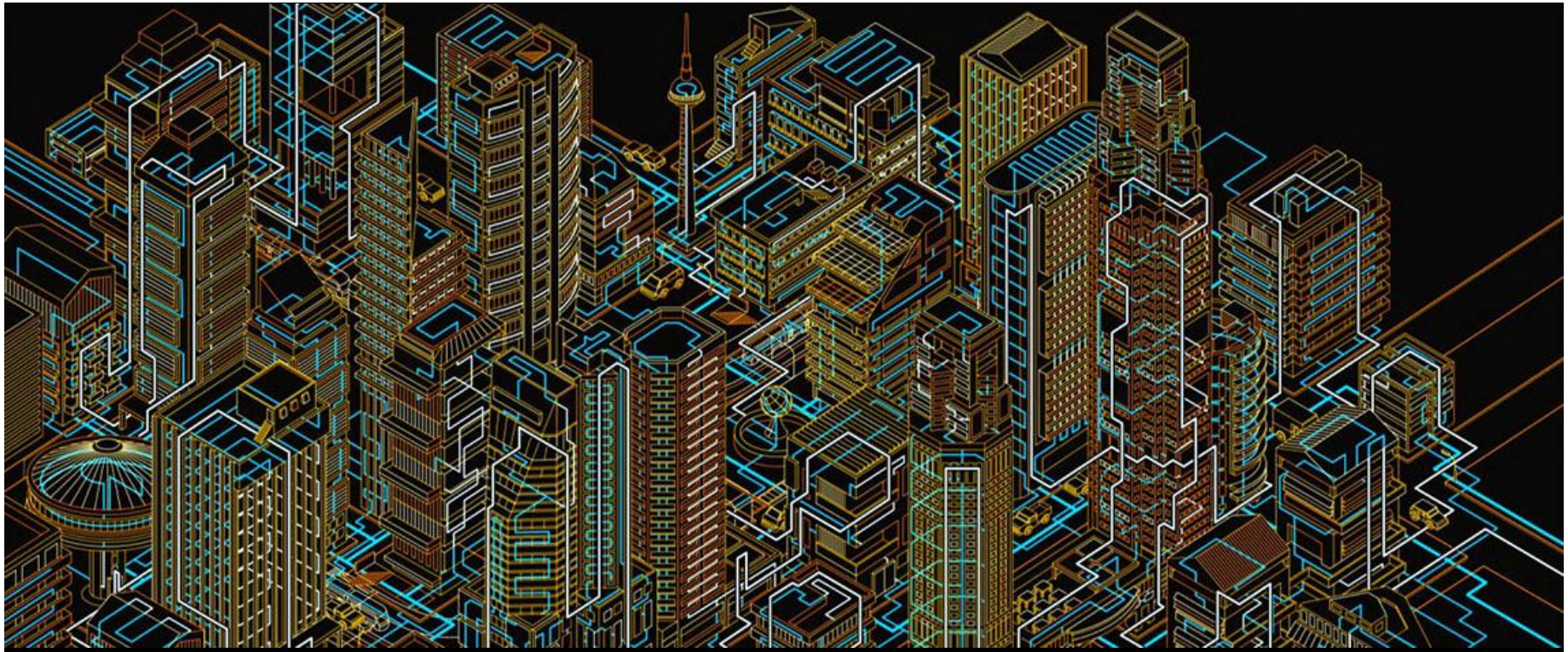


Björn Matthias, ABB Corporate Research, 2015-09-28

The Role of Collision Experiments in Safety Standardization and in the Characterization of Collaborative Robots, Systems and Applications

Workshop IROS 2015 – Towards Standardized Experiments in Human-Robot Interactions

Collision Experiments for Safety and Characterization Overview

- What are we trying to achieve?
  ➔ Objectives
- What do we have today?
  ➔ Overview of present criteria for comparison
- Who needs to do experiments?
  ➔ Players and responsibilities
- What do the experiments need to characterize?
  ➔ Physics of contact
- How should the experiments be done?
  ➔ Methods of measurement
- How can the results of the experiments be used?
  ➔ Quantities for Comparisons
- Summary and outlook

Collision Experiments for Safety and Characterization Objectives

- As stated clearly in workshop scope:
  - "… standardized assessment of robot products and applications in use in terms of safety, performance, user experience, and ergonomics."
- How easy or hard is this going to be?

		Safety	Performance	User Experience	Ergonomics
Principle	Objectivity, generalizable	**0 → +**	+	–	0
Method	Measurable, reproducible	**+**	+	0	+
Dissemination	Documented, available	**0 → +**	+	–	–

Collision Experiments for Safety and Characterization
Overview of Present Criteria for Comparison

- Active standards
  - ISO 8373 “Manipulating industrial robots – Vocabulary”
  - ISO 9283 “Manipulating industrial robots – Performance criteria and related test methods”
  - ISO 9409 “Manipulating industrial robots – Mechanical interfaces”
  - ISO 9787 “Robots and robotic devices – Coordinate systems and motion nomenclatures”
  - ISO 9946 “Manipulating industrial robots – Presentation of characteristics”
  - ISO 11593 “Manipulating industrial robots – Automatic end-effector exchange systems – Vocabulary and presentation of characteristics”
  - ISO 10218-1, -2 “Robots and robotic devices – Safety requirements for industrial robots”
  - ISO 13482 “Robots and robotic devices – Safety requirements for personal care robots”
  - ISO/TR 13309 “Manipulating industrial robots – Informative guide on test equipment and metrology methods of operation for performance evaluation in accordance with ISO 9283
  - ISO 14539 “Manipulating industrial robots – Object handling with grasp-type grippers – Vocabulary and presentation of characteristics”
  - ISO/TS 15066 “Robots and robotic devices – Safety requirements for industrial robots – Collaborative operation”

(red = contains requirements needing experimental verification)

Collision Experiments for Safety and Characterization
Overview of Present Criteria for Comparison

- Typical quantities in specifications and data sheets
  - By inspection – testing not needed
    - Power source, electrical rating (ISO 8846)
    - Type (serial, parallel, Cartesian, …), no. of joints, mounting orientation (ISO 9946)
    - Reach, dimensions of working space (ISO 9946)
    - Coordinate systems, base and flange (ISO 9946, ISO 9787)
    - Base mounting surface (ISO 9946), flange mounting surface (ISO 9946, ISO 9409)
    - Load (ISO 9946)
    - Environmental conditions, ingress protection (ISO 9946)
  - Testing needed for verification and comparison
    - Position accuracy, repeatability (ISO 9283)
    - Path accuracy, repeatability (ISO 9283)
    - Stopping behavior (ISO 10218-1)
    - Pick-and-place cycle 25 mm / 300 mm / 25 mm (adept)
    - Joint ranges, speeds, torques (often given optionally)
    - For power-and-force limited collaborative robots: quasi-static and transient contact situations (ISO/TS 15066)

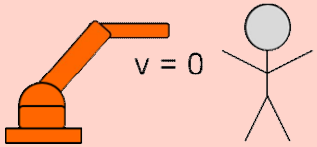
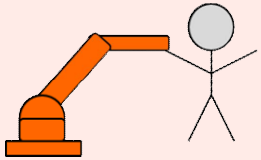
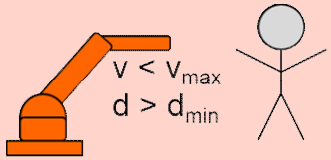
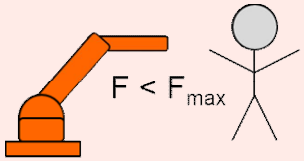
Collision Experiments for Safety and Characterization
Players and Responsibilities

Aspect	Robot Manufacturer	System Integrator	End-User
EU Machinery Directive or equiv.	• Incomplete machinery • Technical construction file • Declaration of incorporation • No CE marking	• Completed machinery • Technical construction file • Declaration of conformity • CE marking	• Operate only CE marked equipment
Risk Assessment	• For robot manipulator	• For complete application • Intended use • Foreseeable misuse	• (with integrator)
ISO 10218-1	• Basic safety requirements for industrial robots	• N/A	• N/A
ISO 10218-2	• N/A	• Basic safety requirements for industrial robot systems	• N/A
ISO/TS 15066	• Specific requirements for collaborative robots	• Specific requirements for collaborative applications	• N/A
Information for Use	• Safety configuration • Exceptions to standards • Exclusions (e.g. do not use this device for xxx)	• Guidance for safe usage • Intended use of equipment • Exceptions, exclusions	• Follow manufacturer and integrator documentation

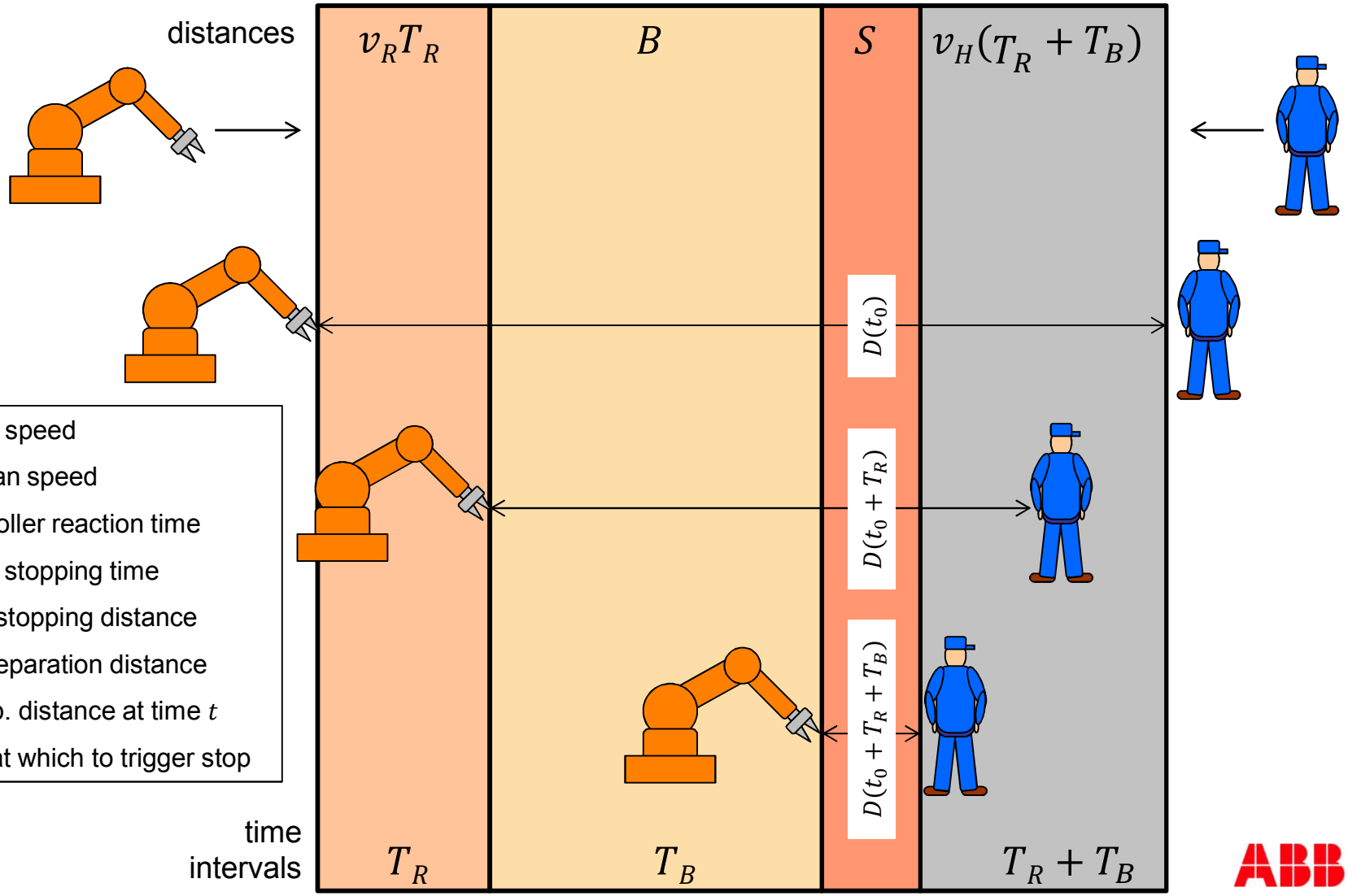
Collision Experiments for Safety and Characterization
Physics of Contact

- Types of collaborative operation
- Human-robot contact
  - Classification
  - Basic hazard types
- Models of contact events
  - Short duration (transient)
    - Two-body (in)elastic collision
    - Constrained / unconstrained
  - Sustained (quasi-static)
    - Forward kinematic transformation of joint torques
    - Constrained

Types of Collaborative Operation According to ISO 10218, ISO/TS 15066

ISO 10218-1, clause	Type of collaborative operation	Main means of risk reduction	
5.10.2	Safety-rated monitored stop (Example: manual loading-station)	No robot motion when operator is in collaborative work space	
5.10.3	Hand guiding (Example: operation as assist device)	Robot motion only through direct input of operator	
5.10.4	Speed and separation monitoring (Example: replenishing parts containers)	Robot motion only when separation distance above minimum separation distance	
5.10.5	Power and force limiting by inherent design or control (Example: *ABB YuMi*® collaborative assembly robot)	In contact events, robot can only impart limited static and dynamics forces	

Speed and Separation Monitoring
Protective Separation Distance



v_R = robot speed

v_H = human speed

T_R = controller reaction time

T_B = robot stopping time

B = robot stopping distance

S = min. separation distance

$D(t)$ = sep. distance at time t

t_0 = time at which to trigger stop

Speed and Separation Monitoring
Protective Separation Distance

$$S_{protective}(t_0) = S_{human} + S_{reaction} + S_{stopping} + C + Z_S + Z_R$$

$$S_{human} = \int_{t_0}^{t_0+T_r+T_s} v_H(t)\, dt$$

$$S_{reaction} = \int_{t_0}^{t_0+T_r} v_R(t)\, dt$$

$$S_{stopping} = \int_{t_0+T_r}^{t_0+T_r+T_s} v_R(t)\, dt$$

Here, t_0 = "now"
and t = integration variable.

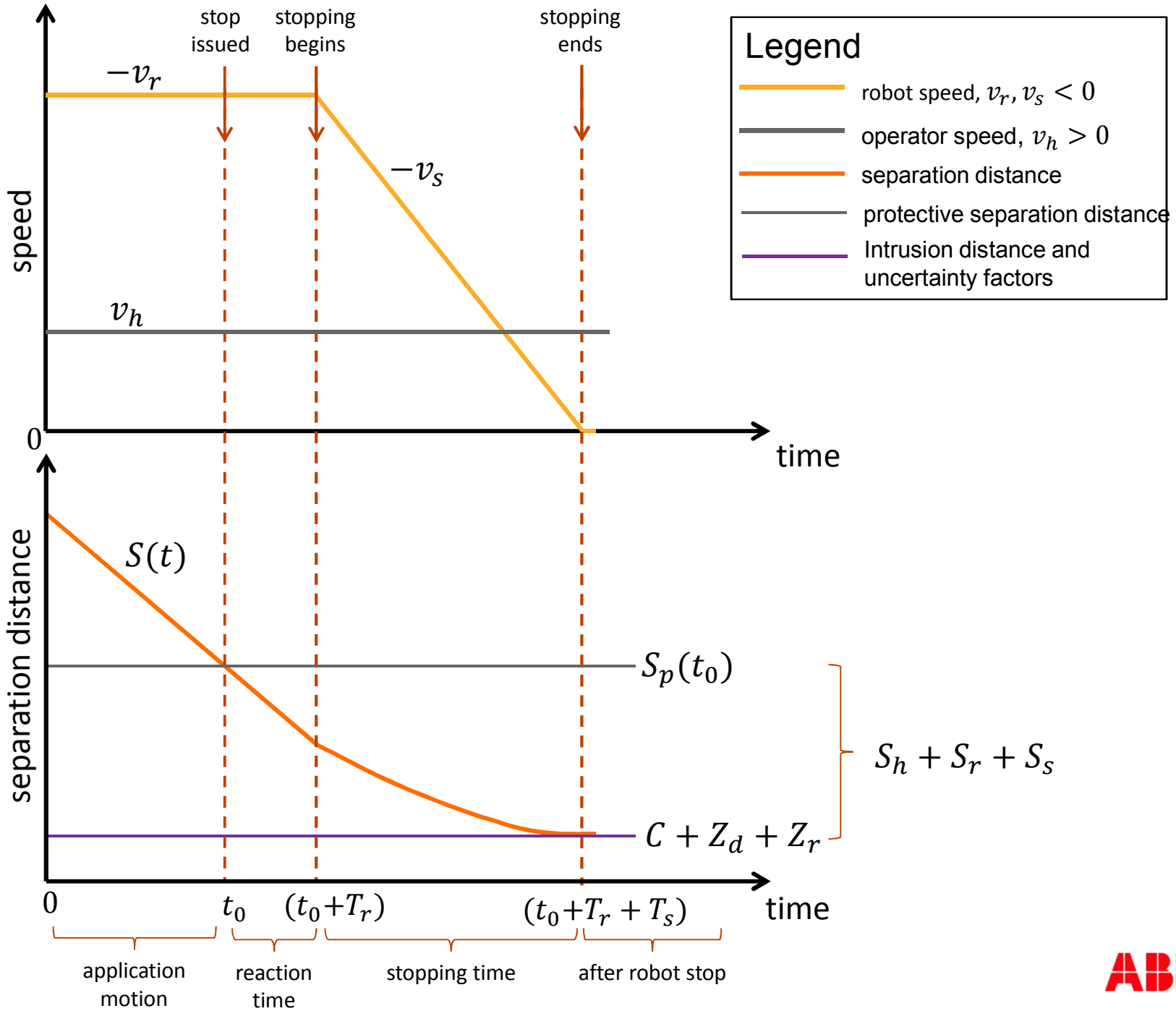
Condition for sufficient protection at t_0 is
$S_{measured}(t_0) \geq S_{protective}(t_0)$.

Simple model assumptions (constant values) for $v_H(t)$ and for $v_R(t)$ in the reaction-phase of the robot motion can be made to give:

$$S_{human} = v_H(t_0) \cdot (T_r + T_s)$$

$$S_{reaction} = v_R(t_0) \cdot T_r$$

Values for the stopping distance $S_{stopping}$ should be obtained, as stated, from the data provided according to ISO 10218-1, Annex B.

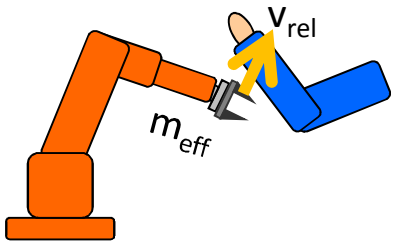


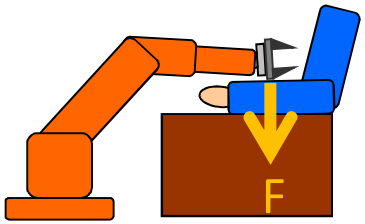
Human-Robot Contact Classification

Contact Type	Relative Speed: Low	Relative Speed: High
Constrained	Limit criteria from experiments at Univ. Mainz	Model-based extrapolation (not presently accepted by WG3)
Non-constrained	Harmless	Model-based extrapolation (described in Annex A)

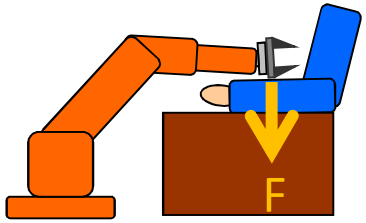
Human-Robot Contact
Basic Hazard Types

	Transient Contact	Quasi-Static Contact
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



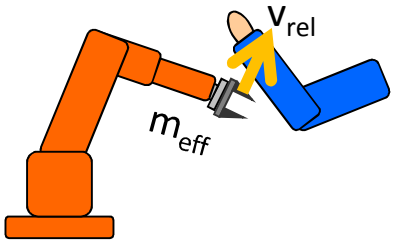


Models of Contact Events
Sustained Duration – Quasi-Static

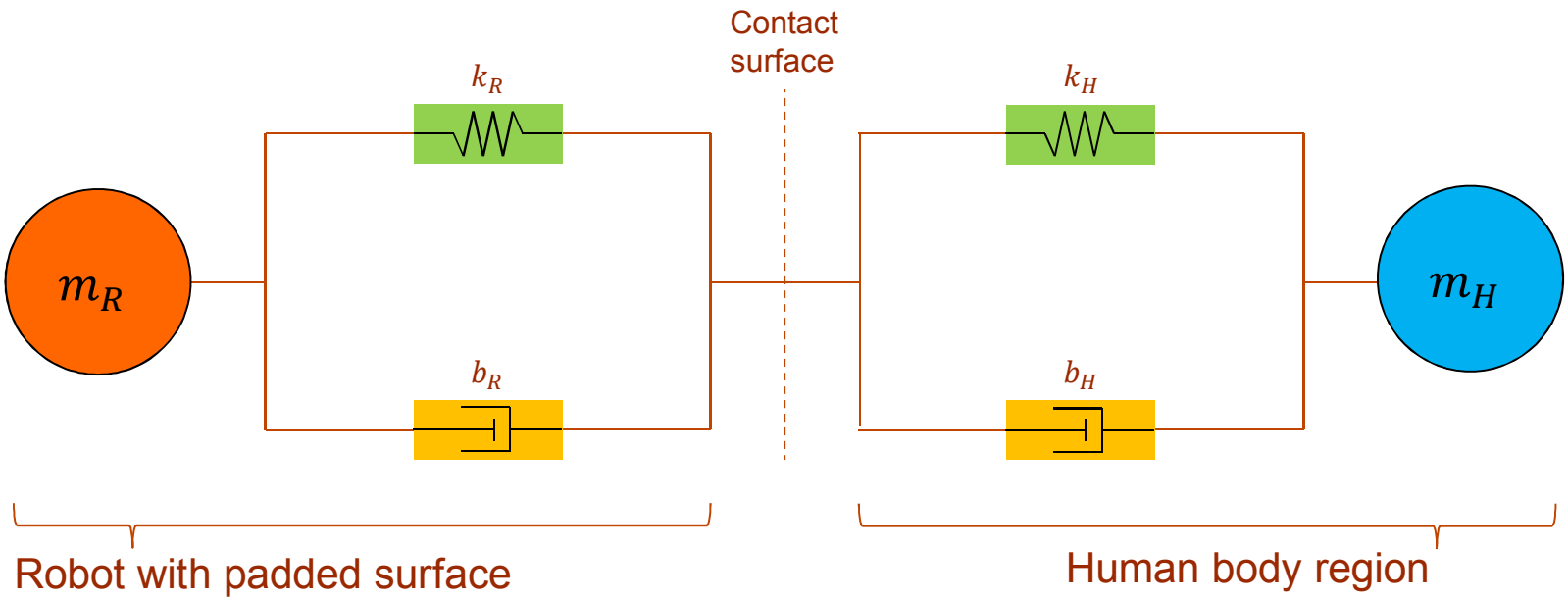


- Compute forward kinematic transformation
- Apply to calculate contact forces and moments from joints torques

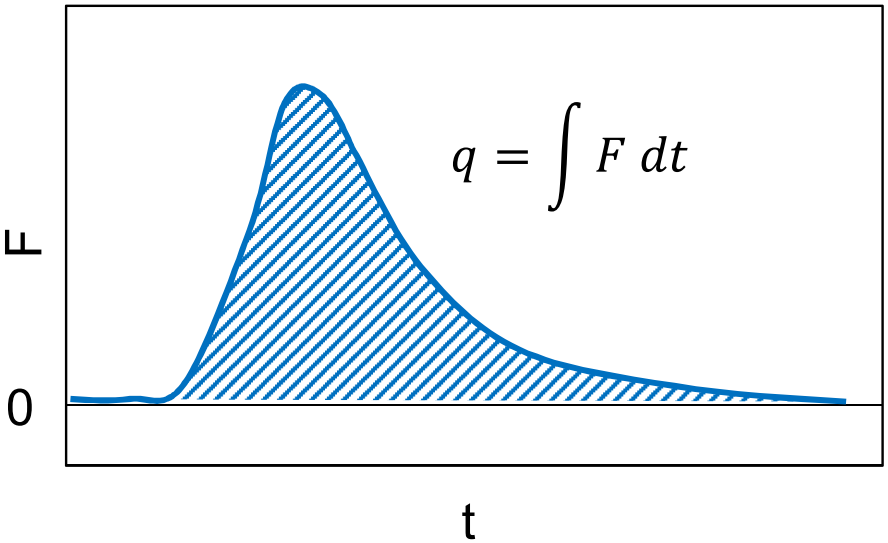
Models of Contact Events
Short Duration – Transient

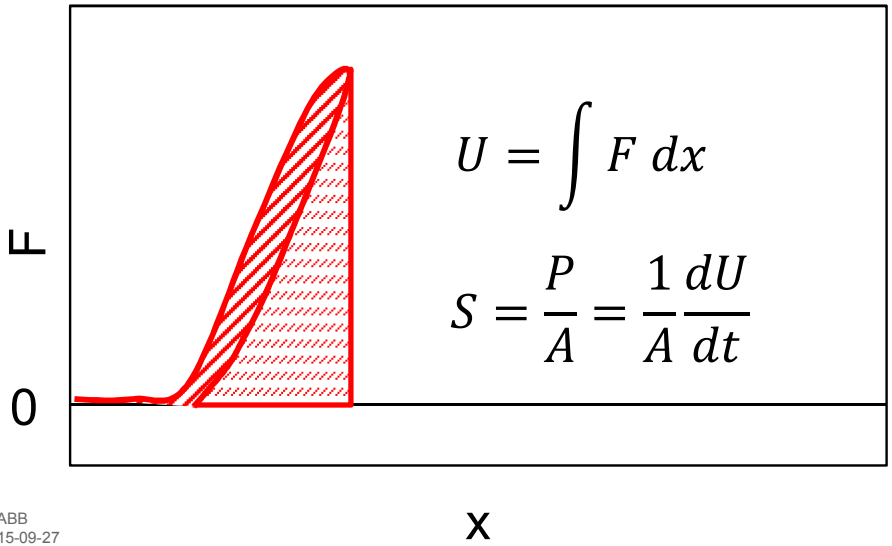


- Inelastic two-body contact
- Conservation of linear momentum
- Kinetic energy partly dissipated



Transient limit criteria related to robot design + control





- Force F $[N]$
- Pressure p $[\frac{N}{m^2} = \frac{J}{m^3}]$
- Momentum transfer q $[\frac{kg \cdot m}{s}]$
- Energy transfer U $[J]$
- Power P $[W = \frac{J}{s}]$
- Energy flux density K $[\frac{J}{m^2}]$
- Power flux density S $[\frac{W}{m^2}]$
- Contact area A $[m^2]$

General approach – effective inelastic 2-body collision

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

Kinetic energy transfer:	Worst-case assumption:	Energy stored in "spring":
$\Delta W = \frac{1}{2}\,\mu v_{rel}^2\,(1 - C_R^2)$	$C_R = 0$ ➔ $\Delta W = \frac{1}{2}\,\mu v_{rel}^2$	$\Delta W = \frac{1}{2}\,k\,x_1^2 = \frac{F^2}{2k}$

Fully deposit kinetic energy into tissue as modeled by spring:

$$\frac{F^2}{2k} = \frac{1}{2}\,\mu v_{rel}^2 \quad \rightarrow \quad v_{rel} = \frac{F}{\sqrt{\mu k}} = \frac{pA}{\sqrt{\mu k}} \quad \overset{F < F_{lim}}{\rightarrow} \quad \boxed{v_{rel} < \frac{F_{lim}}{\sqrt{\mu k}} \approx \frac{p_{lim}\,A_{avg}}{\sqrt{\mu k}}}$$

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

Effective mass of robot (1)
Proper formulation from complete equation of motion of robot

Equation of motion for stiff robot

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

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

Effective mass in direction of unit vector $\boldsymbol{u}$:

$$m_u = [\boldsymbol{u}^T \boldsymbol{\Lambda}_t^{-1}(\boldsymbol{q})\, \boldsymbol{u}]^{-1}$$

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

Kinetic energy

$$T = \frac{1}{2}\, \dot{\boldsymbol{q}}^T\, \boldsymbol{M}(\boldsymbol{q})\, \dot{\boldsymbol{q}}$$

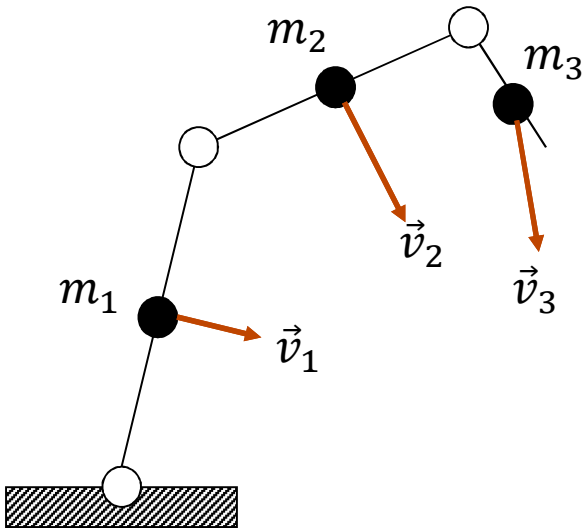
Jacobian matrix $\boldsymbol{J}(\boldsymbol{q})$ such that

$$\dot{\boldsymbol{x}} = \boldsymbol{J}(\boldsymbol{q})\, \dot{\boldsymbol{q}}$$

Translational and rotational parts

$$\boldsymbol{J}(\boldsymbol{q}) = \begin{bmatrix} \boldsymbol{J}_t(\boldsymbol{q}) \\ \boldsymbol{J}_r(\boldsymbol{q}) \end{bmatrix}$$

Effective mass of robot (2)
Approximate formulation: Lumped parameter model

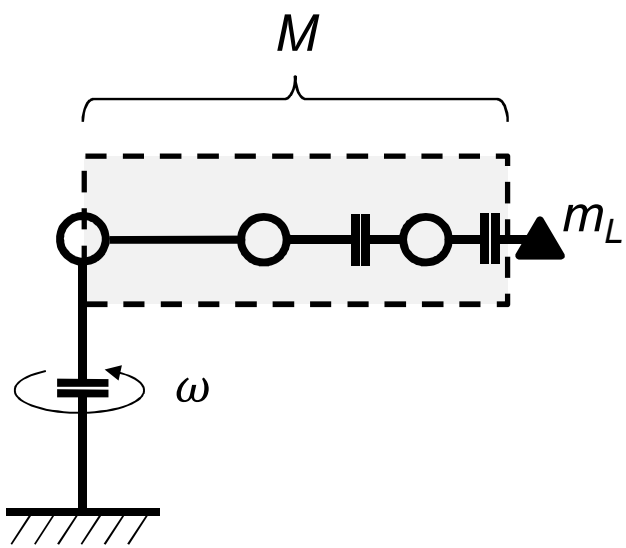


Example for stiff 3 DOF robot

- 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

$$\vec{p}_R = \sum_i m_i \vec{v}_i \qquad m_R = \frac{\vec{p}_R \cdot \vec{v}_R}{v_R^2}$$

6 DOF articulated robot – Pose F (1)
Straight from J2 to Flange, Rotation in J1

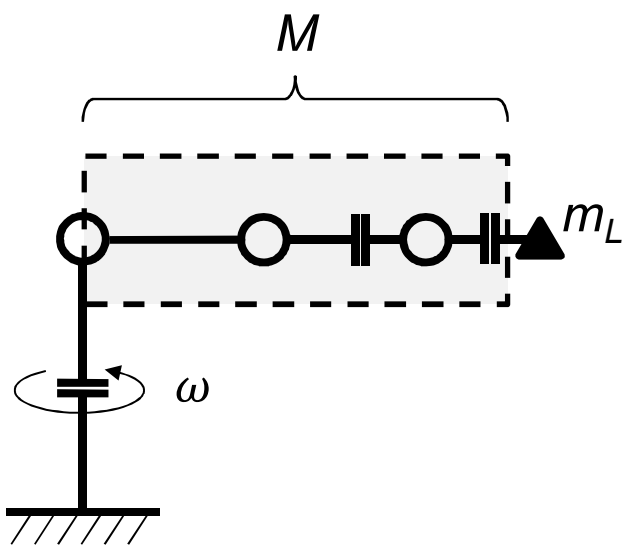


$$M = M_{2F} = m_{23} + m_{34} + m_{45} + m_{56} + m_{6F}$$

$$L_{2F} = L_{23} + L_{34} + L_{45} + L_{56} + L_{6F}$$

- For rotation about J1 and rigid joints J2, J3, J4, J5 and J6
  - Motion of J4, J6 not directly relevant, except if there is a heavy and asymmetric load on the flange
  - Speeds of COGs of links and load
    - $v_{23} = \omega \frac{L_{23}}{2}$
    - $v_{34} = \omega \left(L_{23} + \frac{L_{34}}{2}\right)$
    - $v_{45} = \omega \left(L_{23} + L_{34} + \frac{L_{45}}{2}\right)$
    - $v_{56} = \omega \left(L_{23} + L_{34} + L_{45} + \frac{L_{56}}{2}\right)$
    - $v_{6F} = \omega \left(L_{23} + L_{34} + L_{45} + L_{56} + \frac{L_{6F}}{2}\right)$
    - $v_L = \omega \left(L_{23} + L_{34} + L_{45} + L_{56} + L_{6F}\right)$
  - Speeds at J3, F
    - $v_3 = \omega L_{23}$
    - $v_F = \omega \left(L_{23} + L_{34} + L_{45} + L_{56} + L_{6F}\right)$

6 DOF articulated robot – Pose F (2)
Straight from J2 to Flange, Rotation in J1



$$M = M_{2F} = m_{23} + m_{34} + m_{45} + m_{56} + m_{6F}$$
$$L_{2F} = L_{23} + L_{34} + L_{45} + L_{56} + L_{6F}$$

- For rotation about J1 and rigid joints J2, J3, J4, J5 and J6
  - Motion of J4, J6 not directly relevant, except if there is a heavy and asymmetric load on the flange
  - Momentum of COGs of links and load
    - $p_{23} = m_{23} v_{23} = \omega\, m_{23} \frac{L_{23}}{2}$
    - $p_{34} = m_{34} v_{34} = \omega\, m_{34} \left(L_{23} + \frac{L_{34}}{2}\right)$
    - $p_{45} = m_{45} v_{45} = \omega\, m_{45} \left(L_{23} + L_{34} + \frac{L_{45}}{2}\right)$
    - $p_{56} = m_{56} v_{56} = \omega\, m_{56} \left(L_{23} + L_{34} + L_{45} + \frac{L_{56}}{2}\right)$
    - $p_{6F} = m_{6F} v_{6F} = \omega\, m_{6F} \left(L_{23} + L_{34} + L_{45} + L_{56} + \frac{L_{6F}}{2}\right)$
    - $p_L = m_L v_F = \omega\, m_L \left(L_{23} + L_{34} + L_{45} + L_{56} + L_{6F}\right)$
  - Effective mass for contact at elbow (J3)
    - $m_{eff}(J3) = \frac{p_{23}+p_{34}+p_{45}+p_{56}+p_{6F}+p_L}{v_3} = \frac{L_{2F}}{L_{23}} \left[\frac{M_{2F}}{2} + m_L\right]$
  - Effective mass for contact at flange (F)
    - $m_{eff}(F) = \frac{p_{23}+p_{34}+p_{45}+p_{56}+p_{6F}+p_L}{v_F} = \frac{M_{2F}}{2} + m_L$

ISO/TS 15066 – Present Status
Body Model

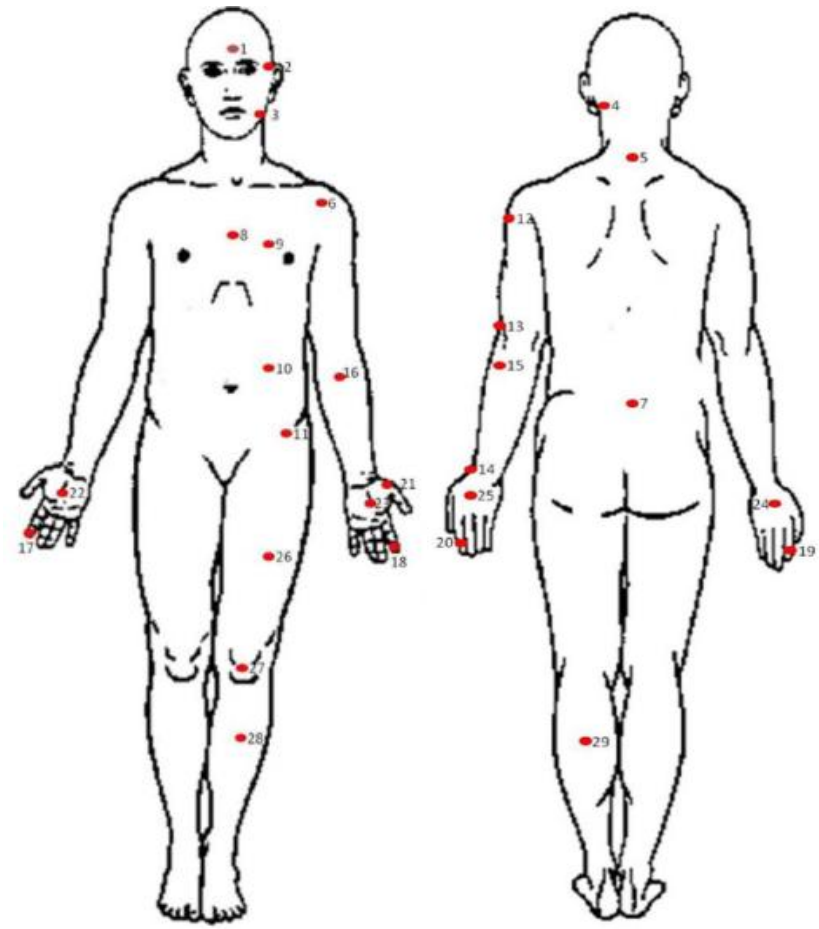


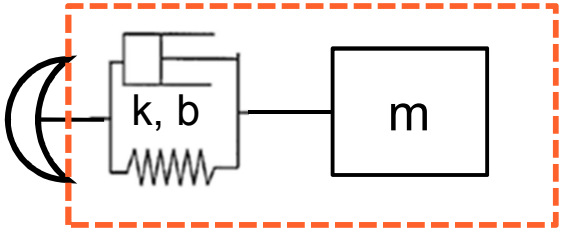
Figure A.1 — Body Model

Table A.1 — Body Model Descriptions

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

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

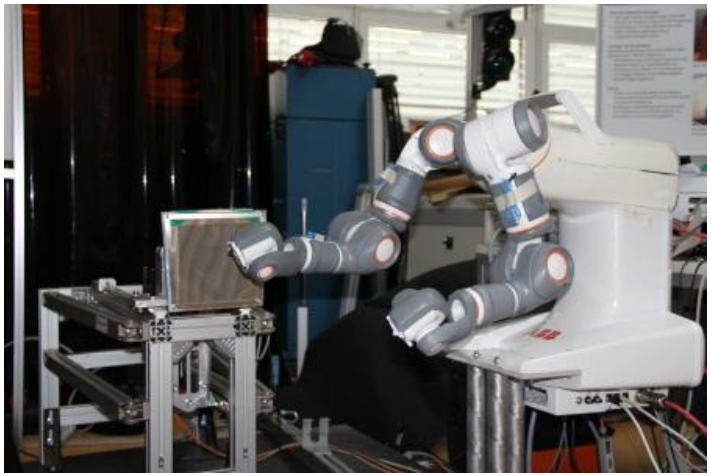
Collision Experiments for Safety and Characterization Methods of Measurement

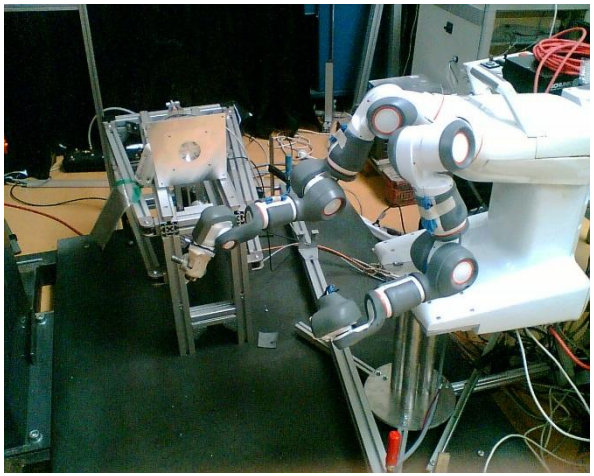


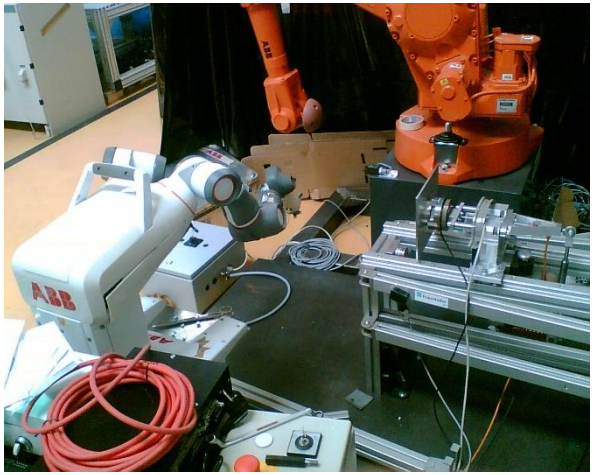
- Visco-elastic properties of body area in spring-damper element
- Mass m chosen to represent effective mass of body area
- Measure over time
  - Contact area, pressure distribution
  - Forces, torques, displacement

Experimental Characterization of Collaborative Robot Collisions

Experimental Setups





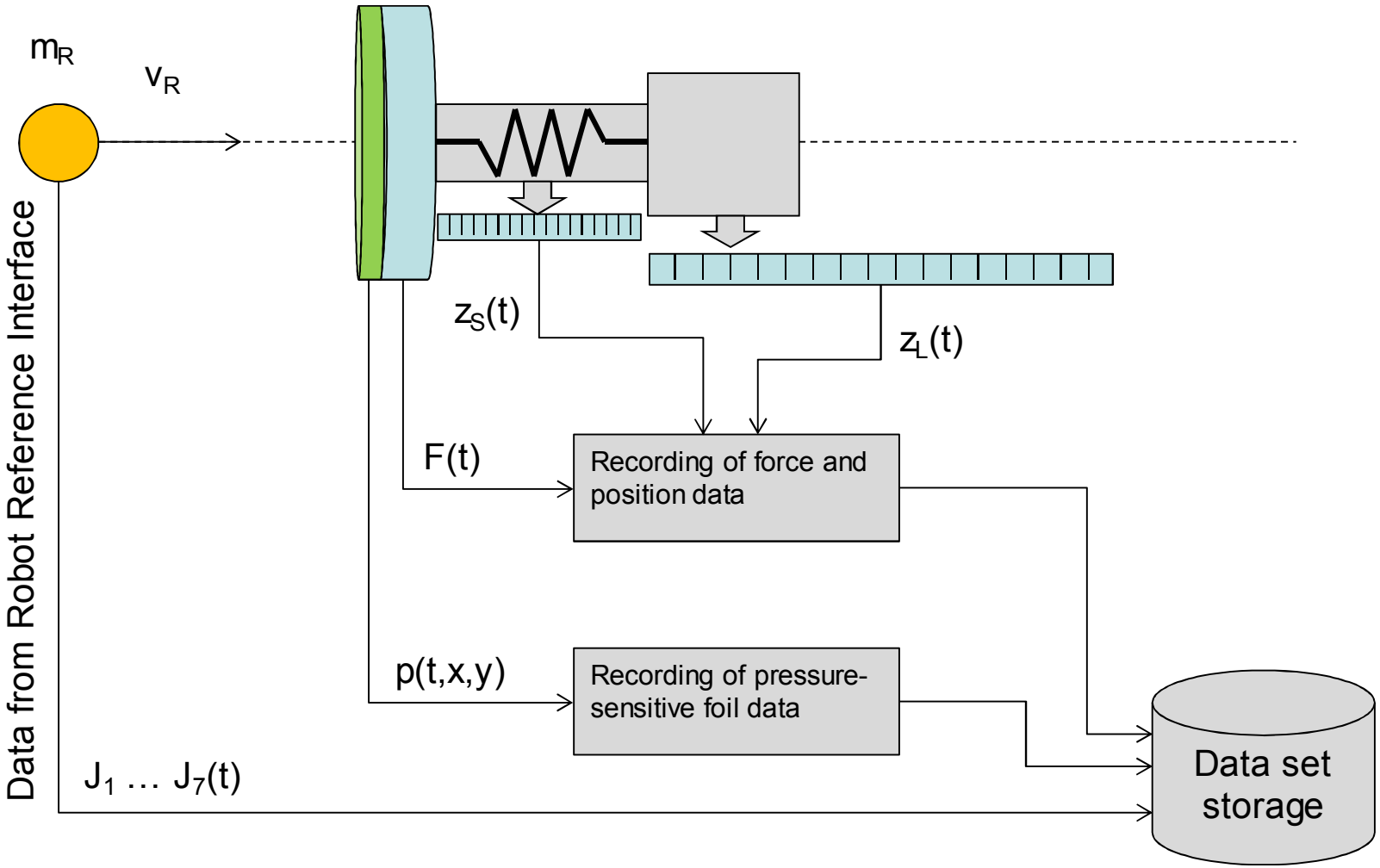


rosetta

Fraunhofer IPA

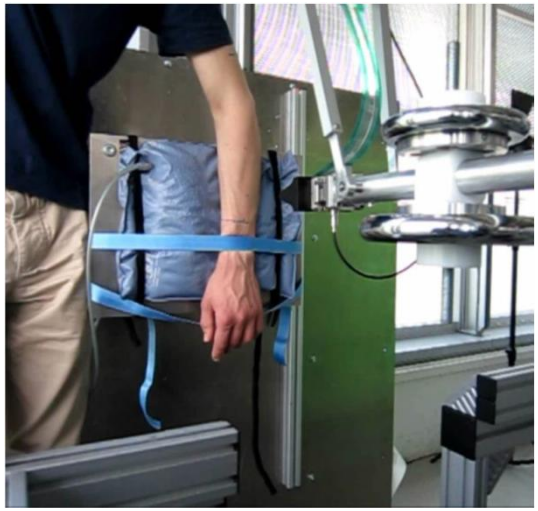
Experimental Characterization of Collaborative Robot Collisions

Experimental Setup



Experimental Characterization of Collaborative Robot Collisions

Experimental Setups



Collision Experiments for Safety and Characterization Quantities for Comparisons

- Quasi-static contact events
  - Characterized by forces and pressures, contact area
  - Controlled by joint torque limitation (safety-related control function or electro-mechanical design)
- Transient contact events
  - Characterized by energy transfer, contact area, duration (power flux density)
  - Controlled by limiting robot speed

Collision Experiments for Safety and Characterization
Summary and Outlook

- Collision experiments are necessary to establish suitability of robots for collaborative operation according to power-and-force-limiting
- Collision data can be used to verify and validate simulations of contact events for a given robot type
- Experimental set ups and practical challenges
- Comparison of contact event characteristics is possible for given robot motion or pose
- Future or deployment of collaborative applications
  - → use validated robot with experimental collision data and simulation model
  - → determine limit parameters (torques, forces, speeds) of robot motion from simulation of target application

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