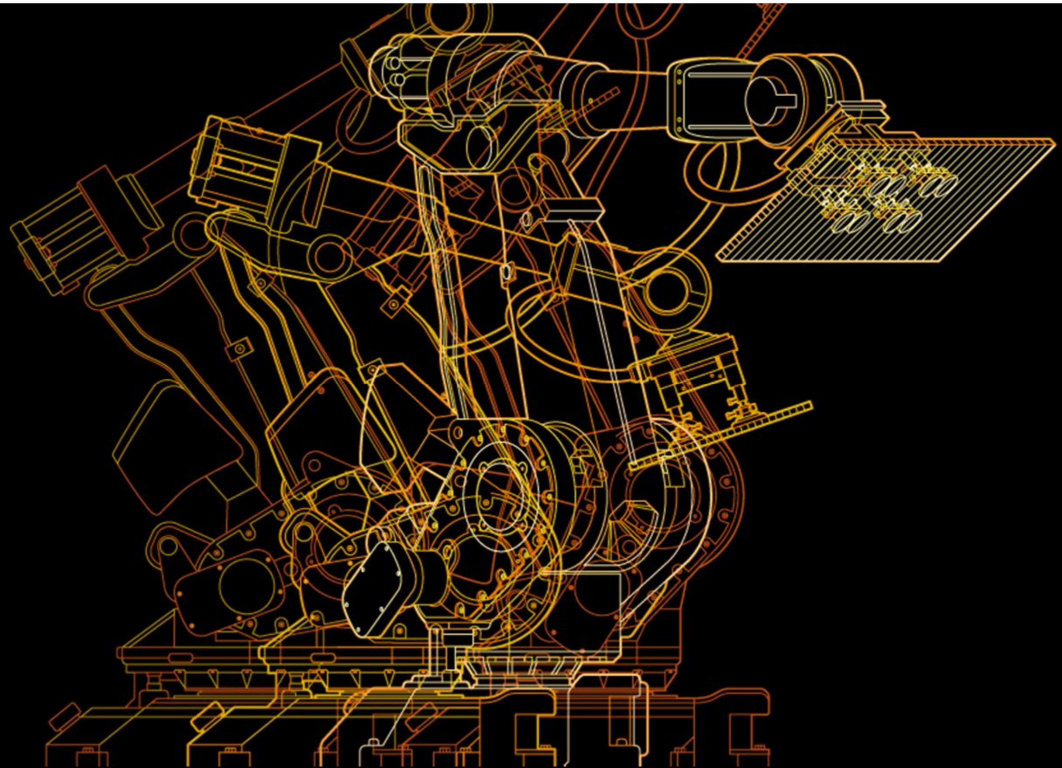


Björn Matthias, ABB Corporate Research, 2014-03-10

Industrial Safety Requirements for Collaborative Robots and Applications

ERF 2014 – Workshop: Workspace Safety in Industrial Robotics: trends, integration and standards

Safety Requirements for Collaborative Robots and Applications

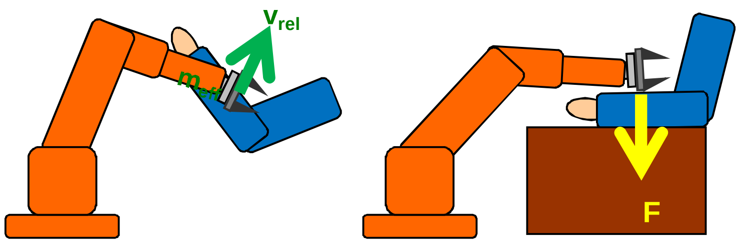

INTERNATIONAL STANDARD ISO 10218-1

Robots and robotic devices — Safety requirements for industrial robots —
Part 1:
Robots


INTERNATIONAL STANDARD ISO 10218-2

Robots and robotic devices — Safety requirements for industrial robots —
Part 2:
Robot systems and integration

- 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
- Present Standardization Projects
  - ISO/TS 15066 – Safety of collaborative robots
  - Biomechanical criteria
- Collaborative operation



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

INTERNATIONAL STANDARD ISO 10218-1

Robots and robotic devices — Safety requirements for industrial robots —

Part 1: Robots

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

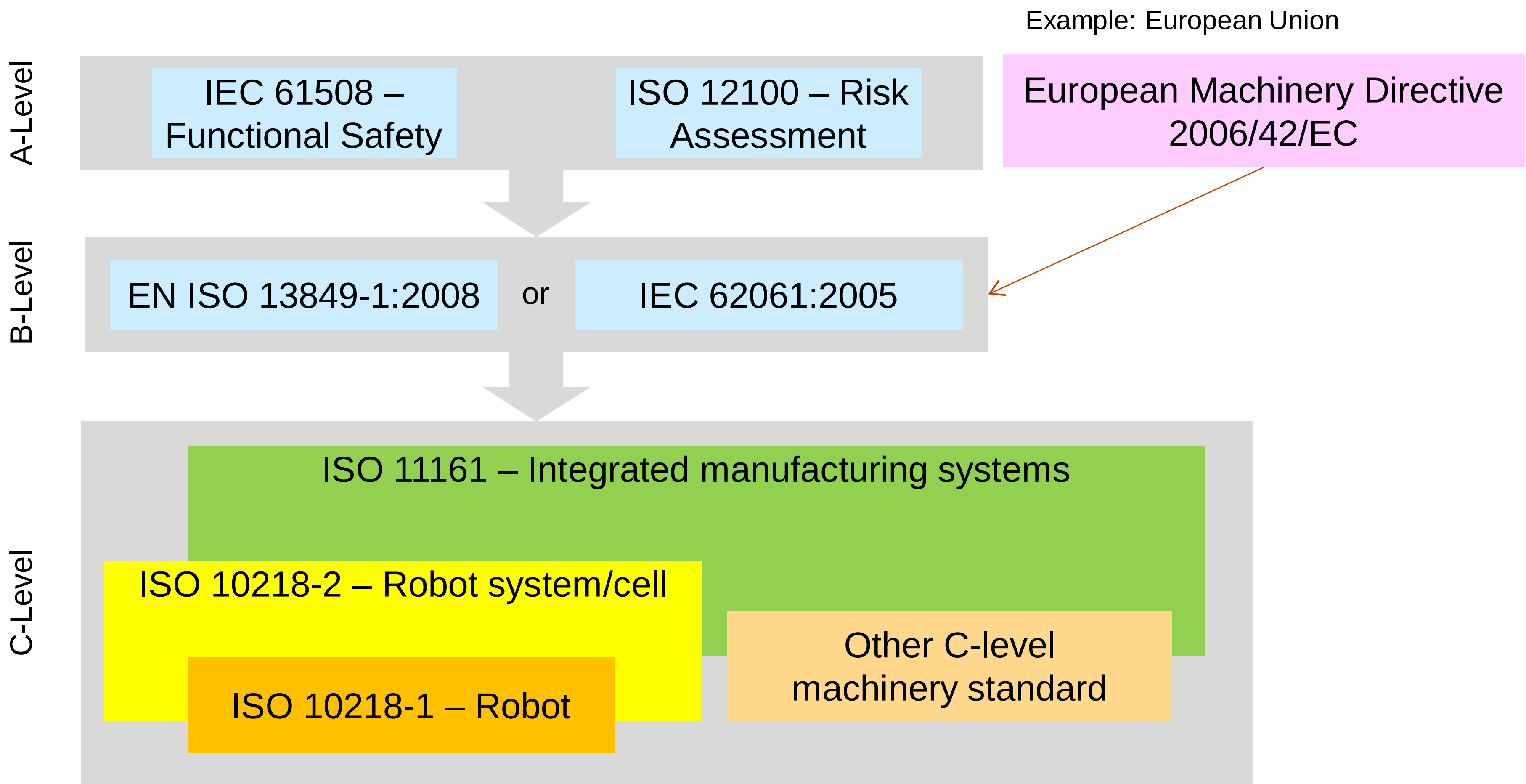
- Robots and robotic devices — Safety requirements for industrial robots — Part 2: Robot systems and integration
- Scope
  - Robot (see Part 1)
  - Tooling
  - Work pieces
  - Periphery
  - Safeguarding
- Main references
  - ISO 10218-1 – Robot
  - ISO 11161 – Integrated manufacturing systems
  - ISO 13854 – Minimum gaps to avoid crushing
  - ISO 13855 – Positioning of safeguards
  - ISO 13857 – Safety distances
  - ISO 14120 – Fixed and movable guards

INTERNATIONAL STANDARD ISO 10218-2

Robots and robotic devices — Safety requirements for industrial robots —

Part 2: Robot systems and integration

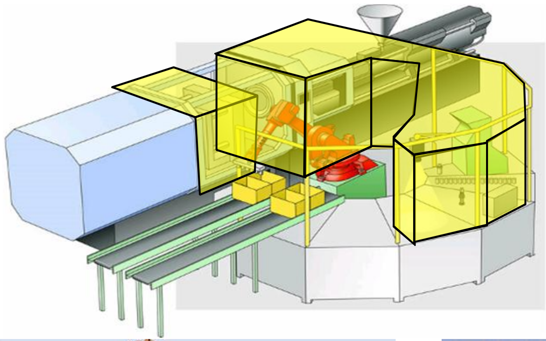
Safety Standards for Applications of Industrial Robots
Related Standards and Directives

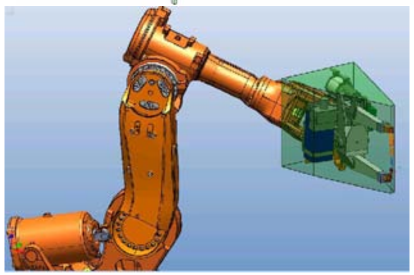


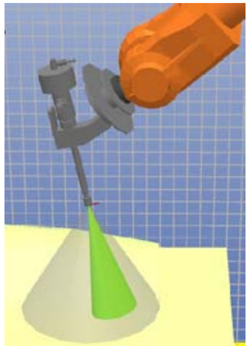
Safety Functions of Industrial Robot Controller
Review of Basic Safety-Related Functions

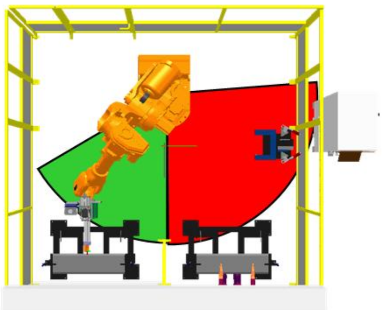
- E-stop
- Protective stop
  - Stop categories (cat. 0, cat. 1, cat. 2 as per IEC 60204-1)
- Operating modes
  - Automatic / manual / manual high-speed
- Pendant controls
  - Enabling
  - Start / restart
  - Hold-to-run
- Limit switches
- Muting functions
  - Enable / limits switches / …

Safety Functions of Industrial Robot Controller
Supervision Functions



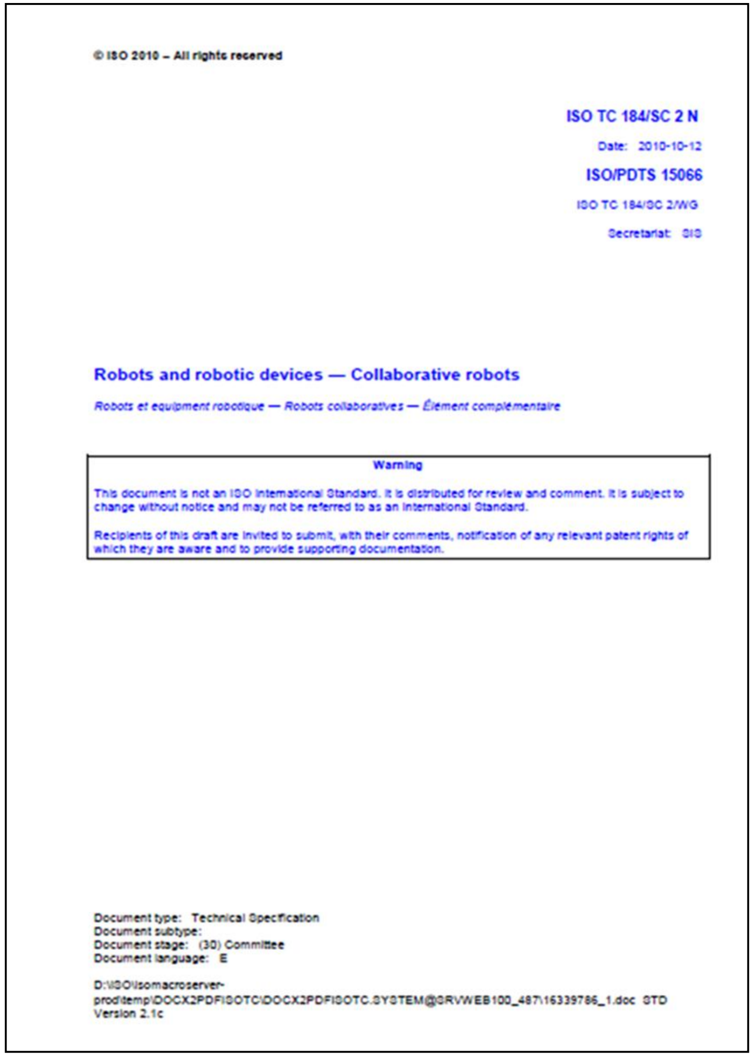






- Basic supervision of robot motion, i.e. motion executed corresponds to motion commanded
- Supervision of kinematic quantities
  - Position
    - TCPs, elbow, solid model of manipulator, tool
  - Speed
    - TCPs, elbow, …
  - Acceleration, braking
- Possibility: Supervision of dynamic quantities, esp. for collaborative operation
  - Torques
  - Forces
- Possibility: Application-related / user-defined supervision functions

Present Standardization Activities
ISO/TS 15066 – Safety of Collaborative Robots



ISO TC 184/SC 2 N

Date: 2010-10-12

ISO/PDTS 15066

ISO TC 184/SC 2/WG

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

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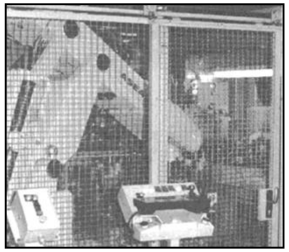
- Design of collaborative work space
- Design of collaborative operation
  - Minimum separation distance S / maximum robot speed K_R
  - Static (worst case) or dynamic (continuously computed) limit values
  - Safety-rated sensing capabilities
  - Ergonomics
- Methods of collaborative working
  - Safety-rated 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.?

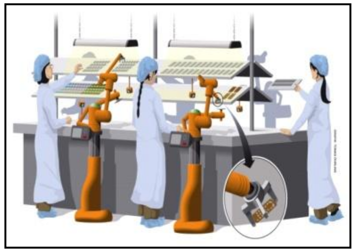
Safety Requirements for Collaborative Robots and Applications

- Short Introduction to Human-Robot Collaboration (HRC)
  - Evolution of Safety Concepts
  - Definition of Collaborative Operation
  - Types of Collaborative Operation
  - Examples of Collaborative Operation
- Collaborative Application Scenarios
  - ABB Dual-Arm Concept Robot
  - Other Relevant Robot Developments
- Present Challenges for Collaborative Small-Parts Assembly (SPA)
  - Safety
  - Ergonomics
  - Productivity
  - Application Design
  - Ease-of-Use

Short Introduction to HRC
Evolution of Safety Concepts







absolute separation of robot and human workspaces

complete union of robot and human workspaces

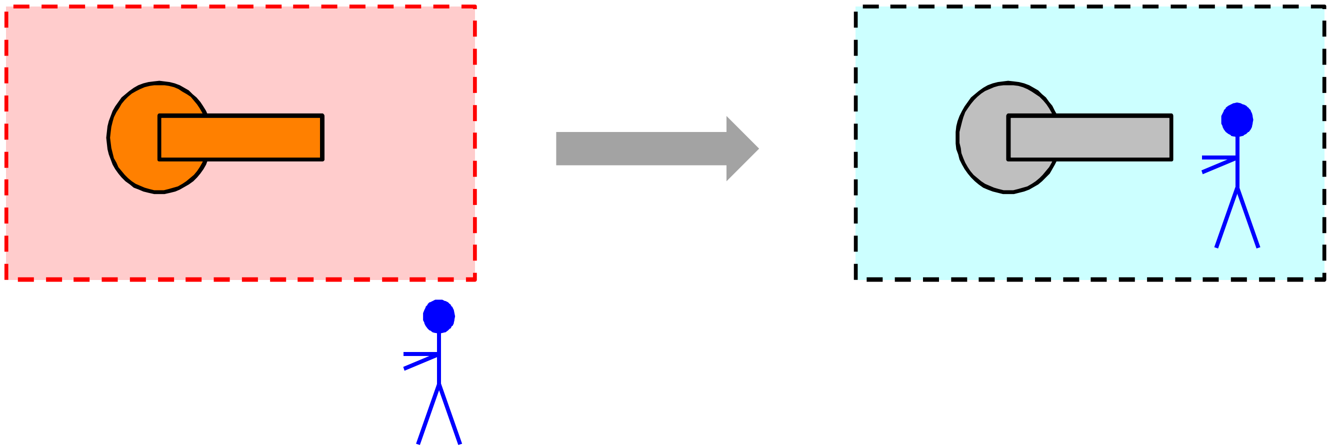
Discrete safety
→ No HRC

Safety controllers
→ Limited HRC

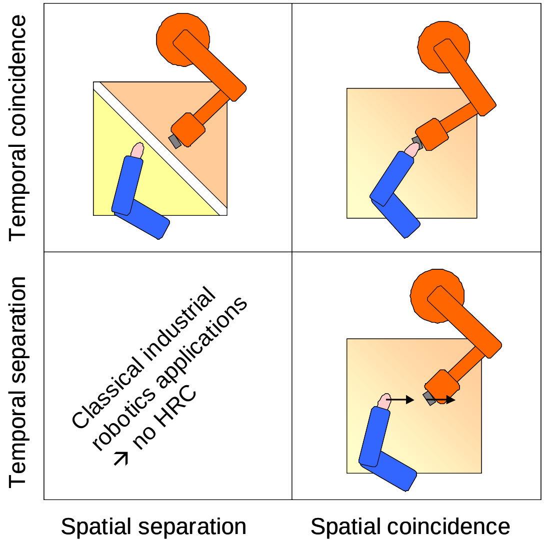
Harmless manipulators
→ Full HRC

Conventional industrial robots

Collaborative industrial robots



Short Introduction to HRC
Definition of Collaborative Operation



(adapted from S. Thiemermann, Dissertation, 2005)

- ISO 10218-1:2011, clause 3.4
  - ***collaborative operation***
    state in which purposely designed robots work in direct cooperation with a human within a defined workspace
- Degree of collaboration
  1. Once for setting up
     (e.g. lead-through teaching)
  2. Recurring isolated steps
     (e.g. manual gripper tending)
  3. Regularly or continuously
     (e.g. manual guidance)

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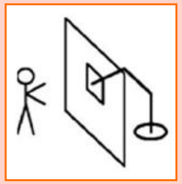
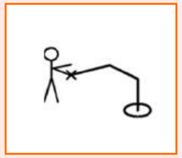
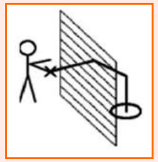
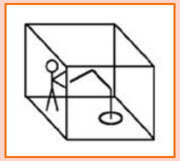
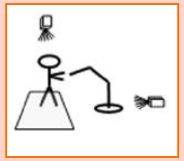
Safety Functions of Industrial Robot Controller
Types of Collaborative Operation According to ISO 10218-1

ISO 10218-1, clause	Type of collaborative operation	Main means of risk reduction	Pictogram (ISO 10218-2)
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 Dual-Arm Concept Robot* collaborative assembly robot)	In contact events, robot can only impart limited static and dynamics forces	

Safety Functions of Industrial Robot Controller
Types of Collaborative Operation According to ISO 10218-1

	Speed	Separation distance	Torques	Operator controls	Main risk reduction
Safety-rated monitored stop	Zero while operator in CWS*	Small or zero	Gravity + load compensation only	None while operator in CWS*	No motion in presence of operator
Hand guiding	Safety-rated monitored speed (PL d)	Small or zero	As by direct operator input	E-stop; Enabling device; Motion input	Motion only by direct operator input
Speed and separation monitoring	Safety-rated monitored speed (PL d)	Safety-rated monitored distance (PL d)	As required to execute application and maintain min. separ. distance	None while operator in CWS*	Contact between robot and operator prevented
Power and force limiting	Max. determined by RA⁺ to limit impact forces	Small or zero	Max. determined by RA⁺ to limit static forces	As required for application	By design or control, robot cannot impart excessive force

* CWS = Collaborative Work Space

⁺ RA = Risk Assessment

ABB

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)
- Application
  - Manual loading of end-effector with drives energized
  - Automatic resume of motion

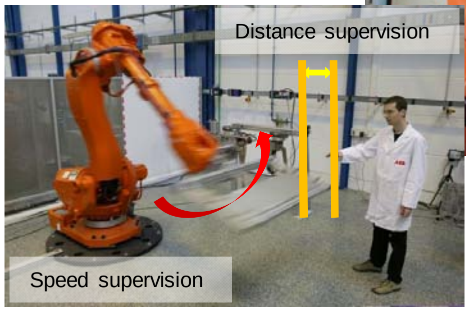
Hand guiding
(ISO 10218-1, 5.10.3, ISO/TS 15066)

- 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-rated monitored speed
- Application
  - Ergonomic work places
  - Coordination of manual + partially automated steps

Safety Functions of Industrial Robot Controller
Collaborative Operation (2)

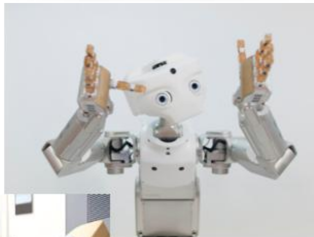
Speed and separation monitoring
(ISO 10218-1, 5.10.4, ISO/TS 15066)

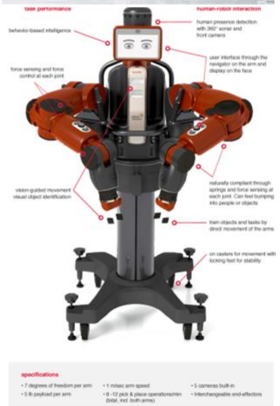
- Reduce risk by maintaining sufficient distance between worker and robot in collaborative workspace
- Achieved by
  - distance supervision, speed supervision
  - protective stop if minimum separation distance or speed limit is violated
  - taking account of the braking distance in minimum separation distance
- Additional requirements on safety-rated periphery
  - for example, safety-rated camera systems

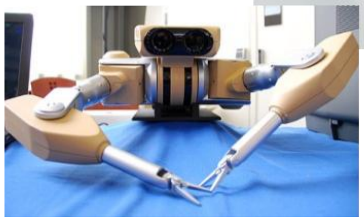


Power and force limiting by inherent design or control
(ISO 10218-1, 5.10.5, ISO/TS 15066)

- 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 (SPA = small parts assembly)

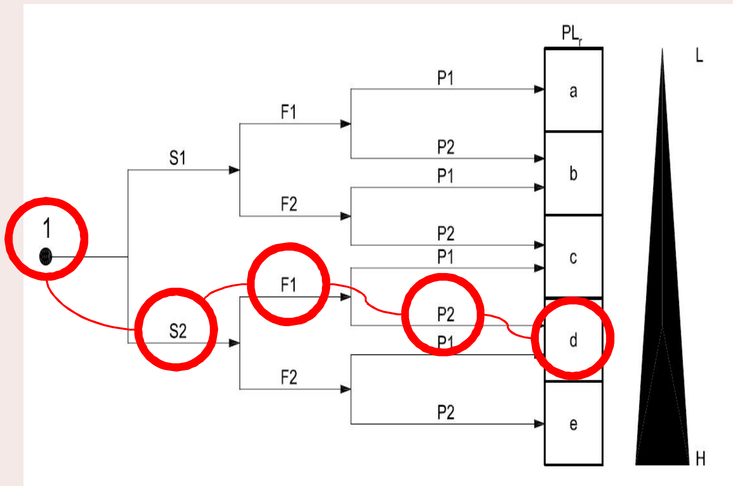


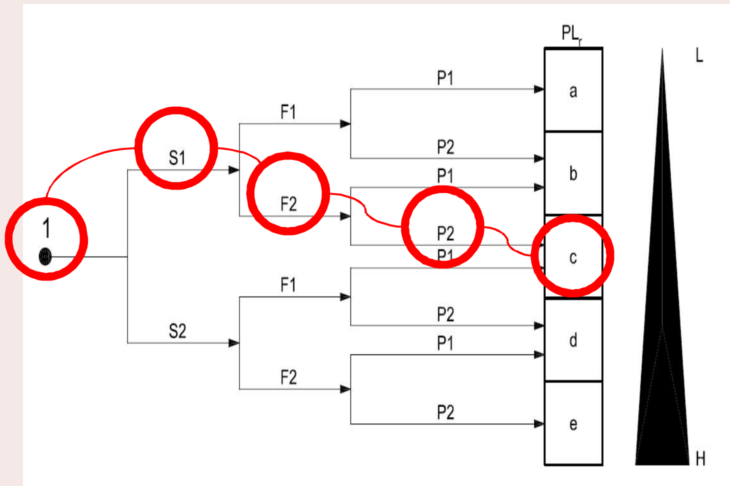




Safety Functions of Industrial Robot Controller
Collaborative Operation (3)

Standard industrial robot	**Special robots for collaborative operation** (following ISO 10218-1, clause 5.10.5)
Injury severity S2 (irreversible)	Injury severity S1 (reversible)
Exposure F1 (rare)	Exposure F2 (frequent)
Avoidability P2 (low)	Avoidability P2 (low)





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”

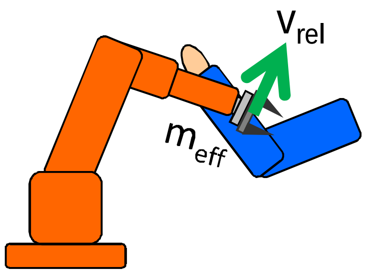
Present projects in standardization:
ISO/TS 15066 “Collaborative robots – safety”
ISO/TS on manual loading stations
Upcoming 2014: review of ISO 10218-1, -2

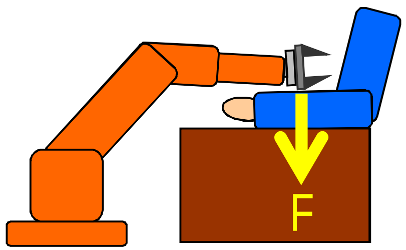
Biomechanical Criteria

Biomechanical Limit Criteria
Types of Contact Events

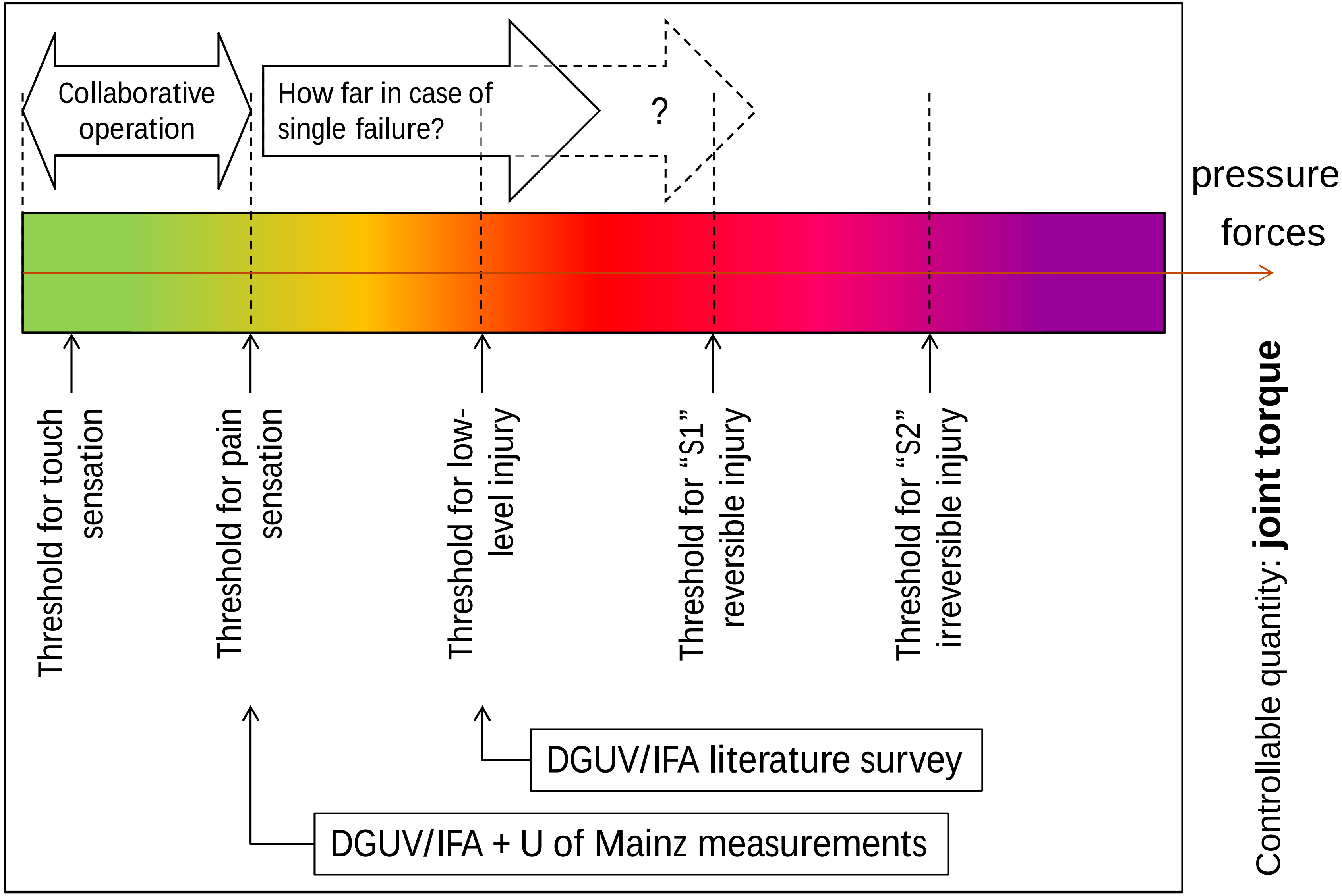
ISO / TS 15066 – clause 5.4.4 “Power and force limiting”

Free impact / transient contact		Constrained contact / quasi-static contact	
• Contact event is “short” (< 50 ms) • Human body part can recoil		• Contact duration is “extended” • Human body part cannot recoil, is trapped	
Accessible parameters in design or control • Effective mass (robot pose, payload) • Speed (relative)		**Accessible parameters in design or control** • Force (joint torques, pose)	
Pain threshold	Minor injury threshold	Pain threshold	Minor injury threshold
Highest loading level accepted in design	Highest loading level accepted in risk assessment in case of single failure	Highest loading level accepted in design	Highest loading level accepted in risk assessment in case of single failure





Quasi-static contact – Severity measures



ABB

Biomechanical Limit Criteria
Barrett Technologies

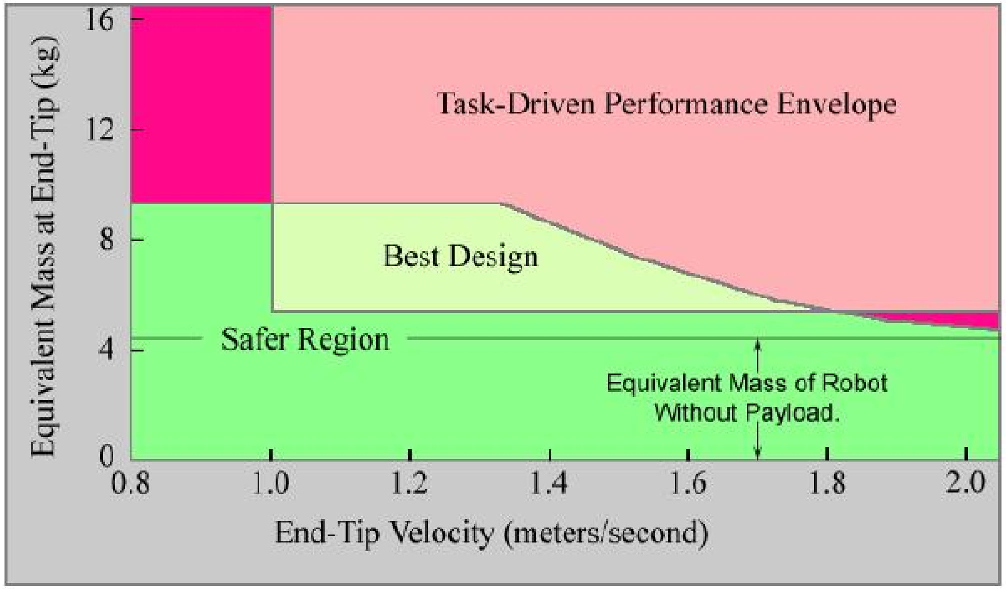


Figure 18 - Safety diagram for the robot design example.

Intrinsically Safer Robots, Prepared May 4, 1995, for the NASA Kennedy Space Center as the Final Report under NASA contract #NAS10-12178

http://www.smpp.northwestern.edu/savedLiterature/UlrichEtAlIntrinsicallySaferRobots.pdf

- Early work by W. Townsend et al. at Barrett Technologies
- Trade-off between moving mass and relative velocity

$$\frac{E}{A} = \frac{mv^2}{2A}$$
$$\approx 2\frac{J}{cm^2}$$

assuming

$$m = 4\,kg$$
$$v = 1\frac{m}{s}$$
$$A = 1\,cm^2$$

Biomechanical Limit Criteria
Standford Univ

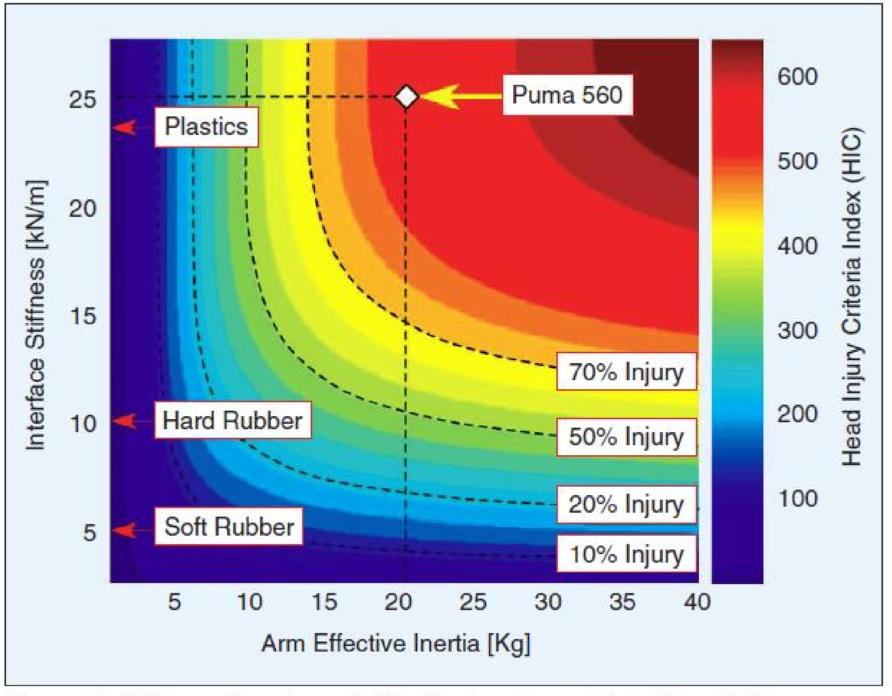


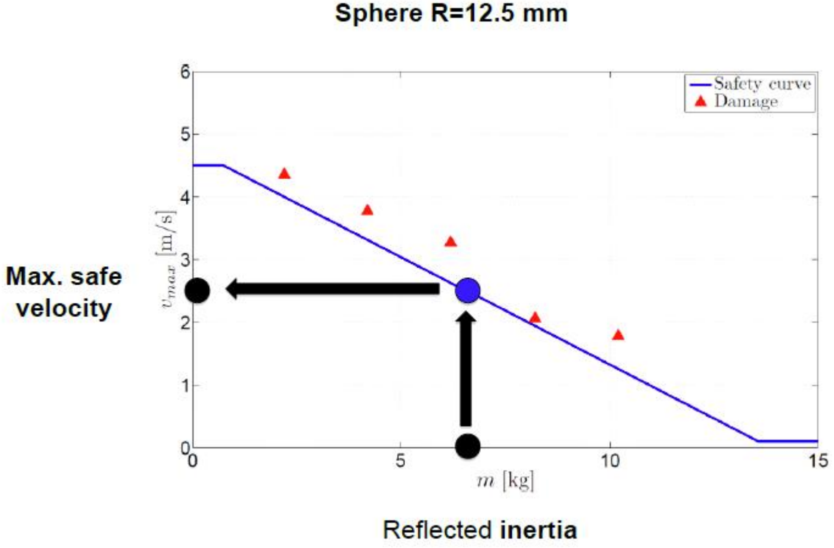
Figure 1. *HIC as a function of effective inertia and interface stiffness.*

M. Zinn, O. Khatib, et al., IEEE Robotics & Automation Magazine, June 2004, p. 12-21

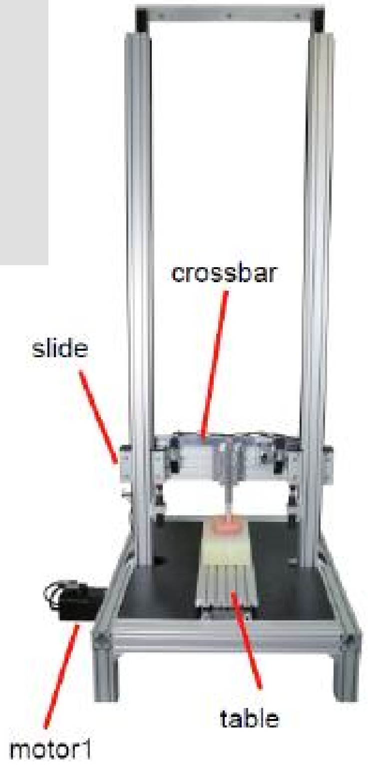
- Early work by Prof. Oussama Khatib et al.at Stanford University
- Transfer assessment criterion from automotive crashes
- Calculated curves
- Considers injury modes of brain collision with inside of skull, i.e. SDH (subdural hematoma), DAI (diffuse axonal injury), etc., but not superficial and less severe mechanisms

$$HIC = \left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2,5}(t_2 - t_1)$$

Biomechanical Limit Criteria
DLR



$$\frac{E}{A} = \frac{mv^2}{4\pi R^2} \approx 2\,\frac{J}{cm^2}$$

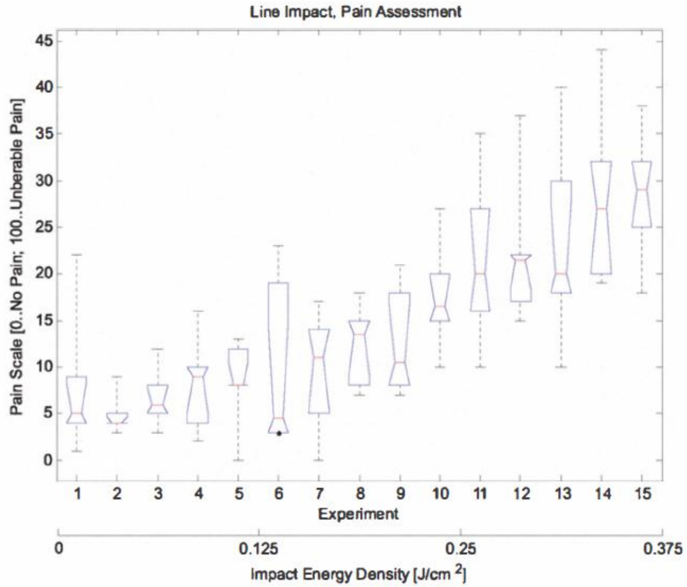


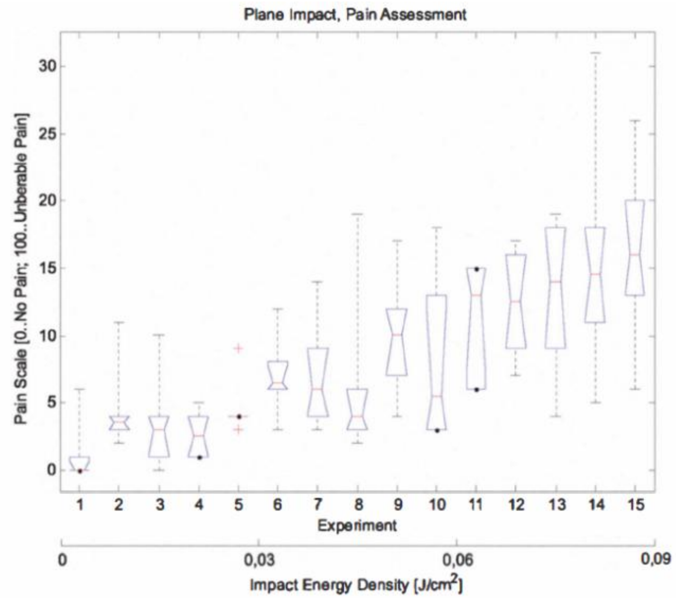
- DLR, Sami Haddadin et al.
- Drop test impact measurements on pig skin samples
- Microscopic analysis for evidence of onset of contusion
- Correlate to human soft tissue due to known similarity of properties
- “safety curves” determined for specific impactor shapes and range of relative velocity and reflected inertia

S. Haddadin, et al., IEEE Robotics & Automation Magazine, Dec. 2011, p. 20-34

Biomechanical Limit Criteria
Univ of Ljublana

- 0 ... 20 No pain
- 20 ... 40 Mild pain
- 40 ... 60 Moderate pain
- 60 ... 80 Horrible pain
- 80 ... 100 Unbearable pain

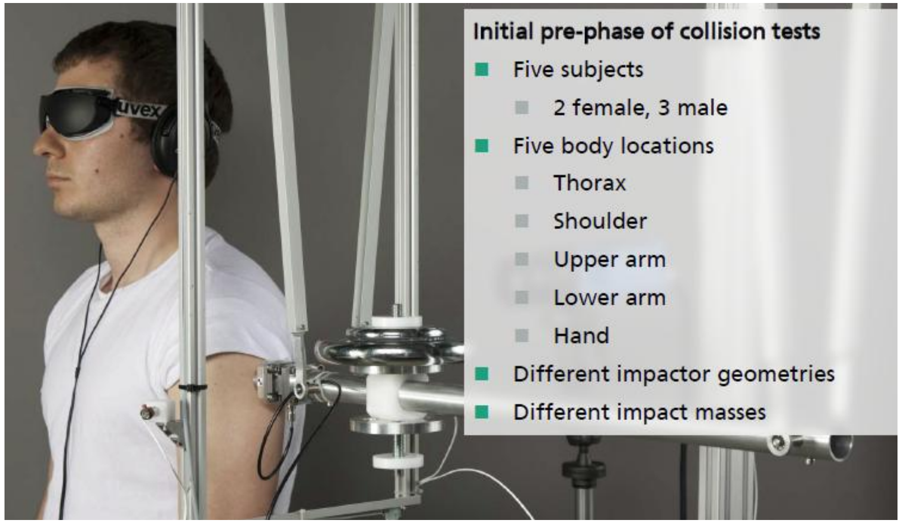




- University of Ljubljana, B. Povse, M. Munich, et al.
- Transient impact with line and plane shaped impactors
- Pain rating on scale 0..100
- Onset of pain around 20
- → onset of pain around 0.1 to 0.2 J/cm^2

Povse et al., Proceedings of the 2010 3rd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics, The University of Tokyo, Tokyo, Japan, September 26-29, 2010

Biomechanical Limit Criteria
Fraunhofer IFF



R. Behrens, N. Elkmann et al., work in progress

- Fraunhofer IFF, Magdeburg, N. Elkmann et al.
- Collision tests with live test subjects
- Study has been ethically approved by the relevant commission
- Investigation of the onset of injury as defined by the following:
  - Swelling
  - Bruise
  - Pain
- Long-term goal:
  - Statistically significant compilation of verified onset of injury thresholds for all relevant body locations

Biomechanical Limit Criteria
DGUV/IFA Limit Values

Table 2: Limit values for the forces, pressures and body deformation constant according to the body regions of the body model

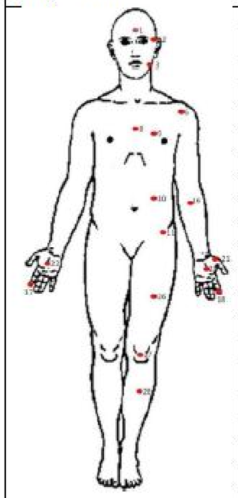
Body model – Main and individual regions with codification			Limit values of the required criteria			
BR		Regions	CSF [N]	IMF [N]	PSP [N/cm²]	CC [N/mm]
1. Head with neck	1.1	Skull/Forehead	130	175	30	150
	1.2	Face	65	90	20	75
	1.3	Neck (sides/neck)	145	190	50	50
	1.4	Neck (front/larynx)	35	35	10	10
2. Trunk	2.1	Back/Shoulders	210	250	70	35
	2.2	Chest	140	210	45	25
	2.3	Belly	110	160	35	10
	2.4	Pelvis	180	250	75	25
	2.5	Buttocks	210	250	80	15
3. Upper extremities	3.1	Upper arm/Elbow joint	150	190	50	30
	3.2	Lower arm/Hand joint	160	220	50	40
	3.3	Hand/Finger	135	180	60	75
4. Lower extremities	4.1	Thigh/Knee	220	250	80	50
	4.2	Lower leg	140	170	45	60
	4.3	Feet/Toes/Joint	125	160	45	75

BR	Body region with codification	IMF	Impact force
Regions	Name of the individual body region	PSP	Pressure/Surface pressing
CSF	Clamping/Squeezing force	CC	Compression constant

- BG/BGIA risk assessment recommendations according to machinery directive – Design of workplaces with collaborative robots, U 001/2009e October 2009 edition, revised February 2011
- Values for quasi-static and transient forces derived from literature study

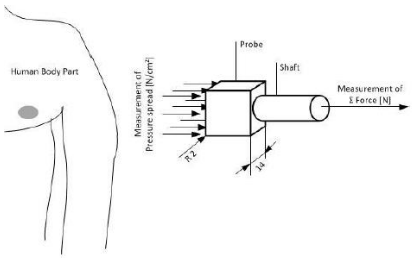
http://publikationen.dguv.de/dguv/pdf/10002/bg_bgia_empf_u_001e.pdf

Biomechanical Limit Criteria
Univ Mainz – Preliminary Results

Measurement localization			Force [N]				Peak pressure [N/cm²]			
Body model		Description	N	Q1	Median	Q3	N	Q1	Median	Q3
	1	Mid of forehead	36	30	45	52	36	92	114	134
	2	Temple	36	17	24	27	35	50	85	154
	3	Masticatory muscle	35	13	18	21	32	46	100	197
	4	Neck muscle	35	15	18	25	33	51	108	153
	5	7th neck muscle	36	27	39	48	36	103	149	194
	6	Shoulder joint	36	19	27	37	36	87	99	156
	7	5th lumbar vertebra	36	50	64	72	36	109	133	190
	8	Sternum	36	31	42	53	36	82	99	118
	9	Pectoral muscle	25	25	30	46	25	63	89	161
	10	Abdominal muscle	35	21	29	38	34	73	119	247
	11	Pelvic bone	36	32	42	54	36	130	181	197
	12	Deltoid muscle	36	33	45	57	35	108	137	181
	13	Humerus	36	38	44	57	36	142	178	251
	14	Radius bone	36	32	38	50	36	116	158	193
	15	Forearm muscle	36	29	34	42	36	90	134	162
	16	Arm nerve	36	36	44	60	35	106	122	175
	17	Forefinger pad nd	36	51	63	83	36	117	163	230
	18	Forefinger pad d	36	50	61	80	36	124	159	215
	19	Forefinger end joint nd	36	38	47	67	36	160	208	269
	20	Forefinger end joint d	36	35	46	61	36	125	176	219
	21	Thenar	36	38	46	59	36	116	144	199
	22	Back of the hand nd	36	49	56	81	36	126	171	214
	23	Back of the hand d	36	45	58	72	35	145	183	215
	24	Palm of the hand nd	36	38	48	56	36	129	166	229
	25	Palm of the hand d	36	36	45	58	36	118	156	214
	26	Thigh muscle	36	44	57	72	36	95	133	236
	27	Kneecap	36	47	65	82	36	135	194	235
	28	Shin splint	36	39	55	67	36	131	168	236
	29	Calf muscle	36	49	63	79	35	107	128	196

- University of Mainz, Prof. A. Muttray
- Experimental research
- Ethics committee approved
- Ongoing to determine pain sensation thresholds for 30 different locations on body for quasi-static loading

A. Muttray et al.



Biomechanical Limit Criteria
Additional Work

- Y. Yamada et al. – Univ. of Nagoya

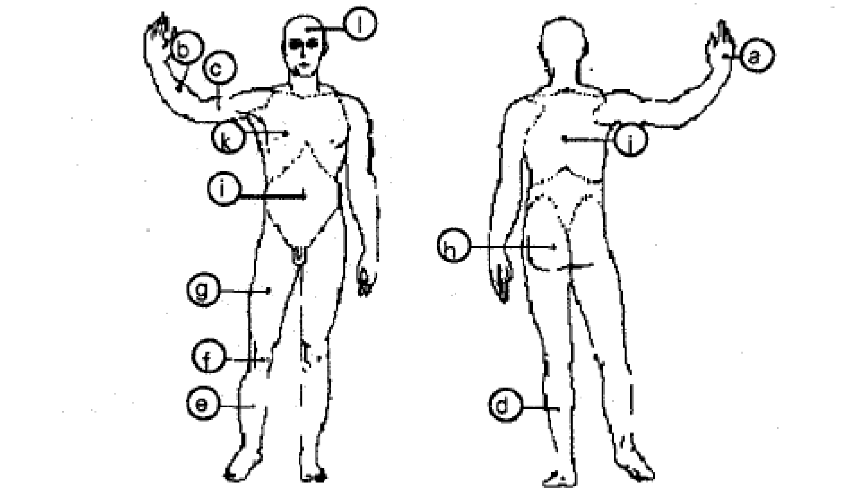


Fig.2 Measurement points for evaluating human pain tolerance

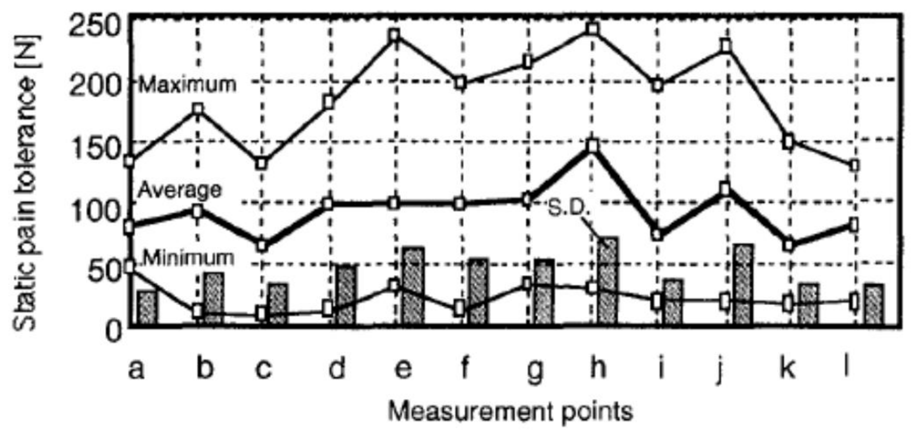


Fig.4 Experimental results of static pain tolerance

Probe diameter approx. 10 – 15 mm

Y. Yamada et al., IEEE/ASME TRANSACTIONS ON MECHATRONICS, VOL. 2, NO. 4, p. 230 (1997)

Examples of Collaborative Robots for Power and Force Limiting

→ ABB Dual-Arm Concept Robot (DACR) a.k.a. “FRIDA”

Collaborative Application Scenarios
ABB Dual-Arm Concept Robot

- 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

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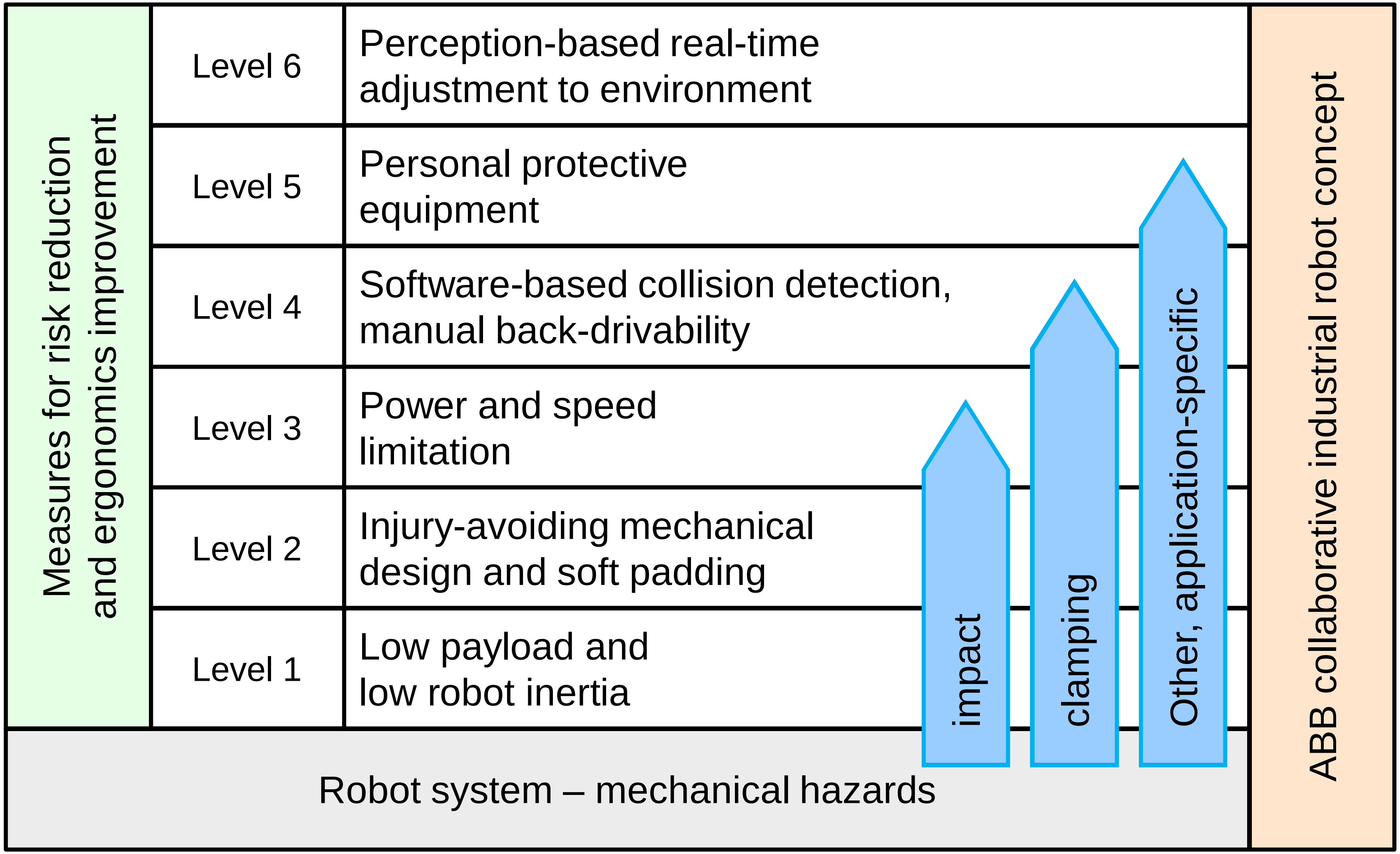
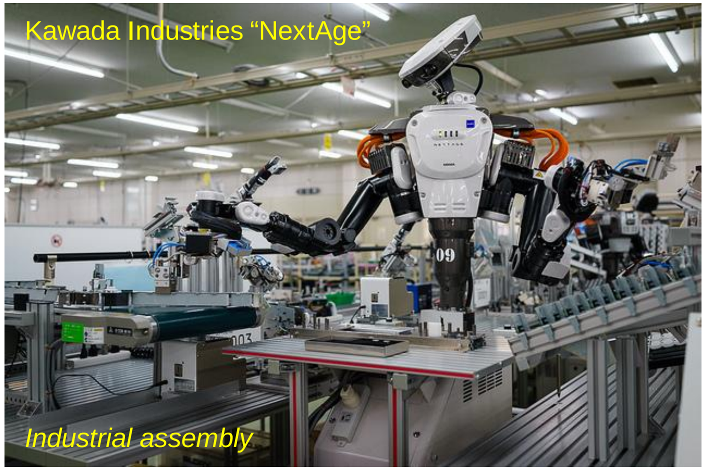
Collaborative Application Scenarios
Protection Levels



Collaborative Application Scenarios
Other Relevant Robot Developments



Kawada Industries "NextAge"

Industrial assembly

Kinova Robotics "JACO"

Assistive robot for upper body disabled

Rethink Robotics "Baxter"

Industrial assembly

Universal Robots "UR5" x 2

Industrial applications

Kuka "LWR iiwa"

Academic research, industrial assembly

Meka Robotics "M1"

Bomb disposal

SRI International "Taurus"

Collaborative Application Scenarios
Volkswagen Salzgitter – Glow Plug Assembly

Collaborative Application Scenarios
BMW Spartanburg – Door Sealing

Ergonomics

Productivity

Application Design

Ease-of-Use

Present Challenges for Collaborative SPA Ergonomics

rosetta

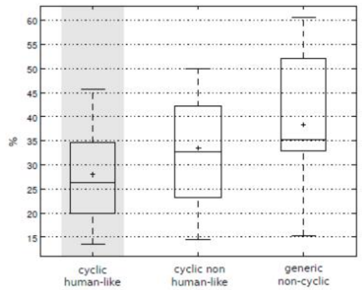
Human-like motion

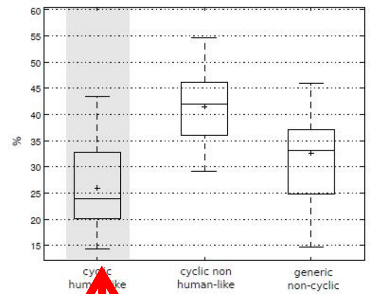
Worker acceptance of collaborative robots in production

- First experimental determination of stress indicators as function of motion characteristics

SCR – relative signal

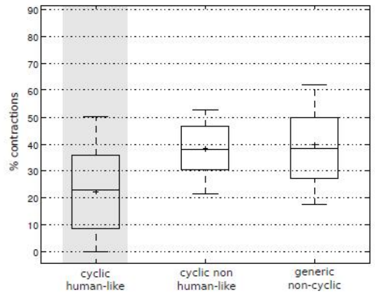
ECG – relative signal





Human-like elbow pattern

EMG – relative signal



- All stress indicators show lowest levels for human-like motion
- ECG – Electrocardiography
- SCR – Skin conductivity, resistivity
- EMG – Electromyography

Reference: P. Rocco, A. Zanchettin, DEI, Politecnico di Milano; work in EU-FP7 Project ROSETTA

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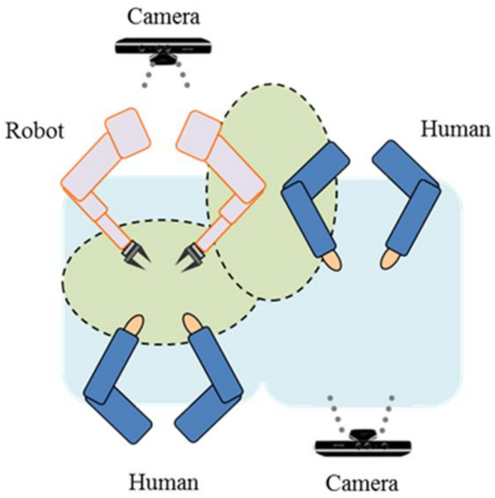
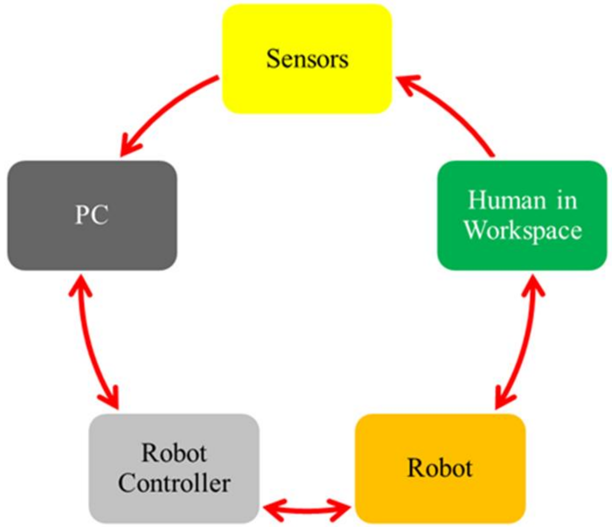
Present Challenges for Collaborative SPA Productivity



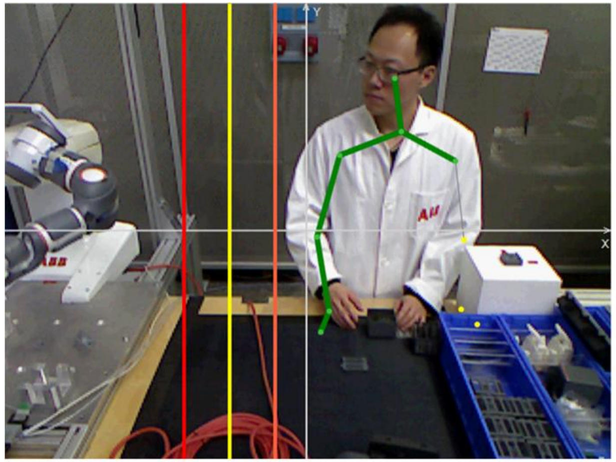
(a)



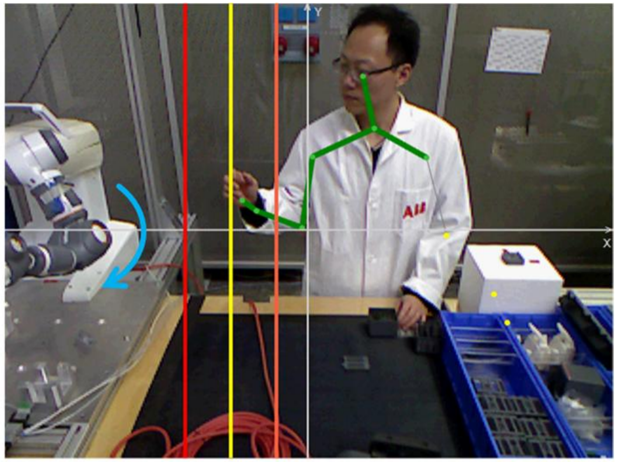
(b)

(c)

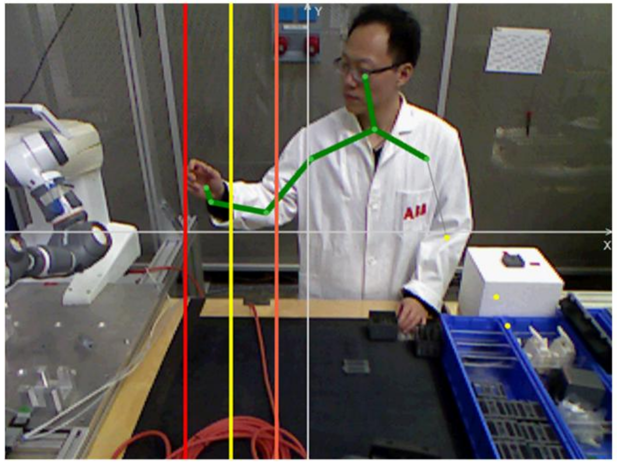
Present Challenges for Collaborative SPA Productivity



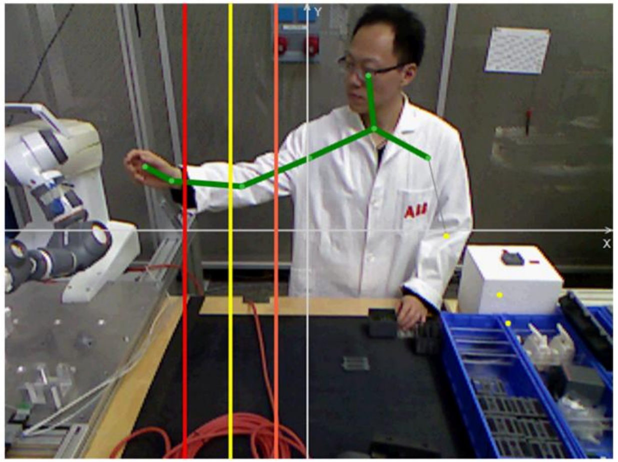
Normal operation



Elbow down

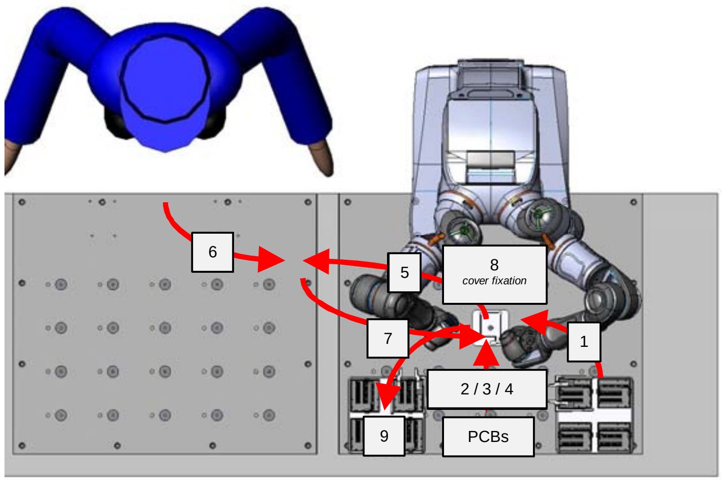


Speed reduction



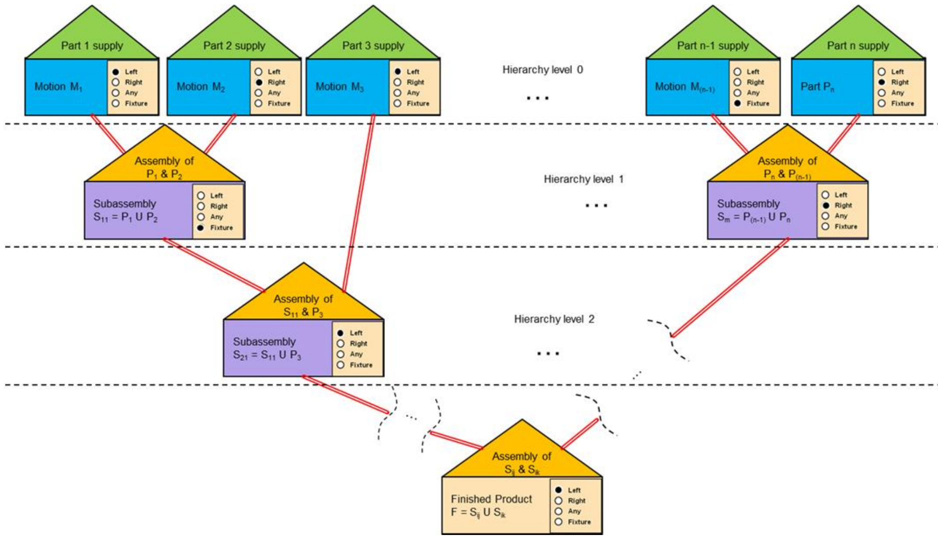
Standstill

Present Challenges for Collaborative SPA Application Design



time slice	right arm (1)	left arm (2)	worker	housing no. left hand	PCB no. left hand	PCB no. right hand	housing+PCB subassembly no.	lid subassembly no.	complete assembly no.
1	0	1	0	1					
2	0	2	0	1					
3	0	3	0		1				
4	5	4	0		1	2			
5	6	7	0		3	2			
6	0	8	11		3			1	
7	9	0	11				1	1	
8	10	0	11				1	1	
9	0	0	12					1	
10	13	1	0	2				1	
11	14	2	0	2					1
12	15	3	0		4				1
13	5	4	0		4	5			
14	6	7	0		6	5			
15	0	8	11		6			2	
16	9	0	11				2	2	
17	10	0	11				2	2	
18	0	0	12					2	
19	13	1	0	3				2	
20	14	2	0	3					2
21	15	3	0		7				2
22	5	4	0		7	8			
23	6	7	0		9	8			
24	0	8	11		9			3	
25	9	0	11				3	3	
26	10	0	11				3	3	
27	0	0	12					3	
28	13	1	0	4				3	
29	14	2	0	4					3
30	15	3	0		10				3
31	5	4	0		10	11			
32	6	7	0		12	11			
33	0	8	11		12			4	
34	9	0	11				4	4	
35	10	0	11				4	4	
36	0	0	12					4	
37	13	0	0					4	
38	14	0	0						4
39	15	0	0						4

- Methodology is research topic
  - Annotated assembly graph
  - Assignment of assembly steps to robots, workers
  - Layout of work cell, assembly line
  - …



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Present Challenges for Collaborative SPA
Ease-of-Use

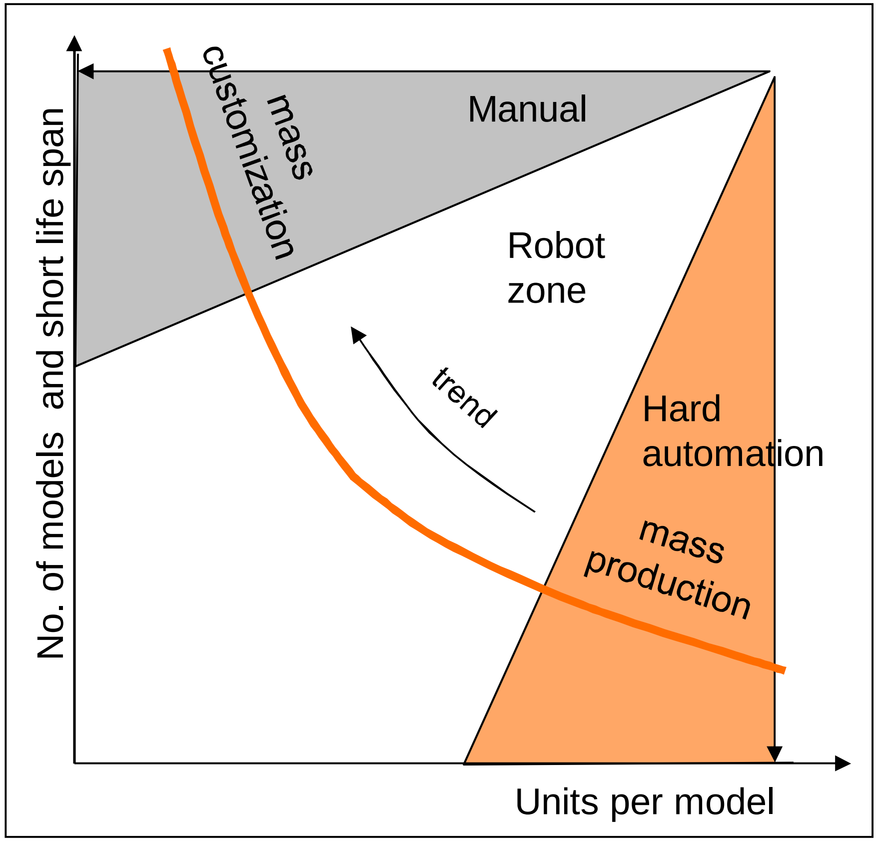
- Criteria and approaches are research topics
  - Alternatives to textual programming
  - Input modality must be intuitive and robust
  - Intelligent default values for configuration parameters
  - Selective hiding / exposing of complexity adapted to user group
  - …

Open Discussion
What are your needs?

- Type of application
  - Assembly, pick-and-place, measurement & testing, …
  - Criteria for suitability of HRC
- Degree of automation
  - Distribution of tasks among robots / operators
  - Types of interfaces, handover, conveying, …
  - Frequency of changeover, typical lot sizes
- Keys for acceptance of partial automation / mixed human-robot environment
  - Ease-of-use
  - Application design
  - Ergonomics
  - Distribution of roles and responsibilities
  - …

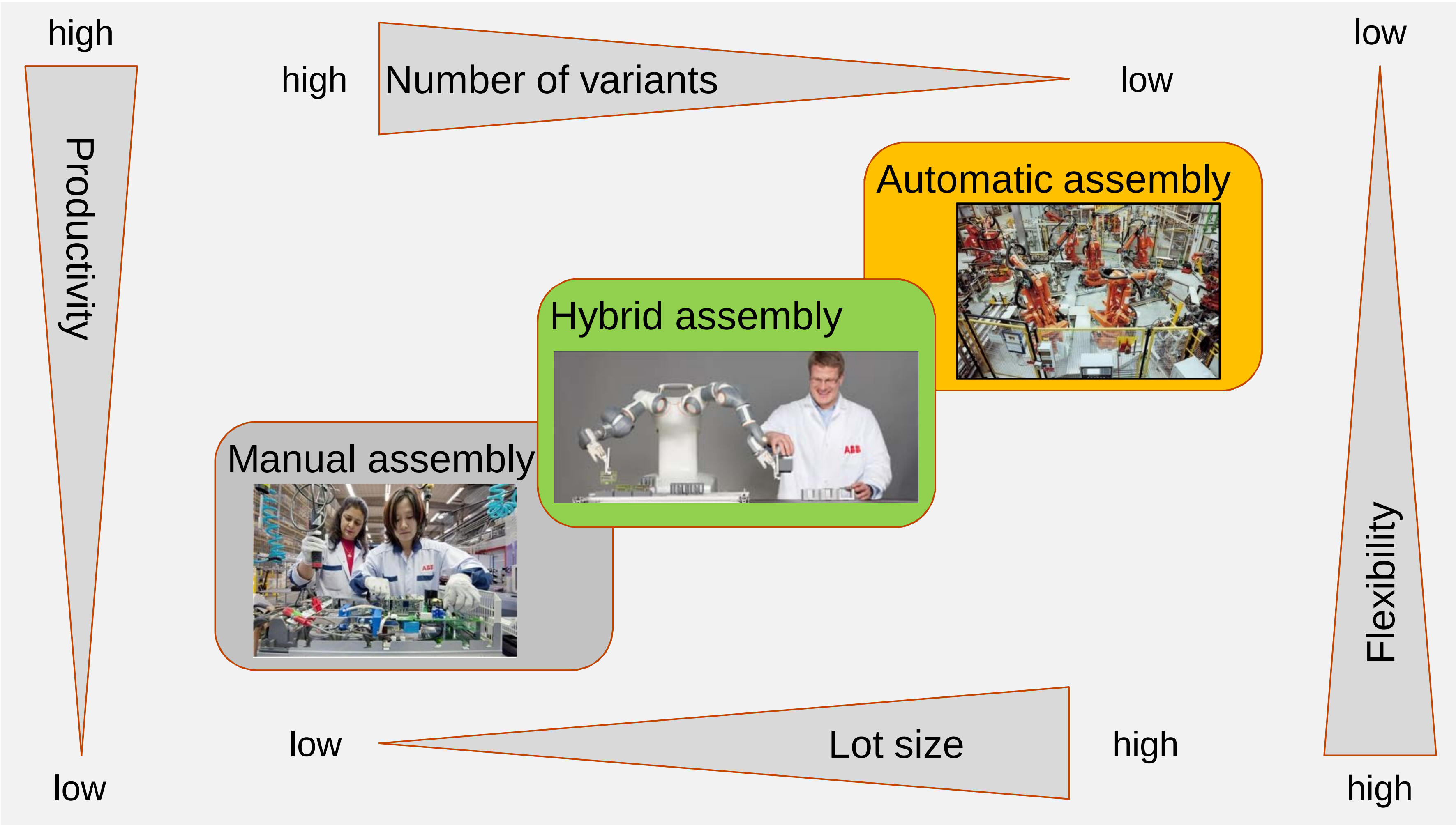
Economic Motivations

Economic Background and Motivation



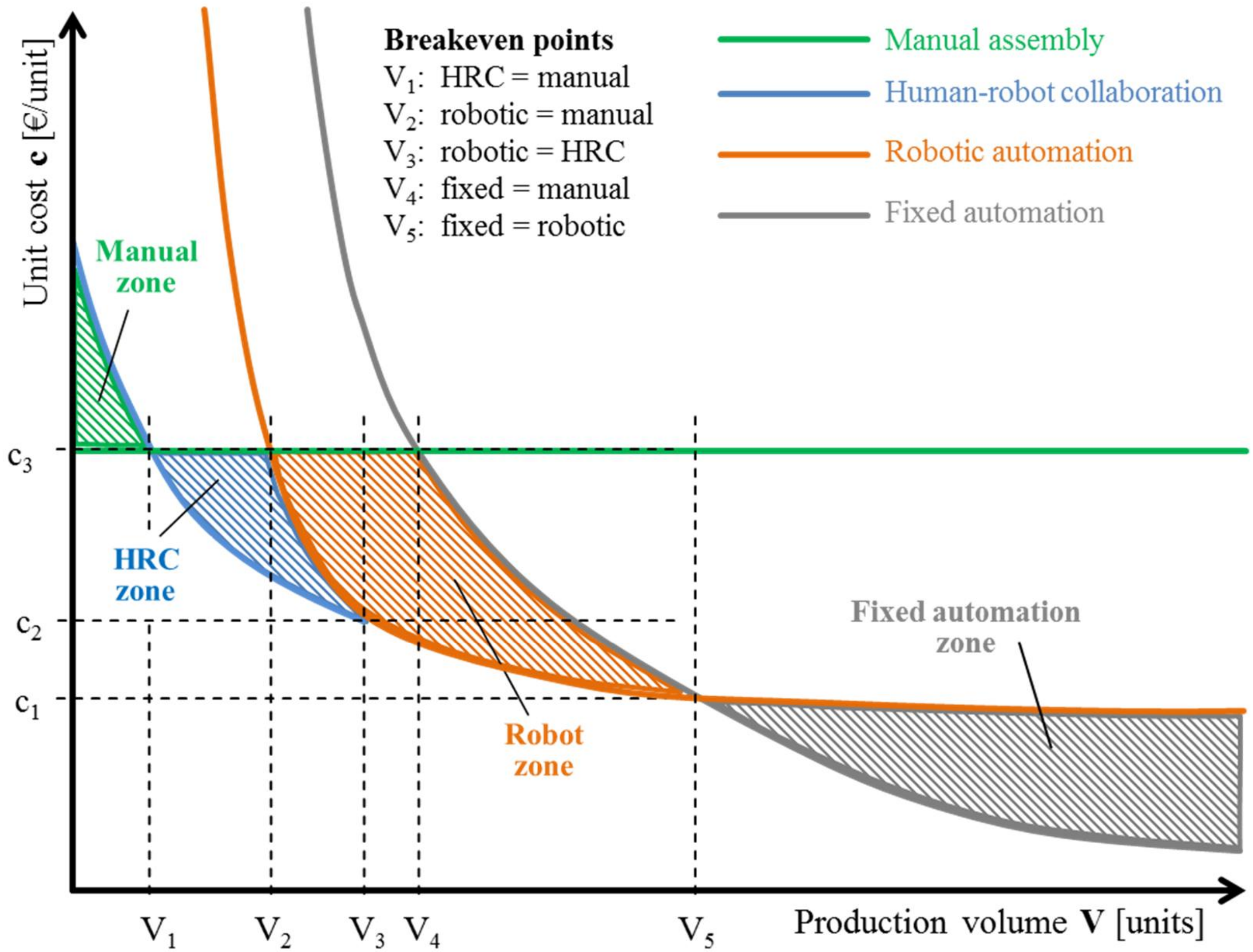
- Societal Trend
  - Individuality and differentiation with respect to peers
- Resulting Market Trend
  - Increasing no. of product variants
  - Decreasing product lifetime
  - Away from “mass production” towards “mass customization”
- Challenge to Industrial Production
  - Efficient handling of large range of variants and short model lifetimes
  - Common solution today: Mostly manual production in Asia

Moving Humans + Robots Closer Together
Productivity (1)



(adapted from B. Lotter)

Moving Humans + Robots Closer Together
Productivity (2)



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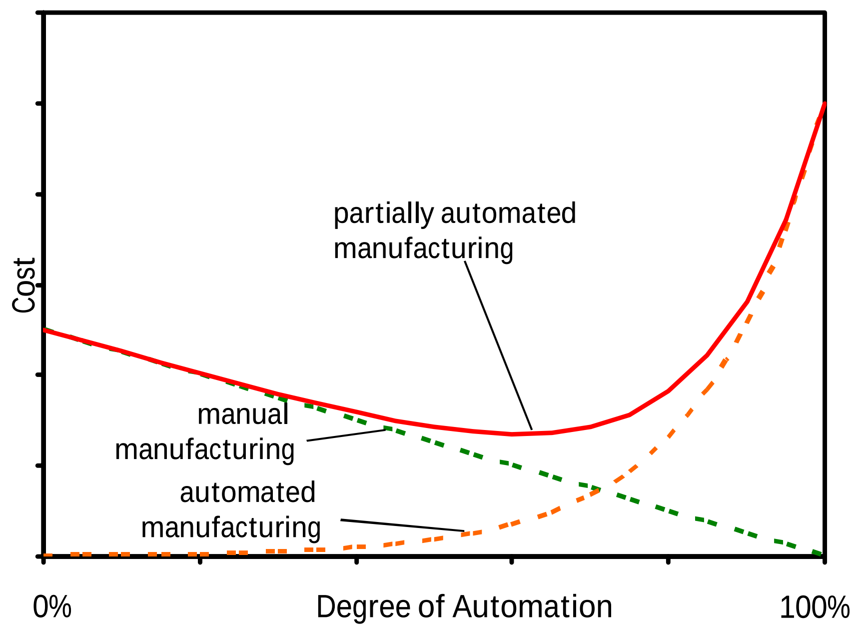
Moving Humans + Robots Closer Together
HRC for scalable degree of automation



- Optimum degree of automation < 100%
  - Raising degree of automation becomes increasingly expensive, esp. on changeover
  - Manual manufacturing becomes increasingly competitive for remaining fraction of production task

- Worker Strengths
  - Cognition
  - Reaction
  - Adaptation
  - Improvisation
- Worker Limitations
  - Modest speed
  - Modest force
  - Weak repeatability
  - Inconsistent quality

- Robot Strengths
  - High speed
  - High force
  - Repeatability
  - Consistent quality
- Robot Limitations
  - No cognitive capability
  - No autonomous adaptation
  - Modest working envelope

- Synergy: HRC
  - Automation of applications requiring high flexibility (variants ↑, lot sizes ↓)
  - New ergonomics functionality
  - New applications in which robots previously have not been used

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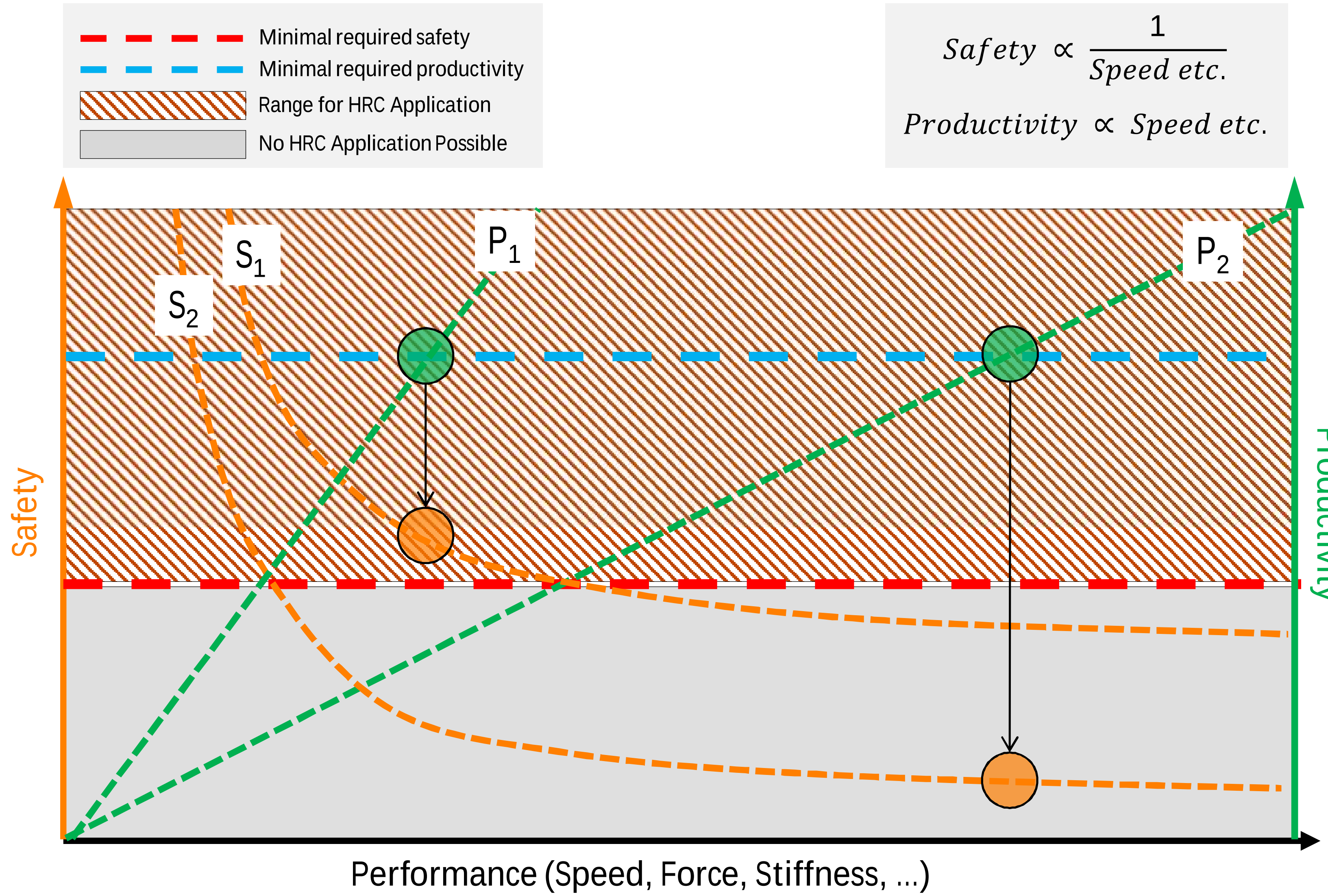

S_k = example dependence of safety on speed for application no. k

P_k = example dependence of productivity on speed for application no. k

Power and productivity
for a better world™

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