VTT Technical Research Centre of Finland

Safety design process for collaborative robots

Malm, Timo

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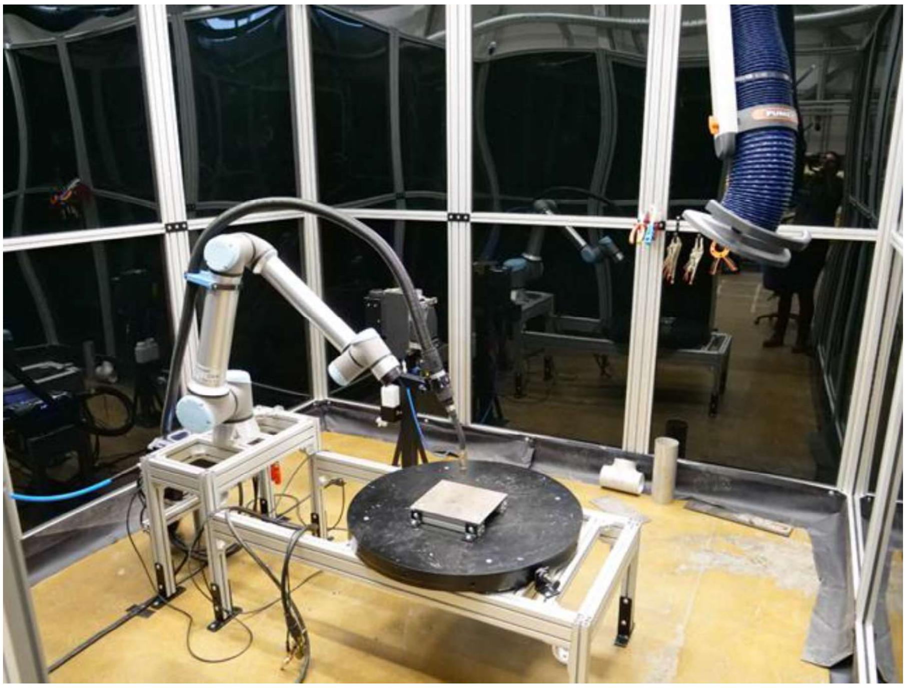
RESEARCH REPORT

VTT-R-00062-22



Safety design process for collaborative robots

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beyond the obvious

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Summary

Safety of collaborative robotics has brought new aspects to safety compared to industrial robots. In collaborative robot cells human can be close to the collaborative robot, whereas in industrial robot cells the robots are mainly isolated from humans. The collaborative robots are assumed to be safer than industrial robots, but the vicinity to humans can create new risks, which need to be controlled. One new protective feature, compared to industrial robots, is limited impact force and pressure.

Here the focus is on collaborative robots in welding applications. This hyperbook gives ideas, how to design safe collaborative robot cells. The text includes plenty of hyperlinks inside the hyperbook and also some links to requirements and sources of standards. The text can be divided into three parts: background to safety requirements, safety design process and examples of applying safety requirements in collaborative robot cells.

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Title:	Research Team Leader

Preface

This hyperbook is part VTT internal project Autonomous manufacturing. The project is divided into work packages and this work is related to collaborative robot welding concept. The large share of input (in Finnish) to this report is from NxtGenRob-project (Uuden sukupolven robotiikkaa), which ended 2020. The work has continued in GG_Auma project and current version is now published. The intention is to continue this hyperbook in future projects and show new aspects to safety of different kinds of robotics. Comments and support to this report has given: Mika Sirén, Janne Sarsama, Tuomas Seppälä, Janne Saukkoriipi and Timo Salmi.

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Safety design process for collaborative robots

Timo Malm
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Guidelines for using this document

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- This document is supposed to be used in pdf format, where the light yellow hyperlinks are in use.Text can be applied using arrow buttons at the keyboard or hyperlinks to relevant subjects.
- Each page may have also other relevant links. The name/symbol of each page is in its upper left corner.
- Each page has also 📖 symbol, which is link to the contents of this document.
- Some pages have also chapter symbol link, which describes the subject and provides link to the starting point of the chapter.

Intro | Re | Ri | Sp | Fo | Co | Sd | Ex

- In this document one can jump also straight to design process: Sp
The beginning of this document describes overall requirements and the end part describes some specific topics and examples.

Contents

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Background to requirements

Guidelines to the document
Background
For manufacturers
Safety policy
Definitions

Requirements
Safety requirements & measures
Robot standards
Robot standards 2
Person enters

Risk assessment
Risk assessment 2
Risk reduction

Design process

Phases
1 2 3 4 5 6
PL d Cat 3
SIL assignment order

Examples of applying requirements

Forces 1
Forces 2
Description
Description 2

Collaborative measures
Collabo ration 1
Collabo ration 2
Collabo ration 3

Turva etäis.
Turvaväli
Safe distance

Stop. Dist.
Esim. 1
Esim. 2
Ulottuma
Ulottuma 13855
Welding example

Portti
Kotiasema
Kotiasema 2
Alue valvonta

Literature

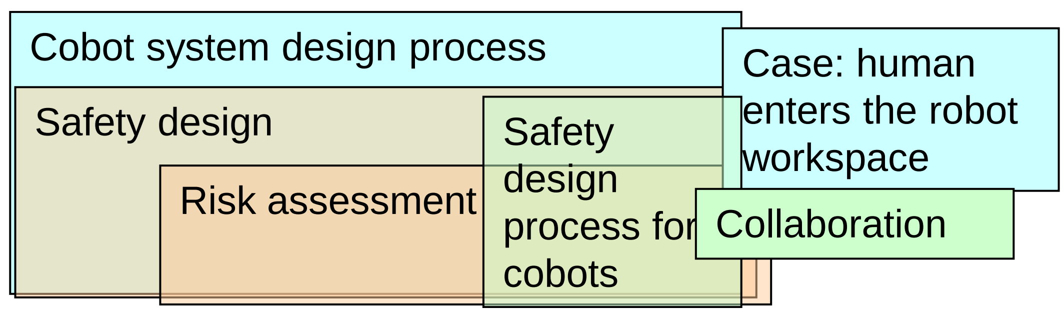
- Introduction — Intro
- Requirements — Re
- Risk assessment — Ri
- **Safety design process for collaborative robots** — Sp
- Force requirements — Fo
- Collaboration — Co
- Separation distance — Sd

Examples — Ex

Background

Risk assessment
Requirements
Person enters
Phases
1

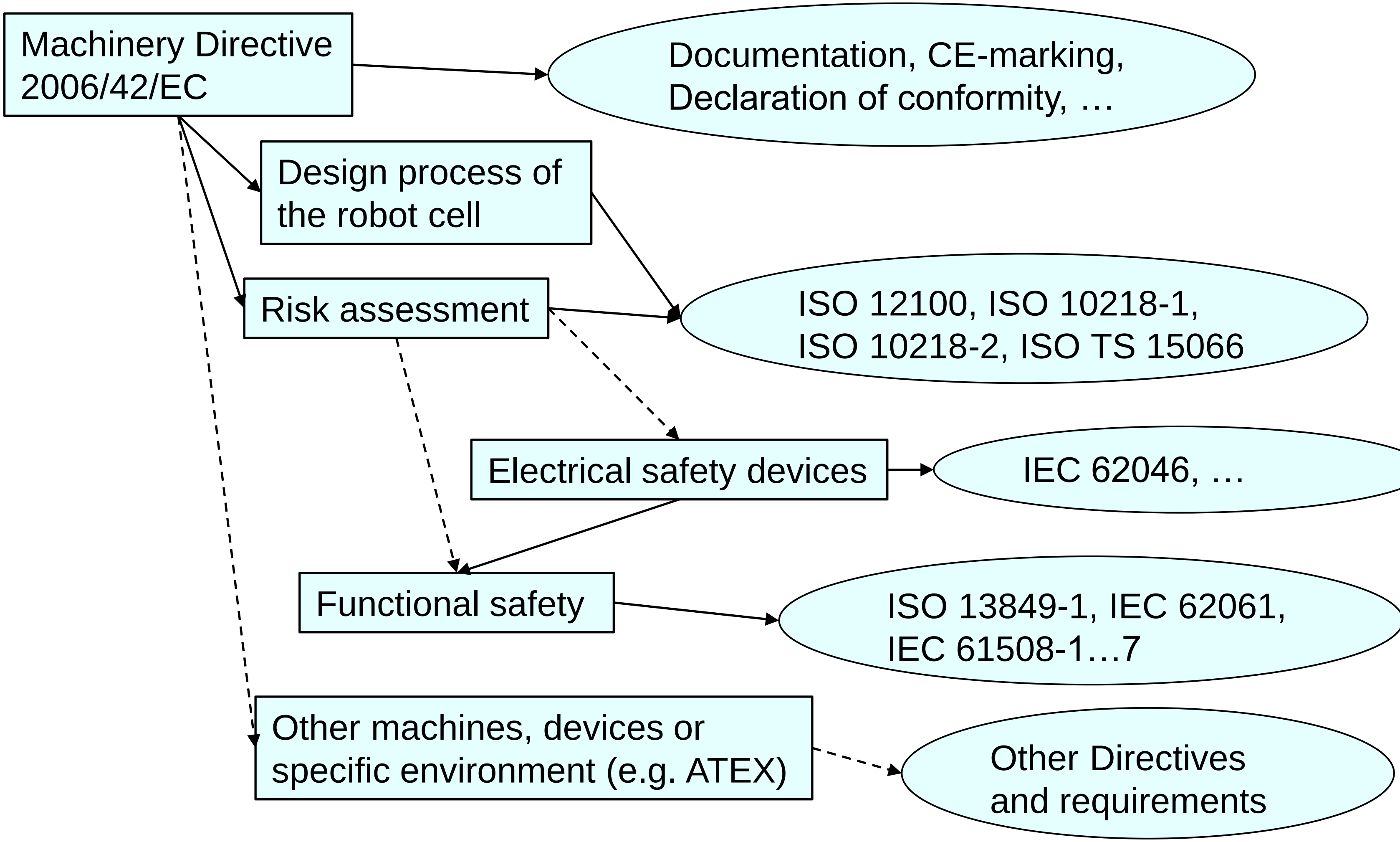
- Safety design process is part of cobot system design process.
- Safety design includes also risk assessment and risk reduction.
- Safety design process for cobots is part of risk assessment and reduction.
- Safety design process for cobots is also part of general case: human enters robot workspace.
- Safety design process for collaborative robots includes phases, which are special for cobots. The risks are related here to the case when person is or enters the cobot workspace and the focus is on impact risk.



Safety policy

- An organization's safety policy is a recognized, written statement of its commitment to protect the health and safety of the employees, as well as the surrounding community. The safety policy also details the measures the company takes and will take to protect the life, limb, and health of their employees, often surpassing the requirements set out by the laws or by the standard practices of the industry. (Ref: Safeopedia)
- 1. Commitment to provide a healthy and safe workplace.
- 2. Employer's responsibility to take precautions to prevent illness and injury.
- 3. Signed by senior management.
- 4. A statement to demonstrate how the commitment to health and safety will be communicated and how it will operate in all levels of the organization.
- 5. Everyone take responsibility for developing and maintaining a healthy, safe workplace.
- Safety policy can be related, in addition, to workplace/production and personnel also to products.

Processes for robot manufacturers/integrators



Design
Risk assessment
Hazard lists

Safety device selection

PL/SIL assignment and requirements

LWD, ATEX, pressure equipment, dust, laser, noise,…

EN ISO 10218-2 definitions

- **Maximum space**: maximum radius including end effector, workpiece and accessories, without limiting measures
- **Restricted space**: portion of the maximum space restricted by limiting devices that establish limits which will not be exceeded.
  - The limiting measure performance should be PL d or adequate mechanical measure. Otherwise maximum space is applied for safety measure dimensioning (e.g. distance to hazardous points).
  - Perimeter guard shall not be installed closer than the restricted space.
- **Operating space**: portion of the restricted space that is actually used while performing all motions commanded by the task programme
- **Safeguarded space:** space defined by the perimeter safeguarding.
- **Collaborative workspace:** workspace within the safeguarded space where the robot and a human can perform tasks simultaneously during production operation.

ISO 10218-2:2011. Robots and robotic devices - Safety requirements for industrial robots - Part 2: Robot systems and integration. 43 p.

EN ISO 10218-1 Definitions 2

- **Safety-rated monitored speed**: Safety-rated function that causes a protective stop when either the Cartesian speed of a point relative to the robot flange (e.g. the TCP), or the speed of one or more axes exceeds a specified limit value
- **Safety-rated reduced speed limit**: safety-rated monitored speed function that limits the robot speed to 250 mm/s or less. NOTE 1 The safety-rated reduced speed value is not necessarily the value set in the reduced speed control function. NOTE 2 The difference between safety-rated monitored speed and safety-rated reduced speed is that safety-rated monitored speed limit can be set to speeds greater than 250 mm/s.
- **Safety-rated reduced speed control**: When provided, safety-rated reduced speed control shall be designed and constructed in accordance with the safety related control system performance so that in the event of a fault, the speed of the TCP does not exceed the limit for reduced speed and a protective stop is issued when a fault occurs.
- **Safety-rated monitored speed**: When provided, the speed of the TCP shall be monitored in accordance with the safety related control system performance. If the speed exceeds the limit selected, a protective stop shall be issued.

ISO 10218-1:2011. Robots and robotic devices - Safety requirements for industrial robots - Part 1: Robots. 72 p.

EN ISO 10218-1 Definitions 3

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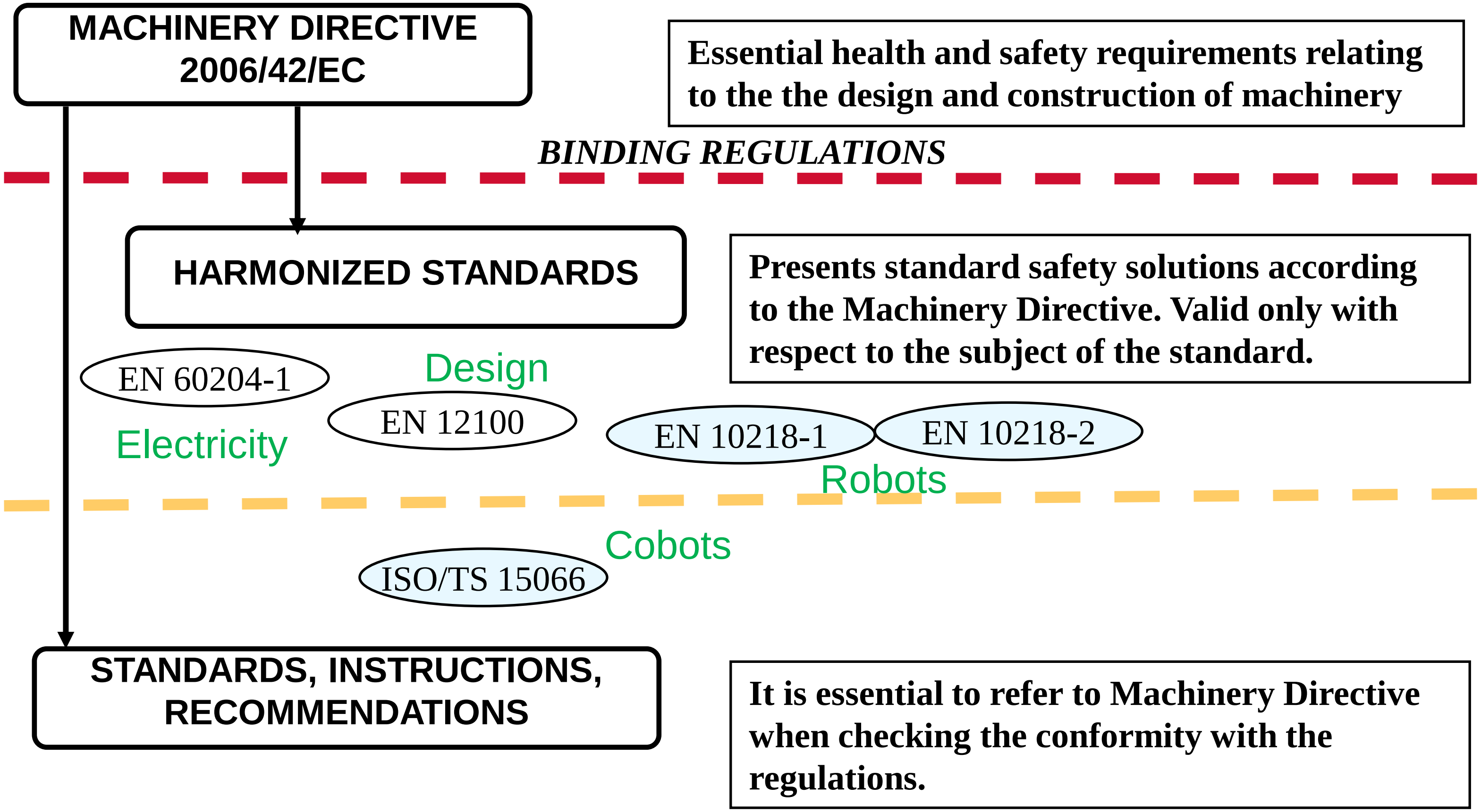
- **Safety-rated monitored stop**: condition where the robot is stopped with drive power active, while a monitoring system with a specified sufficient safety performance ensures that the robot does not move. The robot may decelerate, resulting in a category 2 stop in accordance with IEC 60204-1. Once stopped, this standstill shall be monitored by the safety-related control system in accordance with 5.4. Fault of the safety-rated monitored stop function shall result in a category 0 stop.
- **Protective stop**: The robot shall have one or more protective stop functions designed for the connection of external protective devices. The safety related control system performance shall comply. This stop may be initiated manually or by control logic. At least one protective stop function shall be a stop category 0 or 1, as described in IEC 60204-1. The robot may have an additional protective stop function using stop category 2 as described in IEC 60204-1 that does not result in drive power being removed but does require monitoring of the standstill condition after the robot stops.
- **Emergency stop**: The robot shall have one or more emergency stop functions (stop category 0 or 1, as described in accordance with IEC 60204-1). It is only manual, operator has quick access to it and it removes energy sources of all hazards.

ISO 10218-1:2011. Robots and robotic devices - Safety requirements for industrial robots - Part 1: Robots. 72 p.

Requirements: Machinery Safety Regulations



Machinery Directive 2006/42/EC
https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32006L0042

Application of MD
https://ec.europa.eu/docsroom/documents/24722/attachments/1/translations/en/renditions/native

Harmonised standards
https://ec.europa.eu/growth/single-market/european-standards/harmonised-standards/machinery_en

SFS standards
https://sales.sfs.fi/?_ga=2.64822063.1032228979.1571738824-1269511973.1542098217

Proposal of new machine regulation (replaces MD)
https://ec.europa.eu/docsroom/documents/45508?locale=fi

Robot standards

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Design

General principles for design: risk assessment and protective measures ISO 12100

Industrial robots

ISO 10218-1. Robots and robotic devices - Safety requirements for industrial robots - Part 1: Robots. 2011.

Collaborative robots

ISO/TS 15066. 2016. Robots and robotic devices — Safety requirements for Industrial robots — Collaborative operation. 33 p.

Industrial robot: automatically controlled, reprogrammable multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications. (ISO 10218-1)

Robot cells

ISO 10218-2. Robots and robotic devices - Safety requirements for industrial robots - Part 2: Robot systems and integration. 2011.

Collaborative robot: robot designed for direct interaction with a human within a defined collaborative workspace i.e. workspace within the safeguarded space where the robot and a human can perform tasks simultaneously during production operation. (ISO 10218-2)

Manufacturing systems

SFS-EN ISO 11161. 2010. Safety of machinery — Integrated manufacturing systems — Basic requirements. 80 p.

Common standards related to robots

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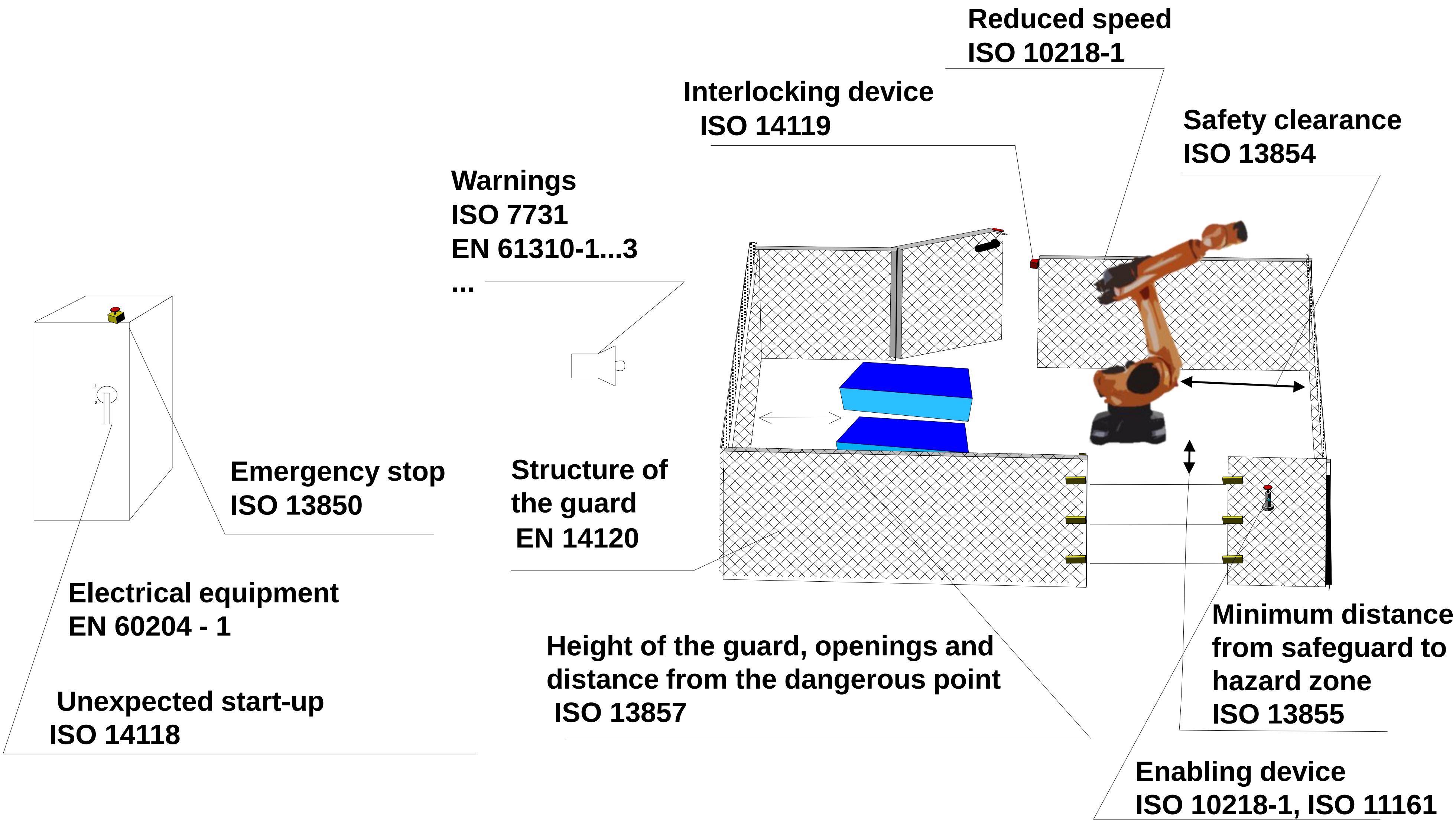
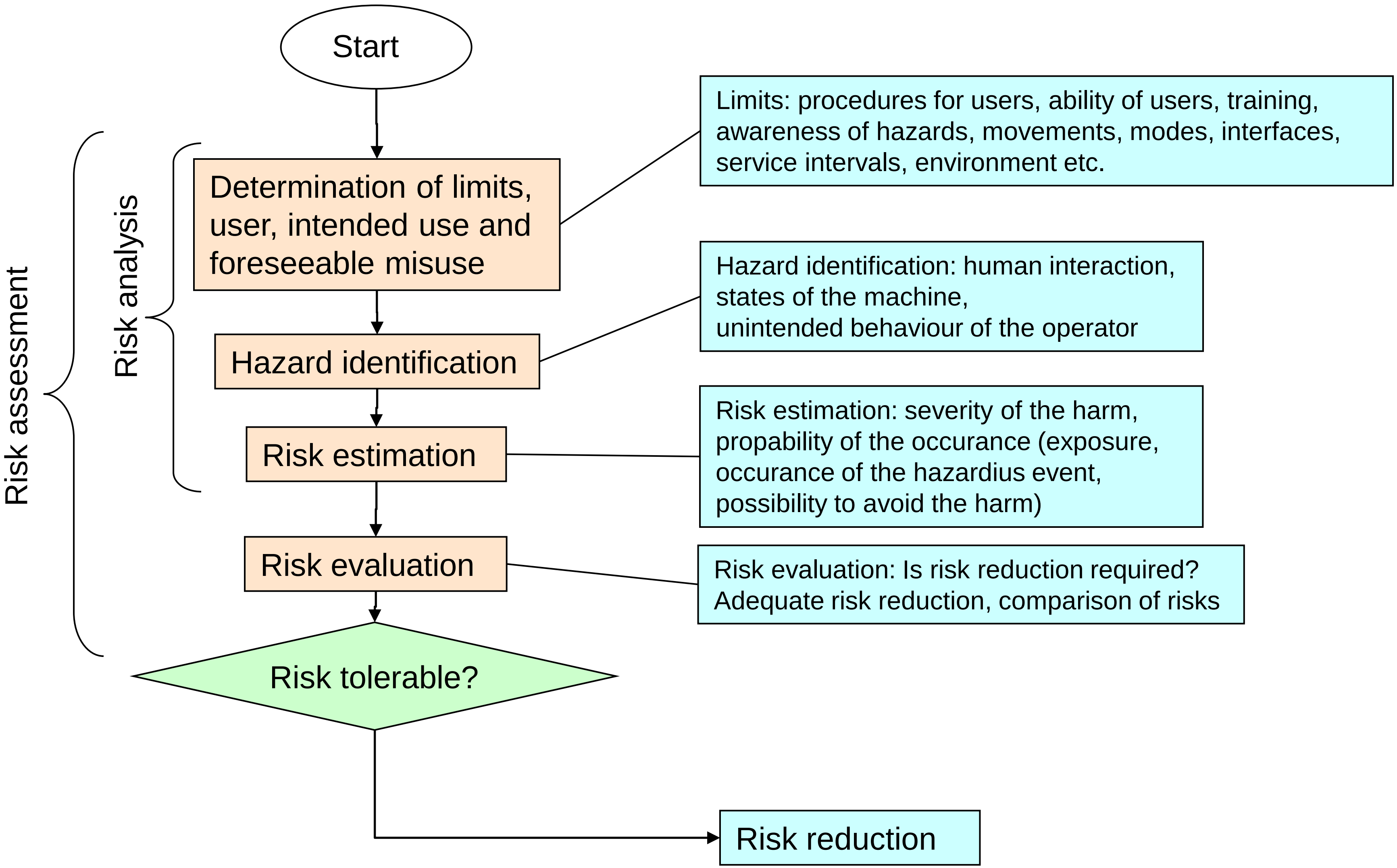


Industrial robot systems (ISO 10218-2)

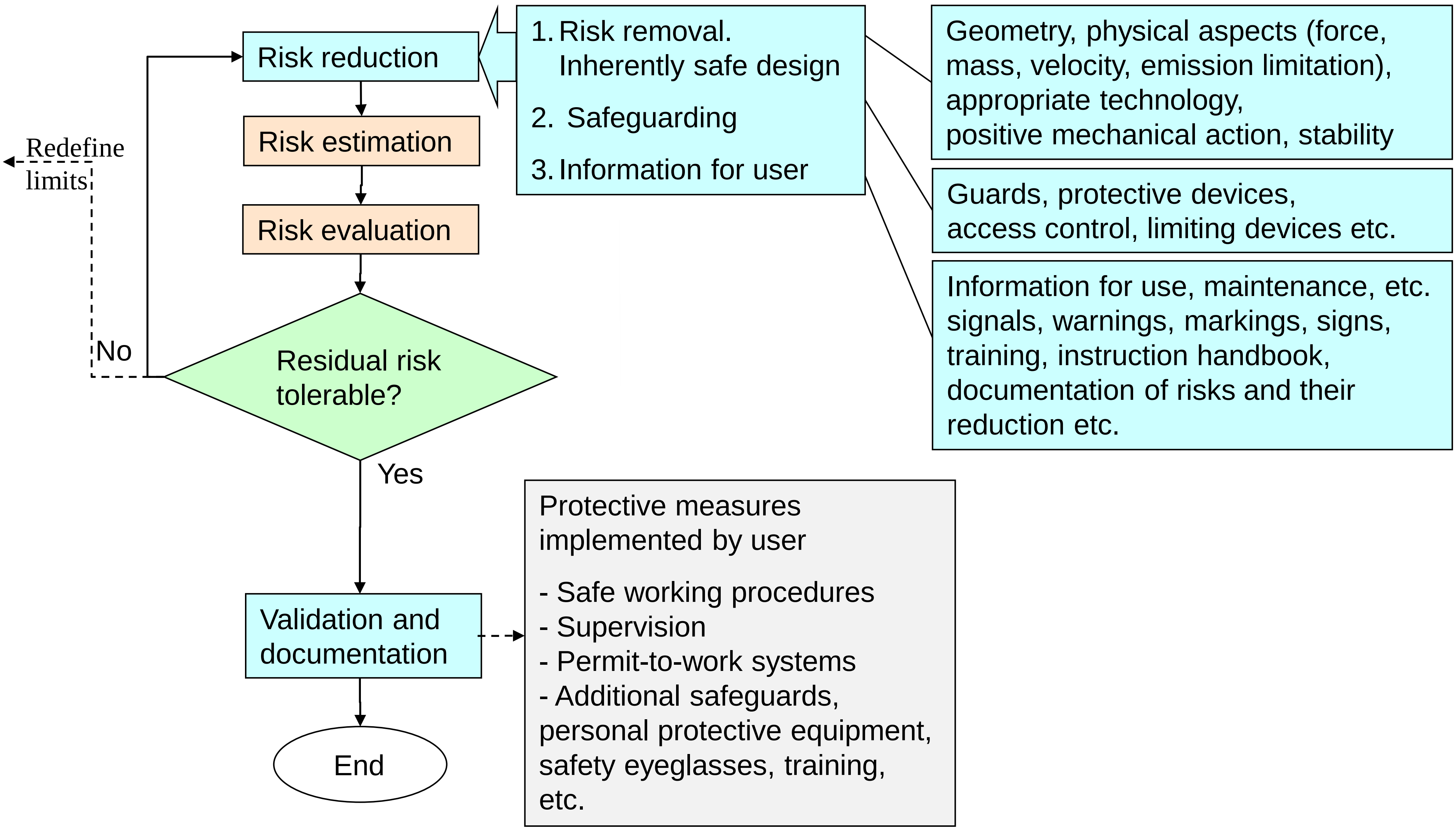
- General principles for design: risk assessment and protective measures ISO 12100
  - Protective devices
    Safety-related parts of control systems ISO 13849-1
    - Fixed and portable devices
      - E-stop ISO 13850
      - Two-hand controls
      - Enabling devices ISO 10218-1
    - Limiting devices
      - speed
      - travel
      - force
      - pressure
  - Safety distances ISO 13857
    Minimum gaps to avoid crushing ISO 13854
    Positioning of protective equipment ISO TS 62046
    - Electro-sensitive protective equipment IEC 61496-1…4
    - Pressure sensitive protective equipment ISO 13856-1…3
  - Guards ISO 14120
    Fixed guards and moveable guards
    - Interlocking devices ISO 14119

Risk assessment process (ISO 12100)



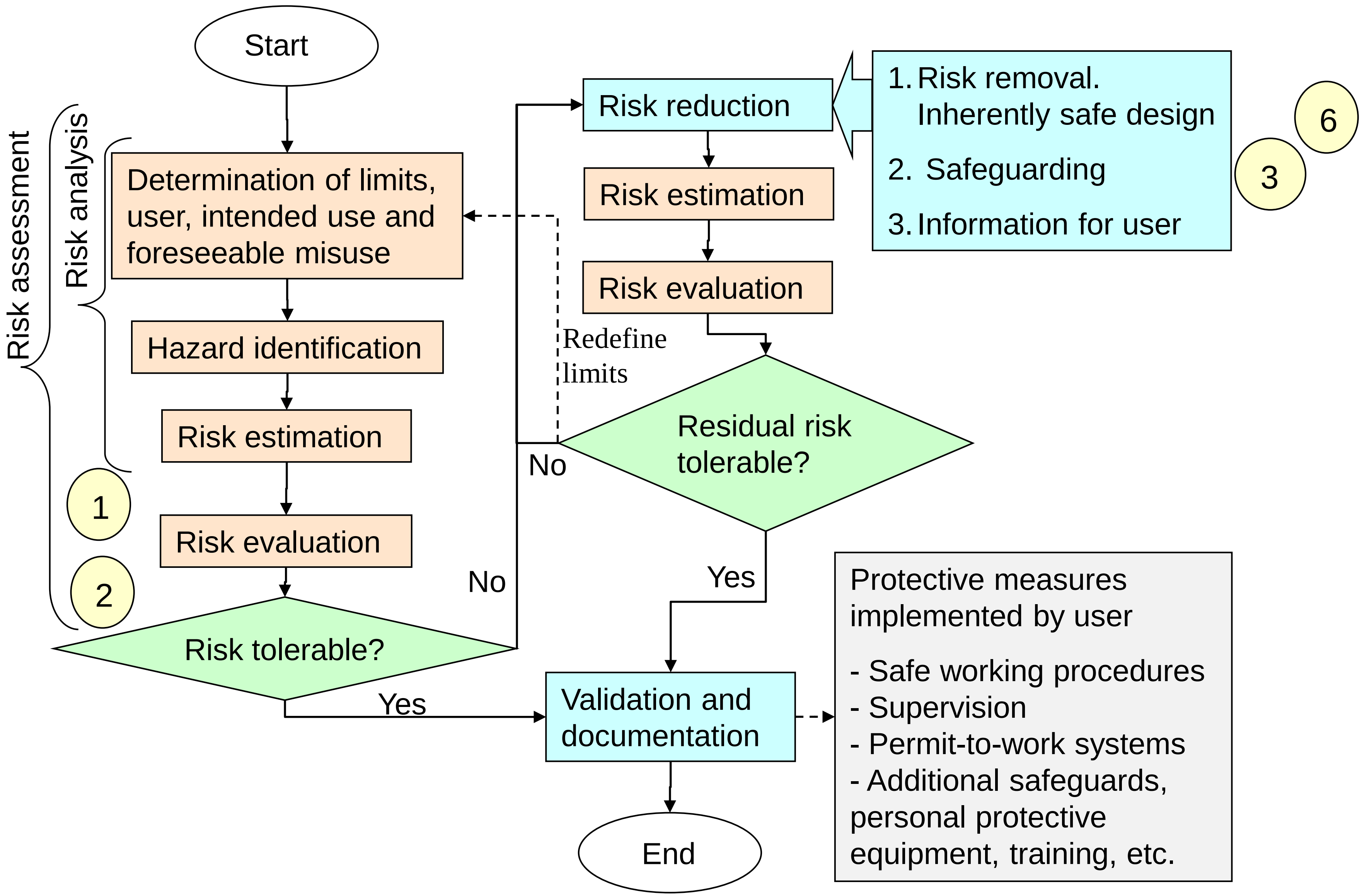
ISO 12100:2010. Safety of machinery. General principles for design. Risk assessment and risk reduction. 77 p.

Risk reduction (ISO 12100)



ISO 12100:2010. Safety of machinery. General principles for design. Risk assessment and risk reduction. 77 p.

Risk reduction process (ISO 12100) – numbers refer to phases of collaborative robot safety process



ISO 12100:2010. Safety of machinery. General principles for design. Risk assessment and risk reduction. 77 p.

Cobot system design process

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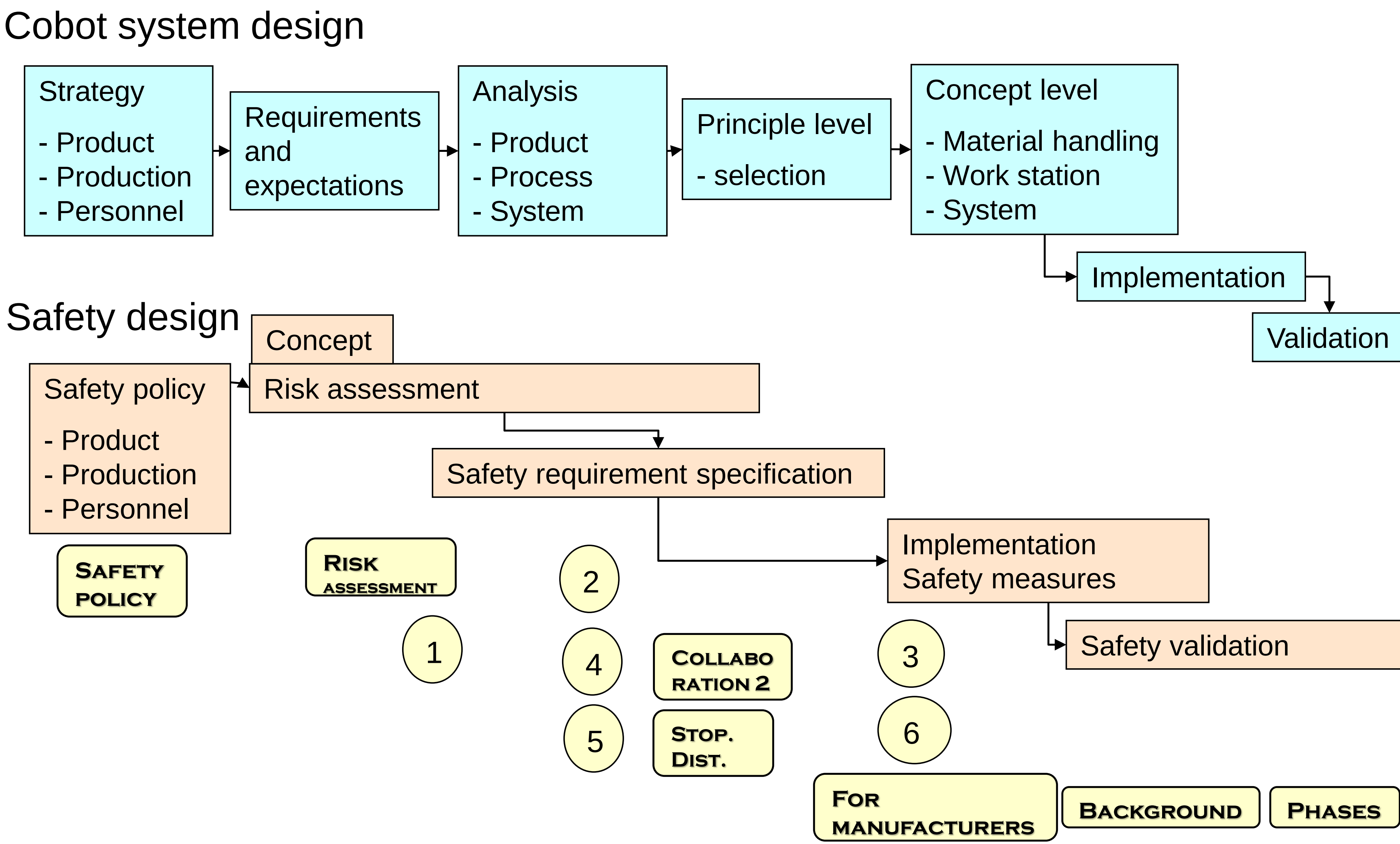

Safety design process for collaborative robots

1 Beginning of the process. There is a collaborative robot, with safety functions i.e. robot for the application is already selected. Also, risk analysis is already made for the robot cell. Person enters the robot work area. First, consider impact to the head and are there sharp edges or tools, which cause hazards.

2 Do the safety functions fulfil the ISO 10218-2 section 5.2.2 requirements (PL d and Cat 3)?

PL D
CAT 3

3 If internal safety functions are not adequate, then apply external safety devices. These can be related to e.g. dynamic safety system, external tactile sensors, external safety-rated monitored stop or area restrictions and isolation.

4 Use PL assignment (risk assessment) for the application to see, if it gives lower requirement than PL d.

5 Can additional measures justify e.g. PL d, Cat 2. After phase 5 return back to previous question, and furthermore to relevant phase.

6 Internal safety functions can be applied, if they fulfil safety requirements. Internal safety functions are related to e.g. impact forces, restricted area, speed or safety-rated monitored stop.

Safety design process for collaborative robots

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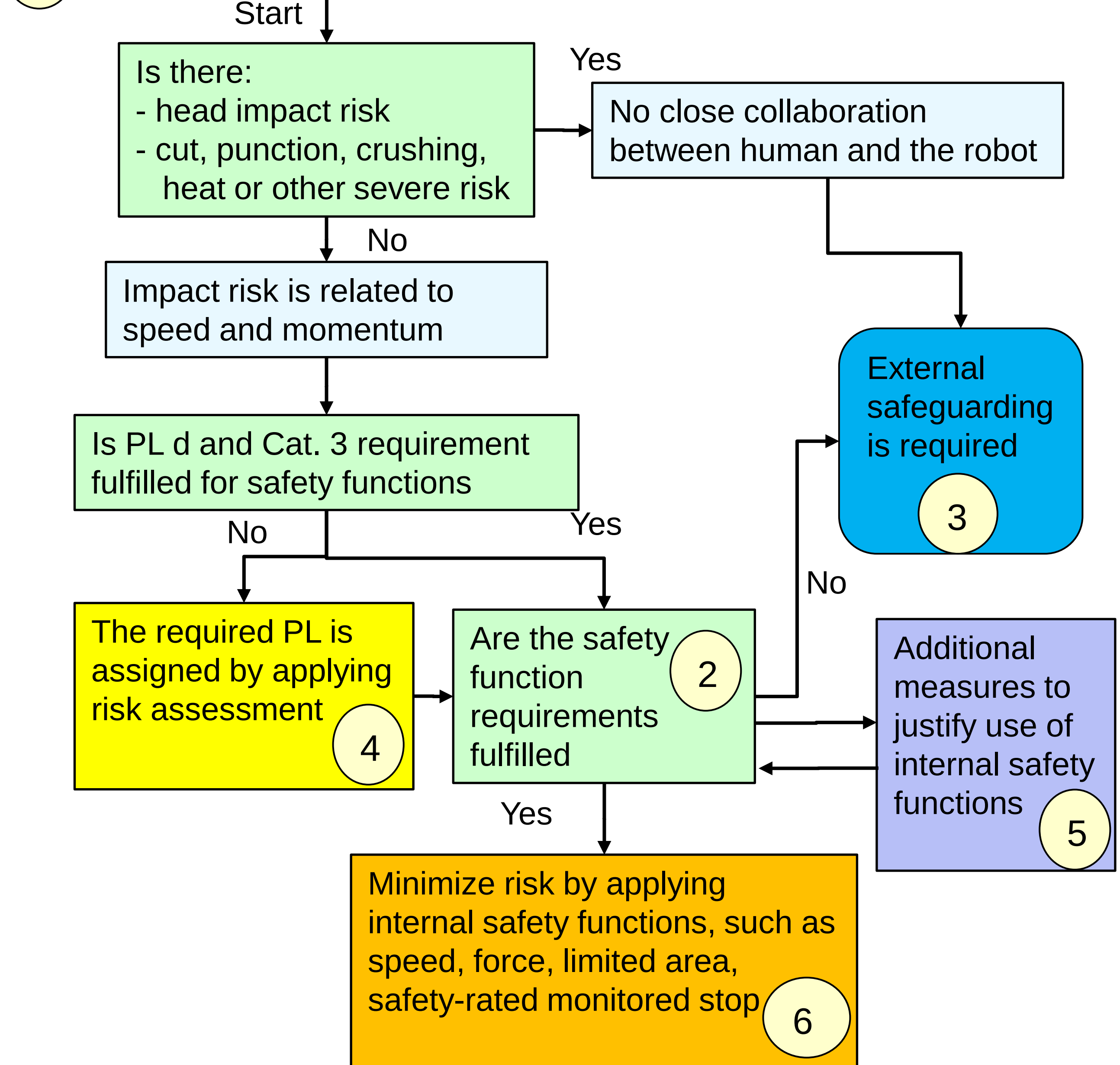

- Initial situation: Collaborative robot, with safety functions.
- Person enters the robot work area
- First consider impact to the head and are there sharp edges or tools.
- Do the safety functions fulfil the ISO 10218-2 section 5.2.2 requirements (PL d and Cat 3)?
- Use PL assignment (risk assessment) for the application to see, if it gives lower requirement than PL d. Can additional measures justify e.g. PL d, Cat 2.
- If internal safety functions are not adequate, then apply external safety devices.
- Internal safety functions can be applied, if they fulfil safety requirements.

Assign performance level (PL)

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4

Sp

Assign PL (and Cat) to match the risks.

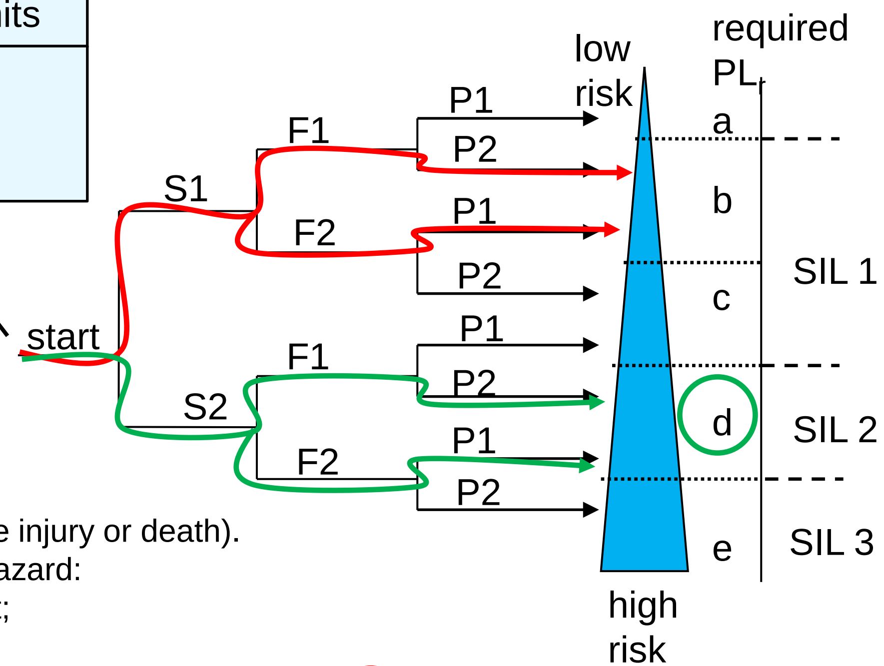
Severity

Severity
Cobot may cause severity 2 injury → see. ISO 13849-1 Severity 2
Cobot can cause only severity 1 injury (e.g. bruise). → see. ISO 13849-1 Severity 1 → see. ISO/TS 15066 force limits
Cobot can cause pain. → see. ISO/TS 15066 pressure limits

Assign PL (ISO 13849-1)

2

Lower PL may enable use of safety functions according to the declared safety function PLs of the applied cobot.



S= severity:
- S1slight ;
- S2 is serious (normally irreversible injury or death).

F= frequency and/or exposure to hazard:
- F1 seldom, exposure time is short;
- F2 frequent-to-continuous .

P= possibility of avoiding hazard or limiting harm:
- P1 possible under specific conditions;
- P2 scarcely possible.

PL b: low risk

PL d: high risk

Essential:
Bruising and/or lacerations without complications would be classified as S1, whereas amputation or death would be S2.

ISO 10218- 1&2 requirement level for typical safety functions

ISO 13849-1:2015. Safety of machinery. Safety-related parts of control systems. Part 1: General principles for design. 86 p.

PL D CAT 3 ⇦ **SIL ASSIGNMENT ORDER**

1

3

Sp

External safety measures

"Traditional safety measures"

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External safeguarding is required

Internal safety functions are not alone safe enough and therefore external safety measures are needed.

External tactile sensors. Sensors detect contact or near contact and stop the robot. Also soft pads can be applied to minimize impact force.

Separation distance monitoring. External safety system to monitor human and robot positions is applied (e.g. VTT dynamic safety system for robots).

STOP. DIST.

Safety-rated monitored stop. Monitoring the performance of stopping with sensors, which detect movements of the robot. Any unauthorized movement cause protective stop.
Automated start-up is possible if the robot work area is monitored. Otherwize, manual restart is required.

Isolate the restricted space. The area can be surrounded by fences, light curtains and gates. Entering the area cause protective stop, which cuts the power.

Finally → Estimate residual risk

COLLABORATIVE MEASURES

SAFETY REQUIREMENTS & MEASURES

1

5

Sp

Additional measures to justify internal safety functions

"Small steps"

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Additional measures to justify use of internal safety functions

The risk reduction need is small.
After applying the selected safety measures one can return to previous phase and estimate, is the risk adeguate.

- Enabling device
- Separation distance enables only hand contact to the robot (STOP. DIST.)
- Human enters the area very seldom. Collaboration type: coexistence
- Obligatory personal protective equipment (e.g. eyeglasses)
- Inherently safe stuctures, like, flexible structures, soft pads, tactile sensors*, etc.
- Safety sensors (e.g. light curtain, laser scanner)*
- Fences, railings, mechanical limitters for the robot
- Robot moves keeping the edges directed away from the humans work station
- Warnings (e.g. signs, lights, voice), education, guidelines at the manual, augmented reality, etc.

* Safety sensors applied in this phase need to fulfill PL d and Cat. 3 requirements, if safety sensors are applied before PL is assigned.

COLLABORATION 1

1

Use of the robot internal safety functions

"True collaboration"

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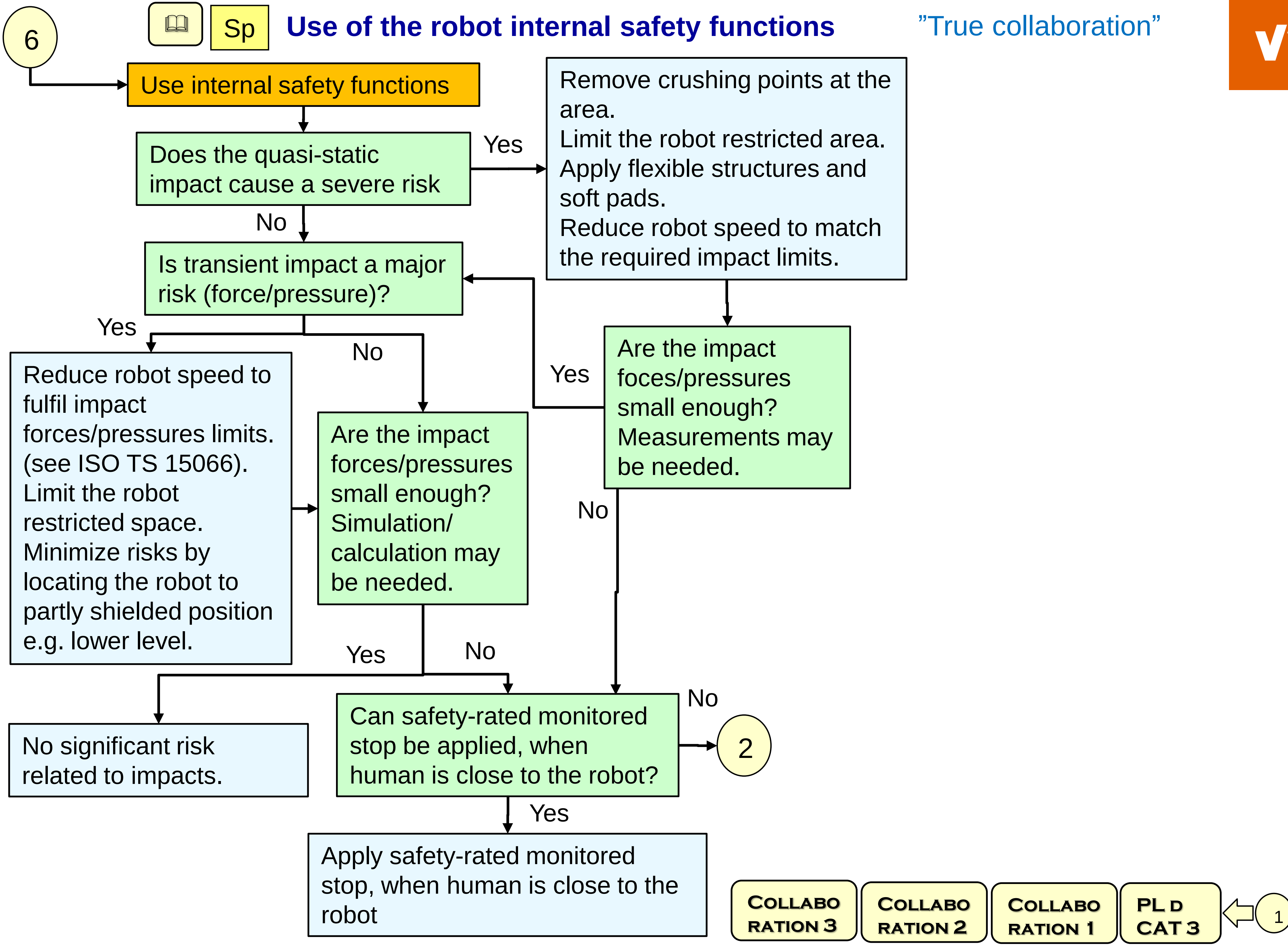

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Order of safety measures and PL assignment

- ISO 13849-1 Annex A (informative): The graph at Figure A.1 (see 4) is based on the situation **prior to the provision of the intended safety function** (see also ISO/TR 22100-2:2013). Risk reduction by technical measures independent of the control system (e.g. mechanical guards), or additional safety functions, are to be taken into account in determining the PL_r of the intended safety function; in which case, the starting point of Figure A.1 is selected after the implementation of these measures (see also Figure 2).

Sp

ISO 10218-2: 5.2 Safety-related control system performance

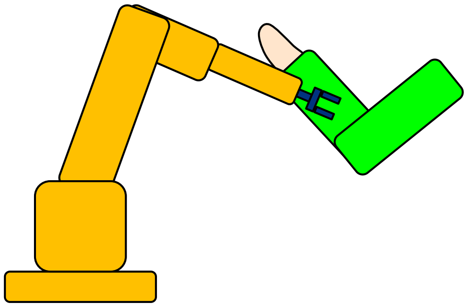
- 5.2.2 Performance requirement
- Safety-related parts of control systems shall be designed so that they comply with PL=d with structure category 3 (same as in ISO 10218-1 section 5.4.2) as described in ISO 13849-1:2006, or so that they comply with SIL 2 with hardware fault tolerance of 1 with a proof test interval of not less than 20 years as described in IEC 62061:2005.

PL d, Cat 3 ≈ SIL 2, HW fault tolerance 1

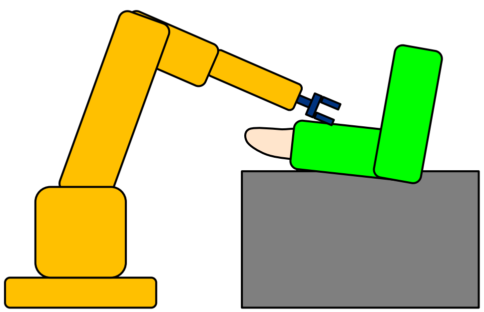
- This means in particular:
- a) a single fault in any of these parts does not lead to the loss of the safety function,
- b) single fault must be detected at or before the next demand of the safety function, if practicable,
- c) when the single fault occurs, the safety function is always performed and a safe state is maintained until the detected fault is corrected,
- d) all reasonably foreseeable faults must be detected.

ISO 10218-2:2011. Robots and robotic devices - Safety requirements for industrial robots - Part 2: Robot systems and integration. 43 p.

Description of contacts



Free impact (transient)



Constrained impact, squeezing
(quasi-static or transient)

Transient contact

- Short contact, robot control cannot react
- Hazard is from energy transfer through contact area in certain time (power flux density)
- Energy transfer depends on relative speed, effective masses of moving robot and body region, contact area

Quasi-static contact:

- Extended (longer than transient), robot control can reduce speed and force
- Hazard is from application of pressure and force
- Force depends on kinematic superposition of joint torques, pressure also on contact area

Protective measures:

- Robot design, shape, mass, …
- Robot control functions, speed, torques, …
- Appropriate application environment

Maximum allowed transient and quasi-static force

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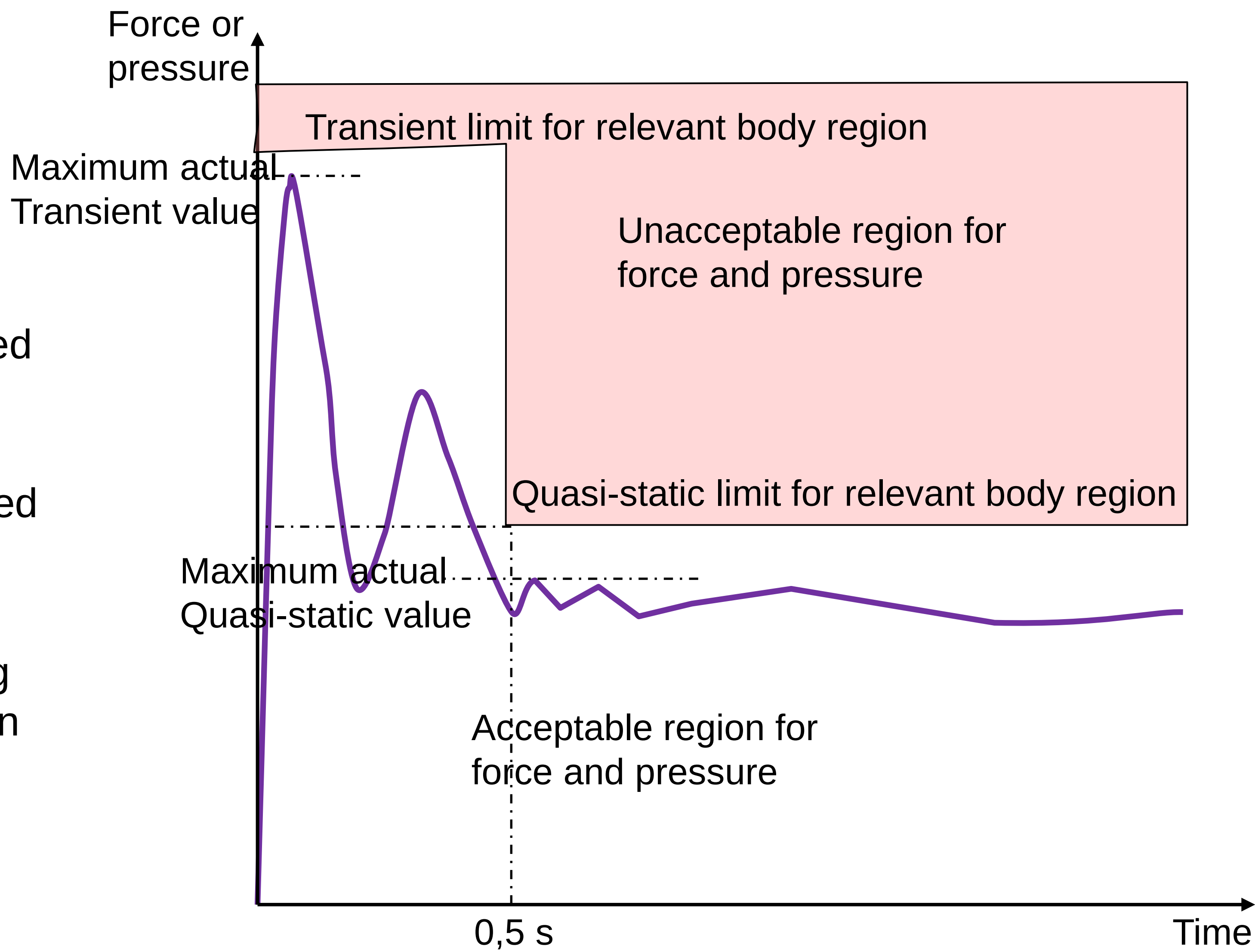
- Acceptable transient contact force = 2 x quasi-static contact
- No impacts to head allowed (practicality ?).
- Static force is the measured max. force after 0.5 s.
- Body model for calculating transient impact forces can (need to) be applied.

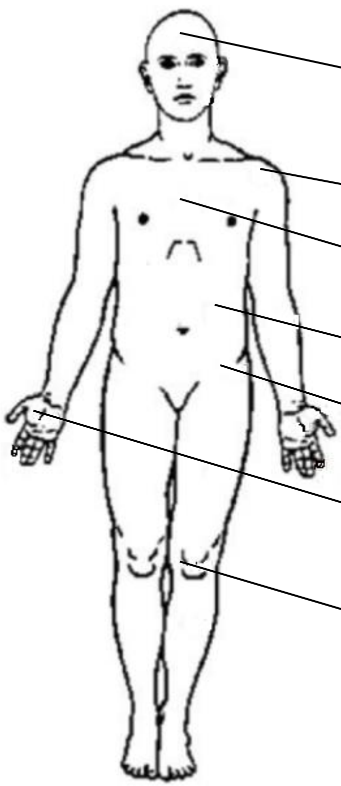


ISO/TS 15066:2016. Robots and robotic devices — Safety requirements for Industrial robots — Collaborative operation. 33 p.

Fo

Safe forces

- No impacts to head allowed although value is presented
- For flat objects force is limiting factor and
- For narrow or sticking objects (1 cm^2) pressure is limiting factor
- Transient contact limit = 2* Quasi-static contact limit

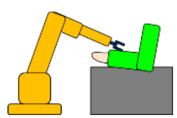


Examples of pressures and forces		Quasi-static contact	
Body region	Specific body area	Maximum permissible pressure (N/cm^2)	Maximum permissible force (N)
Skull and forehead	Middle forehead	130	130
Back and shoulders	Shoulder joint	160	210
Chest	Sternum	120	140
Abdomen	Abdomen muscle	140	110
Pelvis	Pelvis bone	210	180
Hands and fingers	Palm	260	140
Thighs and knees	Kneecap	220	220

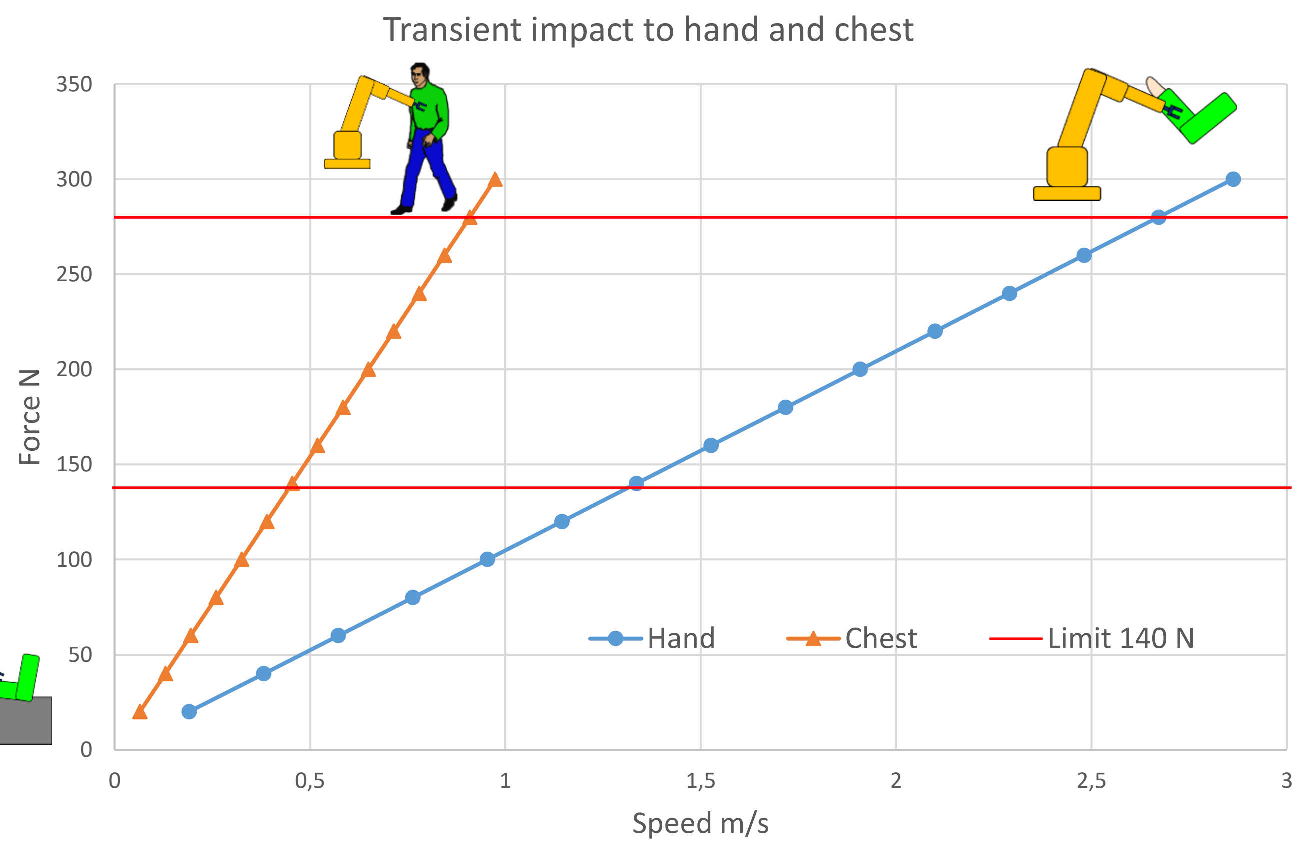
ISO/TS 15066:2016. Robots and robotic devices — Safety requirements for Industrial robots — Collaborative operation. 33 p.

Transient impact forces for cobot as function of speed

- Robot 28,9 kg, 10 kg load
- Force limit for hand and chest is
  140 N (quasi-static),
  280 N (transient)
- Transient impact, use model-based calculation
- Transient impact to hand is, usually, not very critical, but to other body parts, it can be.



- In quasi-static impact the forces can be higher than in the transient model.



Transient impact to the head

- Impact to the head (ISO TS 15066 section 5.5.5.3):
  Contact exposure to sensitive body regions, including the skull, forehead, larynx, eyes, ears or face shall be prevented whenever reasonably practicable.
- Max force against face is yet 65 N.
- By calculating according to ISO TS 15066 (energy based calculation) speed of a large robot, which can cause such force we get speed 0.11 m/s. For collaborative robot weight 33.5 kg and load 10 kg we get value 0.12 m/s.
- The speed 0,11 m/s is not necessarily safe for face, but higher speed is hazardous. Any speed is hazardous to eyes. Safety eyeglasses may help.
- Note! The speed values are calculated and measured values can be different, although the calculation is pessimistic. The actual measurements are difficult to realize, since small change of position can cause huge change in result.

ISO/TS 15066:2016. Robots and robotic devices — Safety requirements for Industrial robots — Collaborative operation. 33 p.

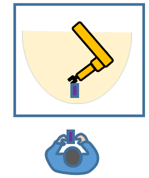
Transient impact to hand

- The max. allowed quasi-static impact force to hand is 140 N.
- By applying ISO TS 15066 (energy-based calculation for transient inelastic impact) the speed that causes the force can be calculated. For large robots 1.5 m/s speed cause the 150 N force to hand, which is below the limit value.
- Avoid points where clamping (quasi-static impact) is possible. Clamping forces are higher than transient impact forces. When the robot is moving at speed 1,5 m/s the limit force value for hands is exceeded.

ISO/TS 15066:2016. Robots and robotic devices — Safety requirements for Industrial robots — Collaborative operation. 33 p.

Types of interaction and safety measures

- No coexistence
  - No collaboration

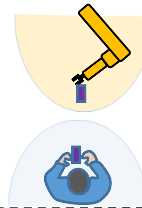


Separating guards

- Coexistence
  - Human and robot have own independent workspaces

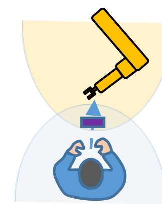
May be acceptable even if safety performance of the robot is not PL d, Cat 3? Due to low exposure time

4



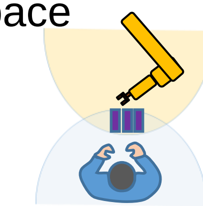
Separating guards
Safety-rated monitored stop
Speed and separation monitoring
Power and force limiting

- Sequential cooperation - Synchronized
  - Human and robot work sequential on the same workpiece
  - No simultaneous activity inside collaborative workspace



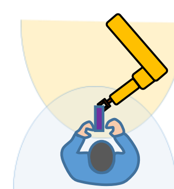
Safety-rated monitored stop
Speed and separation monitoring
Power and force limiting

- Parallel operation - Cooperation
  - Human and robot work simultaneously in the same workspace
  - Simultaneous activity inside collaborative workspace
  - Collisions are not expected



Speed and separation monitoring
Power and force limiting

- Collaboration
  - Human and robot produce something together
  - Simultaneous activity inside collaborative workspace
  - Collisions are possible/allowed



Power and force limiting
Hand guiding

6

Reference:
Pilz, Fraunhofer IFF

Conceptual applications of collaborative robots

VTT

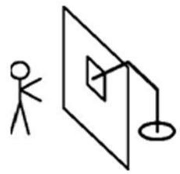
Levels of collaboration

- No coexistence: physical separation.
- Coexistence: human works in (partially or completely) shared space with the robot with no shared goals.
- Cooperation: human and robot work towards a shared goal in (partially or completely) shared space.
- Collaboration: human and robot work simultaneously on a shared object in shared space. Physical contact is allowed, possibility for hand-guiding.

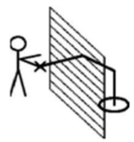
Aaltonen I., Salmi T., Marstio I. Refining levels of collaboration to support the design and evaluation of human-robot interaction in the manufacturing industry. In: 51st CIRP Conference on Manufacturing Systems. Published by: Elsevier B.V. 2018. 6.

Conceptual applications of collaborative robots:

- Hand-over window.
  Autonomous operation, reduced speed near the window, fixed or sensitive guards

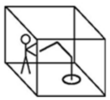


- Interface window.
  Autonomous operation, except at the interface window the robot stops, fixed or sensitive guards, hold-to-run control.

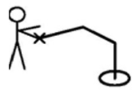


- Collaborative workspace.
  Autonomous operation, person detection system, reduced speed according to distance.

- Inspection.
  Autonomous operation, person detection system or enabling device, reduced speed according to distance



- Hand-guided robot.
  Moving by hand guiding, hold-to-run control, reduced speed according to distance.



ISO 10218-2:2011. Robots and robotic devices - Safety requirements for industrial robots - Part 2: Robot systems and integration. 43 p.

Collaborative operation requirements

VTT

The ISO 10218-1 describe the safety measures to collaborative robots from which at least one measure must be chosen. The safety measures are:

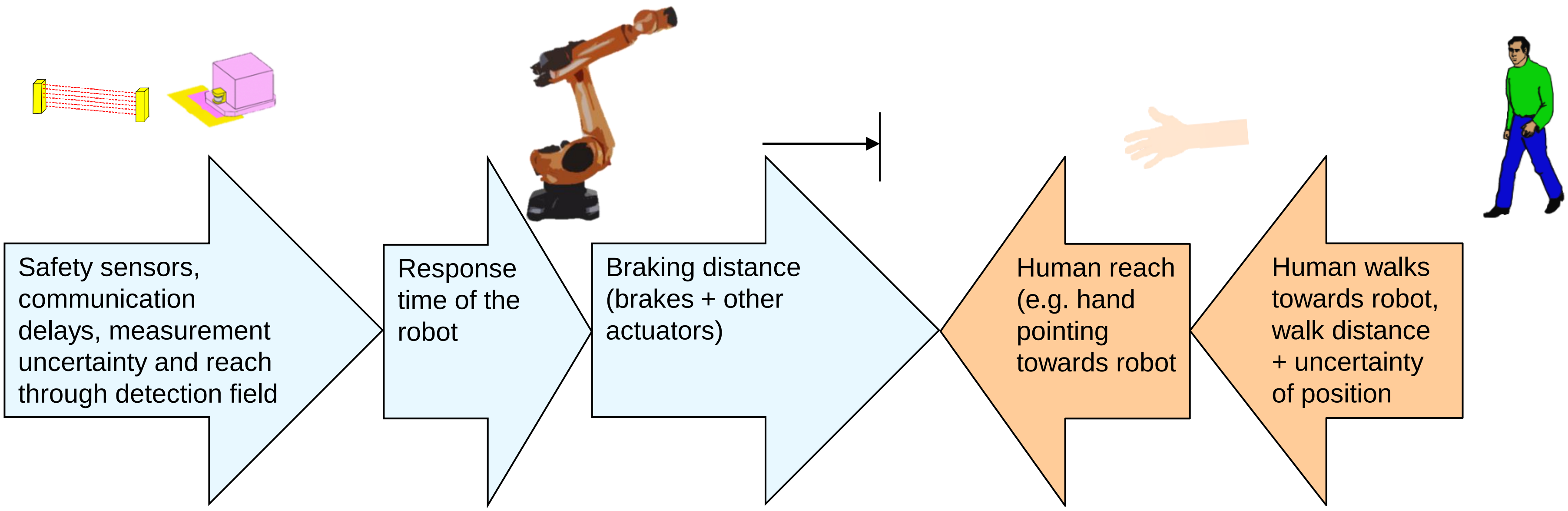
- **Safety-rated monitored stop**. The stopping of the robot is monitored continuously and unauthorized movement case protective stop, which cut the power from servomotors. Robot stops before a person enters collaborative space
- **Hand-guiding**. The robot is operated by applying controls near the end-effector. The controls include also emergency stop and, in some cases, enabling device. The robot applies safety-rated monitored speed, safe stop, etc.
- **Speed and separation monitoring**. The position of the robot and humans are measured, and the robot speed is controlled according to the separation distance. For separation calculation see ISO 13855. Apply safe stop, safe limited speed, etc.
- **Power and force limiting**. It is based on either lightweight construction and/or quick, requirements fulfilling impact detection and stopping. Collision possible, but no injury allowed. Collision leads to safeguarded stop. If collision forces of ISO/TS 15066 are violated additional measures needed. Active measures: power and force limiting, speed limiting, workspace limiting, etc.
- For all safety measures, the safety functions performance is usually: PL d and Cat 3.

Stopping distance and separation distance

Separation distance

$$S_{robot} = \text{travel during delays} + \text{braking distance}$$
$$= v(robot)t(delays) + \tfrac{1}{2}\, v(robot)t(brake)$$

$$S_{walk} = v(\text{walk speed}) * t(delays)$$



Distance = robot speed x time

Estimate also:
- Robot speed: real speed or max. speed
- Robot position uncertainty, sensor accuracy and resolution
- Consider braking: load, posture,
- Tool reach, load reach

Max. stopping distance associated to applied speed or max. speed and load or robot reach. Constant deceleration is often applied if measured value is not available.

Hand reach
Depend on resolution, uncertainty, height, danger point
see. EN 13855, IEC 62046

Human walking speed
1.6 m/s x time,
add uncertainty of position

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

STOP. DIST.

Sd

Defining separation distance

VTT

Identify hazards and human tasks at the area.

Is hand speed (2 m/s) or walk speed (1,6 m/s) applied in separation distance calculation?

Add hand travel or walk travel from detection to stop.

S(hand)= 2 m/s * (stop time + delays)

S(walk)=1,6 m/s * (stop time + delays)

Is the maximum speed of the robot applied in separation distance calculations?

Add robot reach or distance based on stopping

Reach

Robot max. reach

ULOTTUMA

Travel

Robot stopping distance (or speed*stop time/2) + robot travel during delays.

Is the hand reach added to the separation distance?

Hand speed is applied when distance is short, and hand penetrates the hazardous area through the detection field. Walk speed is applied when a person walks into detection zone. Add also delays (robot, communication, sensor) to the time.

If speed control/supervision fulfils requirements (PL d and Cat. 3 or according to risk assessment) the actual speed of the robot can be applied in separation distance calculations. If speed control/supervision does not fulfil requirements then maximum speed should be applied.

If separation distance and robot speed are known or robot movement out of its home position is detected according to requirements, the separation distance can be calculated using separation calculation; otherwize the robot maximum reach should be used.

KOTIASEMA

ALUE VALVONTA

Reach of a hand need to be checked from ISO 13855 equations and tables, which shows how safe distance is estimated according to approach speed, sensor positioning and hazard location and hazard nature.

SAFE DISTANCE

ULOTTUMA 13855

COLLABO RATION 2

5

3

1

ESIM. 2

ESIM. 1

TURVA ETÄIS.

Separation distance from a gate

Opening time of a gate (without guard locking) can be applied to reduce the separation distance. For machine-operated interlocked devices (including rolling doors):

t3= e/v

e is opening size (mm)

v is opening speed (mm/s).

t3 can be estimated also by testing.

S= v(walk)*(stop time + delays – t3)

Note that gate with guard locking can be applied using adequate locking time and distance calculation is not usually necessary.

Ref: ISO 13855:2010. Safety of machinery. Positioning of safeguards with respect to the approach speeds of parts of the human body3

Safe distances from hazard zone to fence

- Standard ISO 13857 describes safe distances from a hazard zone to a fence. It describes the distances when someone reaching over the fence or through the fence openings.
- The standard has tables for cases for upper and lower limbs. The standard has cases for lower and higher risk.
- For high risk case 2700 mm is the limit for hazard zone and for lower risk 2500 mm.
- Fence heights below 1000 mm are not included in the tables, since they do not sufficiently restrict movement of the body.
- Fence height below 1400 mm requires additional measures. The reach over 1400 mm height fence (high risk) is 1100 mm.
- Hand reach through 120 mm opening is 850 mm.

- Note. Standard ISO 13855 describes positioning of safeguards with respect to approachspeeds of parts of the human body.

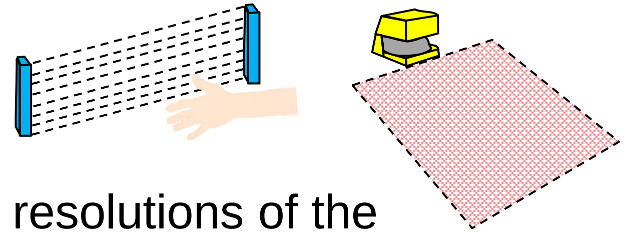
ISO 13857:2019. Safety of machinery — Safety distances to prevent hazard zones being reached by upper and lower limbs. 29 p.

ULOTTUMA 13855

Sd

Minimum distance ISO 13855

from safeguard to hazard zone (S)



- The standard ISO 13855 describes several cases for different resolutions of the electro-sensitive protective device. The minimum distances are described for hand (speed 2 m/s) and walking (speed 1,6 m/s + hand reach).
- When light curtain or laser scanner detects an object with diameter (d) is:
  - < 40 mm → S = 8(d-14) >0 and S > 100 mm
  - 40 mm < d ≤ 70 mm → S = 850 mm
  - Single beam → S = 1200 mm; limitations to safety use due to easy bypassing
  - Detection zone at approaching direction at height (H)
    d = H/15 + 50;   H = 15(d-50) > 0,
    → S = 1200 – 0,4*H

  - Note! For calculating separation distance also robot performance affect calculation.

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

ESIM. 2 | TURVA ETÄIS. | STOP. DIST.

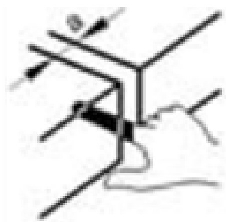
Minimum gaps to avoid crushing

- Robot programs and design should be done by eliminating possible pressing points.
- If the gap is greater than at the figure below, then crushing hazard is small. In these cases for cobots, only transient impact need to be considered (exception head).
- It is good to avoid unnecessary small gaps to rigid objects in robot programs. Preprogramed forbidden zones can be applied to avoid unnecessary gaps.

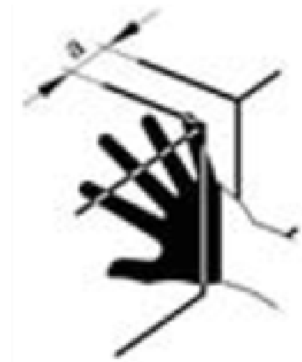
Examples of minimum gaps

Body 500 mm

Finger 25 mm



Hand 100 mm

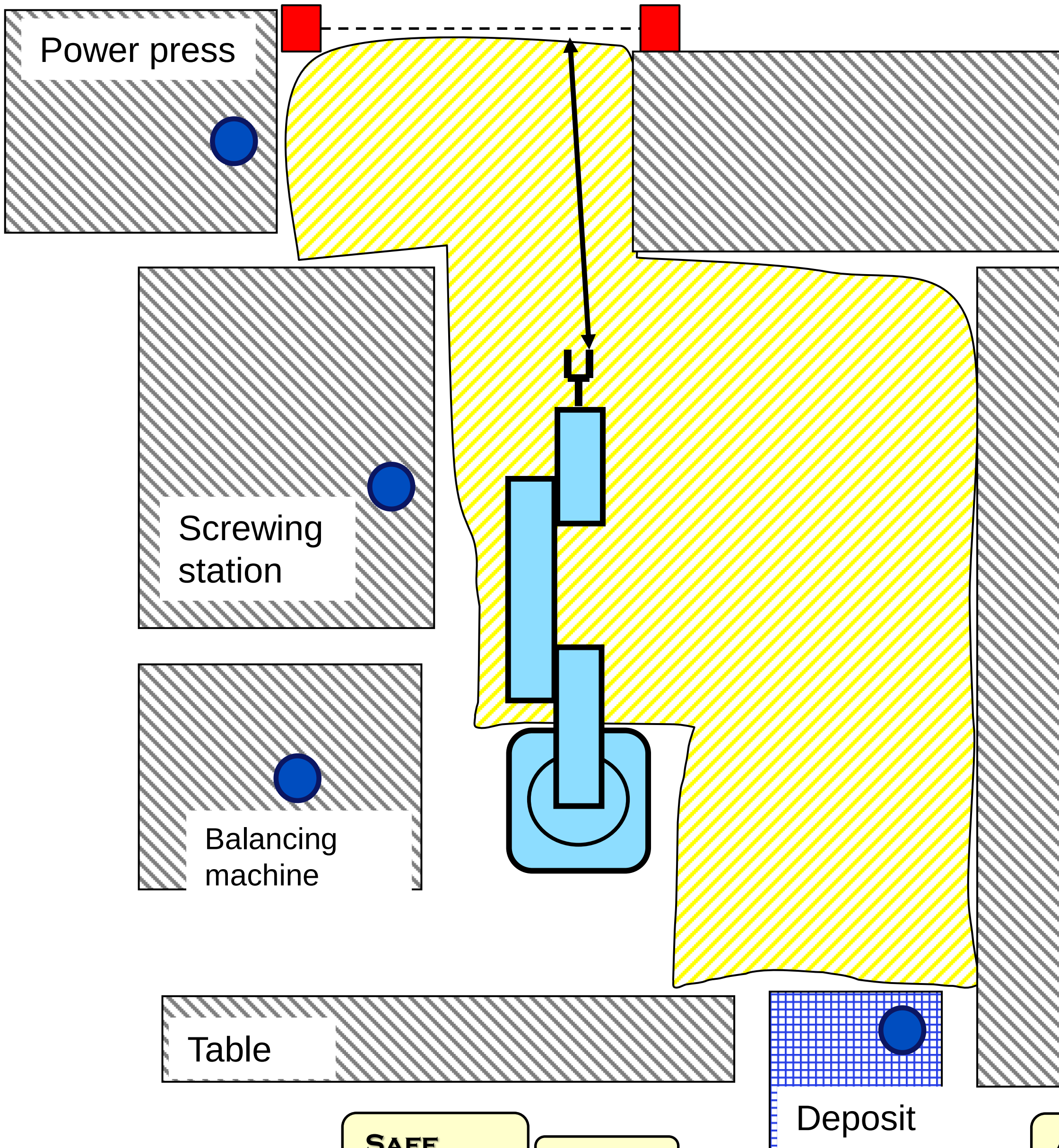


Arm 120 mm

Ref: ISO 13854:2010. Safety of machinery. Positioning of safeguards with respect to the approach speeds of parts of the human body

Separation distance according to maximum robot reach

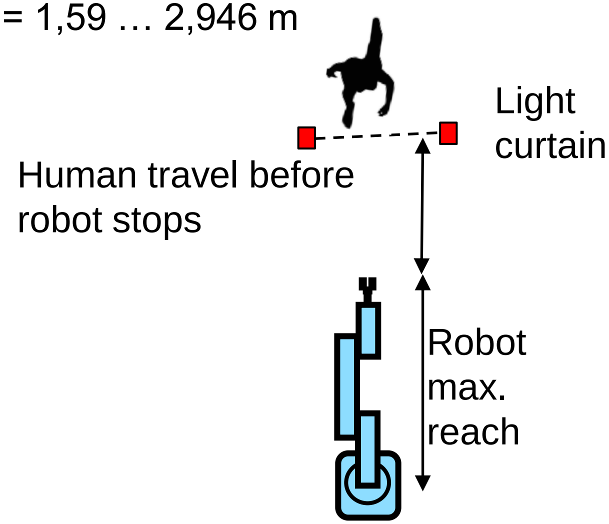
VTT



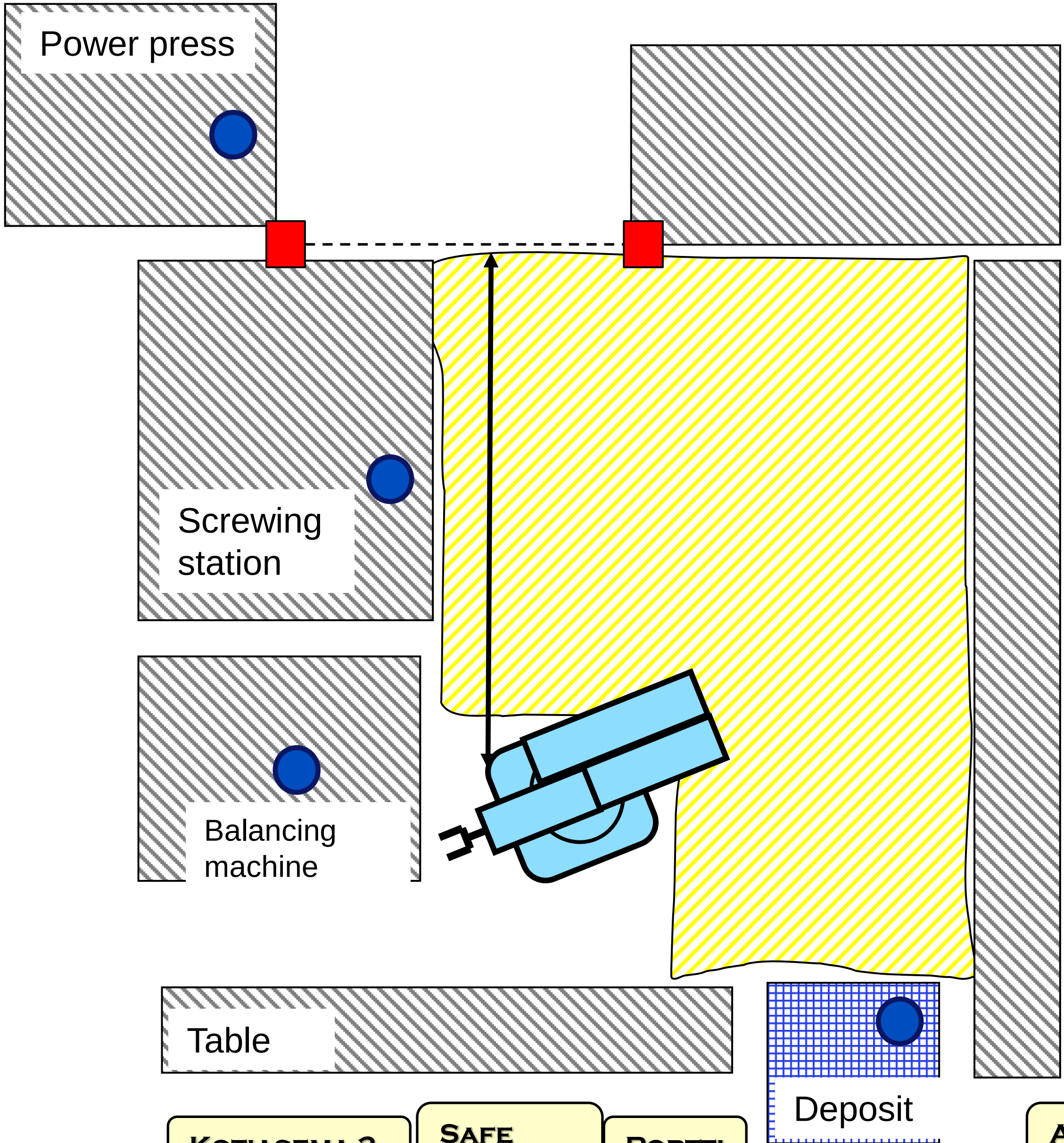
Separation distance is calculated here according to robot maximum reach. Human walk travel from detection to stop and human reach is added to the separation distance.

Robot stopping
Robot max. reach = (UR10 1,3 m, YuMi 0,68 m)

S=v(walk)*(stop time+light curtain delay)+ hand reach (850 … 1200 mm; longer value for detection on floor level)
Stop time of a robot is usually 400-1250 ms
=1,6 m/s*([400…1250] + 60 ms) + 850 mm
= 1,59 … 2,946 m



Separation distance from the home station (1)



Robot is stopped at its home station. Human enters the area and light curtain indicates it and keeps the robot stopped. When exiting, the area is acknowledged to be free. Separation distance is calculated from the light curtain to the home station.

Robot stopping
v = Robot speed
t = braking time
t1 = robot delays + sensor response time
S = vt1 + stop distance (if known)
or
S = vt1 + ½ vt

Human walk travel
S_H=v(walk)*(stop time+light curtain)+ hand reach
=1,6 m/s*(stop time + delays) + 850 mm

Speed at the beginning is 0, and so the stopping should be quick. Home station sensor detects robot movement and triggers protective stop. Here the human walk travel is almost the same as separation distance.

Robot safety-rated monitored stop (2)
- Example home station monitoring

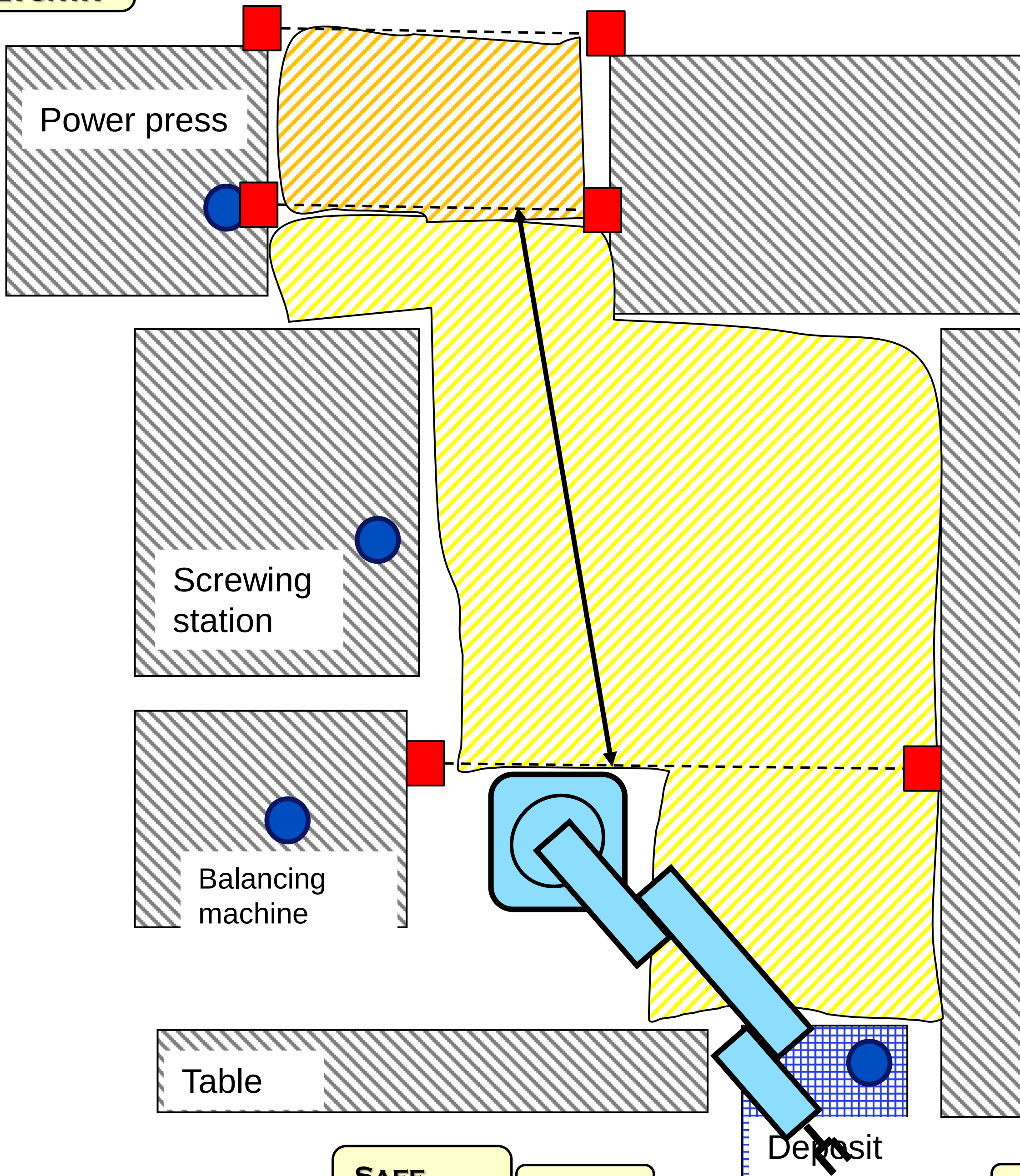
See previous figure

PL D
CAT 3

Operation: safety-rated-monitored stop

- Case 1. Robot has safety controller (Cat 3, PL d) and there is safety-rated monitored stop function.
  When the function is on the safety controller monitors the position of the robot and triggers protective stop if the robot moves.
- Case 2. The robot standstill position is monitored with separate safety sensors (Cat 3, PL d).
  Robot is driven into the monitored position. Sensor can be e.g. limit switch, push button, light curtain, RFID. To reach Cat 3 architecture, usually, duplicated or certified sensors are needed.
- Note that e.g. for limit switch pressing is safer than releasing, since releasing is (unreliable) spring operated function. Robot movement should press the limit switch, not release.
- For light curtain it safer to penetrate into the detection field when the robot moves, since otherwise dirt or poor alignment can easily cause unsafe situation.
- These are technically doable, but more challenging, compared to the unsafe solutions. There are also commercially available switches, which have safe mechanical structure (e.g. key-operated switches).

Operating zones are monitored with light curtains



The operating are is divided into to three zones with light curtains. There is continuously at least one empty zone between human and moving robot or otherwise robot is stopped.

Separation distance is the distance between the light curtains.
v = Robot speed
t = stop time
t1 = robot delays + sensor response time
S(robot) = vt1 + stop distance
Or S = vt1 + ½ vt

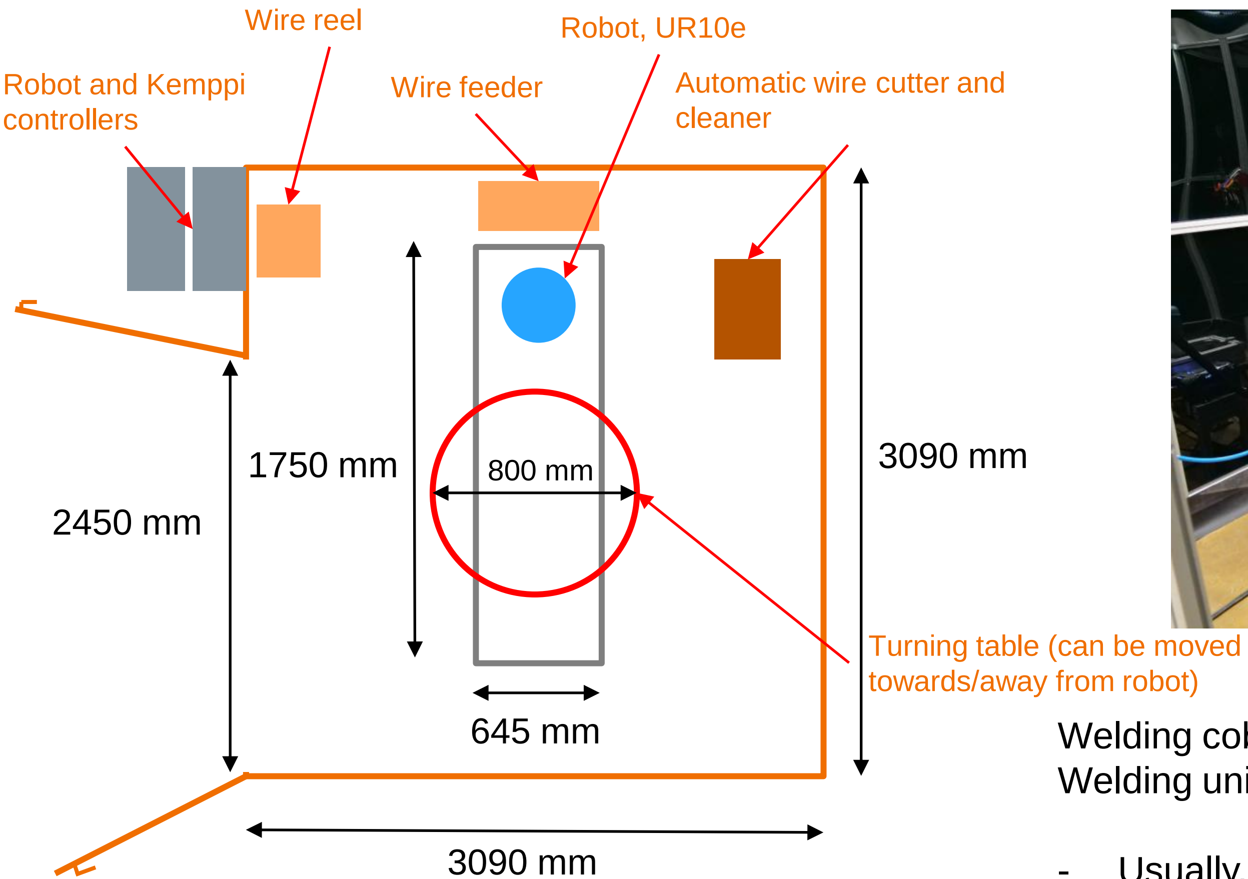
The human walk travel is added to the the distance.
S=v(walk)*(stop time + light curtain)+ hand reach
Total distance from one light curtain to another
= S(robot) + S(walk)
= 1,9 … 4,1 m

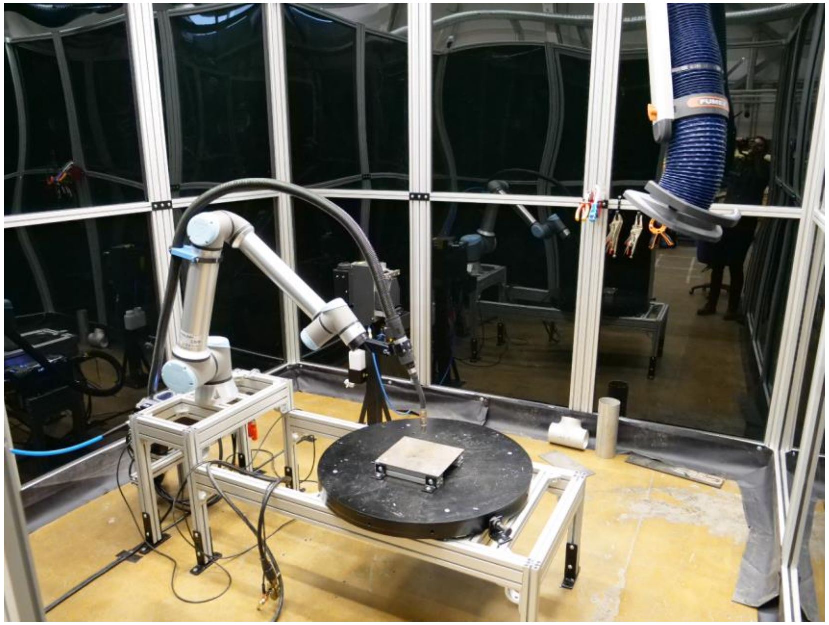
When using full speed the stop time is long and separation distance is unpractical. Idea is doable if speed is low or locked gates are applied.

WELDING EXAMPLE

Ex

Welding cobot example





Welding cobot cell with Universal Robot, UR10e
Welding unit: Kemppi A7, manual turning table Saxlift

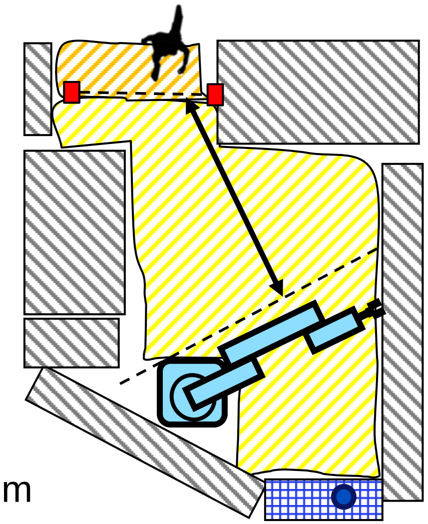
- Usually, in automated mode there are no persons inside the cell and doors are closed. This is to avoid radiation.
- Teaching collaborative robots is typically easier than teaching industrial robots. Also impact risks are small during teaching.
- The robot speed is low during welding, but the transfer from one welding task to the next can be quick. However, in this case, the impact risk is considered to be low.

Considered aspects:

- Polycarbonate ignition resistant sheet to protect persons outside the cell from radiation and sparks (note sheet height and boarders)
- When checking welding inside the robot cell, then welding masks are applied.
- Local ventilation is needed for exhausts.
- The welding equipment cables and hoses are supported above the robot.

Example associated to walk speed

- To calculate minimum safe distance from hazard zone to safeguard the stopping performance delays are calculated and multiplied with hand speed or walking speed (1,6 m/s). Hand reach (e.g. 850 mm) through or over the safeguard is usually added to the calculation. The minimum distance is calculated from safeguard to alternatively robot reach or worst case scenario. If there is high performance (e.g. PL d and Cat 3) safety function it can be applied to reduce the minimum distance. Otherwise the maximum speed and reach are applied.
- Example 1
- Robot are is limited with vertical laser scanner and person is detected with light curtain. The worst case happen when the robot trespasses laser-scanner at the same time as human trespasses light curtain.
- Robot reaction time is 250 ms, robot stopping time is 1000 ms
- Robot speed is 1,5 m/s
- Walking speed is 1,6 m/s
- Robot stopping delays = robot delays * robot speed + braking distance
- =1,5 m/s* 0,25 s + 0,5 * 1,5 m/s * 1 s = 0,375 m + 0,75 m = 1,125 m
- = distance robot can come out of its limited zone before stopping.
- In addition there is laser-scanner delay 60 ms; 1,5 m * 0,06 s = 0,09 m. Result is 1,224 m
- Walking time before robot has stopped is 1310 ms (robot + light scanner delays)
- => 1,31 s * 1,6 m/s = 2,096 m. In addition hand reach, which can be 850 mm – 1200 mm. Here 850 mm
- Total 1,215 m + 2.096 + 0,85 = **4,161 m**



In practice, the distance is too long and a gate is needed instead of light curtain

Esim. 2 | 📖 | Ex

An example associated to hand speed. Minimum distance through a light curtain; resolution of the light curtain is 40 mm

VTT

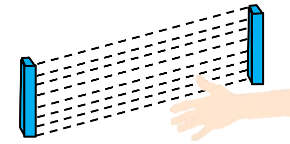
S = (2 000 mm/s x T) + 8 (d - 14 mm)   (Ø 40 mm)

Ulottuma 13855

Hand speed = 2 000 mm/s

T = machine + safety device delays (s)

Hand reach through the light curtain = 8(d - 14) >0



d = resolution of the light curtain

Equation is valid, when resolution < Ø 40 mm

Here it is assumed that robot stops quickly, because slow stopping favours to apply equation related to walk speed. For example, UR10e series robot at speed 0,58 m/s is associated to 70 ms stopping time.

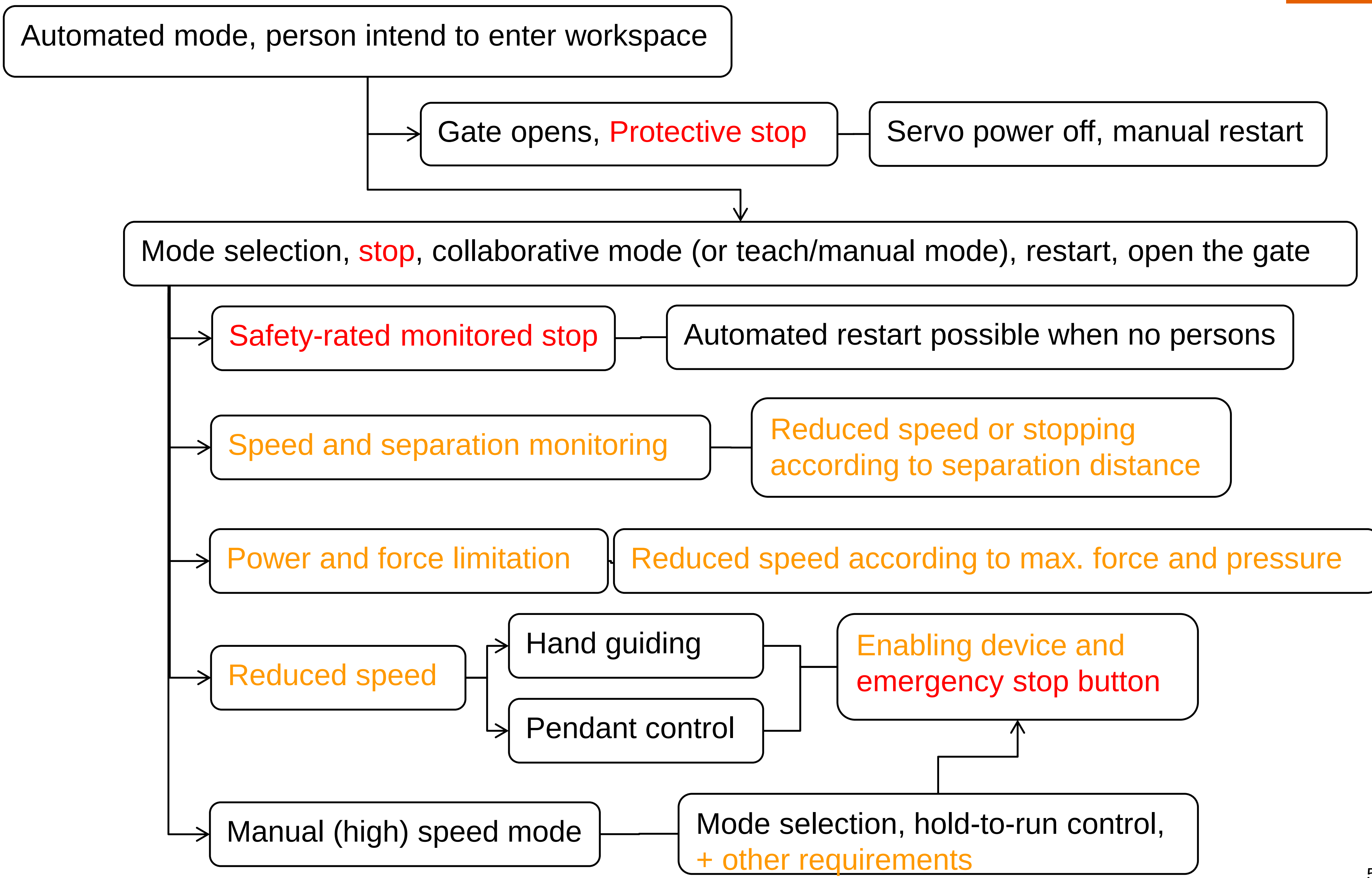
E.G. robot stopping time = 70 ms (robot speed is limited using adequate safety controller), laserscanner = 30 ms, d = 40

S = 2000 x 0,1 + 8(40 - 14) = 408 mm

Distance can also be calculated from light curtain to the robot reach maximum.

The robot reach can be limited using safety controller.

Person enters the workspace of the robot



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VTT

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