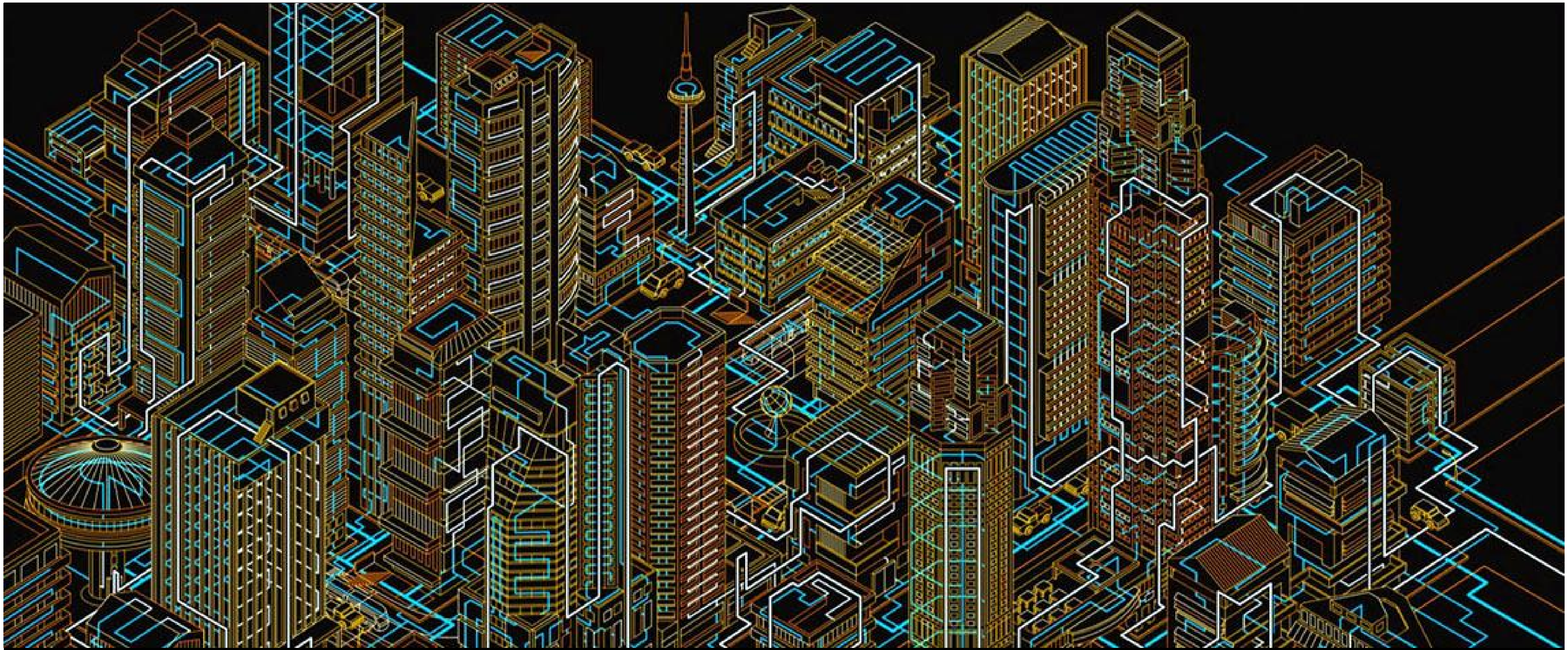
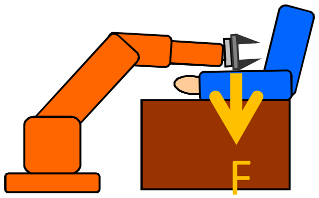


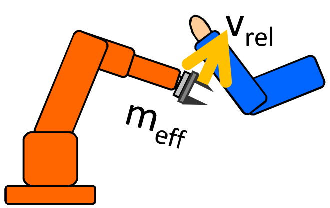
Björn Matthias, ABB Corporate Research, 2015-09-28

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

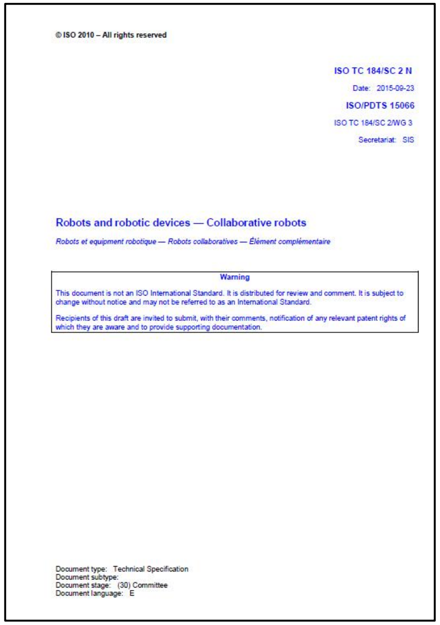
Workshop IROS 2015 – Robotic co-workers – methods, challenges and industrial test cases

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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ISO TC 184/SC 2 N
Date: 2015-09-23
ISO/PDTS 15066
ISO TC 184/SC 2/WG 3
Secretariat: SIS

Robots and robotic devices — Collaborative robots

Robots et equipment robotique — Robots collaboratives — Élément complémentaire

Warning

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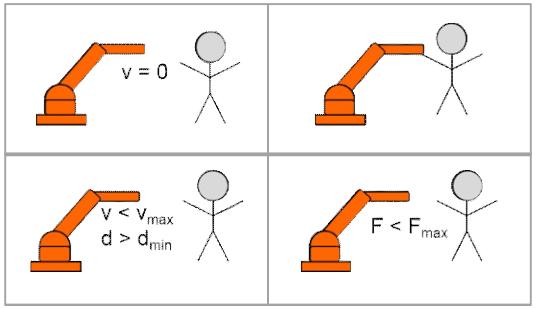
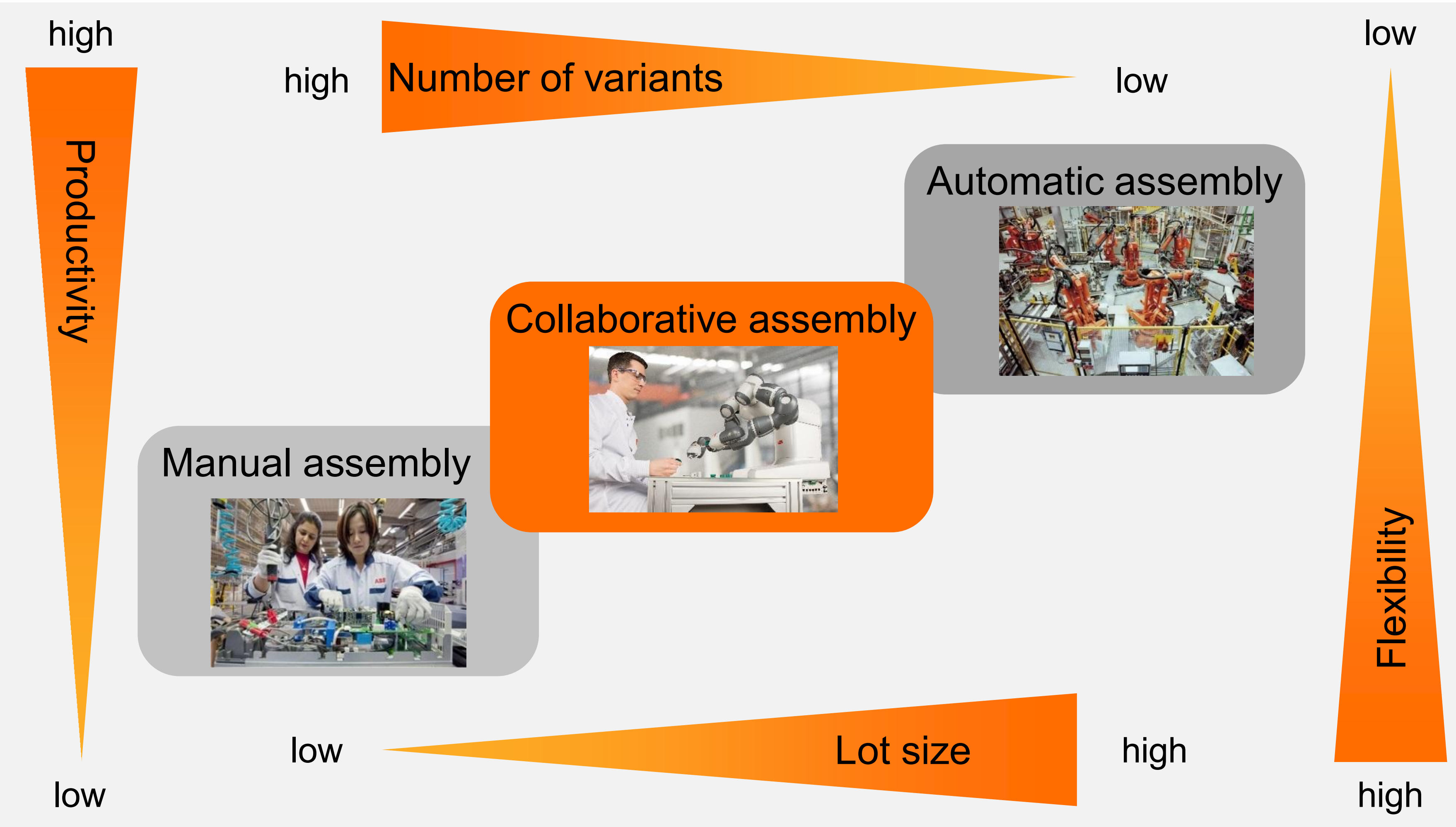
Document type: Technical Specification
Document subtype:
Document stage: (30) Committee
Document language: E



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

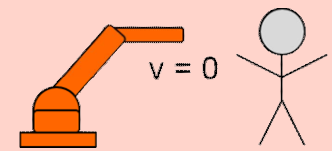
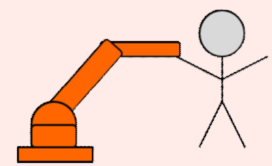
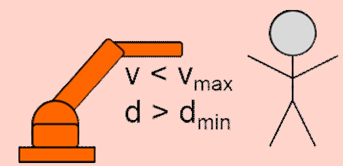
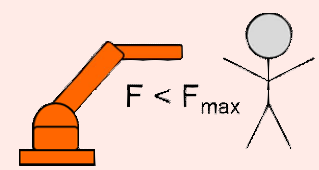
Type A Standards

- IEC 61508 – Functional Safety
- ISO 12100 – Risk Assessment

Laws + Directives

- Example EU:
  European Machinery Directive 2006/42/EC

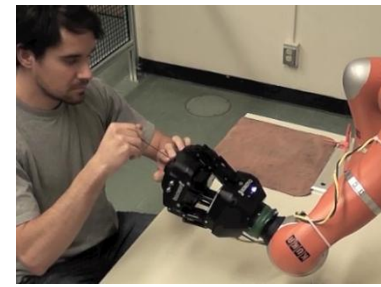
Types of Collaborative Operation According to ISO 10218, ISO/TS 15066

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	

Short Introduction to HRC
Examples of Collaborative Operation (1)

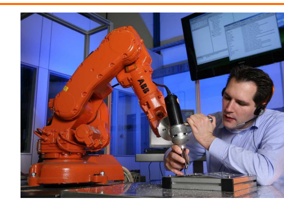
Safety-rated monitored stop
(ISO 10218-1, 5.10.2, ISO/TS 15066)

- 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)

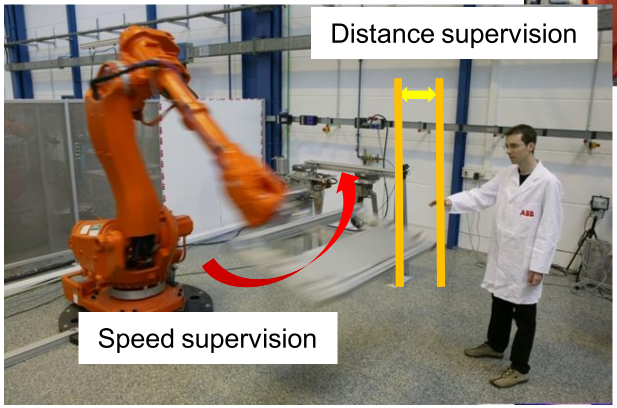
- Reduce risk by providing worker with direct control over robot motion at all times in collaborative workspace
- Achieved by (controls close to end-effector)
  - Emergency stop
  - Enabling device



Short Introduction to HRC
Examples of Collaborative Operation (2)

Speed and separation monitoring
(ISO 10218-1, 5.10.4, ISO/TS 15066)

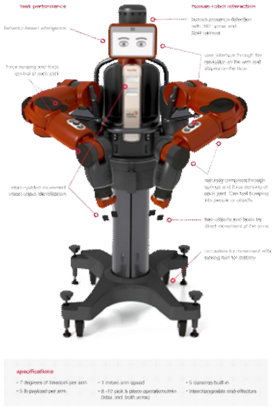
- Reduce risk by maintaining sufficient distance between worker and robot in collaborative workspace
- Achieved by
  - distance supervision, speed supervision
  - protective stop if minimum separation distance or speed limit is violated
  - taking account of the braking distance in minimum separation 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

DC523 KNX Coll. HMI 2011. VR1. VR2. BJE.

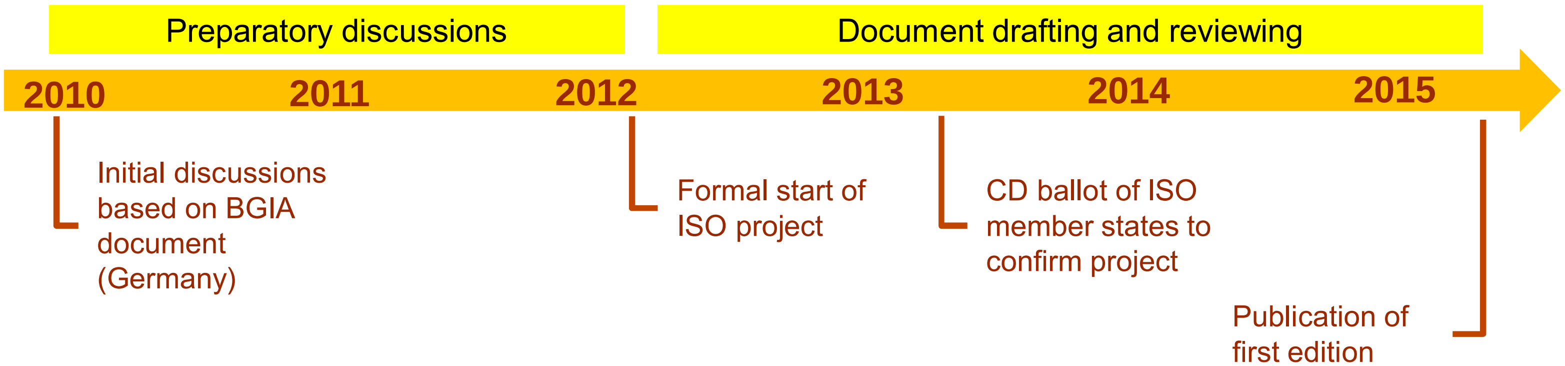


ISO/TS 15066 – Present Status
ISO Project Overview

- 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

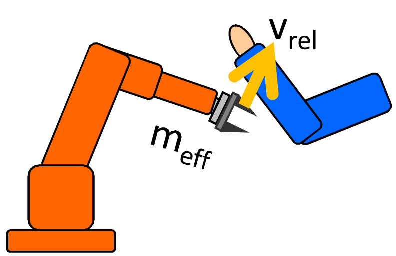


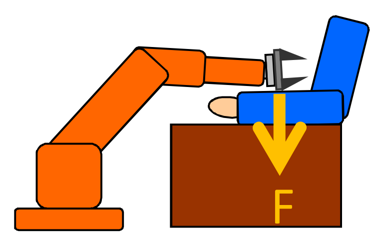
- Project start: 2012
- Project end: 2015-12-05
- Recent meeting schedule
  - SC 2/WG 3 40th Meeting: 2015 June 15-17, at Daimler, Sindelfingen, Germany
  - TC 184/SC 2 22nd Plenary Meeting: 2015 June 18-19, at BGHM, Stuttgart, Germany
  - SC 2/WG 3 41st Meeting: 2015 December 7-9, in Yokohama, Japan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

Biomechanical Limit Criteria

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

	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





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:

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

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

ABB

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

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

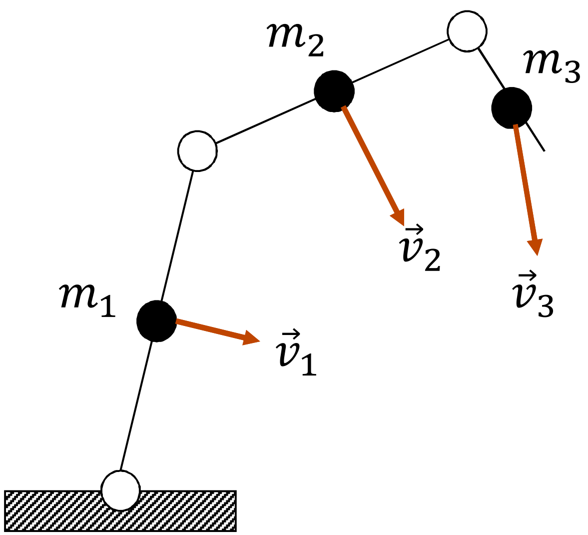
Jacobian matrix $\boldsymbol{J}(\boldsymbol{q})$ such that

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

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

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

ISO/TS 15066 – Present Status
Body Model

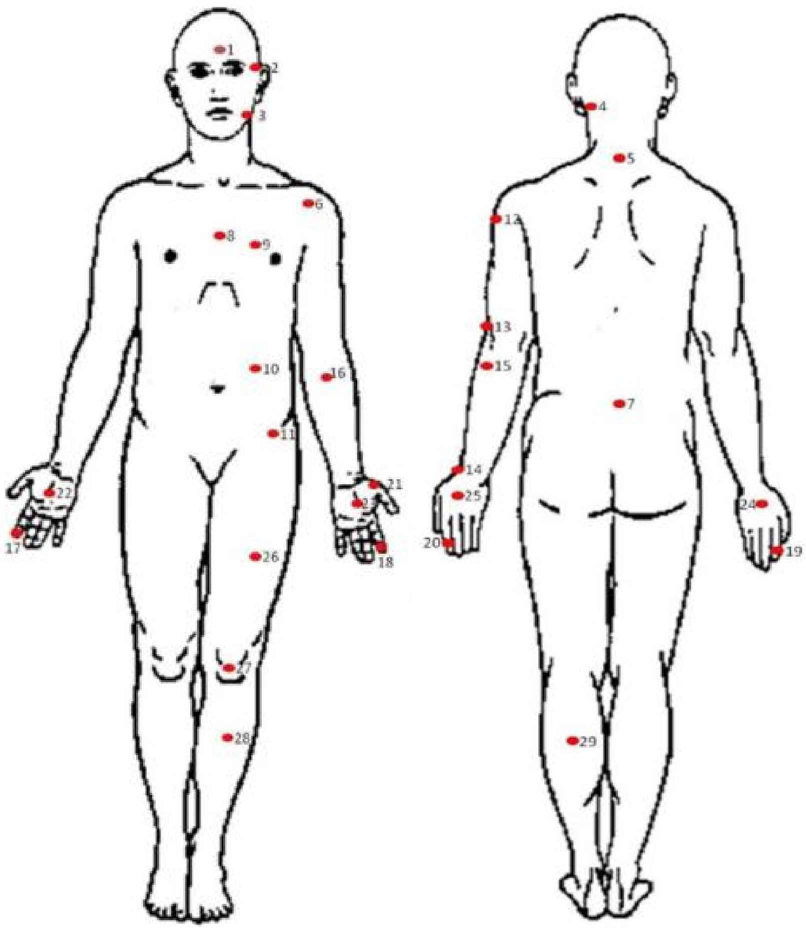


Figure A.1 — Body Model

Table A.1 — Body Model Descriptions

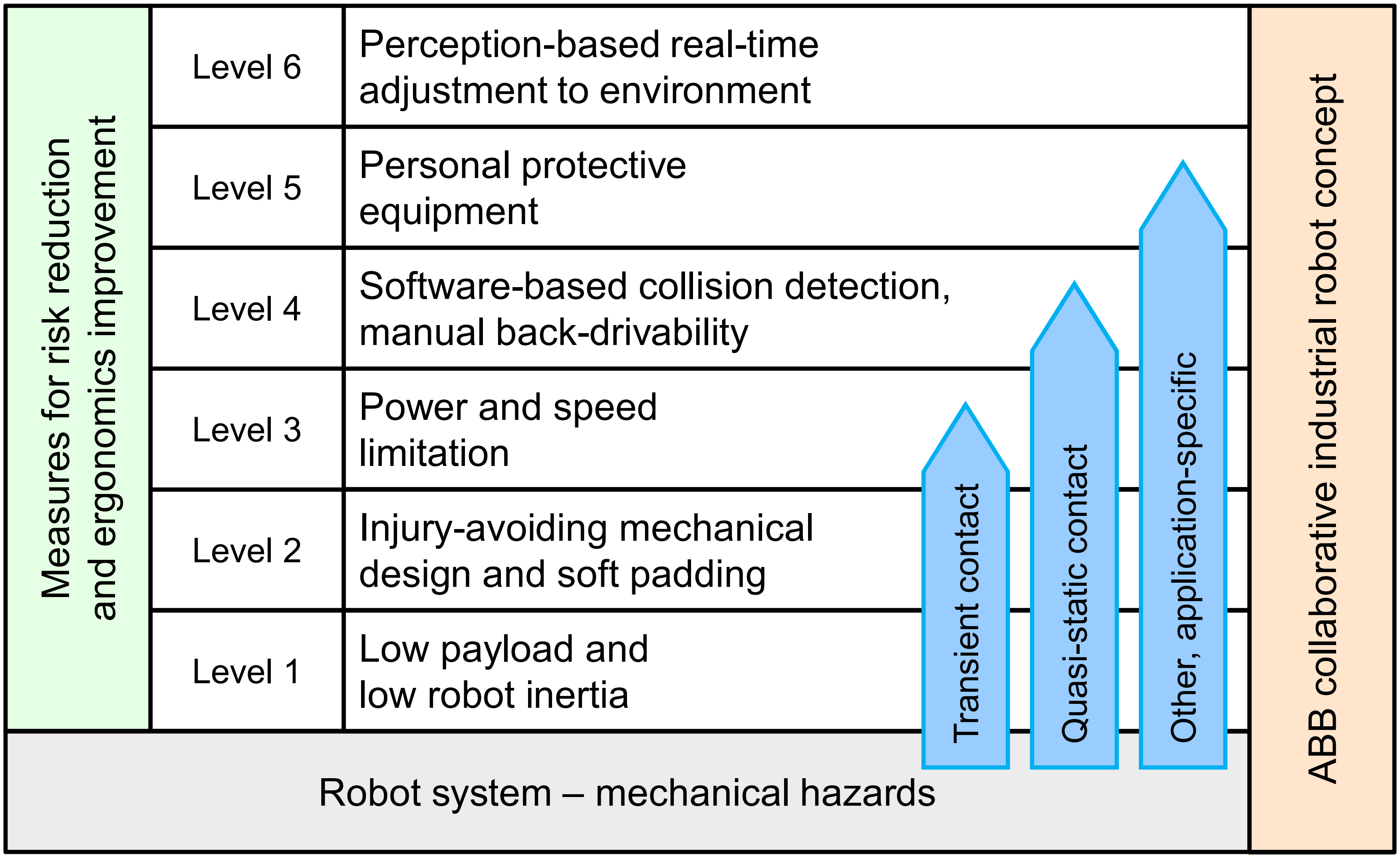
Body Region	Specific Body Area		Front/ Rear
Skull and forehead	1	Middle of forehead	Front
	2	Temple	Front
Face	3	Masticatory muscle	Front
Neck	4	Neck muscle	Rear
	5	Seventh neck vertebra	Rear
Back and shoulders	6	Shoulder joint	Front
	7	Fifth lumbar vertebra	Rear
Chest	8	Sternum	Front
	9	Pectoral muscle	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

YuMi® - IRB 14000 0.5/0.55
Overview

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

ABB YuMi® Safety Concept
Protection Levels



YuMi®
Target growth markets

Small Parts Assembly	Consumer Products	Toy Industry
▪ Collaborative Assembly ▪ Camera-based inspection and assembly ▪ Accurate and fast assembly ▪ Testing and packaging	▪ Collaborative Assembly (Plastic parts etc.) ▪ Packaging of small goods ▪ Multifunction hand for add components	▪ Collaborative Assembly (toys) ▪ Use of feeding and vision options

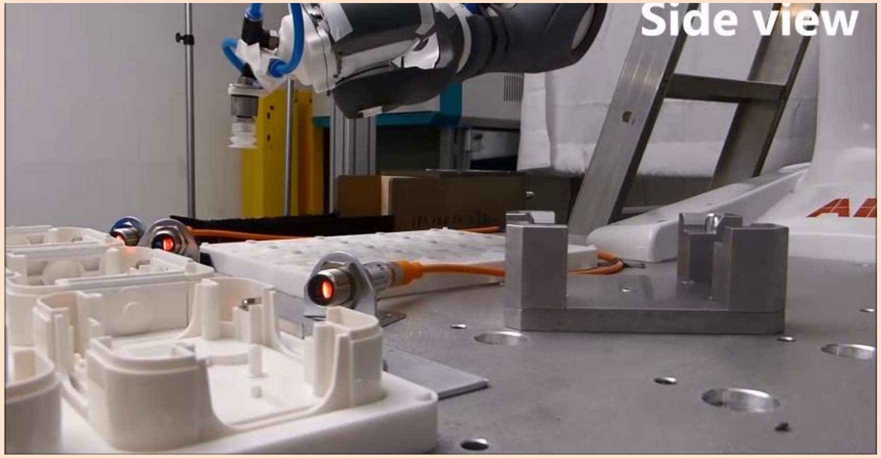
Assembly Process
Sensing Concepts

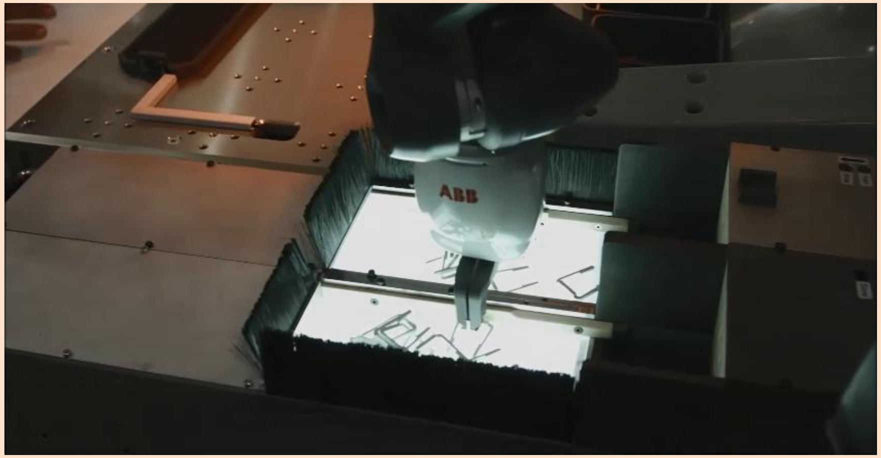
Digital sensor for material detection and sequence control

- Photo sensor
- Proximity sensor

Integrated vision system for flexible part detection

- External camera
- Integrated camera





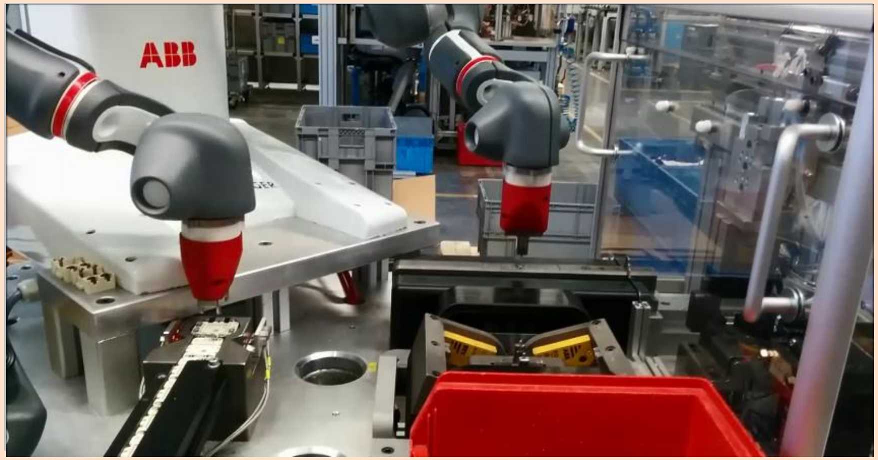
Assembly Process
Dual-Arm Assembly

Independent tasks for cycle time optimization with fixtures in workspace

BJE

Hand-in-hand assembly for flexibility without fixtures in workspace

HMI.



Collaboration & Ergonomics
Integration in Assembly Lines

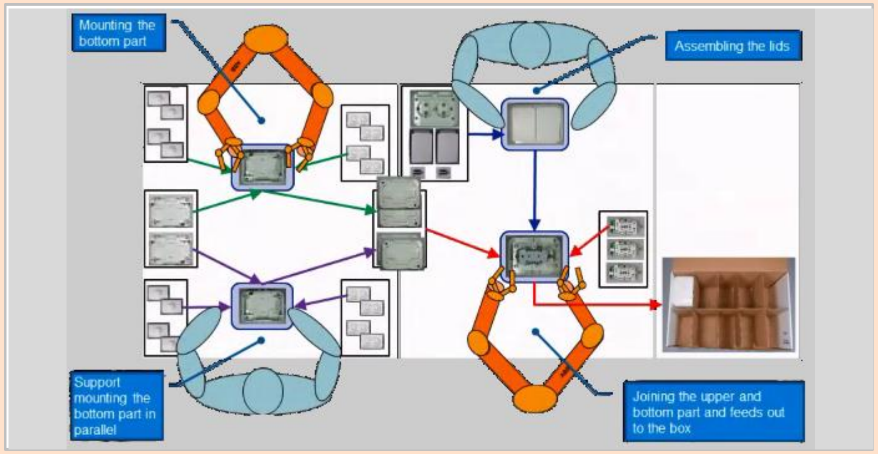
Working side-by-side with humans

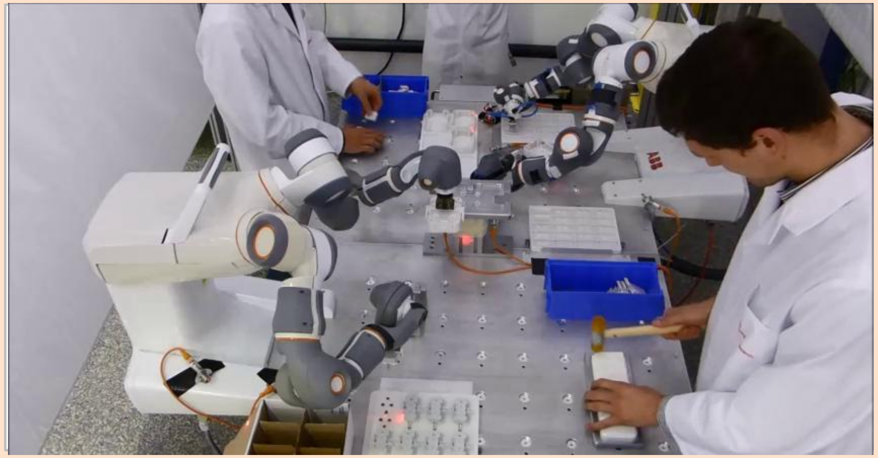
- 7 degree-of-freedom manipulator for kinematic redundancy
- Compact motion w/o disturbing the human worker

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

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