Risk Assessment for Human-Robot Collaborative Applications

Workshop IROS 2015 – Physical Human-Robot Collaboration: Safety, Control, Learning and Applications
Risk Assessment for HRC Applications

Overview

- Motivation for collaborative robots
- Working situation – humans and collaborative robots
- Risk assessment basics
- Requirements on a collaborative robot for power-and-force-limited operation
- Asimov → FRIDA → DACR → YuMi
- Characteristics of YuMi
- Example YuMi application – risk assessment
- Summary and outlook
Motivation for Collaborative Robots

Should we simply continue with incremental improvements and rely on the same market?

- Things are going very well in established markets.

- It’s tempting.

(source: International Federation of Robotics (IFR), World Robotics 2015 Industrial Robots, Executive Summary)
Motivation for Collaborative Robots

What applications will be important in future?

- Automotive still dominates numbers and drives industrial robot technology requirements
- Many other markets, e.g. 3C assembly have very low degrees of automation.

(source: International Federation of Robotics (IFR), World Robotics 2015 Industrial Robots, Executive Summary)
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Motivation for collaborative robots

(adapted from B. Lotter)
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Motivation for collaborative robots

Conventional industrial robots → Separate players

Collaborative industrial robots → Team players

Safety by separation → No collaboration → No moving contact

Safety by supervision functions → Limited collaboration → Contact under strict precautions

Harmless manipulators → Full collaboration → Contact OK

Robot produces according to application design → Limited flexibility, high cost

Human and robot share tasks, according to respective strengths → High flexibility, moderate cost
Risk Assessment for HRC Applications
Working environment – approach
Risk Assessment for HRC Applications

Working situation – humans and collaborative robots

- Production needs
  - Handle uncertain production volumes, determined by product acceptance on the market
  - Often batch production ranging from 100s to 10,000s
  - Frequent model changes in production
  - Changeover time 1h

- Status today
  - Flexible production layouts (mostly tables/lean cells), few conveyors
  - Assembly mostly done manually
  - Tools and fixtures are used
  - Robots only used upstream

- Target approach
  - Mixed human/robot production concept - robots augment humans
  - Harmless robot with integrated controller
  - Multi-purpose gripper
  - Efficient programming concept
  - Competitive overall system cost
Risk Assessment for HRC Applications
Working situation – humans and collaborative robots
Risk Assessment for HRC Applications
Working situation – humans and collaborative robots

Robot

Co-operation

Co-worker

Inspector

Co-existence

Helper

Intrusion
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Working situation – humans and collaborative robots
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Relevant Standards and Directives

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

**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
- ISO/TS 15066 – Collaborative Robots
### 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</td>
<td>No robot motion when</td>
</tr>
<tr>
<td></td>
<td>(Example: manual loading-station)</td>
<td>operator is in collaborative</td>
</tr>
<tr>
<td></td>
<td></td>
<td>work space</td>
</tr>
<tr>
<td>5.10.3</td>
<td>Hand guiding</td>
<td>Robot motion only through</td>
</tr>
<tr>
<td></td>
<td>(Example: operation as assist</td>
<td>direct input of operator</td>
</tr>
<tr>
<td></td>
<td>device)</td>
<td></td>
</tr>
<tr>
<td>5.10.4</td>
<td>Speed and separation monitoring</td>
<td>Robot motion only when</td>
</tr>
<tr>
<td></td>
<td>(Example: replenishing parts</td>
<td>separation distance above</td>
</tr>
<tr>
<td></td>
<td>containers)</td>
<td>minimum separation distance</td>
</tr>
<tr>
<td>5.10.5</td>
<td>Power and force limiting by</td>
<td>In contact events, robot</td>
</tr>
<tr>
<td></td>
<td>inherent design or control</td>
<td>can only impart limited</td>
</tr>
<tr>
<td></td>
<td>(Example: <em>ABB YuMi®</em> collaborative</td>
<td>static and dynamics forces</td>
</tr>
<tr>
<td></td>
<td>assembly robot)</td>
<td></td>
</tr>
</tbody>
</table>

*Image: [ABB YuMi®](https://www.abb.com/yumi)*
Risk Assessment for HRC Applications

Risk Assessment Basics

- Use case identification
- Hazard identification
- Risk estimation
- Risk reduction
- Iterate until acceptable residual risk
ISO 12100 – Safety of Machinery – Risk Assessment

Figure 1 — Schematic representation of risk reduction process including iterative three-step method

Figure 2 — Risk reduction process from point of view of designer
Risk Assessment for HRC Applications
Risk Estimation

Risk Assessment for HRC Applications

### Hazards

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>
</table>
| **Description** | • Contact event is “short” (< 50 ms)  
• Human body part can usually recoil | • Contact duration is “extended”  
• Human body part cannot recoil, is trapped |
| **Limit Criteria** | • Peak forces, pressures, stresses  
• Energy transfer, power density | • Peak forces, pressures, stresses |
| **Accessible in Design or Control** | • Effective mass (robot pose, payload)  
• Speed (relative)  
• Contact area, duration | • Force (joint torques, pose)  
• Contact area, duration |
Risk Assessment for HRC Applications
Requirements on Collaborative Robot for PFL

- Fits in a workspace intended for human worker
- Can easily be moved from one location to another and recommissioned
- Has human-like reach and payload
- Is inherently safe for collaborative operation
Concept for Scalable Automation
“Friendly Robot for Industrial Dual-arm Assembly”

FRIDA / ABB Dual-Arm Concept Robot (DACR) / ABB YuMi®

- 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
Risk Assessment for HRC Applications

YuMi Development History

Initial ideas and technology studies, simpler prototypes → FRIDA → Dual-Arm Concept Robot → Red dot design award

Pilot projects for verification and testing

Shipping to customers

YuMi® - Hannover Fair 2015

https://www.youtube.com/user/ABBRobotics
Participation in Academic Research
EU-FP7 project ROSETTA

- Simulation based safety approval for DACR
- Visual operator tracking
- Human centric robot motion
- Task oriented offline programming of assembly tasks
- Networked, learning assembly robots
- Semantic production knowledge-base on network

www.fp7rosetta.org
ABB YuMi® Safety Concept
Protection Levels

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

Other, application-specific

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

[www.abb.com/yumi](http://www.abb.com/yumi)
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
Risk Assessment for HRC Applications
Example YuMi Application – Risk Assessment

- Internal application example
  - ABB Busch-Jaeger, Lüdenscheid
  - Pick-and-place operation
  - Co-existence in production

- Customer application example
  - Continental
  - Packaging operation
  - Co-existence in production
Collaborative Applications at ABB
Busch-Jaeger (BJE) Lüdenscheid – Pick’n’Place

- Application profile
  - Pick component 1 from in-conveying 1, left arm
  - Pick component 2 from in-conveying 2, right arm
  - Place component 1 to fixture in press
  - Assemble component 2 to component 1
  - Cycle press to clip together
  - Pick finished sub-assembly and place to out-bin (hole in table)

- Running since Feb. 2015
- Integrated in to factory information system
- Phoebus robot waiting to be replaced by YuMi robot
- More applications envisioned esp. for single-arm collaborative robots
Collaborative Applications at ABB
Busch-Jaeger (BJE) Lüdenscheid – Gripper Padding

• Protective padding on gripper
## Risk Assessment – Use Cases

<table>
<thead>
<tr>
<th>Use case</th>
<th>Activity</th>
<th>Person</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setup and programming</td>
<td>Build, program, commission application</td>
<td>Typically specially trained personnel</td>
<td>Rare, only before SOP</td>
</tr>
<tr>
<td>Normal production operation</td>
<td>Use robot system to run production application</td>
<td>Typically simply trained personnel</td>
<td>High</td>
</tr>
<tr>
<td>Manual intervention in production</td>
<td>Reach into robot work space to clear error situation</td>
<td>Typically simply trained personnel</td>
<td>Low</td>
</tr>
<tr>
<td>Foreseeable misuse in production</td>
<td>Non-authorized colleague or visitor entering work space</td>
<td>Typically untrained personnel</td>
<td>Unknown, assumed rare</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Repair, service, modify, optimize application</td>
<td>Typically specially trained personnel</td>
<td>Rare to moderate, depending on production changes</td>
</tr>
<tr>
<td>Cleaning</td>
<td>Clean surfaces, does not include servicing machinery</td>
<td>Typically untrained personnel</td>
<td>Moderate</td>
</tr>
<tr>
<td>Dismounting</td>
<td>Dismount, pack, ship, dispose components of application</td>
<td>Typically untrained personnel</td>
<td>Rare, only after production lifetime</td>
</tr>
</tbody>
</table>
## Risk Assessment – Hazard Identification

<table>
<thead>
<tr>
<th>Use case</th>
<th>Human-robot work space overlap</th>
<th>Free impact hazard</th>
<th>Crushing hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setup and programming</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Normal production operation</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Manual intervention in production</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Foreseeable misuse in production</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Cleaning</td>
<td>n.a.</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Dismounting</td>
<td>n.a.</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Use case</td>
<td>Unprotected risk</td>
<td>Severity of hazard (S)</td>
<td>Exposure to hazard (F)</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>------------------</td>
<td>------------------------</td>
<td>------------------------</td>
</tr>
</tbody>
</table>
| Setup, programming, maintenance| Too high         | S1* → S0†              | High F2                | P2 → P1                 | • Training to reduce P  
                        |                  |                        |                        | • Speed supervision to reduce S                                                      |
| Normal production operation    | Too high         | S1* → S0†              | F1                     | P1                      | • Speed supervision to reduce S                                                        |
| Manual intervention            | Too high         | S1* → S0†              | High F2                | P2 → P1                 | • Training to reduce P  
                        |                  |                        |                        | • Speed supervision to reduce S                                                      |
| Foreseeable misuse             | Too high         | S1* → S0†              | F2 → F1                | Difficult P2            | • Access restriction to reduce F  
                        |                  |                        |                        | • Speed supervision to reduce S                                                      |
| Cleaning, dismounting          | Acceptable       | None associated with robot operation | n.a.                   | n.a.                    | • Standard measures                                                                 |

* Note: exclude applications that would lead to S2, i.e. sharp edges etc.
† Note: Here “S0” designates “no injury”
Required Safety Performance of Safety Functions

Standard Robots and “Typical” Collaborative Robots

Can potentially cause “S2” events, i.e. “irreversible” injury
Required Safety Performance of Safety Functions
“Harmless” Collaborative Robot

Can cause at most “S1” events, i.e. “reversible” injury
Required Safety Performance of Safety Functions
ABB YuMi®

Worst case is minor, fully reversible injury (S1)
Continuous exposure (F2)
Very low probability of hazard occurrence (P1)
# Risk Assessment – Safety Measures and Residual Risk

<table>
<thead>
<tr>
<th>Use case</th>
<th>Safety measures</th>
<th>Safety functions</th>
<th>Safety PL</th>
<th>Residual risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setup, programming, maintenance</td>
<td>• Specially trained personnel</td>
<td>Speed supervision</td>
<td>S1* / F2 / P1</td>
<td>Occasional harmless contact</td>
</tr>
<tr>
<td></td>
<td>• Supervised speed</td>
<td></td>
<td>PL b</td>
<td></td>
</tr>
<tr>
<td>Normal production operation</td>
<td>• Trained personnel</td>
<td>Speed supervision</td>
<td>S1* / F1 / P2</td>
<td>Occasional harmless contact</td>
</tr>
<tr>
<td></td>
<td>• Supervised speed</td>
<td></td>
<td>PL b</td>
<td></td>
</tr>
<tr>
<td>Manual intervention</td>
<td>• Trained personnel</td>
<td>Speed supervision</td>
<td>S1* / F2 / P1</td>
<td>Occasional harmless contact</td>
</tr>
<tr>
<td></td>
<td>• Supervised speed</td>
<td></td>
<td>PL b</td>
<td></td>
</tr>
<tr>
<td>Foreseeable misuse</td>
<td>• Prevent unauthorized access</td>
<td>Speed supervision</td>
<td>S1* / F1 / P2</td>
<td>Rare harmless contact</td>
</tr>
<tr>
<td></td>
<td>• Supervised speed</td>
<td></td>
<td>PL b</td>
<td></td>
</tr>
<tr>
<td>Cleaning, dismounting</td>
<td>• Standard best practice</td>
<td>None</td>
<td>n.a.</td>
<td>None from robot system</td>
</tr>
</tbody>
</table>

* Note: exclude applications that would lead to S2, i.e. sharp edges etc.
† Note: Here “S0” designates “no injury”
Multi-HRC stations for scalable automation
… going to multiple HRC lines – New Questions

- Safety
  - Many persons exposed to multiple robots
  - Increased role of safety sensors?
  - Risk assessment update after reconfiguration of line?

- Flexibility
  - Methods and tools for quick commissioning of new applications
  - Optimal sequence of stations
  - Optimal assignment of manufacturing steps to robots and workers

- Productivity
  - Best layout and operating parameters for ergonomics
Power and productivity for a better world™