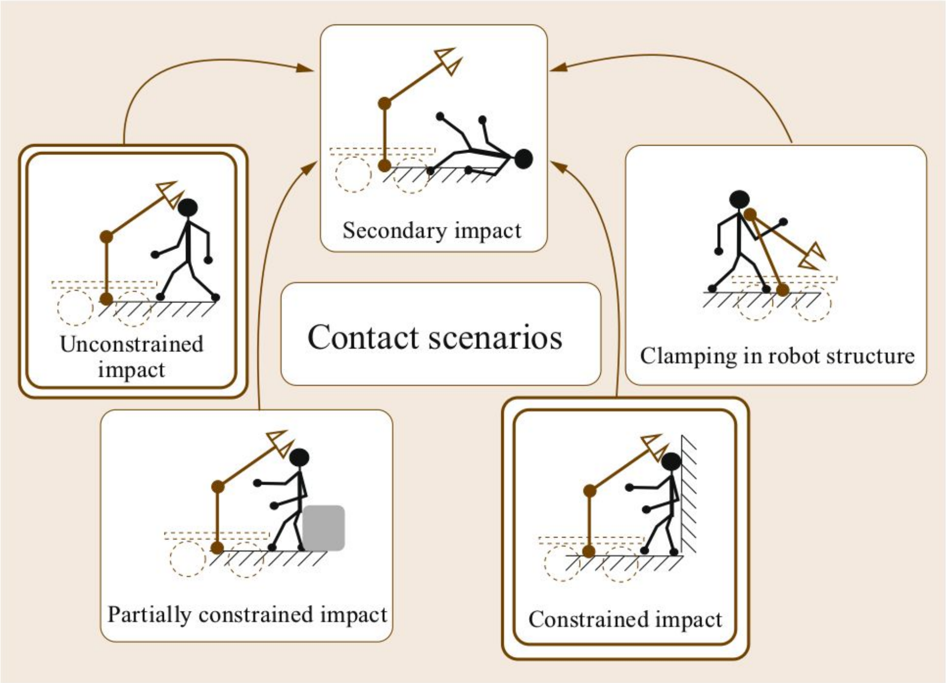
Humanoid robots - Physical human-robot interaction I

Mgr. Matěj Hoffmann, Ph.D.

Outline

- Human safety
- Safety of machines and robots - legislation and standards
- Types of physical human robot collaboration
    - Safety-rated monitored stop
    - Hand-guiding
    - Speed and separation monitoring
    - Power and force limiting
- Speed and separation monitoring

Human safety



http://handbookofrobotics.org/view-chapter/69/videodetails/608

S. Haddadin, A. Albu-Schäffer, M. Strohmayr, M. Frommberger, G. Hirzinger: Injury evaluation of human-robot impacts, Proc. IEEE Int. Conf. Robot. Autom. (ICRA), Pasadena (2008), pp. 2203 – 2204; doi: 10.1109/ROBOT.2008.4543534.

Fig. 69.4 Robot–human impact scenario classes. Unconstrained and constrained impacts are considered the two main scenarios

Haddadin, S., & Croft, E. (2016). Physical human–robot interaction. In *Springer handbook of robotics* (pp. 1835-1874). Springer, Cham.

Impact experiments

more on this next time…

Table 69.1 Overview of selected impact experiments from biomechanics and robotics literature. Body part: Head

Impactor type	Impactor parameters	Collision case	Subject	Mass (kg)	Velocity (m/s)	References
Flat circular						
Maxilla, zygoma, frontal, temporo-parietal, mandible	14.3 mm radius	dynamic constrained (DC)	Cadaver	1.08–3.82	2.99–5.97	[69.27, 28]
Temporo-Parietal	12.7 mm radius	DC	Cadaver	10.6	2.7	[69.29]
Nose	14.3 mm radius	DC	Cadaver	3.2	1.56–3.16	[69.30]
Frontal	35 mm radius	DU	Cadaver	14.3	3.37–6.99	[69.31]
Edge						
Nose	12.5 mm radius	DU	Cadaver	32, 64	2.77–6.83	[69.32]
Maxilla, zygoma, frontal	10 mm radius	DC	Cadaver	14.5	2.4–4.2	[69.33]
Frontal	12.7 mm radius	dynamic partially constrained (DPC)	Cadaver	∞ (human falling on impactor)	2.23–3.14	[69.34]
Cuboid						
Temporo-parietal	50 mm length, 100 mm width	DC	Cadaver	12	4.3	[69.29]
Frontal	Size not specified, padded	DPC	Cadaver	5.31–5.97	3.56–9.6	[69.35]
Frontal	size not specified	DPC	Cadaver	∞ (human falling on impactor)	2.23–3.87	[69.34]
Sphere						
Frontal	120 mm radius	DU, QSC, DPC	Hybrid III dummy	4, 67, 1980	0.2–4.2	[69.36, 37]
Frontal	203.2, 76.2 mm radius	DPC	Cadaver	∞ (human falling on impactor)	2.87–3.5	[69.34]

Table 69.2 Overview of selected impact experiments from biomechanics and robotics literature. Body part: Torso

Impactor type	Impactor parameters	Collision case	Subject	Mass (kg)	Velocity (m/s)	References
Flat circular						
Thorax	76.2 mm radius, 12.77 mm edge radius	DU, DC	Cadaver	1.6–23.6	4.34–14.5	[69.38, 39]
Thorax	76 mm radius, rubber padded	DU	Volunteer	10	2.4–4.6	[69.40]
Thorax	76.2 mm radius, 12.77 mm edge radius	DU	Cadaver	19.27	4.0–10.6	[69.41]
Abdomen	12.7 mm radius	DU	Cadaver	32, 64	4.9–13.0	[69.42]
Sphere						
Thorax	120 mm radius	DU, QSC	Hybrid III dummy	4, 67, 1980	0.2–4.2	[69.36, 37]
Abdomen	5, 12.5 mm radius	DC	Pig tissue	2–10	0.5–4.0	[69.25]
Edge						
Abdomen	45° angle, 200 mm length, 0.2 mm edge radius	DC	Pig tissue	2–10	0.5–4.0	[69.25]

Table 69.3 Overview of selected impact experiments from biomechanics and robotics literature. Body part: Upper extremities

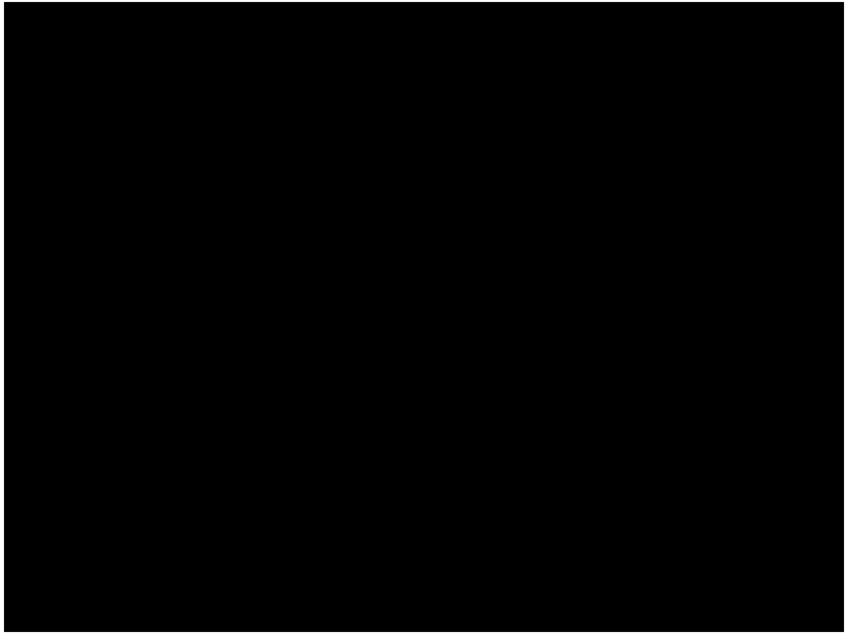
Impactor type	Impactor parameters	Collision case	Subject	Mass (kg)	Velocity (m/s)	References
Edge						
Forearm	12.5 mm radius, angle 0°	DC	Cadaver	9.48	3.63	[69.43]
Forearm	size not specified	DC	Cadaver	9.75	2.44, 4.23	[69.44]
Shoulder, upper arm, forearm	5 mm edge radius, 30° angle	DC	Volunteer	4.16, 8.65	0.45–1.25	
Flat circular						
Forearm, hand	size not specified	QSC	Cadaver	∞ (velocity control)	25 mm/min	[69.45]

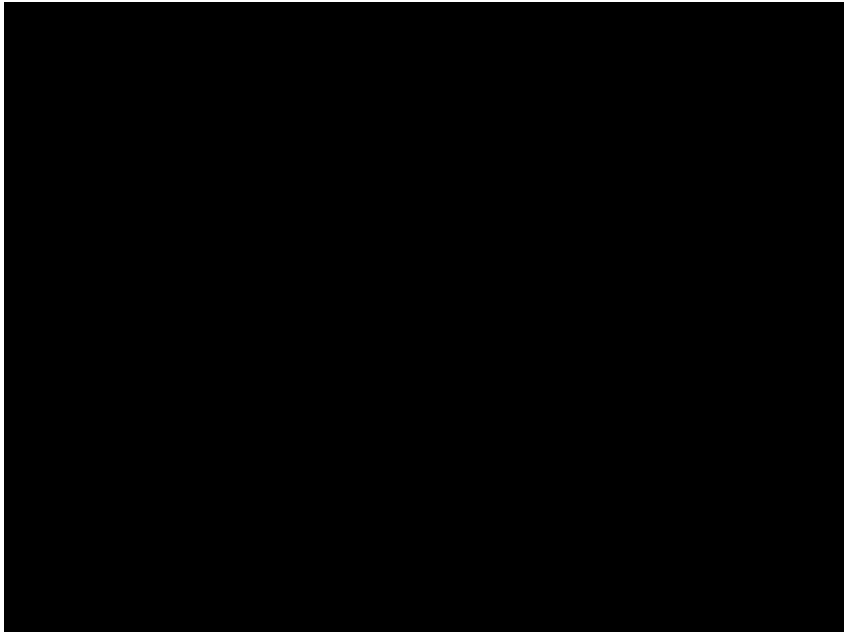
Table 69.4 Overview of selected impact experiments from biomechanics and robotics literature. Body part: Lower extremities

Impactor type	Impactor parameters	Collision case	Subject	Mass (kg)	Velocity (m/s)	References
Sharp	Fig. 69.5	DC	Pig tissue, volunteer	4	0.16–0.8	[69.24]

Haddadin, S., & Croft, E. (2016). Physical human–robot interaction. In *Springer handbook of robotics* (pp. 1835-1874). Springer, Cham.

When is a robot safe?





When is a robot safe? Legislation and standards

Robot safety - European legislation

European directives on product safety

- All products put into circulation in the EU (manufactured, sold, imported, operated, etc.), have to fulfill applicable EU directives
  - Example: Machinery Directive (2006/42/EG), Low Voltage Directive (2006/95/EC), EMC-Directive (2004/108/EG)
    - Containing very general requirements for products
    - Conversion into national law (e.g. “Produktsicherheitsgesetz” in Germany)
- Reference to a list of “harmonized standards”
  - Detailed safety requirements
  - Application voluntarily but recommended
  - Presumption of conformity: If all harmonized standards of a directive are fulfilled it is presumed that the directive itself is fulfilled
- If all requirements from EU directives are fulfilled, a CE mark can be applied

CE

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Slide from: Theo Jacobs, Fraunhofer IPA, Safety standards and risk assessment for robots, 2016

Robot safety - Czech legislation

Legislativa pro výrobce strojů

- Zákon č. 22/1997 Sb. ve znění zákona č. 91/2016 Sb. o technických požadavcích na výrobky
- Nařízení vlády č. 170/1997 Sb., č. 176/2008 Sb. (směrnice 2006/42/ES) ve znění nařízení vlády č. 229/2012 Sb. kterým se stanoví technické požadavky na strojní zařízení
- Nařízení vlády č. 117/2016 Sb. – EMC (zákon č.90/2016 Sb. – upřesňuje posuzování shody)
- Nařízení vlády č. 118/2016 Sb. – nízké napětí
- Nařízení vlády č. 116/2016 Sb. – výbušné prostředí

Legislativa pro provozovatele

- Nařízení vlády č.378/2001 Sb. kterým se stanoví bližší požadavky na bezpečný provoz a používání strojů, technických zařízení, přístrojů a nářadí
- Zákon č.262/2006 Sb., zákoník práce
- Nařízení vlády č.361/2007 Sb., podmínky ochrany zdraví při práci ve znění Nařízení vlády č.32/2016 Sb.
- Zákon č.309/2006 Sb., další požadavky bezpečnosti a ochrany zdraví při práci ve znění zákona č.189/2008 Sb.

“Harmonized” safety standards

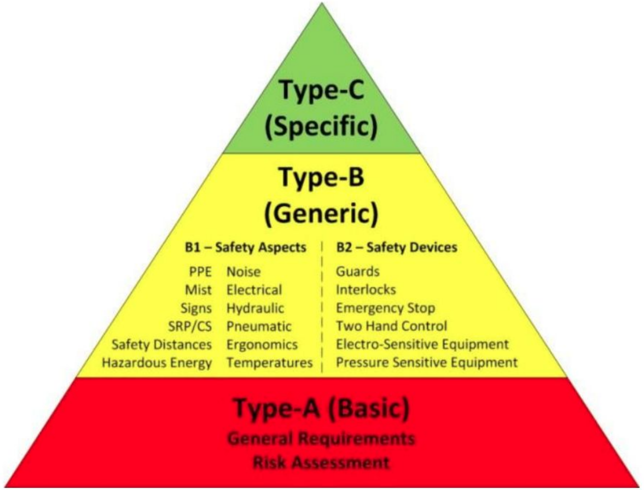
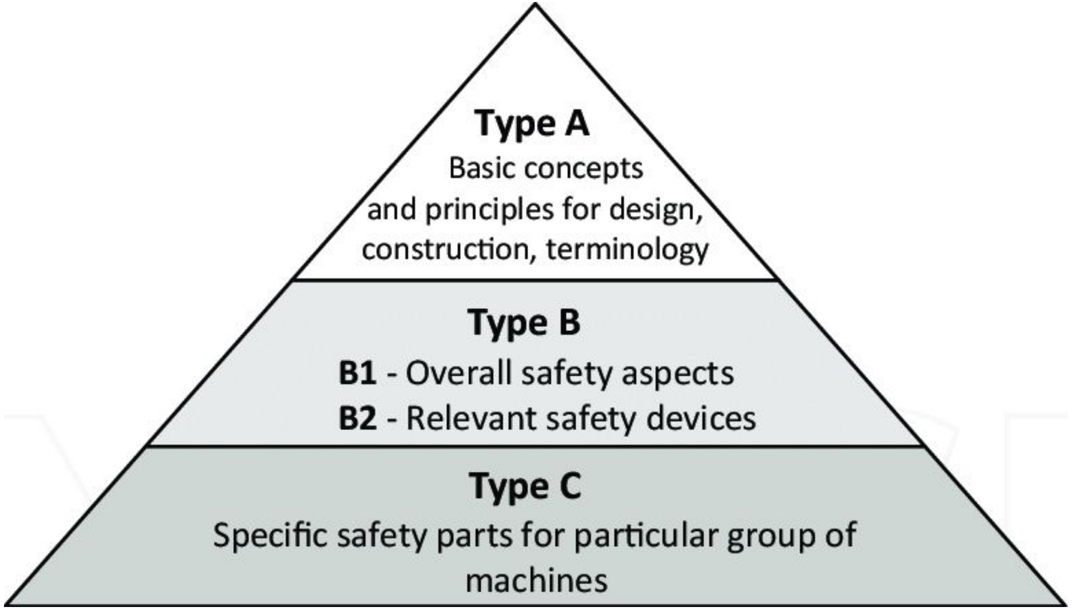


Figure 1: Structural Organization of Standards



SICK, Selecting Safety Standards for Machine Safeguarding Requirements
https://cdn.sick.com/media/content/h94/h35/9692994994206.pdf

Pacaiova, H. (2018). *Machinery safety requirements as an effective tools for operational safety management*. IntechOpen.

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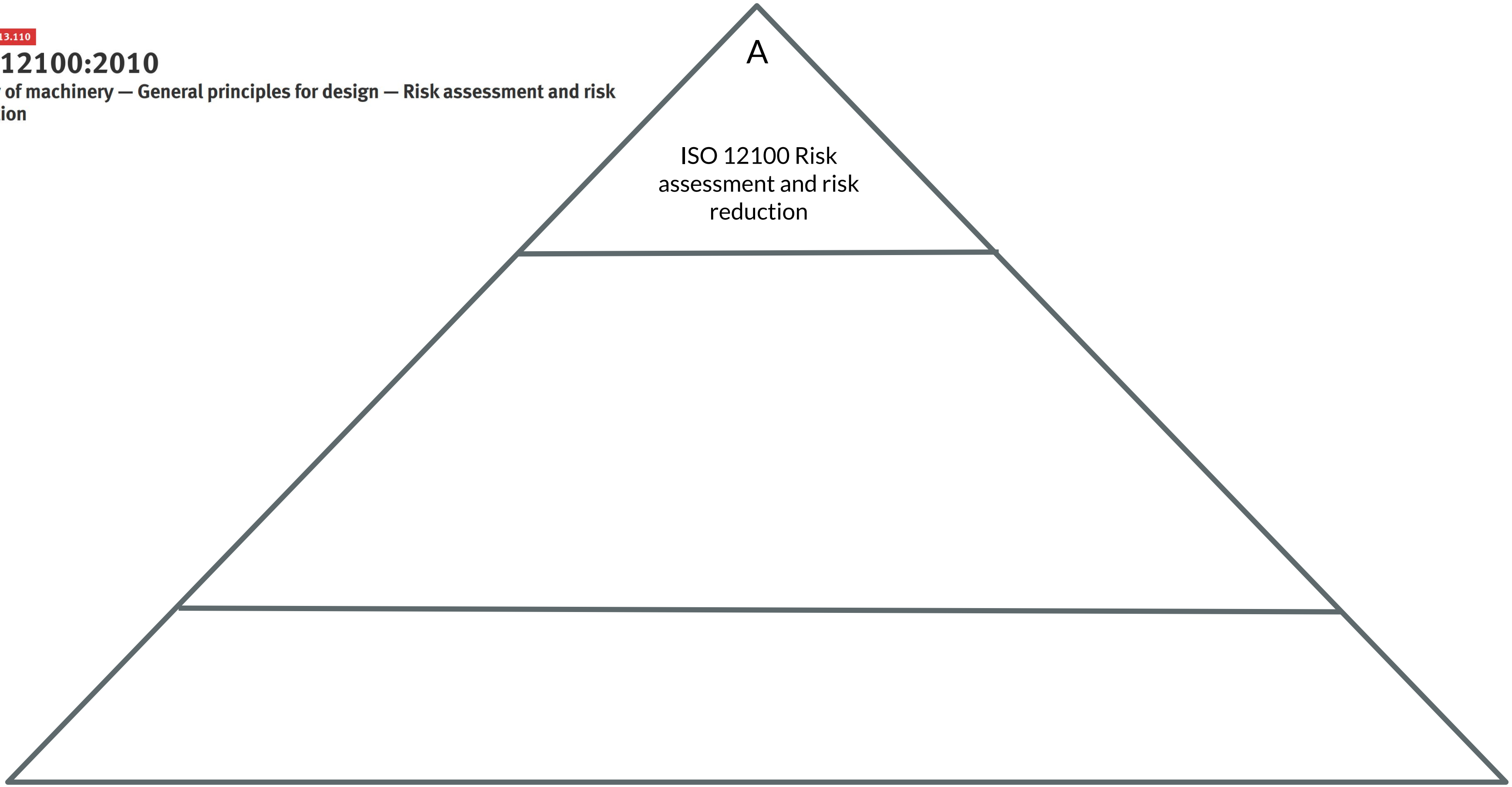
ISO

ICS › 13 › 13.110

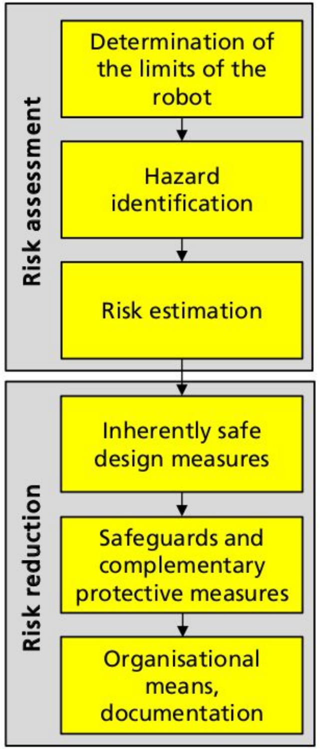
ISO 12100:2010

Safety of machinery — General principles for design — Risk assessment and risk reduction



ISO 12100: Risk assessment and risk reduction

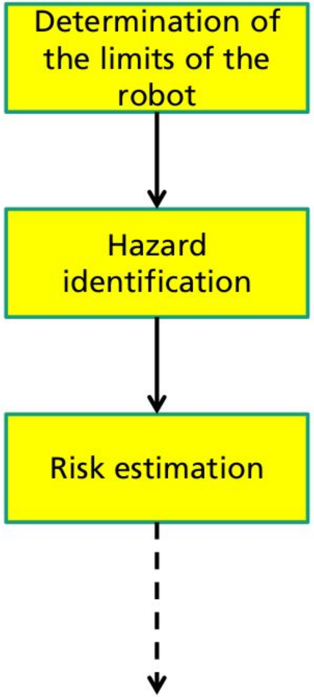
- ISO 12100 – Safety of machinery – General principles for design – Risk assessment and risk reduction
  - General requirements for machines (e.g. emergency stop buttons, start-up, …)
  - Obligation to perform a risk assessment to identify unacceptable risks
  - Reduction of unacceptable risks until the residual risk is acceptable
- Manufacturer has to decide what an acceptable risk is
  - With respect to the current state of the art (e.g. available safeguards)
  - With respect to similar products on the market



Slide from: Theo Jacobs, Fraunhofer IPA, Safety standards and risk assessment for robots, 2016

Fraunhofer IPA

Process of risk assessment and risk reduction in ISO 12100



Risk assessment:

- Limits of the machine: user groups, tasks, environmental conditions, etc.
- Intended use and forseeable misuse
- Identifications of hazards
  - With lists of typical hazards
  - By analysing and testing the machine
- Risk estimation
  - Severity of the expected harm
  - Probability that the harm occurs
- Result
  - List of inacceptable risks
  - Quantitative estimation, how far the risk has to be reduced

Slide from: Theo Jacobs, Fraunhofer IPA, Safety standards and risk assessment for robots, 2016

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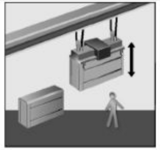
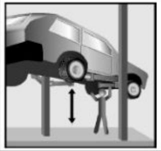
Using checklists for hazard identification

	**Origin** cutting parts **Potential consequences** – cutting – severing		**Origin** falling obje **Potential c** – crushin – impact
	**Origin** moving elements **Potential consequences** – crushing – impact – shearing		**Origin** moving ele (three exar **Potential c** – drawing – friction, – impact
	**Origin** gravity, stability **Potential consequences** – crushing – trapping		**Origin** approach c element to **Potential c** – crushin – impact

No	Type or group	Examples of hazards	
		Origin[a]	**Potential consequences**[b]
1	**Mechanical hazards**	— acceleration, deceleration; — angular parts; — approach of a moving element to a fixed part; — cutting parts; — elastic elements; — falling objects; — gravity; — height from the ground; — high pressure; — instability; — kinetic energy; — machinery mobility; — moving elements; — rotating elements; — rough, slippery surface; — sharp edges; — stored energy; — vacuum.	— being run over; — being thrown; — crushing; — cutting or severing; — drawing-in or trapping; — entanglement; — friction or abrasion; — impact; — injection; — shearing; — slipping, tripping and falling; — stabbing or puncture; — suffocation.
2	**Electrical hazards**	— arc; — electromagnetic phenomena; — electrostatic phenomena; — live parts; — not enough distance to live parts under high voltage; — overload; — parts which have become live under fault conditions; — short-circuit; — thermal radiation.	— burn; — chemical effects; — effects on medical implants; — electrocution; — falling, being thrown; — fire; — projection of molten particles; — shock.

Examples from ISO 12100, type-C standards usually have additional tables

Slide from: Theo Jacobs, Fraunhofer IPA, Safety standards and risk assessment for robots, 2016

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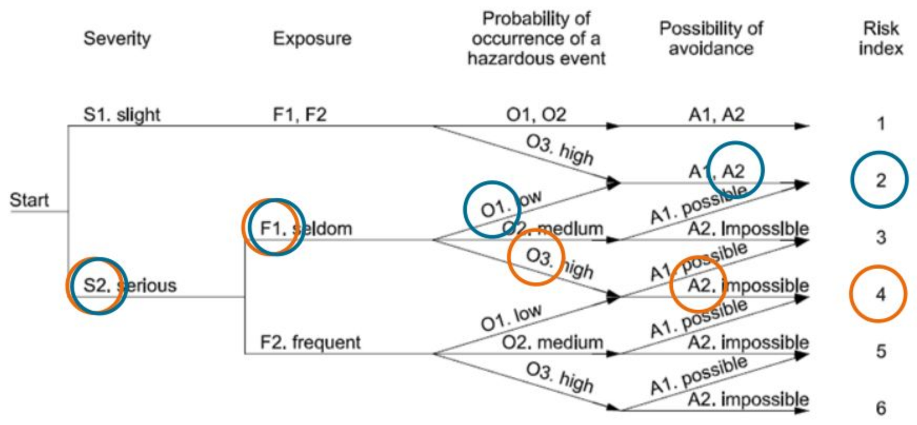
Use of risk graphs and risk matrices for risk estimation



Key

S1	slight injury (usually reversible)	O1	low (very unlikely)
S2	serious injury (usually irreversible)	O2	medium (likely to occur sometime)
F1	seldom / short duration	O3	frequent (likely to occur frequently)
F2	frequent / long duration	A1	possible (person can notice and has time to evade)
		A2	Impossible

Examples from ISO/TR 14121-2 – Individual risk graphs and matrices may be used

		Risk Index calculation					
		O1		O2		O3	
		A1	A2	A1	A2	A1	A2
S1	F1	1				2	
	F2						
S2	F1	2			3		4
	F2	3	4		5		6

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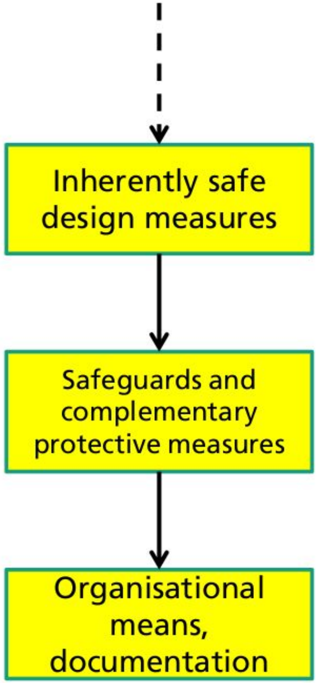
Process of risk assessment and risk reduction in ISO 12100



Risk reduction

- Inherently safe design: Elimination of the risk by change of design
  - e.g. limited drive power to avoid clamping or crushing by a robot manipulator
- Safeguards and protective measures
  - e.g. force control of the arm in it's control system
- Organisational means/ documentation
  - e.g. warning sign: keep distance to the arm
- Priority inside the „three-step-method"
  - Protective measures and safeguards only if inherently safe design is not possible
  - Listing of residual risks in the documentation only if no other measures for risk reduction are possible

Risk assessment and reduction are repeated until all risks have been adequately reduced!

Slide from: Theo Jacobs, Fraunhofer IPA, Safety standards and risk assessment for robots, 2016

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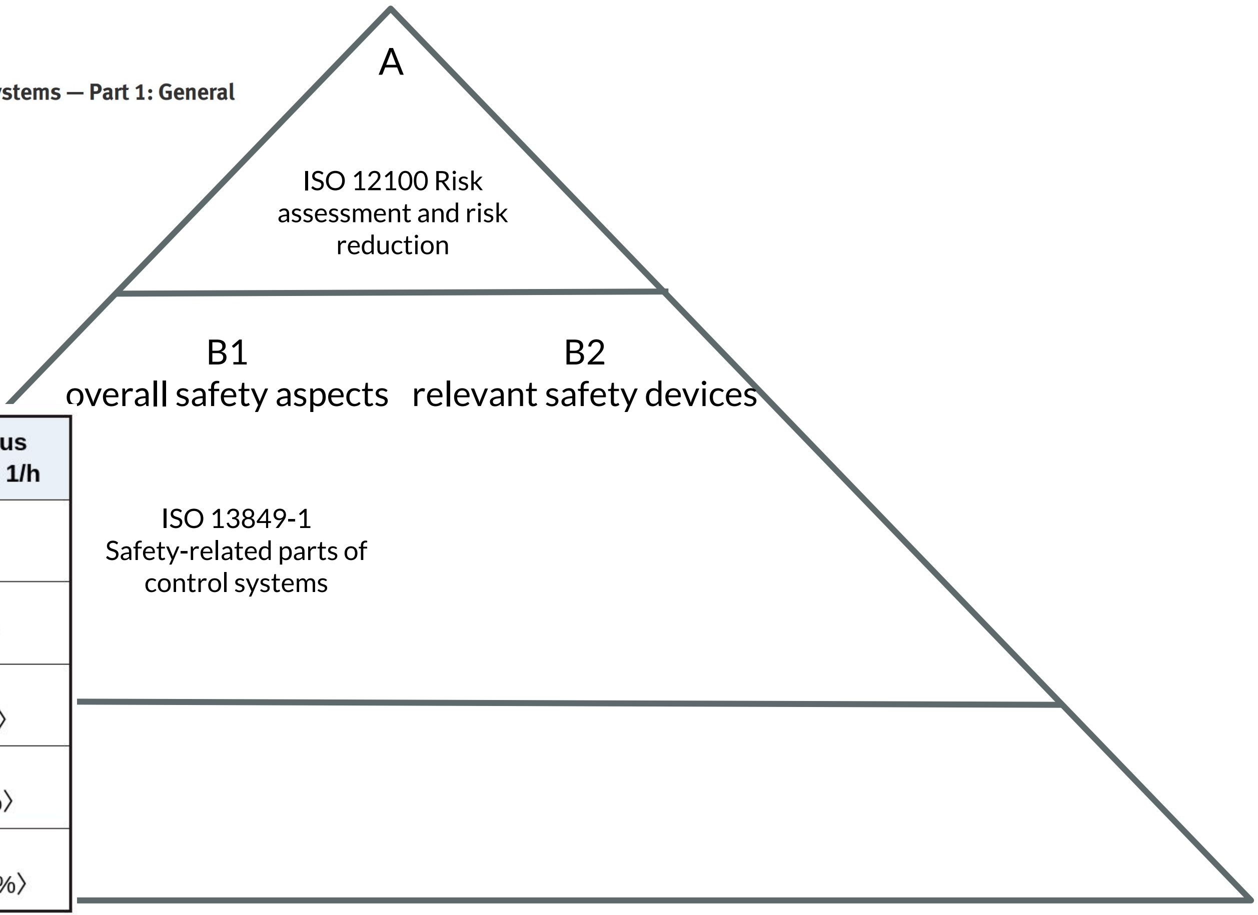
ICS › 13 › 13.110

ISO 13849-1:2015

Safety of machinery — Safety-related parts of control systems — Part 1: General principles for design

https://www.keyence.eu/ss/products/safetyknowledge/performance/level/



Performance Level (PL)	Probability of Dangerous Failure per Hour (PFHd) 1/h
a	$\geq 10^{-5}$ and $<10^{-4}$ 〈0.001% to 0.01%〉
b	$\geq 3 \times 10^{-6}$ and $<10^{-5}$ 〈0.0003% to 0.001%〉
c	$\geq 10^{-6}$ and $<3 \times 10^{-6}$ 〈0.0001% to 0.0003%〉
d	$\geq 10^{-7}$ and $<10^{-6}$ 〈0.00001% to 0.0001%〉
e	$\geq 10^{-8}$ and $<10^{-7}$ 〈0.000001% to 0.00001%〉

ISO 13849 – Safety categories

- Categories B, 1: Single channel system
  - Requirement: Use of well-tried safety principles and proven components
  - Single failure can lead to an accident
- Category 2: Single channel system with test equipment
  - Cyclic testing of the safety function
  - High probability that a failure is detected before the safety function is executed the next time
- Category 3: Two channel system
  - Sensors and all parts of the control system exist twice
  - A single failure is detected before a hazard occurs
- Category 4: Highly reliable two channel system
  - A single failure is detected before a hazard occurs
  - Additional protection against undetected failures and common-cause-failures

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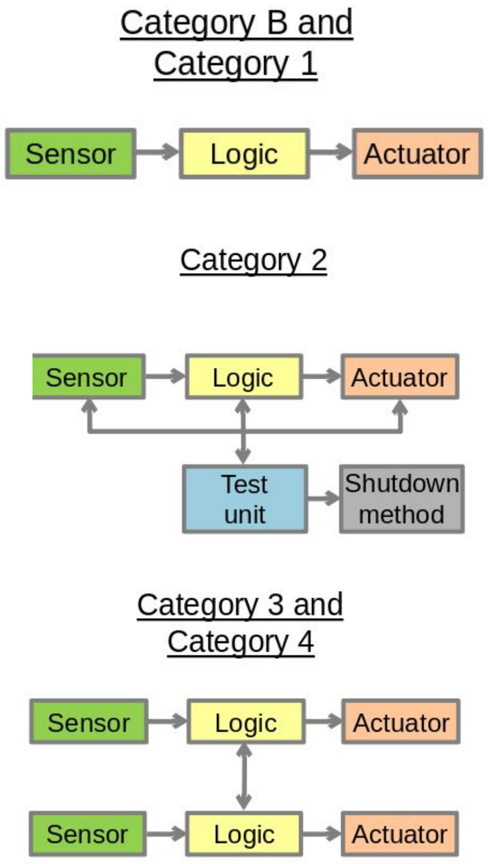
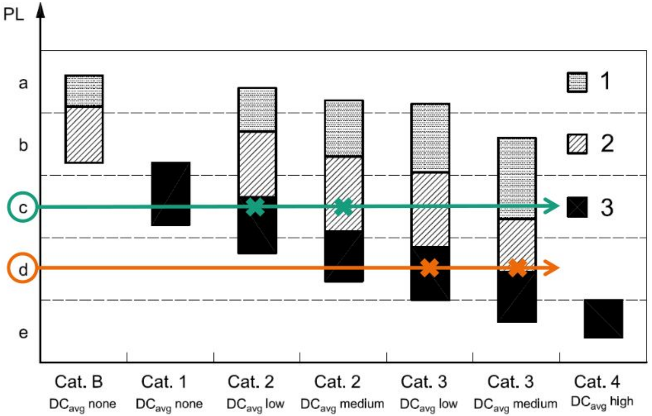


Slide from: Theo Jacobs, Fraunhofer IPA, Safety standards and risk assessment for robots, 2016

Daniel Braun, KUKA, iiwa safety system introduction, 2016

Requirements for the safety-related part of the control system according to ISO 13849-1

- Based on the required performance level the control system needs to comply with a certain safety category, depending on
  - $MTTF_d$: Meantime to the first dangerous failure
  - DC: diagnostic coverage – Ratio of errors that can be detected by a test equipment or a redundant channel in comparison to the total number of



1: low $MTTF_d$

2: medium $MTTF_d$

3: high $MTTF_d$

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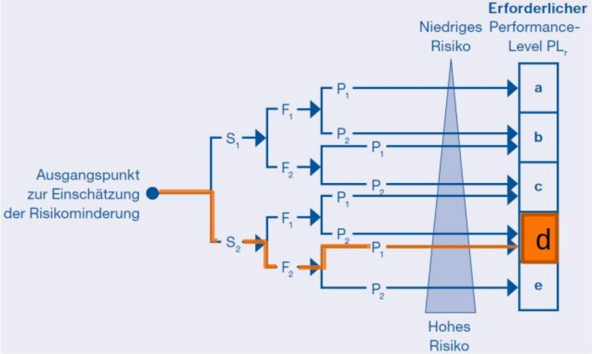
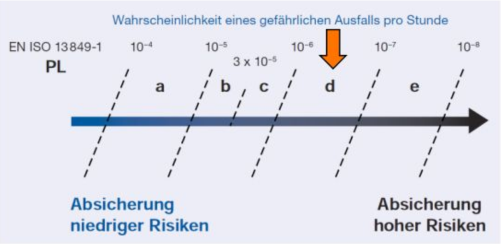
KUKA

ISO 13849-1: Performance Level



Industrial robots:
S2 – F2 – P1 = performance level d

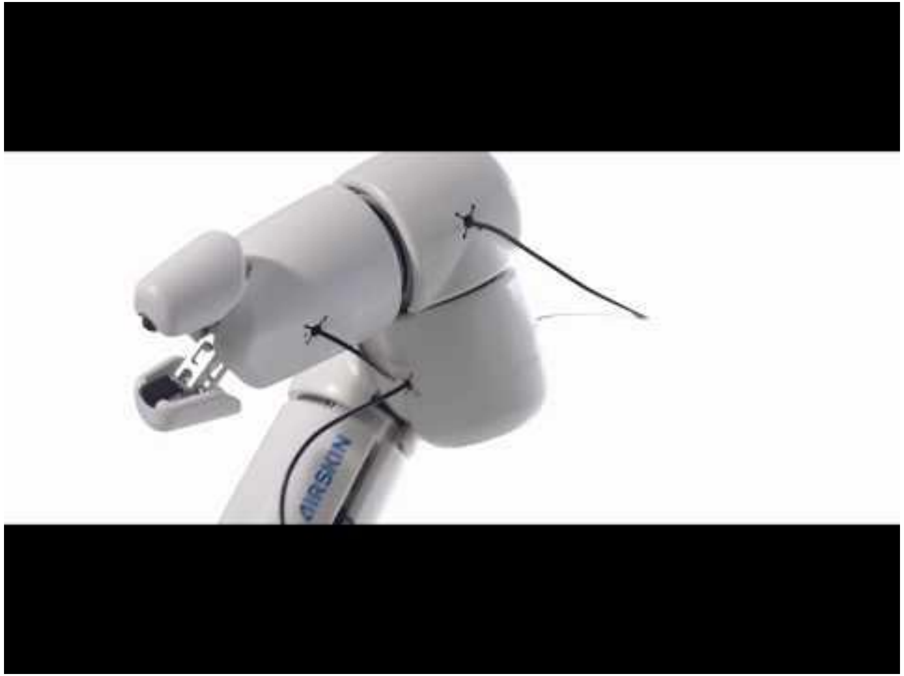
PL d
Probability of failure:



- Risk parameters
  - S Severity of injury
    - S1 - Minor (usually reversible)
    - S2 - Serious (usually irreversible / death)
  - F Frequency and/or duration of exposure to hazard
    - F1 - Rare to infrequent and/or short duration of exposure
    - F2 - Frequent to continuous and/or long duration of exposure
  - P Possibility of avoiding the hazard or limiting the damage
    - P1 - Possible under certain conditions
    - P2 - Scarcely possible

Slide from Daniel Braun, KUKA, iiwa safety system introduction, 2016

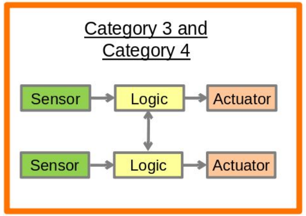
Case study: Airskin



Dual channel OSSD safety device
AIRSKIN is a PLe / Cat. 3 safety device which is easily connected via its 6 wires to any safe I/O of any robot controller.

Performance Level (PL)	Probability of Dangerous Failure per Hour (PFHd) 1/h
a	$\geq 10^{-5}$ and $<10^{-4}$ 〈0.001% to 0.01%〉
b	$\geq 3 \times 10^{-6}$ and $<10^{-5}$ 〈0.0003% to 0.001%〉
c	$\geq 10^{-6}$ and $<3 \times 10^{-6}$ 〈0.0001% to 0.0003%〉
d	$\geq 10^{-7}$ and $<10^{-6}$ 〈0.00001% to 0.0001%〉
e	$\geq 10^{-8}$ and $<10^{-7}$ 〈0.000001% to 0.00001%〉

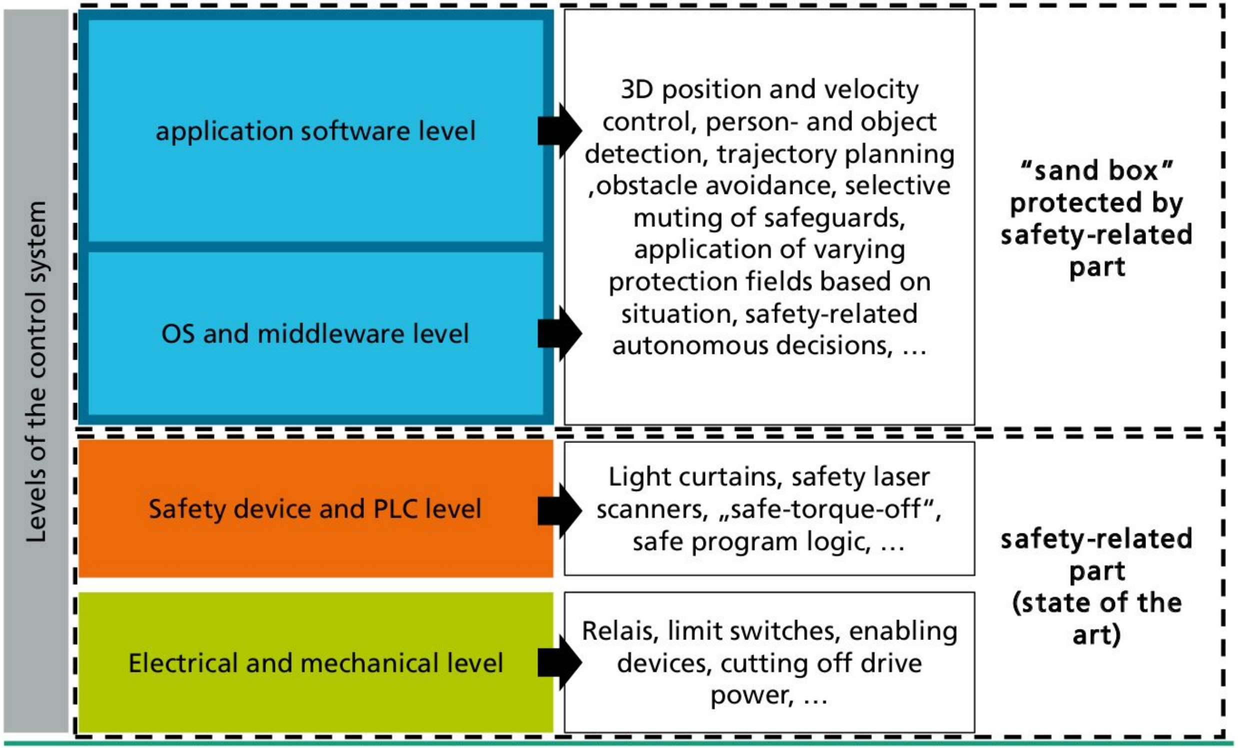
https://www.keyence.eu/ss/products/safetyknowledge/performance/level/



"Dual-channel"

- Category 3: Two channel system
  - Sensors and all parts of the control system exist twice
  - A single failure is detected before a hazard occurs

Safe software: Boundaries of the safety-related control system



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Slide from: Theo Jacobs, Fraunhofer IPA, Safety standards and risk assessment for robots, 2016

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ICS › 25 › 25.040 › 25.040.30

ISO 10218-1:2011

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

- requirements and guidelines for **inherent safe design**, **protective measures** and information for use of industrial robots
- describes **basic hazards associated with robots** and provides requirements to eliminate, or adequately reduce, the risks associated with these hazards

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ISO 10218-2:2011

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

- specifies **safety requirements for the integration** of industrial robots and **industrial robot systems** as defined in ISO 10218-1, and industrial robot cell(s). The integration includes the following:
  - the design, manufacturing, installation, operation, maintenance and decommissioning of the industrial robot system or cell;
  - …

A

ISO 12100 Risk assessment and risk reduction

B1
overall safety aspects

B2
relevant safety devices

ISO 13849-1
Safety-related parts of control systems

C

ISO 10218-1 Robots and robotic devices - Part 1: Robots

ISO 10218-1 Robots and robotic devices - Part 2: Robot systems and integration

"Safety-related parts of control systems must be designed to meet the requirements of PL "d" with structure category 3 as described in ISO 13849-1:2006"

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ISO 10218-1:2011

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

Standards About us News Taking part Store EN

ICS › 25 › 25.040 › 25.040.30

ISO 10218-2:2011

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

(Industrial) robot is an incomplete machine! I.e. can never get a stamp as being safe in any context.

A

ISO 12100 Risk assessment and risk reduction

B1
overall safety aspects

B2
relevant safety devices

ISO 13849-1
Safety-related parts of control systems

C

ISO 10218-1 Robots and robotic devices - Part 1: Robots

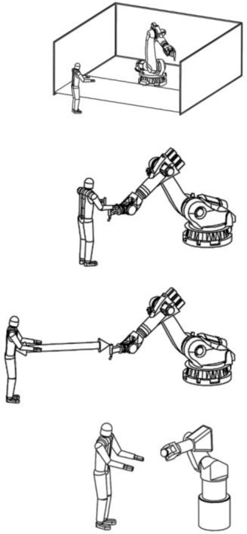
ISO 10218-1 Robots and robotic devices - Part 2: Robot systems and integration

Robot safety-rated features

- Safe velocity monitoring
- Safe workspaces and protected spaces
- Safe collision detection
- Safe force monitoring
- Safe detection of incorrect loads
- Safe motion direction monitoring
- ...

ISO 10218-2 – Types of human-robot-collaboration

1. Safety-rated monitored stop
   - Robot in normal automatic mode
   - Robot stops when human enters the workspace and resumes automatically after leaving
2. Hand guided operation
   - Robot operates at low speed
   - Operation only with enabling switch
3. Speed and separation monitoring
   - Robot operates autonomously at low speed
   - Robot stops when distance to human gets too small
4. Power and force limiting
   - Restriction of force and power of the robot
   - Contact between human and robot allowed



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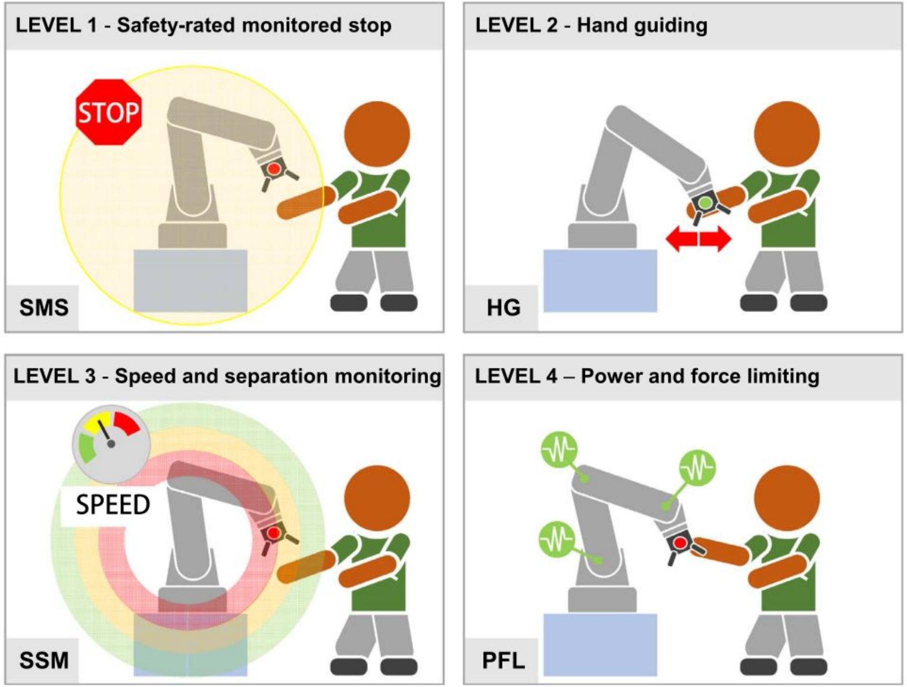

Slide from: Theo Jacobs, Fraunhofer IPA, Safety standards and risk assessment for robots, 2016

Villani, V., Pini, F., Leali, F., & Secchi, C. (2018). Survey on human–robot collaboration in industrial settings: Safety, intuitive interfaces and applications. *Mechatronics*, *55*, 248-266.

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ICS › 25 › 25.040 › 25.040.30

ISO/TS 15066:2016

Robots and robotic devices — Collaborative robots

specifies safety requirements for collaborative industrial robot systems and the work environment, and supplements the requirements and guidance on collaborative industrial robot operation given in ISO 10218-1 and ISO 10218-2.

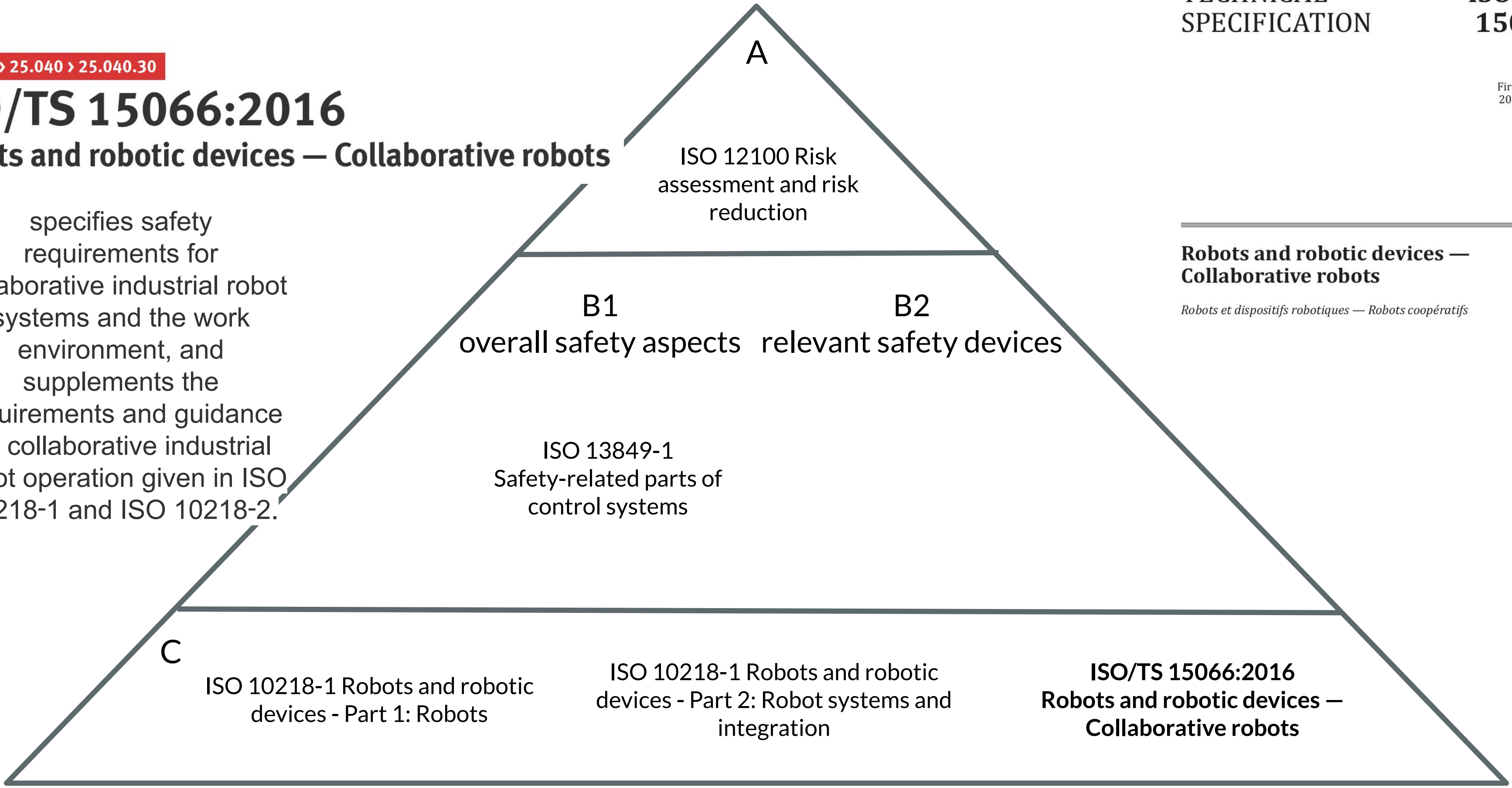
TECHNICAL SPECIFICATION

ISO/TS 15066

First edition
2016-02-15

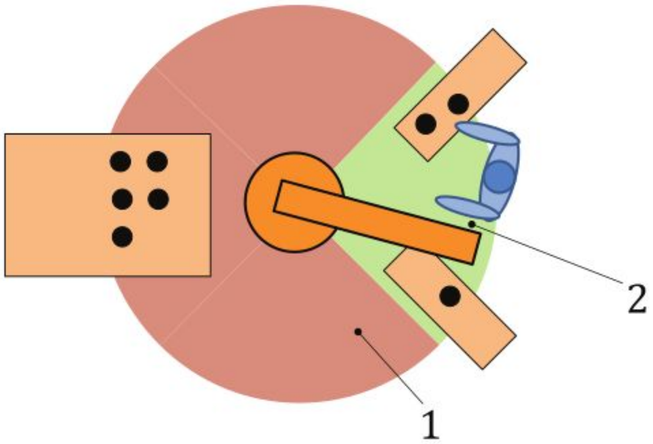
Robots and robotic devices — Collaborative robots

Robots et dispositifs robotiques — Robots coopératifs



Collaborative workspace

ISO/TS 15066:2016(E)



Key

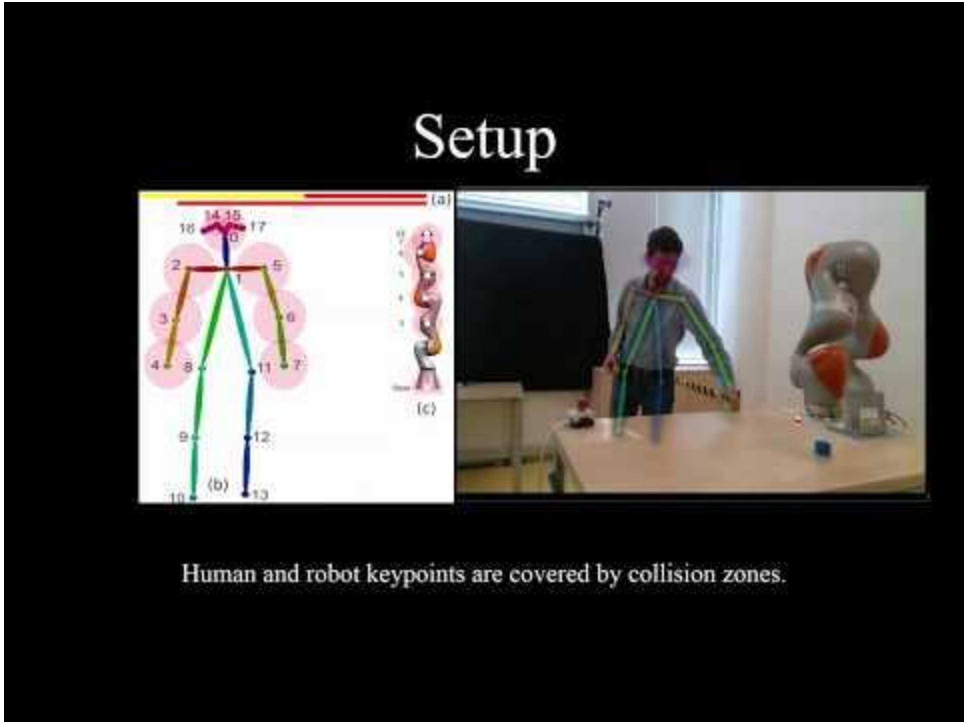
1 operating space

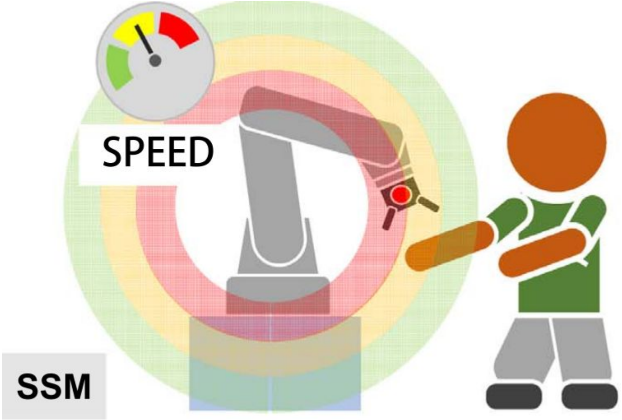
2 collaborative workspace

Figure 1 — Example of a collaborative workspace

collaborative workspace - space within the operating space where the robot system (including the workpiece) and a human can perform tasks concurrently during production operation

Speed and separation monitoring





Villani et al. (2018)

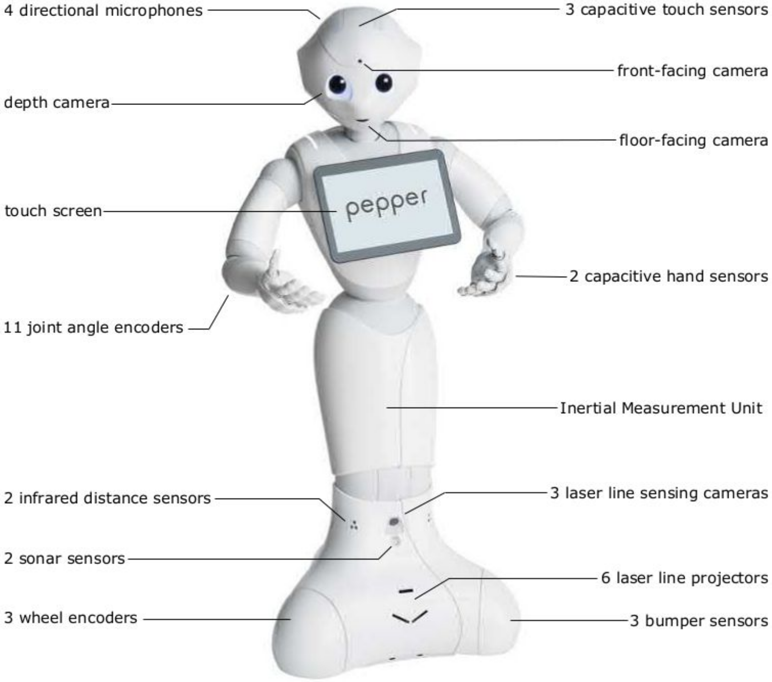
Svarny, P.; Tesar, M.; Behrens, J. K. & Hoffmann, M. (2019), Safe physical HRI: Toward a unified treatment of speed and separation monitoring together with power and force limiting, *in* 'Intelligent Robots and Systems (IROS), 2019 IEEE/RSJ International Conference on', IEEE, pp. 7574-7581.

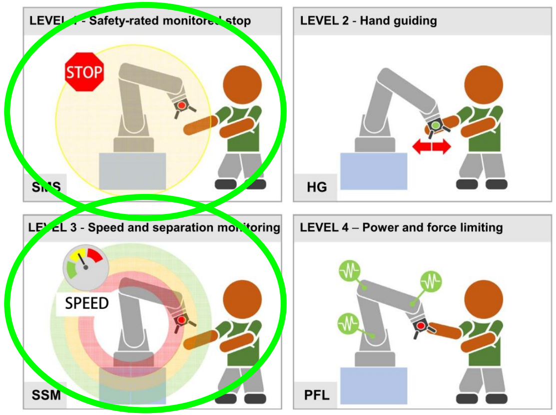
Perception for interaction

- exteroceptive sensing
  - laser scanners, proximity sensors (magnetic, ultrasound, …)
  - cameras (single, stereo, catadioptric, event-based, …), Vicon system

pHRI 54

Physical HRI - Lecture slides by Alessandro de Luca
http://www.diag.uniroma1.it/deluca/pHRI_elective/pHRI_Introduction.pdf





A

ISO 12100 Risk assessment and risk reduction

B1
overall safety aspects

B2
relevant safety devices

ISO 13849-1
Safety-related parts of control systems

ISO 13855:2010
Safety of machinery — Positioning of **safeguards** with respect to the approach speeds of parts of the human body

C

ISO 10218-1 Robots and robotic devices - Part 1: Robots

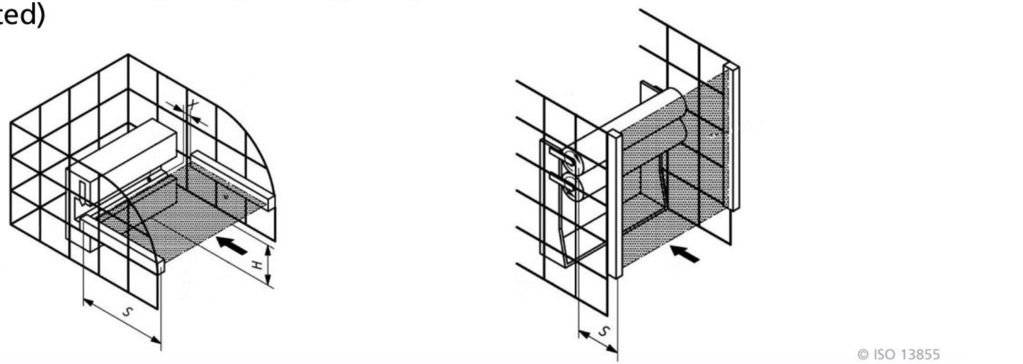
ISO 10218-1 Robots and robotic devices - Part 2: Robot systems and integration

ISO/TS 15066:2016
Robots and robotic devices — Collaborative robots

Safety distances for safeguards

ISO 13855 – Safety of machinery – Positioning of safeguards with respect to the approach speeds of parts of the human body

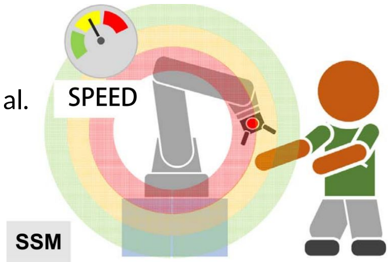
- Hazardous movement needs to stop before a person can reach the hazard zone
- Formulae to calculate safety distances: S = (K*T) + C
  - K … approach speed of the human, usually 1.6 m/s
  - T … Stopping time of the machine
  - C … Additional safety margins (e.g. length of an arm, if the arm itself cannot be detected)



Slide from: Theo Jacobs, Fraunhofer IPA, Safety standards and risk assessment for robots, 2016

Speed and separation monitoring

Villani et al. (2018)



ISO/TS 15066

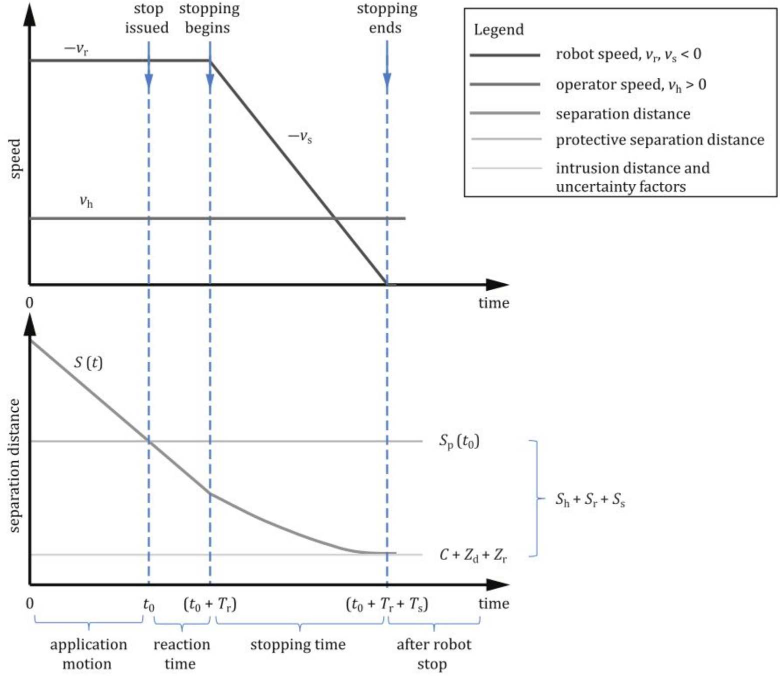


Figure 3 — Graphical representation of the contributions to the protective separation distance between an operator and a robot

The protective separation distance, S_p, can be described by Formula (1):

$$S_p(t_0) = S_h + S_r + S_s + C + Z_d + Z_r \quad (1)$$

where

$S_p(t_0)$ is the protective separation distance at time t_0;

t_0 is the present or current time;

S_h is the contribution to the protective separation distance attributable to the operator's change in location;

S_r is the contribution to the protective separation distance attributable to the robot system's reaction time;

S_s is the contribution to the protective separation distance due to the robot system's stopping distance;

C is the intrusion distance, as defined in ISO 13855; this is the distance that a part of the body can intrude into the sensing field before it is detected;

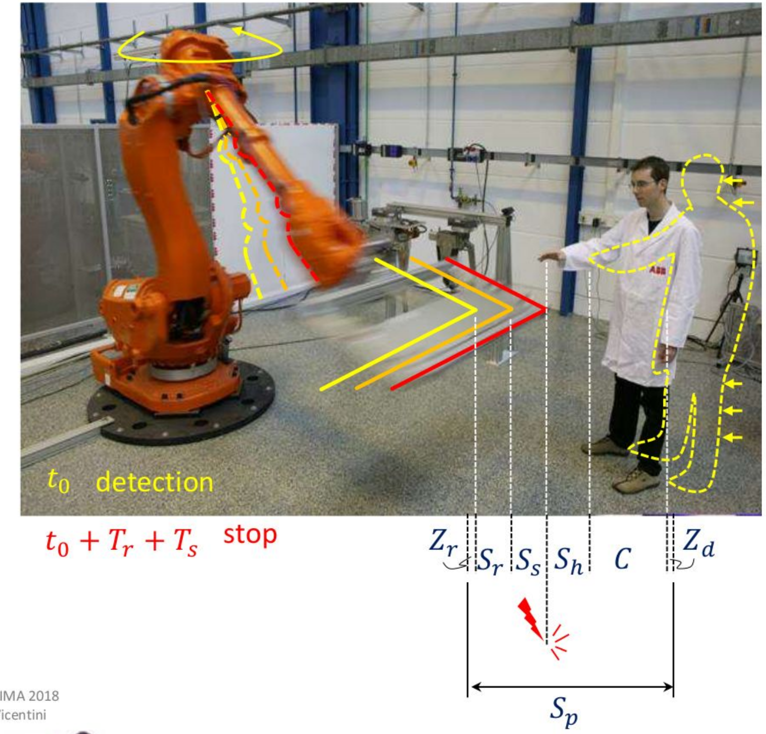
Z_d is the position uncertainty of the operator in the collaborative workspace, as measured by the presence sensing device resulting from the sensing system measurement tolerance;

Z_r is the position uncertainty of the robot system, resulting from the accuracy of the robot position measurement system.

Protective separation distance (S_p)

T_r - reaction time of the robot system
- including time required for detection of operator position, processing of this signal, activation of a robot stop
- excluding the time it takes the robot to come to a stop

T_s - stopping time of the robot
- from the activation of the stop command until the robot has halted;
- T_s is not a constant but a function of robot configuration, planned motion, speed, end effector, and load



$$S_p(t_0) = S_h + S_r + S_s + C + Z_d + Z_r$$

S_h - contribution to S_p due to operator's change in location

$$S_h = \int_{t_0}^{t_0+T_r+T_s} v_h(t)dt$$

S_r - contribution to S_p due to robot system's reaction time

$$S_r = \int_{t_0}^{t_0+T_r} v_r(t)dt$$

S_s - contribution to S_p while the robot is stopping; v_s robot speed in the course of stopping

$$S_s = \int_{t_0+T_r}^{t_0+T_r+T_s} v_s(t)dt$$

C Intrusion distance (ISO 13855)

Z_d, Z_r uncertainties

MADRID 2018 IROS

Slide from F. Vicentini: Safety of collaborative robotics. Speed and separation monitoring @ IROS 2018.

Case study

$$S_p(t_0) = S_h + S_r + S_s + C + Z_d + Z_r \quad (6)$$

with

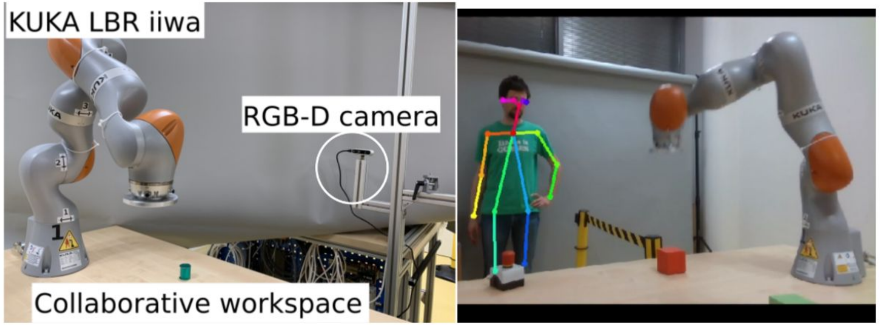
- S_h contribution to the $S_p(t_0)$ attributable to the operators change in location;
- S_r contribution to the $S_p(t_0)$ attributable to the robot systems reaction time;
- S_s contribution to the $S_p(t_0)$ due to the robot systems stopping distance;
- C distance that a part of the body can intrude into the sensing field before it is detected;
- Z_d position uncertainty of the operator in the collaborative workspace, as measured by the presence sensing device resulting from the sensing system measurement tolerance;
- Z_r position uncertainty of the robot system from the accuracy of the robot position measurement.

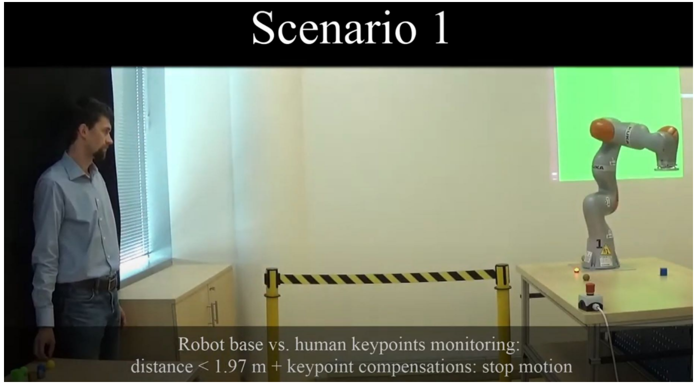
- S_h $(t_r + t_s) \cdot v_h$, where v_h is the default human walking speed (1.6 m/s) [2], t_r is the time it took the robot to react to a issued stop status (0.1 s), and t_s the time it took the robot to stop its movement: 0.43 s, thus $1.6 \cdot (0.1 + 0.43) = 0.85$ m;
- S_r $t_r \cdot v_{max} = 0.1 \cdot 1 = 0.1$ m;
- S_s $t_s \cdot v_r = 0.43 \cdot 0.5 = 0.22$ m;
- C the setup did not allow the operator to enter the workspace without being detected: 0 m;
- Z_d see the h_{compen} values from Subsection III-F: 0 m;
- Z_r the LBR iiwa's repeatability value: 0.0001 m.

The time t_s was determined based on measured calculation times (0.005 s) and the maximal deceleration of the robot which was set to 1.5 rad /s^2.

Using these values, we can calculate the S_p as in Eq. 7.

$$S_p(t_0) = 0.85 + 0.1 + 0.22 + 0.0001 = 1.17 \text{ m} \quad (7)$$

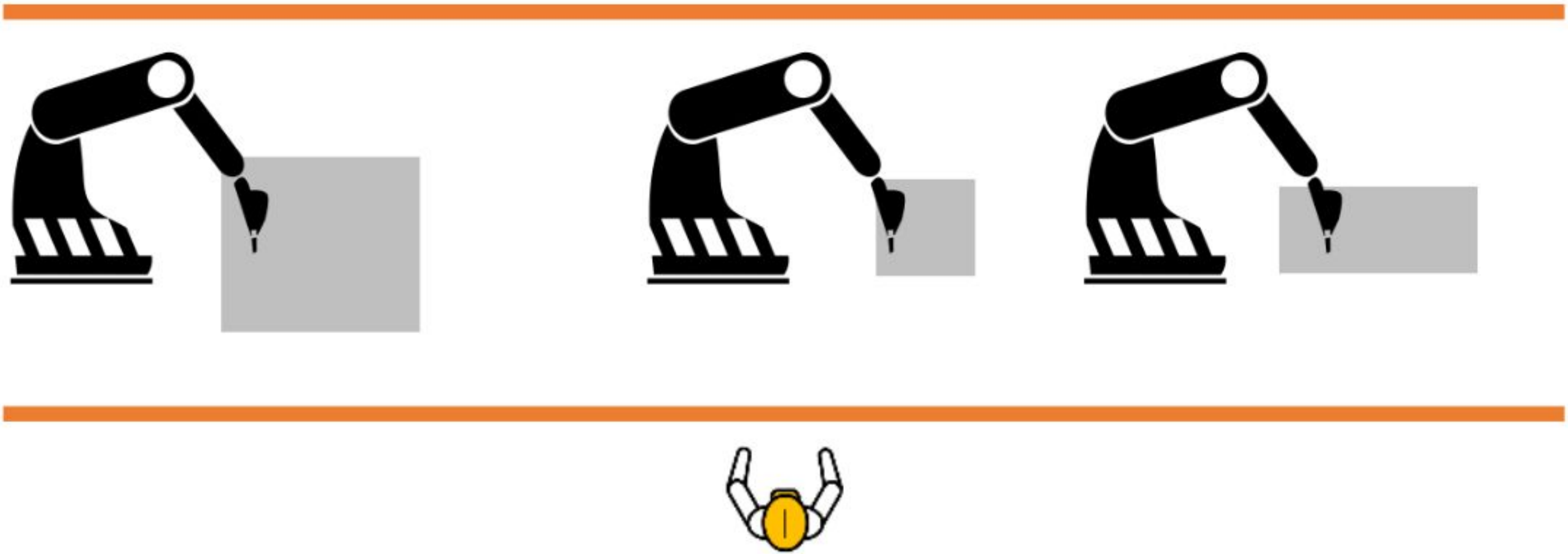




robot base, not robot links considered => full robot reach needs to be added:
$S_p = 1.17 + 0.8 = 1.97$m

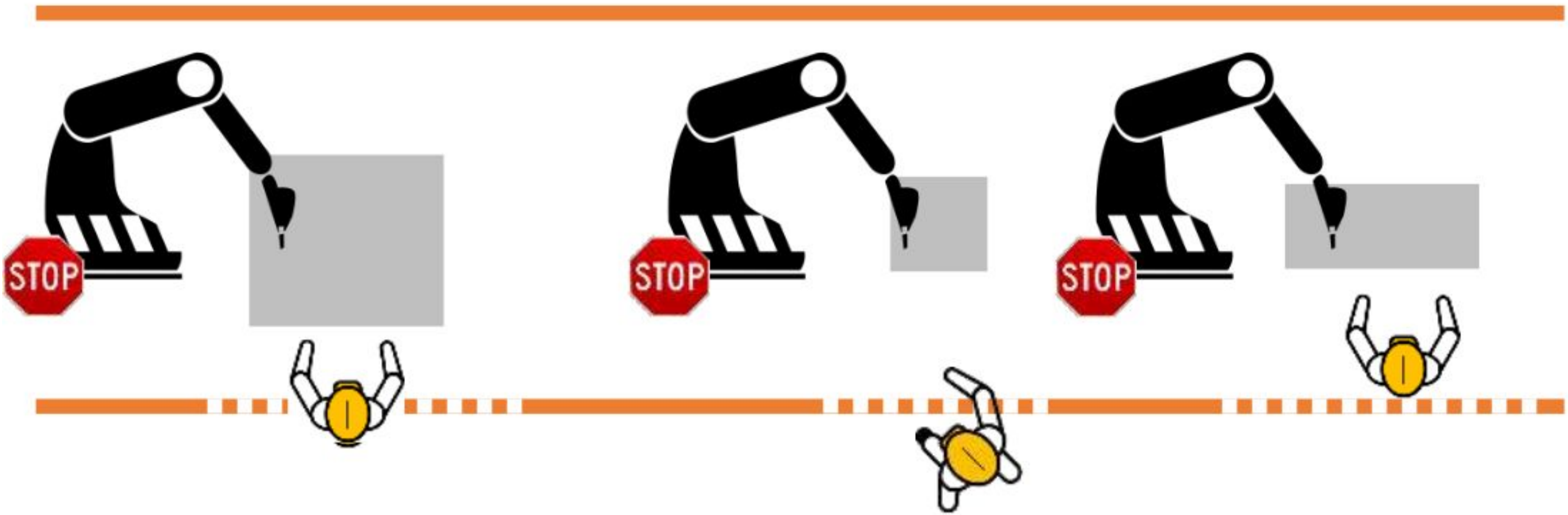
Svarny, P.; Tesar, M.; Behrens, J. K. & Hoffmann, M. (2019), Safe physical HRI: Toward a unified treatment of speed and separation monitoring together with power and force limiting, *in* 'Intelligent Robots and Systems (IROS), 2019 IEEE/RSJ International Conference on', IEEE, pp. 7574-7581.

Shop floor design 1 - traditional



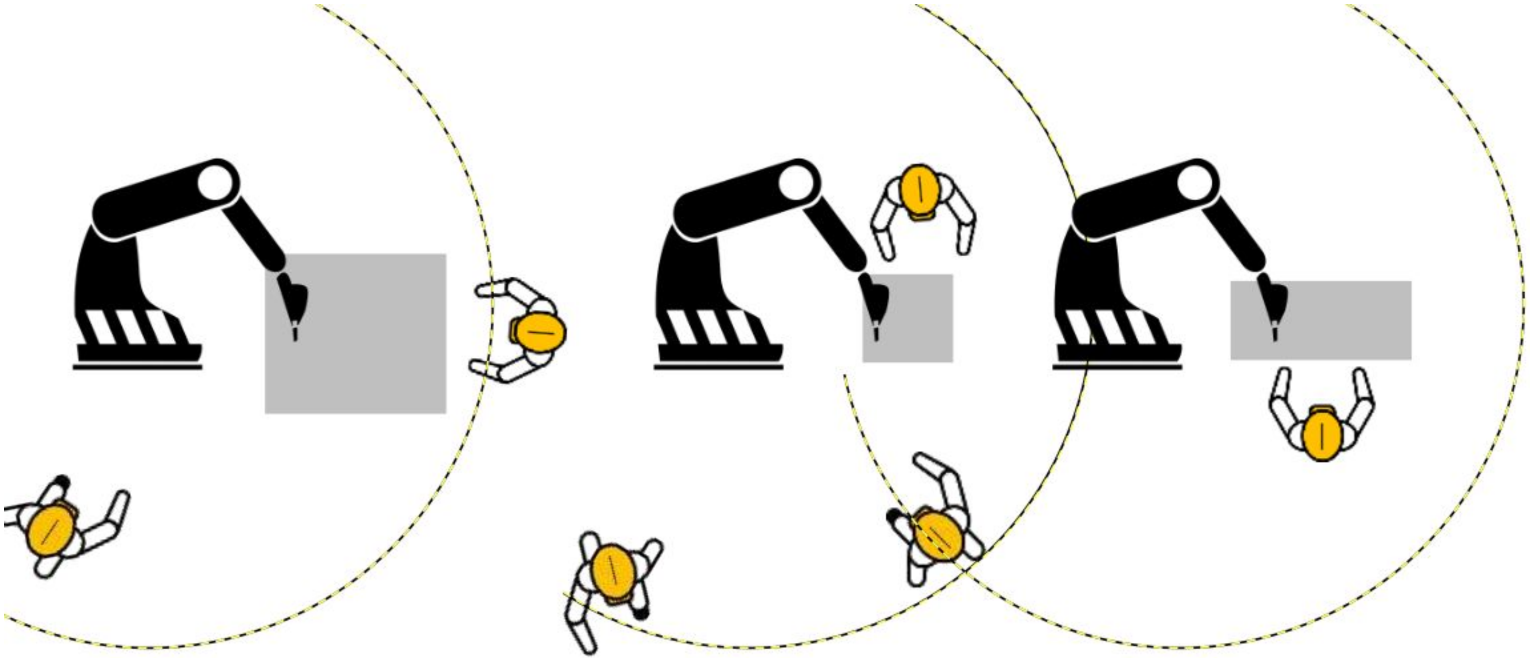
Slide from F. Vicentini: Safety of collaborative robotics. Speed and separation monitoring @ IROS 2018.

Shop floor design 2 - safety-rated monitored stop



Slide from F. Vicentini: Safety of collaborative robotics. Speed and separation monitoring @ IROS 2018.

Shop floor design 3a



large footprint

low flexibility

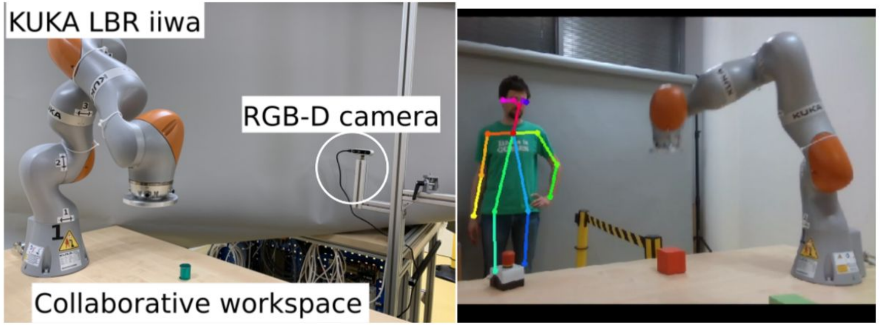
Slide from F. Vicentini: Safety of collaborative robotics. Speed and separation monitoring @ IROS 2018.

$$S_p(t_0) = S_h + S_r + S_s + C + Z_d + Z_r \qquad (6)$$

with

- S_h contribution to the $S_p(t_0)$ attributable to the operators change in location;
- S_r contribution to the $S_p(t_0)$ attributable to the robot systems reaction time;
- S_s contribution to the $S_p(t_0)$ due to the robot systems stopping distance;
- C distance that a part of the body can intrude into the sensing field before it is detected;
- Z_d position uncertainty of the operator in the collaborative workspace, as measured by the presence sensing device resulting from the sensing system measurement tolerance;
- Z_r position uncertainty of the robot system from the accuracy of the robot position measurement.

Case study



- S_h $(t_r + t_s) \cdot v_h$, where v_h is the default human walking speed (1.6 m/s) [2], t_r is the time it took the robot to react to a issued stop status (0.1 s), and t_s the time it took the robot to stop its movement: 0.43 s, thus $1.6 \cdot (0.1 + 0.43) = 0.85$ m;
- S_r $t_r \cdot v_{max} = 0.1 \cdot 1 = 0.1$ m;
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- C the setup did not allow the operator to enter the workspace without being detected: 0 m;
- Z_d see the h_{compen} values from Subsection III-F: 0 m;
- Z_r the LBR iiwa's repeatability value: 0.0001 m.

The time t_s was determined based on measured calculation times (0.005 s) and the maximal deceleration of the robot which was set to 1.5 rad /s^2.

Using these values, we can calculate the S_p as in Eq. 7.

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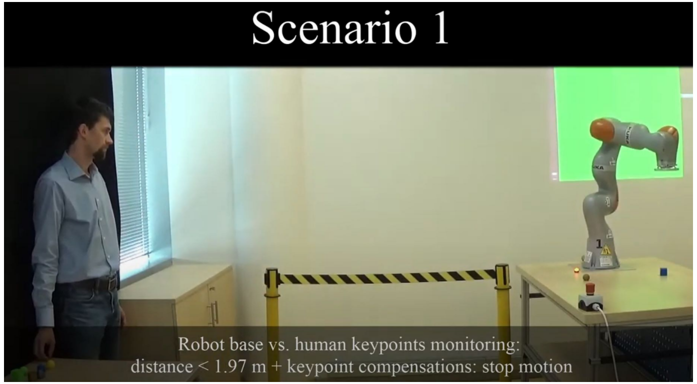
robot base, not robot links considered => full robot reach needs to be added:
S_p = 1.17 + 0.8 = 1.97m



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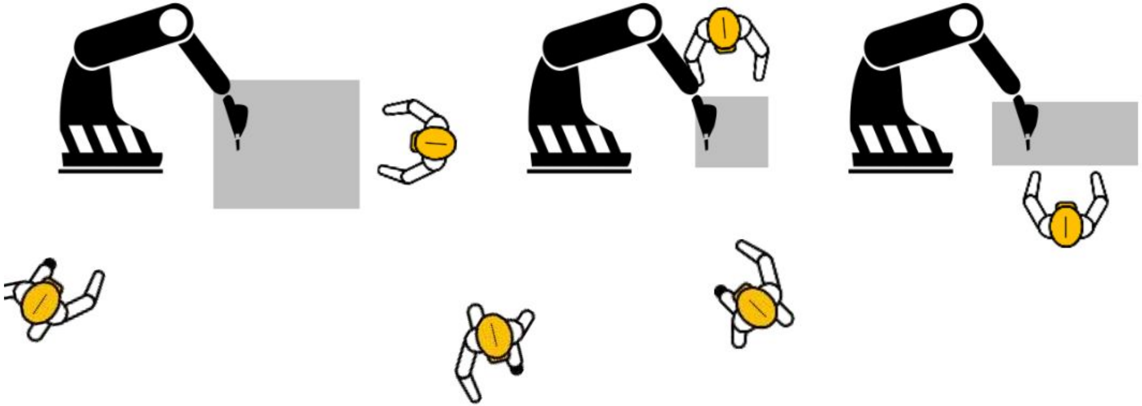
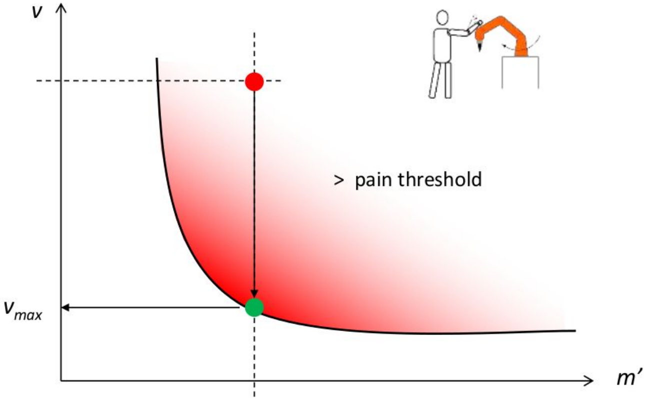
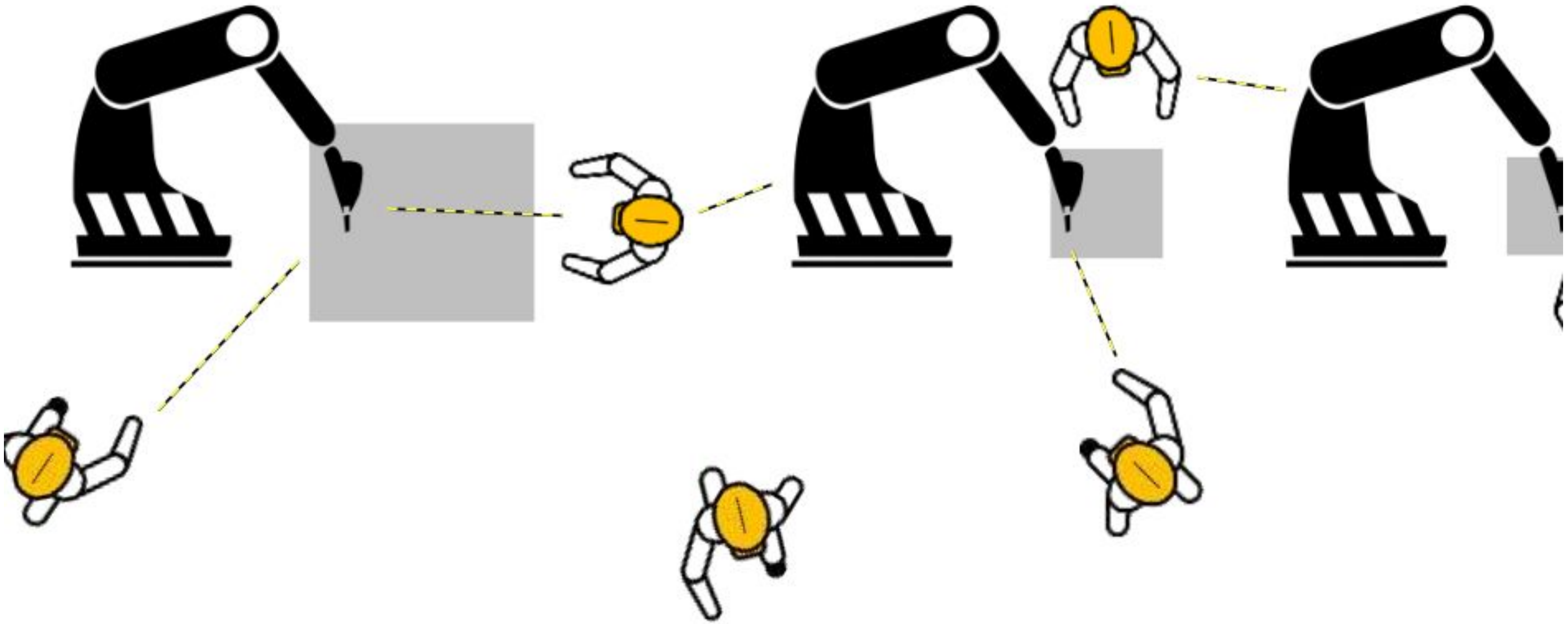
Shop floor design 3b - PFL collaborative mode





Slide from F. Vicentini: Safety of collaborative robotics. Speed and separation monitoring @ IROS 2018.

Shop floor design 3c - SSM collaborative mode



Slide from F. Vicentini: Safety of collaborative robotics. Speed and separation monitoring @ IROS 2018.

$$S_p(t_0) = S_h + S_r + S_s + C + Z_d + Z_r \quad (6)$$

with

- S_h contribution to the $S_p(t_0)$ attributable to the operators change in location;
- S_r contribution to the $S_p(t_0)$ attributable to the robot systems reaction time;
- S_s contribution to the $S_p(t_0)$ due to the robot systems stopping distance;
- C distance that a part of the body can intrude into the sensing field before it is detected;
- Z_d position uncertainty of the operator in the collaborative workspace, as measured by the presence sensing device resulting from the sensing system measurement tolerance;
- Z_r position uncertainty of the robot system from the accuracy of the robot position measurement.

- S_h $(t_r + t_s) \cdot v_h$, where v_h is the default human walking speed (1.6 m/s) [2], t_r is the time it took the robot to react to a issued stop status (0.1 s), and t_s the time it took the robot to stop its movement: 0.43 s, thus $1.6 \cdot (0.1 + 0.43) = 0.85$ m;
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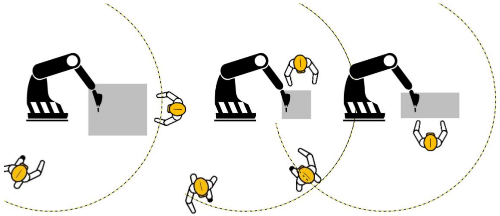
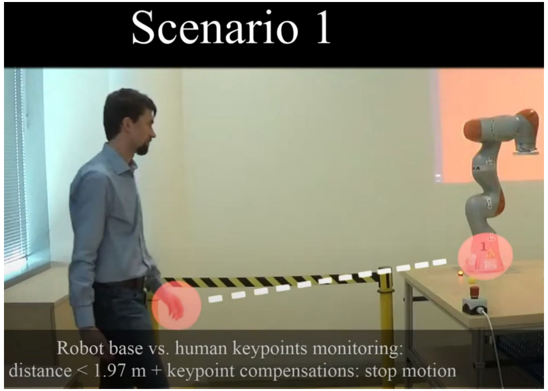
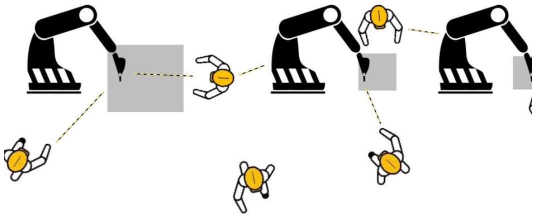
Case study

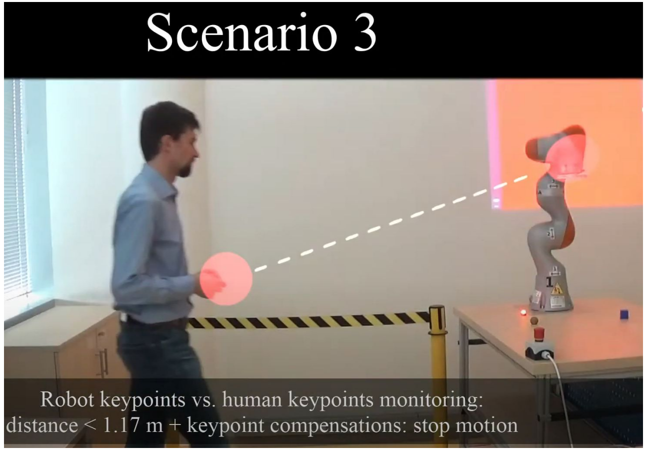


large footprint

low flexibility







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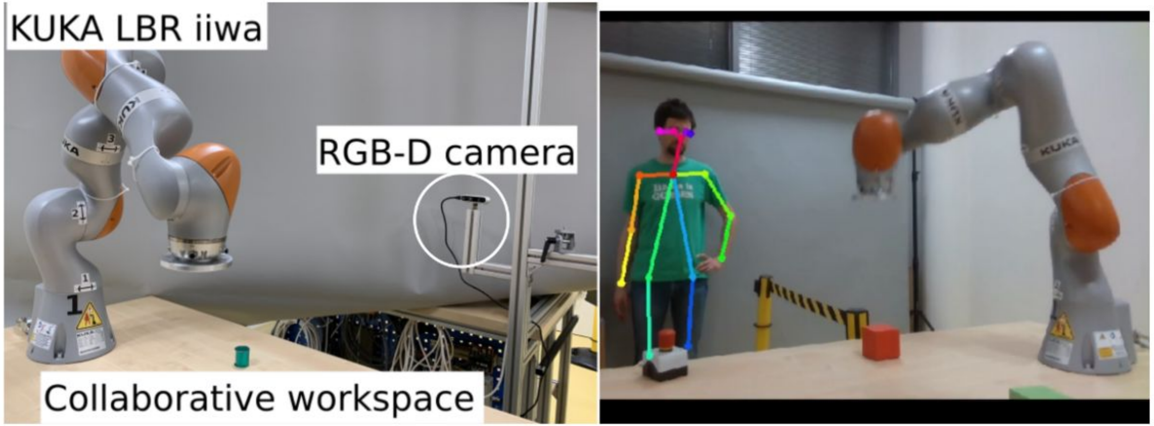
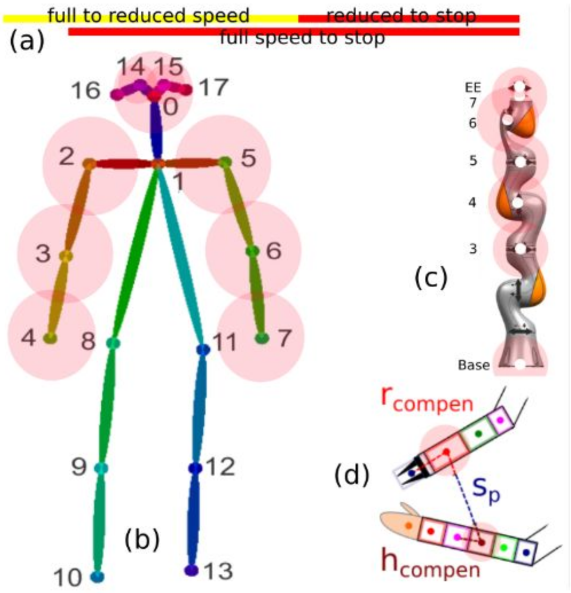




Could we do the risk assessment and deploy this application?

- Intel Realsense performance level (PL)?
- OpenPose performance level?

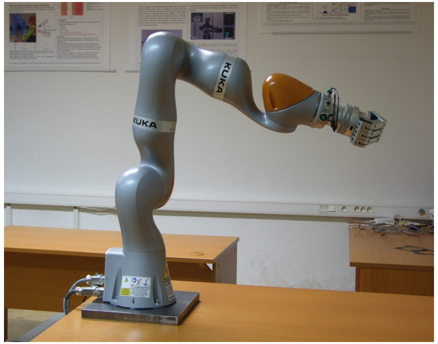
Svarny, P.; Tesar, M.; Behrens, J. K. & Hoffmann, M. (2019), Safe physical HRI: Toward a unified treatment of speed and separation monitoring together with power and force limiting, *in* 'Intelligent Robots and Systems (IROS), 2019 IEEE/RSJ International Conference on', IEEE, pp. 7574-7581.

Table 3
Available commercial cobots (extended from [67–71]).

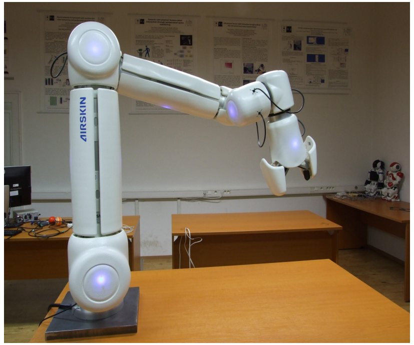
Manufacturers, robot models and specifications	*Manufacturers, robot models and specifications*
ABB (Switzerland) ≀ YuMi - IRB 14000  *DOFs:* 7+7 *Payload:* 0.5 kg *Reach:* 559 mm *Repeatability:* ±0.02 mm *Weight:* 38 kg *Velocity:* 1500 mm/s	**ABB (Switzerland) ≀ Roberta 1 / Roberta 2 / Roberta 3** ell  *DOFs:* 6 *Payload:* 4 kg ∥ 8 kg ∥ 12 kg *Reach:* 600 mm ∥ 800 mm ∥ 1200 mm *Repeatability:* ±0.1 mm *Weight:* 14.5 kg ∥ 19.5 kg ∥ 30.5 kg *Velocity Joints:* 110°/s
FANUC (Japan) ≀ CR-35iA  *DOFs:* 6 *Payload:* 35 kg *Reach:* 1813 mm *Repeatability:* ±0.04 mm *Weight:* 990 kg *Velocity:* 750 mm/s	**FANUC (Japan) ≀ CR4iA / CR-7iA / CR-7iA/L**  *DOFs:* 6 *Payload:* 4 kg ∥ 7 kg ∥ 7 kg *Reach:* 550 mm ∥ 717 mm ∥ 911 mm *Repeatability:* ±0.02 mm ∥ ±0.02 mm ∥ ±0.03 mm *Weight:* 48 kg ∥ 53 kg ∥ 55 kg *Velocity:* 1000 mm/s
Rethink Robotics (Boston-USA) ≀ Baxter / Sawyer  *DOFs:* Baxter 7+7 ∥ Sawyer 7 *Payload:* 2.2 kg per arm ∥ 4 kg *Reach:* 1210 mm per arm ∥ 1260 mm *Repeatability:* ±0.1 mm *Weight:* 75 kg ∥ 19 kg *Velocity:* 1500 mm/s	**UNIVERSAL ROBOT (Denmark) ≀ UR 3 / 5 / 10**  *DOFs:* 6 *Payload:* 3 kg ∥ 5 kg ∥ 10 kg *Reach:* 500 mm ∥ 850 mm ∥ 1300 mm *Repeatability:* ±0.1 mm *Weight:* 11 kg ∥ 18.4 kg ∥ 28.9 kg *Velocity:* 1000 mm/s
MABI Robotics (Switzerland) ≀ SPEEDY 6 / 10 / 12  *DOFs:* 6 *Payload:* 6 kg ∥ 10 kg ∥ 12 kg *Reach:* 800 mm ∥ 1384.5 mm ∥ 1250 mm *Repeatability:* ±0.1 mm *Weight:* 28 kg ∥ 28 kg ∥ 35 kg *Velocity Joints:* 145 → 275°/s ∥ 120 → 180°/s ∥ 75 → 275°/s	**KUKA (Germany) ≀ LBR IIWA**  *DOFs:* 7 *Payload:* 7 kg ∥ 14 kg *Reach:* 800 mm ∥ 820 mm *Repeatability:* ±0.1 mm ∥ ±0.15 mm *Weight:* 22 kg ∥ 30 kg *Velocity Joints:* 90 → 180°/s ∥ 70 → 180°/s
Techman Robot (Taiwan) ≀ TM5-900 / 700  *DOFs:* 6 *Payload:* 4 kg ∥ 6 kg *Reach:* 900 mm ∥ 700 mm *Repeatability:* ±0.05 mm *Weight:* 22.5 kg ∥ 22 kg *Velocity Joints:* 180 → 225°/s	**Productive Robotics (Carpinteria-USA) ≀ OB7**  *DOFs:* 7 *Payload:* 5 kg *Reach:* 1000 mm *Repeatability:* ±0.1 mm *Weight:* 24 kg *Velocity:* 2000 mm/s
Yaskawa (Japan) ≀ Motoman HC10  *DOFs:* 6 *Payload:* 10 kg *Reach:* 1200 mm *Repeatability:* ±0.1 mm *Weight:* 45 kg *Velocity Joints:* 130 → 250°/s	**AUBO Robotics (China) ≀ AUBO-i5**  *DOFs:* 6 *Payload:* 5 kg *Reach:* 880 mm *Repeatability:* ±0.05 mm *Weight:* 24 kg *Velocity:* 2800 mm/s
FRANKA EMIKA (Germany) ≀ FRANKA ARM  *DOFs:* 7 *Payload:* 3 kg *Reach:* 855 mm *Repeatability:* ±0.1 mm *Weight:* 18 kg *Velocity Joints:* 2000 mm/s	**Precise Automation (Fremont-USA) ≀ PP100 - Cartesian**  *DOFs:* 3 *Payload:* 1 kg *Reach:* *X* 635 mm - *Y* 300 mm - *Z* 225 mm *Repeatability:* ±0.1 mm *Weight:* 20 kg *Velocity:* 1500 mm/s
Kawasaki Robotics (Japan) ≀ duAro – Dual-Arm SCARA Robot  *DOFs:* 4+4 *Payload:* 2 kg *Reach:* 760 mm *Repeatability:* ±0.05 mm *Weight:* 200 kg *Velocity:* N/A	**BOSCH (Germany) ≀ APAS**  *DOFs:* 6 *Payload:* 2 kg *Reach:* 911 mm *Repeatability:* ±0.03 mm *Weight:* 230 kg *Velocity:* 500 mm/s

Examples of cobots

in our lab



KUKA LBR iiwa 7R800



UR10e + Airskin

Villani, V., Pini, F., Leali, F., & Secchi, C. (2018). Survey on human–robot collaboration in industrial settings: Safety, intuitive interfaces and applications. *Mechatronics*, *55*, 248-266.

Problems with deployment of AI / deep learning

- Good solutions working 99.9% of the time are not good enough here.

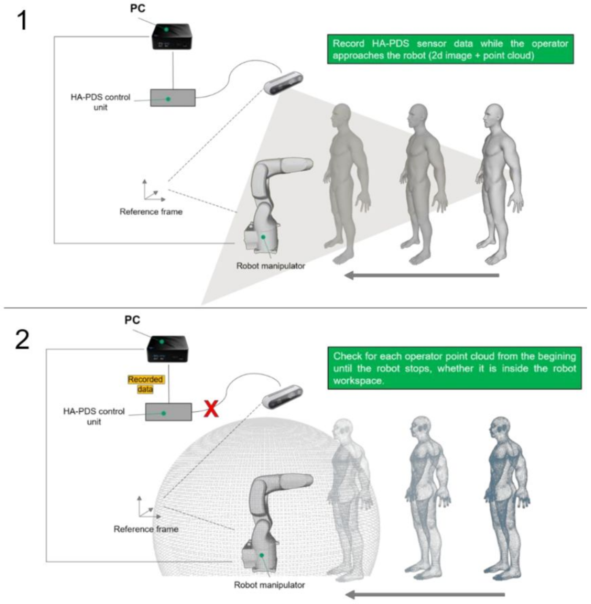


Figure 2: Method to test the HA-PDS for maintaining a safe distance to humans.

Vision-AI-based proximity detection system for industrial applications, https://covrfilestorage.blob.core.windows.net/documents/casestories/Case%20story%20Tekniker.pdf

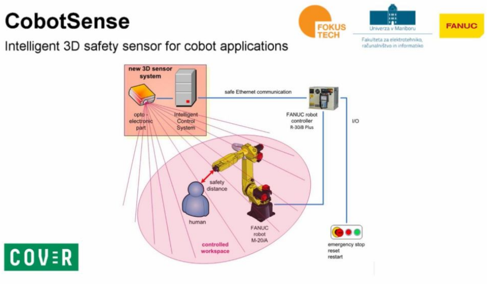


Figure 1: Sensor system and its connection to the robot.

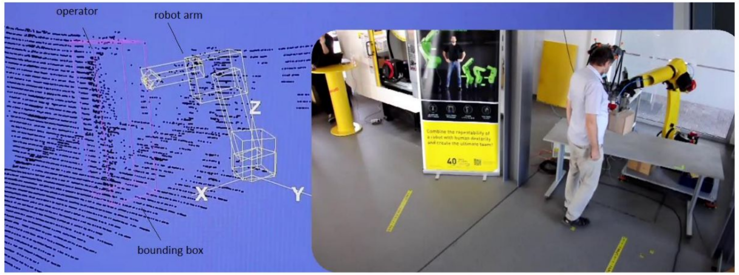


Figure 2: Testing scenario with slow movement of an operator towards a robot arm.

Intelligent 3D safety sensor for cobot applications, https://covrfilestorage.blob.core.windows.net/documents/casestories/CobotSense%20-%20COVR%20Case%20Story%20(Public).pdf

https://www.safearoundrobots.com/toolkit/casestories

Safe design and SSM

What role does safe design play in SSM?

- Not so big - robot stops before contact!
- Breaking distance may depend on robot mass…
- No need for cobot then?
- Robot behavior (Cartesian trajectory, joint trajectory, velocities, breaking time and distance…) needs to be safety-rated.

Safe design

- Lightweight
  - high-strength metals, or composite materials for the robot links
- Tendon-based robots
  - Remote direct drives - actuators in robot base.
  - Low reduction ratios -> back-driveability.
- Elastic actuation
  - Series Elastic Actuation (SEA)
  - Variable Stiffness Actuation (VSA)
  - Variable Impedance Actuations (VIA) - stiffness & damping

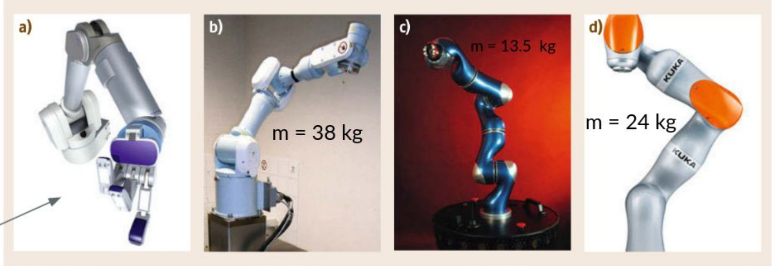


Fig. 69.10 (a) Barrett arm (after [69.58]), (b) Mitsubishi PA10 arm, (c) DLR lightweight robot III (after [69.59]), (d) KUKA LBR iiwa (after [69.60]) (courtesy of Barret Technology Inc., DLR, KUKA)

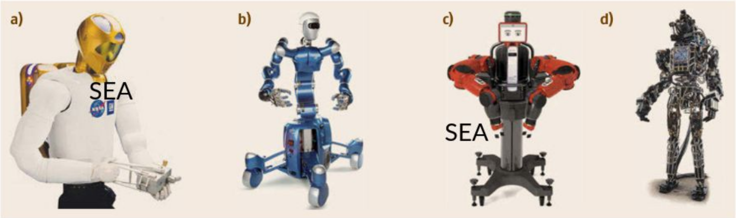
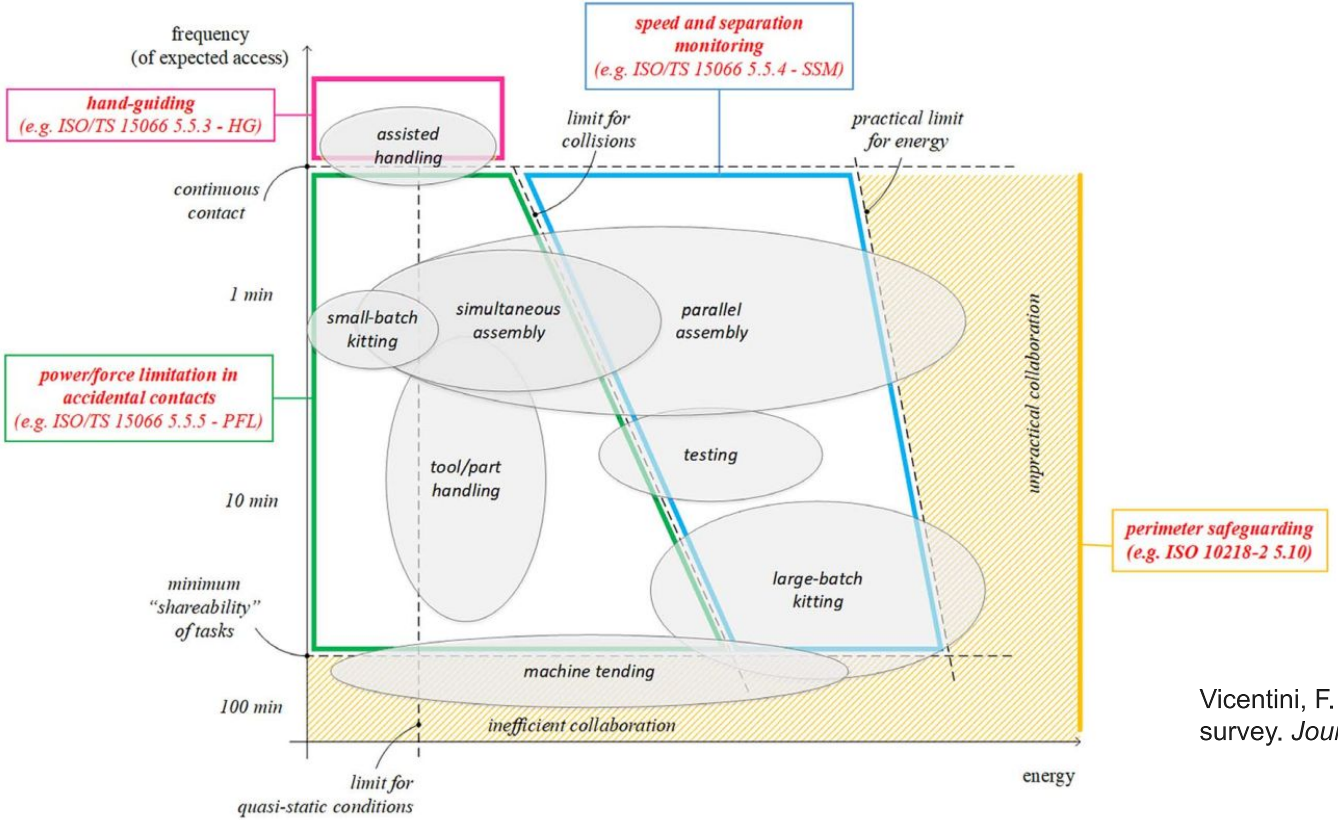


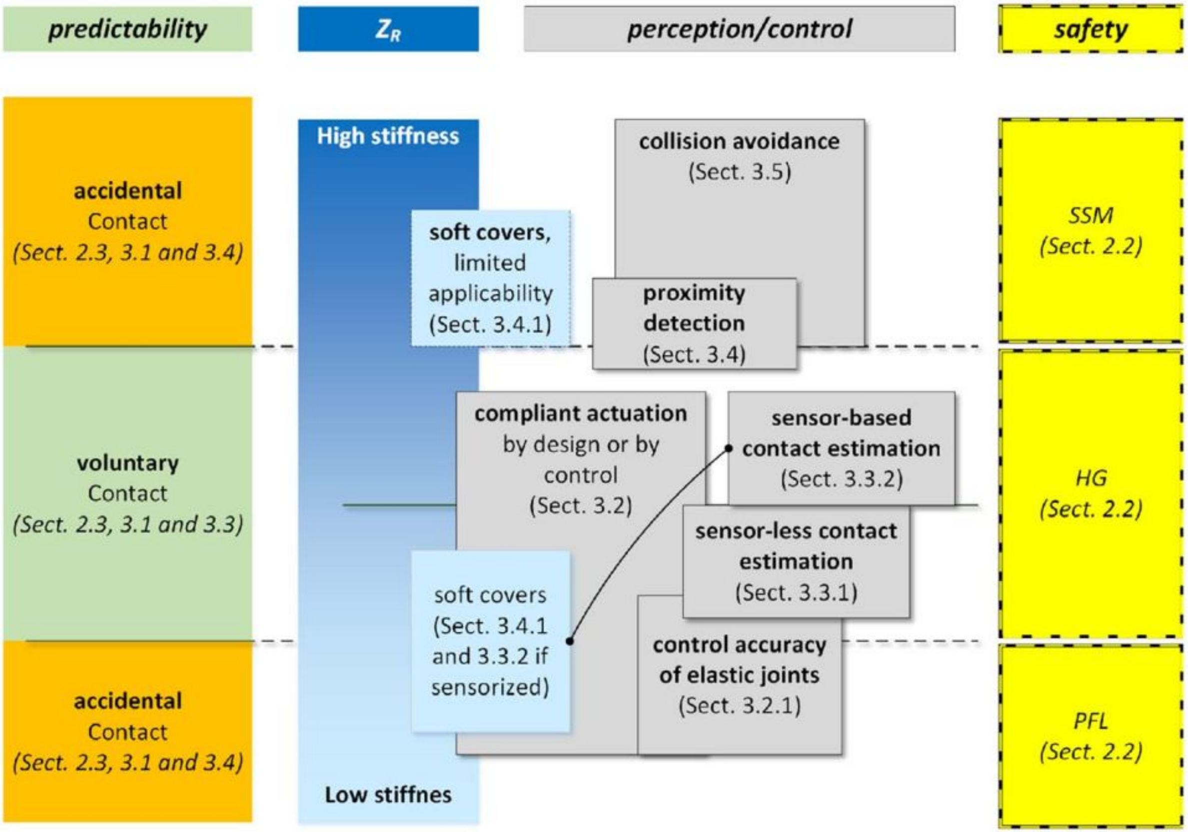
Fig. 69.11 (a) NASA *Robonaut 2*, (b) DLR *Rollin' Justin*, (c) Rethink Robotics *Baxter* and (d) Boston Dynamics *Atlas* (courtesy of NASA, DLR, Rethink Robotics Inc., Boston Dynamics)

Haddadin, S., & Croft, E. (2016). Physical human–robot interaction. In *Springer handbook of robotics* (pp. 1835-1874). Springer, Cham.

Collaborative robot regimes



Vicentini, F. (2021). Collaborative robotics: a survey. *Journal of Mechanical Design*, *143*(4).



Vicentini, F. (2021). Collaborative robotics: a survey. *Journal of Mechanical Design*, *143*(4).

Conclusion – How to design a safe robot

1. Start to worry about safety as early as possible in the robot design process!
2. Look for a type-C standard the defines basic safety requirements for your robot type
3. Perform risk assessment and risk reduction according to ISO 12100 (iterative process!)
    1. Specify the use limits of your robot and think of foreseeable misuse
    2. Identify risks that are not tolerable
    3. Reduce risks according to the three-step-method
4. Look for additional (usually type-B) standards that you need to comply with when using certain safety measures or design features
5. Design and verify safety-related part of the control system
6. Apply the CE mark, sell your product and get rich!

Slide from: Theo Jacobs, Fraunhofer IPA, Safety standards and risk assessment for robots, 2016

Fraunhofer IPA

the big mistakes

“my application is safe
because I use a *collaborative robot*”

No, this is a dangerous shortcut.
*Please, **do** risk assessment*

*Collaborative solutions require **different mindsets**:*
- *design your layout,*
- *prepare your environment,*
- *anticipate errors and misuses.*

***Combine** safeguarding and protective measures*

***Do not force** collaboration when unnecessary*

“any moving part is hazardous, so guards must be installed.
Please **stop this unsafe machine.**”

No, this is preemptive technology rejection.
*Please **review** risk assessment.*

*Collaborative solutions require **different mindsets**:*
- *Understand new machines,*
- *Be aware of advantages and downsides*
- *anticipate errors and misuses.*

***Train** about safeguarding and protective measures*

***Do not deny** collaboration when necessary*

Next

- Modeling of impacts.
- What does impact force depend on?
  - Velocity of colliding bodies.
  - Contact type - quasi-static / transient.
  - Contact area and material properties (stiffness/damping).
  - Robot effective mass.
  - Robot reaction.
- Power and force limiting mode of collaboration.
- Interaction control
  - Collision detection, isolation, reaction…
  - Impedance / admittance control, force control…

Resources

- Books / book sections
  - Haddadin, S., & Croft, E. (2016). Physical human–robot interaction. In *Springer Handbook of Robotics* (pp. 1835-1874). Springer, Cham.
- Online resources
  - Theo Jacobs, Safety standards and risk assessment for robots, https://www.ipa.fraunhofer.de/en/expertise/robot-and-assistive-systems/service-robot-technologies/safe-human-robot-interaction.html
  - project COVR: https://www.safearoundrobots.com/
  - Federico Vicentini - presentations
    - Safety of collaborative robotics. Overview and critical issues. 2019. https://www.etui.org/sites/default/files/ez_import/2019_ETUI_vicentini_collaborative%20robotics.pdf
    - Safety of collaborative robotics. Speed and separation monitoring @ IROS 2018.
  - Alessandro de Luca
    - Physical HRI - Lecture slides by Alessandro de Luca: http://www.diag.uniroma1.it/deluca/pHRI.php.
    - Youtube playlist: https://www.youtube.com/playlist?list=PLvAUmIzqq6oaRtwX9l9sjDhcNMXNCGSN0
    - Talks on youtube. E.g., https://youtu.be/L_QI9P2-ybY
- Articles
  - Vicentini, F. (2021). Collaborative robotics: a survey. *Journal of Mechanical Design*, 143(4).
  - Villani, V., Pini, F., Leali, F., & Secchi, C. (2018). Survey on human–robot collaboration in industrial settings: Safety, intuitive interfaces and applications. *Mechatronics*, 55, 248-266.
- Other resources
  - Filip Pelikán, SICK, Bezpečný stroj, 2018