ABB Robotics Customer Days 2013
Workshop: Safety
→ Status of Standardization
Safety – Status of Standardization

Overview

- 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
  - Collaborative operation
  - Changes from ISO 10218-1:2006 to :2011
- Present Standardization Projects
  - ISO/TS 15066 – Safety of collaborative robots
  - Biomechanical criteria
- Summary
## 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

Example: European Union

- European Machinery Directive 2006/42/EC
- EN ISO 13849-1:2008 or IEC 62061:2005
- IEC 61508 – Functional Safety
- ISO 11161 – Integrated manufacturing systems
- ISO 10218-2 – Robot system/cell
- ISO 10218-1 – Robot
- 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
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)

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 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
## 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:** 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
### Safety Functions of Industrial Robot Controller

#### Changes from ISO 10218-1:2006 to :2011 (1)

<table>
<thead>
<tr>
<th>Functionality, Clause</th>
<th>ISO 10218-1:2006</th>
<th>ISO 10218-1:2011</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2.1 Power transmission components</td>
<td>--</td>
<td>Fixing systems of fixed guards shall remain attached to machine or guard during service access</td>
<td></td>
</tr>
</tbody>
</table>
| 5.4 Safety-related control system performance | • Refers to ISO 13849-1:1999 (EN 954-1)  
  • Usage of safety cat. 3   | • Refers to ISO 13849-1:2006  
  • Usage of PL d and structure cat. 3  
  • Reference to IEC 62061 as alternative | Now well-aligned with (new) Machinery Directive                           |
| 5.5 Protective stop                    | --               | Clarification that PS shall have stop cat. 0 or 1                             | Optional cat. 2 stop is OK as additional function                        |
| 5.6 (Reduced) Speed Control            | • 250 mm/s manual mode (5.6) | • 250 mm/s manual mode (5.6.2)  
  • Reduced speed control (5.6.3), over-speed not possible  
  • Monitored speed limit (5.6.4), exceeding gives PS | New definitions used in collaborative operation                           |
| 5.7.4 Manual high speed                | • Possible to program / teach | • Program verification only  
  • Reset speed to initial speed (max. 250 mm/s) whenever enable-device cycled  
  • Single action to restore higher speed within 5 min. of pause | Hotly contested change! Is e.g. LoadID verification or is it programming? |
| 5.8.3 Enabling device                  | --               | Description provided for switching enabling between left + right hands       | Practical relevance?                                                     |
| 5.8.5 Initiating automatic operation   | Shall not be possible using pendant alone | Shall not be possible using pendant alone | No change, but market requires mode switch on pendant ???                 |
Safety Functions of Industrial Robot Controller
Changes from ISO 10218-1:2006 to :2011 (2)

<table>
<thead>
<tr>
<th>Functionality, Clause</th>
<th>ISO 10218-1:2006</th>
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<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.10.2 (Safety-rated monitored) Stop</td>
<td>Simple stop function</td>
<td>Option of stop cat. 2 safe standstill function</td>
<td>Improved clarity</td>
</tr>
<tr>
<td>5.10.3 Hand guiding</td>
<td>Max. speed from risk assessment, but limited to 250 mm/s</td>
<td>Max. speed from risk assessment</td>
<td>Depending on application details, speeds &gt; 250 mm/s are possible</td>
</tr>
</tbody>
</table>
| 5.10.4 Speed and position / separation monitoring | • Max. speed from risk assessment, but limited to 250 mm/s  
• Reference to ISO 13855 | • Max. speed from risk assessment  
• Reference to ISO 10218-2  
• Reference to ISO/TS 15066  
• Reference to ISO 13855 | If separation distance is sufficient, speeds >> 250 mm/s are possible, allowing productive applications. Guidance from ISO/TS 15066 not yet available |
| 5.10.5, 5.10.6 Power and force limiting | • Max. dynamic power = 80 W  
• Max. static force at TCP = 150 N  
• Limitation by inherent design or by control function(s) | • No numerical values given  
• Risk assessment to determine values  
• Reference to ISO 10218-2  
• Reference to ISO/TS 15066 | Existing solutions using 80 W or 150 N are no longer OK. Transition period of old version expired on 2012-12-31. Guidance from ISO/TS 15066 not yet available |
| 5.12.3 Safety-rated soft axis and space limiting | • Soft limits shall be static. Changes require power-cycle. | • Soft limits shall be static. Changes require restart of safety-related sub-system. | No longer required to reboot the entire controller. |
| 6 Verification and validation | -- | New chapter | The V&V methods were given as footnotes in older version. In newer version, methods given in Table F.1 |
| 6.2 / 7.2 Instruction handbook | | Numerous additional items specified | Improved guidance to achieve conformity to Machinery Directive |
## Safety Functions of Industrial Robot Controller

### Changes from ISO 10218-1:2006 to :2011 (3)

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<tr>
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<th>ISO 10218-1:2011</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annex A</td>
<td>Hazard list based on ISO 14121-1:1999 (normative ?)</td>
<td>Hazard list based on ISO 12100:2010 (informative)</td>
<td></td>
</tr>
</tbody>
</table>
| Annex B, normative    | • Braking distances, angles, times shall be measured  
                        • Cat. 0 stop at 33%, 66%, 100% of max. speed, payload, extension  
                        • Cat. 1 stop at 33%, 66%, 100% of max. speed, payload, extension | • Braking distances, angles, times can be measured or simulated with validated tool  
                        • Cat. 0 stop only for 100% of max.  
                        • Cat. 1 stop at 33%, 66%, 100% of max. speed, payload, extension  
                        • Computation of intermediate values allowed  
                        • Description of measurement procedure must be provided to integrator |          |
| Annex E, informative   | Graphical symbol for manual high speed given | No graphical symbol for manual high speed | ISO deemed it is not permissible to “create” symbol from superposition of symbols 0026 and 0096 |
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 $K_R$
  - $S = K_H(T_R + T_B) + K_R T_R + B + C + Z_S + Z_R$
  - 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.?
ISO / TS 15066 – clause 5.4.4 “Power and force limiting”

<table>
<thead>
<tr>
<th>Free impact / dynamic contact</th>
<th>Constrained contact / quasi-static contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Accessible parameters in design or control</td>
<td>• Accessible parameters in design or control</td>
</tr>
<tr>
<td>• Effective mass (robot pose, payload)</td>
<td>• Force (joint torques, pose)</td>
</tr>
<tr>
<td>• Speed (relative)</td>
<td></td>
</tr>
<tr>
<td>Pain threshold</td>
<td>Pain threshold</td>
</tr>
<tr>
<td>Highest loading level accepted in design</td>
<td>Highest loading level accepted in risk</td>
</tr>
<tr>
<td>Table of values for each body region</td>
<td>assessment in case of single failure</td>
</tr>
<tr>
<td>May design robot / application to respect</td>
<td>Table of values for each body region</td>
</tr>
<tr>
<td>lesser loading levels, depending on ergonomic analysis</td>
<td>May design robot / application to respect higher loading levels, depending on risk assessment</td>
</tr>
</tbody>
</table>

**Highest loading level accepted in design**

**Minor injury threshold**

**Pain threshold**

**Highest loading level accepted in risk assessment in case of single failure**

**Table of values for each body region**

**May design robot / application to respect lesser loading levels, depending on ergonomic analysis**

**May design robot / application to respect higher loading levels, depending on risk assessment**

![Dynamic contact](image1)

![Quasi-static contact](image2)
Present Standardization Activities
Biomechanical Criteria

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

DGUV/IFA literature survey
DGUV/IFA + U of Mainz measurements
Presently valid C-type standards for industrial robotics applications are

- ISO 10218-1:2011 for the robot
- ISO 10218-2:2011 for the robot system and integration

Transition period for ISO 10218-1:2006 has expired on 2012-12-31 and a number of important changes have been made in ISO 10218-1:2011

Collaborative operation is an exciting and promising new area and still the subject of original research in many aspects, especially including determination of applicable biomechanical design criteria

Progress depends on your input! Please voice your views, hopes and concerns!
Research Project: Investigation of change from pressure feeling to pain at the man machine interface of collaborative robots

ABB Customer Days 2013
Mainz (Germany), 18-19 June 2013
Robot safety - Industry

Harmonized standards under EC MD

Industrial robots

Industrial robot system and integration

Robots and robotic devices — Collaborative robots
ISO/TS 15066: 4 Concepts

- Hand guiding
  \[ V = f(\text{overtravel, risk}) \]

- Speed and position monitoring
  \[ s \geq s_{\text{min}} \]
  \[ V \neq \text{const} \]

- Safety-rated monitored stop
  \[ s \geq s_{\text{min}} \]
  \[ V = 0 \]

- Power and force limiting
  \[ F \leq F_{\text{max}} \]
  \[ p \leq p_{\text{max}} \]

Robots and robotic devices — Collaborative robots
Power and force limiting - Risk assessment

Among others:

- Intended Use and foreseeable misuse
- Consider always robot system consisting of robot and environment, e.g. tools, fixtures, jigs ...
- Required space
- Qualification, physiological and mental suitability of personnel
- Ergonomic aspects, e.g. posture
- Access of third persons
- Frequency and severity of potential contact (Force and/or pressure)
No specifically robot related thresholds found

Further research necessary
Research project: Algometer

- Algometer developed at IFA (Institute for Occupational Safety and Health)
- Specifically designed probe according to feedback from robot user
- Algometer stops when pressure feeling changes to pain
- The investigations are below AIS 1 and S1. (no bloody wounds or fracture)
Main study: Start June 2012, ends 2014
- 100 Test person
- Of which 30 metal worker (male and female)
- 3 cycles each test person
- 1 day for medical examination

Pre study: Finalized April 2012
- 10 Test person
- Definition of 29 contact points
- Test machine modified and optimized
- Modified probe for measurement of force and pressure
- Training operation of test machine
- Training treatment of test persons

Contact positions for study
Measurement of force

Body part X

Body part Y

Caution: Do not use diagrams for any conformity assessment!

Release of Enabling Device

Source/Figures: Uni Mainz, BGHM
Aside Force in particular pressure at edges $p \text{ [N/cm}^2\text{]}$ initiates pain.
Pressure spread and $\Sigma$ force (example)

Test conditions:
- Cubic test probe with edge length of 14 mm and rounded edges of 2 mm radius (see figure 1).
- Quasi static increase of contact on human body part by 2 N/s (point 2 and 3) and 5 N/s (all other points).
- Resolution of surface pressure measurement system of at least 1 mm²
Results of interim report

Preliminary data!

Please do not use for any conformity assessment!
Further research

- Pressure $p$ tends to zero in case of flat padded surfaces
- Influence of Force $F$ on deep muscular tissue and inner organs

$p \approx 0$

$F_{\text{max}} = ?$
Further research

In case of short impact the influence of duration time on $p_{\text{max}}, F_{\text{max}}$ is not known

$p_{\text{max}}, F_{\text{max}} = f \left( \text{duration} \right) = \, ?$
Summary

- Interim Report of University of Mainz will be published July 2013
- Preparation of new annex for ISO TS 15066 accordingly
- Provide final research report in 2014. Revise 15066 accordingly
- Development of measurement devices for force and pressure by IFA
- Provide further research
- Traditional robots cannot be replaced by robots with force and pressure limiting
- Example- Application needed for certification of collaborative robots
- First certificates issued by Berufsgenossenschaft
Report in Newspaper:
Meeting of ISO TC 184 SC 2 Industrial Robots at University of Mainz in June 2012
Summary

From the 100 test persons have been tested:

41 test persons tested
(of which 21 metal worker)
36 evaluated
Translation and publication of final report is planned

E-mail response of a tested metal worker:

“… I find that all functioned well. Your staff was very friendly, the tests functioned without trouble. And also the environment was fine. I enjoyed stay in your house.
P.S. 2-3 of my friends are interested as well. Should I connect them to you?”
Ensuring safety in A Hybrid Human-Robot Assistance System

Carsten Thomas | Institute of Production Systems
Welding in Industrial Production

Welding of Tubular and Framework Constructions

- custom-made assemblies, individual construction
- small batch sizes (< 10 pieces)
- high quality requirements
- heavy-weights

Process Steps

- Handling of Single Parts and Pre-Assemblies
- Positioning and Fixation of Parts
- Readjustment of Parts
- Spot and Ground Welding
Welding in Industrial Production

Problems

- labour-intensive tasks with a high amount of manual handling operations
- static body postures of the employees, e.g. when welding overhead or with a bended and twisted back
- working posture during operation is defined by the product geometry
Actual Welding in the Industry

Video
Actual Welding Process
Analysis of the Process Times

- 00:19:08 First Spot Welding
- 00:32:42 First Weld Seam
- 01:44:10 Process Finish

- Welding
- Weld seam finishing
- Other secondary time
- Handling
Development of a multi-robot assistance system with a safe and ergonomic collaboration between humans and robots in an overlapping workspace, to reduce labour-intensive manual handling of heavy parts in welding processes.
Modes of Human-Robot-Collaboration

<table>
<thead>
<tr>
<th>Human</th>
<th>Mode</th>
<th>Robot</th>
</tr>
</thead>
<tbody>
<tr>
<td>manual assembly</td>
<td>1</td>
<td>---</td>
</tr>
<tr>
<td>active</td>
<td>2</td>
<td>not active, safe stand still</td>
</tr>
<tr>
<td>direct cooperation with robot(s)</td>
<td>3</td>
<td>direct cooperation with human(s)</td>
</tr>
<tr>
<td>active, but separate working range</td>
<td>4</td>
<td>active, but separate working range</td>
</tr>
<tr>
<td>not active</td>
<td>5</td>
<td>active</td>
</tr>
<tr>
<td>---</td>
<td>6</td>
<td>automated assembly</td>
</tr>
</tbody>
</table>
Real Demonstrator and view of the SafetyEyes

- Camera-based sensor system SafetyEye
- Safety robot controller ABB SafeMove

→ Flexible layout of the robot cell
→ Safety configuration adaptable for each mode
Offline Simulation of a Robot Assistance System

- simulating a direct collaboration between humans and robots requires a Digital Human Model (DHM) to perform collision analysis and evaluate ergonomic conditions in advance
- implementing a fully operational human kinematic, based on a skeleton model covered by a wire frame overlay and a database of different variation of body sizes
- main tasks of the implemented DHM: collision avoidance during the path planning and evaluation of the ergonomic conditions
Combinated Human-Robot Simulation and using Ergonomic Assessment Procedure OWAS

**Description for OWAS-Categories**

**Analysis of current posture combination**

**Detailed evaluation for back, arms, legs and load**

**Current posture code**
Comparison
Video
Welding in the Robot-Based Assistance System
Contact

TU Dortmund University
Institute of Production Systems | www.IPS.DO
Dipl.-Ing. Carsten Thomas | carsten3.thomas@tu-dortmund.de