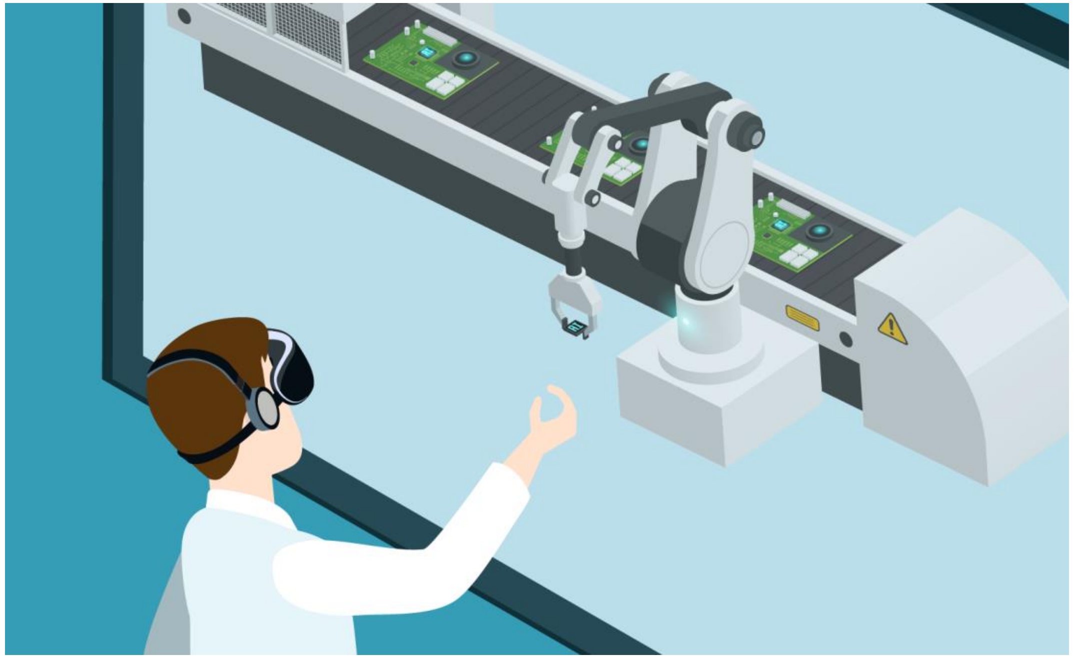
Collaborative robotics

Dr. Ing. Lorenzo Scalera

Polytechnic Department of Engineering and Architecture
University of Udine

Outline

- Introduction to robotics
- Introduction to collaborative robotics
- Regulations and standards for safety
- Robots in the market
- Research in collaborative robotics at University of Udine



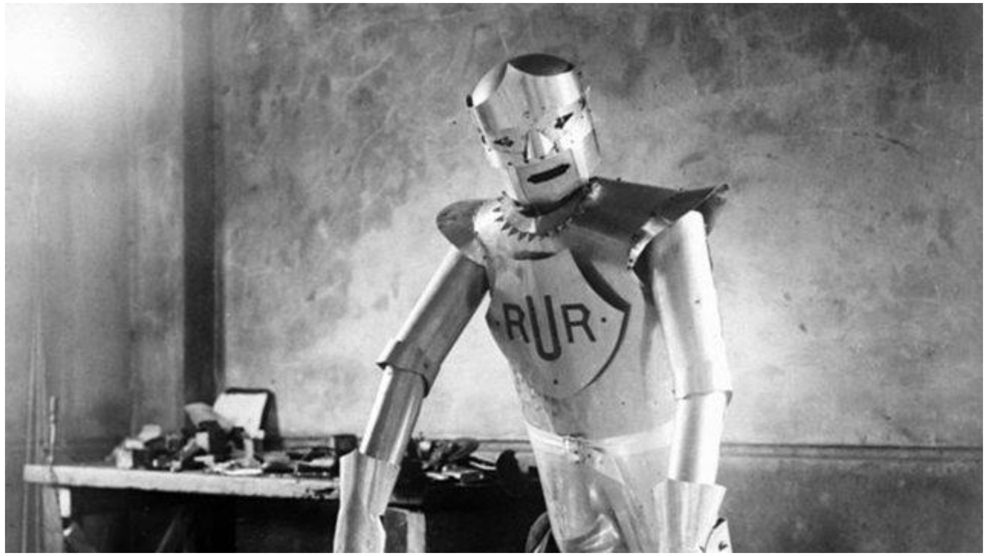
Introduction to Robotics

- What is Robotics?

The study of machines that replaces man in the execution of a task, both in terms of physical activity and decision-making

Automaton:
mechanical creature with the task of replacing the human being in tasks of subordinate work

The term *robot* comes from the Czech word *robota = executive work,* *coined in 1921 by Čapek* in his science fiction play *Rossum's Universal Robots*



The birth of industrial robotics (Unimate)

The term **robot** comes from the Czech word "**robota**," which means "**heavy labor**" or "**forced labor**“.

- Unimate was the first industrial robot ever;
- It was invented by George Devol and Joseph Engelberger (founders of the Unimotion company) with a patent registered in 1954;
- Created for General Motors, the robot served a production line for handling automotive die-cast parts;
- The idea was to substitute humans in hazardous operations (toxic fumes and possible physical injury);

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

Introduction to Robotics

- What is a robotic system?

- **A robotic system is a mechanical / electronic / IT device capable of performing a specific task independently**

- **Elements of a robotic system**
    - Workspace
    - Mechanical structure
    - Sensors
    - Elaboration unit
    - Actuators

Example of a robotic system: vacuum cleaner robot

- Is it a robotic system?

Example of a robotic system: vacuum cleaner robot

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

- It has a very specific **goal**: remove dust from the floor of the room
- It does it alone (**autonomy**)
- It works in a **work environment** (the room)
- It has a **mechanical structure**
- It has **sensors** (position, obstacles, dirt, etc.)
- It has a **processing unit** that controls the operations related to the management of the trajectories and the activation of the aspirator
- It has **actuators** (motors for locomotion and aspiration)

Introduction to Robotics

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

- Robotics can be defined as a science that studies the intelligent connection between **perception** and **action**

- mechanical system (locomotion and manipulation)

- sensory system (proprioceptive and exteroceptive sensors)
  - Proprioceptive = acquire information on the internal state of the mechanical system
  - Exteroceptive = to acquire information on the external state of the environment

- control system
  - ability to intelligently connect action and perception

Introduction to Robotics

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

- proprioceptive sensors measure the internal state of the robot (position and velocity of joints, but also torque at joints or acceleration of links)
- kinematic calibration, identification of dynamic parameters, control

- exteroceptive sensors measure/characterize robot interaction with the environment, enhancing its autonomy (forces/torques, proximity, vision, but also sensors for sound, smoke, humidity, …)
- control of interaction with the environment, obstacle avoidance, localization of mobile robots, navigation in unknown environments

Introduction to Robotics

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

Proprioceptive sensors

- **Position**
  - linear displacements: potentiometers, linear variable differential transformers (LVDT)
  - angular displacements: potentiometers, resolvers, encoders (digital)
- **Velocity and acceleration**
  - Tachometer
  - Accelerometers

Exteroceptive sensors

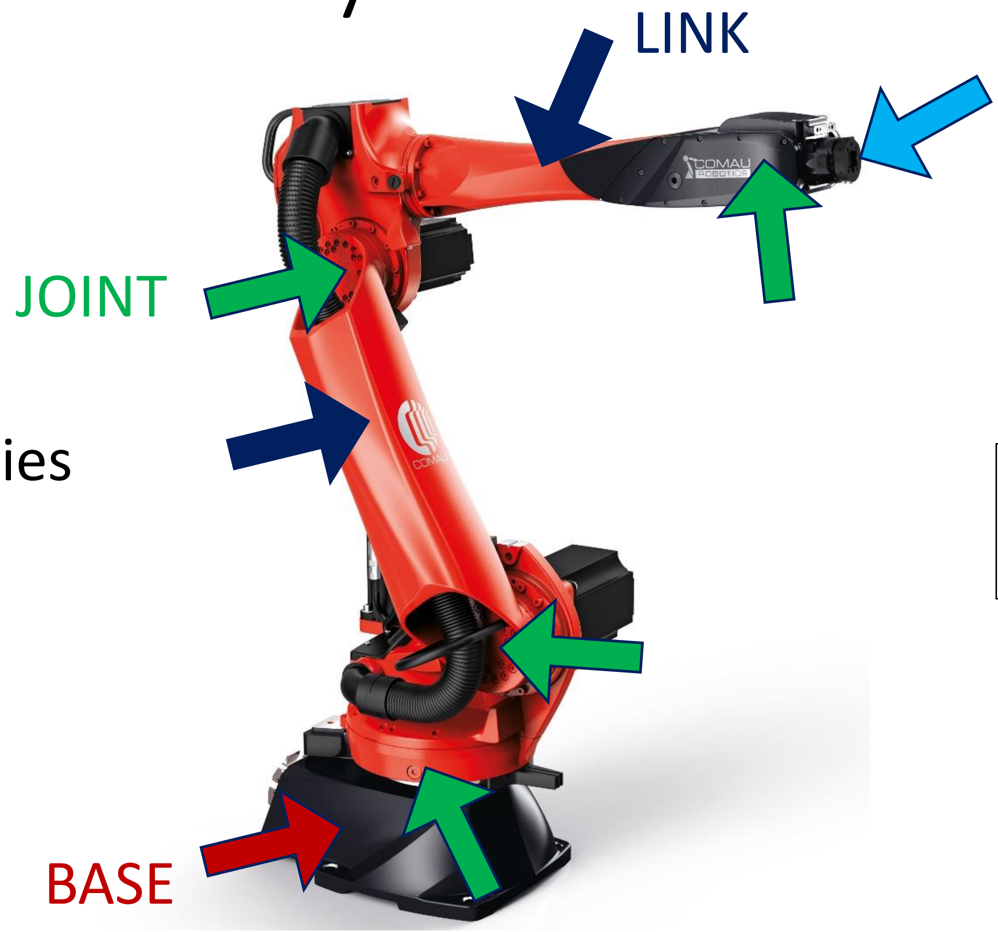
- **Force Sensors**
  - strain gauges and joint torque sensor
- **Proximity/distance sensors**
  - infrared (IF),
  - ultrasound (US),
  - laser with structured light
- **Vision**

What are the components of an industrial robot?

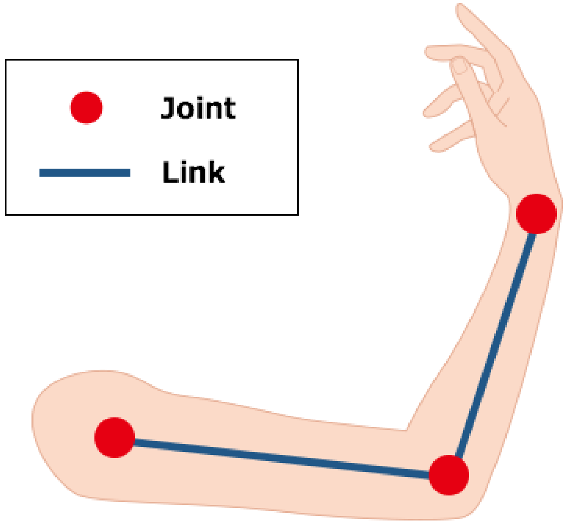
- Mechanical structure (manipulator) with actuators and sensors

- Control system (control logic, drives)

What are the components of the mechanical system?

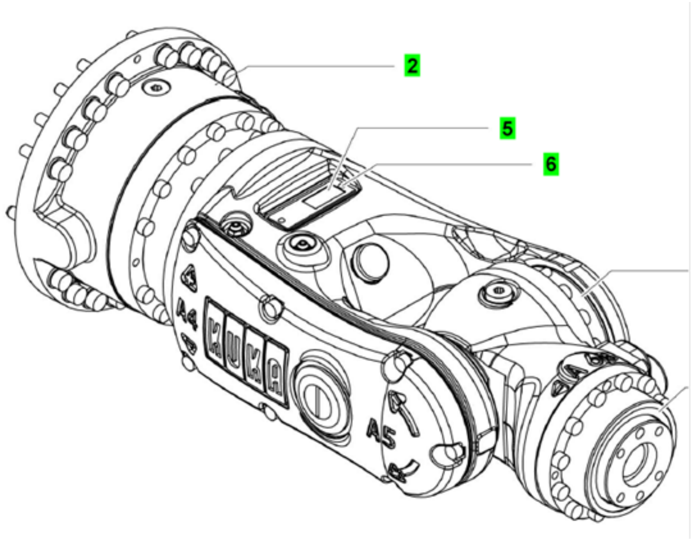


The manipulator is a series of rigid bodies (**links**) connected by **joints**

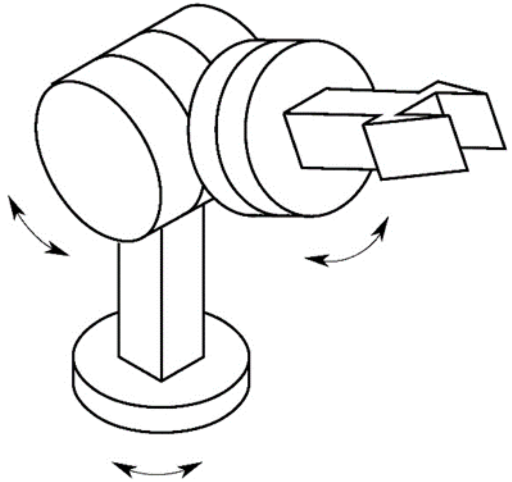


What are the components of the mechanical system?

- **Support structure** and **wrist**, which gives *dexterity*
  - Main function: orient the end-effector in the space
  - I can reach the same point with more than one orientation



- **Actuators** impart the movement of the manipulator through the actuation of the joints
  - Electric, hydraulic and pneumatic actuators



- **Sensors** measure the state of the manipulator (*proprioceptive*) and possibly the state of the surrounding environment (*exteroceptive*)

The control system

- The control system of a robot is a very complex and sophisticated product, which requires high software development times
- Its main tasks are as follows:
  - Interface with the operator
  - Trajectory planning
  - Real-time control of joint motion
  - Data storage
  - Interface management with other machines
  - Diagnose and manage malfunctions

Structure and classification of manipulators

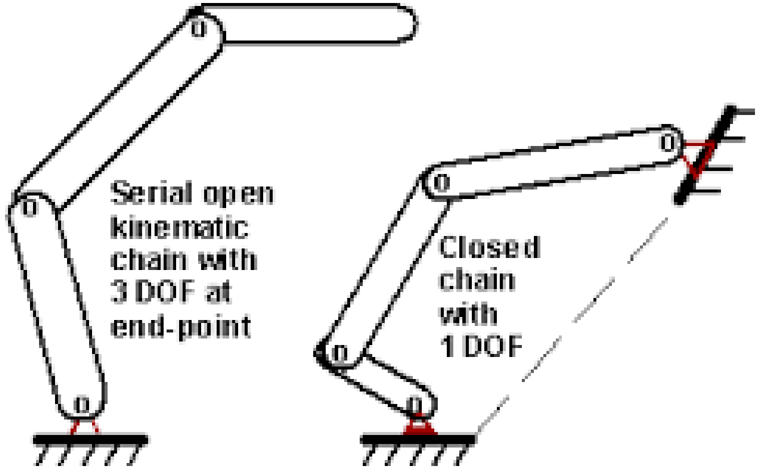
Open kinematic chain

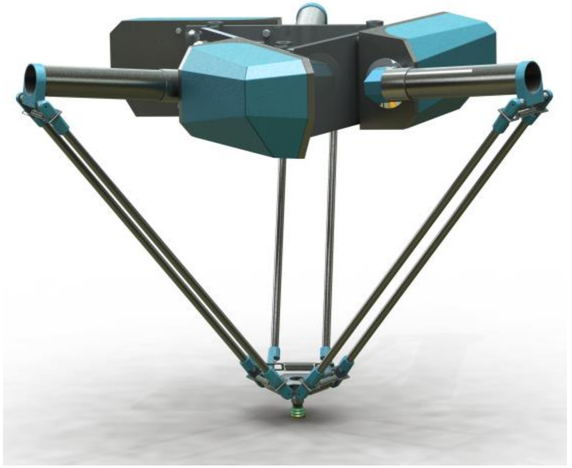
There is only one sequence of arms that connects the two ends of the chain

Closed kinematic chain

The arm sequence of the manipulator constitutes a closed chain (a ring)

Example of serial robot



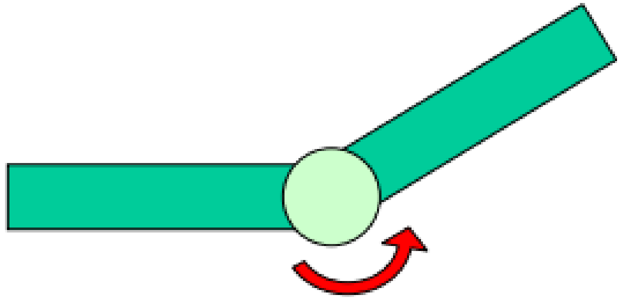


Example of parallel robot (Delta Robot)

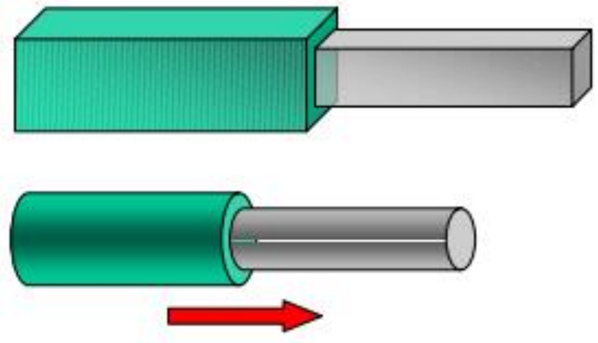
Structure and classification of manipulators

Articulation between two consecutive arms:

- REVOLUTE JOINTS (relative rotation between two joints)
- Allows the link i to move relative to the i-1 link by rotating around an axis passing through the joint i



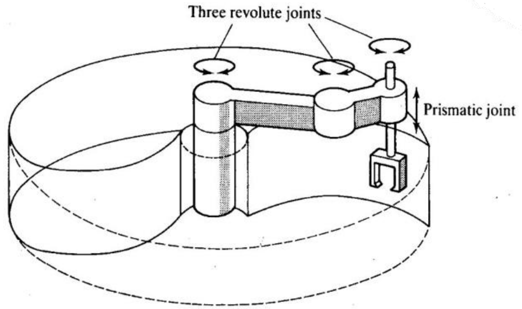
- PRISMATIC JOINTS (relative motion of translation between two joints)
- It allows the link i to move with respect to the i-1 link translating along an axis passing through the joint i

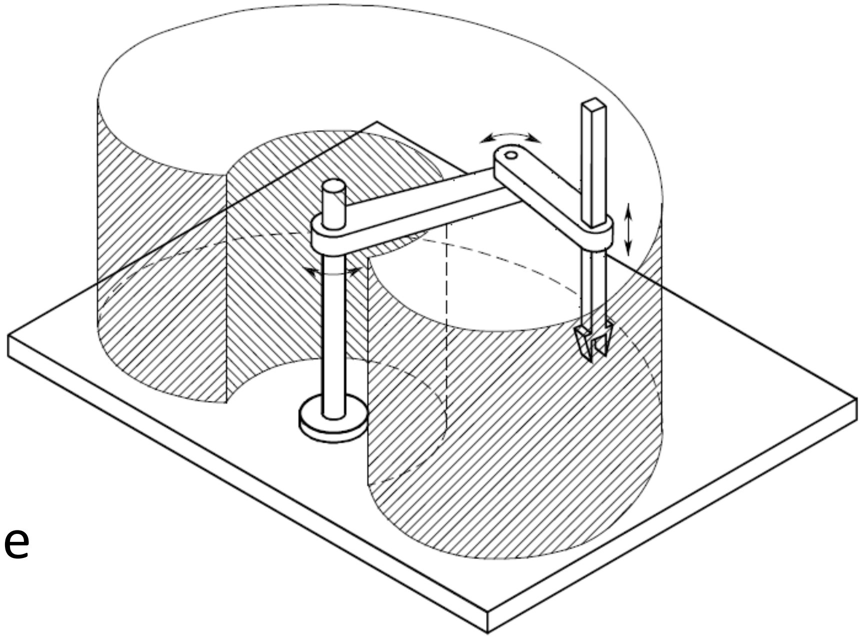


Structure and classification of manipulators

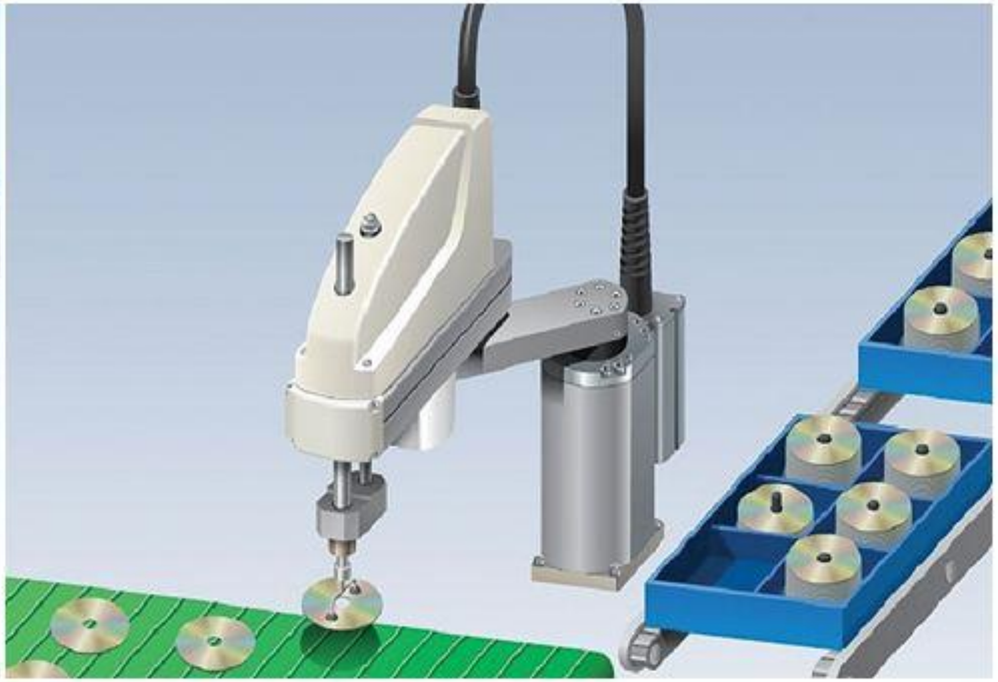
SCARA manipulator (Selective Compliant Assembly Robot Arm)

- 3 or 4 degrees of freedom
- Two revolute joints, one prismatic and eventually one more revolute joint
- The motion axes are all parallel to each other
- High stiffness to vertical loads and compliance to horizontal loads
- Assembly for vertical insertions
- Handling of small objects
- The positioning accuracy of the end-effector is reduced as the distance of the wrist from the axis of the first joint increases

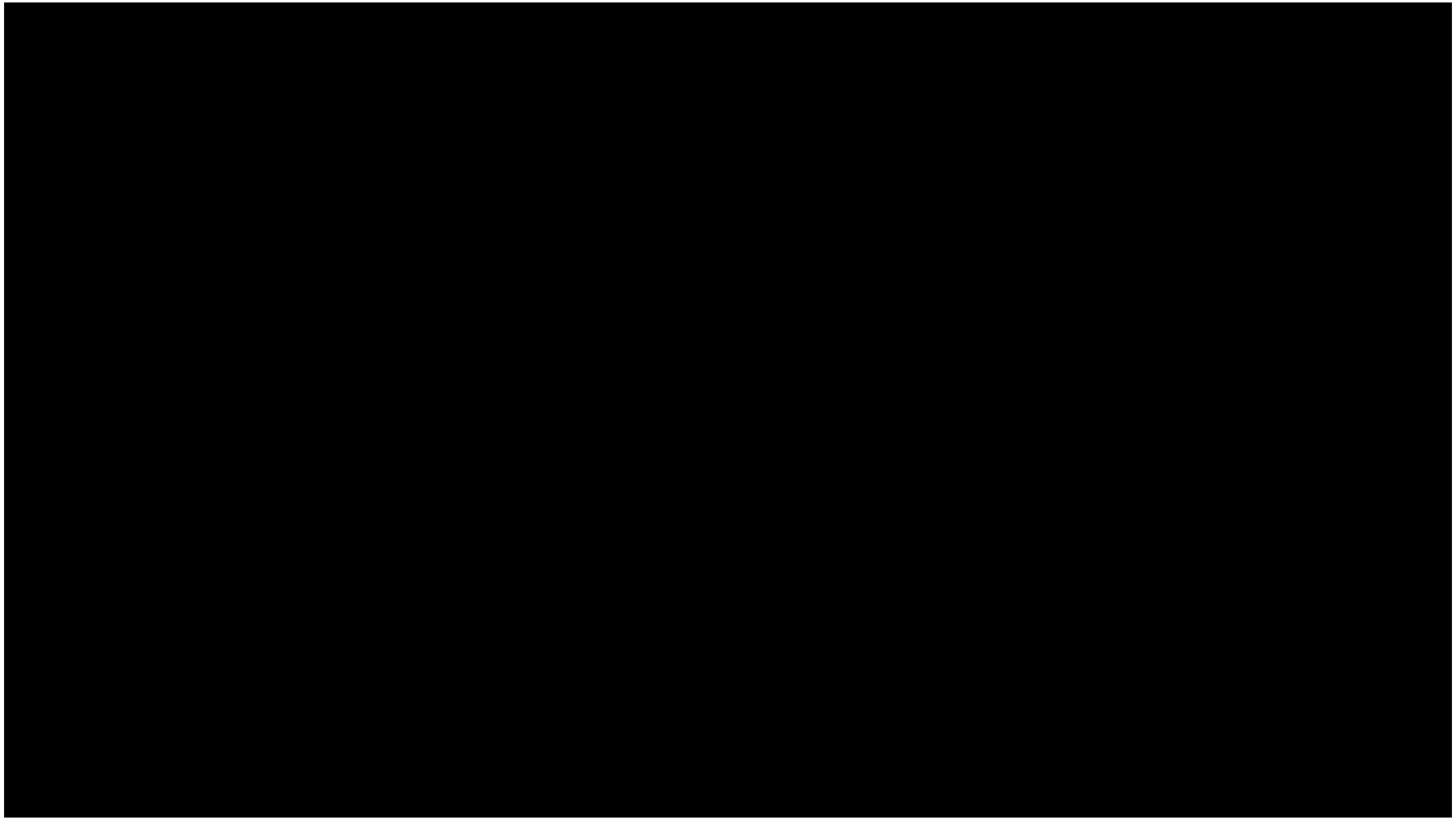




Examples of SCARA manipulators for pick-and-place operations



SCARA manipulators for pick and place

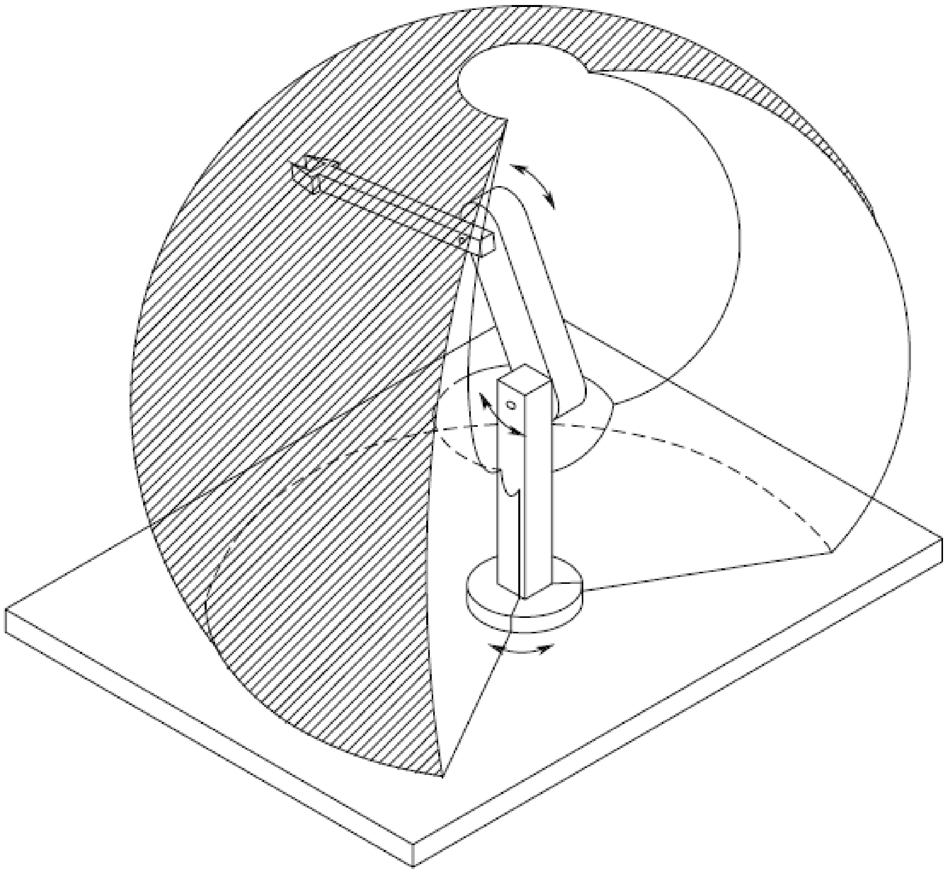


Structure and classification of manipulators

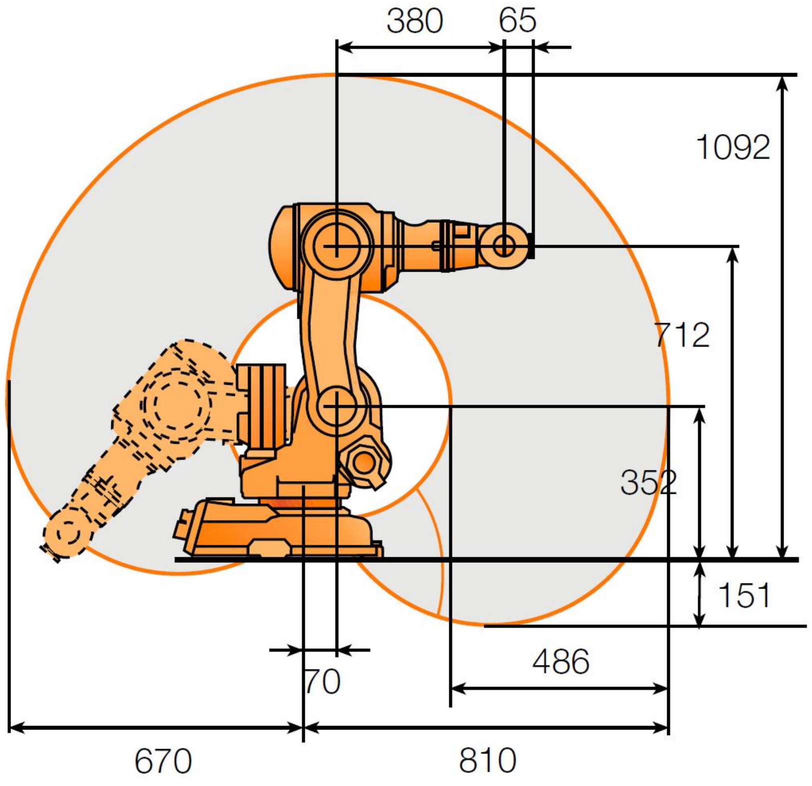
UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

Articulated manipulator

- Three revolute joints
- The axis of rotation of the **base joint** is orthogonal to the other two parallel ones
- The second joint is called **shoulder** while the third **elbow**
- The positioning of the wrist changes throughout the workspace
- Workspace is a portion of a sphere
- Large volume of workspace compared to the volume of the manipulator



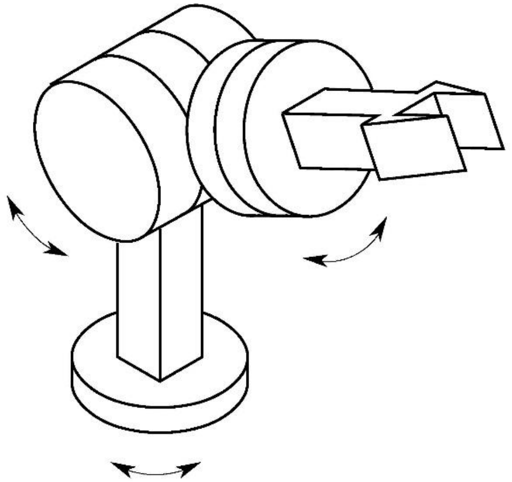
Examples of articulated manipulators

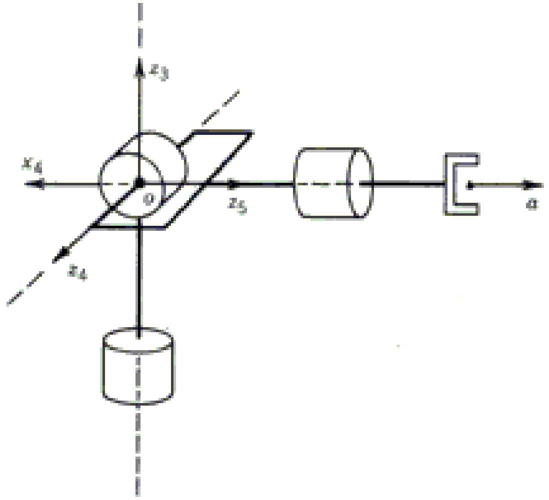


Structure and classification of manipulators

Spherical wrist

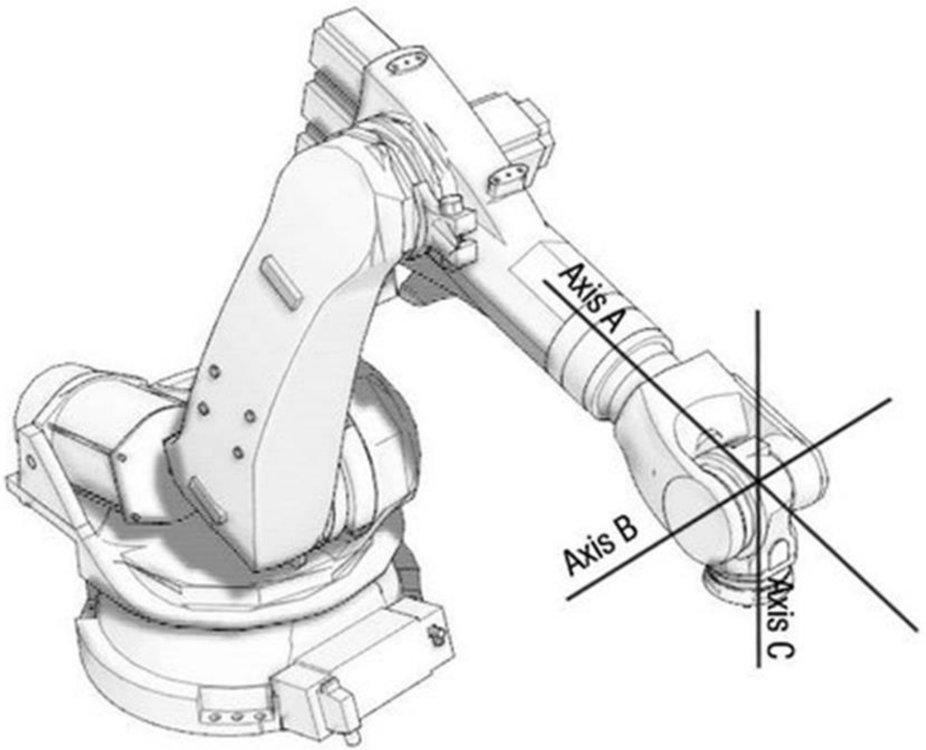
- To guarantee arbitrary orientations in a 3D space, the wrist must have at least three degrees of freedom achieved by rotary joints
- The realization that gives the wrist greater **dexterity** is that in which the three axes of rotation intersect at one point (**spherical wrist**)
- Uncoupling between position and orientation of the end-effector
- The supporting structure positions in the space the intersection point of the three axes of the wrist
- The wrist itself determines the orientation of the end-effector

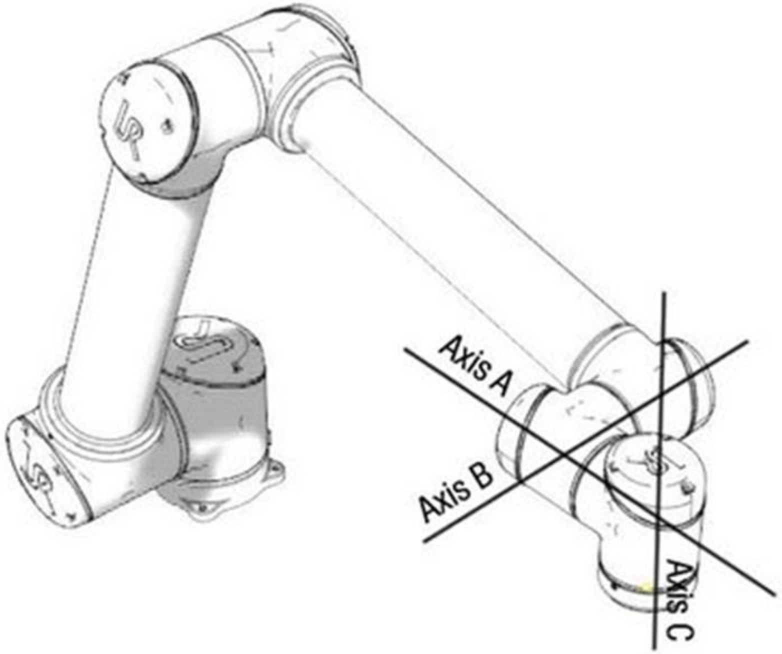




Structure and classification of manipulators

- Spherical wrist
- Non-spherical wrist

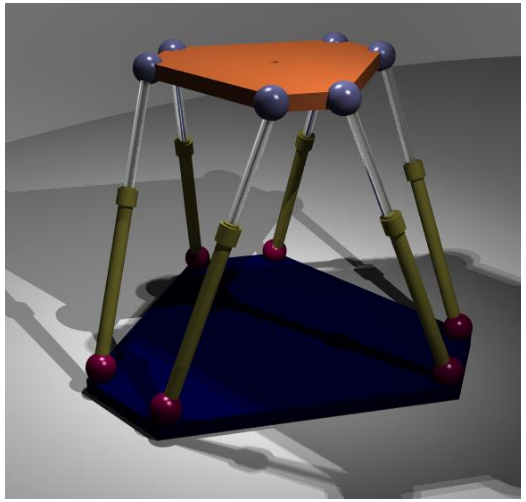




Structure and classification of manipulators

- Parallel robots
- The end-effector is connected directly to its base usually by a number of arms independent of each other and that work in parallel, or work together and coordinated, but not necessarily aligned in parallel

Stewart platform, used for example for flight simulators



Parallel robot, Mitsubishi Electric

Structure and classification of manipulators

- Stewart's platform as a flight simulator

- 6 spatial degrees of freedom
- 6 prismatic joints (hydraulic jacks or linear electric actuators) fixed in pairs from three positions on the platform base plate, to three mounting points on a top plate
- All 12 connections are composed of universal joints
- Three linear movements x, y, z (lateral, longitudinal and vertical) and three rotations in space (pitch, roll and yaw)

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

Structure and classification of manipulators

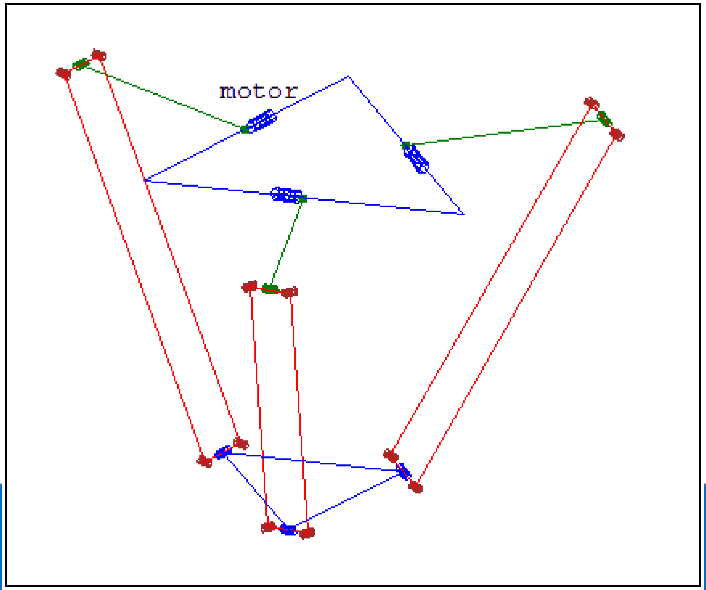
- Parallel robot for haptic interfaces

- Haptic interface: device that allows to operate a robot, real or virtual, and to receive tactile sensations in response (feedback)
- The haptic word derives from the Greek apto, "touch"
- Applications in areas of advanced robotics, such as surgical and space robotics, and those related to virtual reality and tele-manipulation
- Haptic interface (**robot master**) and remote or virtual device (**slave**)

Structure and classification of manipulators

Parallel robots

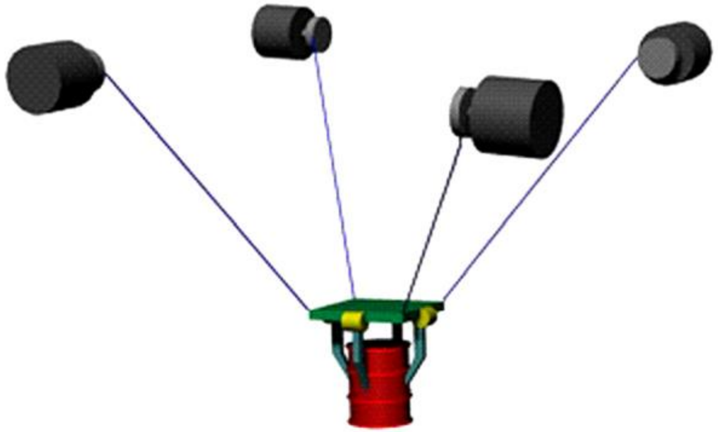
- Fast pick-and-place applications
- Light structure (arms often made of carbon)
- Reduced inertia
- Greater dynamic performance
- High speeds and high accelerations
- Greater stiffness
- Generally low load capacity (a few kilos)
- Parallel robots are generally more limited in the work area; for example, generally they cannot get around obstacles

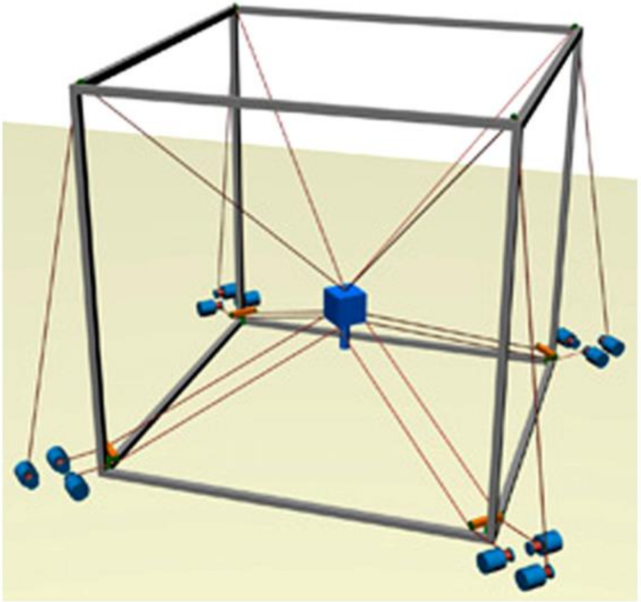


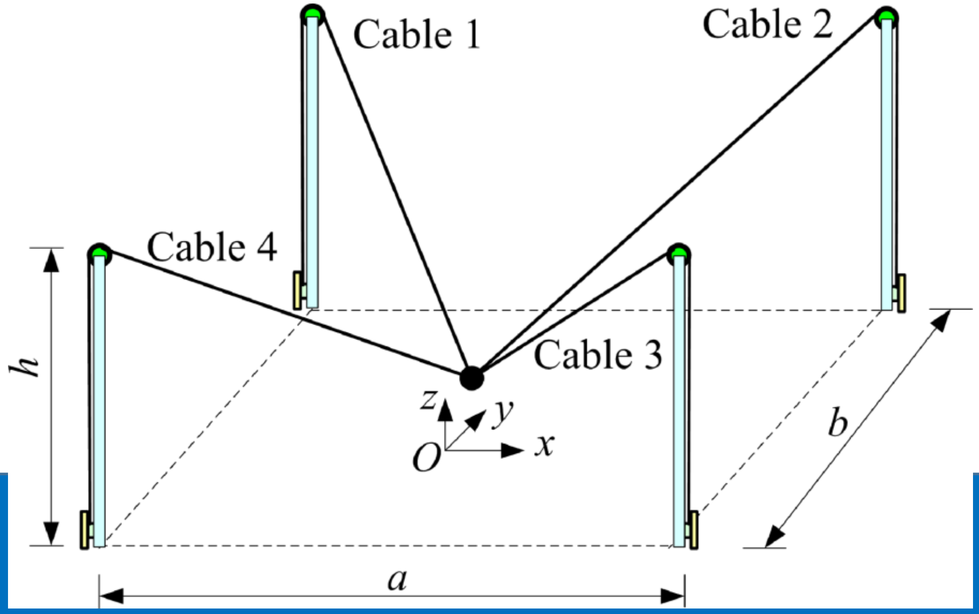
Delta robot - packaging

Cable-driven parallel robots

- Flexible link mechanisms (cables)
- Parallel robots
- Light, easily reconfigurable, transportable
- Used for transporting loads in large workspaces
- The end-effector may be completely constrained or suspended



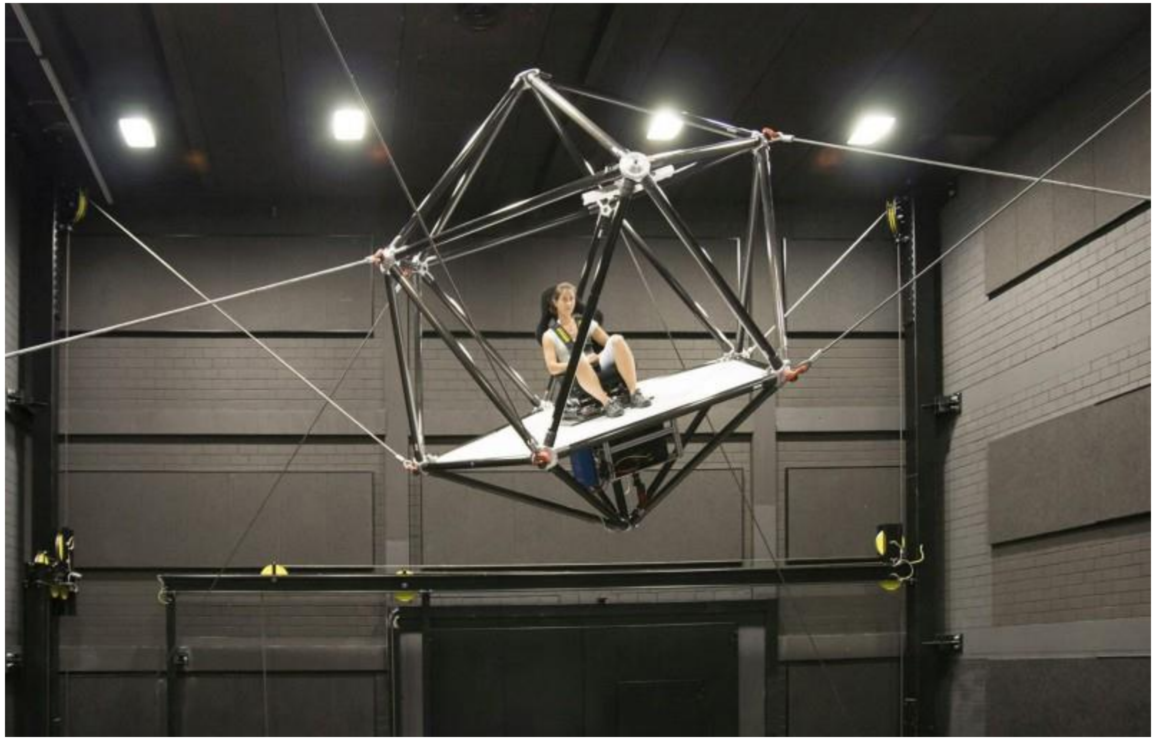




Cable-driven parallel robots

The Skycam

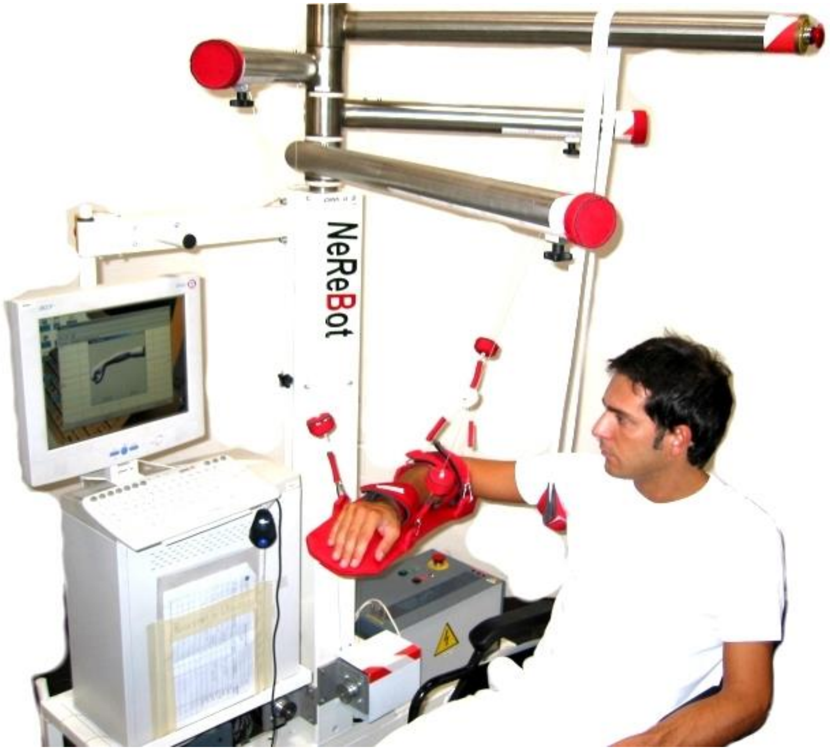
The Cable Robot Simulator



Cable-driven parallel robots

- The Arecibo Radio Telescope (Puerto Rico)

- Cable-robot for rehabilitation



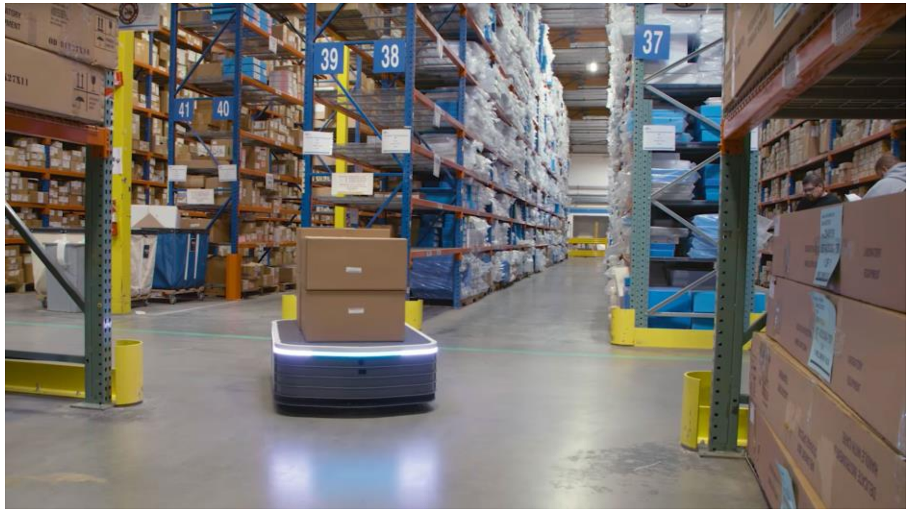
Mobile robots

- Automatic machine able to move in the surrounding environment
- Presence of a moving and autonomous base
- Service applications, where extensive and autonomous mobility is required:
  - Indoor applications
  - Outdoor applications

Mobile robots

Indoor applications:

- Cleaning of large rooms
- Service robotics for shops, museum, industries, etc.
- Internal surveillance of buildings
- Goods storage in automated warehouses
- AGV (Automatic Guided Vehicle) for palletizing and transporting finished products



Mobile robots

Outdoor applications:

- Military applications (mine clearance)
- Space and underwater exploration
- Civil protection
- Automated agriculture

Mobile robots

One or more rigid bodies equipped with a locomotion system:

Wheeled Mobile Robots (WMR):

Consisting of a rigid body (base or chassis) and a system of wheels that move it with respect to the ground

Mobile robots on legs:

Consisting of several rigid bodies, connected to each other by prismatic or revolute joints

Biomimetic robotics: their project is inspired by living organisms

What are the typical applications of an industrial robot?

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

- TRANSPORT
  - Handling
  - Pick-and-place
  - Loading / Unloading machines
  - Palletizing packing
  - Selection of parts

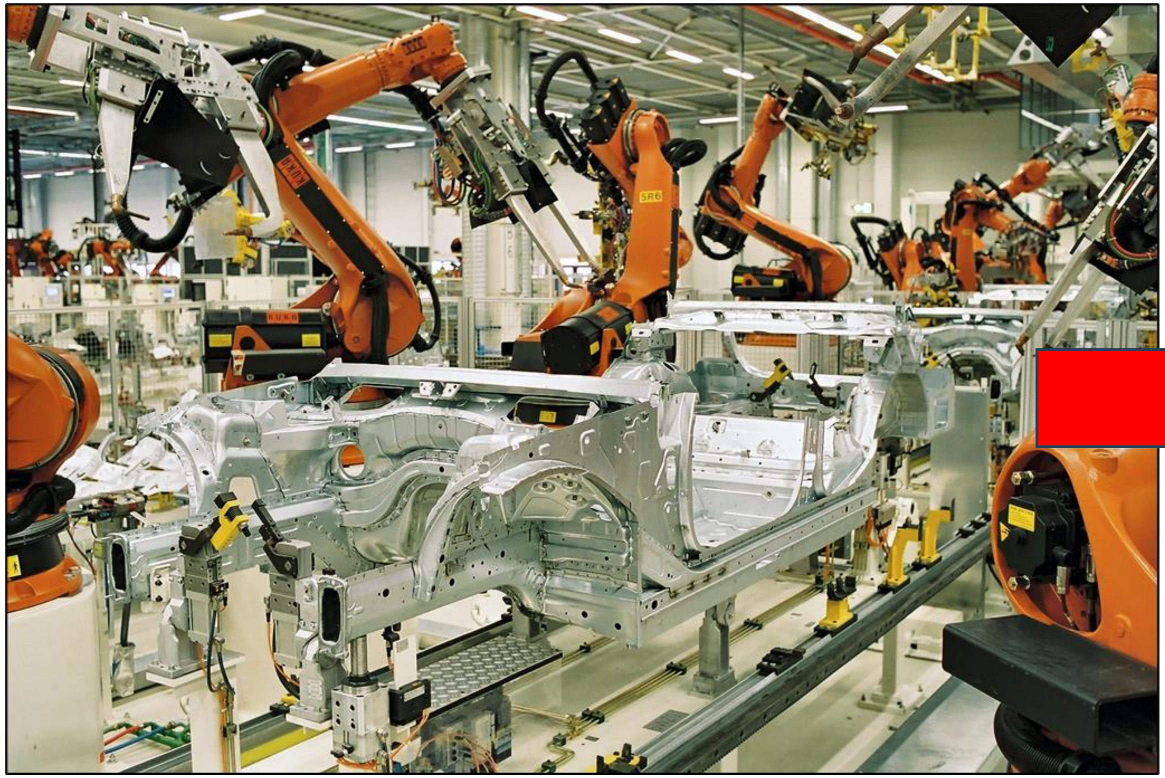
- MANUFACTURE
  - Spot welding
  - Arc welding
  - Sealing, gluing
  - Assembly (assembly)
  - Milling, drilling
  - Pressing
  - Deburring, grinding
  - Screwing, wiring
  - Painting

- MEASURE
  - Dimensional test
  - Profile detection
  - Identification of manufacturing defects

Production line BMW 3 series - welding robots

CMA Robotics - Robotic painting line

From industrial to collaborative robots



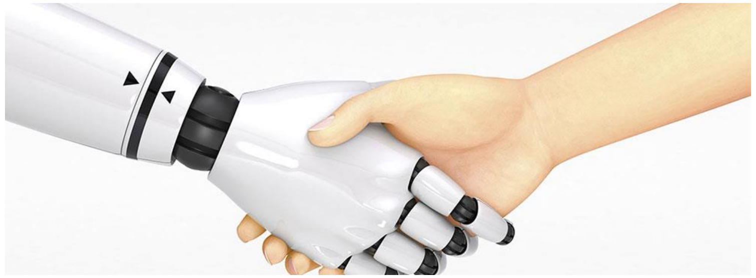
What does *collaborative robotics* mean?

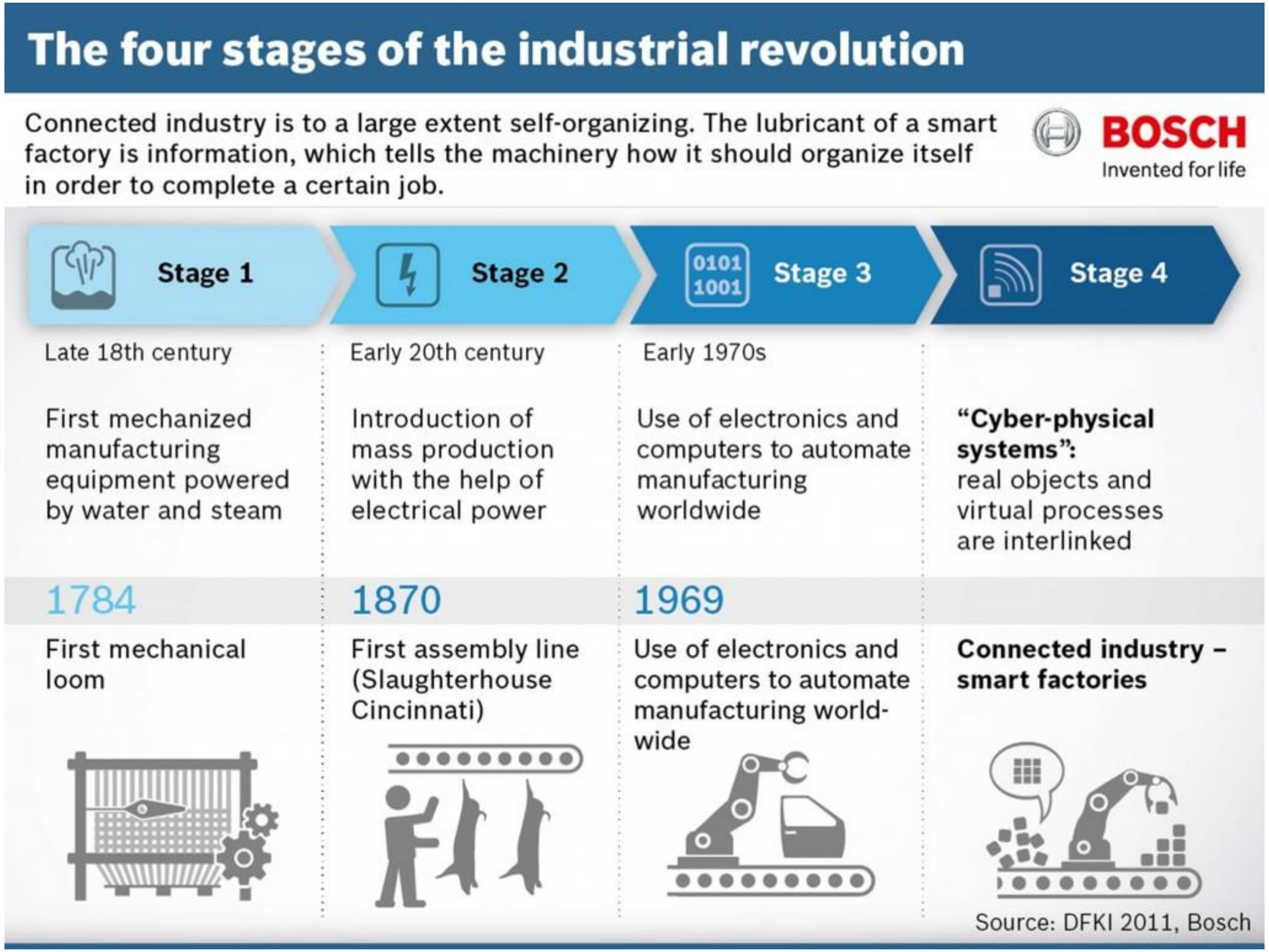
Being collaborative means:

«To work with someone to create or produce something»

Collaborative robots (cobots):

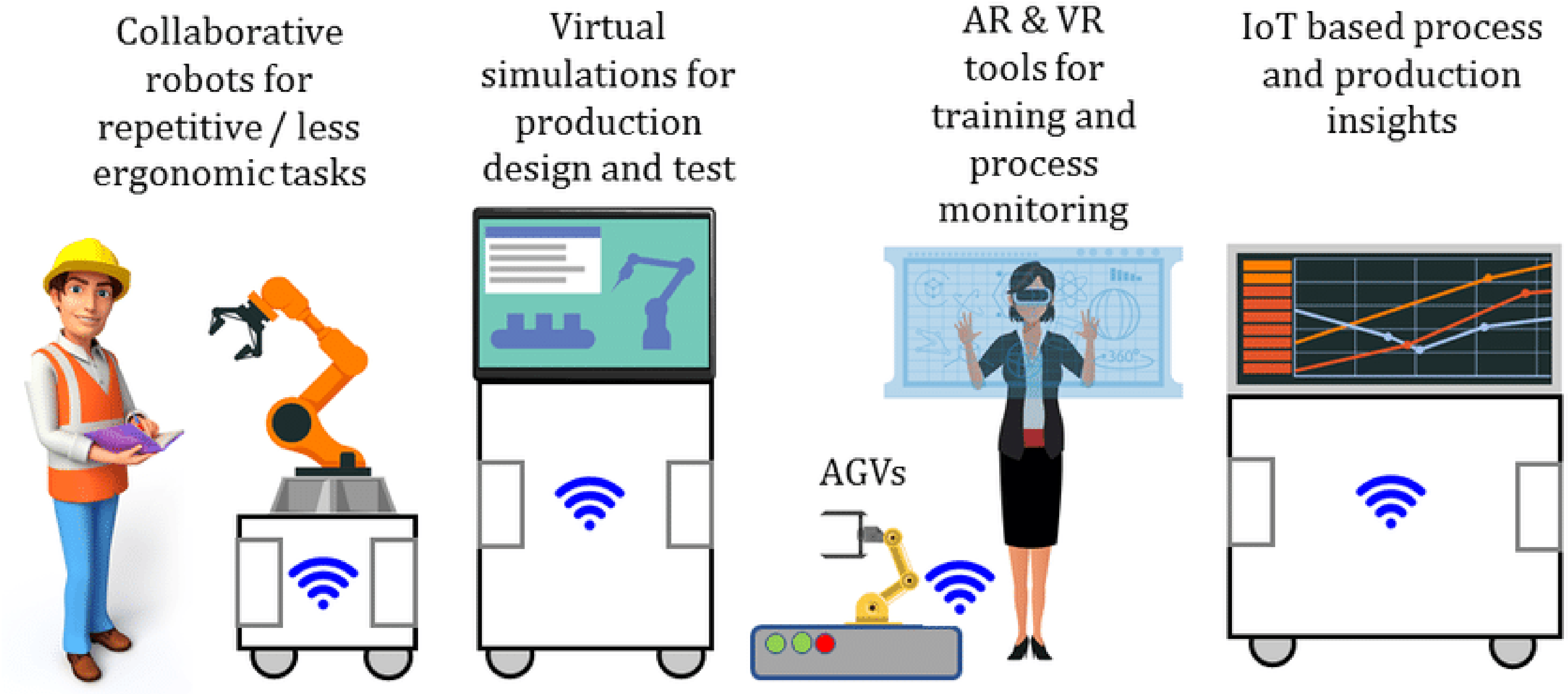
- bring together the potential of human and robot capabilities to complete tasks in a semi-automated manner that were impossible to achieve fully automatically
- are a new generation of industrial robots designed to work together and in safety with human operators, without the need for barriers or protective cages to divide them
- collaborate with humans in the Smart Factory





The concept of collaborative robotics is strictly related to the framework of Industry 4.0

Collaborative robotics in the framework of Industry 4.0



Collaborative robots

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

- Slower and less powerful than traditional robots
- Work at the same level of strength and speed as humans
- Safe, light, transportable and flexible
- Easy to program thanks to intuitive interfaces and the provision of tablets (teach pendant)
- Simplify the production layout (no barriers, small footprint)
- Simplify the installation
- Improve working conditions of human operators
- Reduce prolonged repetition of the same gestures
- Staff qualification and gratification

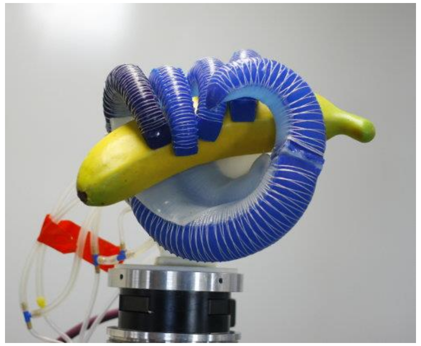
Security features of collaborative robots

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

- Collaborative robots are provided with safety systems for speed limitation, force and power control
- They have rounded joint covers, made of plastic or covered with special materials, to ensure the protection of operators in the event of contacts
- They are as ergonomic as possible, on a human scale
- There are no motors, cables, mechanical or electronic components exposed
- Joints of collaborative robots are usually variable-stiffness joints, to decrease contact forces in cases of contacts or shocks

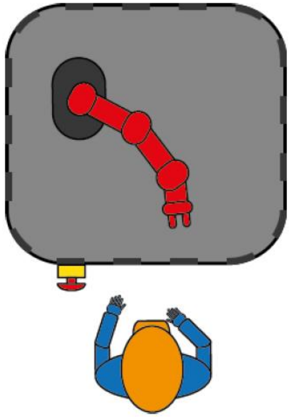
Enabling technologies for collaboration

- **Sensitive Lightweight Robots**
  - reduced mass = reduced kinetic energy
  - advanced sensors for torque sensing
- **Safety-rated functions & reliability**
  - Safety sensors & actuators
  - Functionally-safe control schemes
  - Redundant system architecture
- **Safe Gripping**
  - Never cause injuries
  - Detect human contact
  - Never loose the manipulated object
- **Safe Mobile Manipulation**
  - Operate in shared environments
  - Full body interaction
  - Perceive the environment



Enabling technologies for collaboration

- A safe sensitive manipulator and a safe gripper are not enough!
- We also have to consider workpiece, task, environment, context
- Essential aspects of applications in collaborative robotics are:
    - Safe (sensitive) robot
    - Safe (sensitive) gripper
    - Safe grasp
    - The manipulated objects
    - The object’s fixture
    - The path of the robot



Common applications for collaborative robots

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

- Structured tasks, if high precision is not required
- Unstructured tasks where it is difficult or too expensive to use traditional industrial robots
- Examples are:
  - Pick-and-place operations
  - Packaging
  - Manufacturing industry
  - Assembly tasks
  - Test, quality control

Traditional industrial robots and collaborative robots

Traditional industrial robots	Collaborative robots
"Blind" and unaware of the surrounding environment	They see, perceive the environment and people
Dangerous	Safe
Characterized by high precision and repeatability	Limited precision and repeatability
Programmed for a specific task	Flexible, in a way similar to a human operator
They require components and integration	Perfectly integrated
They require expert programmers	Easy to used and to be programmed
Generally expensive	Generally low-cost

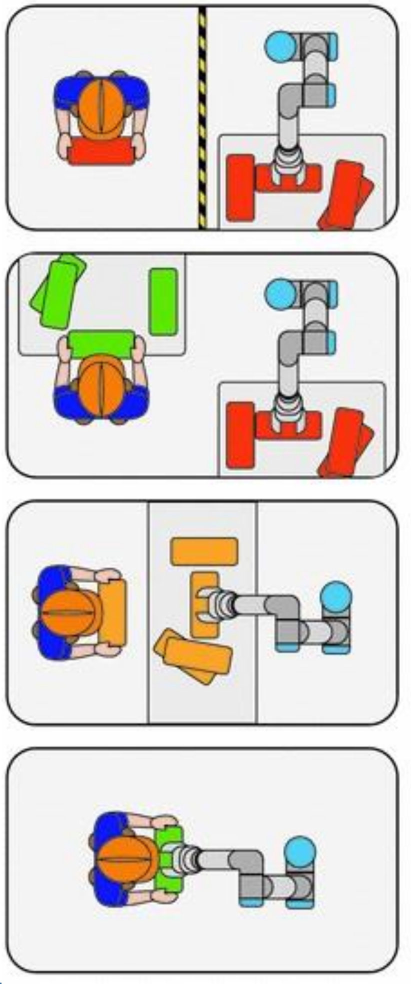
Types of interaction with industrial robots

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

Human-Robot Co-X

From the perspective of the human:

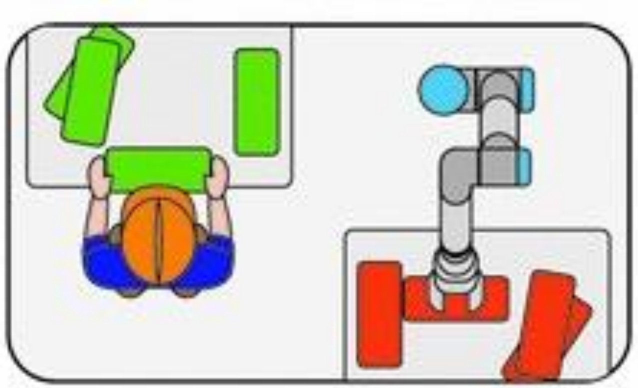
- *Separation* between robot and human
- *Co-existence* between robot and human
- *Co-operation* between robot and human
- *Collaboration* between robot and human



To date, coexistence and cooperation, defined by the fundamental parameters of **space** and **time**, have accounted for about 90% of the situations of interaction between man and robot!

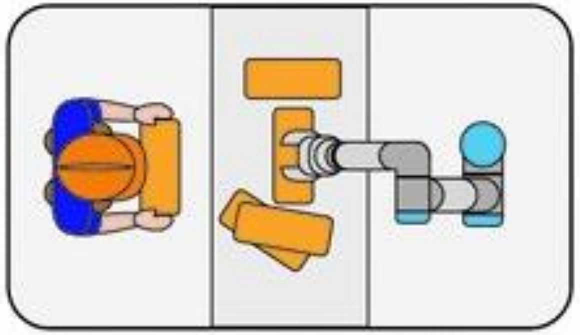
Coexistence between robot and human

- **Different spaces, same time**
- Situation in which human operators and machines operate simultaneously in adjacent work areas
- Typical example: loading station with a rotating table in a robotic area
- Operating simultaneously and safely in adjacent work areas is possible, for example, thanks to the use of safety barriers



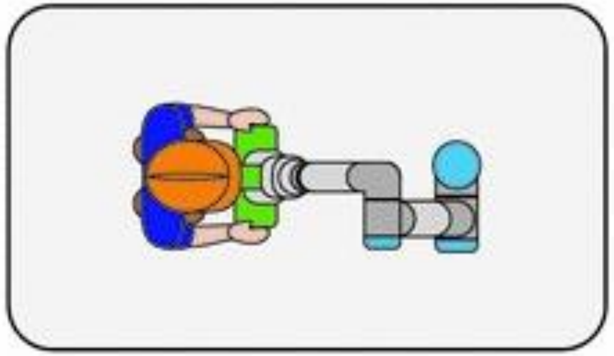
Cooperation between robot and human

- **Same space, different times**
- Humans and robots operate in the same working area, but at different times
- Typical example: robotic assembly station
- The robot and the operator alternate in the assembly area
- The distance between operators and robots becomes the key parameter for safety
- A safety laser scanner is usually adopted to detect the operator's position and to ensure that the robot's speed is reduced or eventually stopped in case of a potential collision

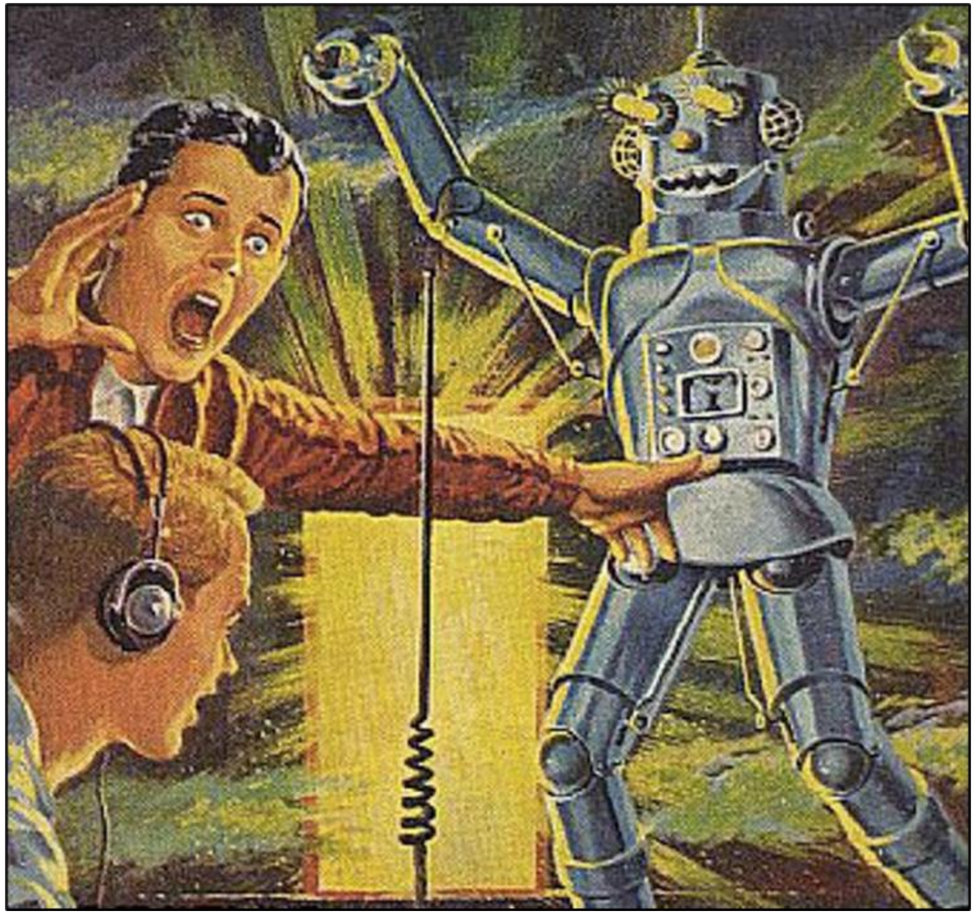


Collaboration between robot and human

- **Same space, same time**
- The type of full interaction between robot and human
- Sharing the same workspace at the same time
- Example: mobile platform where a robot collects pieces from a conveyor belt and supplies them to a workstation chaired by an operator
- The security parameters used for the cases of coexistence and cooperation are no longer sufficient
- The position and speed of the robot must be monitored, limited and, if necessary, interrupted according to the degree of danger
- The robot thus acts as a flexible production assistant which lightens the operator's work during ergonomically unfavorable manual work sequences



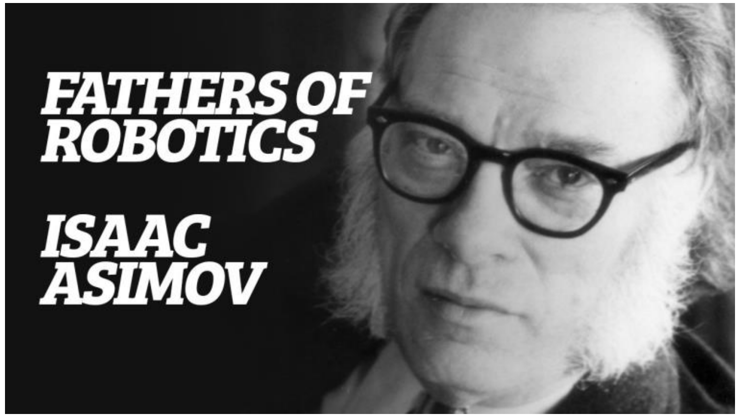
Regulations & Standards for Safety

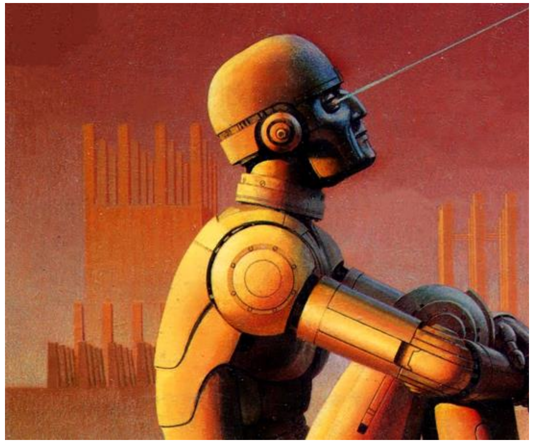


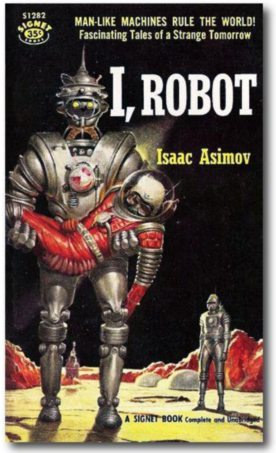
Regulations & Standards for Safety

The 3 fundamental laws of Robotics
(Isaac Asimov, 1940s, science fiction writer):

- A robot cannot hurt a human being or allow, by remaining inactive, a human being in danger
- A robot must obey orders given by human beings, unless those orders conflict with the first law
- A robot must protect its existence unless such protection conflicts with the first or second law







Regulations & Standards for Safety

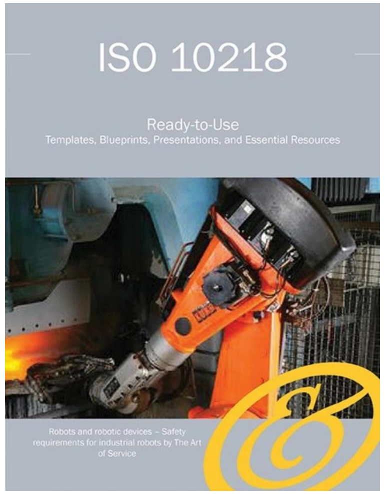
Industrial robot systems operate according to:

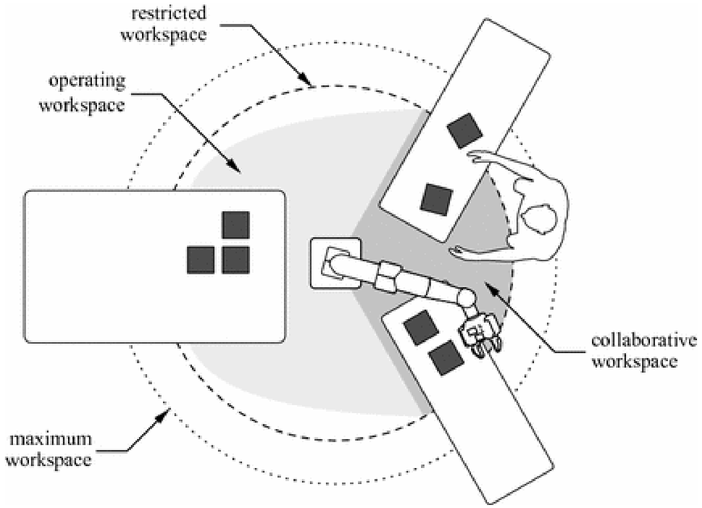
- **ISO 10218: Robots and robotic devices: Safety requirements for industrial robots**
- **ISO/TS 15066: Robots and robotic devices: Collaborative Robots**
- ISO 13849 or IEC 62061: Safety of machinery: Safety-rated parts of control systems
- IEC 61508: Functional Safety
- ISO 12100: Risk Analysis
- 2006/42/EC: Machinery Directive

UNIVERSITÀ DEGLI STUDI DI UDINE

Regulations & Standards for Safety

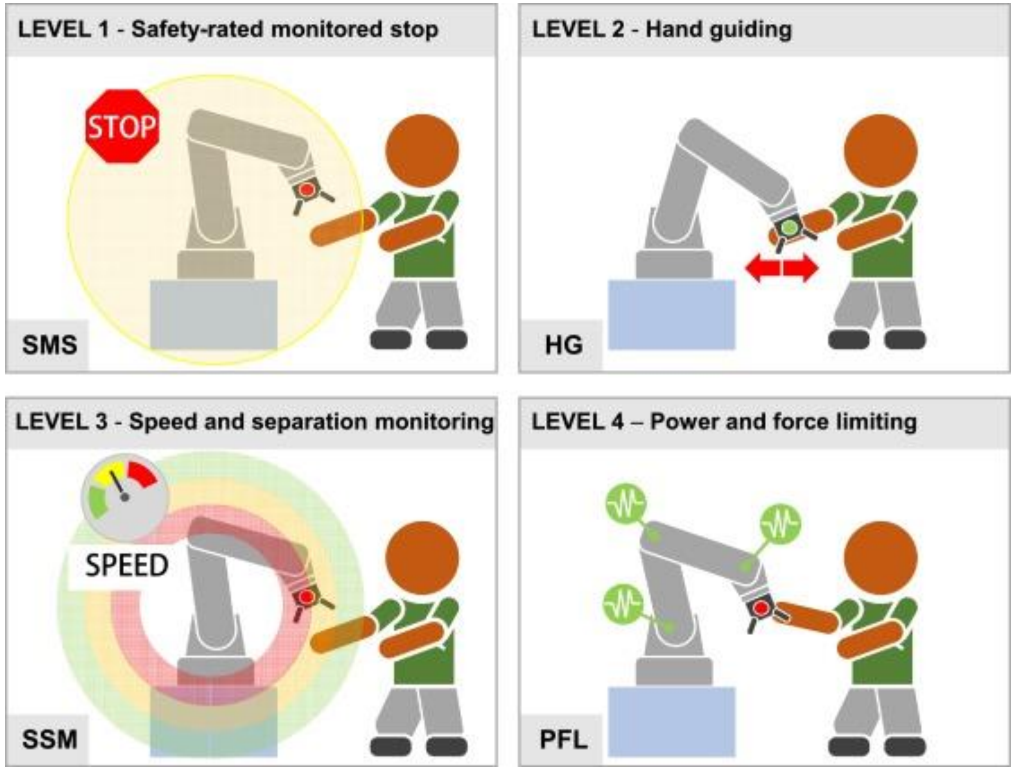
- The concept of humans and robots working hand in hand is not new
- ISO 10218 defines human-robot collaboration as:
- **“State in which a <u>purposely designed robot</u> works in direct cooperation with a human within a <u>defined workspace</u>”**
- *purposely designed* means that highly reliable components and redundancy are exploited
- *defined workspace* means collaborative workspace, which is identified as:
- “Space inside the protected area where robot and man can perform tasks simultaneously during production operations” (ISO 10218 / ANSI RIA 15.06)





Regulations & Standards for Safety

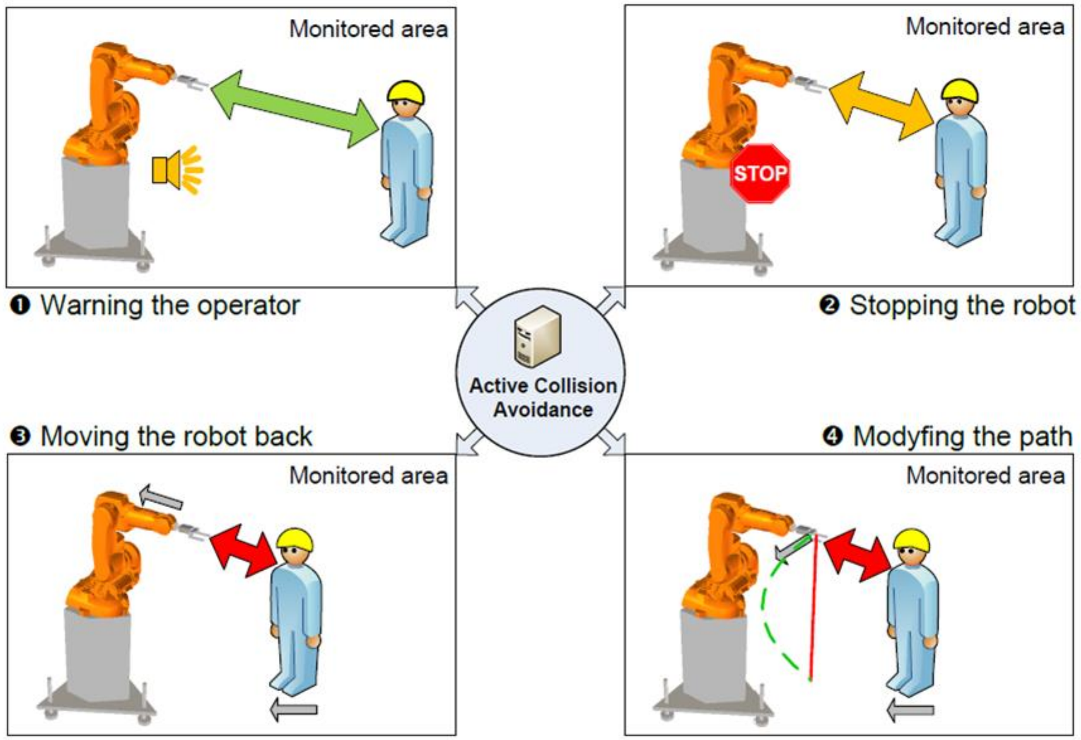
- ISO 10218 allows collaboration in four basic principles of protection as part of the human robot collaboration:
  1. **Safety-rated monitored stop:** The robot stops as soon as the operator enters the common workspace and goes back to work as soon as he/she leaves it
  2. **Hand guiding:** The movements of the robot are actively controlled by the operator thanks to suitable devices
  3. **Speed and separation monitoring:** Contact between the operator and the moving robot is prevented
  4. **Power and force limiting:** The forces released by the contact between the operator and the robot are rendered harmless with technical measures



Regulations & Standards for Safety

Safety-rated monitored stop

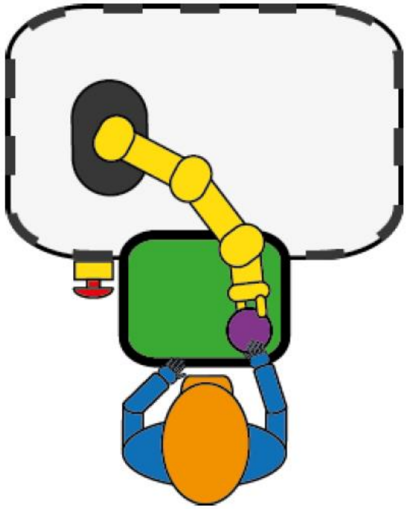
- Safety-rated control system ensures that the robot remains in a clearly defined pose and re-starts in a defined and monitored way
- If a human enters the safety zone, the active collision avoidance is activated, declined in various ways:
    - audible warning (if the operator has just entered the safety zone)
    - controlled stop (the robot must stop - it does not turn off, but the brakes are activated)
    - recession from the operator or path modification
- The active collision avoidance is mainly used when a robot works mostly alone, but occasionally a human operator can enter its workspace



Regulations & Standards for Safety

Hand Guiding (ISO 10218-1/5.10.4 & ISO/TS 15066)

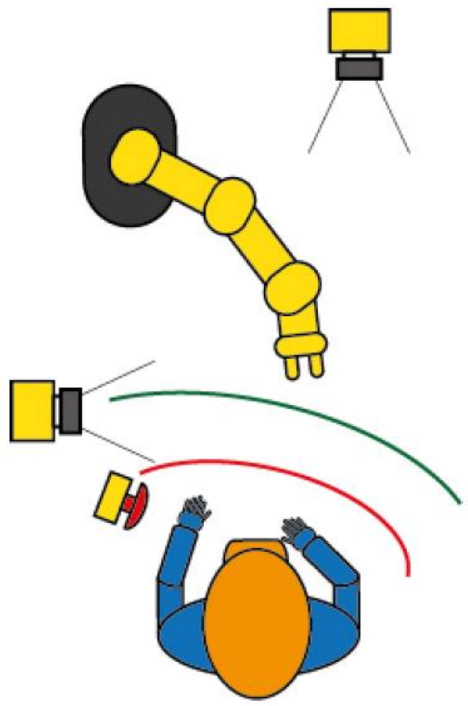
- The safety of the human–robot collaboration is assured by the robot being guided manually and controlled at an appropriately reduced speed
- The operator can teach the robot positions by moving the robot without the need of an extra interface, e.g., a robot teach pendant
- User can release the robot through holding the enabling device
- Ensured maximum speed (according to the risk analysis)
- Safety-rated monitored stop when released from hand guidance



Regulations & Standards for Safety

Speed and Separation Monitoring (ISO 10218-1/5.10.4 & ISO/TS 15066)

- Both speed and motion path of the robot are supervised and adjusted based on the position and speed of the operator in the safeguarded space
- The risk is mitigated by ensuring a sufficiently large separation between robot and human
- Static regions and dynamic distances are identified
- Distances are defined according to the risk analysis that takes into account: robot, tool, workpiece and task
- A safety-rated monitored stop is implemented in case of violation (reaction-time & stopping-time need to be considered)
- This scenario requires safety-rated hard-and software for robot, distance-and speed monitoring



Regulations & Standards for Safety

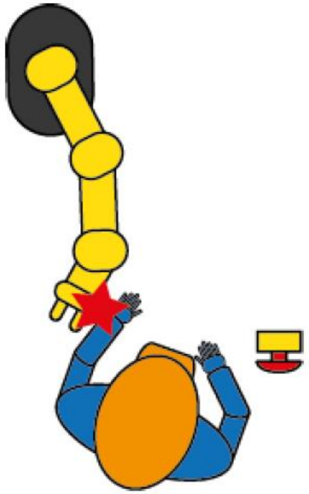
Speed and Separation Monitoring (ISO 10218-1/5.10.4 & ISO/TS 15066)

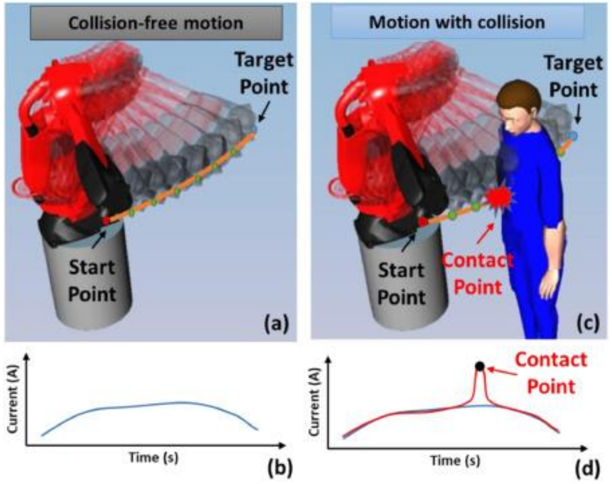
- The work environment is equipped with lasers or vision systems in order to track the position of the operators
- Safety zones are graduated so that the robot can react differently based on the position of the operator
- the robot can operate at full speed when the human is in the green zone, at reduced speed in the yellow zone, and stops when the human moves into the red zone, which defines the minimum separation distance
- It waits until it receives a command to be able to resume its task

Regulations & Standards for Safety

Power and Force Limiting (ISO 10218-1/5.10.5 & ISO/TS 15066)

- The risk is mitigated by limiting the mechanical impact
- The risk analysis considers robot, tool, workpiece and task
- A protective stop is implemented in case the safety-rated force monitoring reports limit-violations
- This scenario is widely adopted in modern collaborative robot applications
- It is realized though speed reduction, reduced masses, limited torques, specific geometry and padding, inherently safe actuators, inherently safe control schemes, workplace ergonomics, and clearly defined task of the robot
- Both **foreseeable transient** and **quasi-static contact situations** are considered





Collision classification between human and robot

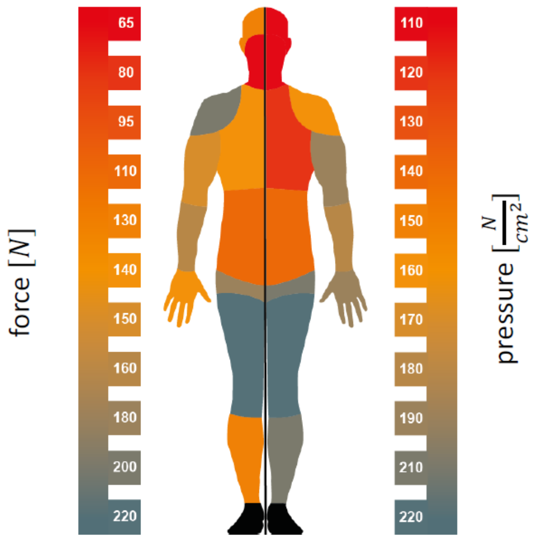
Collision Classification and Pain Thresholds (ISO/TS15066)

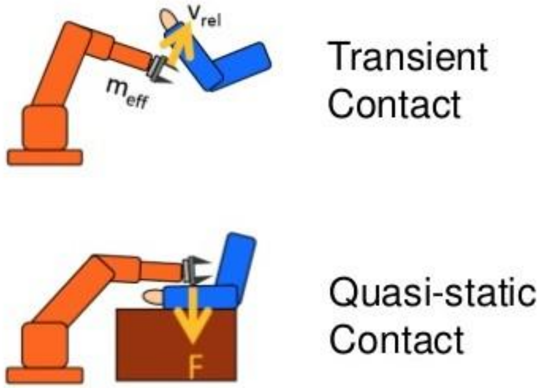
Transient (short-term) contact

- Quick contact, in which the robot control system does not have time to act
- Energy transfer linked to the relative speed between robot and human, from the moving masses and from the contact area
- Example: unconstrained collision of the moving robotic arm with the human operator's arm

Quasi-static (prolonged) contact

- Extended contact over time, the control system has time to reduce speed and force
- Danger due to the application of force and pressure
- Example: crushing of the operator's hand trapped between the robot arm and the work bench



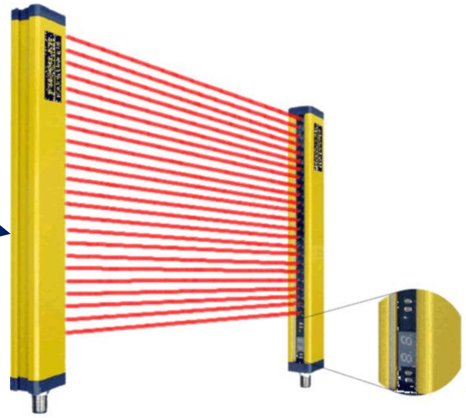


Sensors for collaborative robots

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

To ensure safety without using physical barriers, the following are used:

- Safety curtains and laser systems



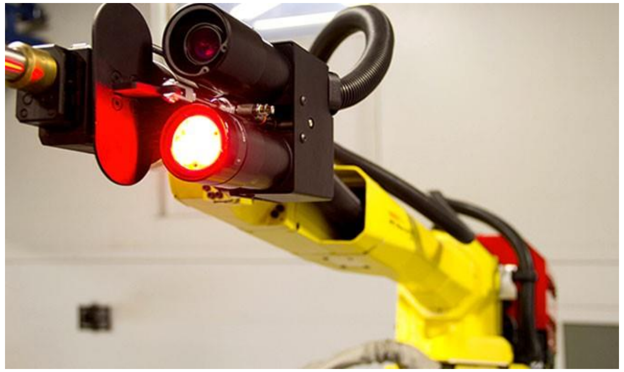
- Non-contact safety switches

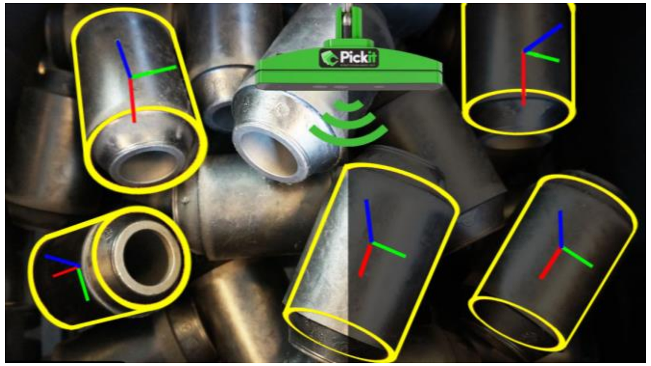
- Safety laser scanner

- Force and torque sensors (integrated in the robot or external)

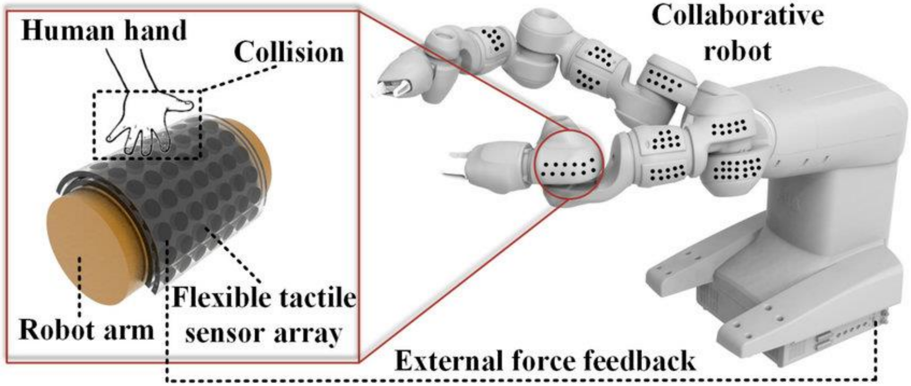
Sensors for collaborative robots

- Vision systems



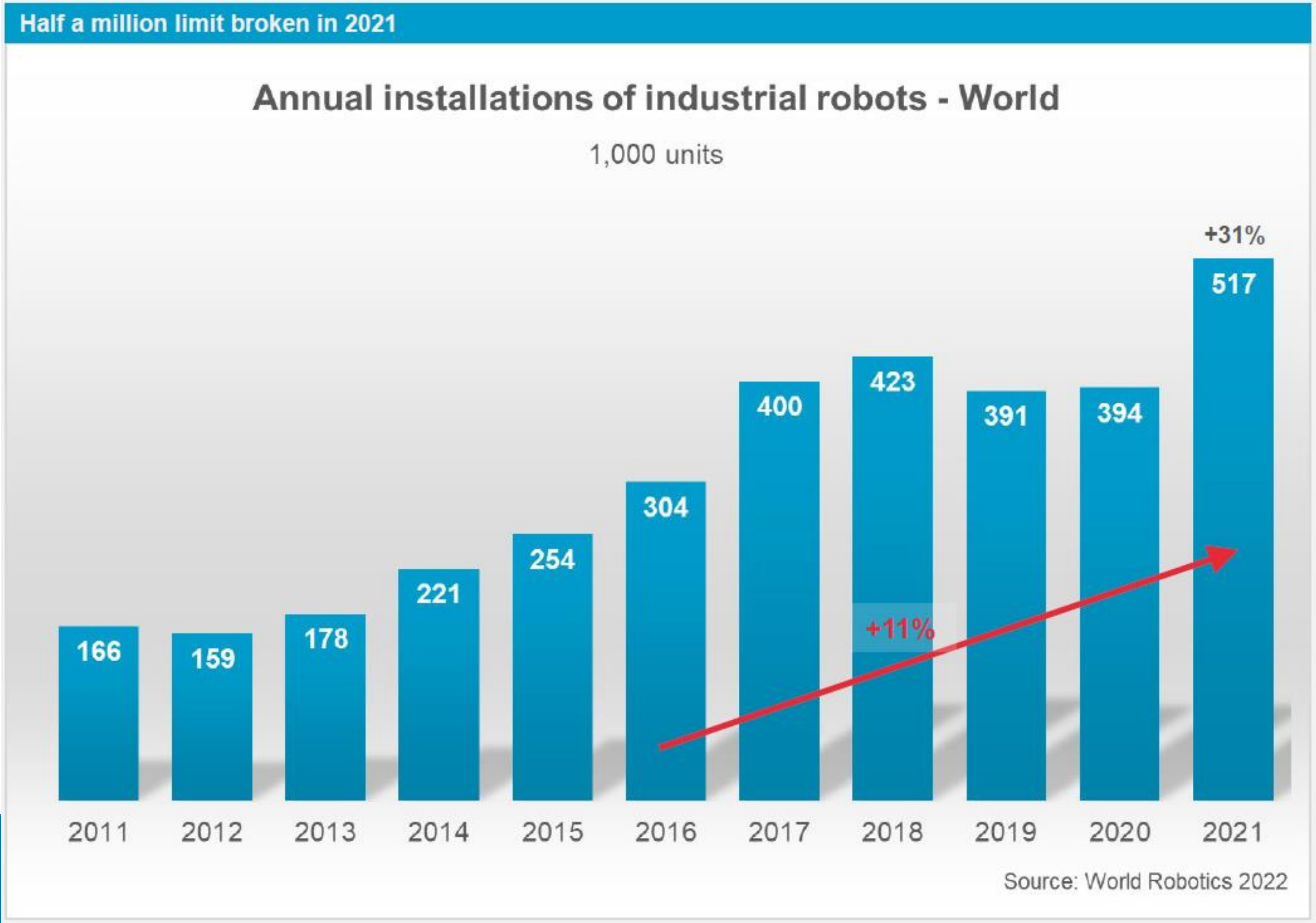


- Recognition of voice commands

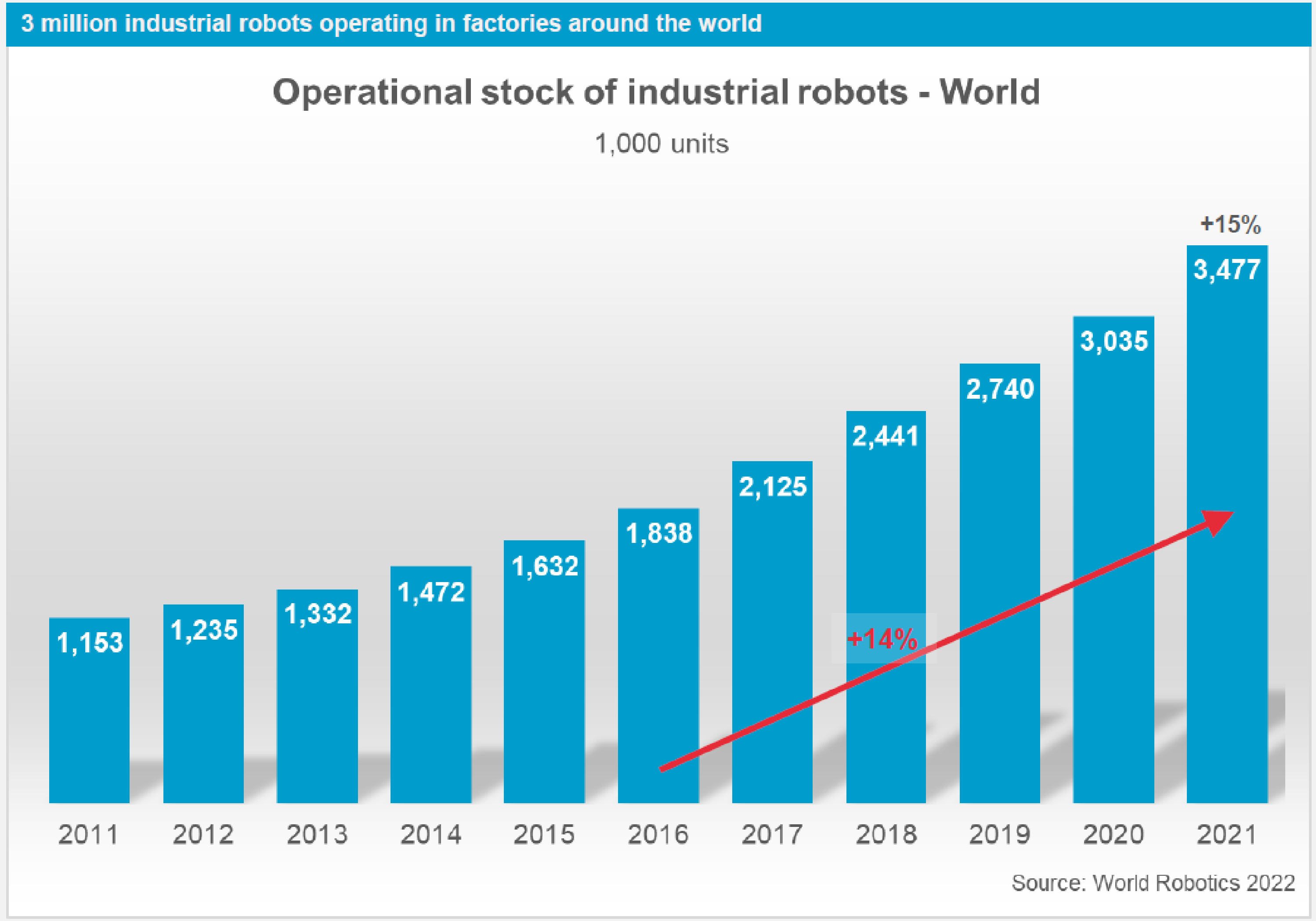


- Contact sensors

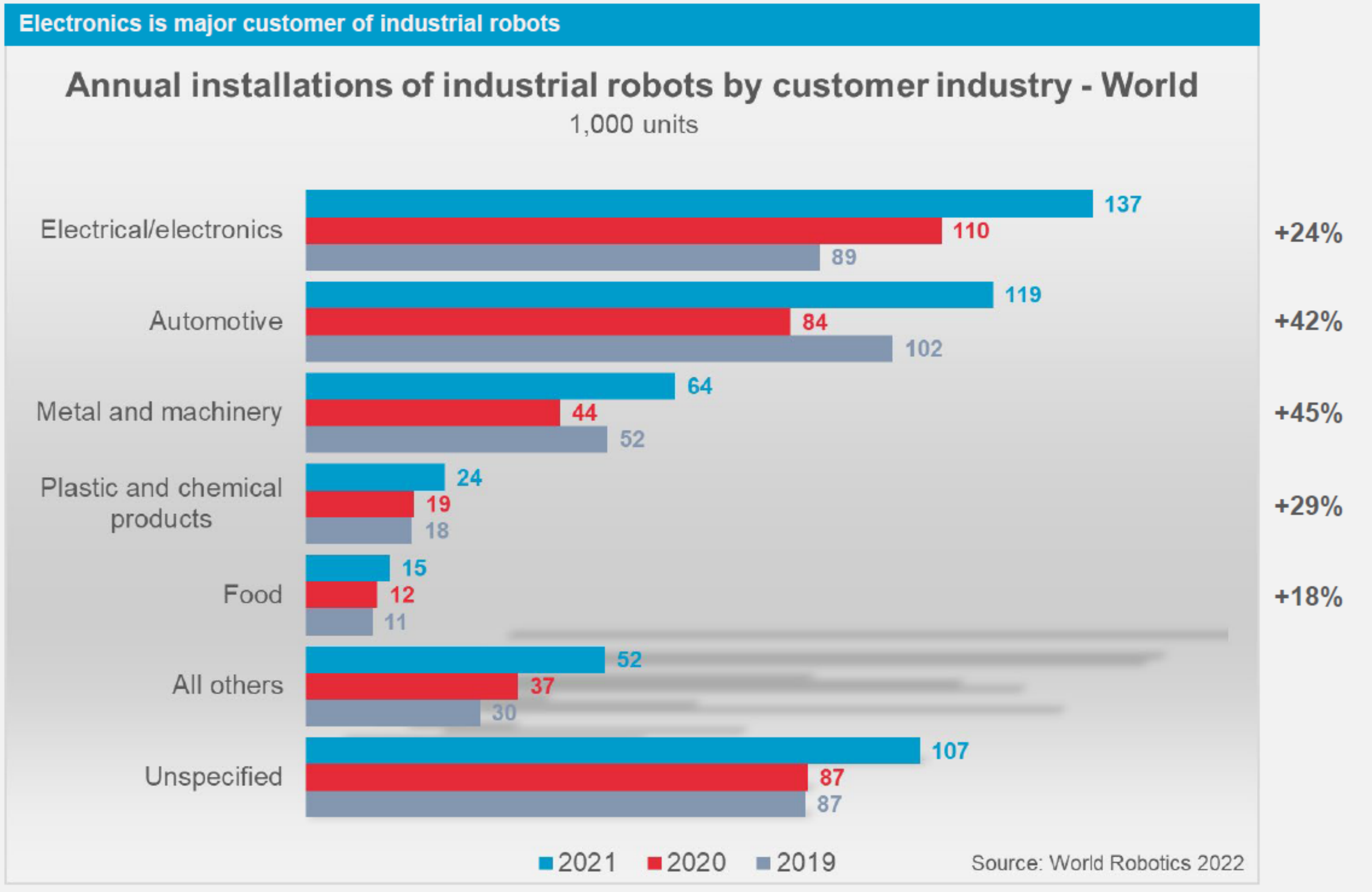
Annual installation of industrial robots



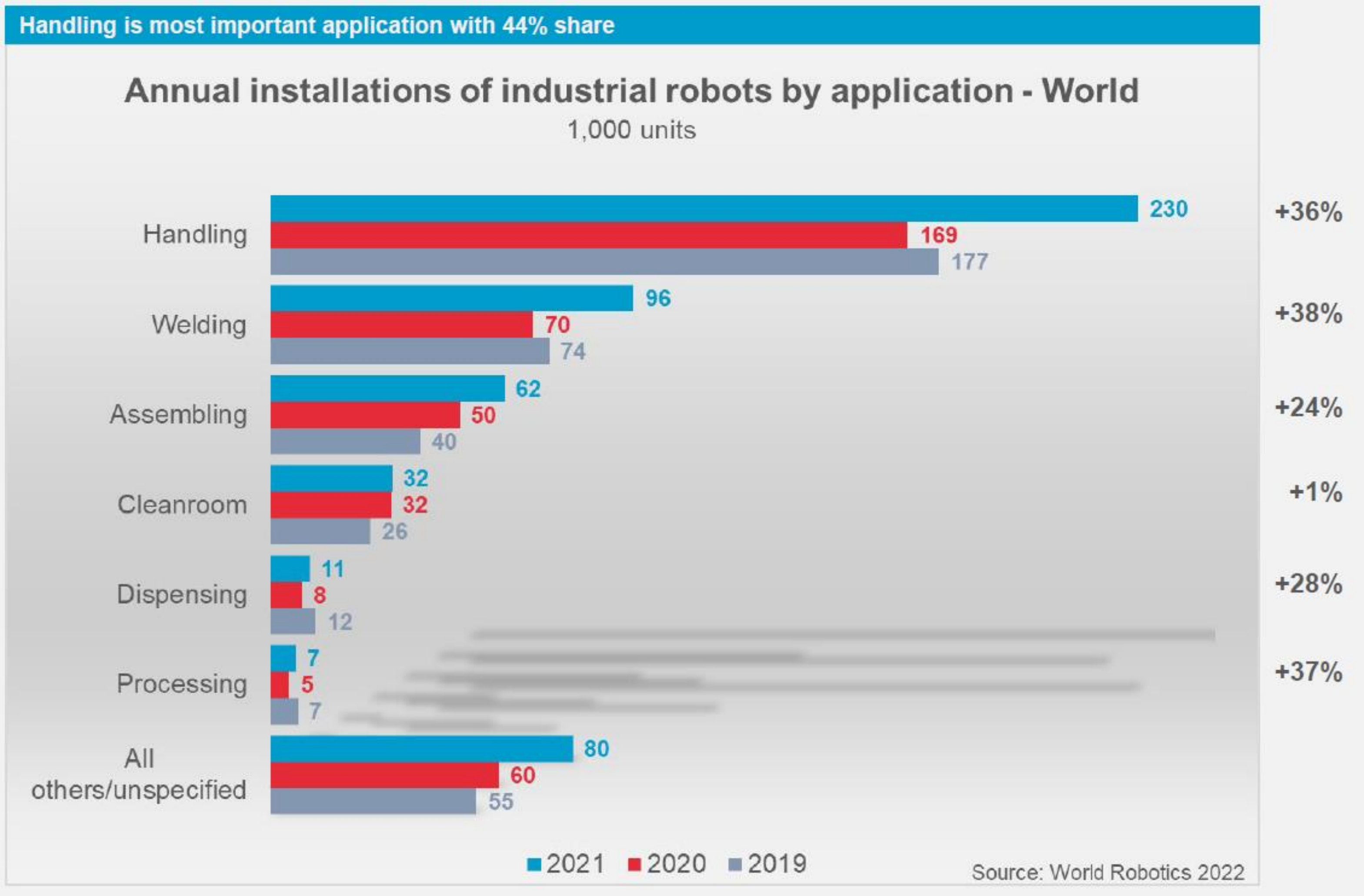
Operational stock of industrial robots



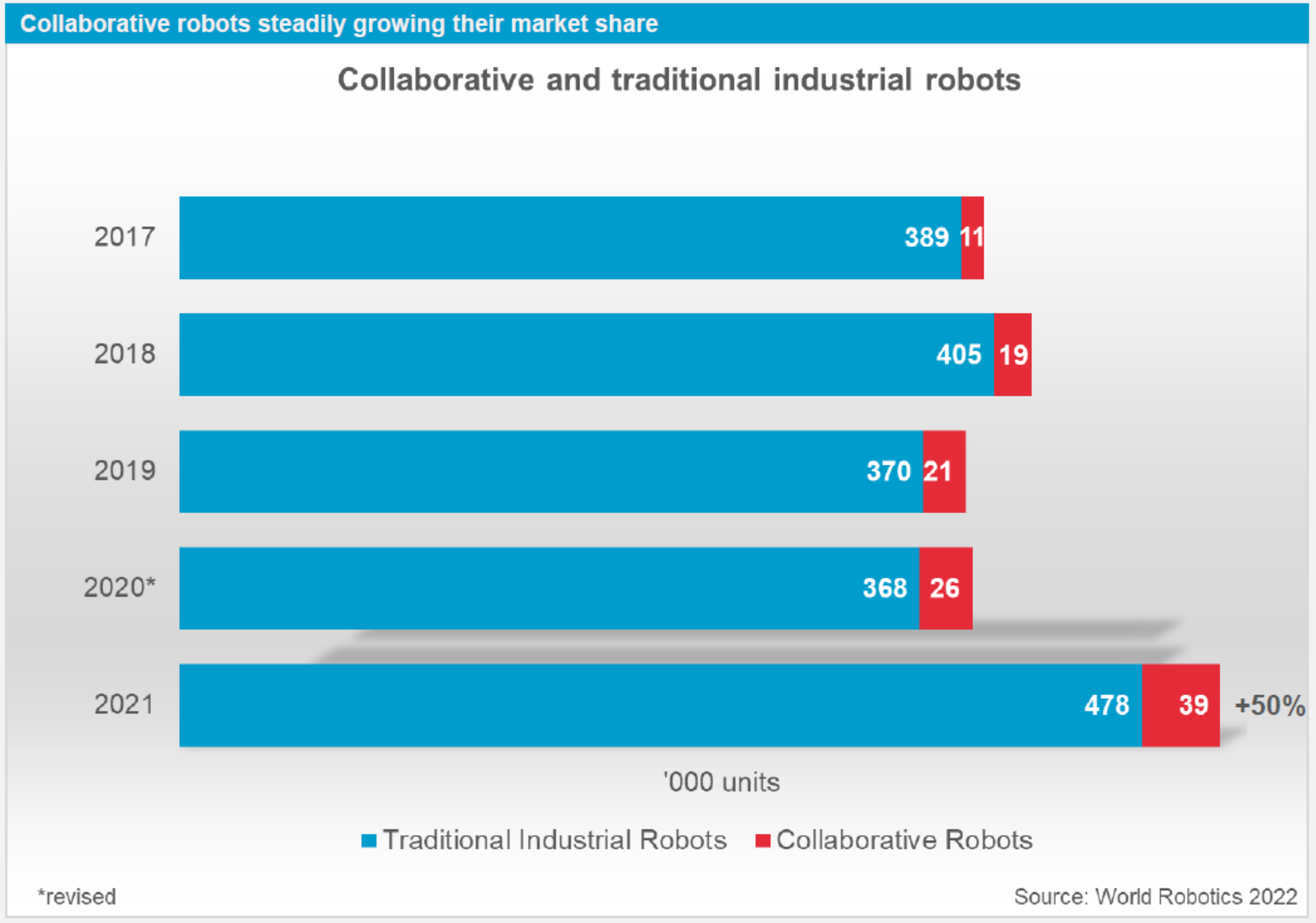
Annual installation of industrial robots



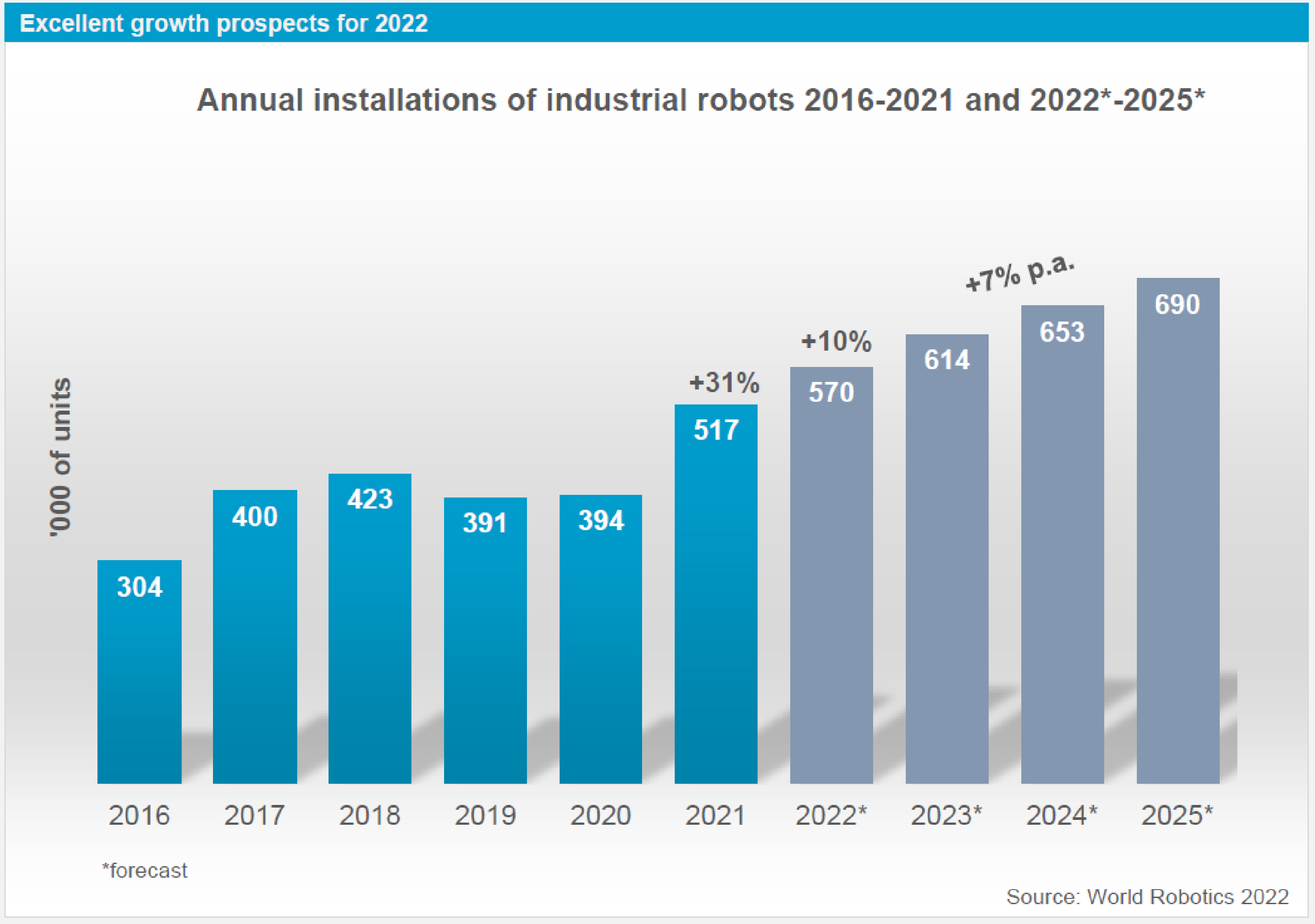
Industrial robots by application



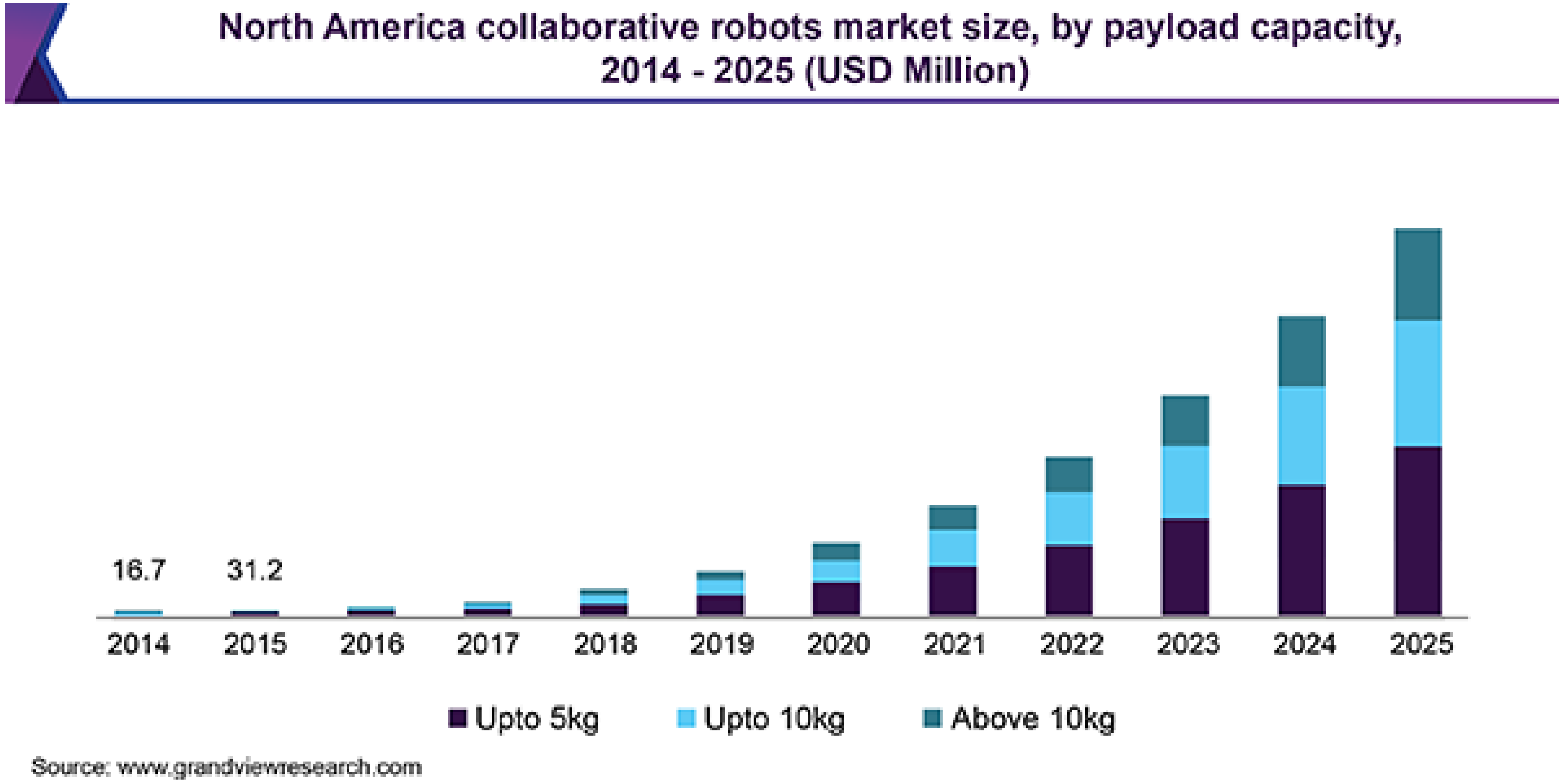
Collaborative and traditional industrial robots



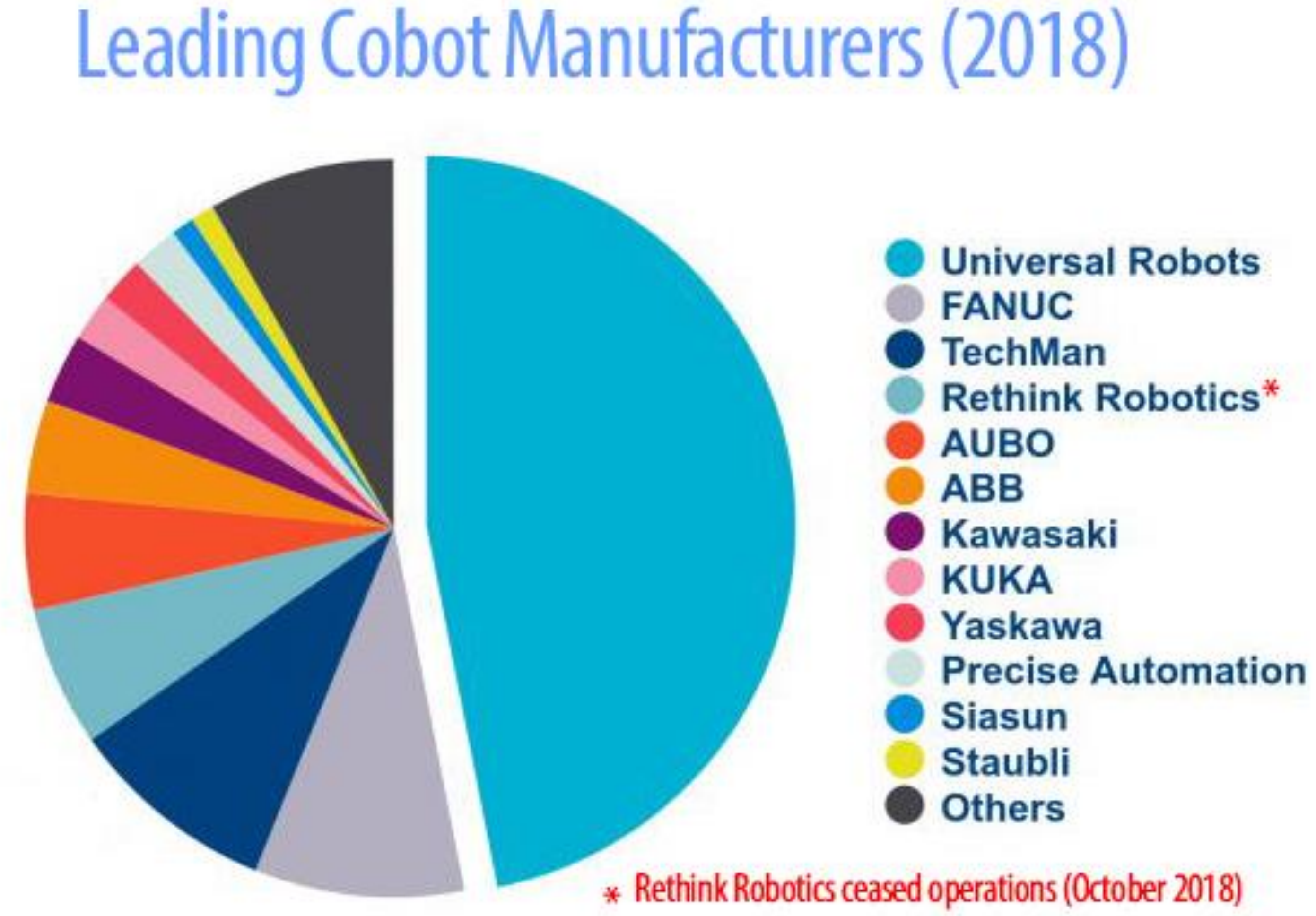
Annual installation of industrial robots

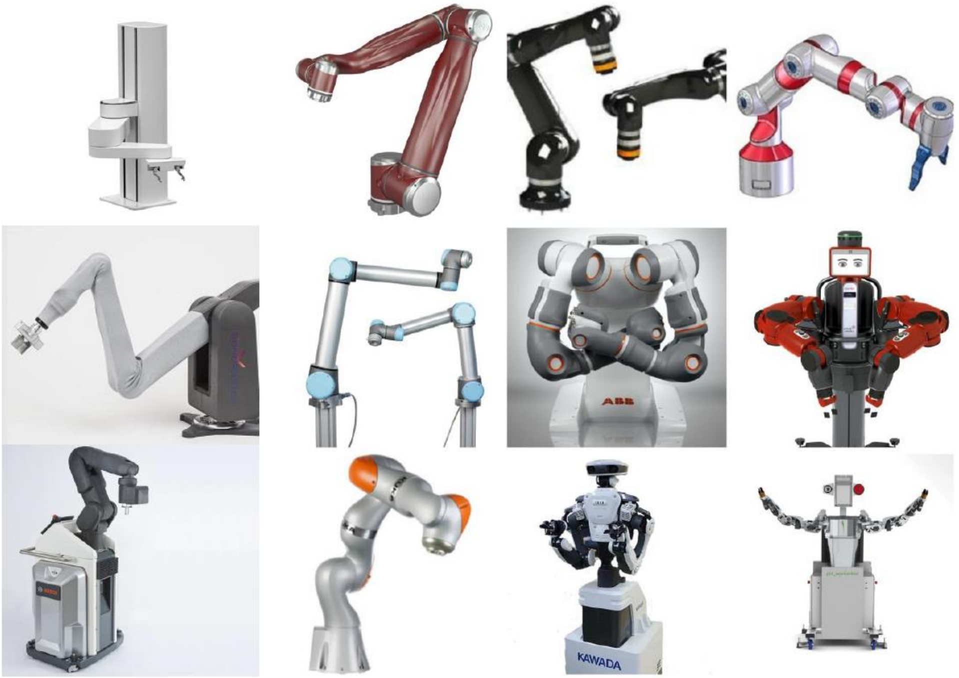


North America collaborative robot market size, by payload capacity



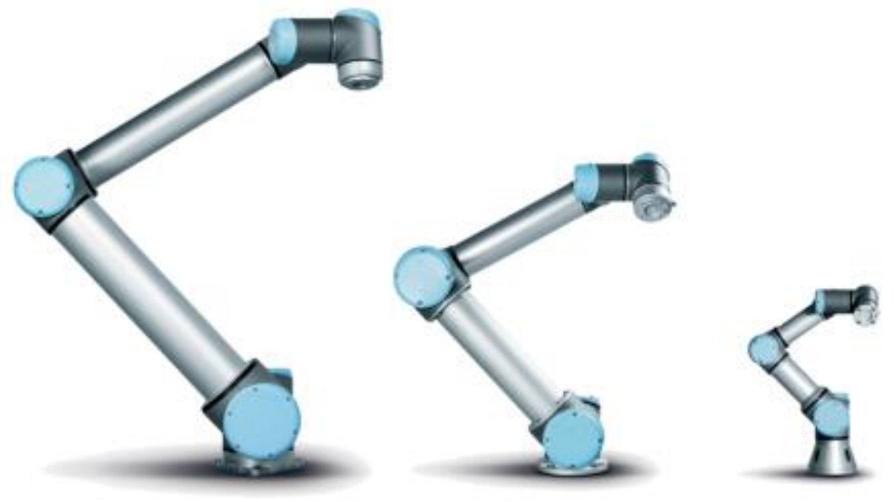
Leading manufacturers of collaborative robots





Leading manufacturers of collaborative robots

Universal Robots UR3, UR5, UR10



	UR10 robot arm	UR5 robot arm	UR3 robot arm
Working radius	1300 mm/51.2 ins	850 mm/33.5 ins	500 mm/19.7 ins
Payload	10 kg/22 lbs	5 kg/11 lbs	3 kg/6.6 lbs
Weight	28.9 kg/63.7 lbs	18.4 kg/40.6 lbs	11 kg/24.3 lbs
Footprint	190 mm/7.5 ins	149 mm/5.9 ins	118 mm/4.6 ins

- Danish company founded in 2005
- 60% of the market
- More than 10,000 robots installed worldwide
- Simple and cheap
- Force / torque sensor on the wrist
- Light
- Wide range of accessories
- New model: UR16e: load 16 kg, reach 0.90 m, weight 33 kg

Leading manufacturers of collaborative robots

Fanuc

Robot collaborativo CR-4iA

Collaborative robot

- **Payload:** 4 kg
- **Reach:** 550 mm

Robot collaborativi CR-7iA e CR-7iA/L

Robot collaborativo

- **Payload**: 7 kg
- **Portata**: 717 mm (CR-7iA)
- **Portata**: 911 mm (CR-7iA/L)

CR-14iA/L

Robot a 6 assi, versione a braccio lungo

- Assi: 6
- Portata massima: 14 kg
- Sbraccio: 911 mm"

Robot collaborativo CR-15iA

Robot collaborativo

- **Portata massima:** 15 kg
- **Sbraccio:** 1441 mm

CR-35*i*A

Robot collaborativo a 6 assi

- **Carico utile:** 35 kg
- **Estensione**: 1813 mm

Leading manufacturers of collaborative robots

TechMan – OMRON

2018: strategic alliance between Techman Robot and OMRON, leader in industrial automation, to promote the distribution of collaborative robots of the TM series to the global market

TM ROBOT

OMRON

TM 12

TM 14

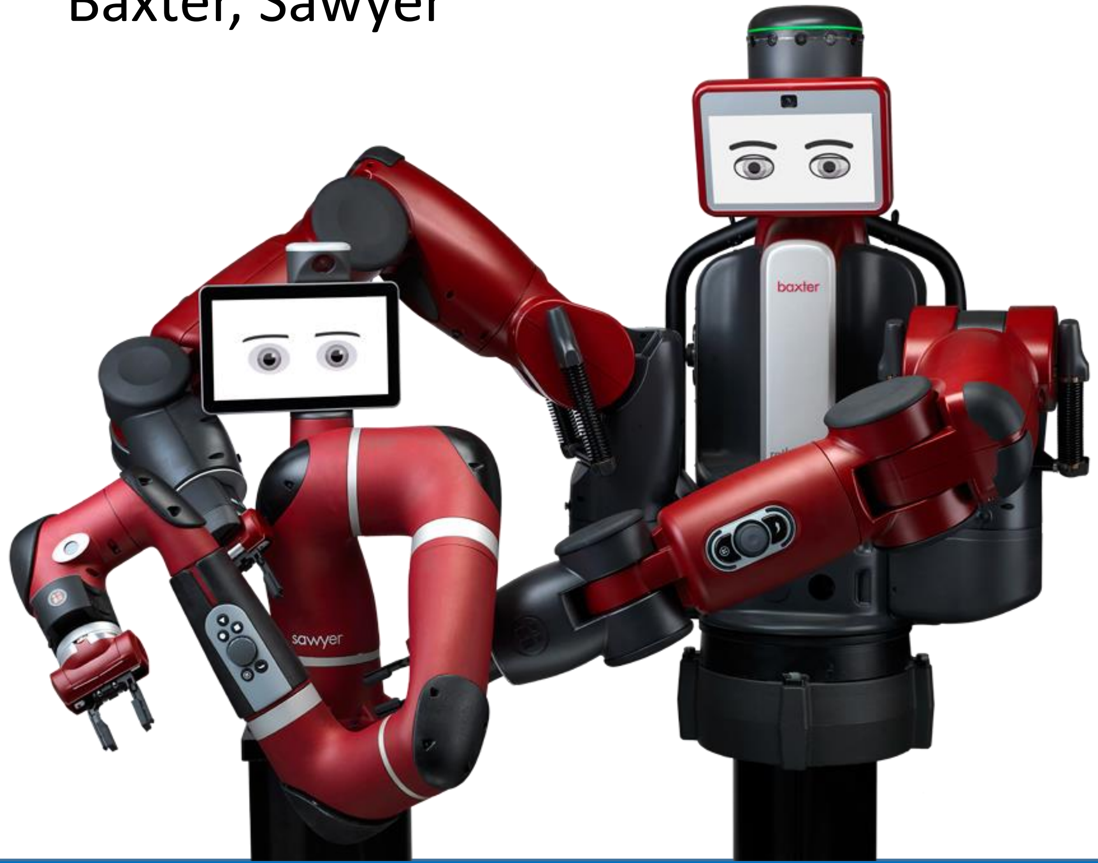
TM12 & TM14 Series

Model		TM12	TM14	TM12M	TM14M
Weight		33.3Kg	32.6Kg	33.3Kg	32.6Kg
Payload		12kg	14kg	12kg	14kg
Reach		1300mm	1100mm	1300mm	1100mm
Max Speed		1.3m/s	1.1m/s	1.3m/s	1.1m/s
Joint ranges	J1	+/- 270°			
	J2,J4,J5	+/- 180°			
	J3	+/- 166°	+/- 163°	+/- 166°	+/- 163°
	J6	+/- 270°			
Speed	J1~J2	120°/s			
	J3	180°/s			
	J4~J5	180°/s	150°/s	180°/s	150°/s
	J6	180°/s			
Repeatability		+/- 0.1 mm			
Degrees of freedom		6 rotating joints			
I/O ports		Control box		Tool conn.	
	Digital in	16		4	
	Digital out	16		4	
	Analog in	2		1	
	Analog out	1		0	
I/O power supply		24V 1.5A for control box and 24V 1.5A for tool			
IP classification		IP54			
Power Consumption		Typical 300 watts		Typical 300 watts	
Maximum Power Capacity		Max. 2200 watts		Max. 1500 Watts②	
Temperature		The robot can work in a temperature range of 0-50°C			
Power supply		100-240 VAC, 50-60 Hz		DC 20V~60V	
I/O Interface		3×COM, 1×HDMI, 3×LAN, 4×USB2.0, 2×USB3.0			
Certification		CE, SEMI S2(Option)			
Variation Models		X: without hand eye camera, SEMI: SEMI S2 certified			
Robot Vision					
Eye in Hand (Built in)		1.2M/5M pixels, color camera			
Eye to Hand (Optional)		Support Maximum 2 GigE cameras			

Leading manufacturers of collaborative robots

Rethink Robotics (2012-2018)

Baxter, Sawyer

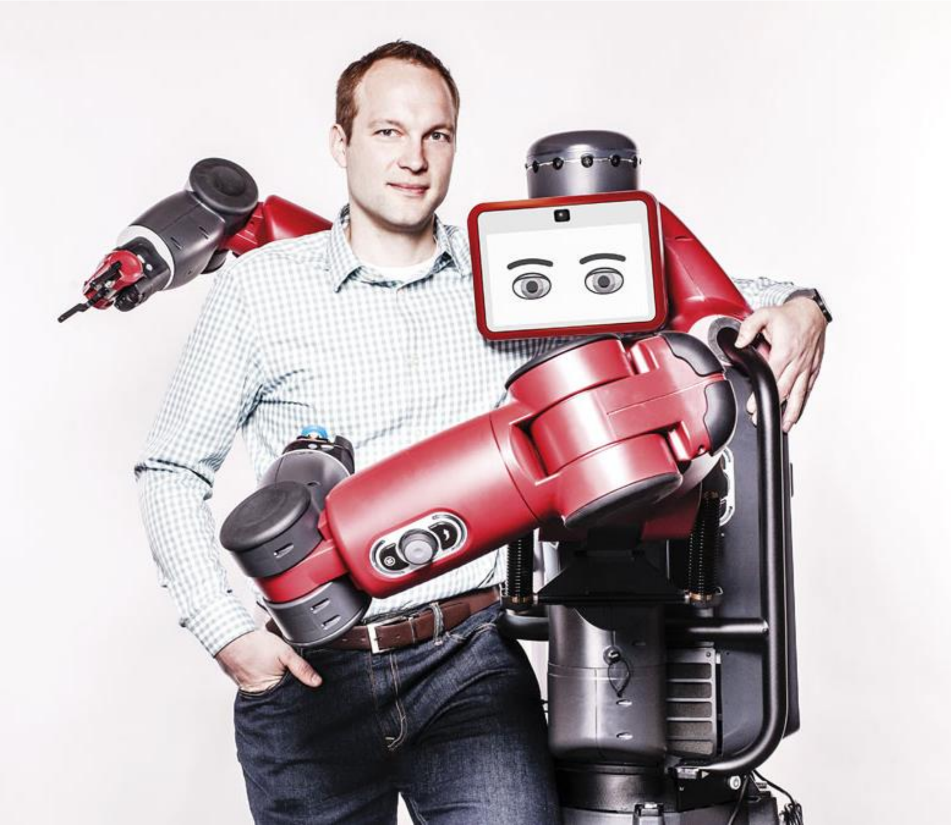


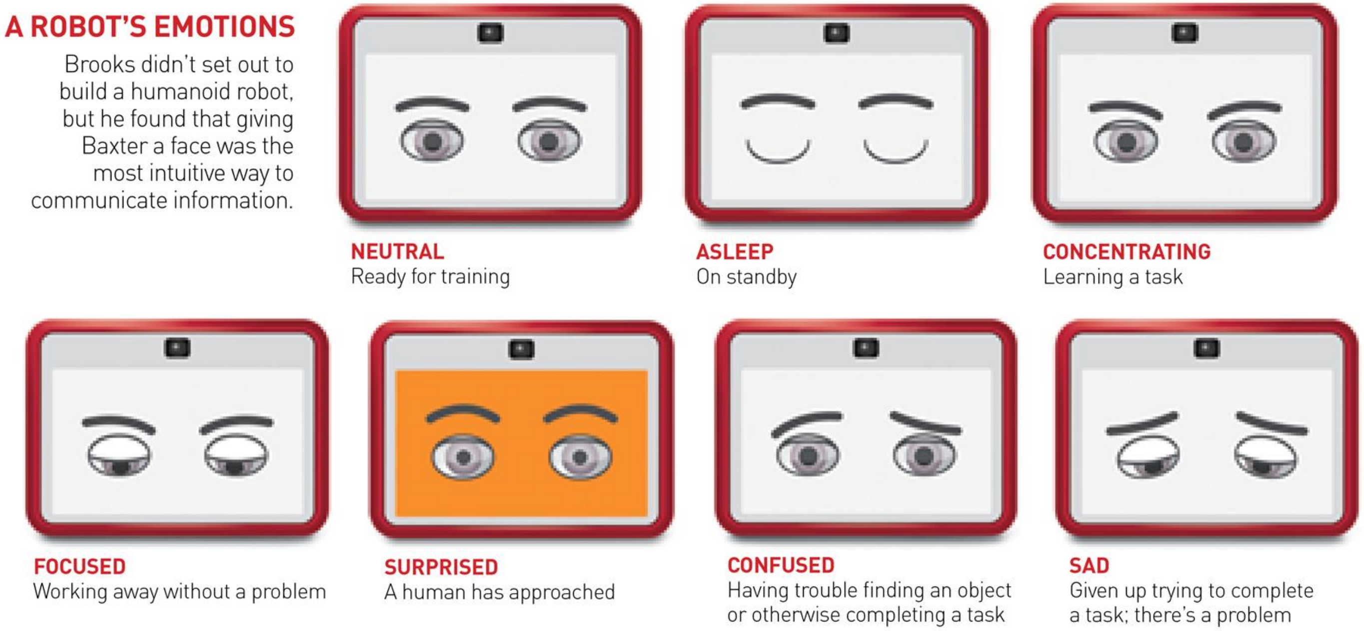
Baxter:

- 360 ° laser scanner for identification of people and obstacles
- Flexible movement guided by the vision and object recognition system
- 7 degrees of freedom per arm
- Interchangeable end-effector to face different tasks and operations
- Flexible joints with force sensors and force control to increase safety

Leading manufacturers of collaborative robots

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

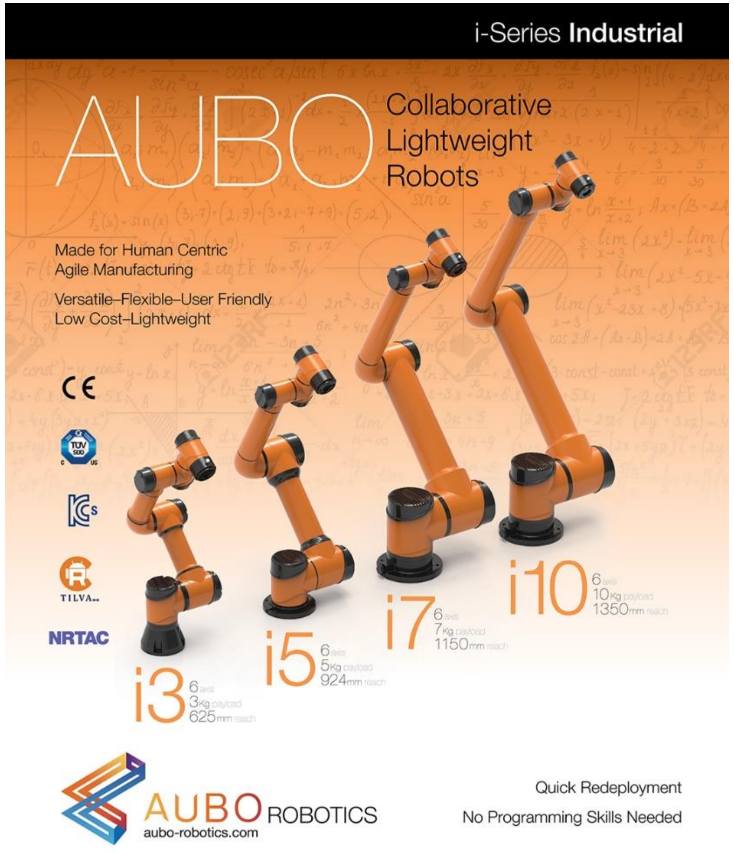




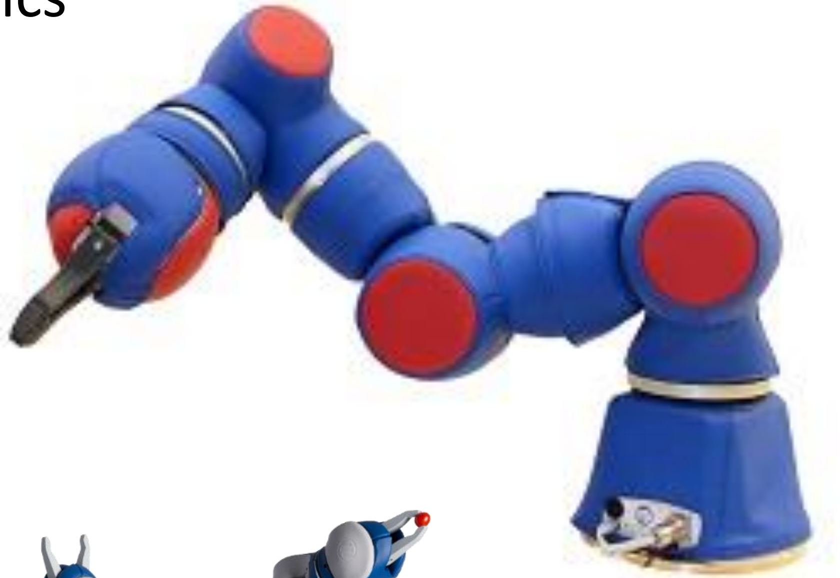
Rethink Robotics Baxter

Leading manufacturers of collaborative robots

AUBO Robotics



F&P Robotics

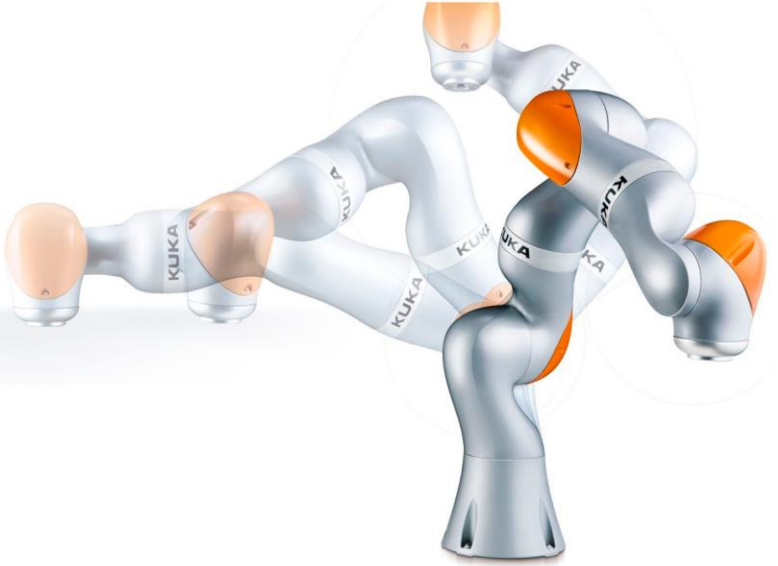


Leading manufacturers of collaborative robots

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

KUKA LBR iiwa

- *«intelligent industrial work assistant»*
- *LBR: 7 axis e 7/14 kg payload; programmable in Java*
- Torque sensors at joints
- Possible to be mounted on a mobile robot



Leading manufacturers of collaborative robots

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

ABB Yumi

It means "you and me"

- 2 coordinated arms
- Limited payload (500 g x2)
- Weight: 38 Kg
- Reach: 559 mm
- Accuracy: 0.02mm
- Cost: $ 40,000 approx
- Used for assembling or moving instruments

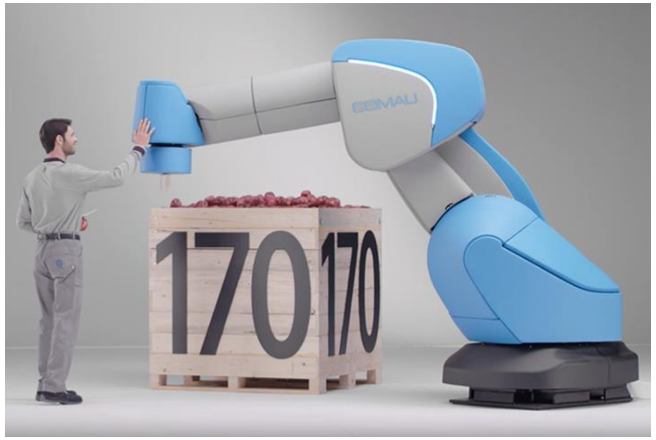
Leading manufacturers of collaborative robots

Franka Emika

- *Panda robot*
- Articulated robot with 7 DOF
- 3 Kg payload, reach 855 mm

Comau Aura

- *Advanced Use Robotic Arm*
- Contact sensitive coating
- Integrated vision system
- Industrial derivation
- Force / torque sensor on the wrist
- Load: 170 kg
- Reach: 2.8 m



Mobile collaborative robots

KUKA

MIR Mobile Industrial Robots

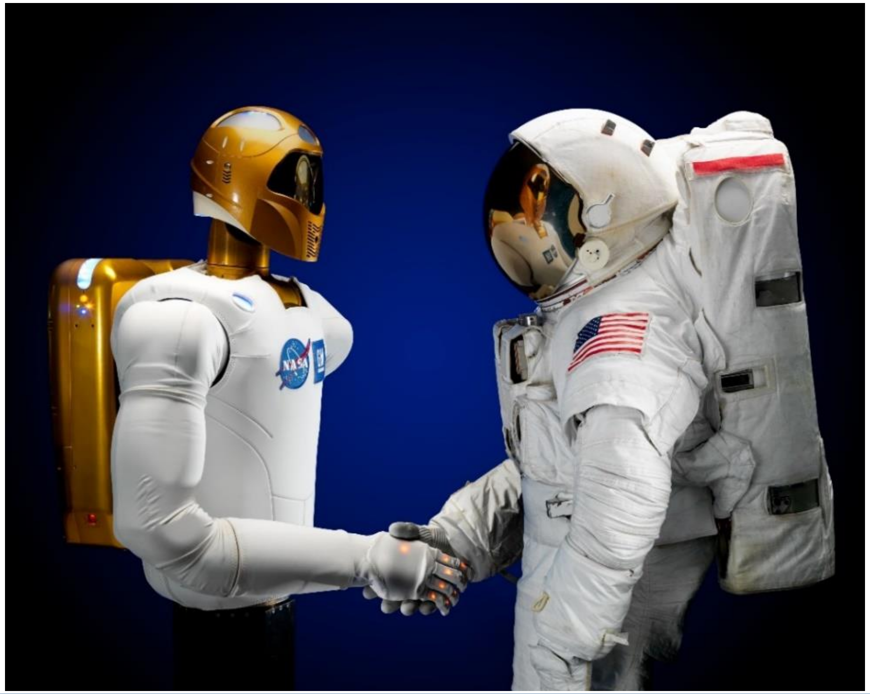
CLEARPATH ROBOTICS

Clearpath Robotics

OMRON

Humanoid collaborative robots

Robonaut 2 (NASA)

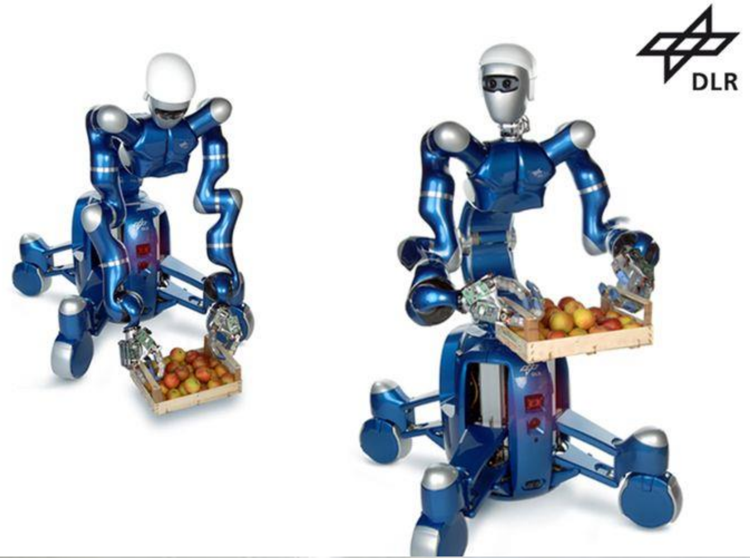


NextAge by Kawada Industries

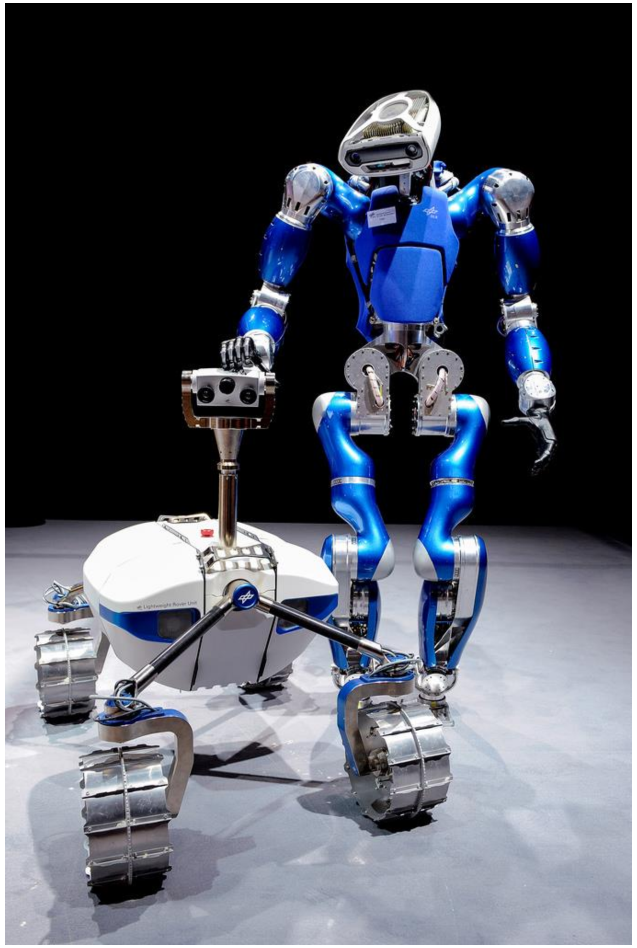
Humanoid collaborative robots

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

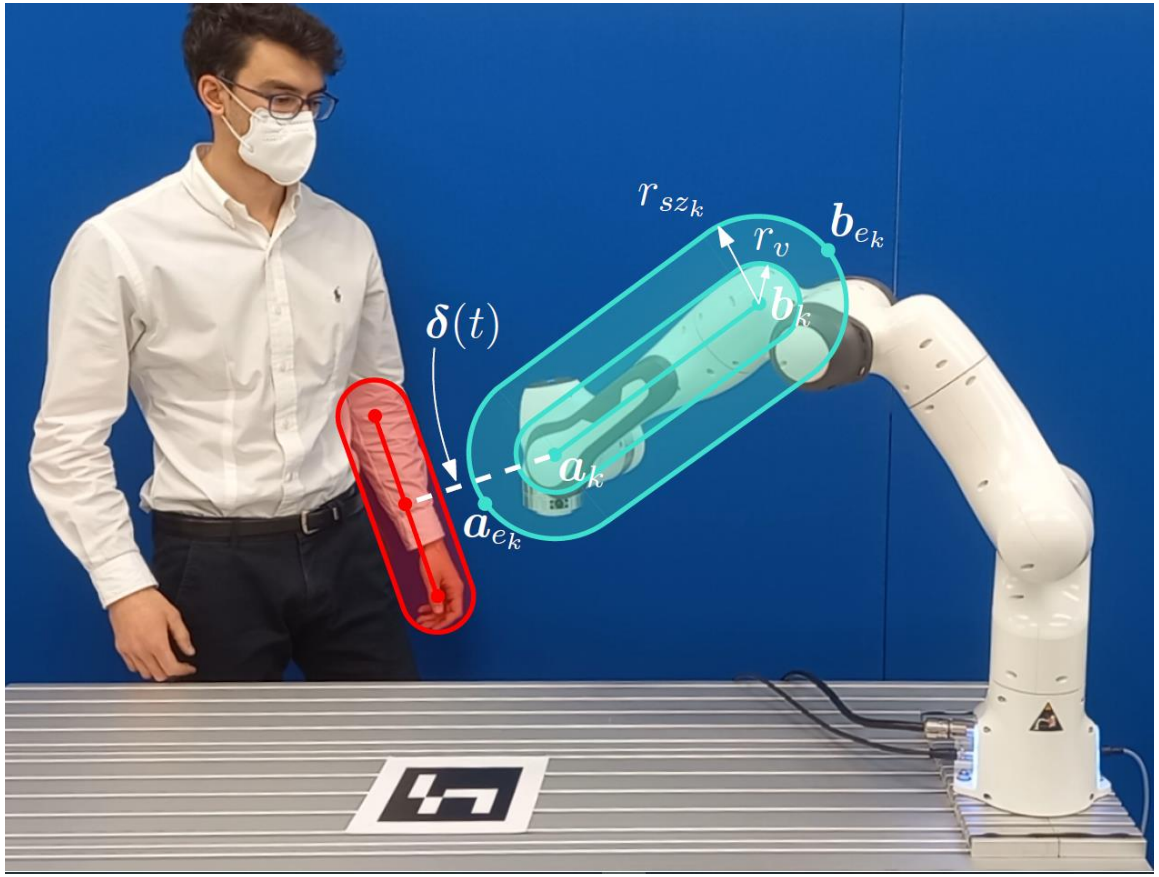
Justin by DLR (German Aerospace Center)



Toro by DLR



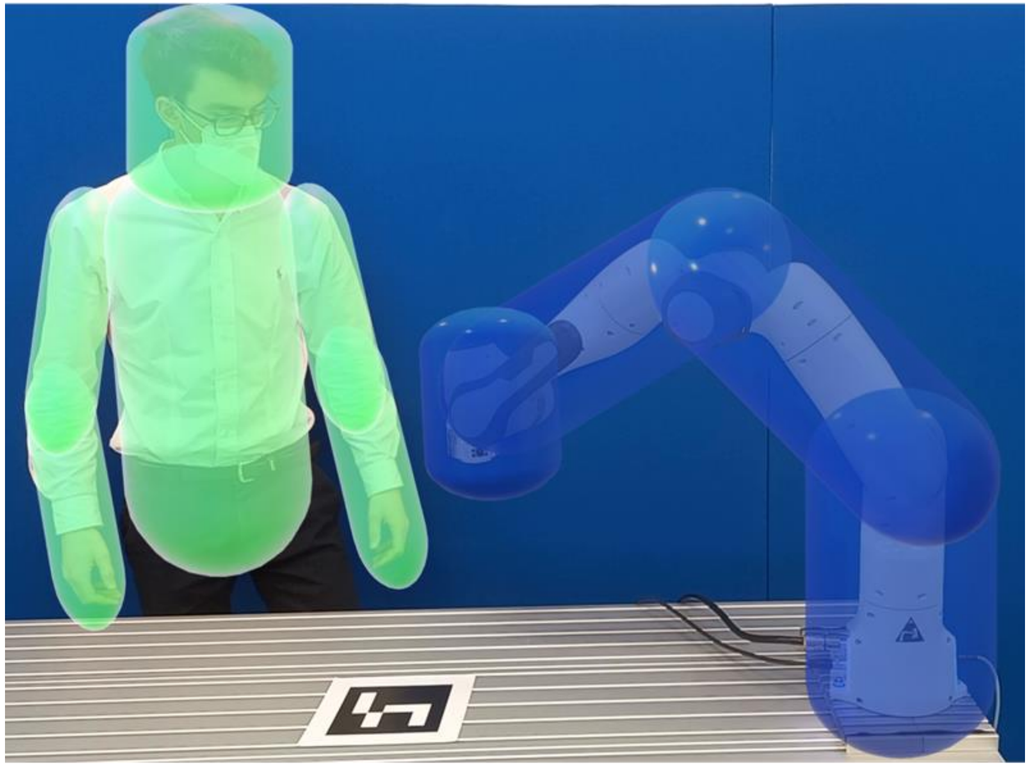
Research in collaborative robotics at University of Udine



An approach for collision avoidance in collaborative robotics

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

- Human and robot are considered to be enclosed in **bounding volumes** (capsules)
- The **robot safety zones** are considered **dynamic**: their size changes with respect to the actual speed of the robot
- A **supervisory controller** checks the **distance between human and robot** in real time
- If a potential collision is detected, the robot is steered to stop engaging a **stop trajectory**



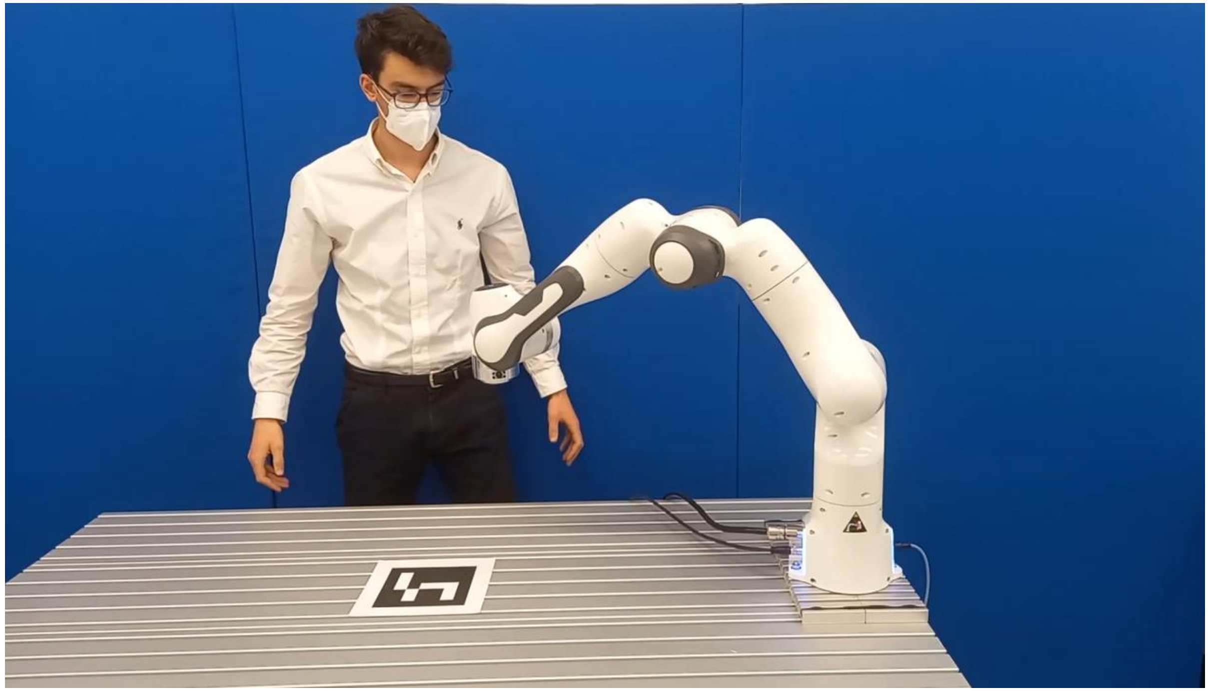
Proposed approach

- The collision avoidance algorithm computes in real time the **minimum stop time** needed for the robot to stop

- The stop time of the robot has to satisfy the kinematic and dynamic limits of the manipulator

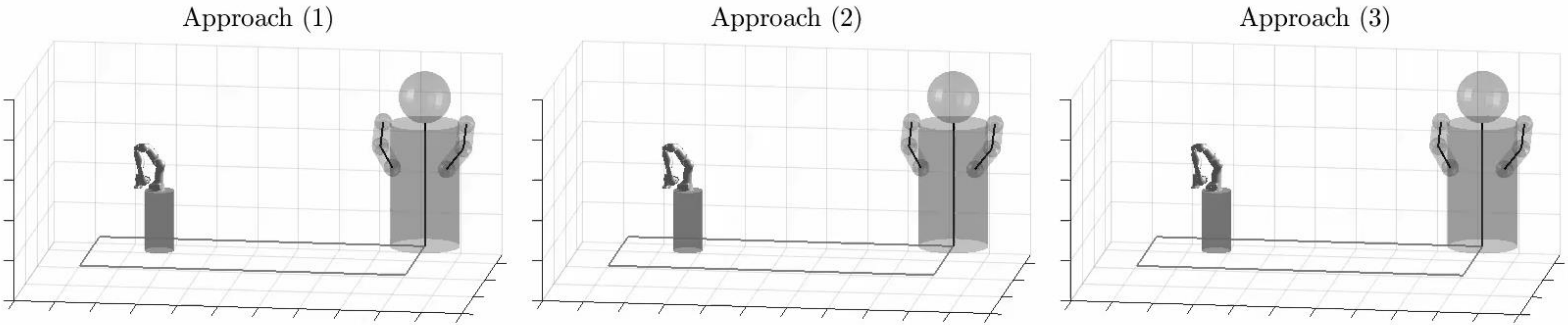
- If a **potential collision** is detected, the robot is stopped with a stop trajectory

- The robot restarts as soon as the safety condition is respected



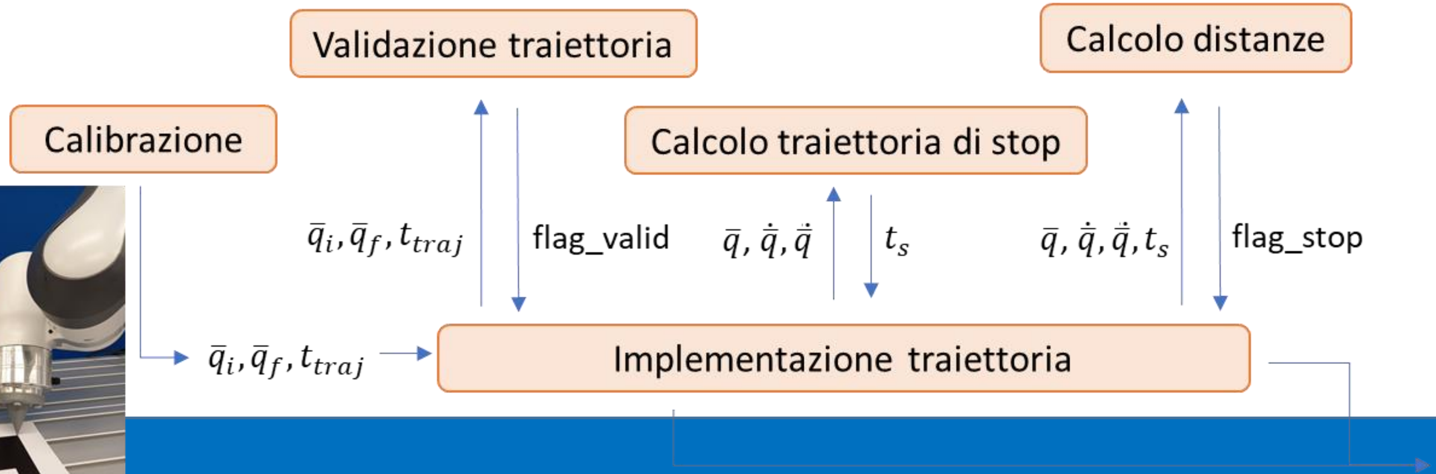
Numerical simulations

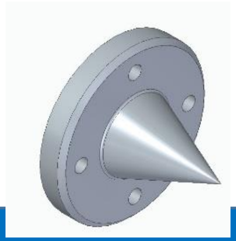
- Three different approaches have been compared:
  - Approach (1): online optimization of the stop time
  - Approach (2): selection of the stop time among predefined values
  - Approach (3): implementation of the ISO/TS 15066, resulting in static safety zones

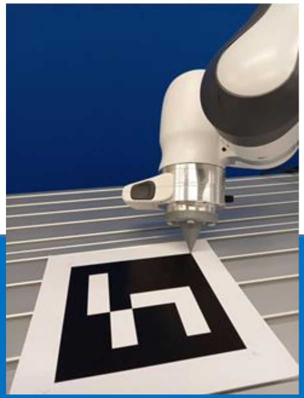


Experimental validation

- Franka Emika Panda robot with 7 degrees of freedom
- Stereo camera RGB-D Intel Realsense D435
- Workstation
- Software implemented in ROS Melodic using Ubuntu 18.04 and Python
- Marker and calibration tip printed in 3D

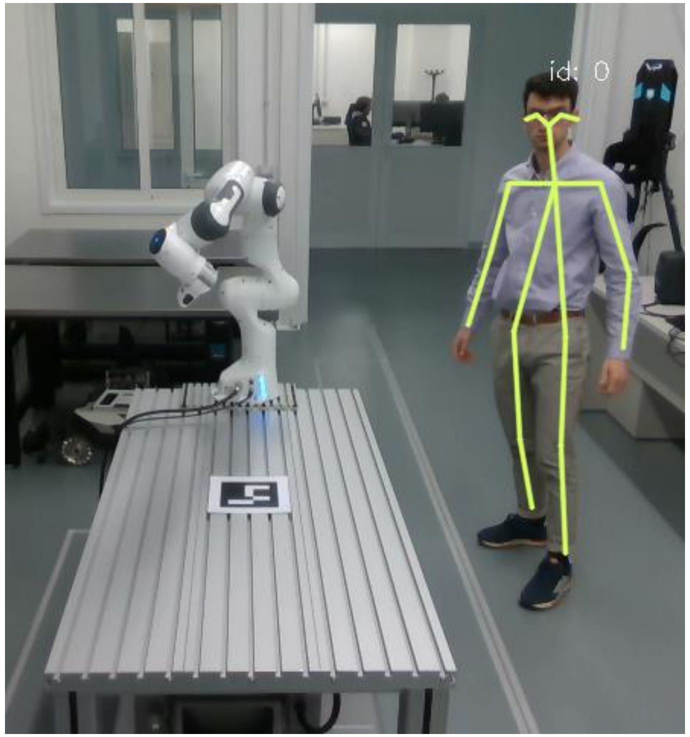


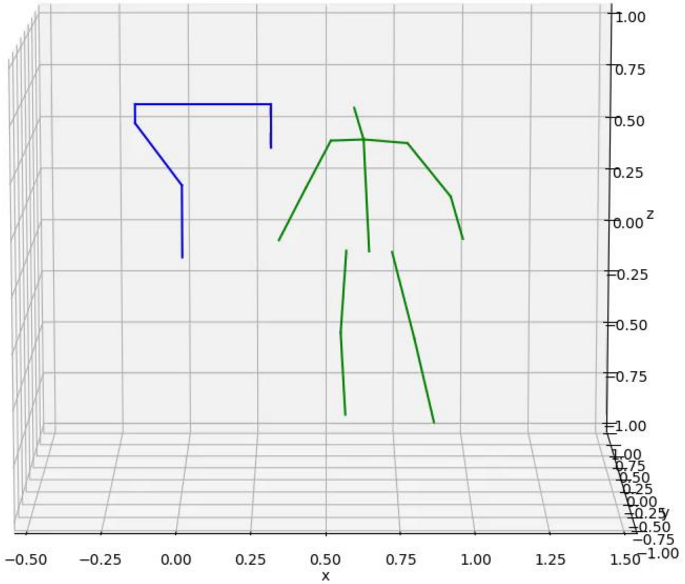




Online computation of the distance between human and robot

- Position of the human derived by the camera and a skeleton tracking software
- Position of the robot derived from the forward kinematics
- Computation of the distance between each segment belonging to the human and to the robot

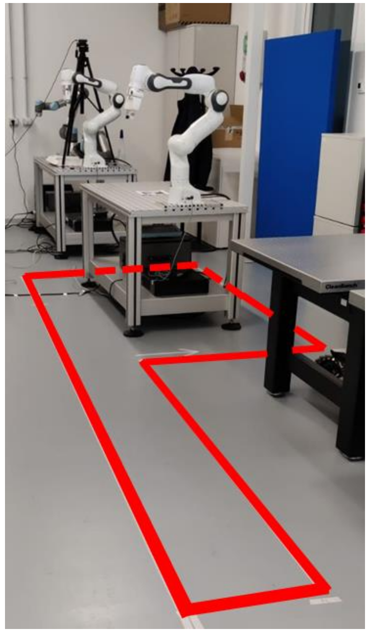


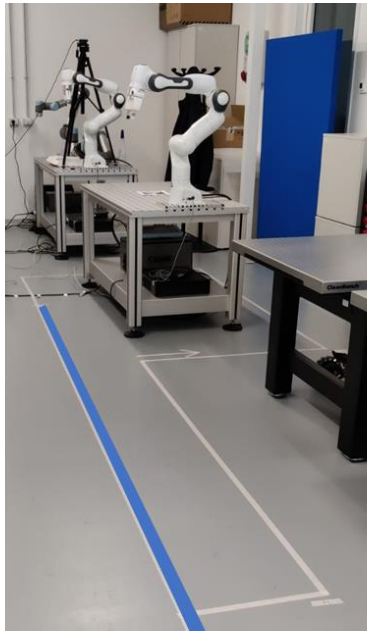


UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

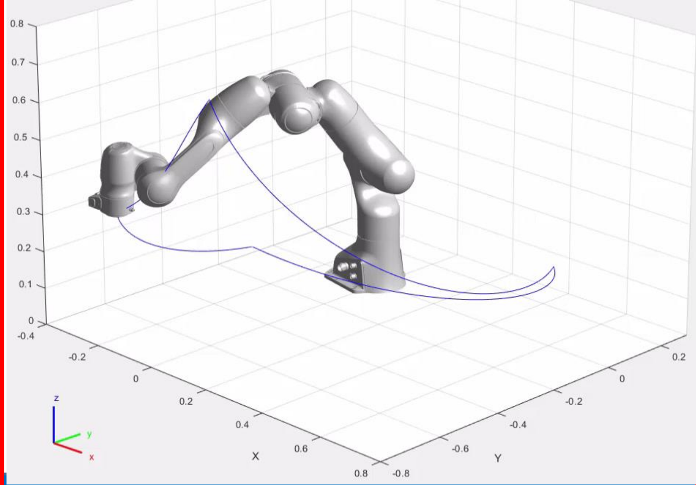
Experimental tests

- 27 subjects participated to the experimental tests
- The human has to walk along a predefined path close to the robot
- The robot has to repeat a predefined task, stopping in case a potential collision with the human is detected

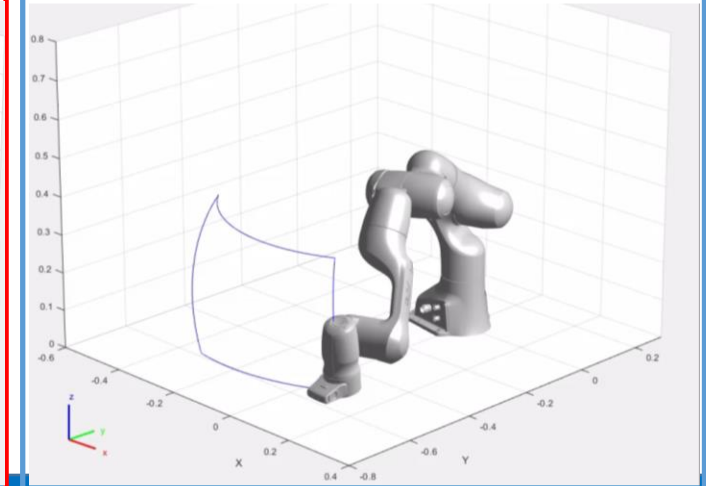




Test n.1, percorso in rosso, 2 metodi, capsule dinamiche



Test n.2, percorso in blu, 3 metodi, statico e dinamico



Experimental test (Test 1)

Experimental test (Test 2)

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

Static capsules

Test completato
Tempo totale di task: 81.72 s

Dynamic safety zones – iterative search

Test completato
Tempo totale di task: 42.34 s

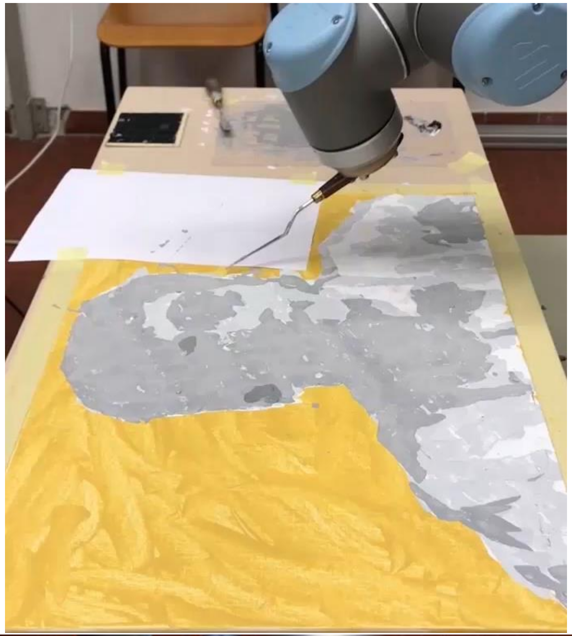
Dynamic safety zones – online optimization

Test completato
Tempo totale di task: 35.81 s

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

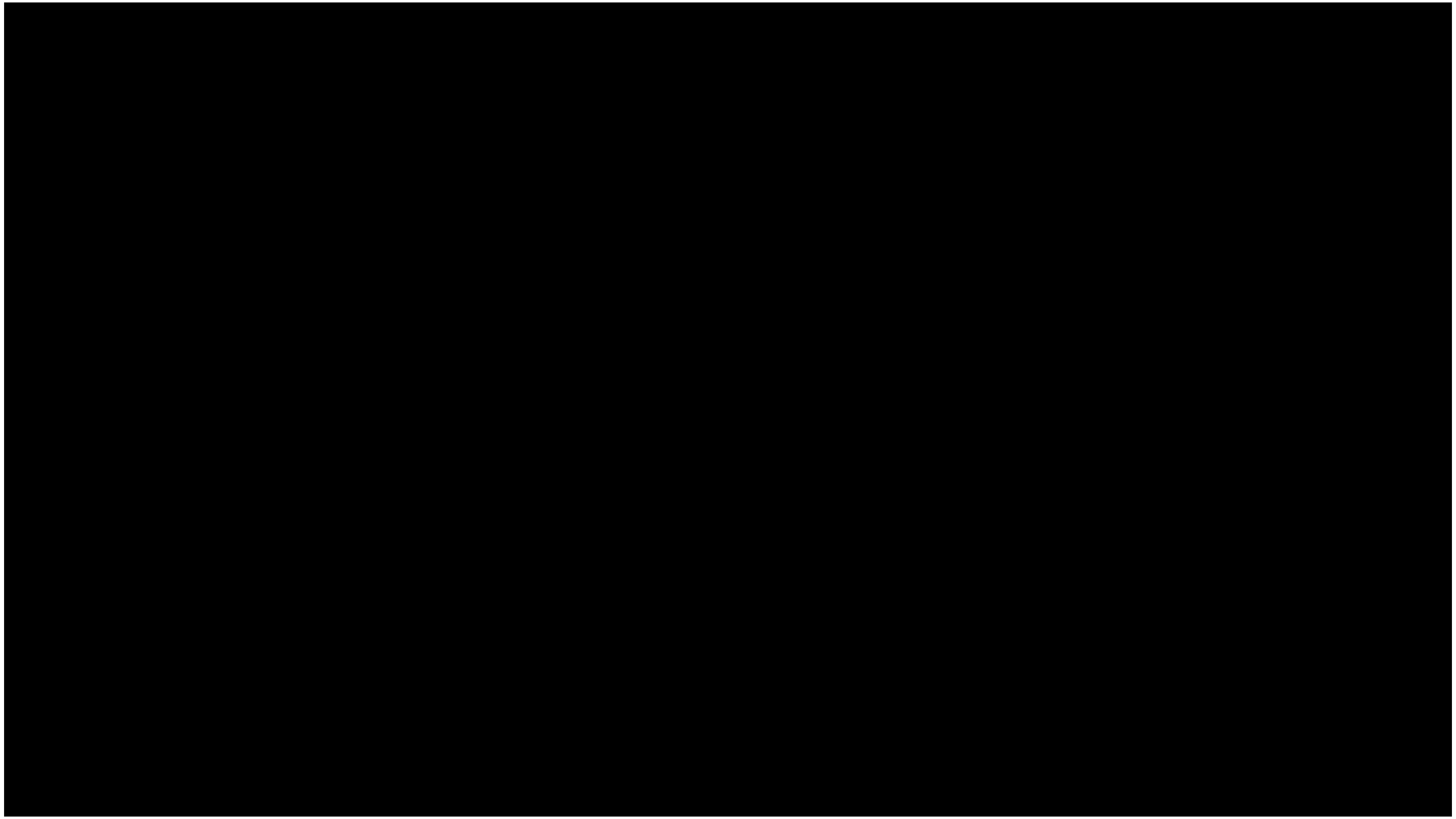
… not only industrial applications!

- Development and test of image processing and path planning algorithms for artistic applications
- Watercolor, tempera, palette-knife techniques
- Recently, we adopt an eye-tracker device to control the painting robot with eye gaze only



Artistic robotic painting

Robotic painting with eyes



Thank you for your attention!

Dr. Lorenzo Scalera

Polytechnic Department of
Engineering and Architecture
University of Udine
Via delle Scienze, 206
33100 Udine
lorenzo.scalera@uniud.it