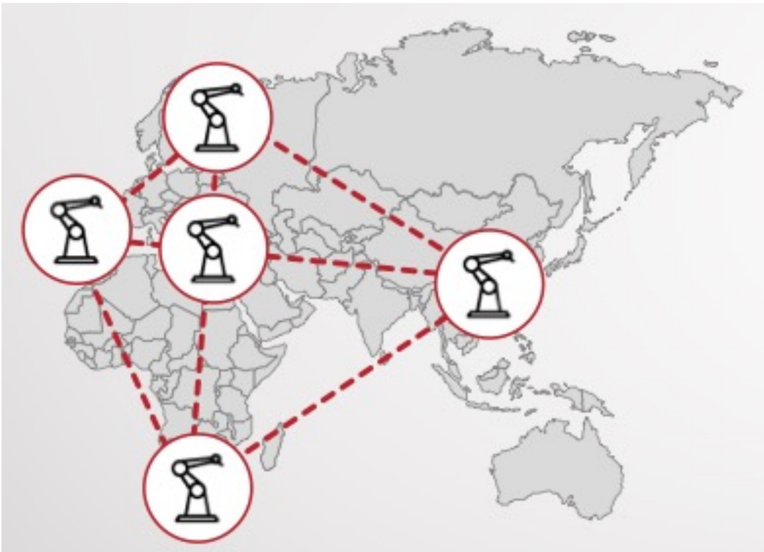
Collaboration

- **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?

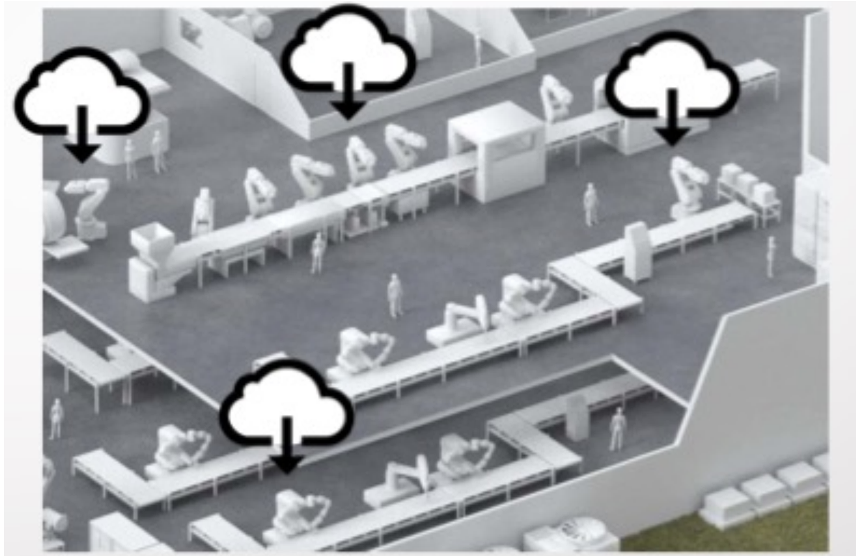
"connected" future of robotics

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