Industrial Safety Requirements for Collaborative Robots and Applications

Safety Requirements for Collaborative Robots and Applications

- Safety Standards for Applications of Industrial Robots
  - ISO 10218-1, ISO 10218-2
  - Related standards and directives
- Safety Functions of Industrial Robot Controller
  - Review of basic safety-related functions
  - Supervision functions
- Present Standardization Projects
  - ISO/TS 15066 – Safety of collaborative robots
  - Biomechanical criteria
- Collaborative operation
Safety Standards for Applications of Industrial Robots
ISO 10218-1, ISO 10218-2

**ISO 10218-1**
- Robots and robotic devices — Safety requirements for industrial robots — Part 1: Robots
  - Scope
    - Industrial use
    - Controller
    - Manipulator
  - Main references
    - ISO 10218-2 – Robot systems and integration
- Common references
  - ISO 13849-1 / IEC 62061 – Safety-related parts of control systems
  - IEC 60204-1 – Electrical equipment (stopping fnc.)
  - ISO 12100 – Risk assessment
  - ISO 13850 – E-stop

**ISO 10218-2**
- Robots and robotic devices — Safety requirements for industrial robots — Part 2: Robot systems and integration
  - Scope
    - Robot (see Part 1)
    - Tooling
    - Work pieces
    - Periphery
    - Safeguarding
  - Main references
    - ISO 10218-1 – Robot
    - ISO 11161 – Integrated manufacturing systems
    - ISO 13854 – Minimum gaps to avoid crushing
    - ISO 13855 – Positioning of safeguards
    - ISO 13857 – Safety distances
    - ISO 14120 – Fixed and movable guards
Safety Standards for Applications of Industrial Robots
Related Standards and Directives

A-Level
- IEC 61508 – Functional Safety
- ISO 12100 – Risk Assessment

Example: European Union
- European Machinery Directive 2006/42/EC

B-Level
- EN ISO 13849-1:2008
- IEC 62061:2005

C-Level
- ISO 10218-2 – Robot system/cell
- ISO 10218-1 – Robot
- ISO 11161 – Integrated manufacturing systems
- Other C-level machinery standard
Safety Functions of Industrial Robot Controller
Review of Basic Safety-Related Functions

- E-stop
- Protective stop
  - Stop categories (cat. 0, cat. 1, cat. 2 as per IEC 60204-1)
- Operating modes
  - Automatic / manual / manual high-speed
- Pendant controls
  - Enabling
  - Start / restart
  - Hold-to-run
- Limit switches
- Muting functions
  - Enable / limits switches / ...
Safety Functions of Industrial Robot Controller

Supervision Functions

- Basic supervision of robot motion, i.e. motion executed corresponds to motion commanded
- Supervision of kinematic quantities
  - Position
    - TCPs, elbow, solid model of manipulator, tool
  - Speed
    - TCPs, elbow, ...
  - Acceleration, braking
- Possibility: Supervision of dynamic quantities, esp. for collaborative operation
  - Torques
  - Forces
- Possibility: Application-related / user-defined supervision functions
Present Standardization Activities
ISO/TS 15066 – Safety of Collaborative Robots

- Design of collaborative work space
- Design of collaborative operation
  - Minimum separation distance $S$ / maximum robot speed $K_R$
  - Static (worst case) or dynamic (continuously computed) limit values
  - Safety-rated sensing capabilities
  - Ergonomics
- Methods of collaborative working
  - Safety-rated monitored stop
  - Hand-guiding
  - Speed and separation monitoring
  - Power and force limiting (biomechanical criteria!)
- Changing between
  - Collaborative / non-collaborative
  - Different methods of collaboration
- Operator controls for different methods, applications
  - Question is subject of debate: What if a robot is purely collaborative? Must it fulfill all of ISO 10218-1, i.e. also have mode selector, auto / manual mode, etc.?
Safety Requirements for Collaborative Robots and Applications

- Short Introduction to Human-Robot Collaboration (HRC)
  - Evolution of Safety Concepts
  - Definition of Collaborative Operation
  - Types of Collaborative Operation
  - Examples of Collaborative Operation
- Collaborative Application Scenarios
  - ABB Dual-Arm Concept Robot
  - Other Relevant Robot Developments
- Present Challenges for Collaborative Small-Parts Assembly (SPA)
  - Safety
  - Ergonomics
  - Productivity
  - Application Design
  - Ease-of-Use
Short Introduction to HRC
Evolution of Safety Concepts

Conventional industrial robots

- Discrete safety → No HRC
- Safety controllers → Limited HRC

Collaborative industrial robots

- Harmless manipulators → Full HRC

Absolute separation of robot and human workspaces

Complete union of robot and human workspaces
Short Introduction to HRC
Definition of Collaborative Operation

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

- Degree of collaboration
  1. Once for setting up (e.g. lead-through teaching)
  2. Recurring isolated steps (e.g. manual gripper tending)
  3. Regularly or continuously (e.g. manual guidance)
# Safety Functions of Industrial Robot Controller

## Types of Collaborative Operation According to ISO 10218-1

<table>
<thead>
<tr>
<th>ISO 10218-1, clause</th>
<th>Type of collaborative operation</th>
<th>Main means of risk reduction</th>
<th>Pictogram (ISO 10218-2)</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>
<td><img src="image1.png" alt="Pictogram" /></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>
<td><img src="image2.png" alt="Pictogram" /></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>
<td><img src="image3.png" alt="Pictogram" /></td>
</tr>
<tr>
<td>5.10.5</td>
<td>Power and force limiting by inherent design or control (Example: <em>ABB Dual-Arm Concept Robot</em> collaborative assembly robot)</td>
<td>In contact events, robot can only impart limited static and dynamics forces</td>
<td><img src="image4.png" alt="Pictogram" /></td>
</tr>
</tbody>
</table>
# Safety Functions of Industrial Robot Controller

<table>
<thead>
<tr>
<th>Types of Collaborative Operation According to ISO 10218-1</th>
<th>Speed</th>
<th>Separation distance</th>
<th>Torques</th>
<th>Operator controls</th>
<th>Main risk reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety-rated monitored stop</td>
<td>Zero while operator in CWS*</td>
<td>Small or zero</td>
<td>Gravity + load compensation only</td>
<td>None while operator in CWS*</td>
<td>No motion in presence of operator</td>
</tr>
<tr>
<td>Hand guiding</td>
<td>Safety-rated monitored speed (PL d)</td>
<td>Small or zero</td>
<td>As by direct operator input</td>
<td>E-stop; Enabling device; Motion input</td>
<td>Motion only by direct operator input</td>
</tr>
<tr>
<td>Speed and separation monitoring</td>
<td>Safety-rated monitored speed (PL d)</td>
<td>Safety-rated monitored distance (PL d)</td>
<td>As required to execute application and maintain min. separ. distance</td>
<td>None while operator in CWS*</td>
<td>Contact between robot and operator prevented</td>
</tr>
<tr>
<td>Power and force limiting</td>
<td>Max. determined by RA* to limit impact forces</td>
<td>Small or zero</td>
<td>Max. determined by RA* to limit static forces</td>
<td>As required for application</td>
<td>By design or control, robot cannot impart excessive force</td>
</tr>
</tbody>
</table>

* CWS = Collaborative Work Space

* RA = Risk Assessment
Safety Functions of Industrial Robot Controller
Collaborative Operation (1)

**Safety-rated monitored stop**
(ISO 10218-1, 5.10.2, ISO/TS 15066)
- Reduce risk by ensuring 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)
- Application
  - Manual loading of end-effector with drives energized
  - Automatic resume of motion

**Hand guiding**
(ISO 10218-1, 5.10.3, ISO/TS 15066)
- Reduce risk by providing worker with direct control over robot motion at all times in collaborative workspace
- Achieved by (controls close to end-effector)
  - Emergency stop, enabling device
  - Safety-rated monitored speed
- Application
  - Ergonomic work places
  - Coordination of manual + partially automated steps
Safety Functions of Industrial Robot Controller
Collaborative Operation (2)

**Speed and separation monitoring**
(ISO 10218-1, 5.10.4, ISO/TS 15066)

- Reduce risk by maintaining sufficient distance between worker and robot in collaborative workspace
- Achieved by
  - distance supervision, speed supervision
  - protective stop if minimum separation distance or speed limit is violated
  - taking account of the braking distance in minimum separation distance
- Additional requirements on safety-rated periphery
  - for example, safety-rated camera systems

**Power and force limiting by inherent design or control**
(ISO 10218-1, 5.10.5, ISO/TS 15066)

- Reduce risk by 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, control functions, …
- Applications involving transient and/or quasi-static physical contact (SPA = small parts assembly)
### Safety Functions of Industrial Robot Controller
**Collaborative Operation (3)**

<table>
<thead>
<tr>
<th>Standard industrial robot</th>
<th>Special robots for collaborative operation (following ISO 10218-1, clause 5.10.5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injury severity S2 (irreversible)</td>
<td>Injury severity S1 (reversible)</td>
</tr>
<tr>
<td>Exposure F1 (rare)</td>
<td>Exposure F2 (frequent)</td>
</tr>
<tr>
<td>Avoidability P2 (low)</td>
<td>Avoidability P2 (low)</td>
</tr>
</tbody>
</table>

#### Required safety performance level:
- **Standard industrial robot**: PL d
- **Special robots**: PL c

**ABB-activities in standardization:**
- ISO/TC 184/SC 2/WG 3 “Robots and robotic devices - Industrial safety”
- DIN NA 060-30-02 AA “Roboter und Robotikgeräte”

**Present projects in standardization:**
- ISO/TS 15066 “Collaborative robots – safety”
- ISO/TS on manual loading stations
- Upcoming 2014: review of ISO 10218-1, -2
Biomechanical Criteria
## Biomechanical Limit Criteria

### Types of Contact Events

<table>
<thead>
<tr>
<th>ISO / TS 15066 – clause 5.4.4 “Power and force limiting”</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Free impact / transient contact</strong></td>
</tr>
<tr>
<td>- Contact event is “short” (&lt; 50 ms)</td>
</tr>
<tr>
<td>- Human body part can recoil</td>
</tr>
<tr>
<td>Accessible parameters in design or control</td>
</tr>
<tr>
<td>- Effective mass (robot pose, payload)</td>
</tr>
<tr>
<td>- Speed (relative)</td>
</tr>
<tr>
<td><strong>Pain threshold</strong></td>
</tr>
<tr>
<td><strong>Minor injury threshold</strong></td>
</tr>
<tr>
<td><strong>Highest loading level accepted in design</strong></td>
</tr>
</tbody>
</table>

| **Constrained contact / quasi-static contact**            |
| - Contact duration is “extended”                          |
| - Human body part cannot recoil, is trapped              |
| Accessible parameters in design or control               |
| - Force (joint torques, pose)                            |
| **Pain threshold**                                       |
| **Minor injury threshold**                               |
| **Highest loading level accepted in design**             |

- *v*<sub>rel</sub>*
- *m<sub>eff</sub>*
- *F*
Quasi-static contact – Severity measures

- Threshold for touch sensation
- Threshold for pain sensation
- Threshold for low-level injury
- Threshold for “S1” reversible injury
- Threshold for “S2” irreversible injury

Collaborative operation

How far in case of single failure?

Controllable quantity: joint torque

DGUV/IFA + U of Mainz measurements

DGUV/IFA literature survey

Pressures forces

Quasi-static contact – Severity measures

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- Threshold for pain sensation
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DGUV/IFA + U of Mainz measurements

DGUV/IFA literature survey

Pressures forces
Biomechanical Limit Criteria
Barrett Technologies

- Early work by W. Townsend et al. at Barrett Technologies
- Trade-off between moving mass and relative velocity

Figure 18 - Safety diagram for the robot design example.

Intrinsically Safer Robots, Prepared May 4, 1995, for the NASA Kennedy Space Center as the Final Report under NASA contract #NAS10-12178

http://www.smpp.northwestern.edu/savedLiterature/UlrichEtAllIntrinsicallySaferRobots.pdf

\[
\frac{E}{A} = \frac{mv^2}{2A} \\
\approx 2 \frac{f}{cm^2}
\]

assuming

\[
m = 4 \text{ kg} \\
v = \frac{m}{s} \\
A = 1 \text{ cm}^2
\]
Biomechanical Limit Criteria
Standford Univ

- Early work by Prof. Oussama Khatib et al. at Stanford University
- Transfer assessment criterion from automotive crashes
- Calculated curves
- Considers injury modes of brain collision with inside of skull, i.e. SDH (subdural hematoma), DAI (diffuse axonal injury), etc., but not superficial and less severe mechanisms

Figure 1. HIC as a function of effective inertia and interface stiffness.


\[ HIC = \left[ \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) dt \right]^{2.5} (t_2 - t_1) \]
Biomechanical Limit Criteria

DLR

- DLR, Sami Haddadin et al.
- Drop test impact measurements on pig skin samples
- Microscopic analysis for evidence of onset of contusion
- Correlate to human soft tissue due to known similarity of properties
- “safety curves” determined for specific impactor shapes and range of relative velocity and reflected inertia

\[
\frac{E}{A} = \frac{mv^2}{4\pi R^2} \approx 2 \frac{f}{cm^2}
\]

Biomechanical Limit Criteria
Univ of Ljubljana

- 0 ... 20 No pain
- 20 ... 40 Mild pain
- 40 ... 60 Moderate pain
- 60 ... 80 Horrible pain
- 80 ... 100 Unbearable pain

University of Ljubljana, B. Povse, M. Munich, et al.

Transient impact with line and plane shaped impactors

Pain rating on scale 0..100
Onset of pain around 20
\[ \rightarrow \text{onset of pain around 0.1 to 0.2 J/cm}^2 \]

Povse et al., Proceedings of the 2010 3rd IEEE RAS & EMBS
International Conference on Biomedical Robotics and Biomechatronics,
The University of Tokyo, Tokyo, Japan, September 26-29, 2010
Biomechanical Limit Criteria
Fraunhofer IFF

Fraunhofer IFF, Magdeburg, N. Elkmann et al.
Collision tests with live test subjects
Study has been ethically approved by the relevant commission
Investigation of the onset of injury as defined by the following:
  - Swelling
  - Bruise
  - Pain
Long-term goal:
  - Statistically significant compilation of verified onset of injury thresholds for all relevant body locations

R. Behrens, N. Elkmann et al., work in progress
Biomechanical Limit Criteria
DGUV/IFA Limit Values

- Values for quasi-static and transient forces derived from literature study

**Table 2: Limit values for the forces, pressures and body deformation constant according to the body regions of the body model**

<table>
<thead>
<tr>
<th>Body model – Main and individual regions with codification</th>
<th>Limit values of the required criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR</td>
<td>Regions</td>
</tr>
<tr>
<td>1.1</td>
<td>Skull/Forehead</td>
</tr>
<tr>
<td>1.2</td>
<td>Face</td>
</tr>
<tr>
<td>1.3</td>
<td>Neck (sides/neck)</td>
</tr>
<tr>
<td>1.4</td>
<td>Neck (front/larynx)</td>
</tr>
<tr>
<td>2.1</td>
<td>Back/Shoulders</td>
</tr>
<tr>
<td>2.2</td>
<td>Chest</td>
</tr>
<tr>
<td>2.3</td>
<td>Belly</td>
</tr>
<tr>
<td>2.4</td>
<td>Pelvis</td>
</tr>
<tr>
<td>2.5</td>
<td>Buttocks</td>
</tr>
<tr>
<td>3.1</td>
<td>Upper arm/Elbow joint</td>
</tr>
<tr>
<td>3.2</td>
<td>Lower arm/Hand joint</td>
</tr>
<tr>
<td>3.3</td>
<td>Hand/Finger</td>
</tr>
<tr>
<td>4.1</td>
<td>Thigh/Knee</td>
</tr>
<tr>
<td>4.2</td>
<td>Lower leg</td>
</tr>
<tr>
<td>4.3</td>
<td>Feet/Toes/Joint</td>
</tr>
</tbody>
</table>

http://publikationen.dguv.de/dguv/pdf/10002/bg_bgia_empf_u_001e.pdf
Biomechanical Limit Criteria
Univ Mainz – Preliminary Results

- University of Mainz, Prof. A. Muttray
- Experimental research
- Ethics committee approved
- Ongoing to determine pain sensation thresholds for 30 different locations on body for quasi-static loading

<table>
<thead>
<tr>
<th>Body model</th>
<th>Description</th>
<th>Measurement localization</th>
<th>N</th>
<th>Q1</th>
<th>Median</th>
<th>Q3</th>
<th>N</th>
<th>Q1</th>
<th>Median</th>
<th>Q3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid of forehead</td>
<td>1</td>
<td>36</td>
<td>36</td>
<td>46</td>
<td>62</td>
<td>36</td>
<td>92</td>
<td>114</td>
<td>134</td>
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<tr>
<td>Temple</td>
<td>2</td>
<td>36</td>
<td>36</td>
<td>24</td>
<td>27</td>
<td>35</td>
<td>50</td>
<td>65</td>
<td>154</td>
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<tr>
<td>Musculary muscle</td>
<td>3</td>
<td>36</td>
<td>35</td>
<td>18</td>
<td>21</td>
<td>32</td>
<td>48</td>
<td>100</td>
<td>197</td>
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<td>Neck muscle</td>
<td>4</td>
<td>36</td>
<td>35</td>
<td>18</td>
<td>25</td>
<td>33</td>
<td>51</td>
<td>108</td>
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<td>7th neck muscle</td>
<td>5</td>
<td>36</td>
<td>36</td>
<td>27</td>
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<td>103</td>
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<td>Shoulder joint</td>
<td>6</td>
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<td>36</td>
<td>19</td>
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<td>38</td>
<td>87</td>
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<td>5th lumbar vertebra</td>
<td>7</td>
<td>36</td>
<td>36</td>
<td>50</td>
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<td>Radius bone</td>
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<td>Arm nerve</td>
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<td>Forefinger pad</td>
<td>17</td>
<td>36</td>
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<td>Forefinger pad d</td>
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<td>36</td>
<td>36</td>
<td>50</td>
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<td>80</td>
<td>124</td>
<td>159</td>
<td>215</td>
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<td>Forefinger end joint</td>
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<td>36</td>
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<td>Forefinger end joint</td>
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<td>36</td>
<td>46</td>
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<td>Thescarial</td>
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<td>116</td>
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<tr>
<td>Back of the hand</td>
<td>22</td>
<td>36</td>
<td>36</td>
<td>49</td>
<td>56</td>
<td>81</td>
<td>126</td>
<td>171</td>
<td>214</td>
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<tr>
<td>Back of the hand d</td>
<td>23</td>
<td>36</td>
<td>36</td>
<td>45</td>
<td>56</td>
<td>72</td>
<td>145</td>
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<td>215</td>
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<tr>
<td>Palm of the hand</td>
<td>24</td>
<td>36</td>
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<td>Palm of the hand d</td>
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<td>119</td>
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<td>214</td>
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<tr>
<td>Thigh muscle</td>
<td>26</td>
<td>36</td>
<td>36</td>
<td>44</td>
<td>57</td>
<td>72</td>
<td>36</td>
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<tr>
<td>Kneecap</td>
<td>27</td>
<td>36</td>
<td>36</td>
<td>47</td>
<td>65</td>
<td>82</td>
<td>135</td>
<td>194</td>
<td>235</td>
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<tr>
<td>Shin splint</td>
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<td>36</td>
<td>36</td>
<td>39</td>
<td>55</td>
<td>67</td>
<td>131</td>
<td>168</td>
<td>236</td>
<td></td>
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<tr>
<td>Calf muscle</td>
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<td>36</td>
<td>36</td>
<td>43</td>
<td>53</td>
<td>75</td>
<td>107</td>
<td>128</td>
<td>195</td>
<td></td>
</tr>
</tbody>
</table>

A. Muttray et al.
Biomechanical Limit Criteria
Additional Work

- Y. Yamada et al. – Univ. of Nagoya

Fig. 2 Measurement points for evaluating human pain tolerance

Fig. 4 Experimental results of static pain tolerance

Probe diameter approx. 10 – 15 mm

Y. Yamada et al., IEEE/ASME TRANSACTIONS ON MECHATRONICS, VOL. 2, NO. 4, p. 230 (1997)
Examples of Collaborative Robots for Power and Force Limiting

→ ABB Dual-Arm Concept Robot (DACR) a.k.a. “FRIDA”
Collaborative Application Scenarios
ABB Dual-Arm Concept Robot

- Harmless robotic co-worker for industrial assembly
- Human-like arms and body with integrated IRC5 controller
- Agile motion based on industry-leading ABB robot technology
- Padded dual arms safely ensure productivity and flexibility
- Complements human labor for scalable automation
- Light-weight and easy to mount for fast deployment
- Multi-purpose lightweight gripper for flexible material handling
Collaborative Application Scenarios Protection Levels

<table>
<thead>
<tr>
<th>Measures for risk reduction and ergonomics improvement</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
<th>Level 5</th>
<th>Level 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robot system – mechanical hazards</td>
<td>Low payload and low robot inertia</td>
<td>Injury-avoiding mechanical design and soft padding</td>
<td>Power and speed limitation</td>
<td>Software-based collision detection, manual back-drivability</td>
<td>Personal protective equipment</td>
<td>Perception-based real-time adjustment to environment</td>
</tr>
</tbody>
</table>

ABB collaborative industrial robot concept

Other, application-specific

Impact

Clamping
Collaborative Application Scenarios
Other Relevant Robot Developments

Kawada Industries “NextAge”
Industrial assembly

Kinova Robotics “JACO”
Assistive robot for upper body disabled

Rethink Robotics “Baxter”
Industrial assembly

Universal Robots “UR5” x 2
Industrial applications

Kuka “LWR iiwa”
Academic research, industrial assembly

Meka Robotics “Mi”

SRI International “Taurus”
Bomb disposal
Collaborative Application Scenarios
Volkswagen Salzgitter – Glow Plug Assembly
Collaborative Application Scenarios
BMW Spartanburg – Door Sealing
Ergonomics
Productivity
Application Design
Ease-of-Use
Present Challenges for Collaborative SPA
Ergonomics

Worker acceptance of collaborative robots in production
First experimental determination of stress indicators as function of motion characteristics

- All stress indicators show lowest levels for human-like motion
  - ECG – Electrocardiography
  - SCR – Skin conductivity, resistivity
  - EMG – Electromyography

Reference: P. Rocco, A. Zanchettin, DEI, Politecnico di Milano; work in EU-FP7 Project ROSETTA
Present Challenges for Collaborative SPA Productivity
Present Challenges for Collaborative SPA Productivity

Normal operation

Elbow down

Speed reduction

Standstill
Present Challenges for Collaborative SPA Application Design

- Methodology is research topic
  - Annotated assembly graph
  - Assignment of assembly steps to robots, workers
  - Layout of work cell, assembly line
  - …
Present Challenges for Collaborative SPA
Ease-of-Use

- Criteria and approaches are research topics
  - Alternatives to textual programming
  - Input modality must be intuitive and robust
  - Intelligent default values for configuration parameters
  - Selective hiding / exposing of complexity adapted to user group
  - ...
Open Discussion
What are your needs?

- Type of application
  - Assembly, pick-and-place, measurement & testing, …
  - Criteria for suitability of HRC
- Degree of automation
  - Distribution of tasks among robots / operators
  - Types of interfaces, handover, conveying, …
  - Frequency of changeover, typical lot sizes
- Keys for acceptance of partial automation / mixed human-robot environment
  - Ease-of-use
  - Application design
  - Ergonomics
  - Distribution of roles and responsibilities
  - …
Economic Motivations
Economic Background and Motivation

- **Societal Trend**
  - Individuality and differentiation with respect to peers

- **Resulting Market Trend**
  - Increasing no. of product variants
  - Decreasing product lifetime
  - Away from “mass production” towards “mass customization”

- **Challenge to Industrial Production**
  - Efficient handling of large range of variants and short model lifetimes
  - Common solution today: Mostly manual production in Asia
Moving Humans + Robots Closer Together

Productivity (1)

- Number of variants: high
- Lot size: high
- Flexibility: low
- Productivity: high

- Automatic assembly
- Hybrid assembly
- Manual assembly

(adapted from B. Lotter)
Moving Humans + Robots Closer Together
Productivity (2)

Breakeven points
V₁: HRC = manual
V₂: robotic = manual
V₃: robotic = HRC
V₄: fixed = manual
V₅: fixed = robotic

- Manual assembly
- Human-robot collaboration
- Robotic automation
- Fixed automation

Unit cost $c_{[\text{€/unit}]}$

Production volume $V_{[\text{units}]}$
Moving Humans + Robots Closer Together
HRC for scalable degree of automation

- Worker Strengths
  - Cognition
  - Reaction
  - Adaptation
  - Improvisation
- Worker Limitations
  - Modest speed
  - Modest force
  - Weak repeatability
  - Inconsistent quality

- Robot Strengths
  - High speed
  - High force
  - Repeatability
  - Consistent quality
- Robot Limitations
  - No cognitive capability
  - No autonomous adaptation
  - Modest working envelope

- Synergy: HRC
  - Automation of applications requiring high flexibility (variants ↑, lot sizes ↓)
  - New ergonomics functionality
  - New applications in which robots previously have not been used

- Optimum degree of automation < 100%
  - Raising degree of automation becomes increasingly expensive, esp. on changeover
  - Manual manufacturing becomes increasingly competitive for remaining fraction of production task
Minimal required safety

Minimal required productivity

Range for HRC Application

No HRC Application Possible

Safety $\propto \frac{1}{\text{Speed etc.}}$

Productivity $\propto \text{Speed etc.}$

$S_k = \text{example dependence of safety on speed for application no. } k$

$P_k = \text{example dependence of productivity on speed for application no. } k$
Power and productivity for a better world™