New safety standards for collaborative robots, ABB YuMi® dual-arm robot

Workshop IROS 2015 – Robotic co-workers – methods, challenges and industrial test cases
Collaborative Robots
Status of Standardization – Example Robot: YuMi®

- Introduction
- Standardization
  - Overview of relevant standards
  - Types of collaborative operation
  - ISO/TS 15066 – status of work
  - Risk mitigation in collaborative assembly
- YuMi®
  - Collaborative Automation
  - Collaboration & Ergonomics
  - Assembly Processes
  - Material Flow
  - Application Examples
- Open questions
- Summary and outlook
Trend towards individualization
Driver for Human-Machine Collaboration

(adapted from B. Lotter)
Safety and Human-Robot Collaboration
Relevant Standards and Directives

Type C Standards
- ISO 10218-2 – Robot system/cell
- ISO 10218-1 – Robot

ISO/TS 15066 – Collaborative Robots

Type B Standards
- ISO 11161 – Integrated manufacturing systems
- EN ISO 13849-1:2008
- IEC 62061:2012

Type A Standards
- IEC 61508 – Functional Safety
- ISO 12100 – Risk Assessment

Laws + Directives
- Example EU: European Machinery Directive 2006/42/EC
### Types of Collaborative Operation

According to ISO 10218, ISO/TS 15066

<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>
Short Introduction to HRC
Examples of 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)

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
Short Introduction to HRC
Examples of 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, sensory input, control functions, …
- Applications involving transient and/or quasi-static physical contact
ISO/TS 15066 – Present Status

ISO Project Overview

- Motivation and Purpose
  - End users waiting for standards document before willing to implement applications
  - Complex nature of protection schemes for collaborative applications
  - Meet the developing interest in collaborative robots with specific guidance

- Objective
  - Generate a TS (technical specification) document, valid for 3 years
  - After 3 years, review options
    - Confirm for 3 more years (if still deemed unsuitable for a standard)
    - Integrated into ISO 10218-2 (this is the preferred outcome)
    - Discard (if it turns out to be without practical relevance)

- Responsible international working group
  - ISO / TC184 (Automation systems) / SC2 (Robots and robotic devices) / WG3 (Industrial safety)
  - Convenor: Pat Davison, Robotic Industries Association (USA)

- Remaining work before first publication
  - Review and process remaining technical and editorial comments from WG3 members
ISO/TS 15066 – Present Status

ISO Project Timeline

- Concurrent research work on biomechanical criteria at:
  - DGUV/IFA (formerly BGIA)
  - University of Mainz, Occupational Medicine
  - Fraunhofer IFF, Magdeburg

- Project start: 2012
- Project end: 2015-12-05
- Recent meeting schedule
  - SC 2/WG 3 40th Meeting: 2015 June 15-17, at Daimler, Sindelfingen, Germany
  - TC 184/SC 2 22nd Plenary Meeting: 2015 June 18-19, at BGHM, Stuttgart, Germany
  - SC 2/WG 3 41st Meeting: 2015 December 7-9, in Yokohama, Japan
- First publication of ISO/TS 15066: 2015-12-05
Biomechanical Limit Criteria

ISO / TS 15066 – clause 5.5.4 “Power and force limiting”

<table>
<thead>
<tr>
<th>Description</th>
<th>Transient Contact</th>
<th>Quasi-Static Contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Contact event is “short” (&lt; 50 ms)</td>
<td>Contact duration is “extended”</td>
</tr>
<tr>
<td></td>
<td>Human body part can usually recoil</td>
<td>Human body part cannot recoil, is trapped</td>
</tr>
<tr>
<td>Limit Criteria</td>
<td>Peak forces, pressures, stresses</td>
<td>Peak forces, pressures, stresses</td>
</tr>
<tr>
<td></td>
<td>Energy transfer, power density</td>
<td></td>
</tr>
<tr>
<td>Accessible in Design or Control</td>
<td>Effective mass (robot pose, payload)</td>
<td>Force (joint torques, pose)</td>
</tr>
<tr>
<td></td>
<td>Speed (relative)</td>
<td>Contact area, duration</td>
</tr>
<tr>
<td></td>
<td>Contact area, duration</td>
<td></td>
</tr>
</tbody>
</table>

![Diagram](image)
General approach –
effective inelastic 2-body collision

- $\mu = \text{reduced mass of 2-body system of robot and human body section}$
- $v_{rel} = \text{relative speed between robot and human body section}$
- $C_R = \text{coefficient of restitution}$
- $k = \text{effective spring constant of body area (here assumed constant)}$
- $x_1 = \text{maximum compression of tissue in area of contact}$
- $A_{avg} = \text{average contact area during contact event}$
- $F_{lim}, p_{lim} = \text{force, pressure limit values for specific body region}$

**Kinetic energy transfer:**

$$\Delta W = \frac{1}{2} \mu v_{rel}^2 (1 - C_R^2)$$

**Worst-case assumption:**

$$C_R = 0 \Rightarrow \Delta W = \frac{1}{2} \mu v_{rel}^2$$

**Energy stored in “spring”:**

$$\Delta W = \frac{1}{2} k x_1^2 = \frac{F^2}{2k}$$

**Fully deposit kinetic energy into tissue as modeled by spring:**

$$\frac{F^2}{2k} = \frac{1}{2} \mu v_{rel}^2 \Rightarrow v_{rel} = \frac{F}{\sqrt{\mu k}} = \frac{pA}{\sqrt{\mu k}} \Rightarrow v_{rel} < F_{lim}$$

$$\mu = \left[ \frac{1}{m_R} + \frac{1}{m_H} \right]^{-1}$$

$$\frac{F_{lim}}{\sqrt{\mu k}} \approx \frac{p_{lim} A_{avg}}{\sqrt{\mu k}}$$
Effective mass of robot (1)
Proper formulation from complete equation of motion of robot

Equation of motion for stiff robot

\[ M(q)\ddot{q} + C(q, \dot{q})\dot{q} + g(q) = \tau + \tau_c \]

- \( q \in \mathbb{R}^n \): vector of \( n \) joint angles
- \( M \in \mathbb{R}^{n\times n} \): mass/inertia matrix
- \( C \in \mathbb{R}^{n\times n} \): centripetal and Coriolis matrix
- \( g \in \mathbb{R}^n \): gravity vector
- \( \tau \in \mathbb{R}^n \): joint motor torque vector
- \( \tau_c \in \mathbb{R}^n \): external contact torque vector

Kinetic energy

\[ T = \frac{1}{2} \dot{q}^T M(q) \dot{q} \]

Jacobian matrix \( J(q) \) such that

\[ \dot{x} = J(q) \dot{q} \]

Effective mass in direction of unit vector \( u \) :

\[ m_u = [u^T \Lambda_t^{-1}(q) u]^{-1} \]

where \( \Lambda(q) = \left( J(q) \left( M(q) \right)^{-1} J^T(q) \right)^{-1} \)

Translational and rotational parts

\[ J(q) = \begin{bmatrix} J_t(q) \\ J_r(q) \end{bmatrix} \]
Effective mass of robot (2)
Approximate formulation: Lumped parameter model

- Effective moving mass at contact location (reflected inertia) – \( m_R \)
- Speed of contact location – \( \dot{v}_R \)
- Material properties of contact location
  - E.g. padding
- Compliance of kinematic chain
  - Can reduce effective mass

\[
\vec{p}_R = \sum_i m_i \dot{v}_i \quad \quad m_R = \frac{\vec{p}_R \cdot \dot{v}_R}{v_R^2}
\]

Example for stiff 3 DOF robot
# ISO/TS 15066 – Present Status

## Body Model

**Table A.1 — Body Model Descriptions**

<table>
<thead>
<tr>
<th>Body Region</th>
<th>Specific Body Area</th>
<th>Front/Rear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skull and forehead</td>
<td>1 Middle of forehead</td>
<td>Front</td>
</tr>
<tr>
<td></td>
<td>2 Temple</td>
<td>Front</td>
</tr>
<tr>
<td>Face</td>
<td>3 Masticatory muscle</td>
<td>Front</td>
</tr>
<tr>
<td>Neck</td>
<td>4 Neck muscle</td>
<td>Rear</td>
</tr>
<tr>
<td>Back and shoulders</td>
<td>5 Seventh neck vertebra</td>
<td>Rear</td>
</tr>
<tr>
<td></td>
<td>6 Shoulder joint</td>
<td>Front</td>
</tr>
<tr>
<td></td>
<td>7 Fifth lumbar vertebra</td>
<td>Rear</td>
</tr>
<tr>
<td>Chest</td>
<td>8 Sternum</td>
<td>Front</td>
</tr>
<tr>
<td></td>
<td>9 Pectoral muscle</td>
<td>Front</td>
</tr>
<tr>
<td>Abdomen</td>
<td>10 Abdominal muscle</td>
<td>Front</td>
</tr>
<tr>
<td>Pelvis</td>
<td>11 Pelvic bone</td>
<td>Front</td>
</tr>
<tr>
<td>Upper arms and elbow joints</td>
<td>12 Deltoid muscle</td>
<td>Rear</td>
</tr>
<tr>
<td></td>
<td>13 Humerus</td>
<td>Rear</td>
</tr>
<tr>
<td></td>
<td>16 Arm nerve</td>
<td>Front</td>
</tr>
<tr>
<td>Lower arms and wrist joints</td>
<td>14 Radial bone</td>
<td>Rear</td>
</tr>
<tr>
<td></td>
<td>15 Forearm muscle</td>
<td>Rear</td>
</tr>
<tr>
<td>Hands and fingers</td>
<td>17 Forefinger pad D</td>
<td>Front</td>
</tr>
<tr>
<td></td>
<td>18 Forefinger pad ND</td>
<td>Front</td>
</tr>
<tr>
<td></td>
<td>19 Forefinger end joint D</td>
<td>Rear</td>
</tr>
<tr>
<td></td>
<td>20 Forefinger end joint ND</td>
<td>Rear</td>
</tr>
<tr>
<td></td>
<td>21 Thenar eminence</td>
<td>Front</td>
</tr>
<tr>
<td></td>
<td>22 Palm D</td>
<td>Front</td>
</tr>
<tr>
<td></td>
<td>23 Palm ND</td>
<td>Front</td>
</tr>
<tr>
<td></td>
<td>24 Back of the hand D</td>
<td>Rear</td>
</tr>
<tr>
<td></td>
<td>25 Back of the hand ND</td>
<td>Rear</td>
</tr>
<tr>
<td>Thighs and knees</td>
<td>26 Thigh muscle</td>
<td>Front</td>
</tr>
<tr>
<td></td>
<td>27 Kneecap</td>
<td>Front</td>
</tr>
<tr>
<td>Lower legs</td>
<td>28 Middle of shin</td>
<td>Front</td>
</tr>
<tr>
<td></td>
<td>29 Calf muscle</td>
<td>Rear</td>
</tr>
</tbody>
</table>

**NOTE:** D = dominant body side (right or left); ND = non-dominant body side

**Figure A.1 — Body Model**
## YuMi® - IRB 14000 0.5/0.55

### Overview

<table>
<thead>
<tr>
<th>Feature</th>
<th>IRB 14000 – 0.5/0.55</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Payload</strong></td>
<td>0.5 kg per arm</td>
</tr>
<tr>
<td><strong>Reach</strong></td>
<td>559 mm</td>
</tr>
<tr>
<td><strong>Repeatability</strong></td>
<td>0.02 mm</td>
</tr>
<tr>
<td><strong>Footprint</strong></td>
<td>399 mm x 497 mm</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>38 kg</td>
</tr>
<tr>
<td><strong>Controller</strong></td>
<td>IRC5 integrated in torso</td>
</tr>
<tr>
<td><strong>Programming</strong></td>
<td>Lead-through or RAPID</td>
</tr>
<tr>
<td><strong>Gripper</strong></td>
<td>Servo, 2x suction, integrated vision</td>
</tr>
<tr>
<td><strong>Application supplies</strong></td>
<td>Ethernet, 24 V, air to flanges</td>
</tr>
<tr>
<td><strong>Connections</strong></td>
<td>Ethernet, digital I/O 8in/8out, air</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>5 °C – 40 °C</td>
</tr>
<tr>
<td><strong>IP Protection</strong></td>
<td>IP 30</td>
</tr>
<tr>
<td><strong>ESD Protection</strong></td>
<td>Certified</td>
</tr>
<tr>
<td><strong>Clean room / food grade</strong></td>
<td>No</td>
</tr>
<tr>
<td><strong>Speed Supervision</strong></td>
<td>Configurable up to 1.5 m/s</td>
</tr>
<tr>
<td><strong>Safety Performance</strong></td>
<td>PL b, cat. B (ISO 13849-1)</td>
</tr>
</tbody>
</table>
**ABB YuMi® Safety Concept**

Protection Levels

<table>
<thead>
<tr>
<th>Level</th>
<th>Measures for risk reduction and ergonomics improvement</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

- Transient contact
- Quasi-static contact
- Other, application-specific
YuMi®
Target growth markets

Small Parts Assembly
- Collaborative Assembly
- Camera-based inspection and assembly
- Accurate and fast assembly
- Testing and packaging

Consumer Products
- Collaborative Assembly (Plastic parts etc.)
- Packaging of small goods
- Multifunction hand for add components

Toy Industry
- Collaborative Assembly (toys)
- Use of feeding and vision options
Assembly Process
Sensing Concepts

Digital sensor for material detection and sequence control
- Photo sensor
- Proximity sensor

Integrated vision system for flexible part detection
- External camera
- Integrated camera
Assembly Process
Dual-Arm Assembly

Independent tasks for cycle time optimization with fixtures in workspace

Hand-in-hand assembly for flexibility without fixtures in workspace
Collaboration & Ergonomics
Integration in Assembly Lines

Working side-by-side with humans
- 7 degree-of-freedom manipulator for kinematic redundancy
- Compact motion w/o disturbing the human worker

Task distribution between human and robot
- Sharing tasks for agility
  - Repetitive tasks assigned to the robot
  - Complex tasks assigned to the human worker
- Duplicate capacity for scalable production

SMDSO.
Status of Standardization – Example Robot: YuMi®

Open Questions

- Safety
  - Safety-rated sensors for tracking humans in speed-and-separation-monitoring
  - More data on biomechanical limit criteria for human body regions
  - Design rules for safety-related mechanical design of collaborative manipulators
  - Dynamic adaptation of safety-configuration to momentary requirements

- Acceptance
  - Dynamic adaptation of robot behavior to collaborative situation
  - Definition and quantification of ergonomics for collaborative situations
  - Operator controls for collaborative operation
  - Possibility of programming complex assembly tasks without expert knowledge

- Productivity
  - Application concepts for productive collaborative assembly
  - Optimal distribution of tasks to robot or human in mixed environment
  - Economical combinations of lot sizes, variants, application complexity, …
  - Practical experience with business models
Status of Standardization – Example Robot: YuMi®

Summary and Outlook

- Safety standardization
  - ISO/TS 15066 publication in Dec. 2015
  - Requirements on collaborating robots incl. biomechanical criteria for power-and-force-limiting
  - Eventual integration into ISO 10218-2 is planned

- YuMi® - IRB 14000 0.5/0.55
  - Collaborative robot according to power-and-force-limiting
  - Assembly of small lot-size / high-variant orders
  - Humans and robots combine their respective strengths

- Outlook
  - Interdisciplinary research
  - Technological improvements and progress
  - Proving in practice
  - Revisions of standards