Industrial Safety Requirements for Collaborative Robots and Applications


Björn Matthias, ABB Corporate Research, 2014-03-10
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

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

Example: European Union
European Machinery Directive 2006/42/EC
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: absolute separation of robot and human workspaces
  - Discrete safety → No HRC
  - Safety controllers → Limited HRC
- Collaborative industrial robots: complete union of robot and human workspaces
  - Harmless manipulators → Full HRC
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)
<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

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

<table>
<thead>
<tr>
<th></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><strong>Standard industrial robot</strong></th>
<th><strong>Special robots for collaborative operation</strong> (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:** PL d |
| **Required safety performance level:** 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
ISO / TS 15066 – clause 5.4.4 “Power and force limiting”

<table>
<thead>
<tr>
<th>Types of Contact Events</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free impact / transient contact</td>
<td>Contact event is “short” (&lt; 50 ms)</td>
</tr>
<tr>
<td></td>
<td>Human body part can recoil</td>
</tr>
<tr>
<td>Accessible parameters in design or control</td>
<td>Effective mass (robot pose, payload)</td>
</tr>
<tr>
<td></td>
<td>Speed (relative)</td>
</tr>
<tr>
<td>Pain threshold</td>
<td></td>
</tr>
<tr>
<td>Minor injury threshold</td>
<td></td>
</tr>
<tr>
<td>Highest loading level accepted in design</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Highest loading level accepted in risk assessment in case of single failure</td>
</tr>
<tr>
<td>Constrained contact / quasi-static contact</td>
<td>Contact duration is “extended”</td>
</tr>
<tr>
<td></td>
<td>Human body part cannot recoil, is trapped</td>
</tr>
<tr>
<td>Accessible parameters in design or control</td>
<td>Force (joint torques, pose)</td>
</tr>
<tr>
<td>Pain threshold</td>
<td></td>
</tr>
<tr>
<td>Minor injury threshold</td>
<td></td>
</tr>
<tr>
<td>Highest loading level accepted in design</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Highest loading level accepted in risk assessment in case of single failure</td>
</tr>
</tbody>
</table>
Quasi-static contact – Severity measures

Collaborative operation

How far in case of single failure?

Threshold for touch sensation

Threshold for pain sensation

Threshold for low-level injury

Threshold for “S1” reversible injury

Threshold for “S2” irreversible injury

Controllable quantity: joint torque

DGUV/IFA literature survey

DGUV/IFA + U of Mainz measurements

Pressure forces
Biomechanical Limit Criteria
Barrett Technologies

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

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

assuming
\[ m = 4 \text{ kg} \]
\[ v = 1 \text{ m/s} \]
\[ A = 1 \text{ cm}^2 \]

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/UlrichEtAlIntrinsicallySaferRobots.pdf
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

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

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
- \( \rightarrow \) 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**

<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.</td>
<td>Head with neck</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.</td>
<td>Trunk</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.</td>
<td>Upper extremities</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.</td>
<td>Lower extremities</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>

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

[http://publikationen.dguv.de/dguv/pdf/10002/bg_bgia_empf_u_001e.pdf](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

### Measurement localization

<table>
<thead>
<tr>
<th>Body model</th>
<th>Description</th>
<th>Force [N]</th>
<th>Peak pressure [N/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Q1 Median</td>
<td>Q3</td>
</tr>
<tr>
<td>1</td>
<td>Mid of forehead</td>
<td>36 36</td>
<td>45 46</td>
</tr>
<tr>
<td>2</td>
<td>Temple</td>
<td>36 17</td>
<td>34 44</td>
</tr>
<tr>
<td>3</td>
<td>Musculatory muscle</td>
<td>36 13</td>
<td>19 21</td>
</tr>
<tr>
<td>4</td>
<td>Neck muscle</td>
<td>36 71</td>
<td>18 25</td>
</tr>
<tr>
<td>5</td>
<td>7th neck muscle</td>
<td>36 27</td>
<td>39 48</td>
</tr>
<tr>
<td>6</td>
<td>Shoulder joint</td>
<td>36 17</td>
<td>32 47</td>
</tr>
<tr>
<td>7</td>
<td>5th lumbar vertebra</td>
<td>36 50 64 72</td>
<td>76 109 109</td>
</tr>
<tr>
<td>8</td>
<td>Sternum</td>
<td>36 31</td>
<td>42 53</td>
</tr>
<tr>
<td>9</td>
<td>Pectoral muscle</td>
<td>36 25</td>
<td>30 46</td>
</tr>
<tr>
<td>10</td>
<td>Abdominal muscle</td>
<td>36 21</td>
<td>29 36</td>
</tr>
<tr>
<td>11</td>
<td>Pelvic bone</td>
<td>36 42</td>
<td>42 54</td>
</tr>
<tr>
<td>12</td>
<td>Deltoid muscle</td>
<td>36 33</td>
<td>45 57</td>
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<tr>
<td>13</td>
<td>Humerus</td>
<td>36 38</td>
<td>44 57</td>
</tr>
<tr>
<td>14</td>
<td>Radius bone</td>
<td>36 32</td>
<td>36 50</td>
</tr>
<tr>
<td>15</td>
<td>Forearm muscle</td>
<td>36 29</td>
<td>34 42</td>
</tr>
<tr>
<td>16</td>
<td>Arm nerve</td>
<td>36 44</td>
<td>60 55</td>
</tr>
<tr>
<td>17</td>
<td>Forefinger pad n</td>
<td>36 51</td>
<td>63 83</td>
</tr>
<tr>
<td>18</td>
<td>Forefinger pad d</td>
<td>36 50</td>
<td>61 80</td>
</tr>
<tr>
<td>19</td>
<td>Forefinger end joint n</td>
<td>36 36</td>
<td>47 67</td>
</tr>
<tr>
<td>20</td>
<td>Forefinger end joint d</td>
<td>36 36</td>
<td>46 61</td>
</tr>
<tr>
<td>21</td>
<td>Thigh</td>
<td>36 46</td>
<td>55 72</td>
</tr>
<tr>
<td>22</td>
<td>Back of the hand</td>
<td>36 49</td>
<td>56 81</td>
</tr>
<tr>
<td>23</td>
<td>Back of the hand d</td>
<td>36 45</td>
<td>56 72</td>
</tr>
<tr>
<td>24</td>
<td>Palm of the hand</td>
<td>36 45</td>
<td>48 56</td>
</tr>
<tr>
<td>25</td>
<td>Palm of the hand d</td>
<td>36 45</td>
<td>46 56</td>
</tr>
<tr>
<td>26</td>
<td>Thigh muscle</td>
<td>36 44</td>
<td>57 72</td>
</tr>
<tr>
<td>27</td>
<td>Knee cap</td>
<td>36 47</td>
<td>65 82</td>
</tr>
<tr>
<td>28</td>
<td>Shin splint</td>
<td>36 39</td>
<td>55 67</td>
</tr>
<tr>
<td>29</td>
<td>Calf muscle</td>
<td>36 43</td>
<td>63 75</td>
</tr>
</tbody>
</table>

A. Muttray et al.
Biomechanical Limit Criteria

Additional Work

- Y. Yamada et al. – Univ. of Nagoya

Probe diameter approx. 10 – 15 mm

Fig. 2 Measurement points for evaluating human pain tolerance

Fig. 4 Experimental results of static pain tolerance

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>ABB collaborative industrial robot concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 6</td>
<td>Perception-based real-time adjustment to environment</td>
</tr>
<tr>
<td>Level 5</td>
<td>Personal protective equipment</td>
</tr>
<tr>
<td>Level 4</td>
<td>Software-based collision detection, manual back-drivability</td>
</tr>
<tr>
<td>Level 3</td>
<td>Power and speed limitation</td>
</tr>
<tr>
<td>Level 2</td>
<td>Injury-avoiding mechanical design and soft padding</td>
</tr>
<tr>
<td>Level 1</td>
<td>Low payload and low robot inertia</td>
</tr>
</tbody>
</table>

Robot system – mechanical hazards

Other, application-specific clamping

Impact

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Collaborative Application Scenarios

Other Relevant Robot Developments

Kawada Industries "NextAge"

Kuka "LWR iiwa"

Kinova Robotics "JACO"

Rethink Robotics "Baxter"

Meka Robotics "Mi"

SRI International "Taurus"

Universal Robots "UR5" x 2

Assistive robot for upper body disabled

Academic research, industrial assembly

Bomb disposal

Industrial applications

Industrial assembly
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

Human-like motion

Human-like elbow pattern
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
  - ...

ABB
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)
Moving Humans + Robots Closer Together

Productivity (2)

Breakeven points

- $V_1$: HRC = manual
- $V_2$: robotic = manual
- $V_3$: robotic = HRC
- $V_4$: fixed = manual
- $V_5$: fixed = robotic

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

Unit cost $c$ [€/unit]

Production volume $V$ [units]
Moving Humans + Robots Closer Together
HRC for scalable degree of automation

- **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

- **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
Minimal required safety

Minimal required productivity

Range for HRC Application

No HRC Application Possible

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

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

$S_k =$ example dependence of safety on speed for application no. $k$

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