Collaborative Robots – Power and Force Limiting

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Overview

• Human-Robot Collaboration (HRC)
• Power and Force Limiting (PFL)
• Possible Misconceptions
• Biomechanical Limit Criteria
• Risk Reduction Measures
• Modeling Contact Events
• Different Perspectives
  – Robot Manufacturer
  – System Integrator
  – End-User
• Conclusions and Outlook
Human-Robot Collaboration (HRC)

- Absolute separation → Mixed environment

- Discrete safety → No HRC
- Safety controllers → Limited HRC
- Harmless manipulators → Full HRC

Conventional industrial robots

Collaborative industrial robots
Power and Force Limiting (PFL)

• Form of collaborative operation in which **incidental contact** between moving robot and human body region can occur
• Contact is not excluded, thus it **must be thoroughly understood and controlled** to minimize risk
• Risk reduction uses
  – Suitable robot design
  – Suitable application design (tooling, work pieces, fixtures, motion patterns, etc.)
  – Biomechanical limit criteria on contact events
  – Design and control means to respect limit criteria
PFL – Possible Misconceptions

• Use of collaborative robots featuring PFL does not mean
  – Simply remove fences without further considerations
  – “Safe” robot will render entire application “safe”
  – Requires a higher safety performance level than standard industrial robots
  – Will be too slow for productive applications
# 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>Contact event is “short” (&lt; 50 ms)</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.png)
Biomechanical Limit Criteria

Collaborative operation

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; Fraunhofer IFF experiments

DGUV/IFA, U of Mainz, Faunhofer IFF experiments

J. Fryman, B. Matthias, Proceedings of ROBOTIK 2012, Munich
http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6309480
Biomechanical Limit Criteria

- Safety = freedom from injury
  - “A bruise a day ...” is unacceptable.
- Safety ≠ ergonomically agreeable workplace
  - Non-injuring but subjectively painful contacts are not forbidden, but not recommended from an ergonomics perspective.
- Design measures for collaborative robots using PFL technology
  - Must include sufficient risk reduction to prevent injury
  - Can include ergonomics and usability features to bolster acceptance by the workforce
## Risk Reduction Measures

<table>
<thead>
<tr>
<th></th>
<th>Transient Contact</th>
<th>Quasi-Static Contact</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical Design</strong></td>
<td>• Reduce effective mass</td>
<td>• Increase contact area</td>
</tr>
<tr>
<td></td>
<td>• Increase contact area</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Increase contact duration</td>
<td></td>
</tr>
<tr>
<td><strong>Control Design</strong></td>
<td>• Reduce relative speed</td>
<td>• Decrease maximum joint torques, forces</td>
</tr>
<tr>
<td></td>
<td>• (Reduce effective mass by suitable choices of pose)</td>
<td>• Decrease contact duration</td>
</tr>
</tbody>
</table>

- Design choices are a balance between performance characteristics and safety requirements.
- Safety-related control functions must be designed and implemented according to appropriate choice of safety performance level (PL) / safety integrity level (SIL) and designated architecture (ISO 13849-1, IEC 62061)
ABB YuMi® Safety Concept

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

Robot system – mechanical hazards

ABB collaborative industrial robot concept

ABB

YuMi®

Safety Concept

Other, application-specific

Quasi-static contact

Transient contact
Modeling Contact Events

- Properties of robot
- Properties of human body region
- Characteristics of contact
- Describe as inelastic 2-body collision
- Estimate worst case forces and energy transfer
Properties of Robot

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

Example for stiff 3 DOF robot

\[
\vec{p}_R = \sum_i m_i \vec{v}_i \\
\]

\[
m_R = \frac{\vec{p}_R \cdot \vec{v}_R}{\vec{v}_R^2}
\]
### Properties of Human Body Region

#### Body Segment Masses

<table>
<thead>
<tr>
<th></th>
<th>5th percentile</th>
<th>50th percentile</th>
<th>95th percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>kg</td>
<td>[%]</td>
<td>[kg]</td>
<td>[%]</td>
</tr>
<tr>
<td>0 whole body</td>
<td>65.8</td>
<td>100%</td>
<td>82.2</td>
</tr>
<tr>
<td>1 head</td>
<td>4.26</td>
<td>6.5%</td>
<td>4.4</td>
</tr>
<tr>
<td>2 neck</td>
<td>0.93</td>
<td>1.4%</td>
<td>1.1</td>
</tr>
<tr>
<td>3 thorax</td>
<td>20.42</td>
<td>31.0%</td>
<td>26.11</td>
</tr>
<tr>
<td>4 abdomen</td>
<td>2.03</td>
<td>3.1%</td>
<td>2.5</td>
</tr>
<tr>
<td>5 pelvis</td>
<td>9.42</td>
<td>14.3%</td>
<td>12.3</td>
</tr>
<tr>
<td>6 upper arm</td>
<td>1.6</td>
<td>2.4%</td>
<td>2.5</td>
</tr>
<tr>
<td>7 forearm</td>
<td>1.18</td>
<td>1.8%</td>
<td>1.45</td>
</tr>
<tr>
<td>8 hand</td>
<td>0.46</td>
<td>0.7%</td>
<td>0.53</td>
</tr>
<tr>
<td>9 hip flap</td>
<td>2.89</td>
<td>4.4%</td>
<td>3.64</td>
</tr>
<tr>
<td>10 thigh minus flap</td>
<td>5.48</td>
<td>8.3%</td>
<td>6.7</td>
</tr>
<tr>
<td>11 calf</td>
<td>3.32</td>
<td>5.0%</td>
<td>4.04</td>
</tr>
<tr>
<td>12 foot</td>
<td>0.84</td>
<td>1.3%</td>
<td>1.01</td>
</tr>
<tr>
<td>sum</td>
<td>65.71</td>
<td>100%</td>
<td>82.51</td>
</tr>
<tr>
<td>5+4+3 torso</td>
<td>31.87</td>
<td>48.4%</td>
<td>40.91</td>
</tr>
<tr>
<td>9+10 thigh</td>
<td>8.37</td>
<td>12.7%</td>
<td>10.34</td>
</tr>
<tr>
<td>7+8 forearm + hand</td>
<td>1.64</td>
<td>2.5%</td>
<td>1.98</td>
</tr>
</tbody>
</table>

- Effective mass at contact location – $m_H$
- Speed of contact location – $\mathbf{v}_H$
- Material properties of contact location – Nearly elastic at relevant speeds
- Compliance of kinematic chain

[http://msis.jsc.nasa.gov/sections/section03.htm](http://msis.jsc.nasa.gov/sections/section03.htm)
Characteristics of Contact

- Duration $\Delta t$
- Compression, displacement $x$
- Contact area and shape $A(x)$
- Contact force $F(x)$, pressure $p(x)$
- Energy transfer $W(x)$, power $P(x)$
Displacement + Contact Area

**Spherical contact**

Radius \( R = R_s \)

Contact area

\[ A_s(x) = 2\pi R_s x \]

\[ A_s(R_s) = 2\pi R_s^2 \]

**Cylindrical contact**

Radius \( R = R_c \)

Length \( \ell \)

\[ A_c(x) = \ell R_c \cos \left( 1 - \frac{x}{R_c} \right) \]

\[ A_c(R_c) = \pi \ell R_c \]
Inelastic 2-BODY COLLISION

\[ \mu \ddot{x} + b \dot{x} + kx = 0 \]

**Differential Equation**

\[ \omega_0^2 = \frac{k}{\mu}, \quad \gamma = \frac{b}{2\mu}, \quad \omega^2 = \omega_0^2 - \gamma^2 \]

**Substitutions**

\[ x(t) = e^{-\gamma t} \frac{v_0}{\omega} \sin \omega t \]

**Solution, assuming:**

\[ k = \text{const.}, \quad x(0) = 0, \quad \dot{x}(t) = v_0 \]

\[ \dot{x}(t) = v_0 e^{-\gamma t} \left( \cos \omega t - \frac{\gamma}{\omega} \sin \omega t \right) \]

Solve in center-of-mass coordinates:

- **Total mass:** \( M = m_R + m_H \)
- **Reduced mass:** \( \mu = \left[ \frac{1}{m_R} + \frac{1}{m_H} \right]^{-1} \)
- **Center-of-mass coordinate:** \( \ddot{X} = \frac{m_R \ddot{x}_R + m_H \ddot{x}_H}{m_R + m_H} \)
- **Relative coordinate:** \( \ddot{x} = \ddot{x}_R - \ddot{x}_H \)
Inelastic 2-Body Collision

Assuming $k = \lambda A(x)$ with $\lambda = \text{const.}$

$\mu \ddot{x} + b \dot{x} + \lambda A(x) x = 0$

Spherical contact

$F_s(x) = \pi \lambda R_s x^2$

$p_s(x) = \frac{F_s(x)}{A_s(x)} = \frac{1}{2} \lambda x$

$W_s(x) = \frac{1}{3} \pi \lambda R_s x^3$

Cylindrical contact

$F_c(x) = \lambda \ell R_c^2 \left[ \sqrt{1 - u^2} - u \cos u \right]$

$p_c(x) = \frac{F_c(x)}{A_c(x)} = \lambda R_c \left[ \frac{\sqrt{1 - u^2}}{\cos u} - u \right]$

$W_c(x) = \frac{1}{4} \lambda \ell R_c^3 \left[ \frac{\pi}{2} - 3u \sqrt{1 - u^2} - \sin u + 2u^2 \cos u \right]$

Power

$P(x) = \frac{dW}{dt} = \frac{dW}{dx} \frac{dx}{dt} = F \cdot v$
Force + Pressure

Spherical contact

$F_s(x)$ [N]

$\nu_0 = 1000 \text{ mm/s}$

$\lambda = 10 \text{ N/mm/cm}^2$

$\mu = 1000 \text{ g}$

$R_{sph} = 5 \text{ mm}$

Cylindrical contact

$F_c(x)$ [N]

$\nu_0 = 1000 \text{ mm/s}$

$\lambda = 10 \text{ N/mm/cm}^2$

$\mu = 1000 \text{ g}$

$R_{cyl} = 5 \text{ mm}$

$l_{cyl} = 50 \text{ mm}$
Energy Transfer + Power

Spherical contact

\[ W_s(x) [J] \]

- \( v_0 = 1000 \text{ mm/s} \)
- \( \lambda = 10 \text{ N/mm/cm}^2 \)
- \( \mu = 1000 \text{ g} \)
- \( R_{sph} = 5 \text{ mm} \)

\[ P_s(x) [W] \]

Cylindrical contact

\[ W_c(x) [J] \]

- \( v_0 = 1000 \text{ mm/s} \)
- \( \lambda = 10 \text{ N/mm/cm}^2 \)
- \( \mu = 1000 \text{ g} \)
- \( R_{cyl} = 5 \text{ mm} \)
- \( l_{cyl} = 50 \text{ mm} \)

\[ P_c(x) [W] \]
## Comparison to Criteria

### Spherical contact

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{max } A_s$</td>
<td>$3.09 \text{ cm}^2$</td>
</tr>
<tr>
<td>$\text{max } F_s$</td>
<td>$152.28 \text{ N}$</td>
</tr>
<tr>
<td>$\text{max } p_s$</td>
<td>$49.23 \text{ N/cm}^2$</td>
</tr>
<tr>
<td>$\text{max } W_s$</td>
<td>$0.500 \text{ J}$</td>
</tr>
<tr>
<td>$\text{max } P_s$</td>
<td>$68.65 \text{ W}$</td>
</tr>
<tr>
<td>$\text{max } W_s/A_s$</td>
<td>$0.1616 \text{ J/cm}^2$</td>
</tr>
<tr>
<td>$\text{max } P_s/A_s$</td>
<td>$28.06 \text{ W/cm}^2$</td>
</tr>
</tbody>
</table>

### Cylindrical contact

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{max } A_c$</td>
<td>$4.74 \text{ cm}^2$</td>
</tr>
<tr>
<td>$\text{max } F_c$</td>
<td>$194.50 \text{ N}$</td>
</tr>
<tr>
<td>$\text{max } p_c$</td>
<td>$41.00 \text{ N/cm}^2$</td>
</tr>
<tr>
<td>$\text{max } W_c$</td>
<td>$0.500 \text{ J}$</td>
</tr>
<tr>
<td>$\text{max } P_c$</td>
<td>$89.66 \text{ W}$</td>
</tr>
<tr>
<td>$\text{max } W_c/A_c$</td>
<td>$0.1054 \text{ J/cm}^2$</td>
</tr>
<tr>
<td>$\text{max } P_c/A_c$</td>
<td>$22.87 \text{ W/cm}^2$</td>
</tr>
</tbody>
</table>

### Criteria

**Example: back of hand, non-dominant**

- Static $F < 81 \text{ N}$ → transient $F < 162 \text{ N}$
- Static $p < 214 \text{ N/cm}^2$ → transient $p < 428 \text{ N/cm}^2$

**Example: lower arm, muscle**

- Static $F < 42 \text{ N}$ → transient $F < 84 \text{ N}$
- Static $p < 162 \text{ N/cm}^2$ → transient $p < 324 \text{ N/cm}^2$
Comparison to Criteria

• Factor of ≥ 2 between quasi-static ($\Delta t \to \infty$) and transient ($\Delta t \leq 100$ ms)

Fig. 7 Experimental results of dynamic pain tolerance

Y. Yamada et al., IEEE International Conference on Robotics and Automation (ICRA) 1995
Robot Manufacturer – The PFL Robot

- Follow ISO 10218-1
- Follow ISO/TS 15066
  - Experimental type tests of PFL robots
  - Simulation tools for assessment of biomechanical criteria on PFL robot
- Carry out risk assessment on generic level with respect to robot alone
- Generate user information on configuration of safety functions to meet biomechanical criteria and on exclusions
- Machinery Directive: incomplete machinery, no CE marking
System Integrator – The PFL System

- Rely on work of robot manufacturer
- Follow ISO 10218-2
- Follow ISO/TS 15066
  - Computation of mechanical loading of exposed body parts in use cases
  - Determination of speed limits to respect biomechanical limits
- Do application level risk assessment with respect to robot, tooling, work pieces, ...
  - Intended use
  - Reasonably foreseeable misuse
- Generate user information on intended use of equipment
- Machinery Directive: completed machinery, needs CE marking in EU
End-User – The PFL Application

• Rely on work of integrator
• Observe user information on intended use and on exclusions
• Machinery Directive: need CE marked equipment
Conclusions and Outlook

- PFL-type collaborative robots are on the verge of larger scale deployment
- Biomechanical limit criteria for transient and quasi-static contact are under development
- Important risk reduction methods for PFL robots have been identified
- Model-based estimations of transient contact events can be very helpful in estimating whether or not a particular case is permissible or not
- Roles of manufacturer, integrator and end-user are different in their responsibilities and in their needs for data and calculation methods to estimate biomechanical loading data
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