Industrial automation and robotics

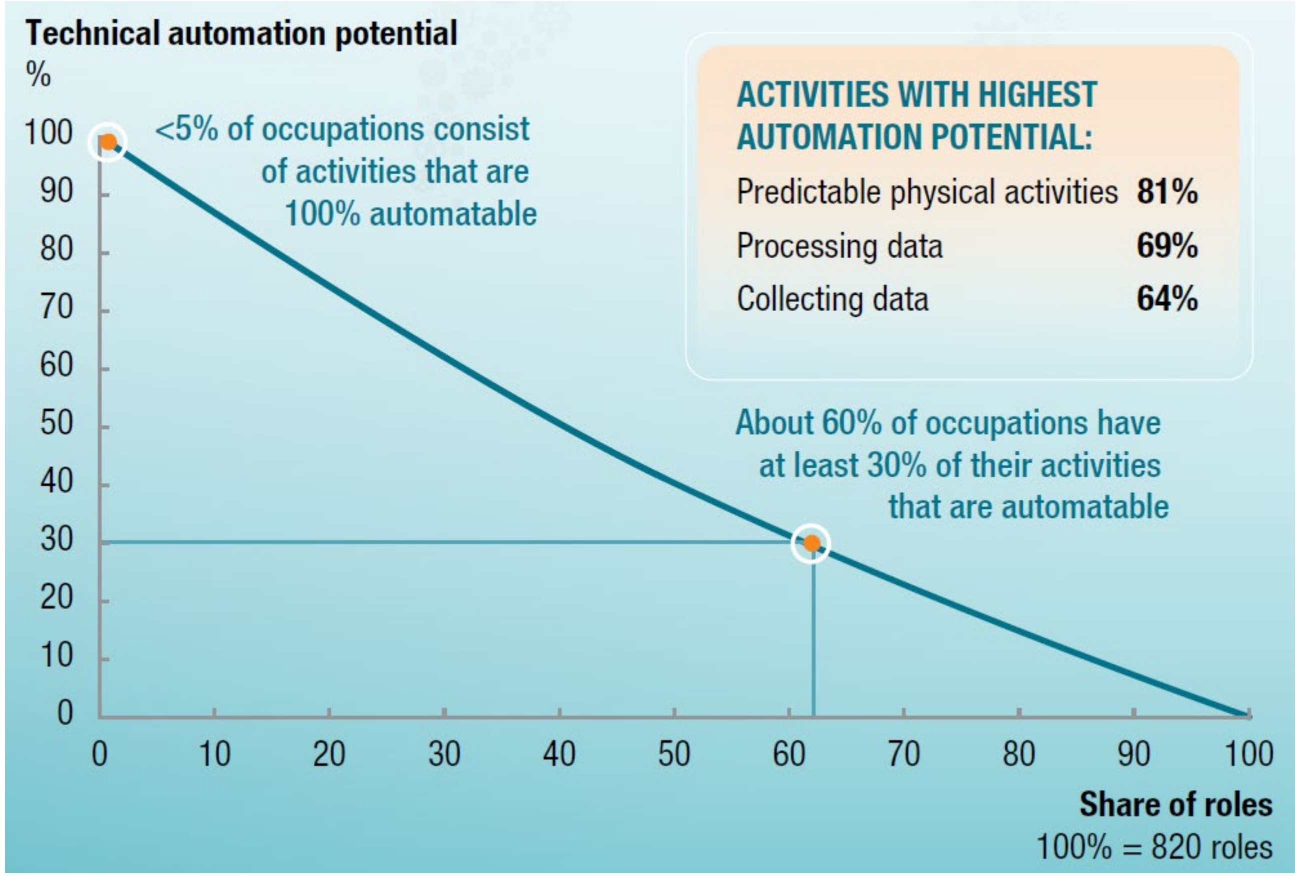
Collaborative robotics

Prof. Paolo Rocco (paolo.rocco@polimi.it)

Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria

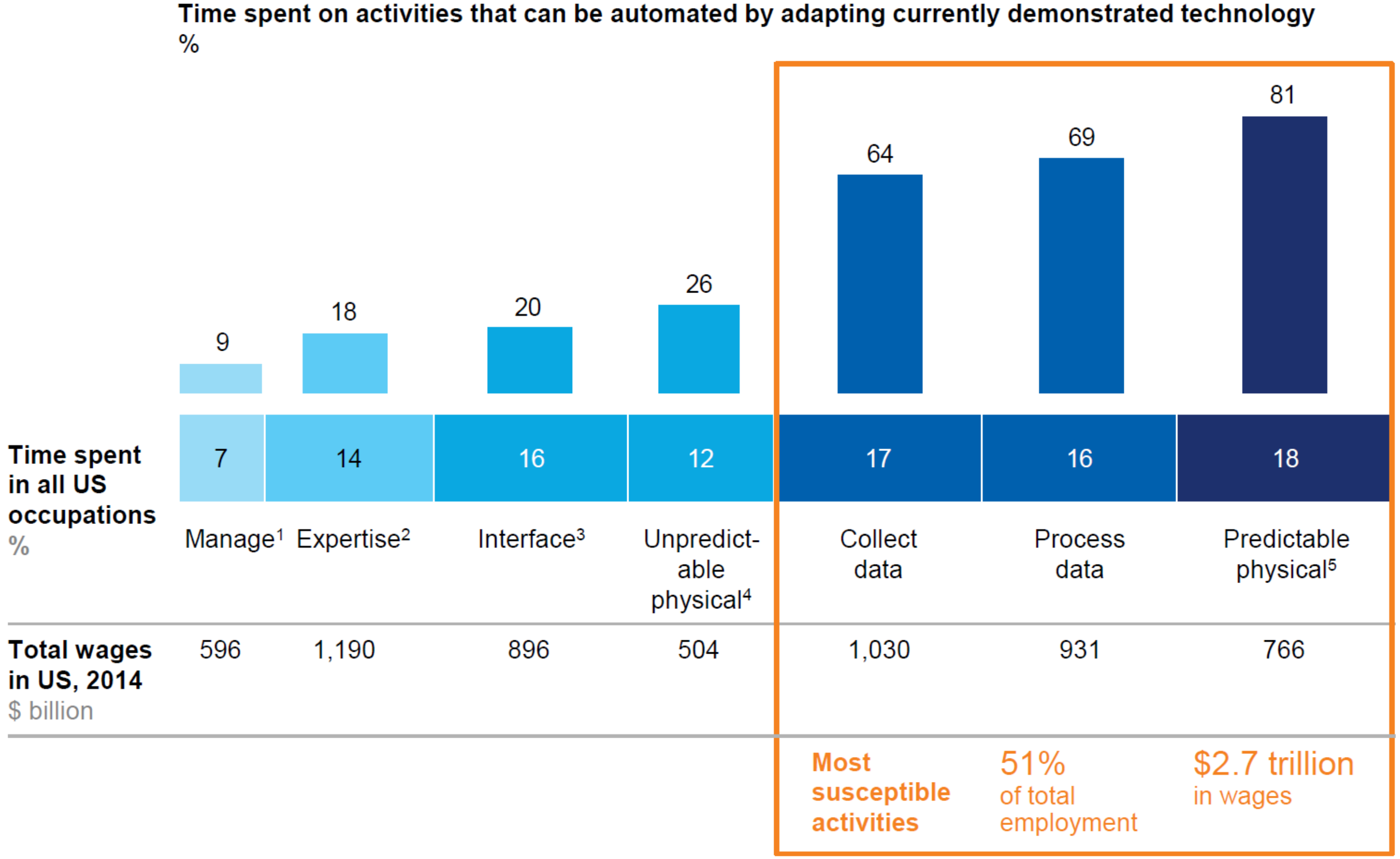
Potential of automation of the activities

Source: McKinsey Global Institute

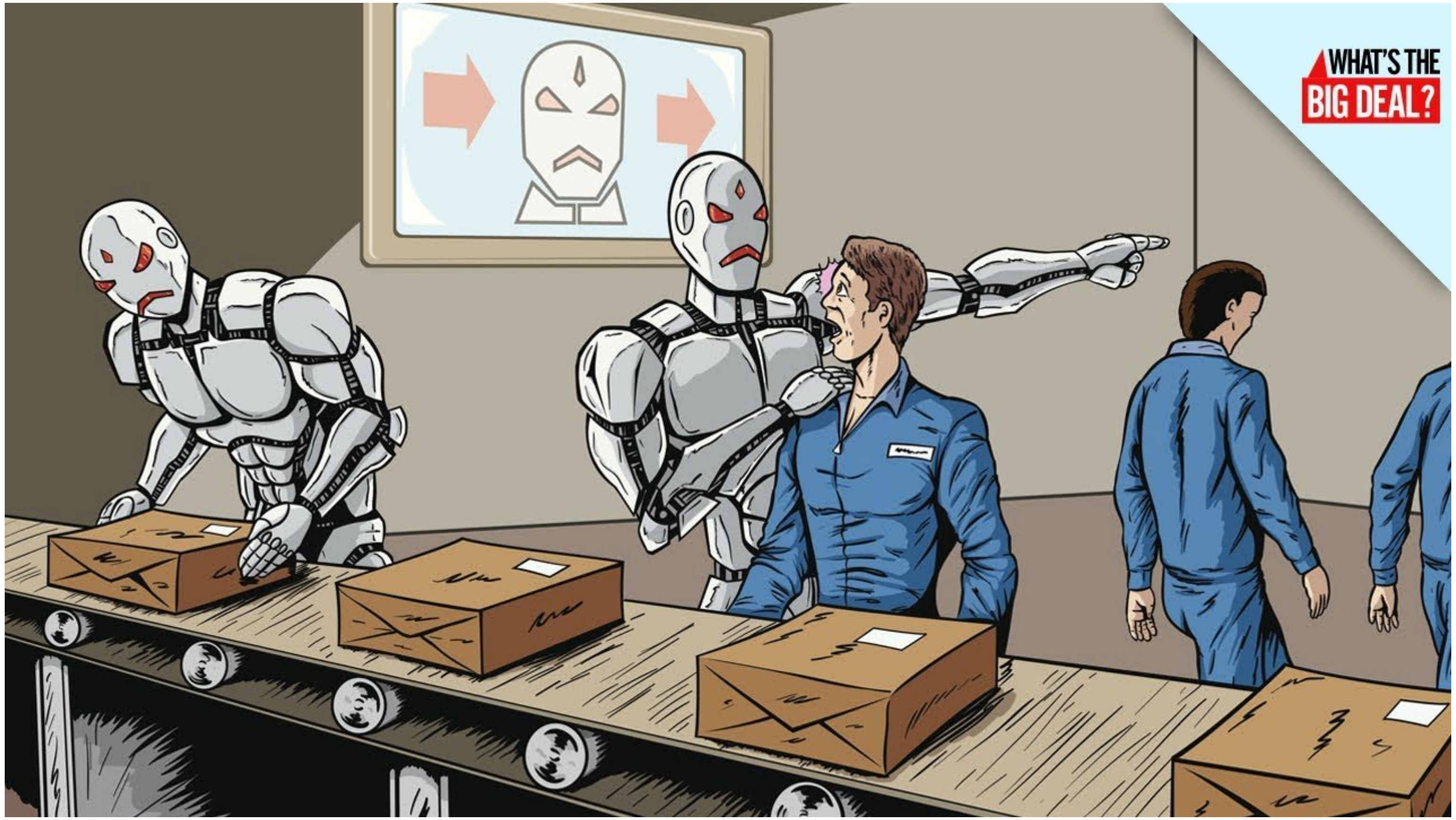


Automation, a risk or an opportunity?

Source: McKinsey Global Institute



Will workers disappear from the factories?



… not necessarily

Fonte: Universal Robots

Collaborative robotics

Collaborative robotics is a new paradigm in industrial robotics, where humans and robots share the same environment and collaborate at the same tasks.

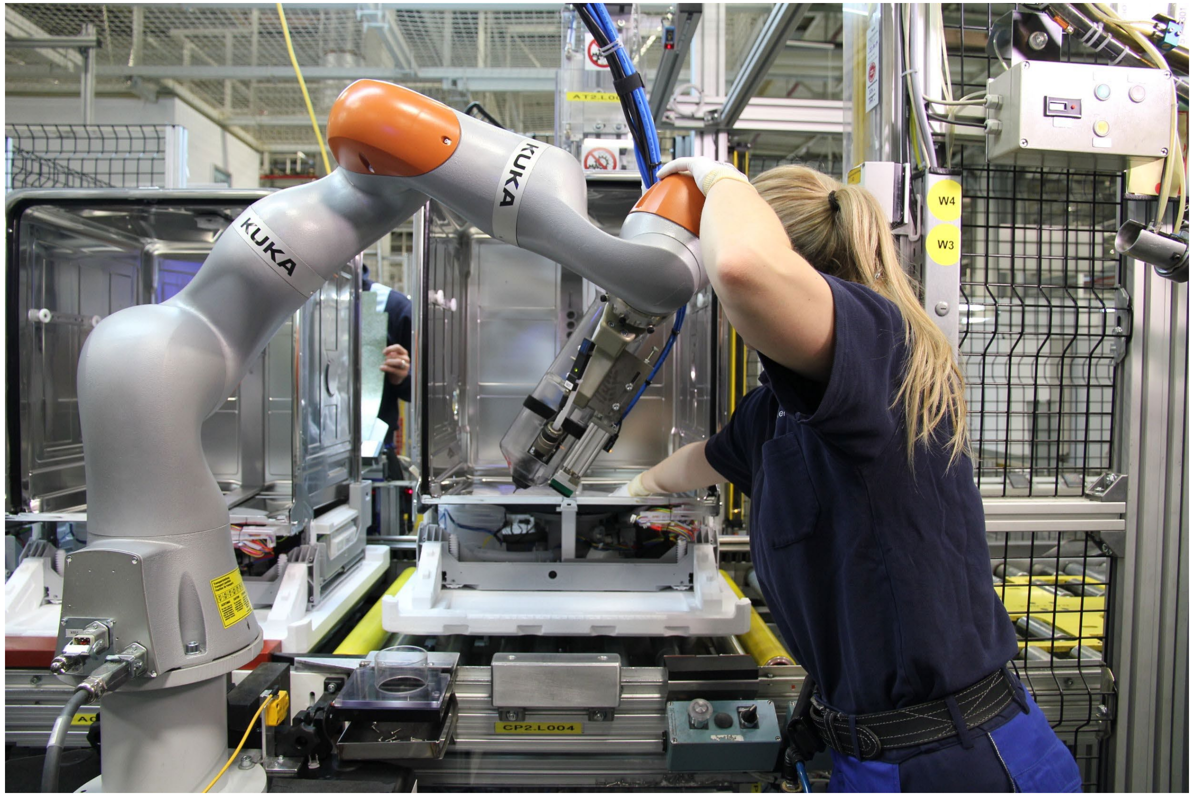
New collaborative robots (cobots) are now entering the market and all the major robot manufacturers have their collaborative solution.

Though still a niche in the big market of industrial robotics, collaborative robotics is growing fast and is expected to be a breakthrough in the coming years.

Source: Universal Robots

Collaborative robotics (1/3)

- Humans and robots collaborating at the same task
- Protective fences are not needed
- Particularly interesting for SMEs (reduced cost, reduced foot print)



Source: KUKA

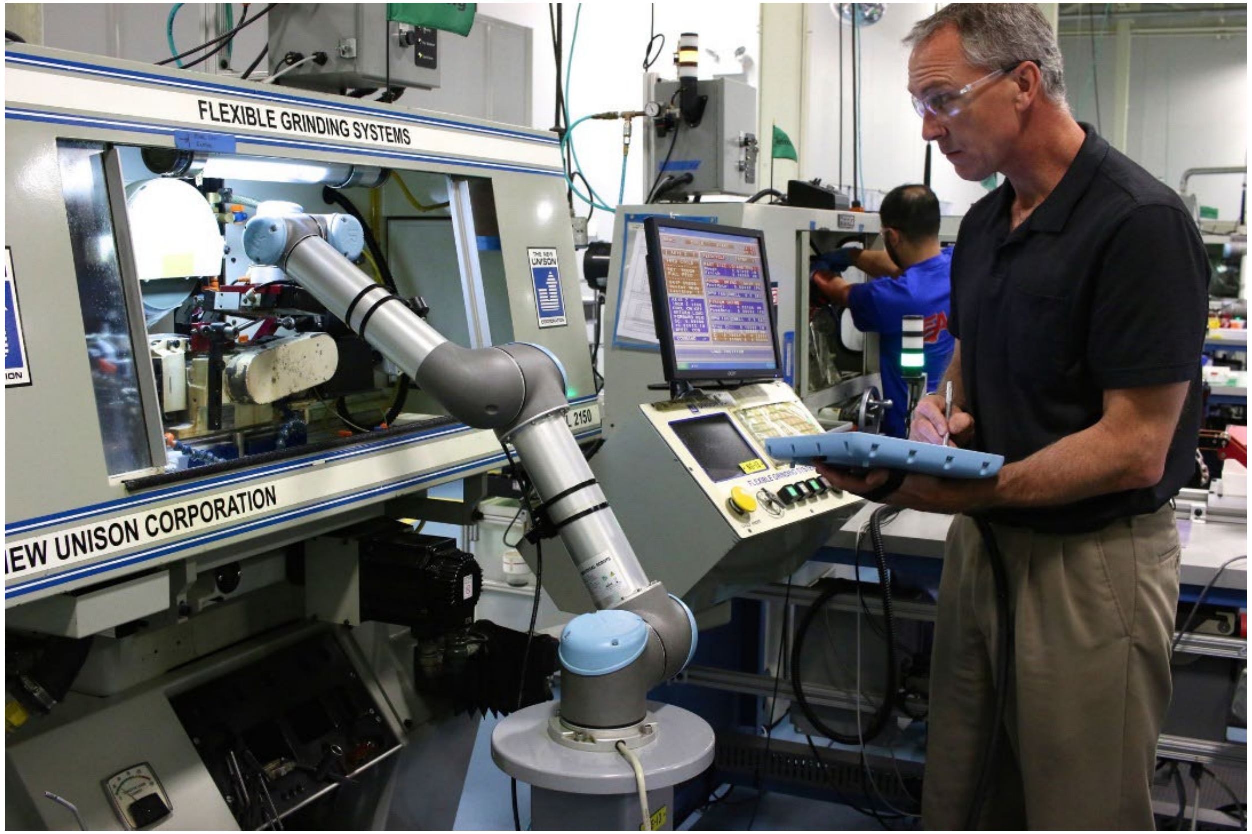
Collaborative robotics (2/3)

- Redundant, dual arm manipulators, characterized by low inertia and low payload (reduced risk when impact)
- Still good precision available
- Good potential for assembly of electronic parts

Source: ABB

Collaborative robotics (3/3)

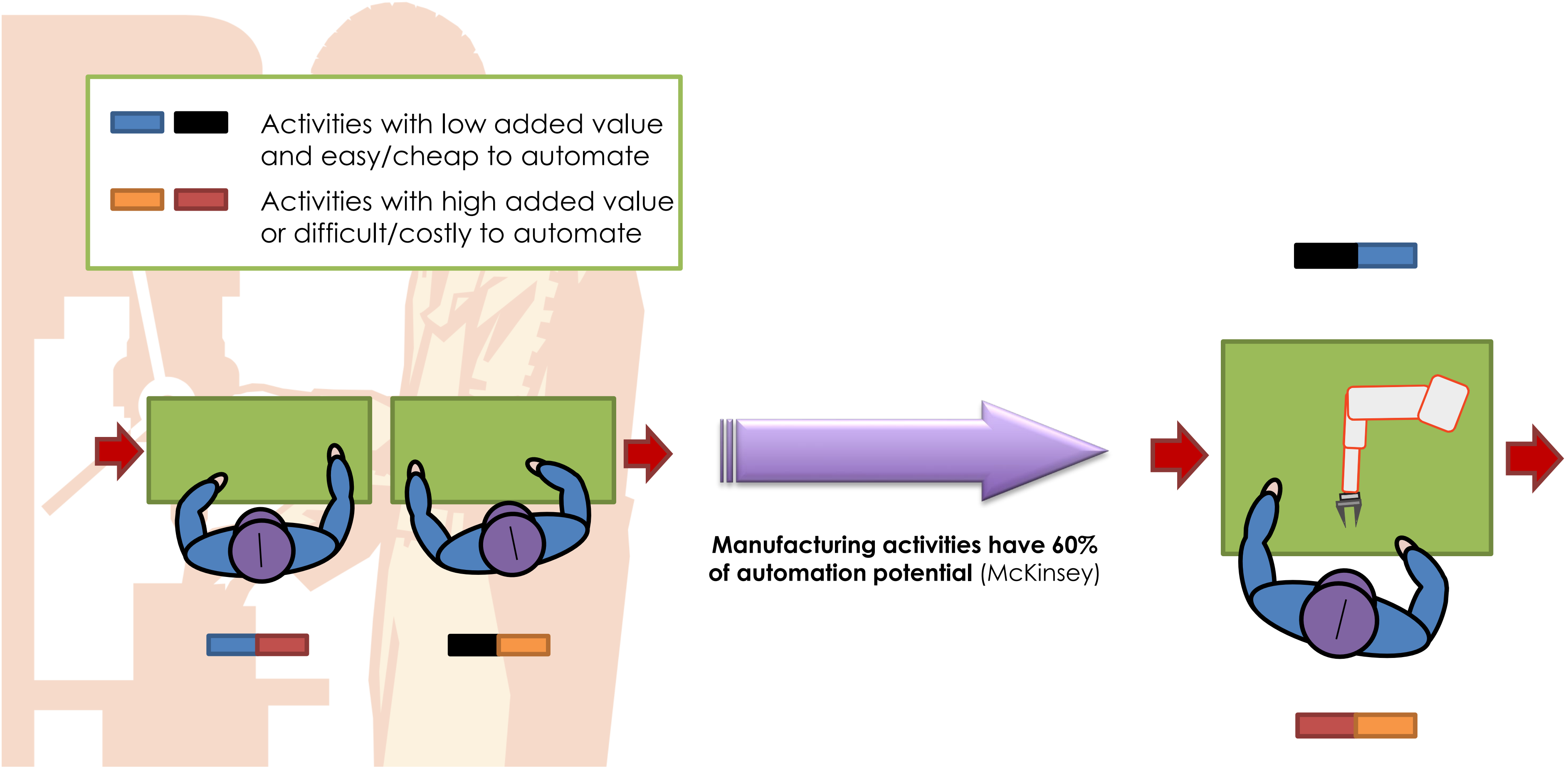
- New programming interfaces
- Decrease of the deployment time
- High potential for SMEs



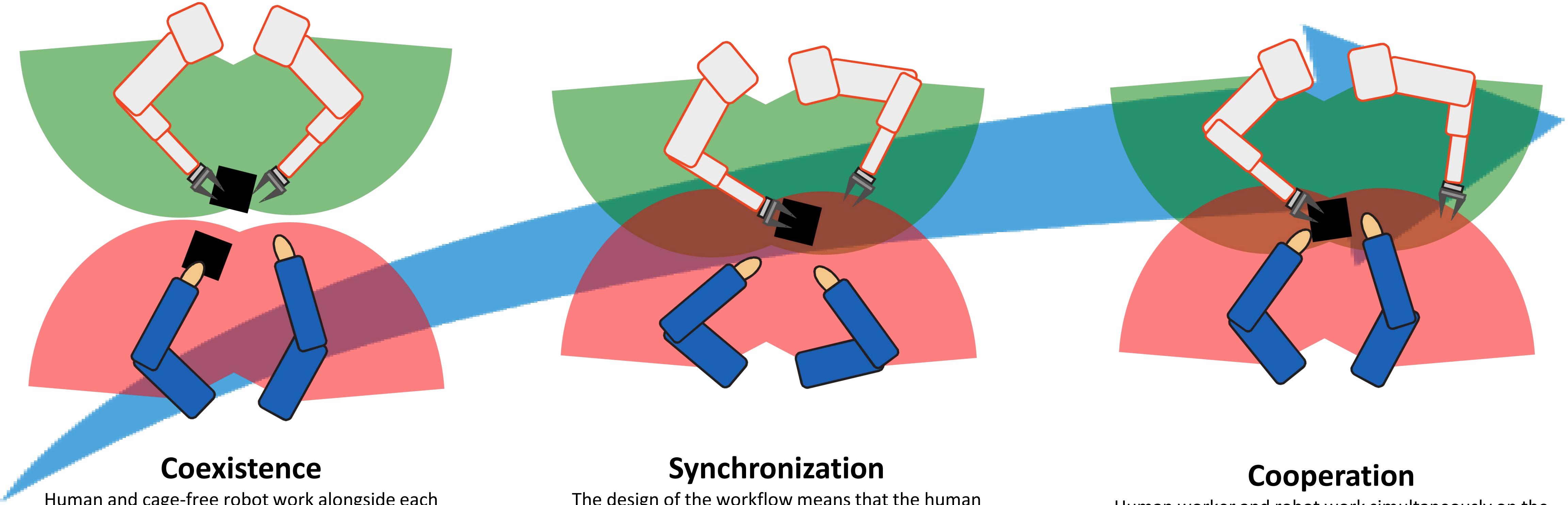
Source: Universal Robots

Collaborative assembly

Opportunities



An evolving paradigm



Coexistence

Human and cage-free robot work alongside each other but do not share a workspace. Humans can work away, but may need to *sporadically* access the workspace of the robot (e.g. to load/unload parts).

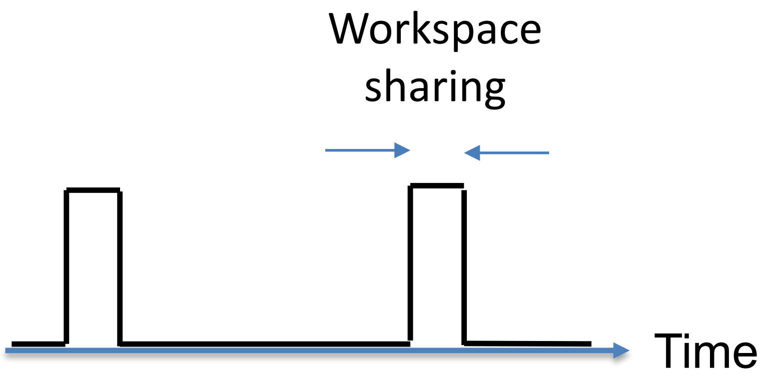
Synchronization

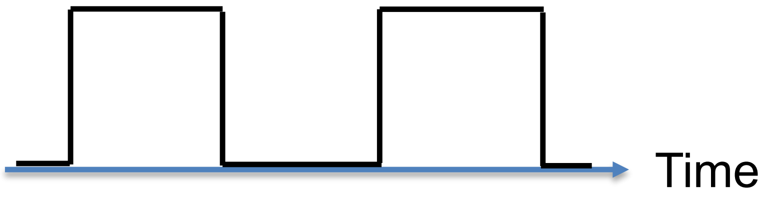
The design of the workflow means that the human worker and the robot share a workspace but that only one of the interaction partners is actually present in the workspace at any one time, or they do not work simultaneously on the same product or component.

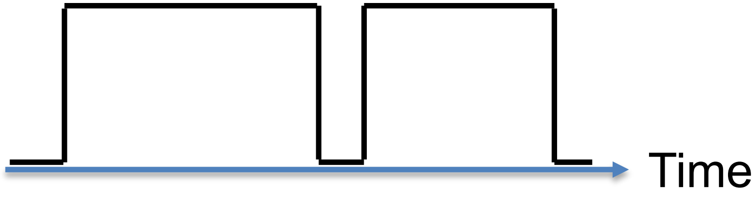
Cooperation

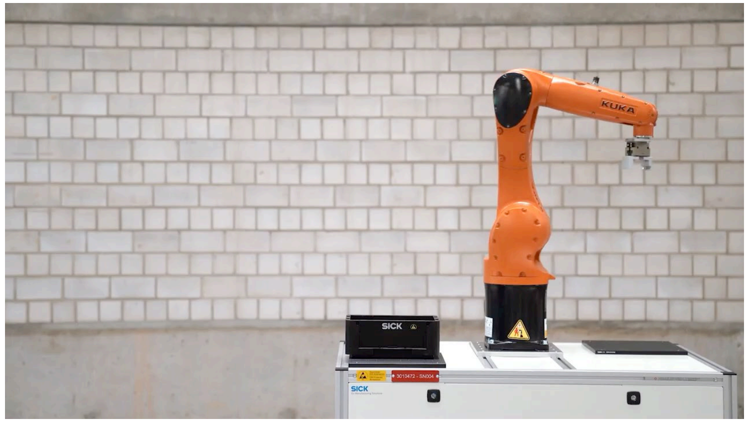
Human worker and robot work simultaneously on the same product or component.

An evolving paradigm









Sporadic

Frequent

Persistent

A bit of history of collaborative robotics

2000 2000 2002 2004 2006 2008 2010 2012 2014 2016 **2017**

1960 - 2000
Industrial robots are separated from humans; they requires significant investments and programming skills

2000
The world cobot enters the dictionary
cobot: noun. A collaborative robot designed to help workers on the job instead of replacing them. Source: Wall Street Journal, Jan 2000

2005
Universal Robots is founded in Denmark to develop an affordable, low-cost collaborative robot
UR5 was launched in 2008 and certified by TUV in 2014

2012
Rethink Robotics is founded and launches Baxter

2013
KUKA launches LBR iiwa

2015
ABB launches YuMi and acquires Gomtec

2016
ISO sets a new standard for cobots

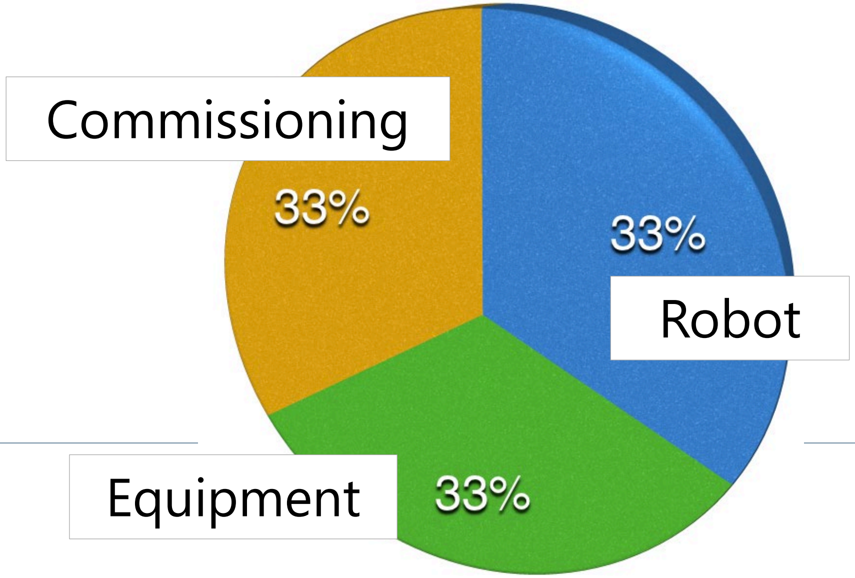
Source: A.M. Zanchettin

Installation costs of cobots

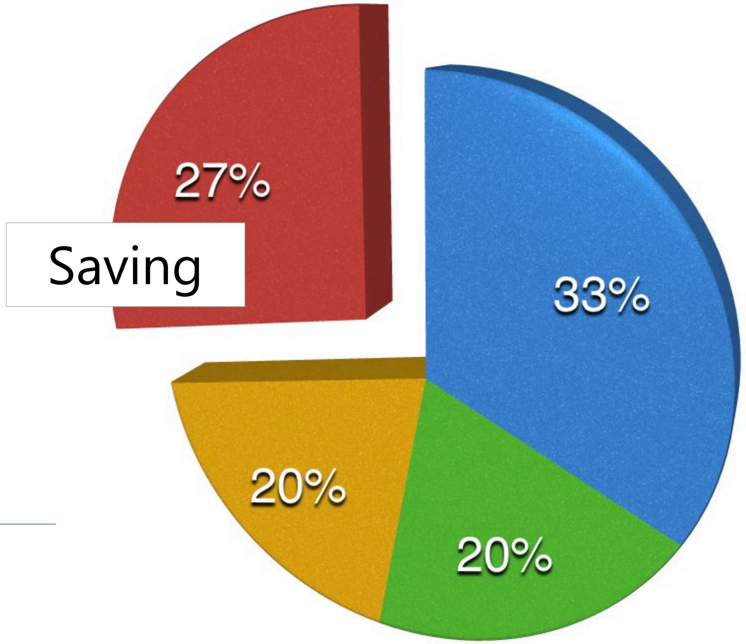
- Collaborative robots have no (or reduced) physical protection devices to allow the human operator to directly interact with them.

- The limited need of safeguarding devices allows a smaller footprint, making cobots more affordable, especially for SMEs, as compared with traditional industrial robots.

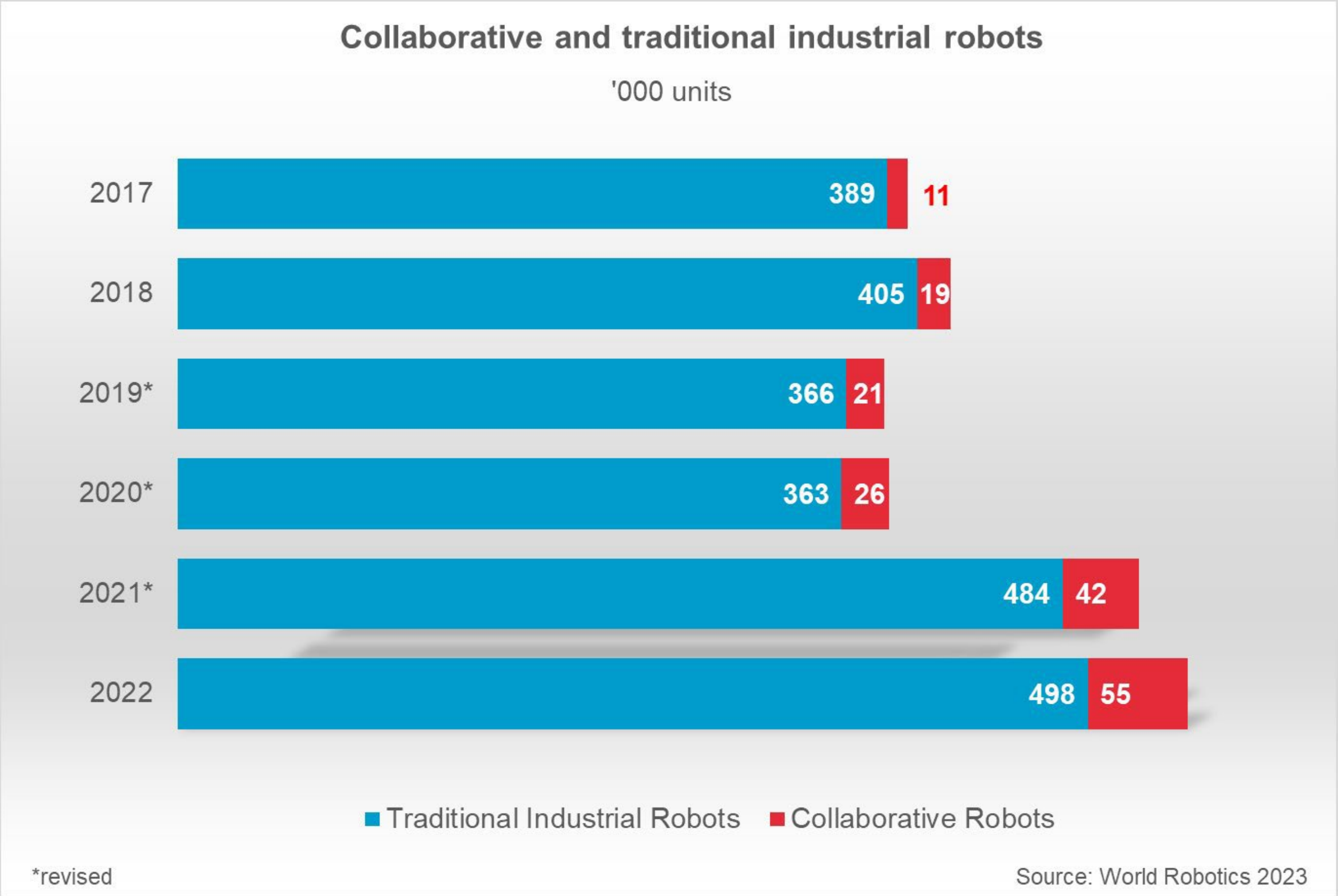
Industrial Robot



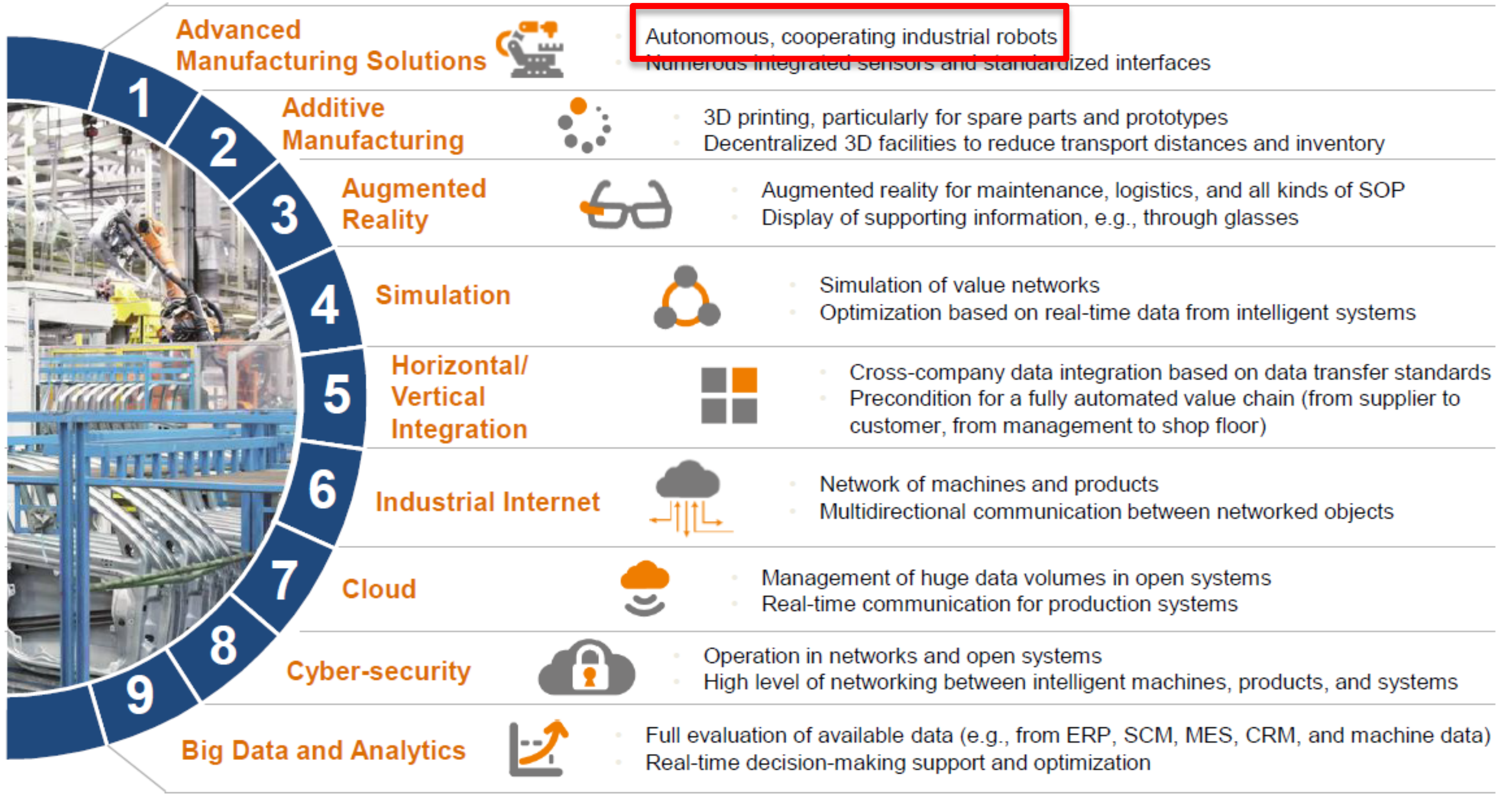
Collaborative Robot



Market of the cobots

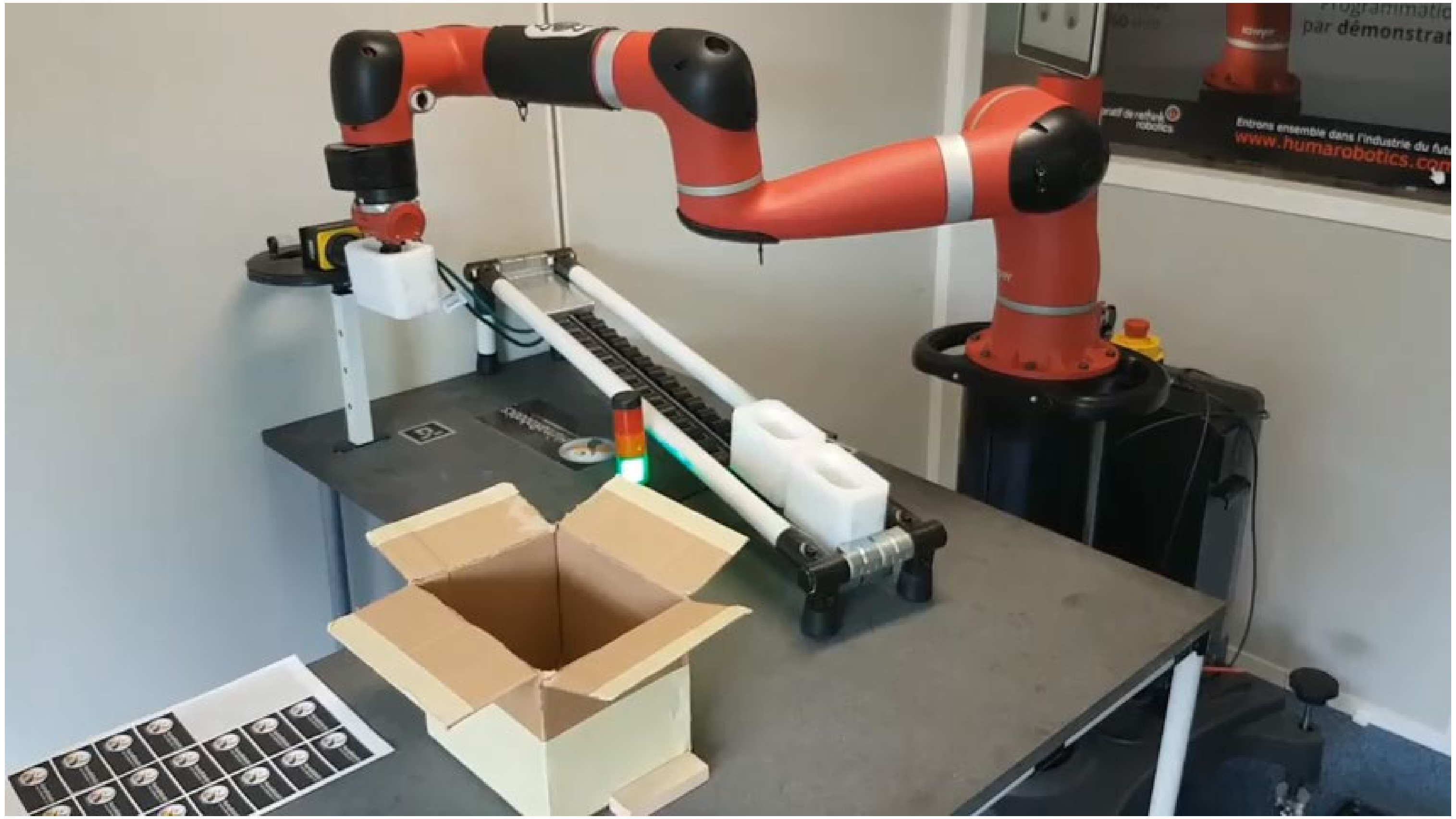


Collaborative robotics and industry 4.0



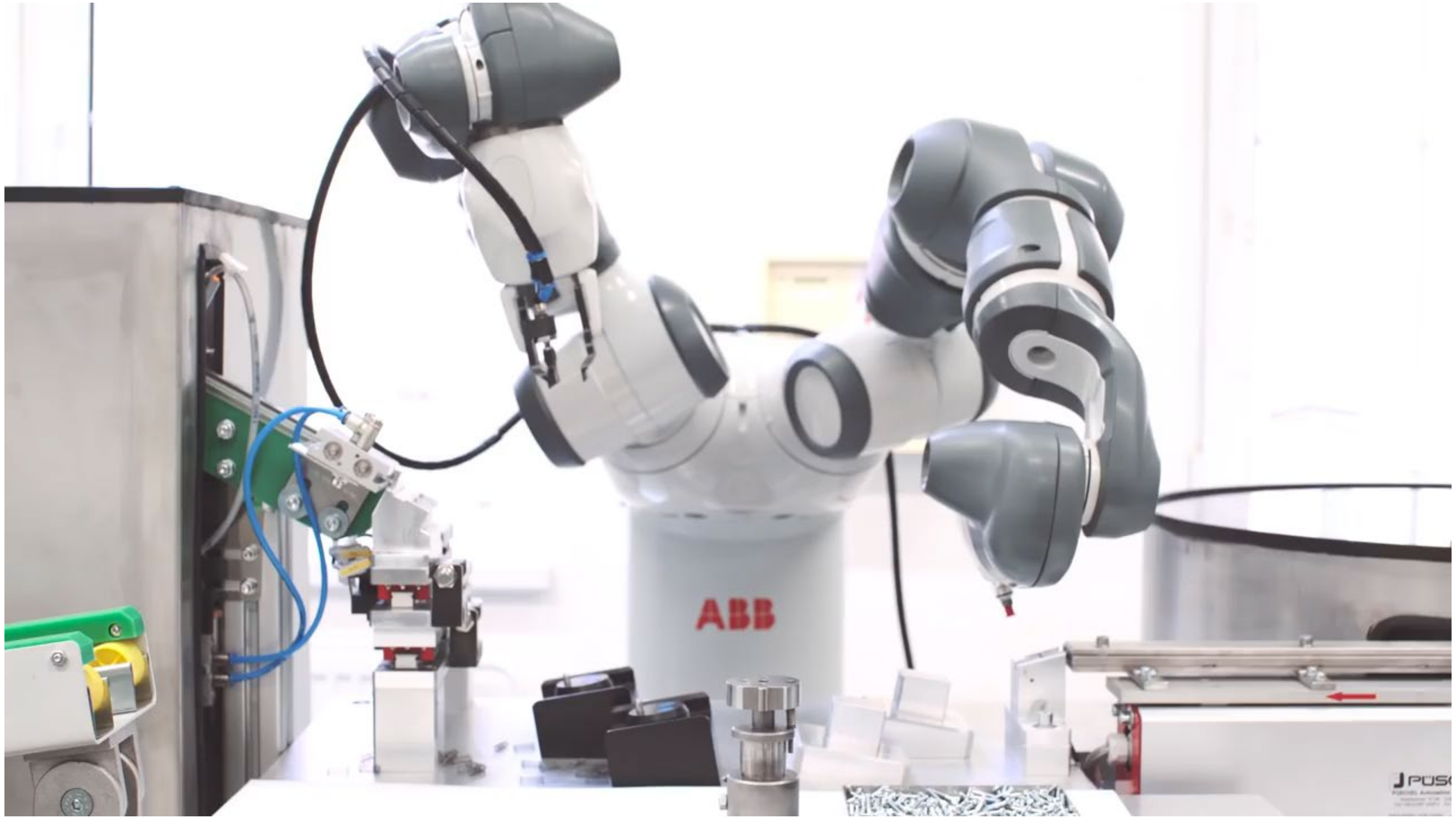
- Collaborative robotics is considered one of the enabling technologies of the industry 4.0 paradigm
- Humans and machines are expected to actively cooperate in the smart factory

From robots to cobots

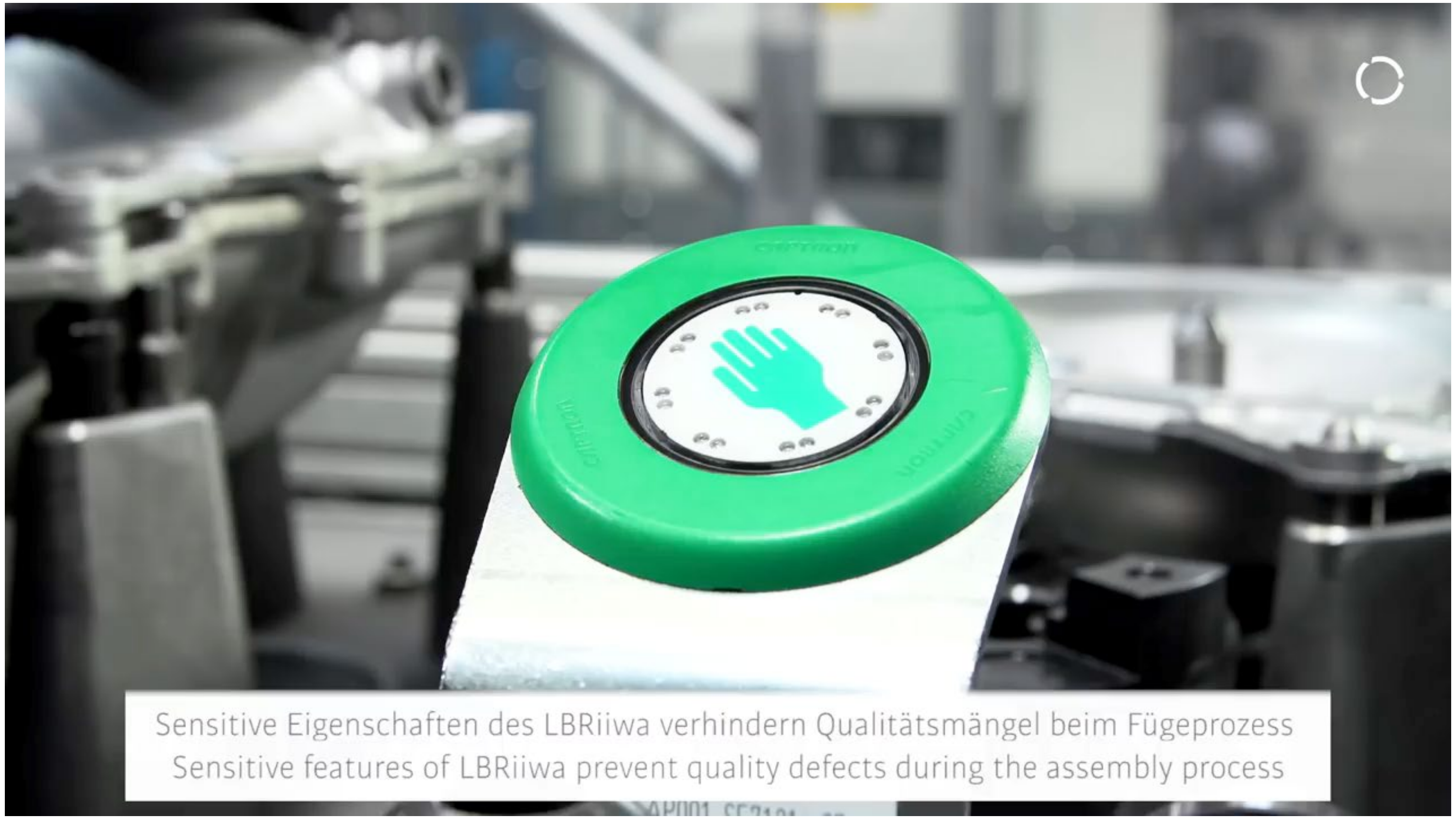


From robots to cobots

From robots to cobots

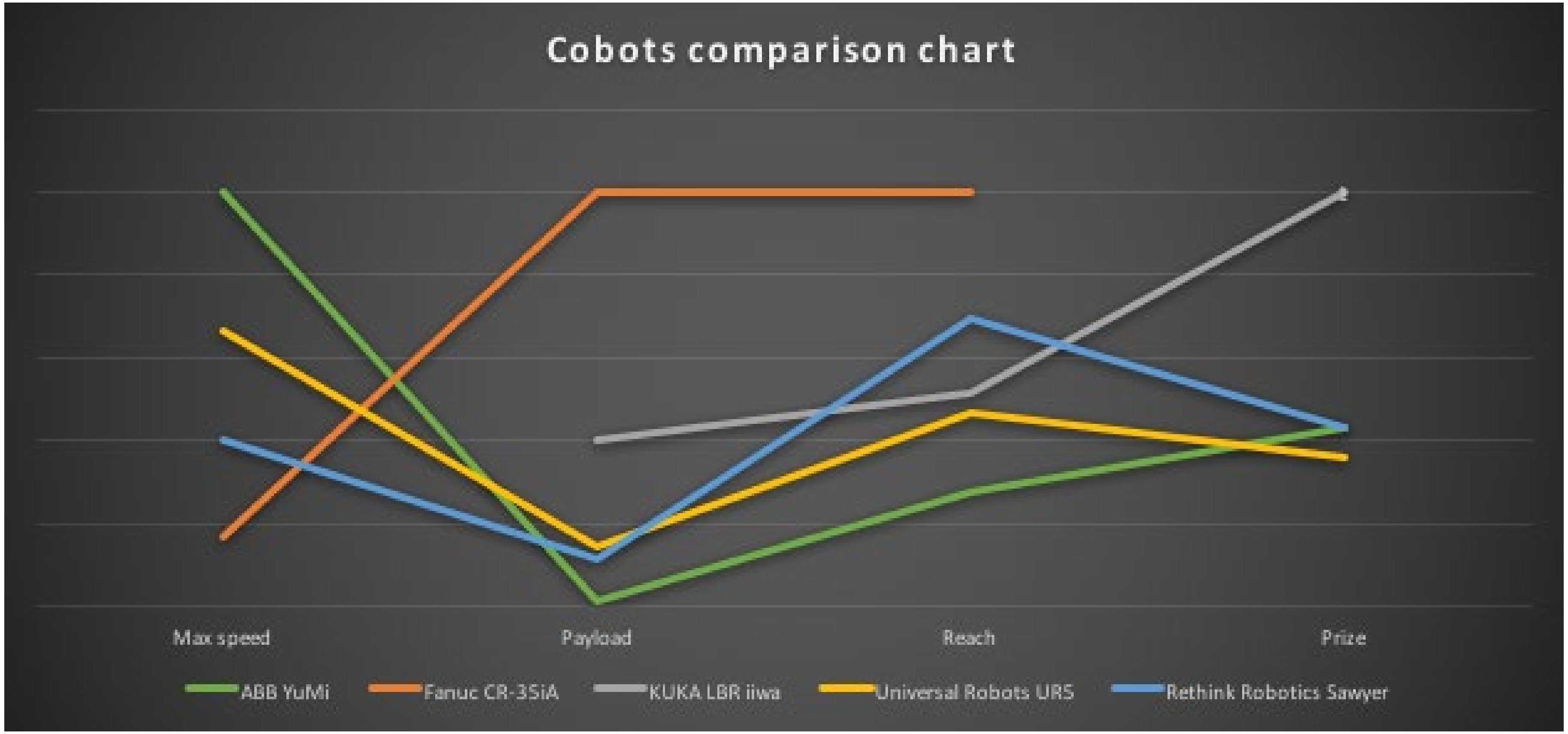


From robots to cobots



From robots to cobots

Available cobots (comparison charts)

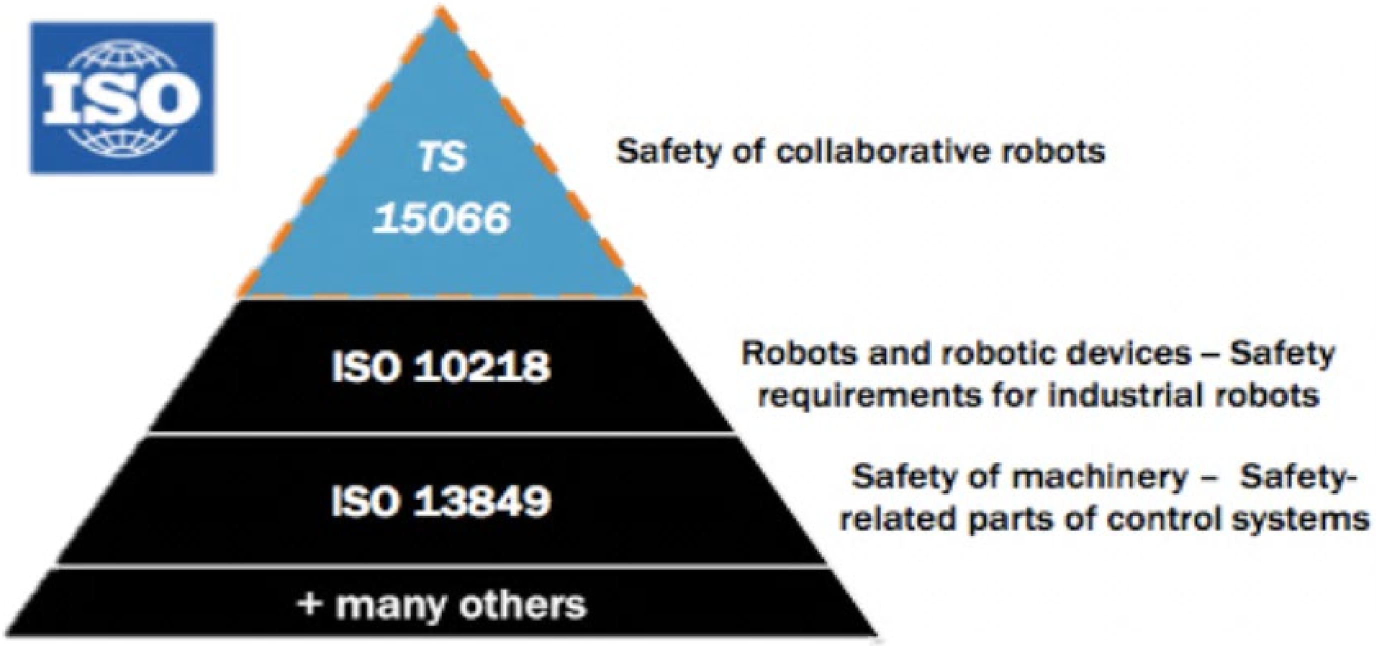


A large size cobot

Safety

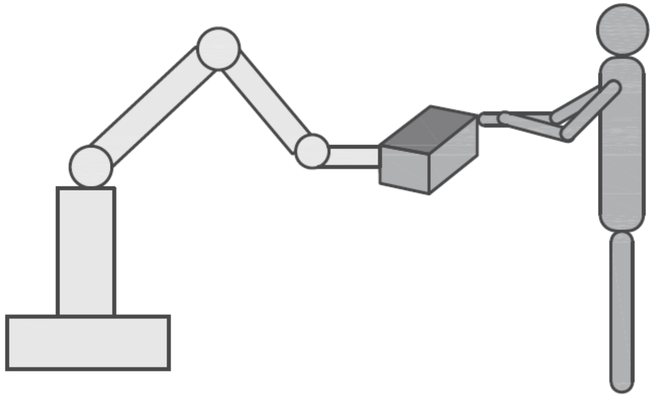
- This robot is safe
- However it is not collaborative
- How can we guarantee safety while allowing for collaboration?

Safety standards for robotics



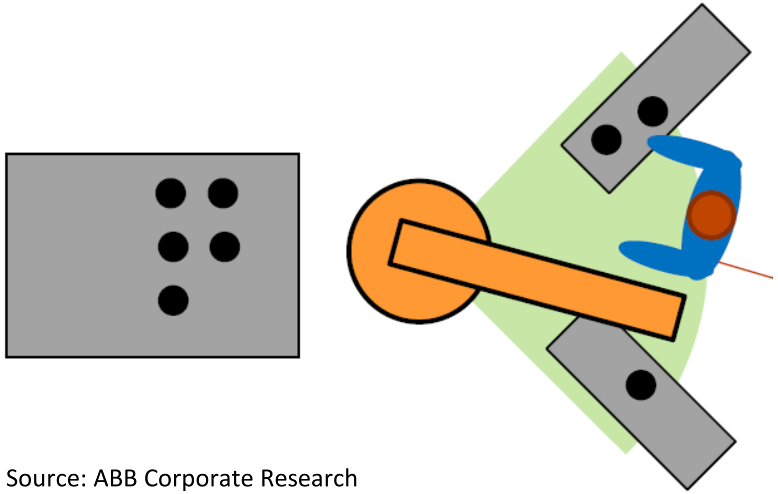
Source: A.M. Zanchettin

Safety standards: definitions



Collaborative operation

- ISO 10218-1:2011, clause 3.4
- State in which purposely designed robots work in direct cooperation with a human within a defined workspace

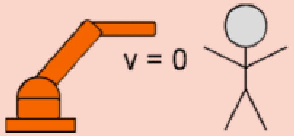
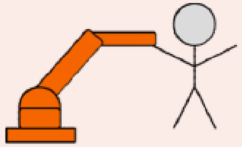
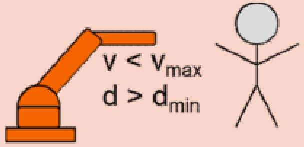
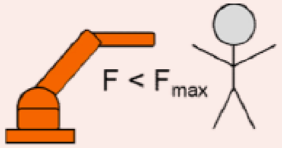


Source: ABB Corporate Research

Collaborative workspace

- ISO 10218-1:2011, clause 3.5
- Workspace within the safeguarded space where the robot and a human can perform tasks simultaneously during production operation

Types of collaborative operations

ISO 10218-1, clause	Type of collaborative operation	Main means of risk reduction	
5.10.2	Safety-rated monitored stop (Example: manual loading-station)	No robot motion when operator is in collaborative work space	
5.10.3	Hand guiding (Example: operation as assist device)	Robot motion only through direct input of operator	
5.10.4	Speed and separation monitoring (Example: replenishing parts containers)	Robot motion only when separation distance above minimum separation distance	
5.10.5	Power and force limiting by inherent design or control (Example: *ABB YuMi®* collaborative assembly robot)	In contact events, robot can only impart limited static and dynamics forces	

Source: ABB Corporate Research

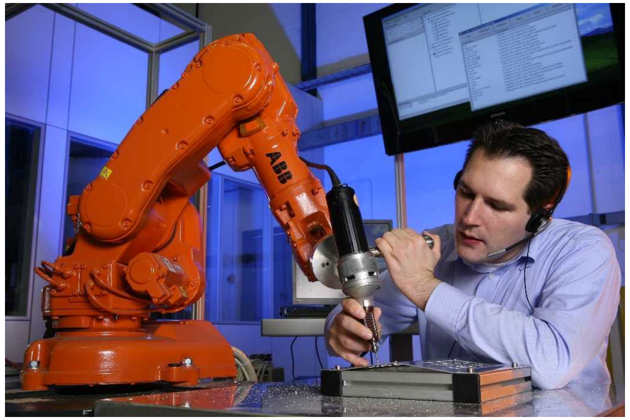
Safety-rated monitored stop

A very conservative mode. Collaboration is limited with a robot in a stand-still position. Power is still enabled and the robot is ready to resume its motion.

- **Clauses in standards and TS**
  - ISO 10218-1, clause 5.10.2
  - ISO 10218-2, clause 5.11.5.2
  - ISO/TS 15066, clause 5.5.2
- **Risk reduction**
  - Ensure robot standstill whenever a worker is in collaborative workspace
- **Achieved by**
  - Supervised standstill - Category 2 stop (IEC 60204-1)
  - Category 0 stop in case of fault (IEC 60204-1)
- **Typical applications**
  - Loading / unloading end-effector

Source: ABB Corporate Research

Hand guiding



Source: ABB Corporate Research

- **Clauses in standards and TS**
  - ISO 10218-1, clause 5.10.3
  - ISO 10218-2, clause 5.11.5.3
  - ISO/TS 15066, clause 5.5.3
- **Risk reduction**
  - Provide worker with direct control over robot motion at all times in collaborative workspace
- **Achieved by**
  - Controls close to end-effector
  - Input means for motion commands
  - Emergency stop (red button)
  - Enabling device (dead man)
- **Typical applications**
  - Lift assist, load positioning

Hand guiding

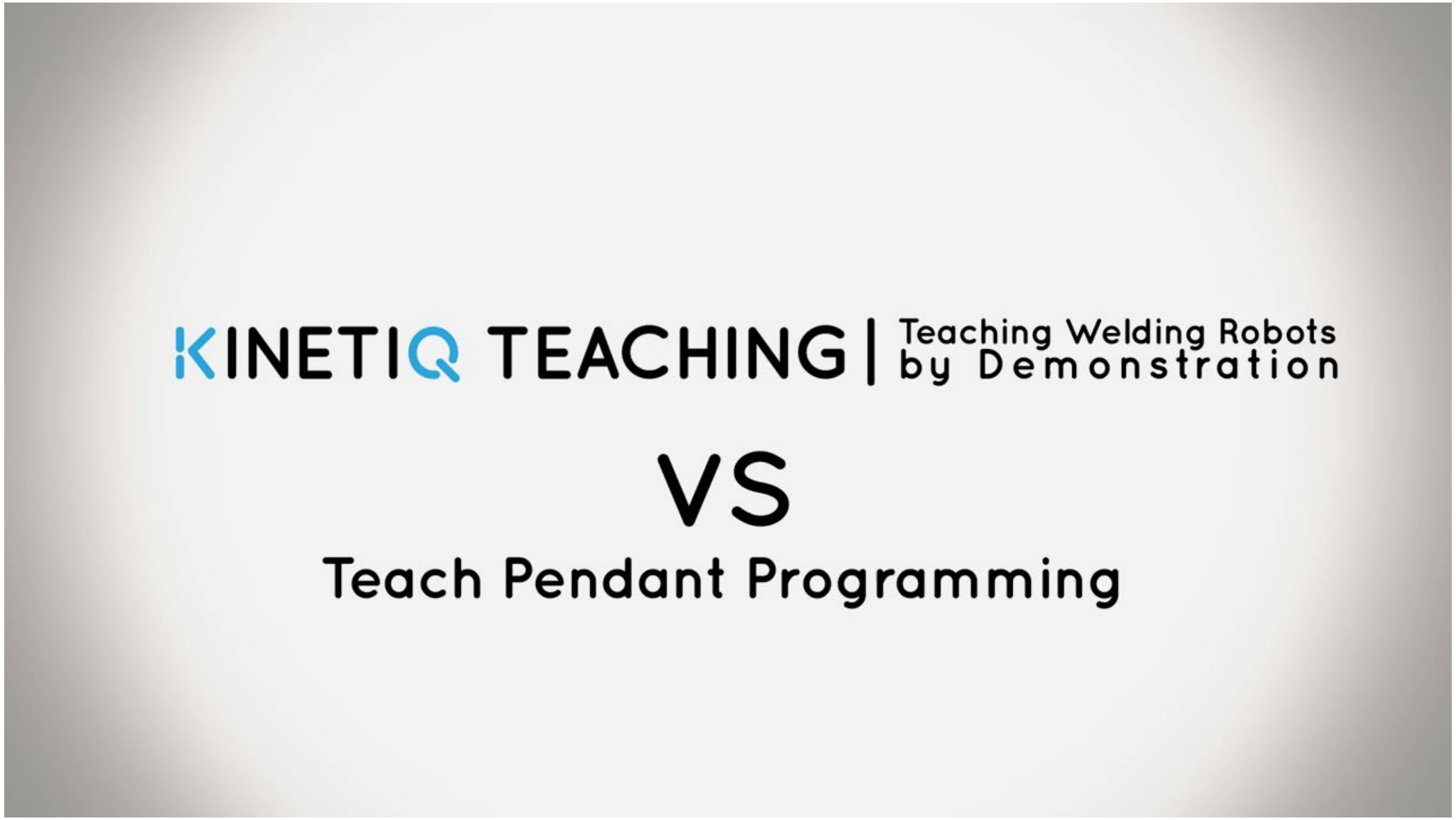
Hand guided robot:

- Potentially unsafe
- Requires expensive hardware (motors, force/torque sensor)
- Provides assistive torques (reduced inertia)
- Mid/low payload

Handling device:

- Inherently safe (passive device)
- Less expensive
- No assistive torque (no inertia reduction)
- High payload

Hand guidance for robot programming



Speed and separation monitoring

Source: ABB Corporate Research

- **Clauses in standards and TS**
  - ISO 10218-1, clause 5.10.4
  - ISO 10218-2, clause 5.11.5.4
  - ISO/TS 15066, clause 5.5.4
- **Risk reduction**
  - Maintain sufficient distance between worker and robot in collaborative workspace
- **Achieved by**
  - Supervision of distance, speed
  - Protective stop if minimum separation distance or speed limit is violated
- **Typical applications**
  - Working in common area on separate tasks

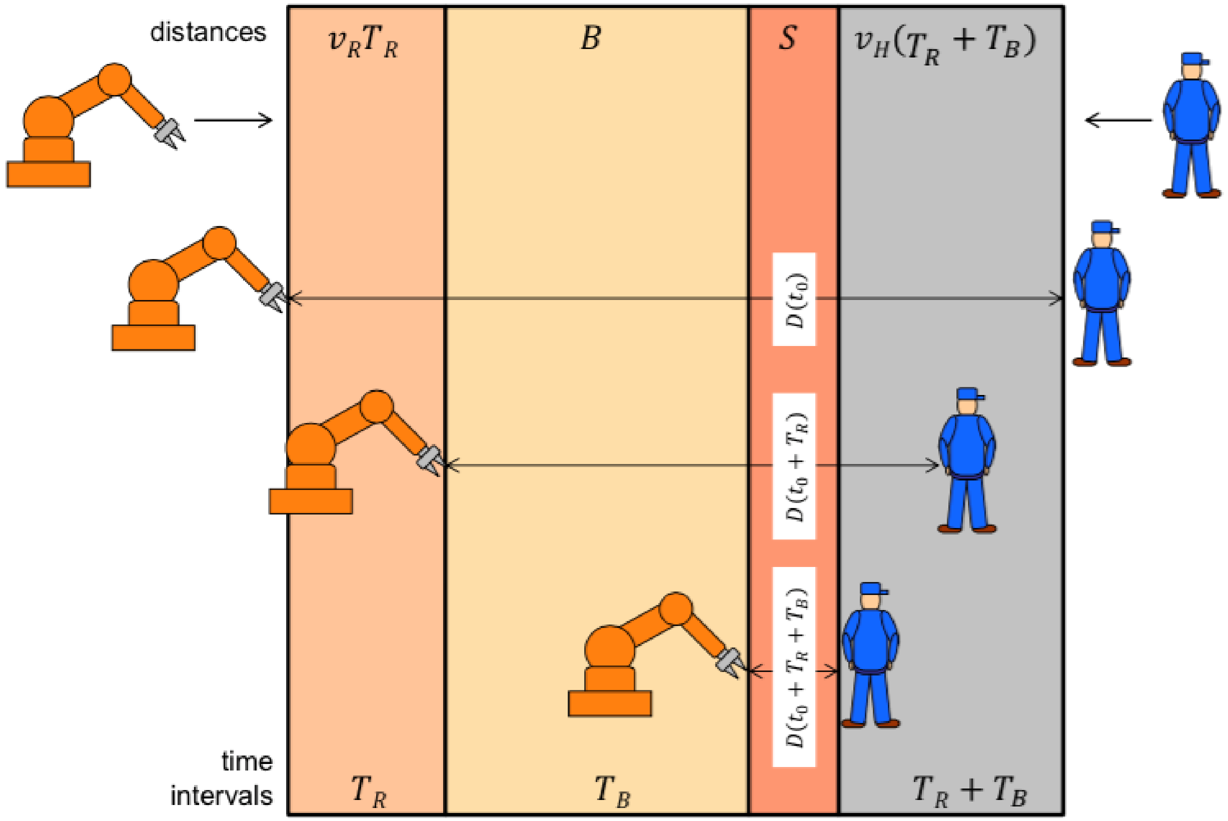
Speed and separation monitoring

- The closer the operator is, the slower the robot must move
- A **safety-rated device is needed** to monitor the distance of the operator from the robot

Speed and separation monitoring

Laser scanners measure the distance between the objects that fall into their sensing field

Speed and separation monitoring



Source: ABB Corporate Research

v_R = robot speed

v_H = human speed

T_R = robot controller reaction time

T_B = robot stopping time

S = minimum separation distance

$D(t_0)$ = separation distance at time t_0

$$D(t_0) - v_R(T_R + T_B) - v_H(T_R + T_B) \geq S$$

The distance has to be larger than the space that the robot and the human can cover plus a minimum distance

Speed and separation monitoring

$$D(t_0) - v_R(T_R + T_B) - v_H(T_R + T_B) \geq S$$

$$v_R \leq \frac{D(t_0) - S}{T_R + T_B} - v_H$$

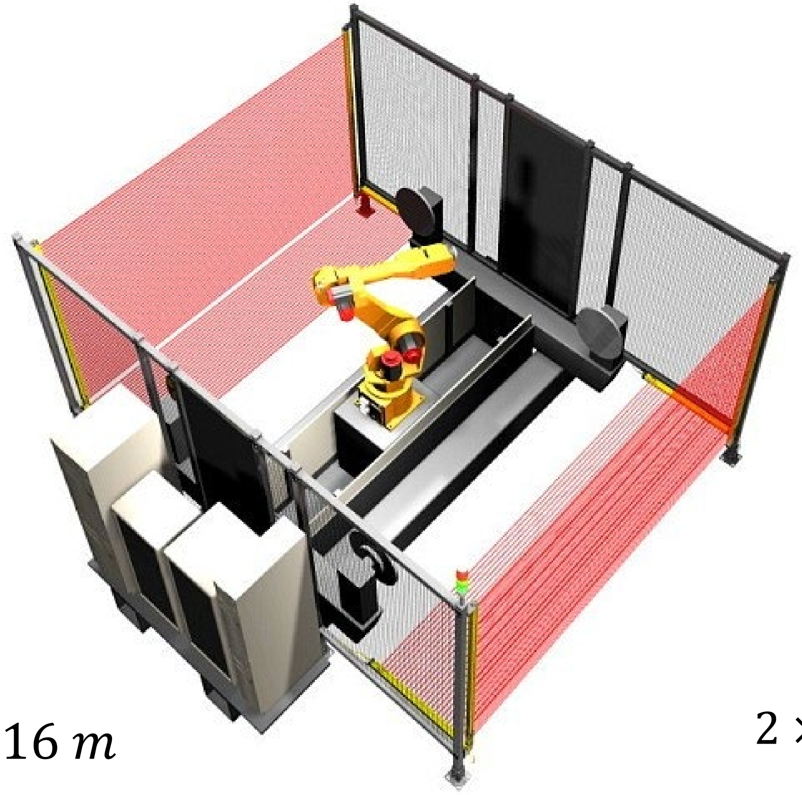
- If the **human speed** is not monitored, it can be assumed to be $v_H = 1.6\ m/s$ in the direction that reduces the separation distance the most
- The **robot speed** v_R can be either constant or variable
  - if the robot's speed v_R is not being monitored, the system design shall assume that v_R is the maximum speed of the robot
  - if the robot's speed is being monitored, the system design may use the current speed of the robot

Speed and separation monitoring: a conservative design

- v_H is in the order of 1.6 m/s (walking speed)
- T_R in the order of 10 ms (reaction time of the robot controller)
- T_B in the order of 1 s (braking time of the robot actuators)

$$D(t_0) \geq v_H(T_R + T_B) = 1.6 \times 1.01 = 1.616\, m$$

Distance to be kept for whatever robot speed



Assuming the reach of the robot to be of 1 m (3.14 m^2), the cell must be large at least

$$2 \times (1 + 1.616) = 5.232\, m\ (27\, m^2)$$

(almost 10x the workspace of the robot)

Speed and separation monitoring

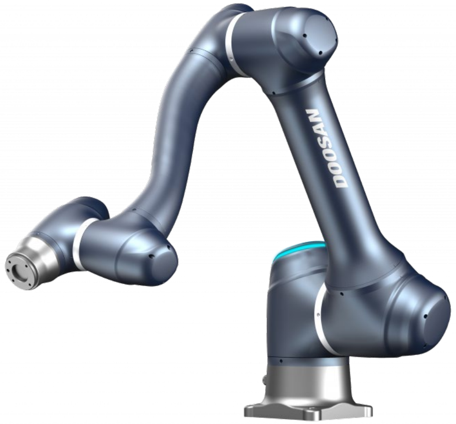
https://www.youtube.com/watch?v=Z7DgzHC9e9E

Power and force limiting

Source: ABB

Source: KUKA

Source: Universal Robots



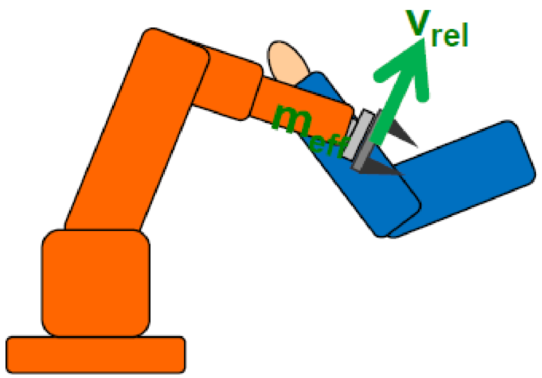
Source: Doosan

- **Clauses in standards and TS**
  - ISO 10218-1, clause 5.10.5
  - ISO 10218-2, clause 5.11.5.5
  - ISO/TS 15066, clause 5.5.5
- **Risk reduction**
  - Limiting mechanical loading of human-body parts by moving parts of robot, end-effector or work piece
- **Achieved by**
  - Low inertia, suitable geometry and material, sensory input, control functions, …
- **Typical applications**
  - Mixed environment, involving possibility of transient and/or quasi-static physical contact

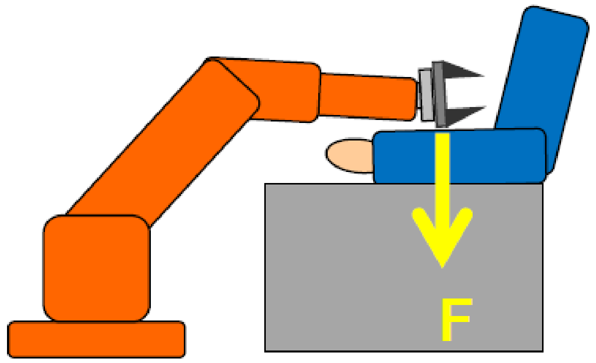
Source: ABB Corporate Research

Power and force limiting

Transient contact



Quasi-static contact



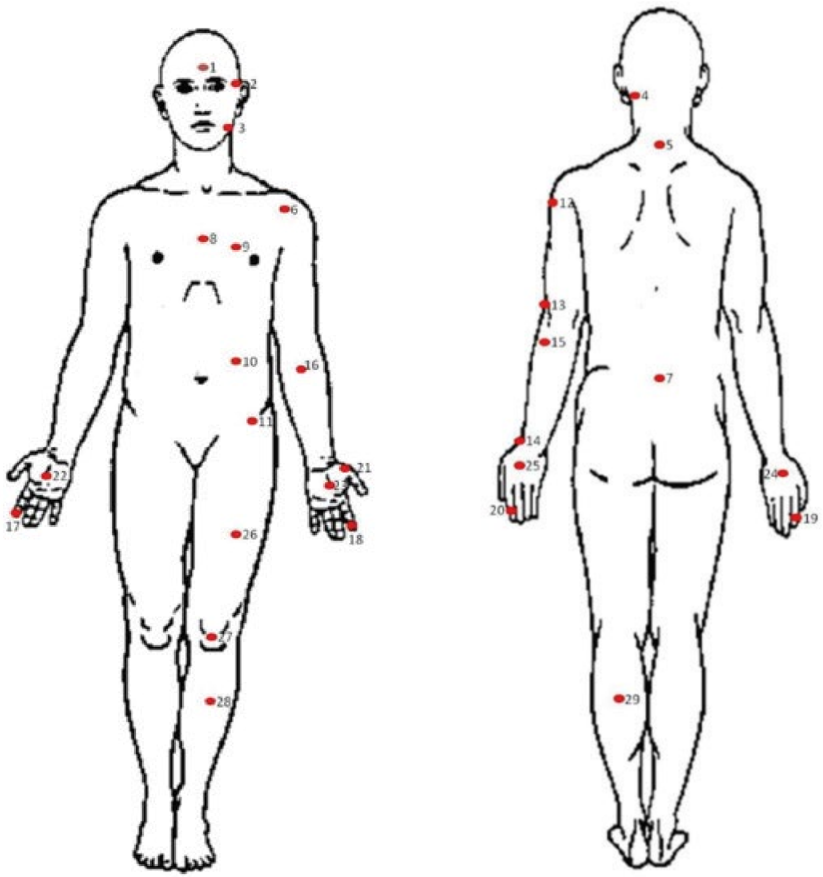
Source: ABB Corporate Research

The energy transferred during an impact is mainly kinetic:

$$\Delta T = \frac{1}{2} m v_R^2$$

This is why collaborative robots are lightweight and quite slow.

Biomechanical limits



Source: ABB Corporate Research

ISO/TS 15066, Annex A

- Establishes threshold limit values on the collaborative robot system, particularly on power and force limiting applications.
- Based on pain sensitivity thresholds
- Can be used to establish pressure and force limit values for various body areas using a body model.
- Speed limits can then be prescribed for a robot moving through a collaborative workspace.
- The speed limit values would maintain force and pressure values below the pain sensitivity threshold if contact with an operator and a robot were to occur.

Collaborative grippers

Source: ABB

- It is not just the robot that has to be collaborative
- The **grippers** as well need to be designed for safe human-robot collaboration

Robot as an element in the collaborative station

The robot is simply a component in a final collaborative robot system and is not in itself sufficient for a safe collaborative operation. The collaborative operation applications are dynamic and shall be determined by the **risk assessment** performed during the application system design.