



Robotics 1

Industrial Robotics

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What is a robot?

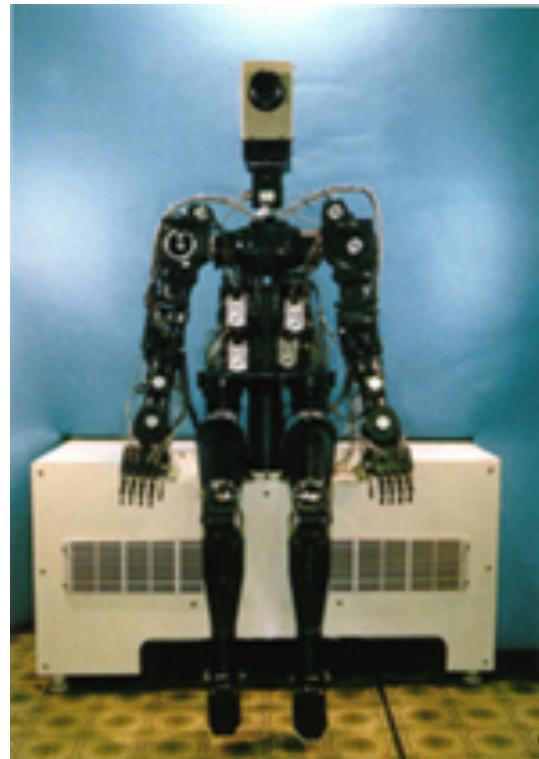
- industrial definition (RIA = Robotic Institute of America)
 - re-programmable multi-functional manipulator
 - designed to move materials, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks, which also acquire information from the environment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

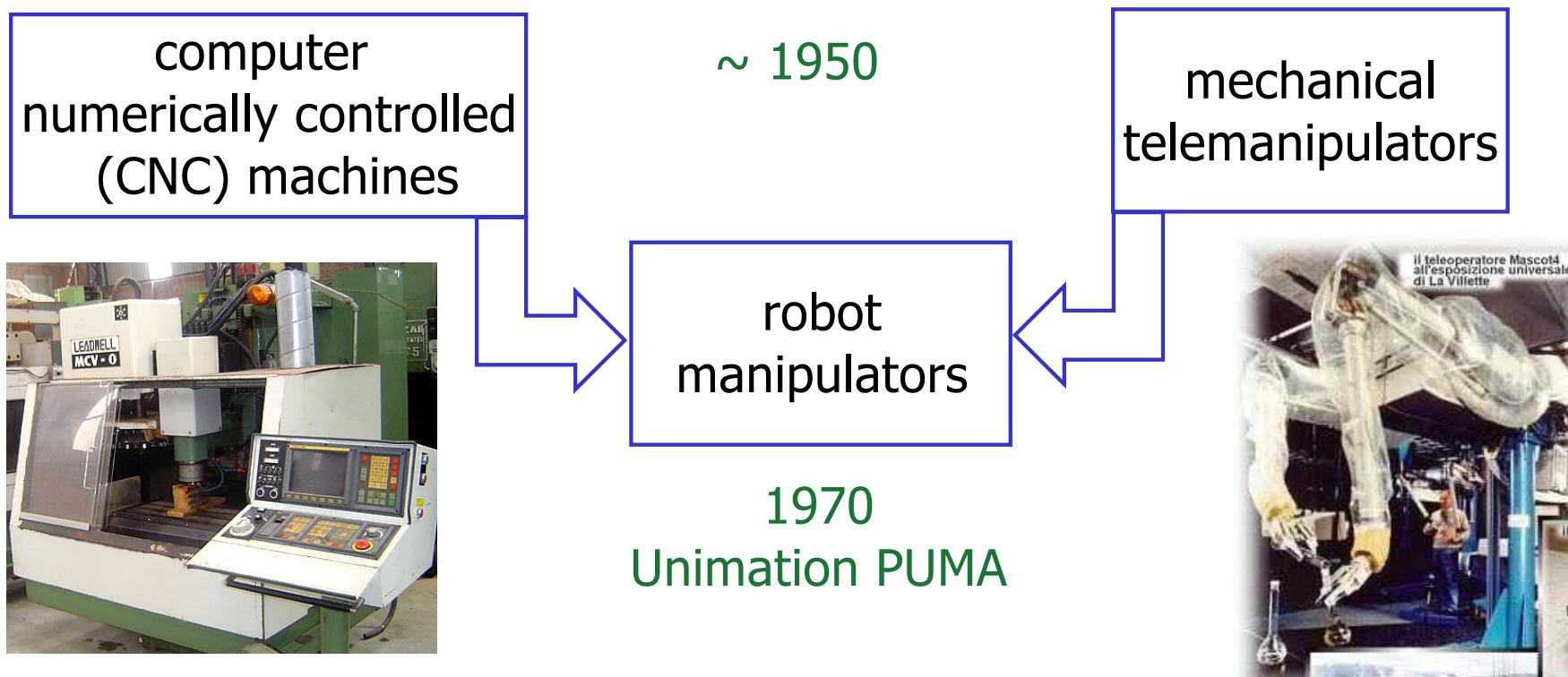


A bit of history

- **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



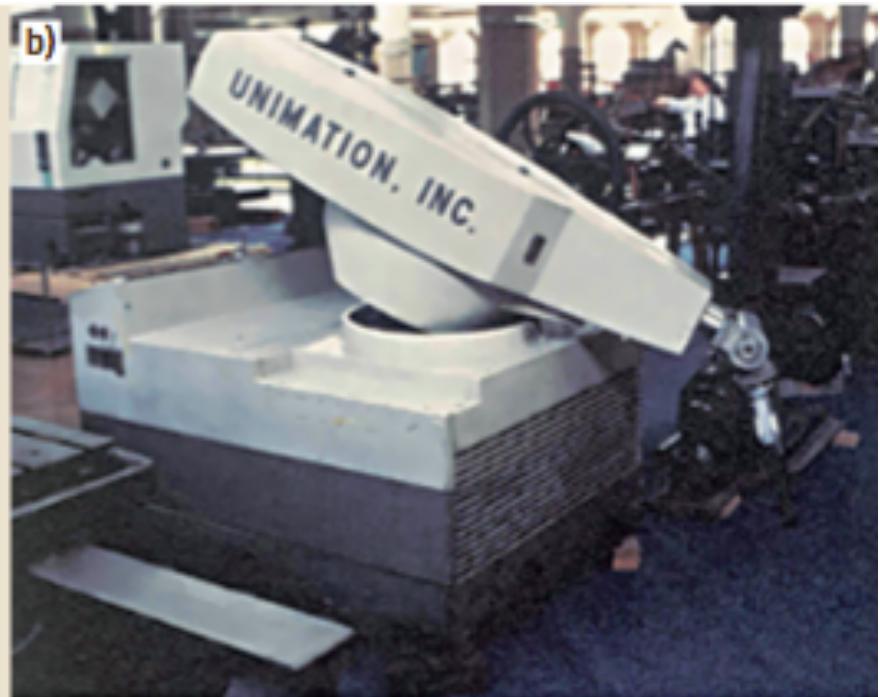
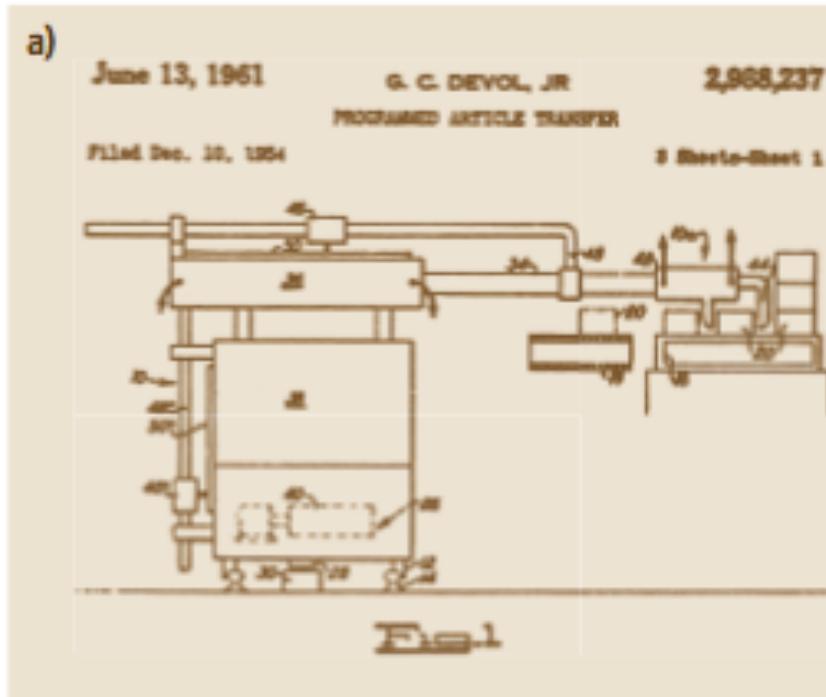
Evolution toward industrial robots



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



The first industrial robot



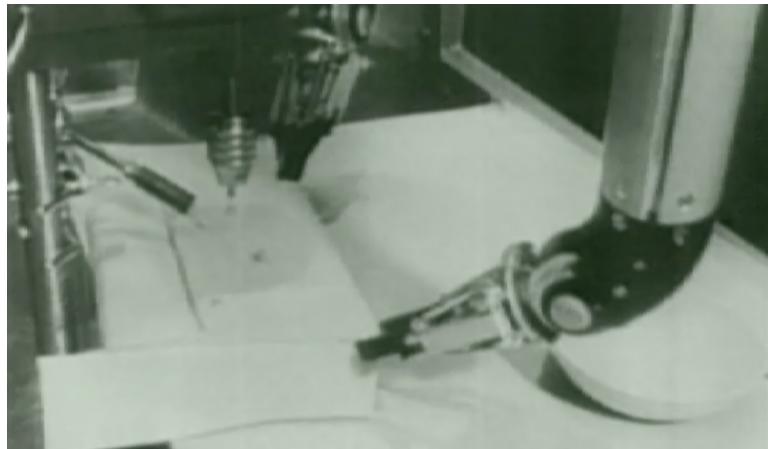
US Patent

General Motor plant, 1961

G. Devol and J. Engelberger (Unimation)



Historical pictures and clips



bimanual remote manipulation
at Oak Ridge Nat'l Labs



video



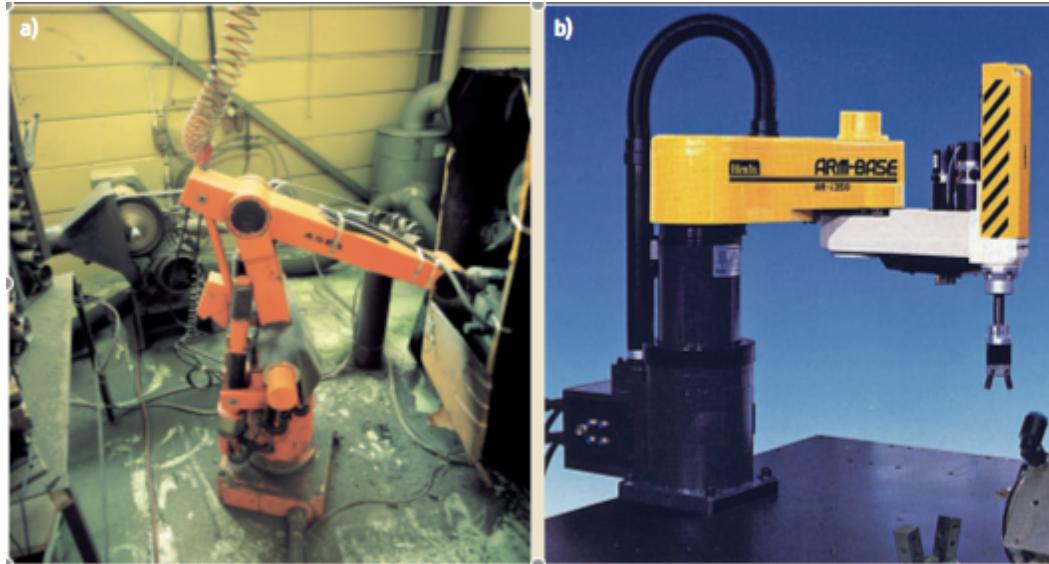
video

Unimate 6-dof robots

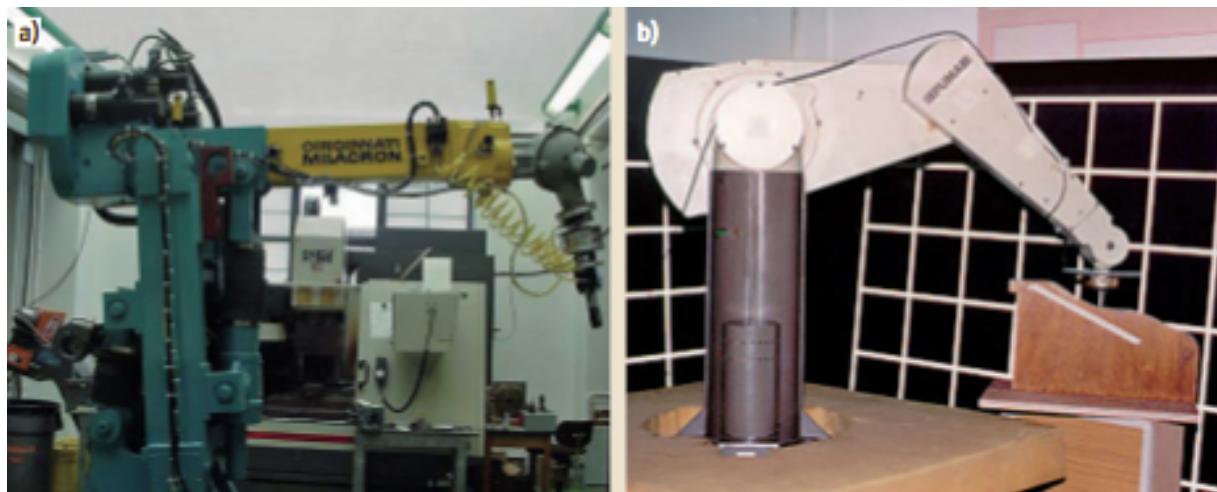


Robot manipulators

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



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

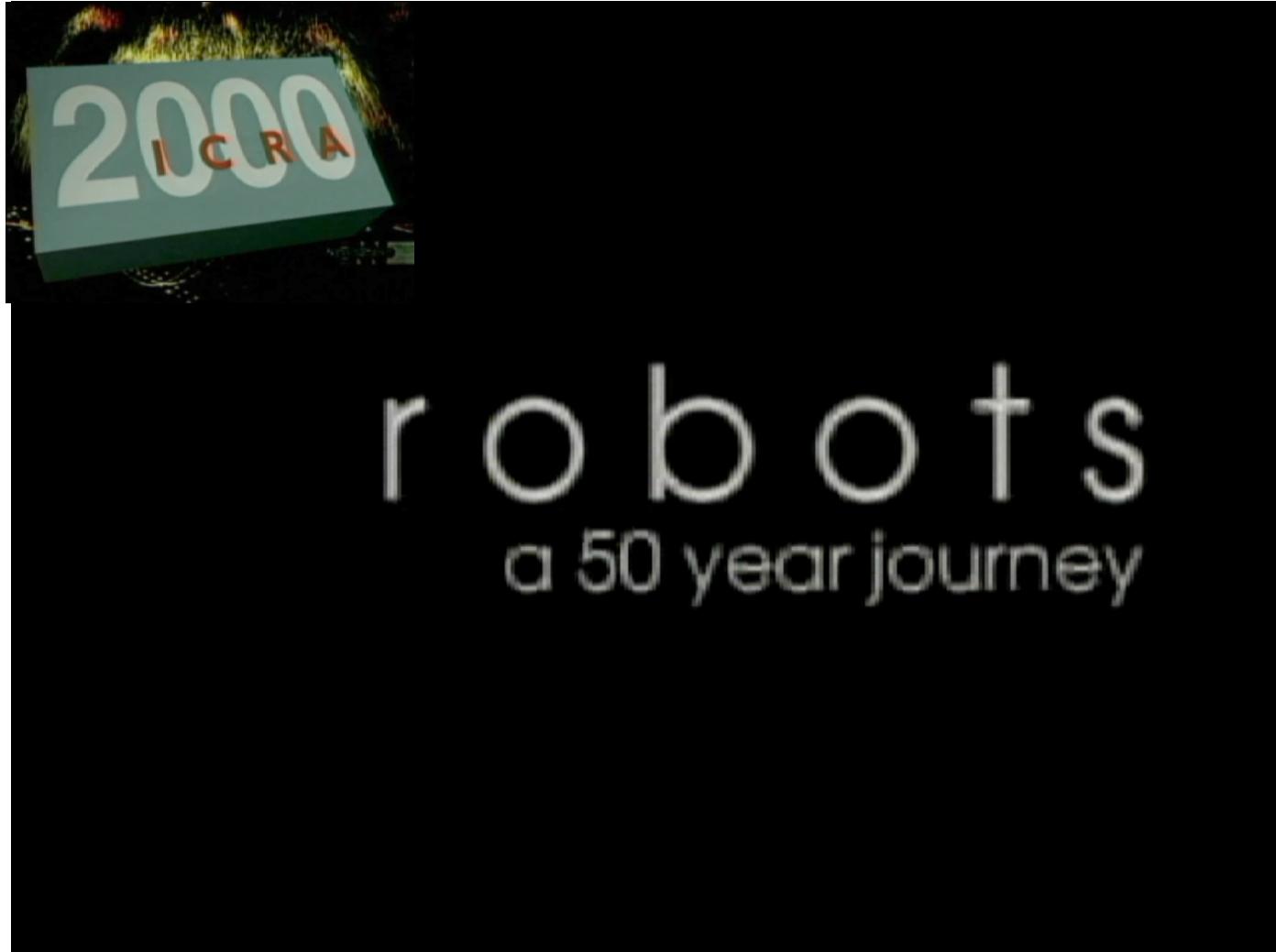


Hirata AR-300
(1978)
first SCARA
robot

Unimation
PUMA 560
(1979)
6R with
human-like
dexterity

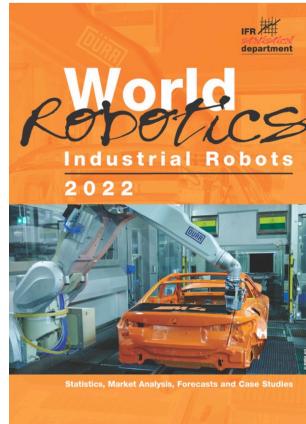
robots – a 50-year journey

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)

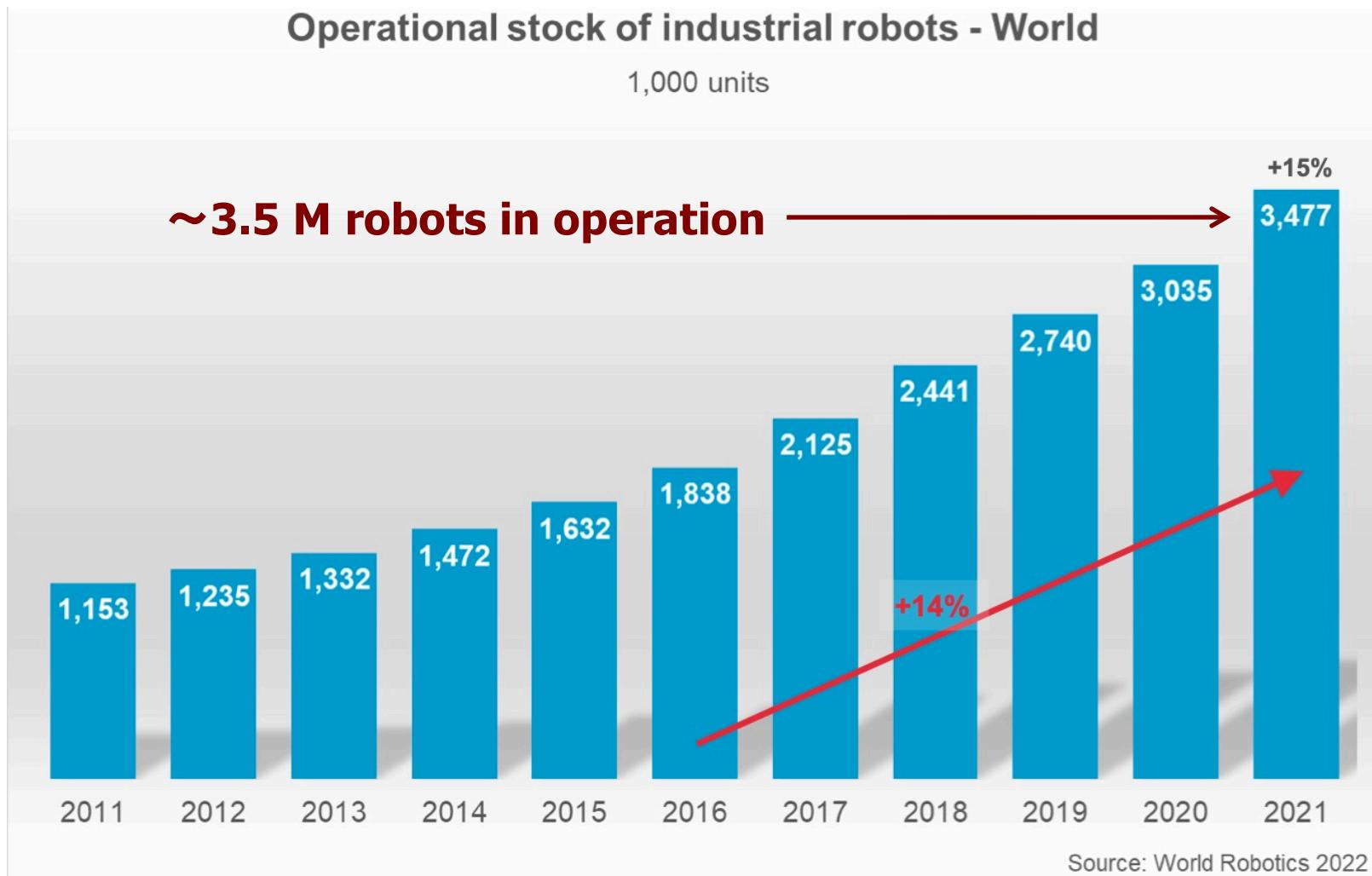


- total worldwide stock at end 2021: **3.5 million units** of operational industrial robots (+15% w.r.t. 2020, +14% CAGR in 2016-21)
- new robot sales in 2021: **517K** (+31%, highest number ever, +11% CAGR)
- strong recovery after two pandemic years, expected to leverage in next future
- robot market 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

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



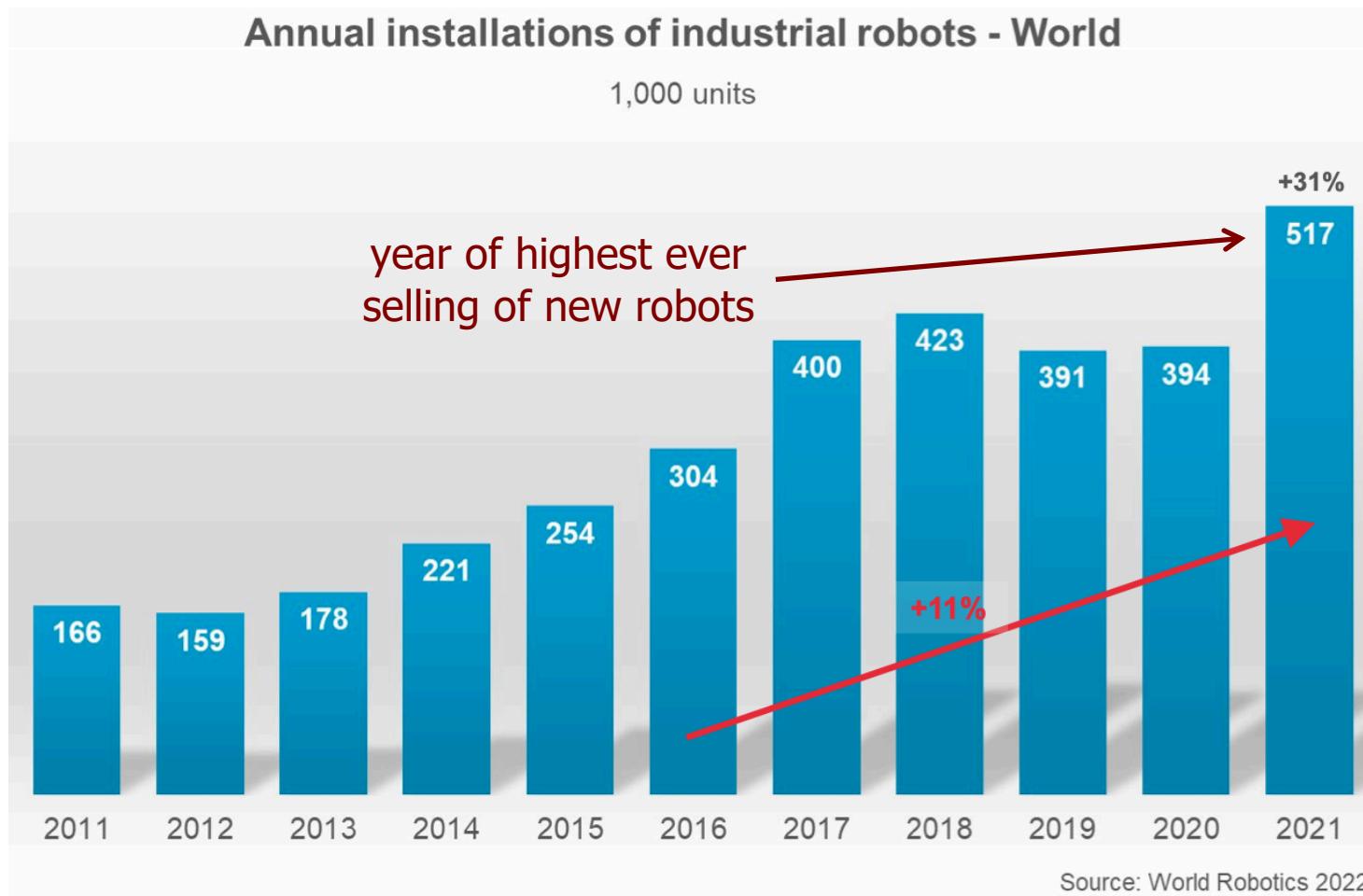
Diffusion industrial robots in operation worldwide



(as reference, industrial robots in 1973 = 3K, 1983 = 66K, 1993 = 575K, 2003 = 800K)
length of robot service life is estimated in 12-15 years



Annual supply new industrial robots worldwide

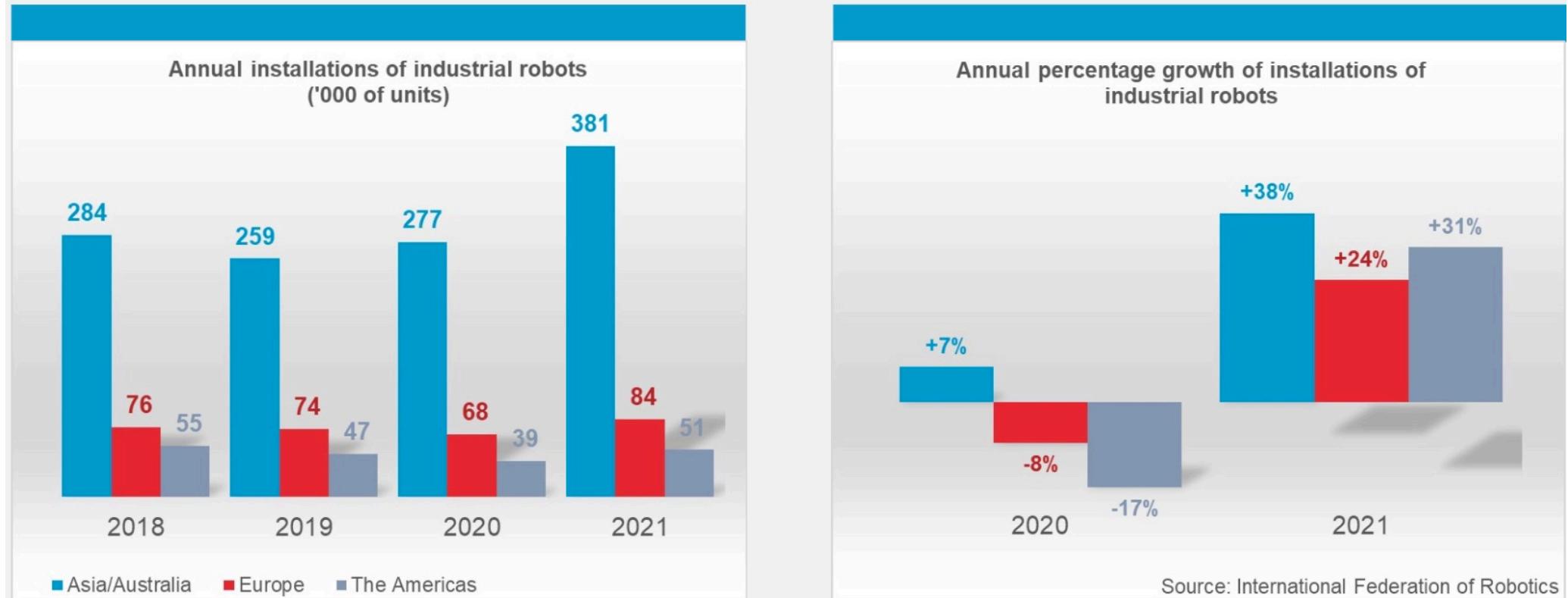


stop of growth rate in 2019: automotive transition, trade & political headwinds

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



Annual supply of industrial robots by world area



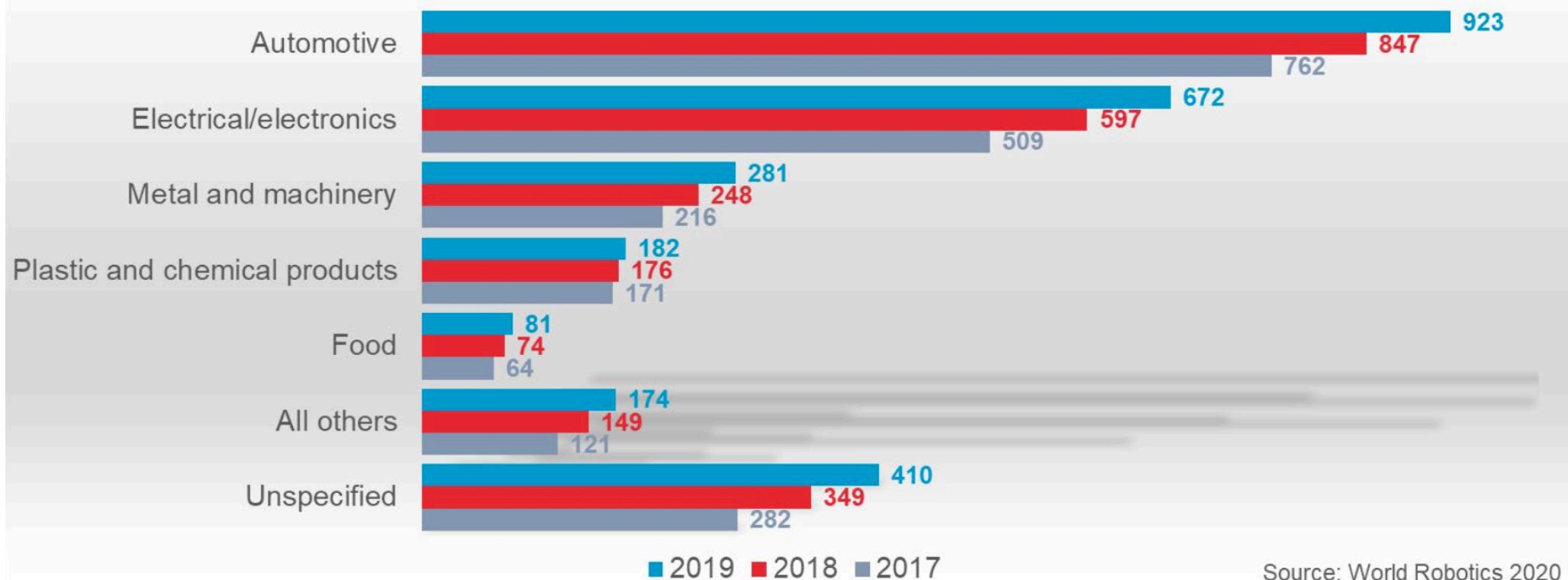
strong recovery in all regions



Diffusion robots in industrial sectors [as of 2019]

Operational stock of industrial robots by customer industry - World

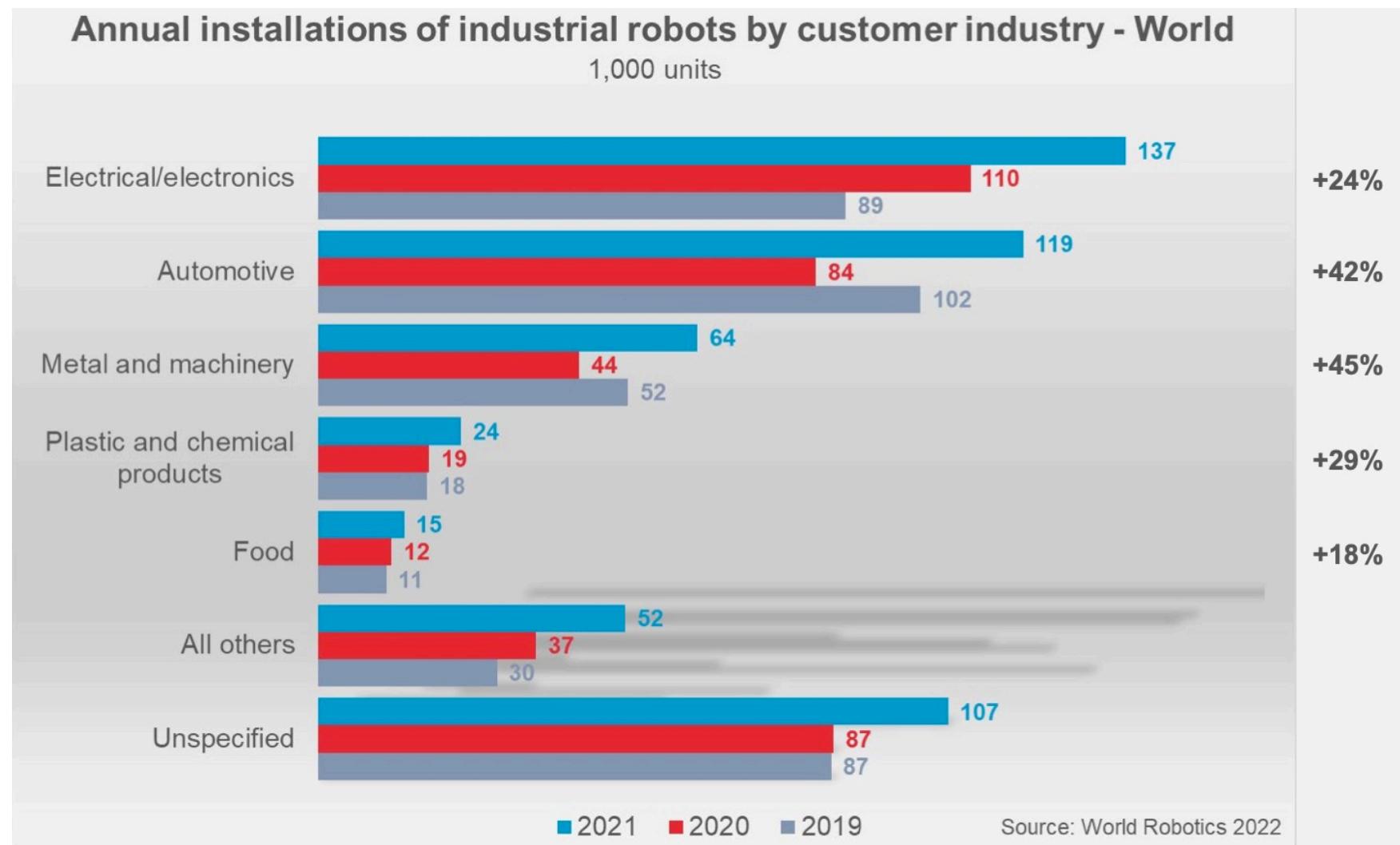
1,000 units



70% of robots were deployed in three main industries



Annual supply new robots by industrial sectors

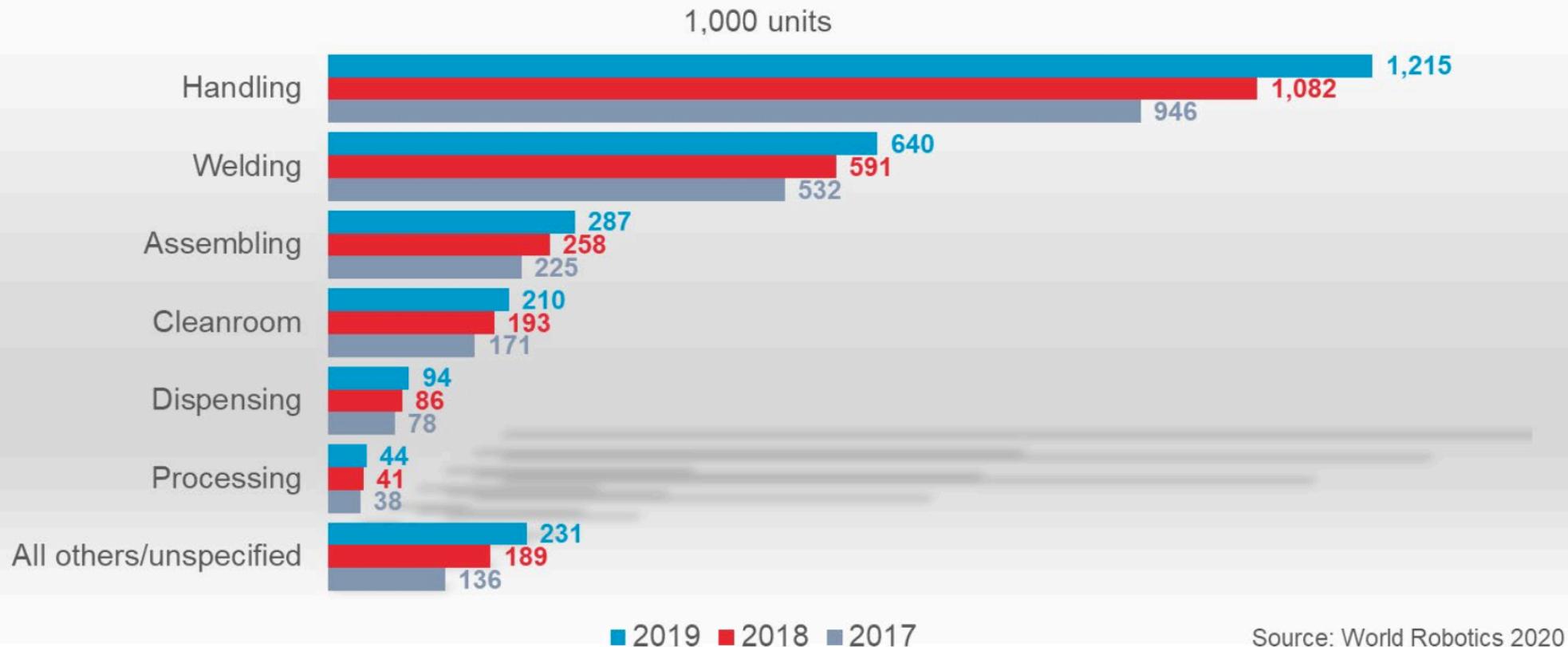


electronics is now the major of customer of robots (surpassing automotive)



Diffusion robots by main application [as of 2019]

Operational stock of industrial robots by application - World

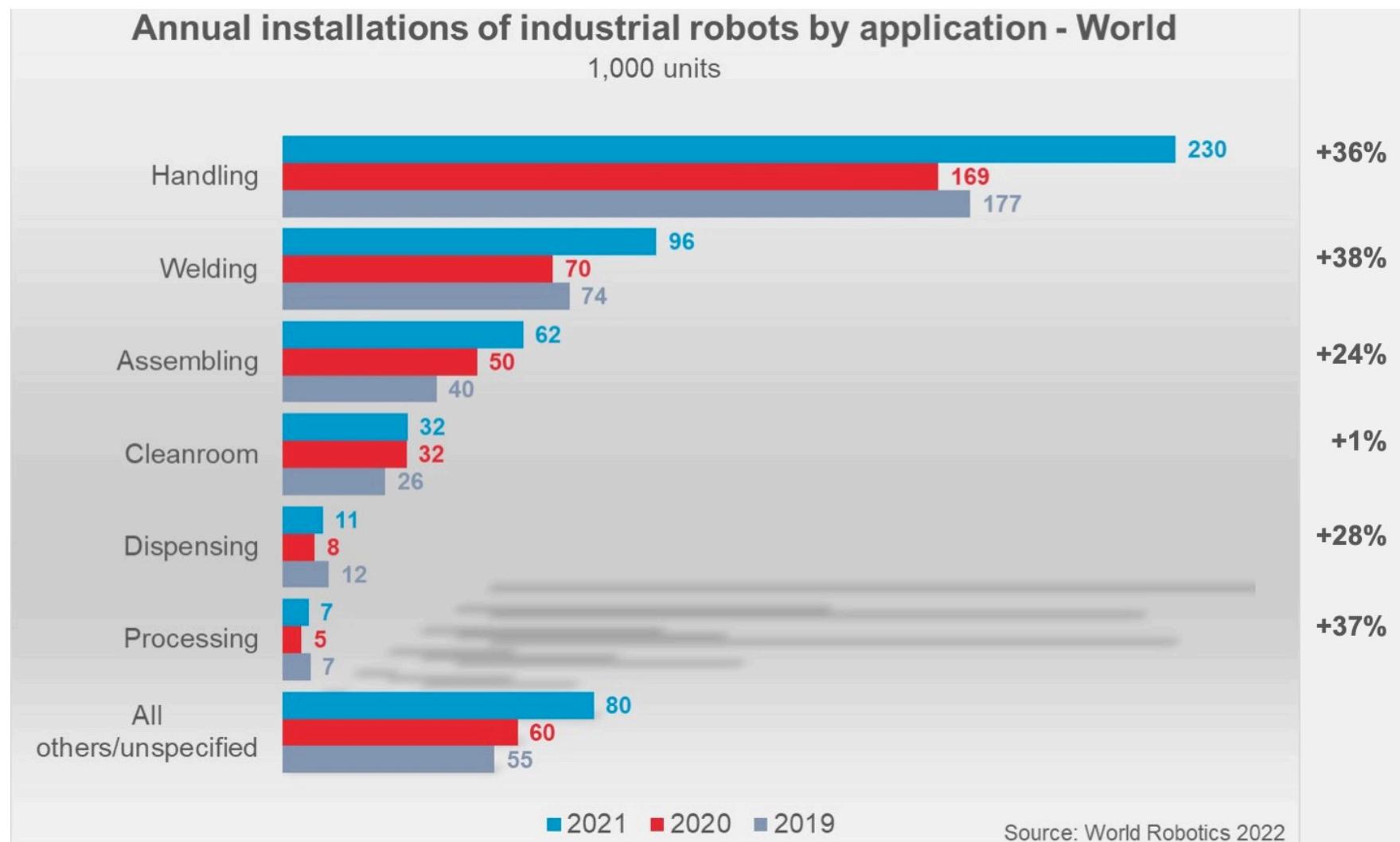


Source: World Robotics 2020

almost 70% of robots were used for material handling or welding



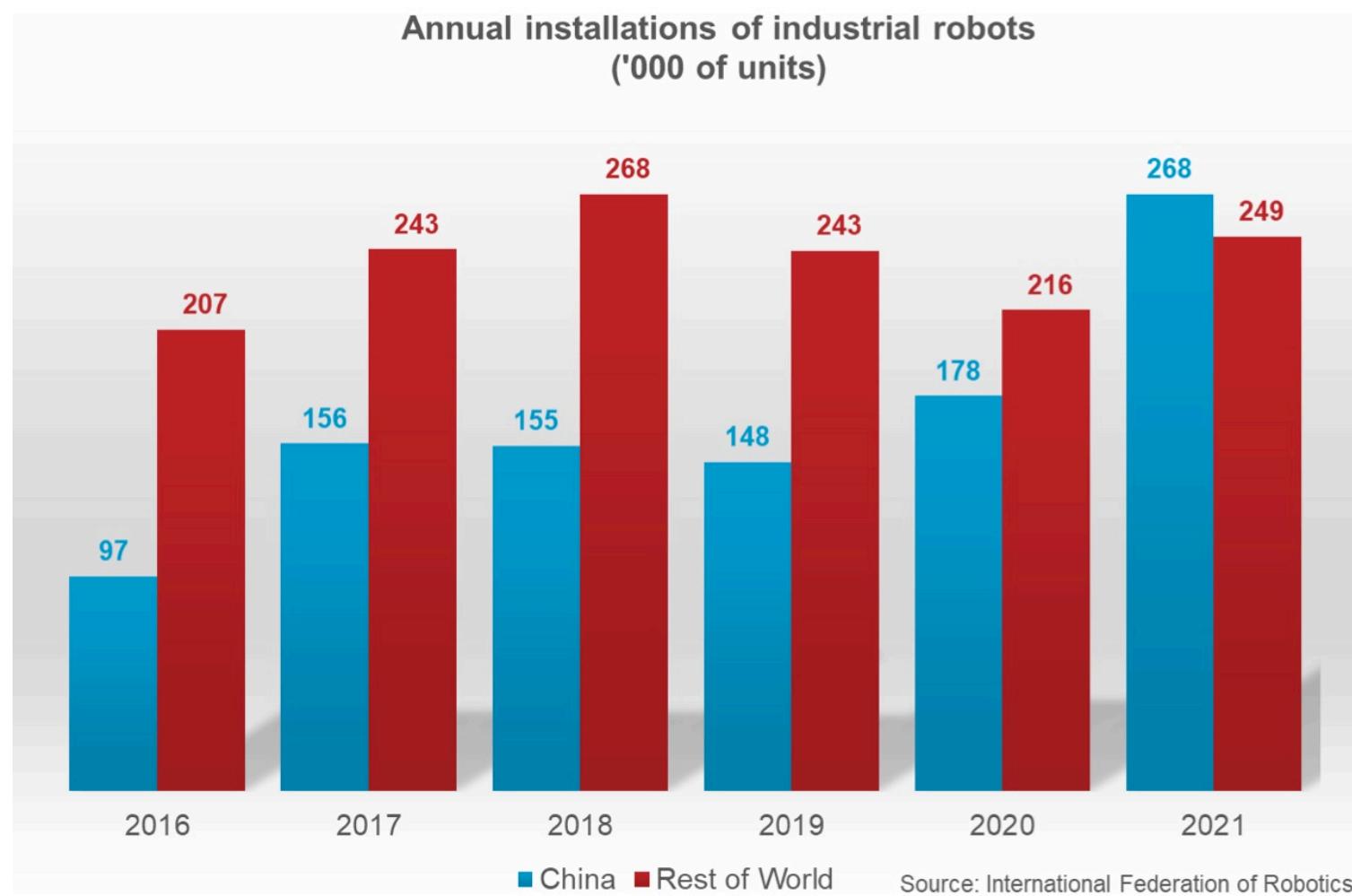
Annual supply new robots by main application



material handling is the most important with a 44% share



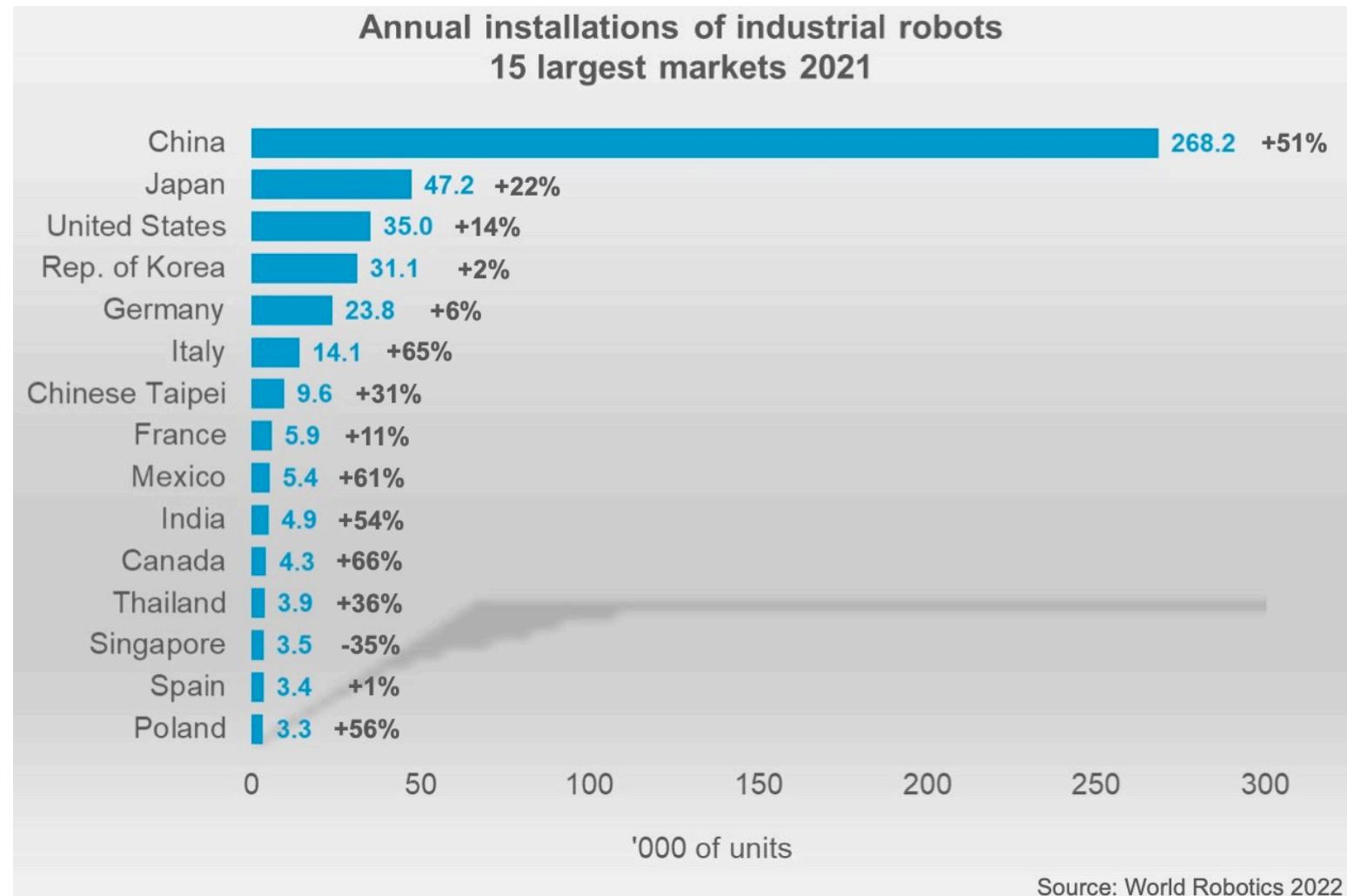
Annual supply new installations in China/Rest of World



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



Annual supply new installations in top markets (countries)



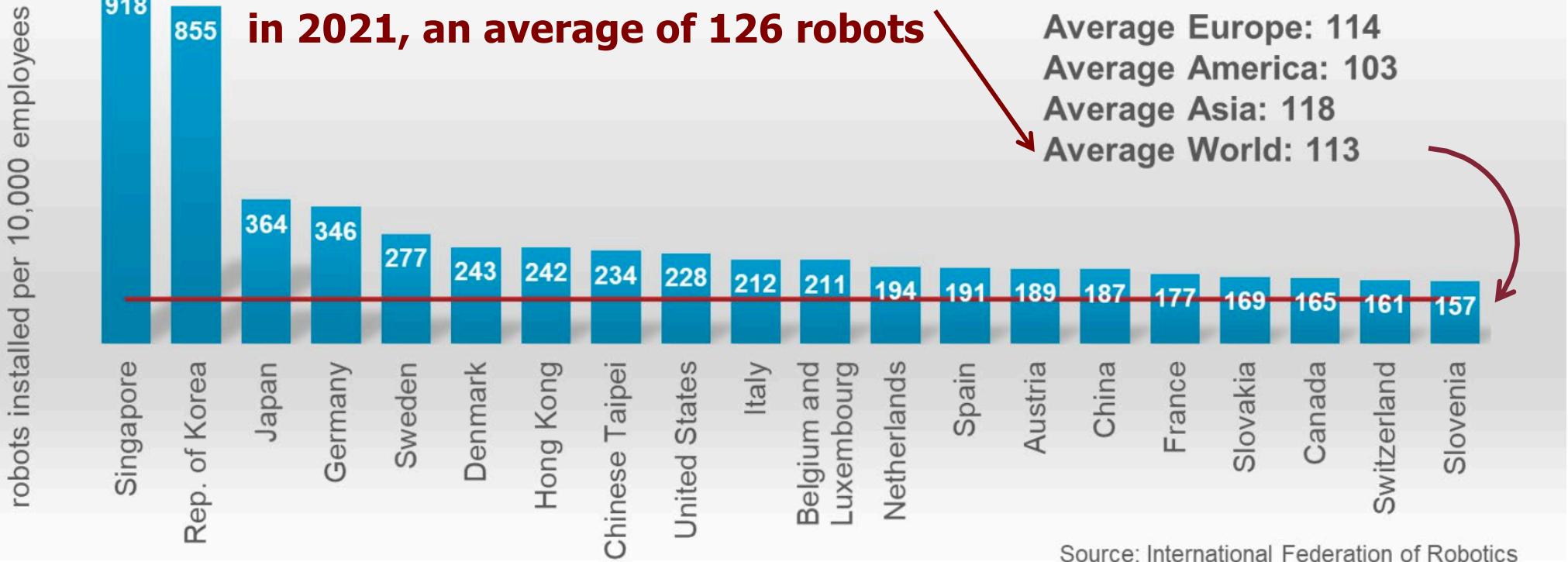
Italy (2nd EU market): three times as many new robots installed as in 2015



Density of robots [as of 2019]

Robot density in the manufacturing industry 2019

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



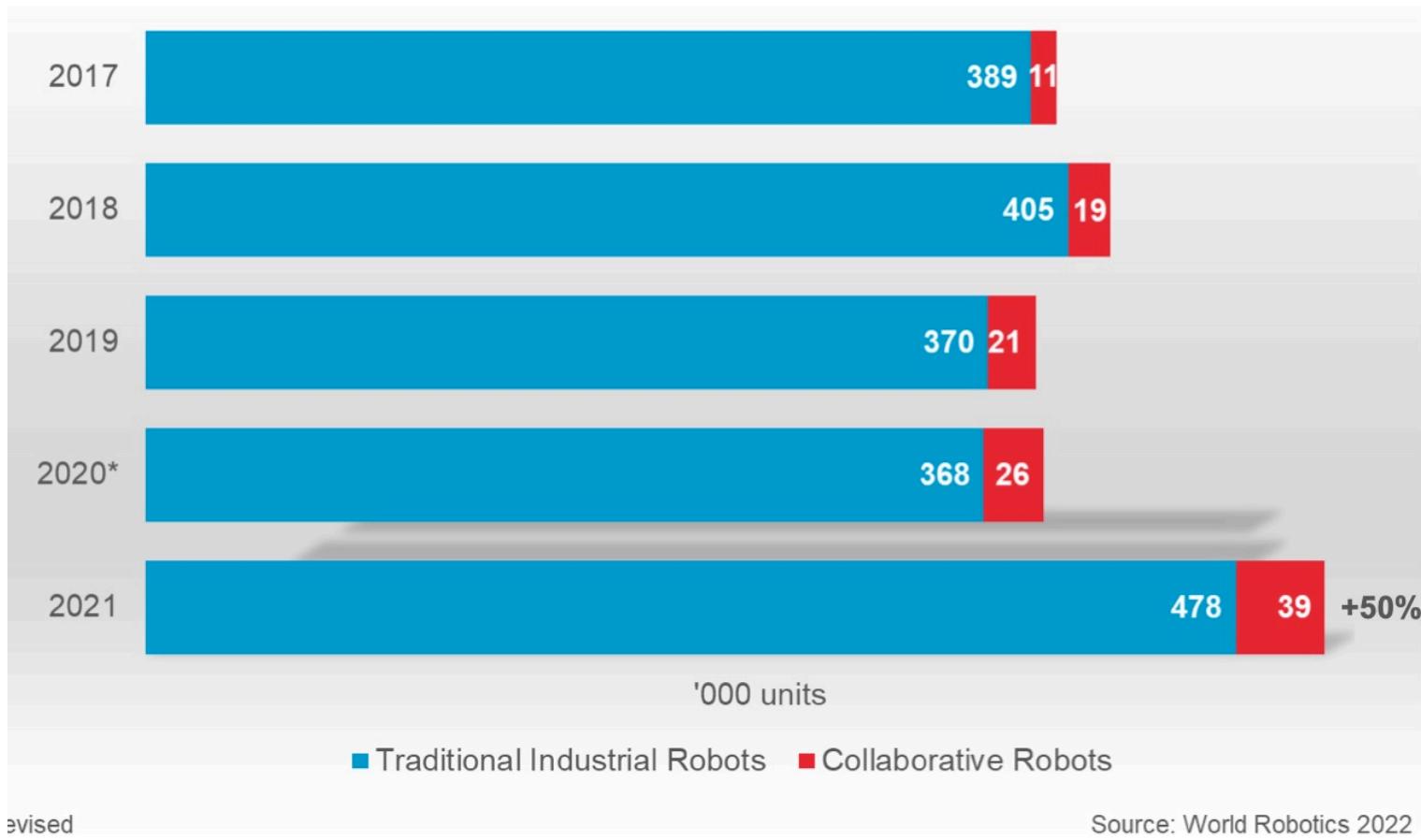
Source: International Federation of Robotics

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



Collaborative robots

Collaborative and traditional industrial robots
(annual installations)



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

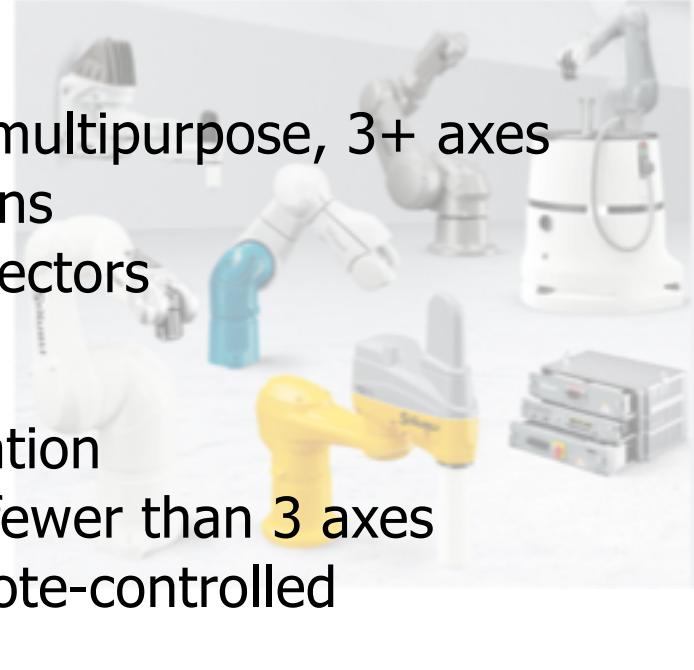
Service robots

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

different customers, pricing, machinery, distribution channels, suppliers

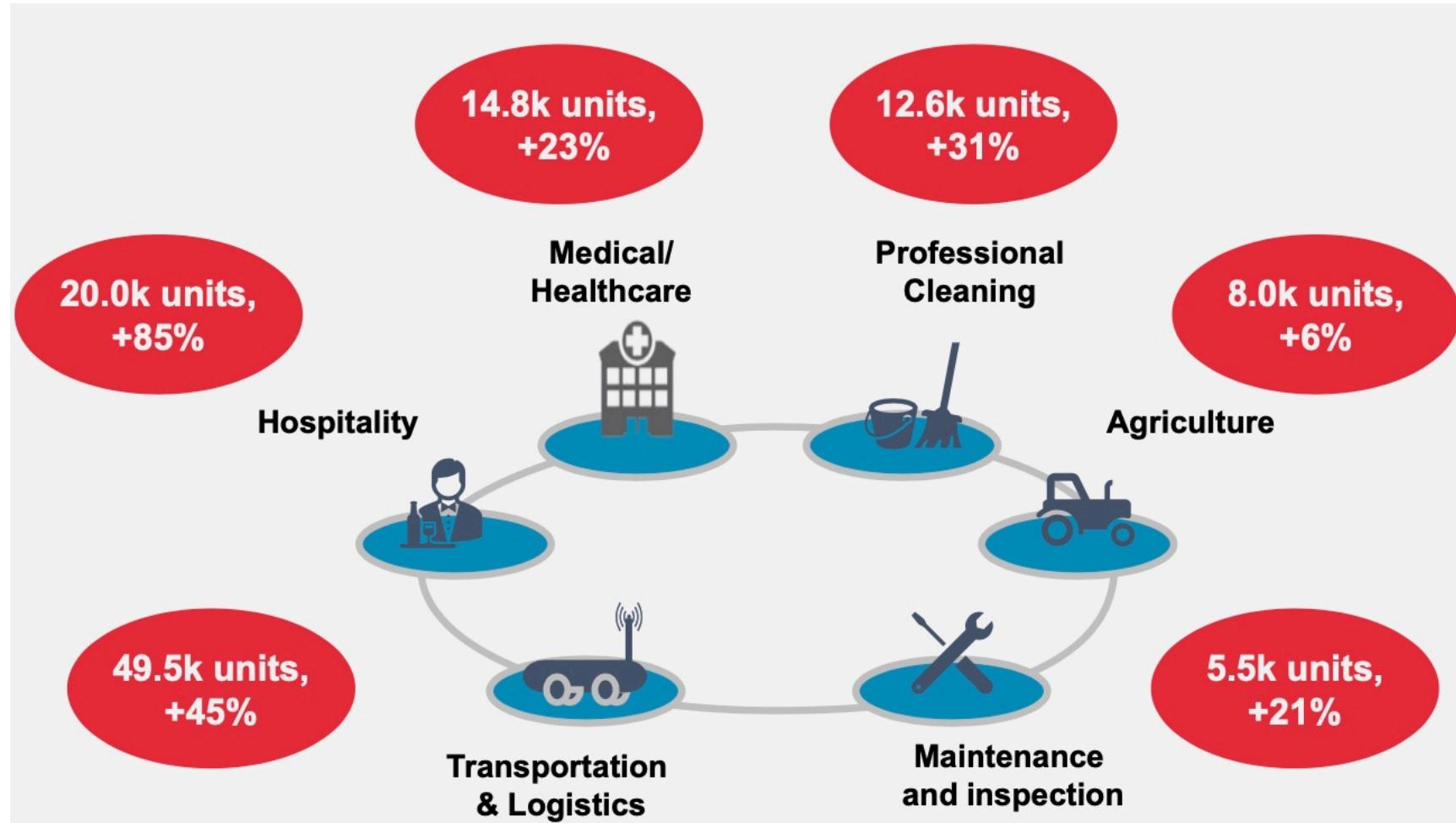


... **but** separation
line is blurring:
same unit can act
as both, depending
on the application





Professional service robots



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

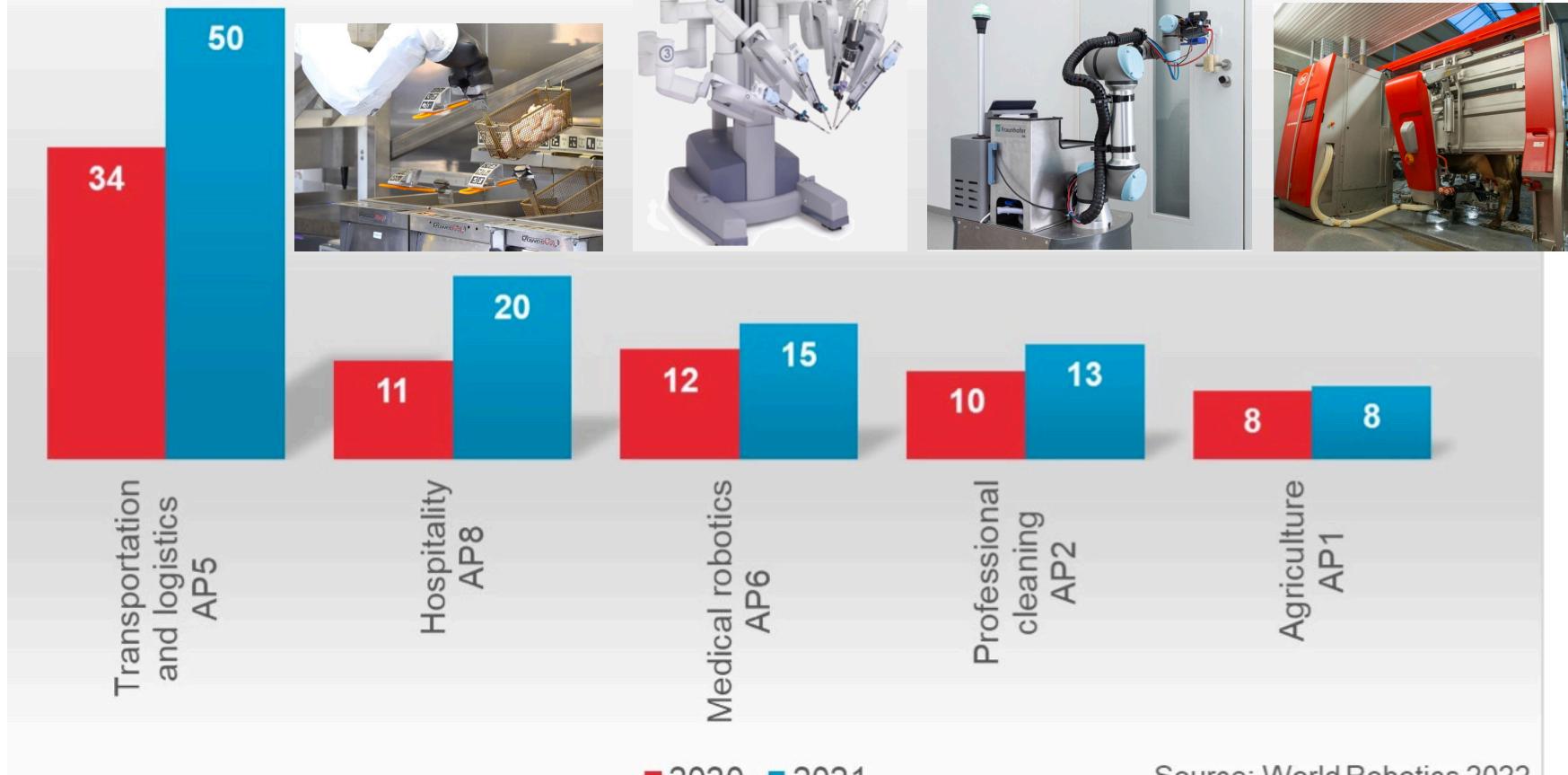
... compare with new personal/domestic service robots: **19M units!! (+9%)**



Professional service robots



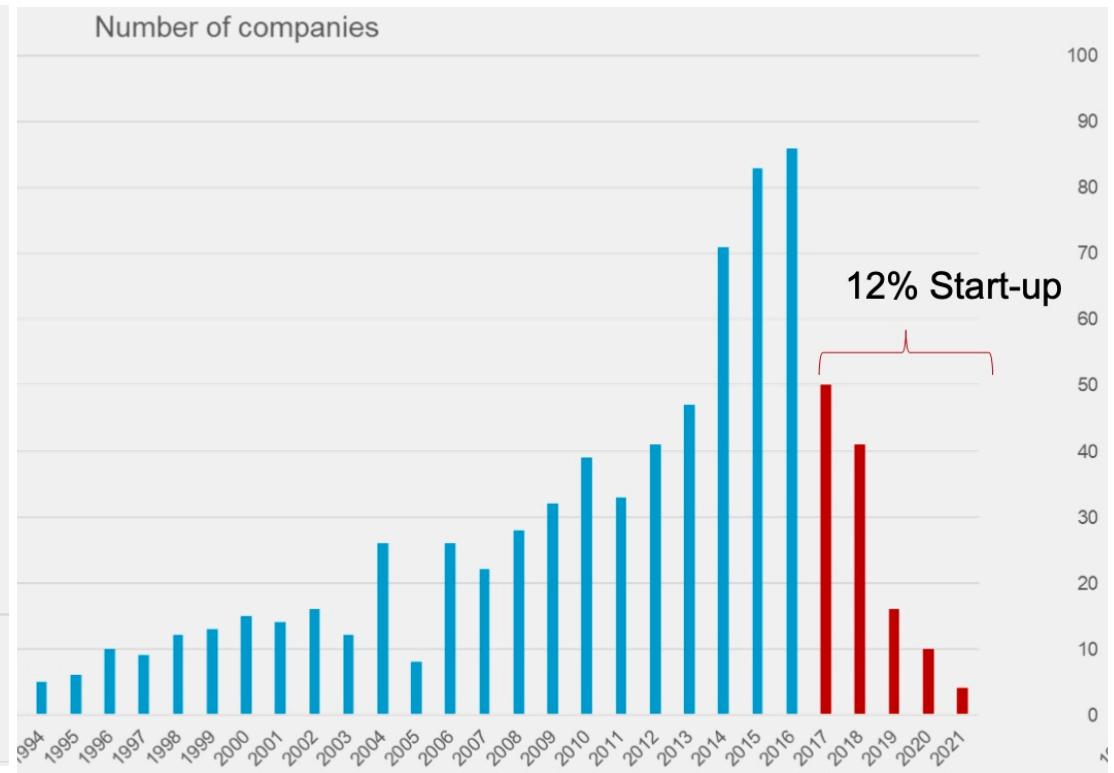
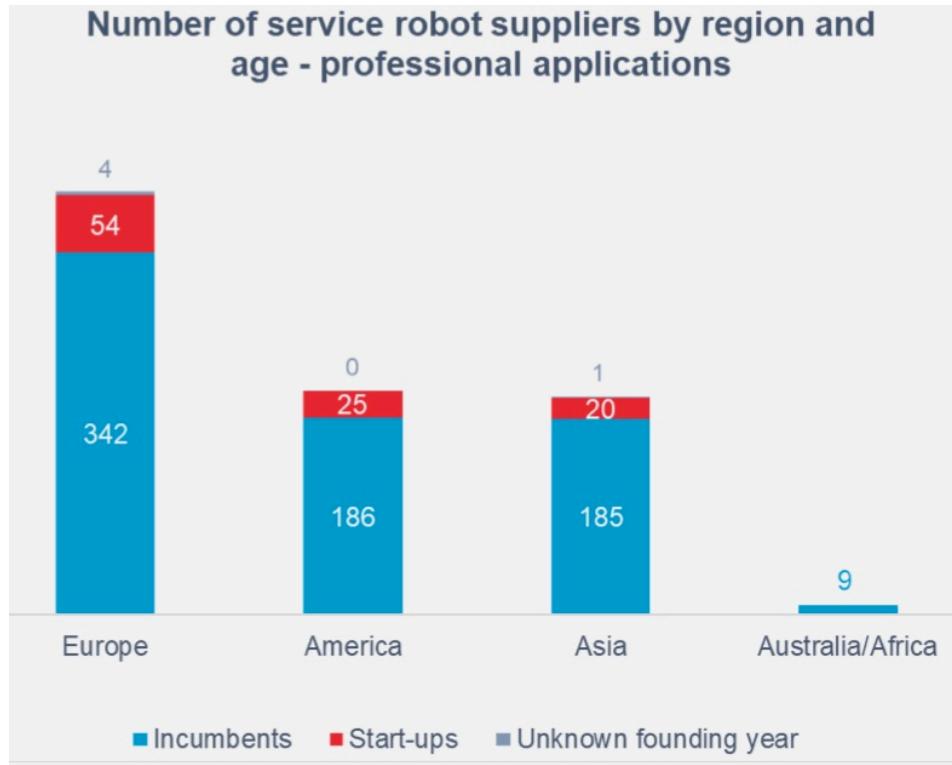
Service robots for professional use. Top 5 applications
Unit sales 2020 and 2021
'000 of units



Source: World Robotics 2022



Professional service robots

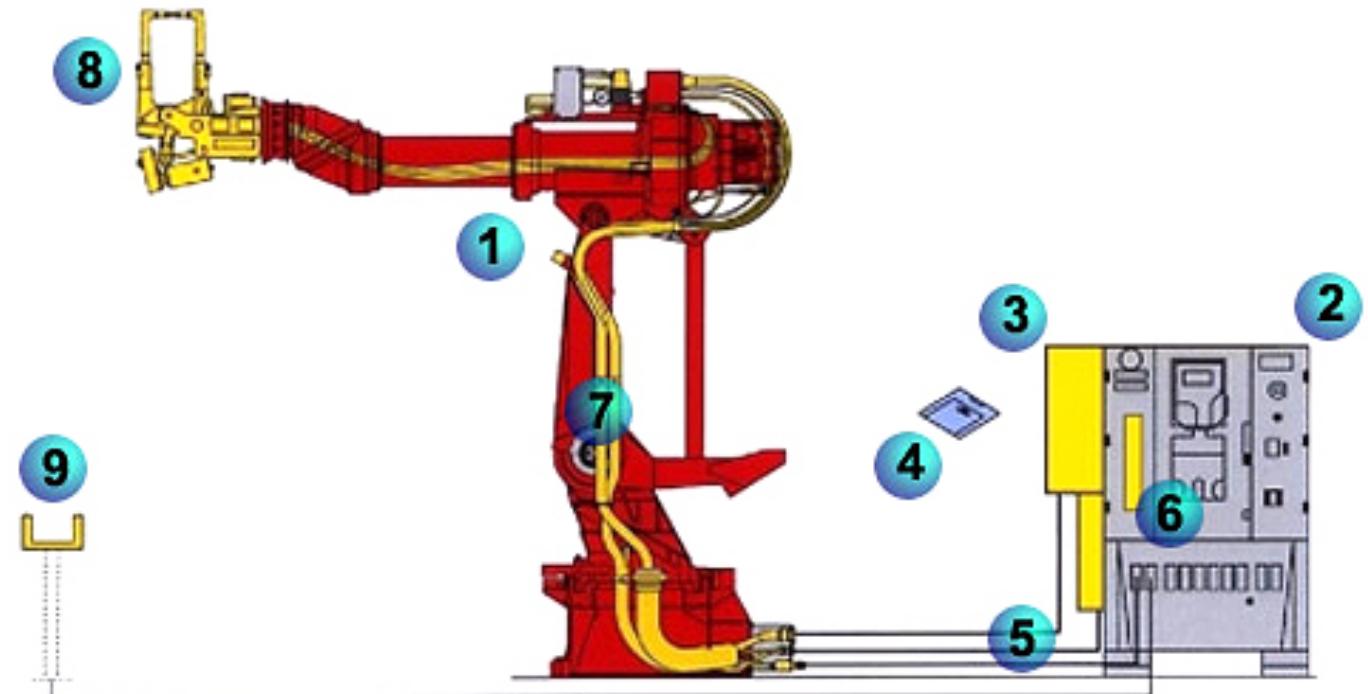


- more than 1000 service robot suppliers worldwide
- 80% of service robot suppliers are SMEs
- start-ups becoming mature



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



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



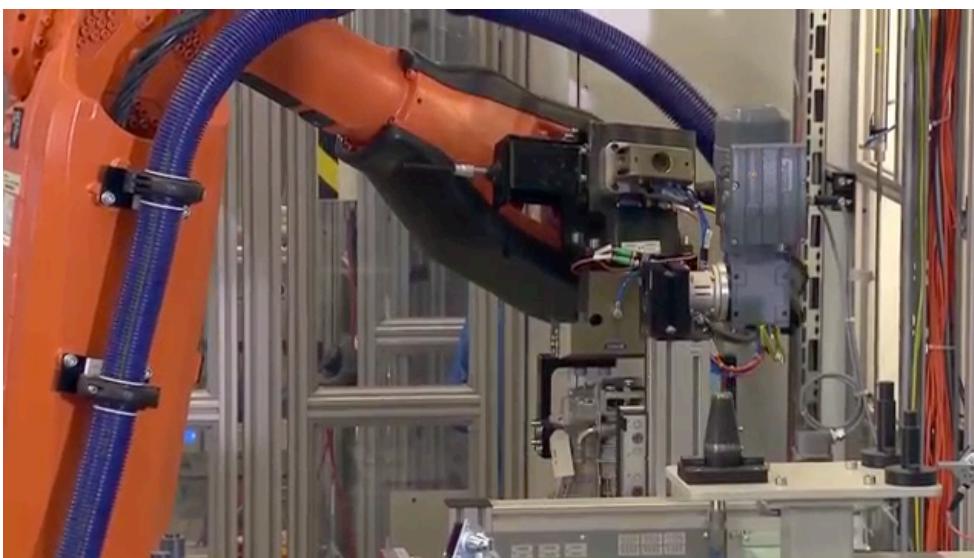


A day in the life of an industrial robot

- 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

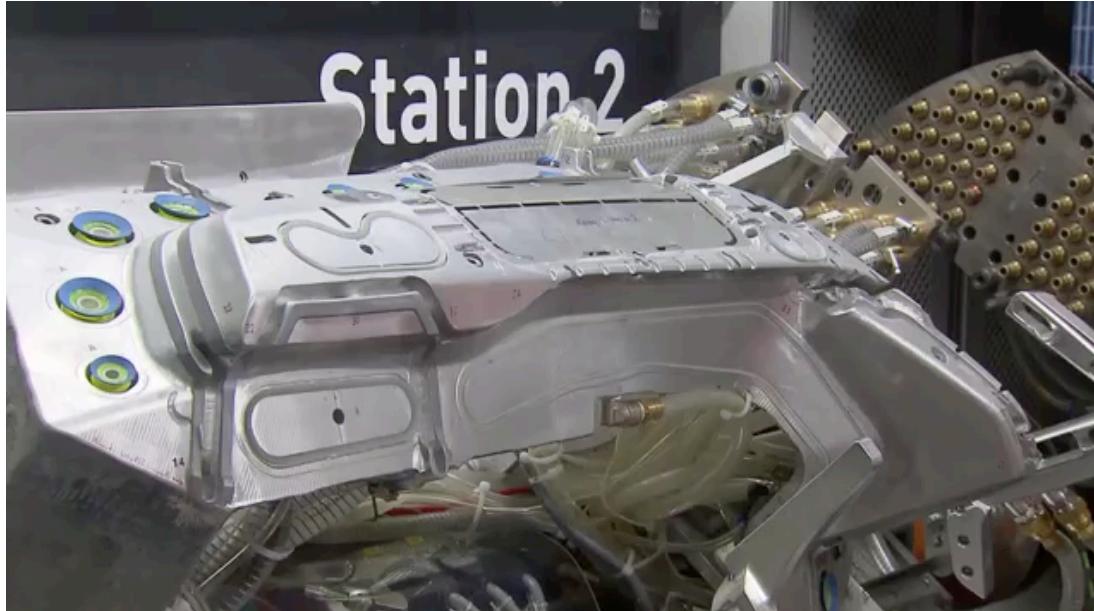


A day in the life of an industrial robot



[video](#)
[video](#)

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!)

video

video



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



A day in the life of an industrial robot



video

video

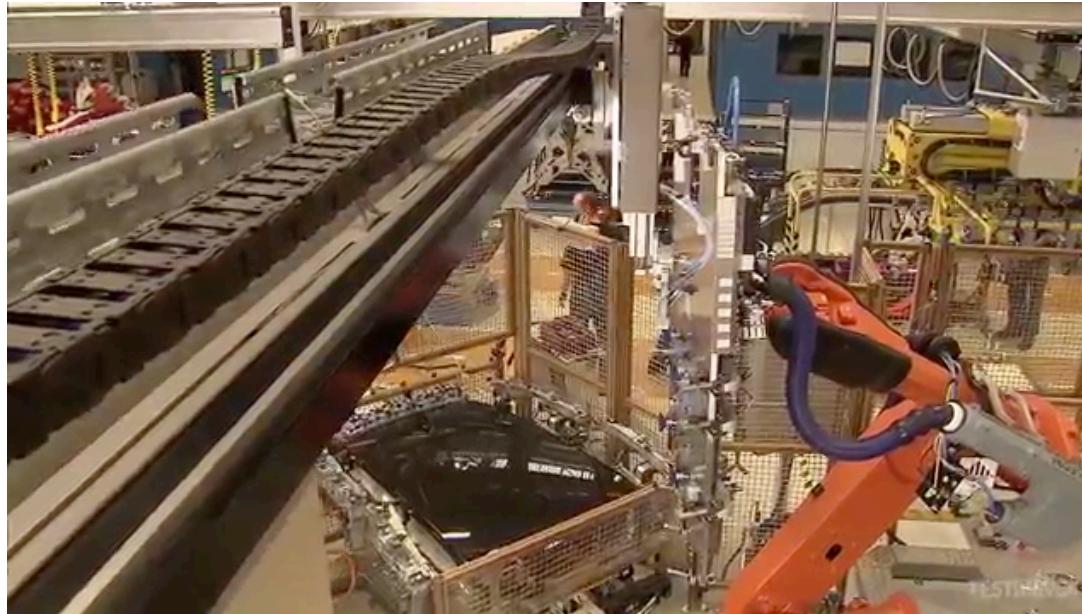
coating parts
for rust and corrosion
protection



spray painting



A day in the life of an industrial robot



hood deburring
with a suspended tool

[video](#)

[video](#)



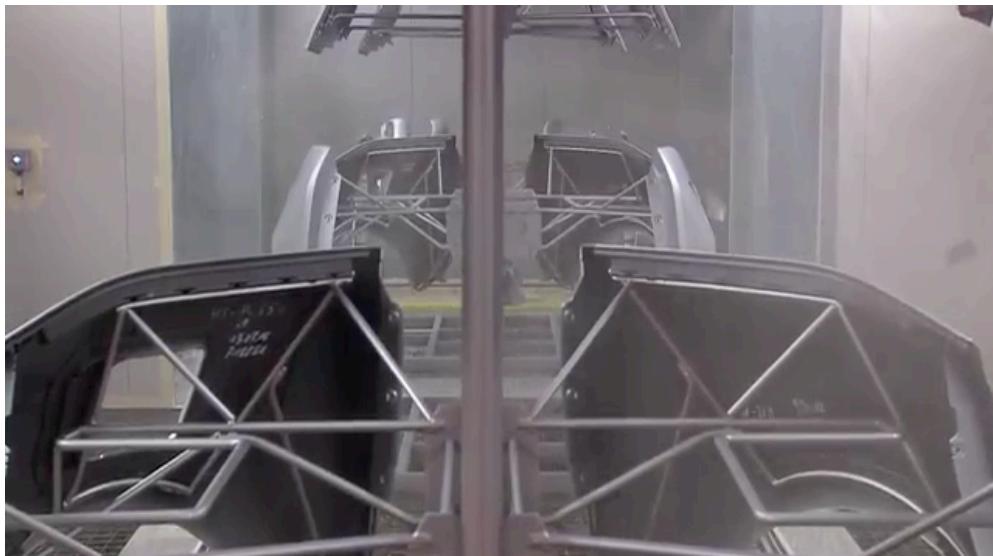
test measurements
with assembly on a AGV



What a robot should do and what cannot do

Yet

video



spray painting
very unhealthy
for human operators

video

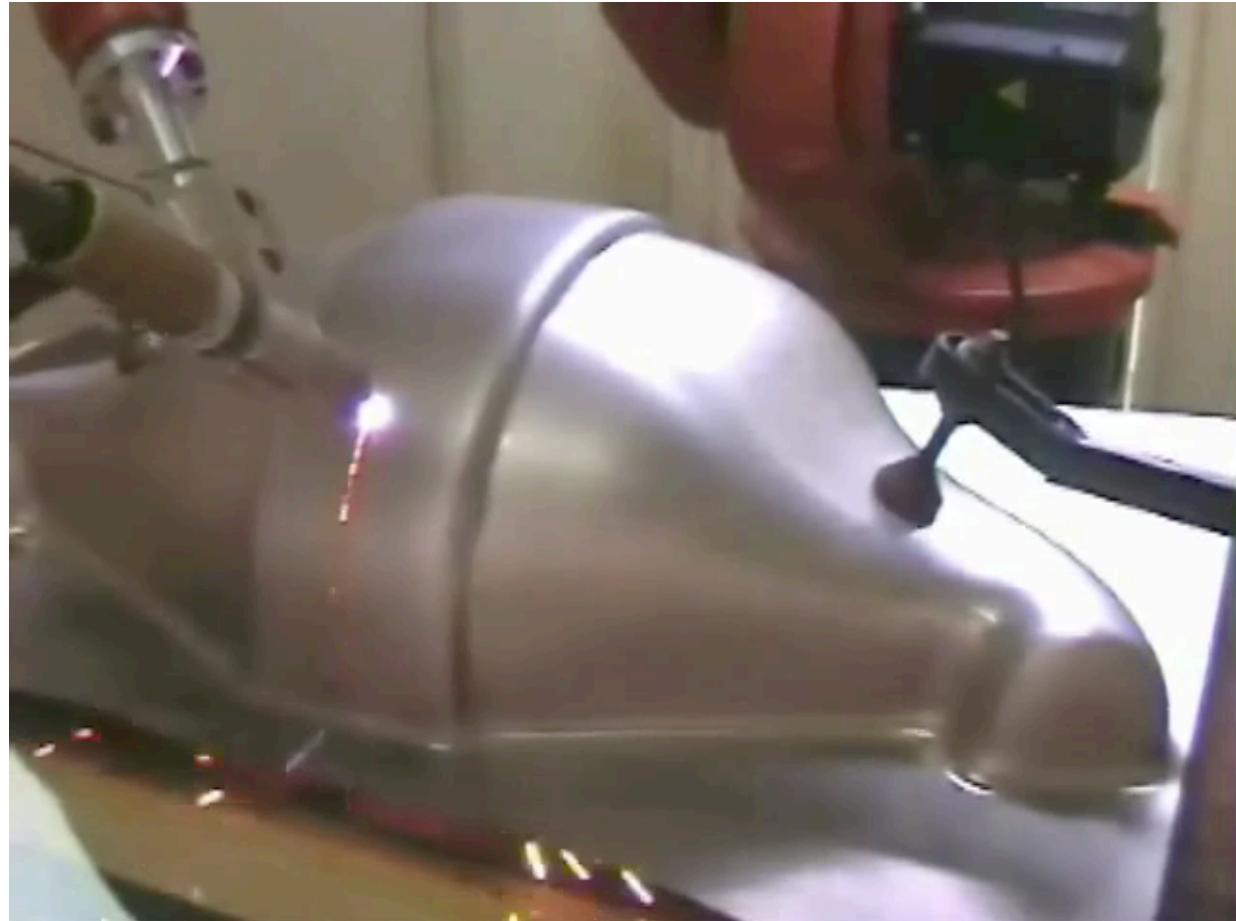
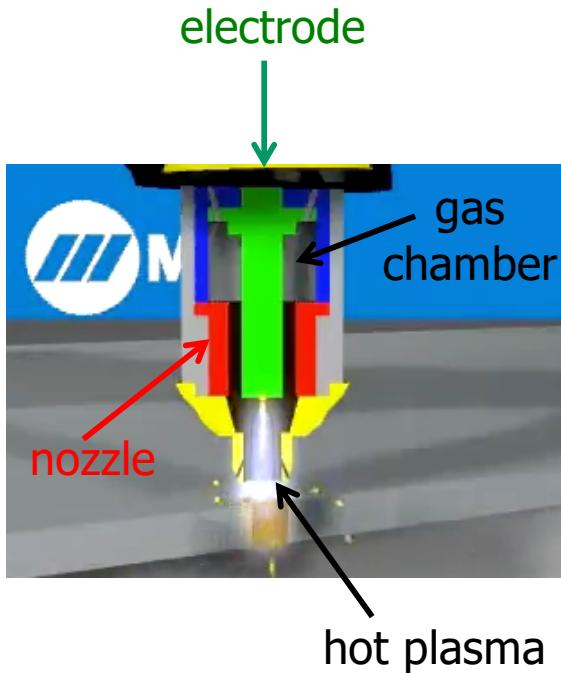


assembly of flexible
or complex parts
(here a car dashboard)

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



Plasma cutting

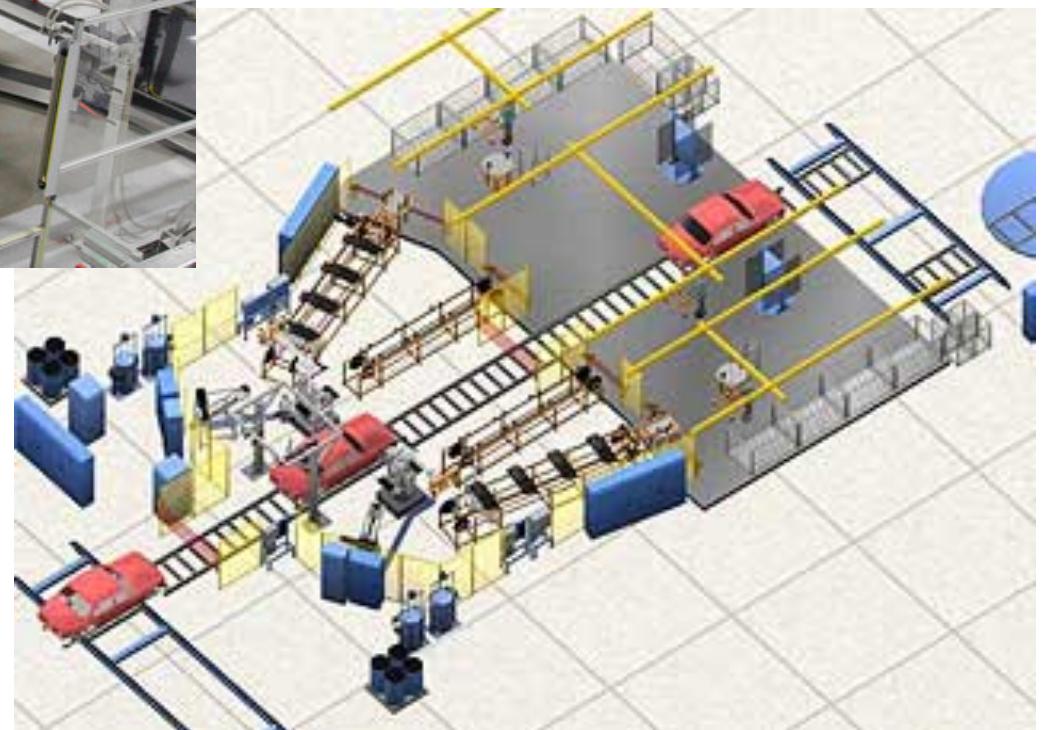


video

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

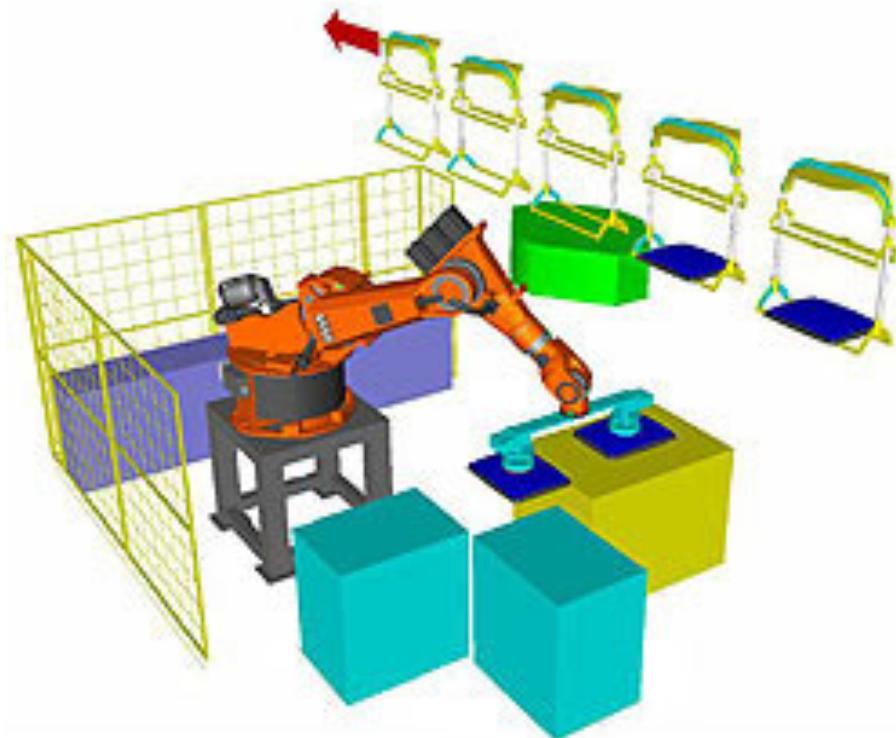


Robotized workcells





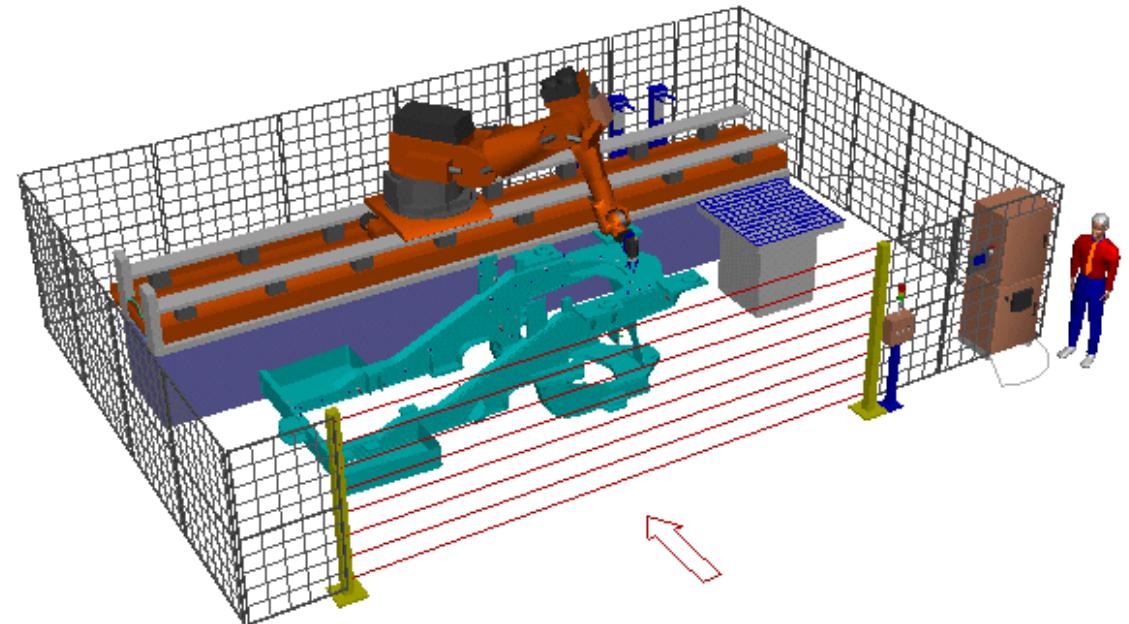
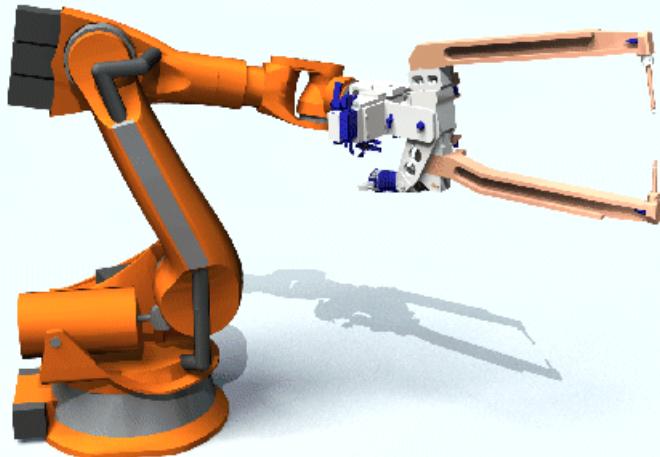
3D simulation of robotic tasks



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



Welding - 1

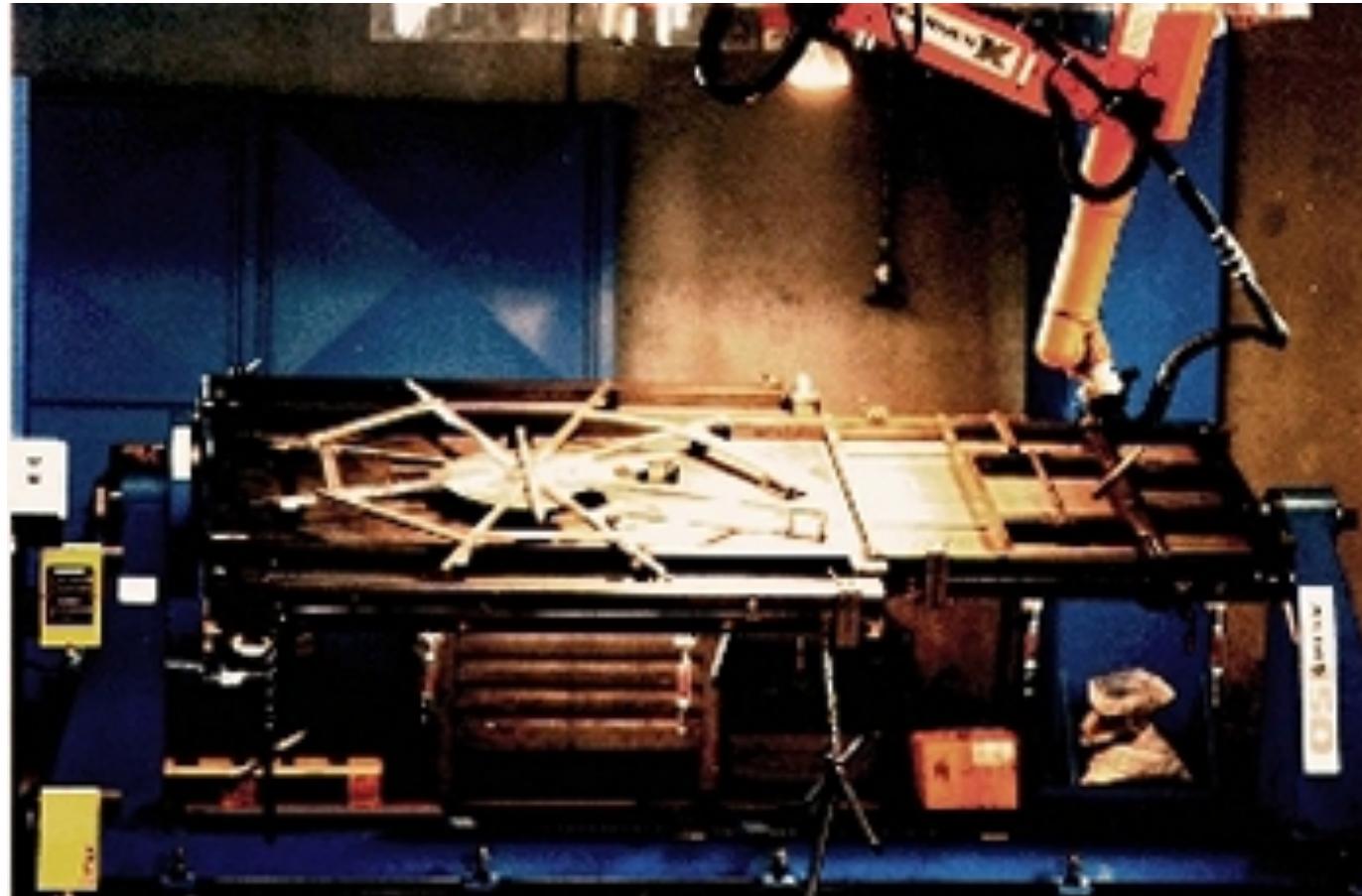


- spot with servo-controlled gun

- stud welding



Welding - 2



- spot (discrete) or arc (continuous)



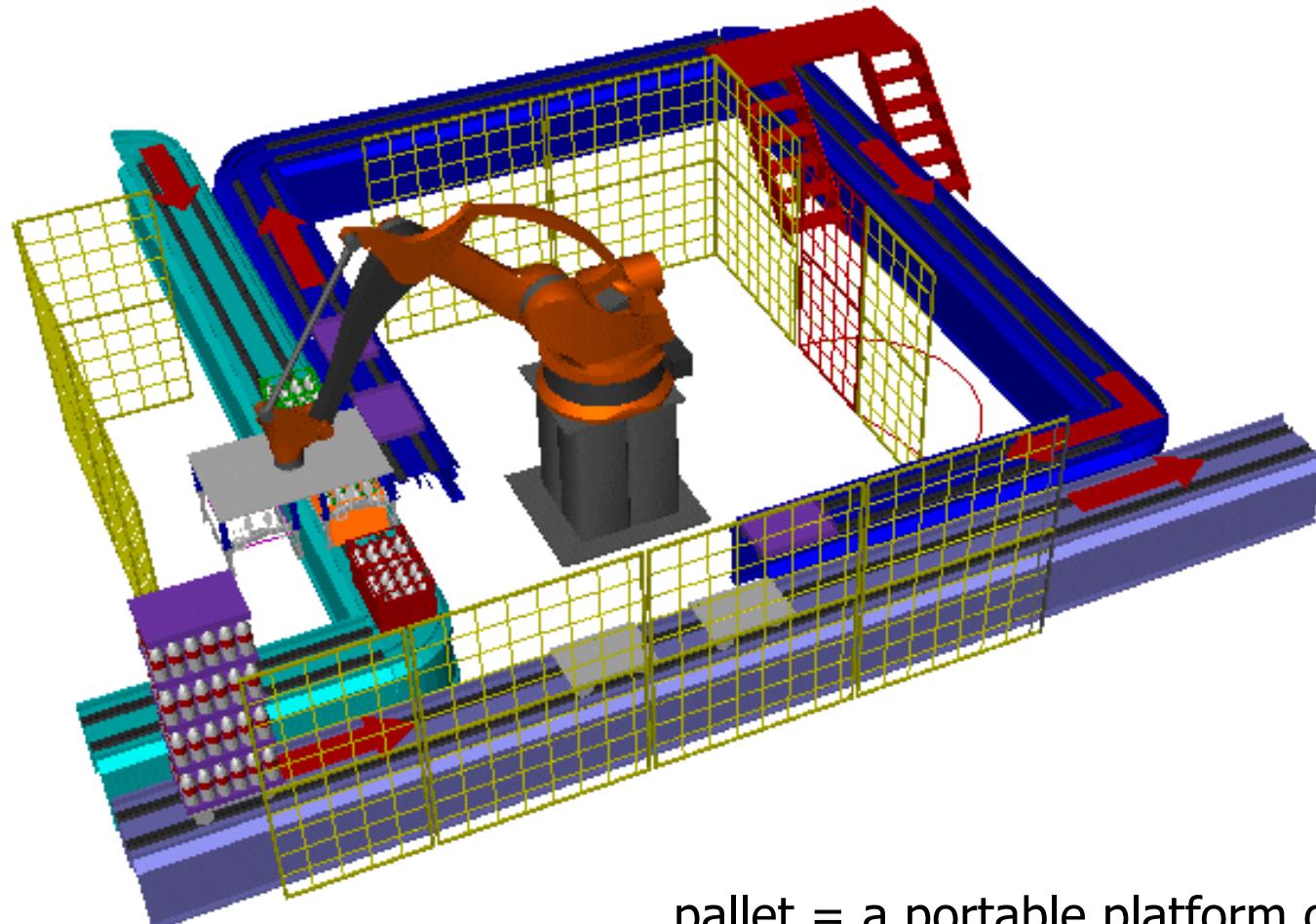
Two cooperating robots in arc welding



ABB video at Laxa, Sweden



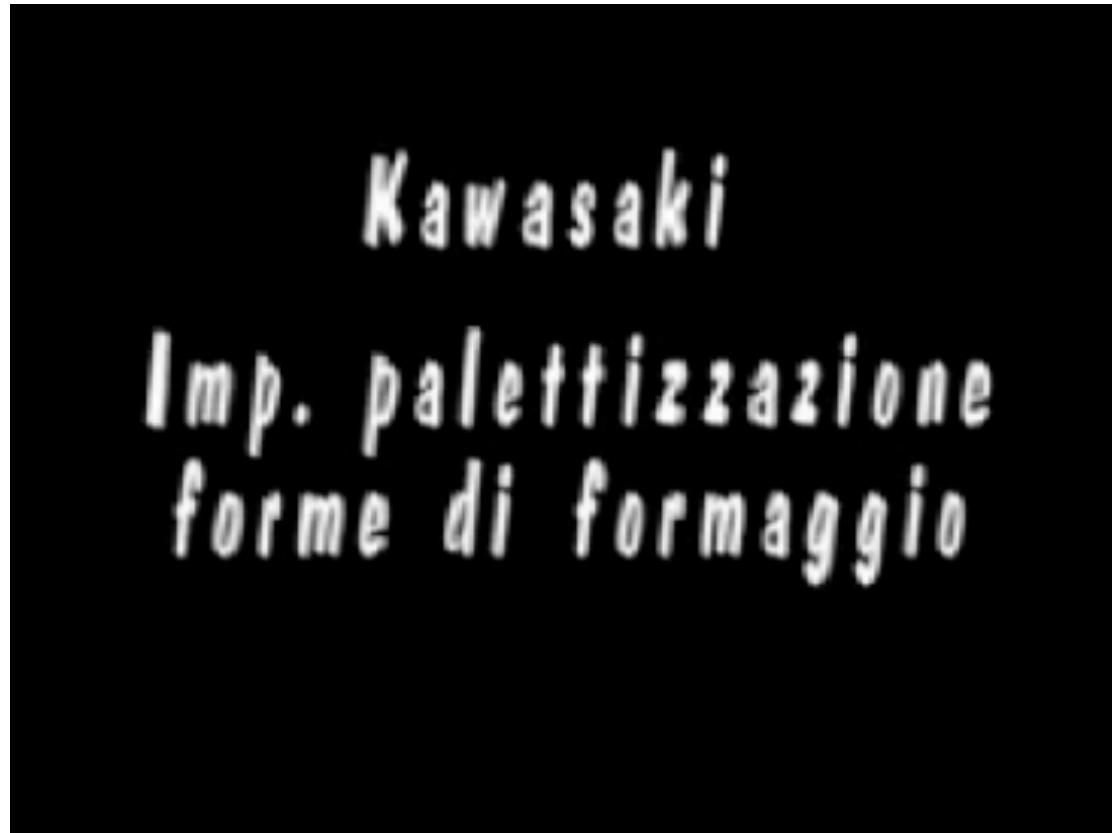
Palletizing



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



Palletizing of cheese forms

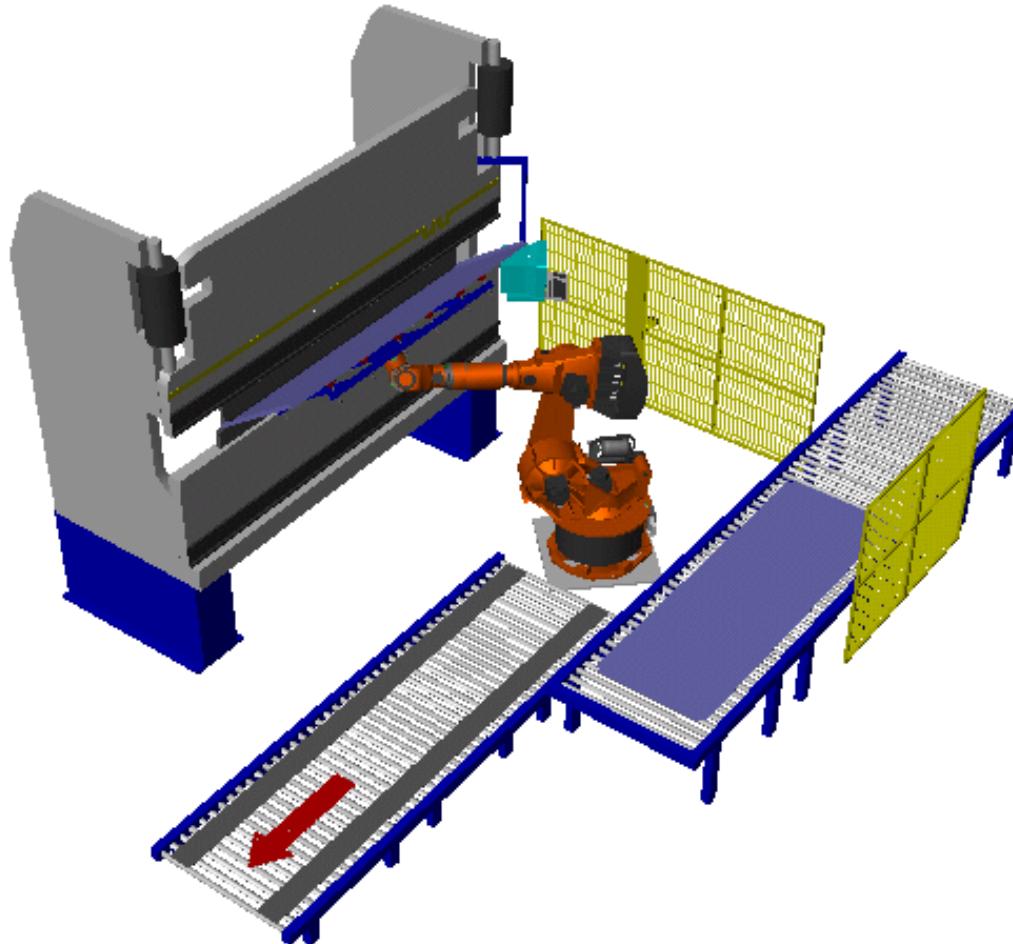


video

using Kawasaki robots (courtesy of Effedue Engineering)



Folding

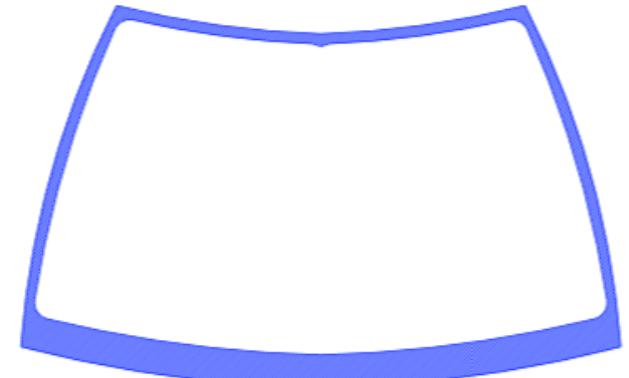
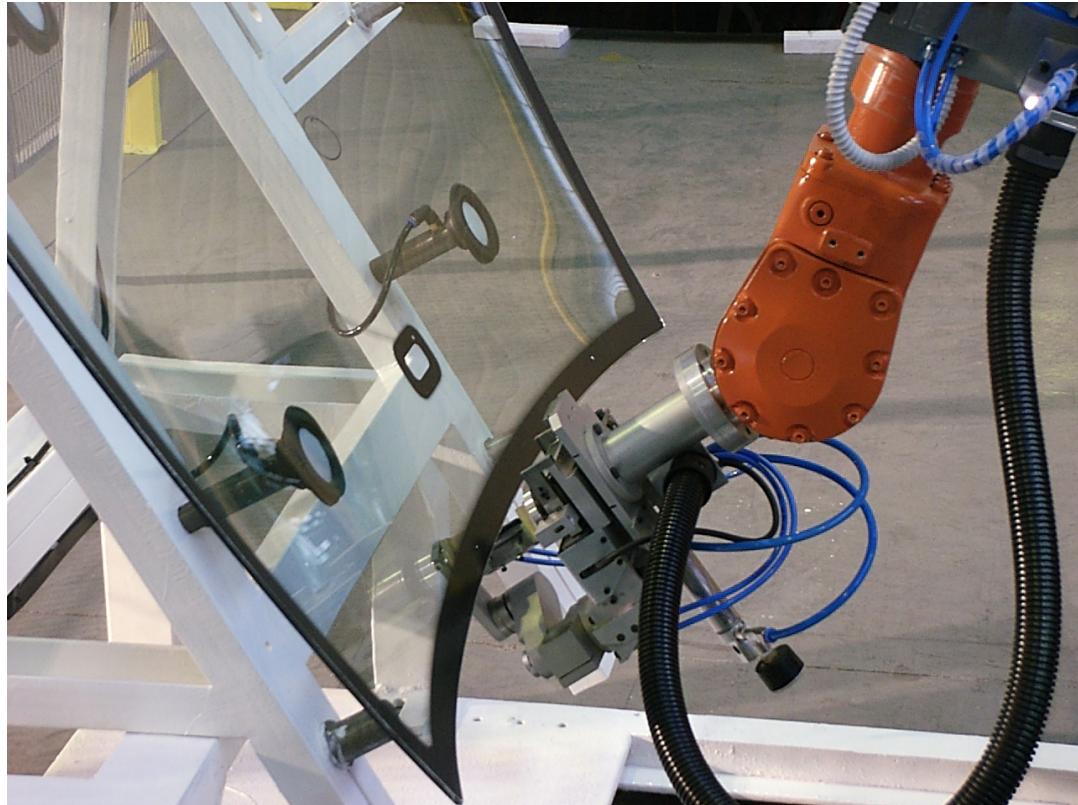


with loading of sheets under the press



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



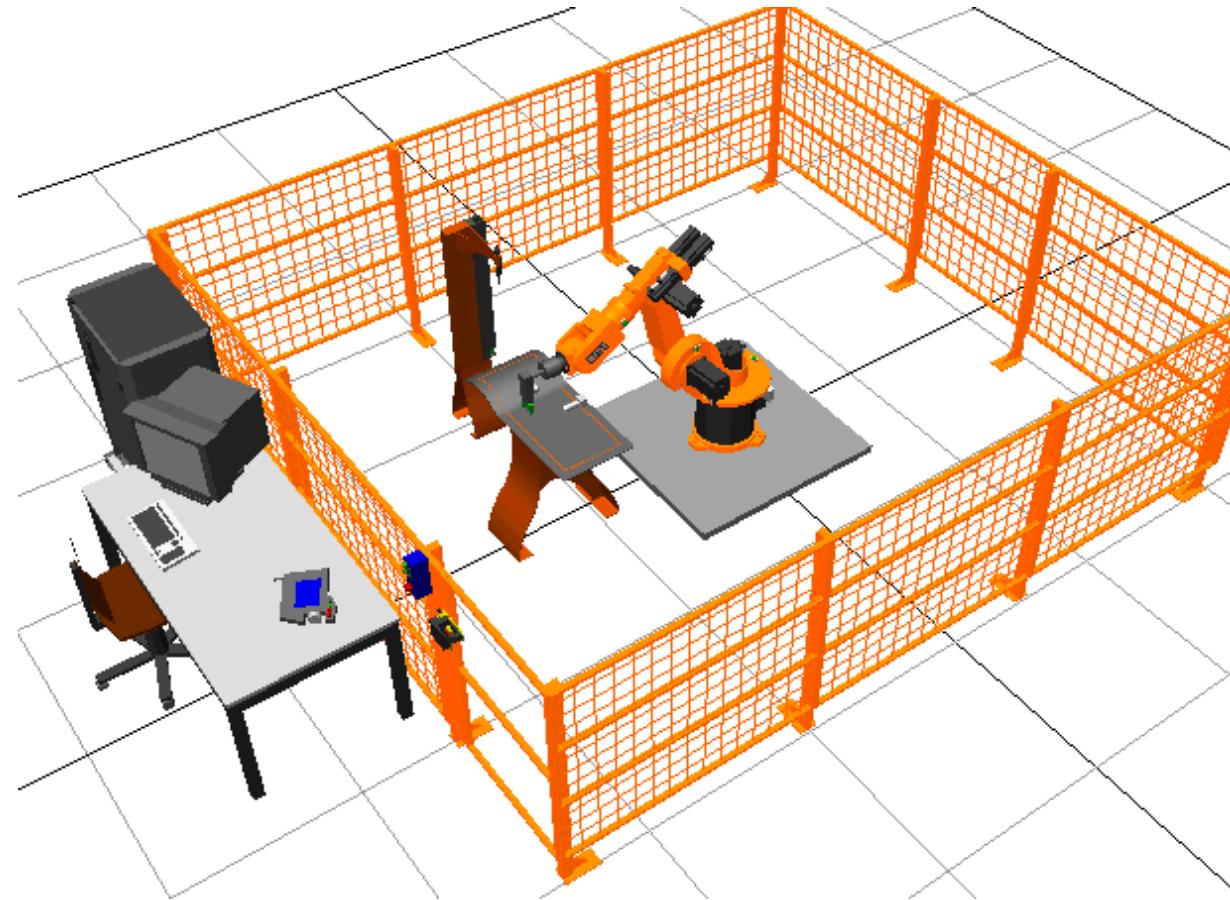
Deburring center



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



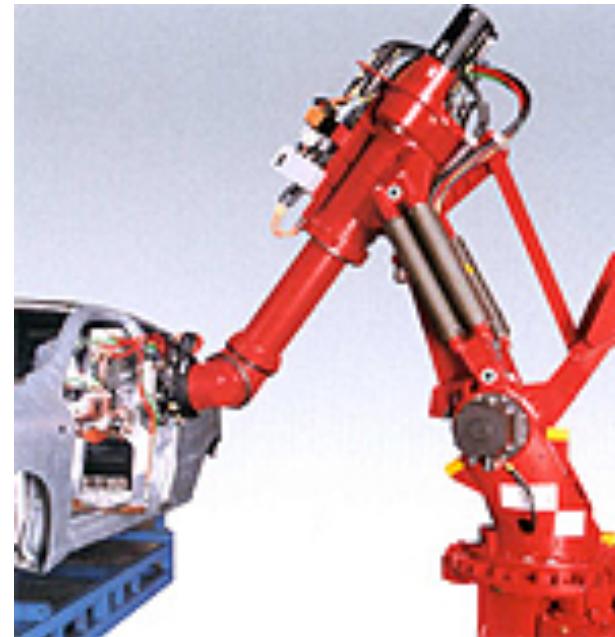
commercial [video](#) from ABB
SafeMove (2008) cell monitoring system: no fences!



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!



Other types of robots



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

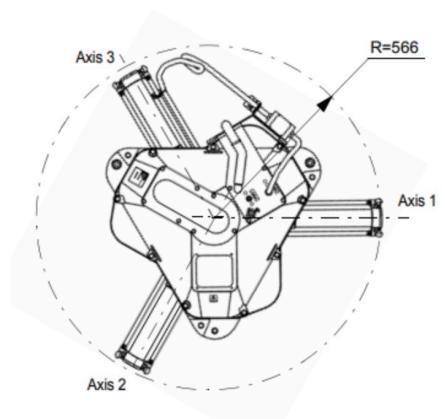
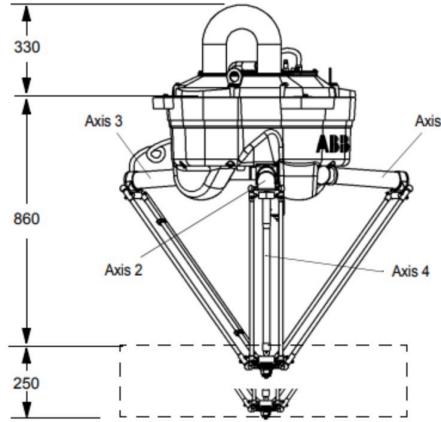
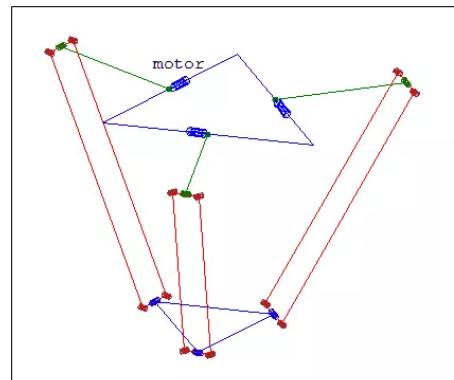


ABB 340 Flexpicker

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

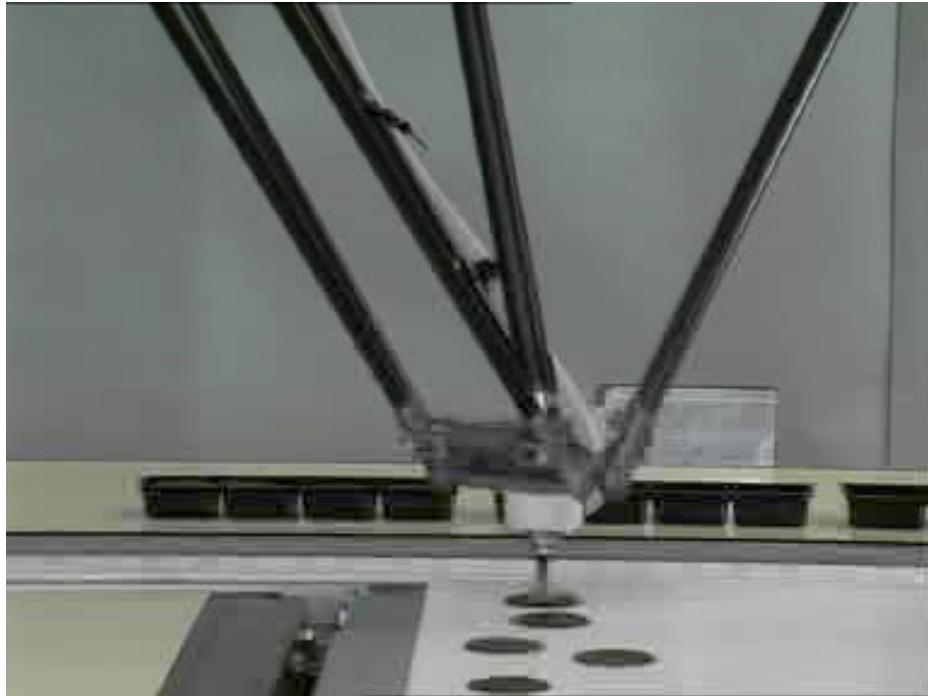
Delta in motion
(<https://link> to web)



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

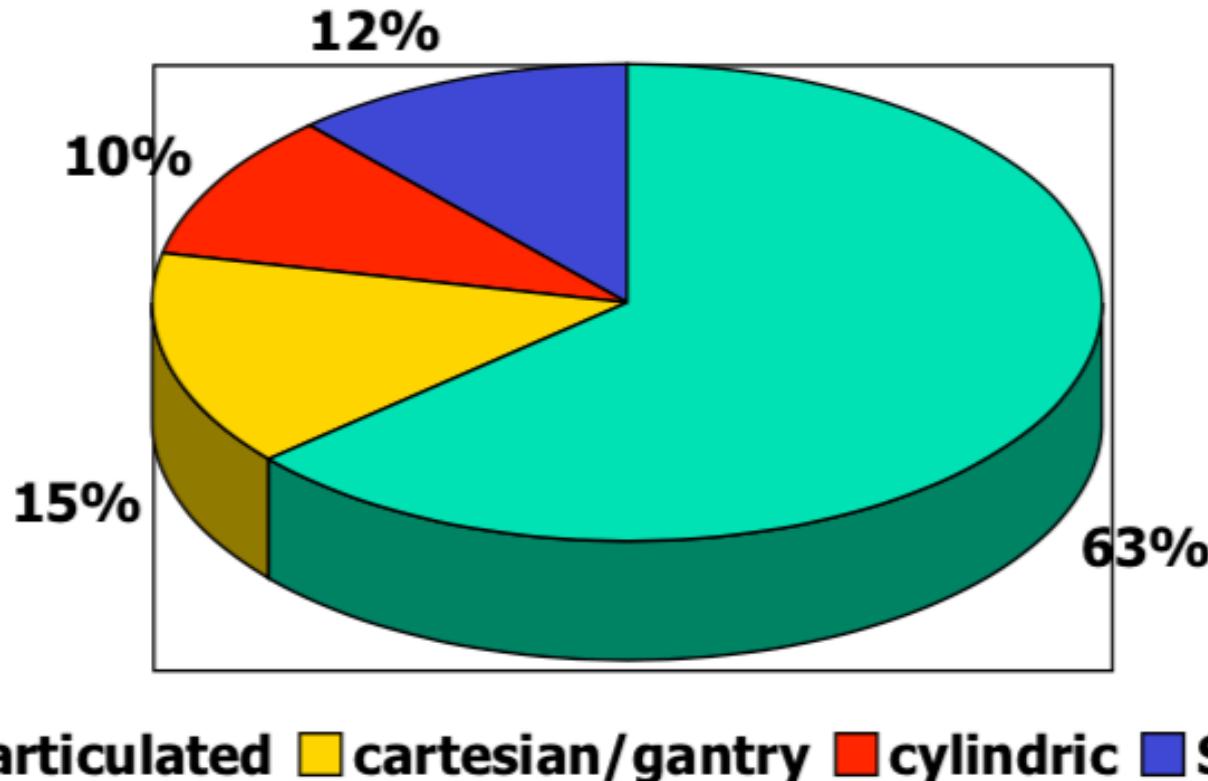


[video](#) with
Adept Quattro s650



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

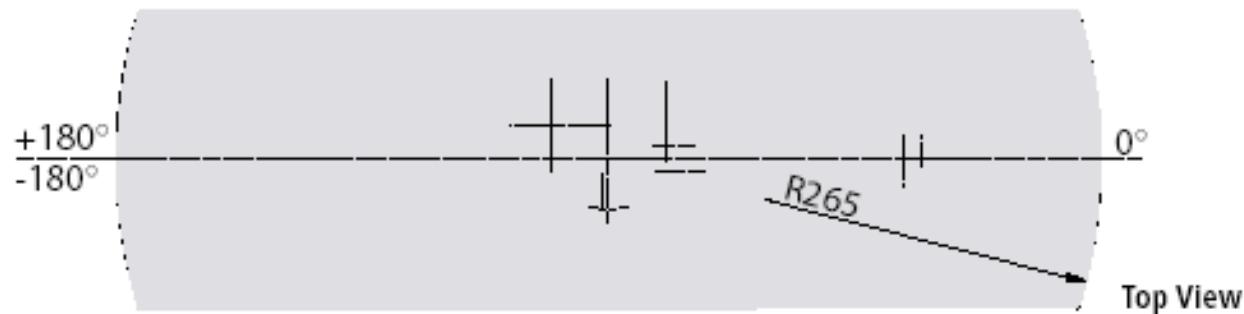
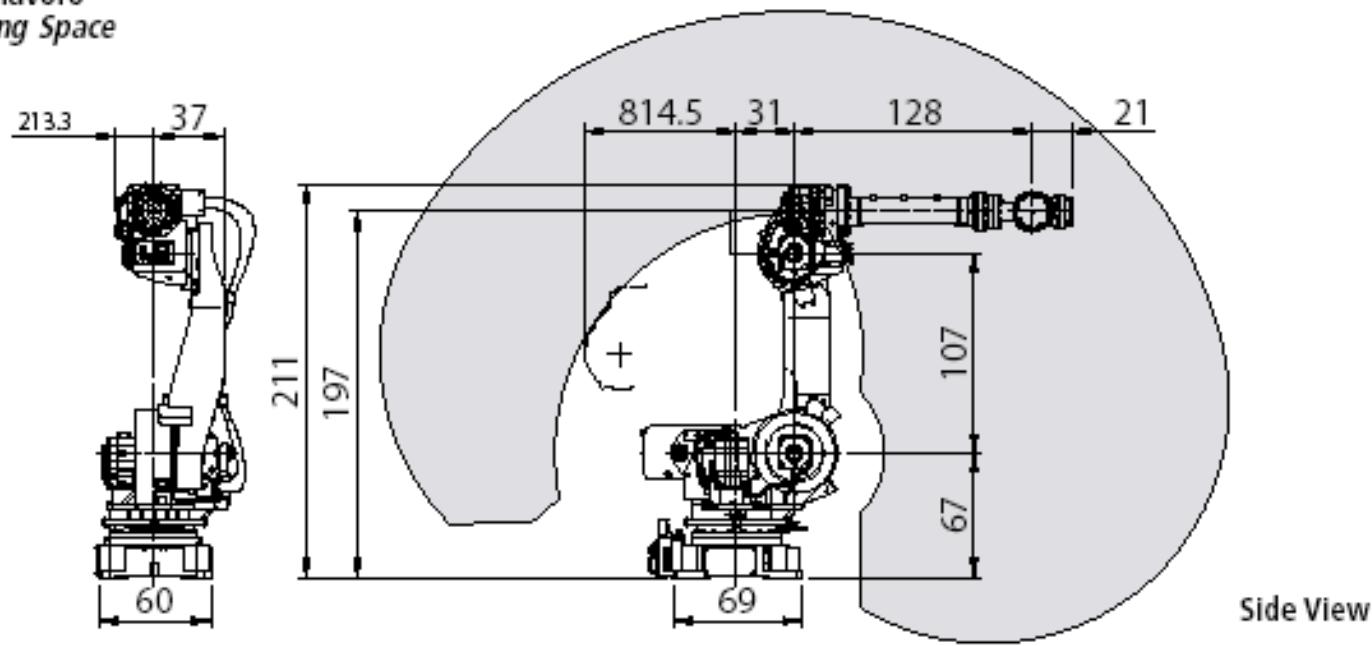
Specifiche tecniche

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	94kgf.m	921Nm
	Asse J5	94kgf.m	921Nm
	Asse J6	47kgf.m	461Nm
Momento di inerzia max. al polso	Asse J4	800kgfcm ²	78,4kgm ²
	Asse J5	800kgfcm ²	78,4kgm ²
	Asse J6	410kgfcm ²	40,12kgm ²
Tipo di azionamento	Motori elettrici AC		
Ripetibilità	± 0,3 mm		
Peso	1.210 kg		
Ambiente	Installazione	Temperatura ambiente:	0-45° C
Umidità ambiente		Normale:	≤ 75%
Breve (In un mese)		≤ 95%	
Vibrazioni		0,5 G max.	



Workspace

Area di lavoro
Operating Space



Visualization of workspace and mobility



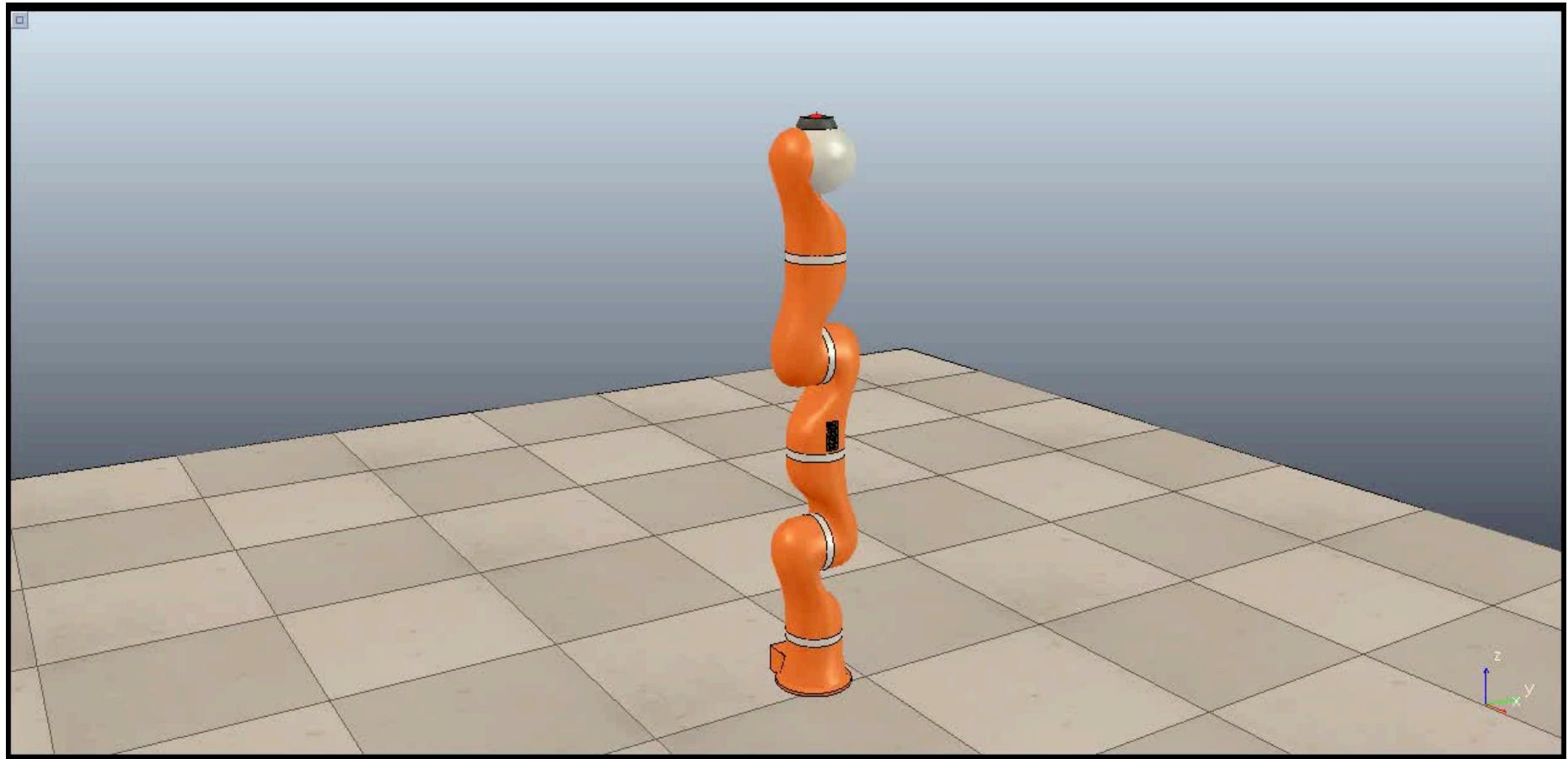
[video](#)

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

Visualization of workspace and mobility



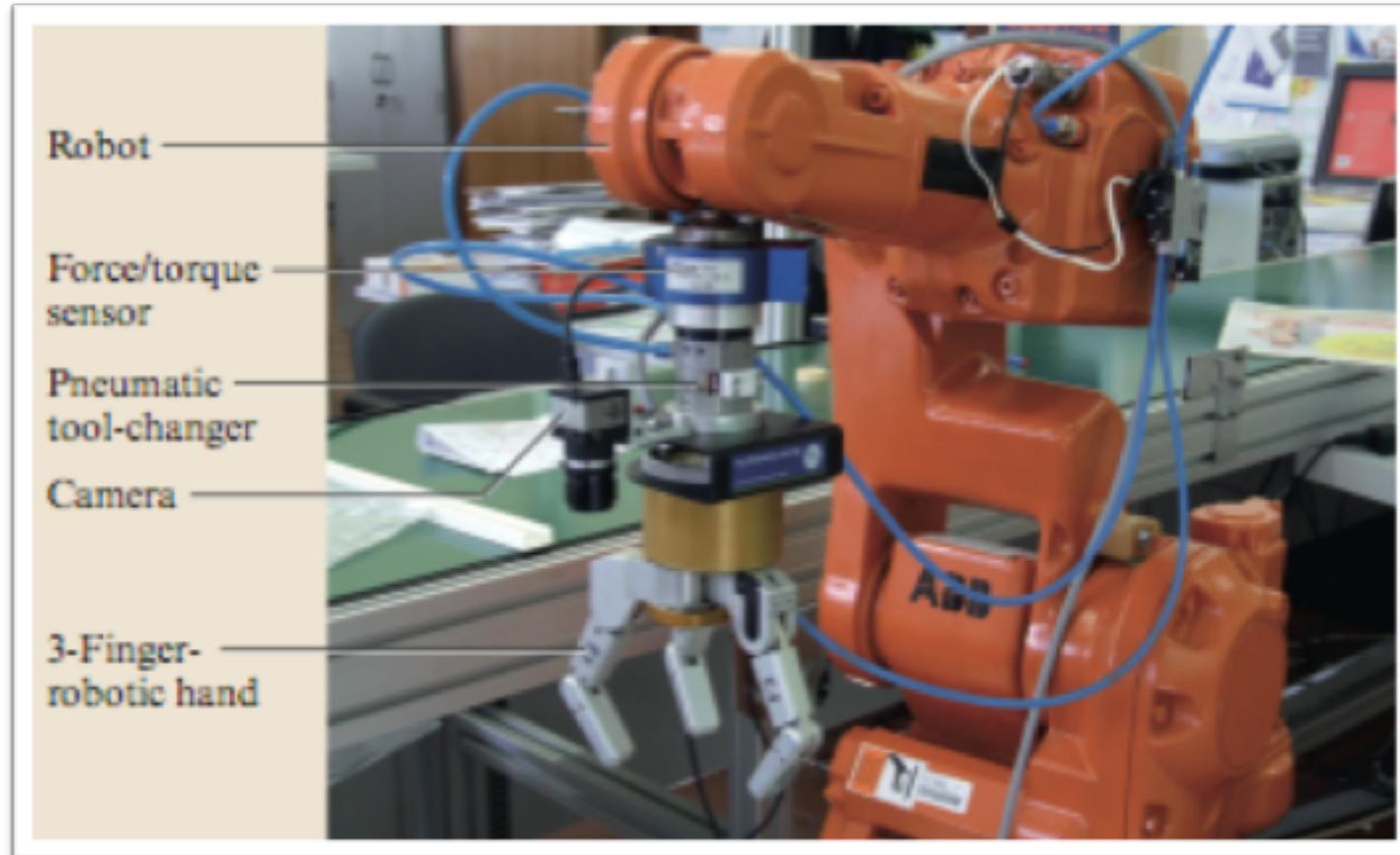
video



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

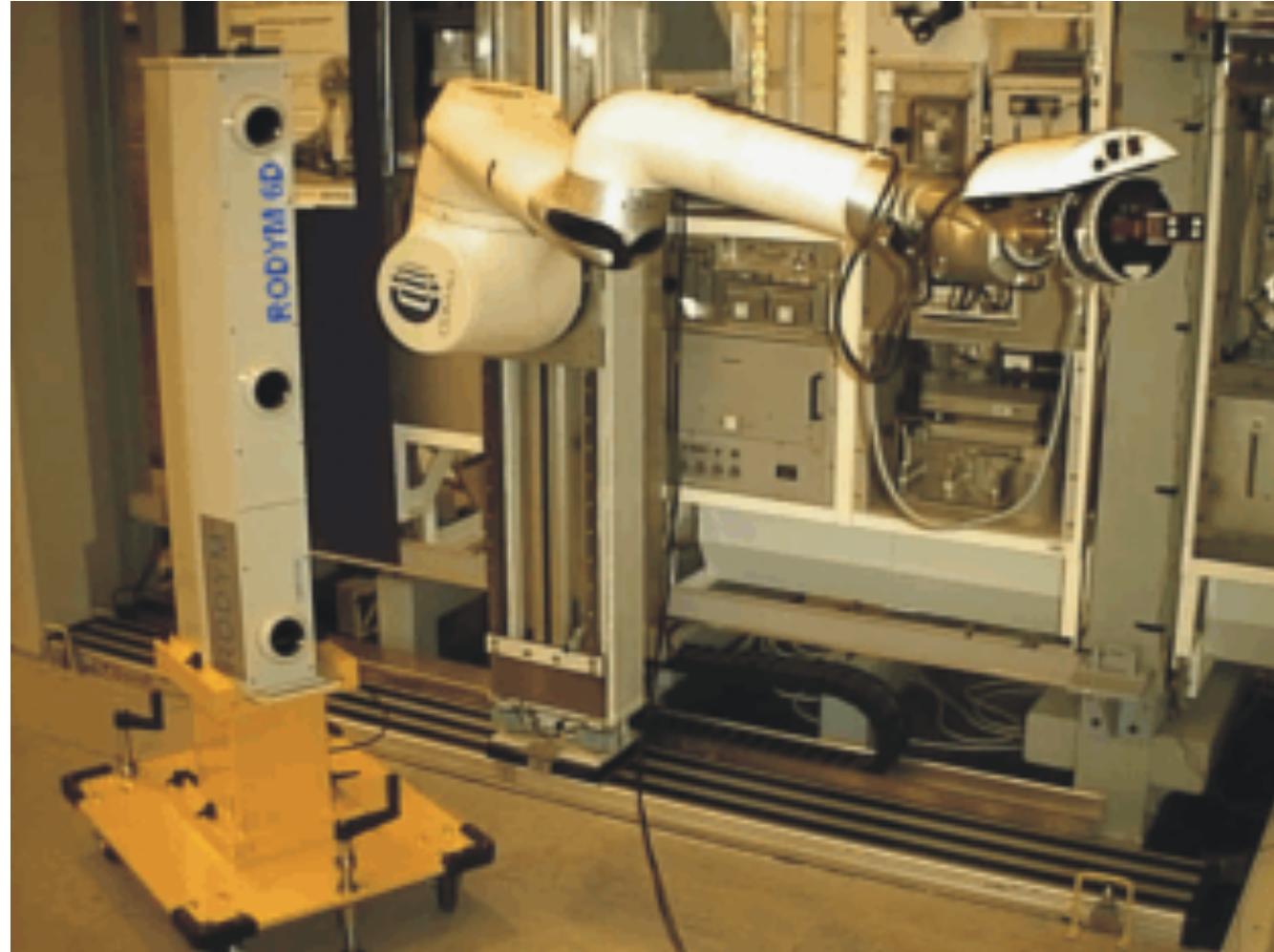


Robot end-effector sensors and tools





Calibration of robot kinematics





Man-machine interface



- teach-box pendant used as robot programming interface

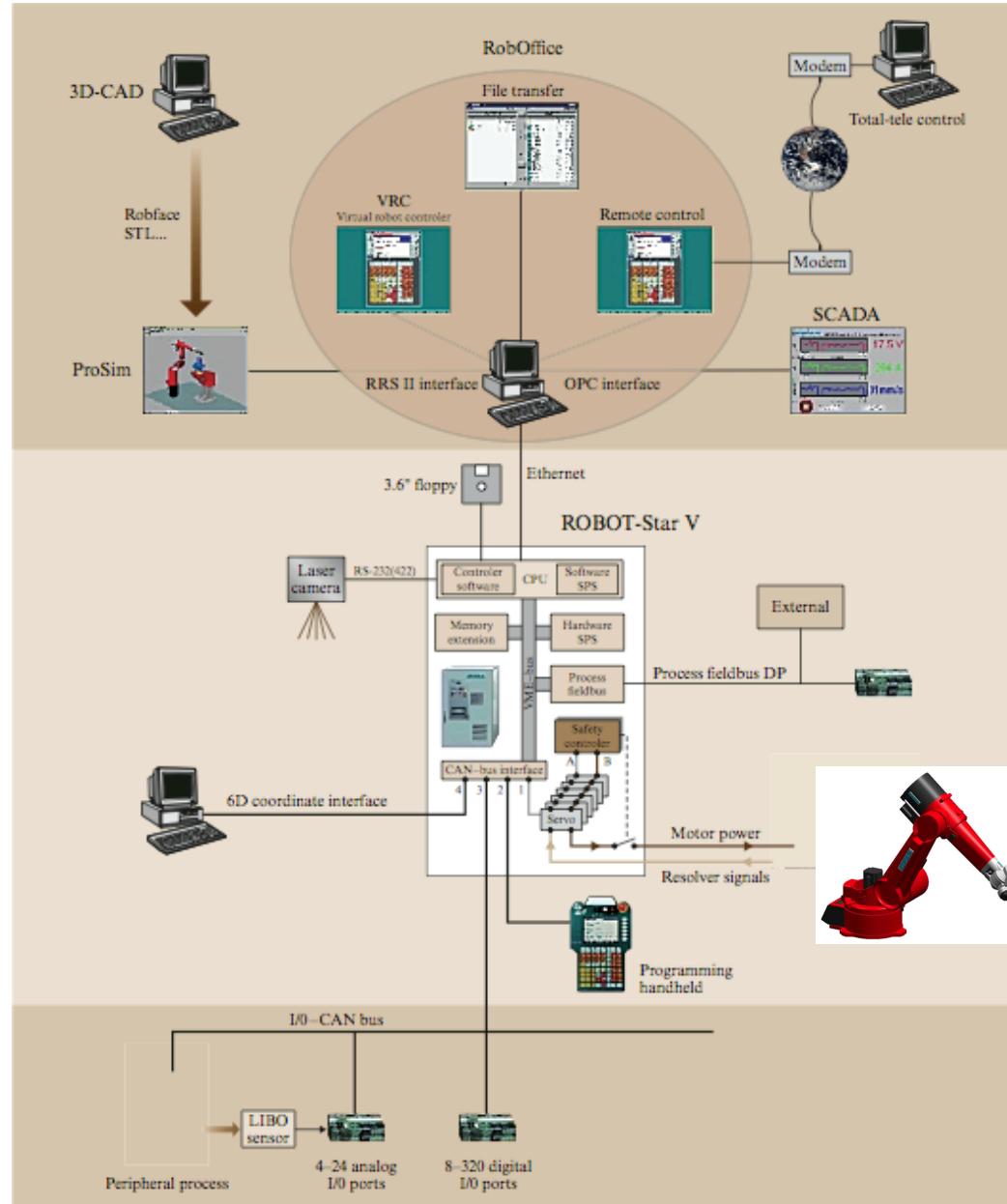


- cabinet with power electronics for robot supervision and control



Programming and control environment

control modules
and interfaces
(Reis Robotics)





Motion programming and scaling



commercial [video](#) from ABB
TrueMove & QuickMove fast motion control performance

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/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



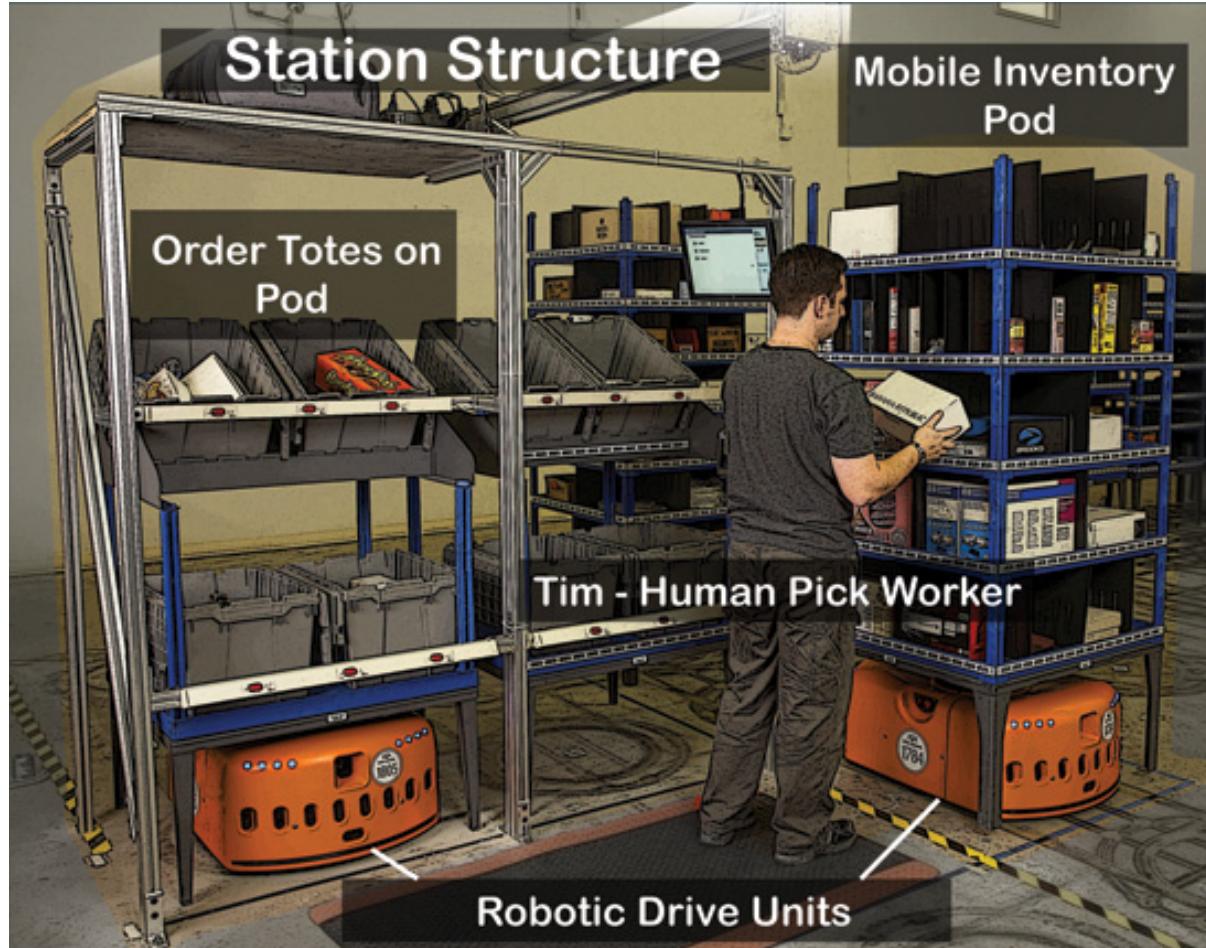
Lifting AGV for warehouses



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
(with additions..)



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 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

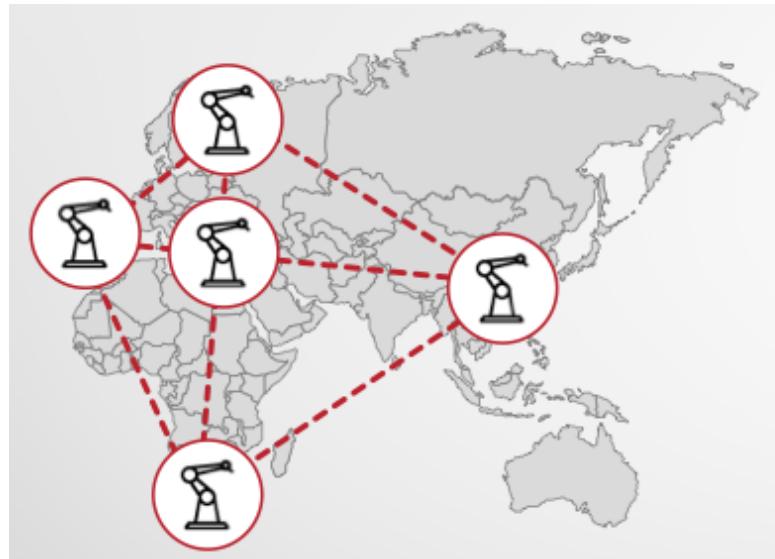
- **collaborative robotics** is shifting traditional limits of "what can be automated?"
- cobots increase manufacturing flexibility as 'low-volume, high-mix' becomes the main standard
- collaboration is also about productivity with increased physical and cognitive **human/robot interaction**



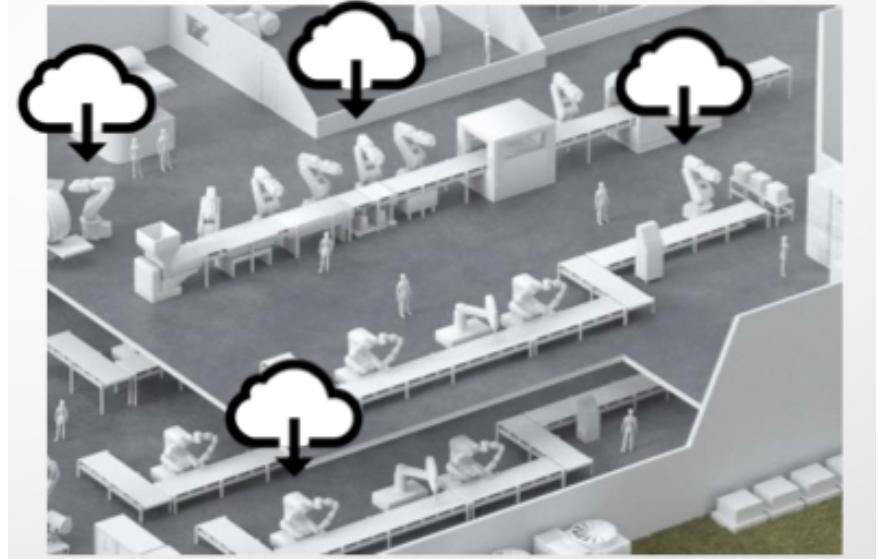
What's next in industrial robotics?

"connected" future of robotics

self-optimizing production



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)

[video](#)

