Control of industrial robots

Collaborative robotics

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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.
Humans and robots collaborating at the same task
Protective fences are not needed
Particularly interesting for Small and Medium Enterprises (SMEs) thanks to 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
Why human-robot collaboration?

- High flexibility
  - Limited productivity
- High productivity
  - Limited flexibility
- High flexibility
  - High productivity

Source: A.M. Zanchettin
Collaborative assembly

Flexibility

Manual labor

Collaborative automation

+ robot

Hard automation

Productivity/Investment
Opportunities

Activities with low added value and easy/cheap to automate
Activities with high added value or difficult/costly to automate

Manufacturing activities have 60% of automation potential (McKinsey)
1960 - 2000
Industrial robots are separated from humans; they require significant investments and programming skills.

2000
The world cobot enters the dictionary:

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
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.

Cost breakdown of a robotic station

**Traditional robots**
- Engineering: 15%
- Programming/Testing: 25%
- Purchased parts: 35%
- Robot: 15%
- Assembly: 10%

**Collaborative robots**
- Engineering: 10%
- Purchased parts: 15%
- Programming/Testing: 15%
- Robot: 50%
- Assembly: 10%
Market of the cobots

Collaborative and traditional industrial robots

- Traditional Industrial Robots
- Collaborative Robots

<table>
<thead>
<tr>
<th>Year</th>
<th>Traditional</th>
<th>Collaborative</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>409,000</td>
<td>14,000</td>
</tr>
<tr>
<td>2017</td>
<td>389,000</td>
<td>11,000</td>
</tr>
</tbody>
</table>

Source: International Federation of Robotics
Market of the cobots

ABI Research, Marker report on collaborative robotics, 2015
From robots to cobots
From robots to cobots
From robots to cobots
From robots to cobots
Sensitive Eigenschaften des LBRiiwa verhindern Qualitätsmängel beim Fügeprozess
Sensitive features of LBRiiwa prevent quality defects during the assembly process
From robots to cobots
Safety

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

ISO

TS 15066

Safety of collaborative robots

ISO 10218

Robots and robotic devices – Safety requirements for industrial robots

ISO 13849

Safety of machinery – Safety-related parts of control systems

+ many others

Source: A.M. Zanchettin
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

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

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

Source: ABB Corporate Research
Safety-rated monitored stop

- **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

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.

Source: ABB Corporate Research
Hand guiding

- **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

Source: ABB Corporate Research
**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 guiding can be used for robot programming (lead-through programming)
Control of industrial robots – Collaborative robotics – Paolo Rocc

- **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

Source: ABB Corporate Research
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

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

Source: ABB Corporate Research

\(v_R\) = robot speed
\(v_H\) = human speed
\(T_R\) = controller reaction time
\(T_B\) = robot stopping time
\(B\) = robot stopping distance
\(S\) = min. separation distance
\(D(t)\) = sep. distance at time \(t\)
\(t_0\) = time at which to trigger stop
Speed and separation monitoring

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

- \( v_H \) 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)

The closer the operator is, the slower the robot must move.
Speed and separation monitoring

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

**A simple exercise**

A robot has a reaction time of 10 ms and a braking time of 1 second. Evaluate the minimum distance of a light curtain from the workspace of the robot.

$$D(t_0) \geq v_H(T_R + T_B) = 1.6 \times 1.01 = 1.616 \, \text{m}$$
Speed and separation monitoring

Link to the video: https://www.youtube.com/watch?v=Z7DgzHC9e9E
Power and force limiting

- **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
The energy transferred during an impact is mainly kinetic:

\[ \Delta T = \frac{1}{2} m v^2_R \]

This is why collaborative robots are lightweight and quite slow.
Biomechanical limits

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.

Source: ABB Corporate Research
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.
There are many examples of operations with poor ergonomics. A collaborative robot might support the operator as an autonomous positioner of the workpiece in order to increase the ergonomics of the workstation.
Cobots as assistive fellow co-workers

Through a vision system, the robot is able to track the position of the operator (based on his shoulders) and evaluate the best positioning of the workpiece that minimize the risk of musculoskeletal disorders.
Cobots as intelligent fellow co-workers

Through a vision system the robot is able to infer the intention of the human operator and decide the most convenient action to perform according to the collaborative task.
Collaborative operation

Link to the video: https://www.youtube.com/watch?v=P1p1-hejjaQ
Feedback to the operator
Prediction of activity patterns

The robot perceives the human and predicts when assistance is needed. In the meanwhile, it keeps doing its job. As a result, the robot is always ready to help, and productivity is maximized.

Link to the video: https://www.youtube.com/watch?v=yHK2vXf0mrk
Prediction of activity patterns

Cycle time is reduced by 20%
A collaborative assembly
Integration with mix-reality

Collaborative assembly with holographic cues

C. Messeri, A.M. Zanchettin, P. Rocco