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Robots' Safety

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Thesis abstract

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Human-robot-collaboration is considered one of the answers to the flexible needs of more and more customizing manufacturing. Its purpose is to fit together the best qualities of both human and robots to reduce the cost and time of manufacturing. One of the key questions in this area is safety.

The purpose of this thesis was to define the required safety functionality of cartesian, delta and articulated robots based on the current machine needs. Using the future robotic concepts investigate and propose using the Schneider Electric portfolio the most appropriate architecture as well as the interconnection to the robotic world.

The architectures were constructed by using Schneider Electrics machine safety products and the PHARO safety laser scanner manufactured by ReeR. Also the risk assessment example and general guidelines for risk reduction process for this type of application were demonstrated.

Keywords: collaborative, robot, machine safety, laser scanner, risk assessment, collaborative method

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Opinnäytetyön tiivistelmä

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Ihminen-robotti-yhteistyötä pidetään yhtenä vastauksena kasvaviin vaatimuksiin koneellisessa valmistuksessa. Yhteistyön tarkoituksena on liittää sekä työntekijän että robotin parhaat ominaisuudet yhteen ja täten tuoda tuotantoon tarvittavaa joustavuutta ja vähentää tuotantoon kulunutta aikaa ja rahaa. Yhtenä avainkysymyksenä ihminen-robotti-yhteistyössä nousee esiin turvallisuus.

Tämän opinnäytetyön tarkoituksena oli määrittää cartesian, delta ja articulated-robottityypeille tarvittava turvallisuuteen liittyvä toiminallisuus ottaen huomioon nykyisten koneiden vaatimukset. Tulevaisuuden konsepteja käyttäen tarkoituksena oli tutkia ja ehdottaa sopivin arkkitehtuuri hyödyntämällä Schneider Electricin tuotevalikoimaa sekä osoittaa yhteys robotiikan maailmaan.

Arkkitehtuurit luotiin Schneider Electricin koneturvallisuustuotteita sekä ReeR:in valmistamaa PHARO- turvalaserskanneria käyttäen. Esimerkki riskien arvioinnista ja yleiset ohjeet riskien vähennysprosessiin tämän tyyppiseen arkkitehtuuriin on myöskin demonstroitu tässä opinnäytetyössä.

Asiasanat: yhteistyö, robotti, koneturvallisuus, turvalaserskanneri, riskien arviointi, yhteistyö metodi

TABLE OF CONTENTS

Terms and Abbreviations

Collaboration	Interactive cooperation of two or more persons or machines.
ISO	The International Organization for Standardization.
Manipulator	Used to move material without direct contact. Simpler version of a robot.
OSSD	Output Signal Switching Device
PLC	Programmable Logic Controller
Teach pendant	Control interface for a worker for the motion programming of a robot.

Tables, Figures and Pictures

1 Introduction

History of the robotics goes back to the year 1954 when George C. Devol applied the patent for a programmable manipulator. The model called ‘’Unimate’’ made and designed by Devol and Joseph. F Engelbeer was commissioned at General Motors in 1962. From that day, the robotics has been quickly adapting in the industrial manufacturing and nowadays collaborative robots are examples of this development in the field of technology.

Collaborative robots have become solutions to applications where competencies from both human and robot must be applied for the best result with minimal costs. This considers situations where full labour or a fully automated solution is not possible to be commissioned or it is found ineffective. It could be summarized, that human-robot-collaboration is giving dynamic semi-automation solutions for production. Human is ahead in flexibility, fast adaptation to changing tasks and decision making whereas robots are tireless, powerful and could handle dangerous items and thus be commissioned to dangerous places. By using collaborative applications, the strengths of both a human and a robot could be used to improve production efficiency, quality, capacity, employee environment, cost and cycle times. Also, manufacturing of complex and several work phases including products in small quantities are more efficient when comparing fully automated and fully manual production.

1.1 Schneider Electric Automation GmbH

Schneider Electric Automation GmbH is a subsidiary of Schneider Electric SE, which is a French originated multinational company founded in 1836. The company specialties consist of power management, process & machine management, IT room management, building management, security management, industrial software design, simulation and optimisation, industrial automation, control and safety systems and instrumentation. The company has over 185 000 employees in over 100 countries. (Schneider Electric 2016a.)

Figure 1: Company logo (Schneider Electric 2016a)

Schneider Electric Automation GmbH, based in Marktheidenfeld is the international headquarter of the Machine Solutions and System Consistency- sector. The globally active company develops and produces products and services by approximately 400 employees from over 26 different nations in particular hardware and software products for automation solutions in machine and plant engineering. (Schneider Electric 2016a.)

1.2 Thesis background, goals and structure

The goal of this thesis was to investigate and study the safety methods used in the collaborative robotics. By using this information, example application for demonstration purposes using the safety components and devices manufactured by ReeR and Schneider Electric was constructed.

This thesis consists of five main parts, which are; introduction, theory, technical investigation, an example of risk assessment and a summary and cogitation.

2 Theory

2.1 Clarification for the terminology

There are several different ways in naming of human collaborative robots and for the general clarification and for this thesis the following terminology is applied:

Force limited robots are specially designed to work alongside the humans. Force and torque are monitored and in case of a contact the robot is stopped. (Robotiq 2015.)

Collaborative robots are designed to work alongside the human, but are not necessarily force-limited. This is also considering applications where standard industrial robot is made collaborative by external devices or technologies. (Robotiq 2015.)

Cobot is a slang term describing a collaborative robot and could be used to describe both of the previous, but needs corrective determination alongside. (Robotiq 2015.)

2.2 Machine safety in general

With a short ethical cogitation, it could be said that there is a clear moral obligation against a situation where the industrial machine is harming a person. The harm caused by an accident is not limited only to the injury of the worker, but also has financial impact to insurance costs, lost production, damaged machine, lost customers and even loss of reputation of the company. (Schneider Electric 2009.)

To prevent this, it is important to recognize, plan and supervise safety aspects from the start, already at the designing phase, until the decommissioning and scrapping of the machine. The risk assessment has an important role when commissioning human-robot applications. The basic risk assessment consists of recognizing the system's scope, identifying risk sources, estimating and evaluating the risk and determining these attributes to conduct the needed risk reduction process (Schneider Electric 2009.). An example of the risk assessment for a constructed example application layout will be introduced in section 4.

2.3 Introduction to the standards

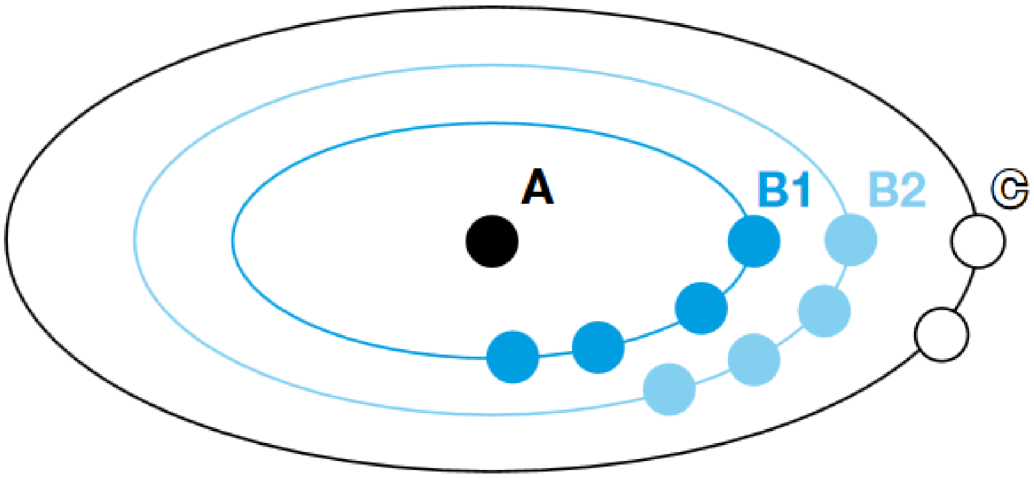

Figure 2: Structure of the standards for the safety of machinery (Schneider Electric 2009, 12.)

Type A standards are basic safety standards which give the basic concepts, principles for design and general aspects that can be applied to all machinery. (Schneider Electric 2009.)

Type B standards are generic safety standards which are dealing with one safety aspect or one type of safeguard that can be used across a wide range of machinery. Breaking this down to Type B1 and Type B2 standards, where B1 standards concentrate on particular safety aspects, for example, contact surfaces, temperature and noise. B2 standards consider safeguarding methods, for example two-hand controls, interlocking devices, pressure sensitive devices and guards. (Schneider Electric 2009.)

Type C standards are machine safety standards which consider safety requirements for a particular machine or group of machines. (Schneider Electric 2009.)

The following table is explaining the main standard structures which were used during the investigation.

Table 1: Standard structure

A	ISO 12100	
B	ISO 62061	ISO 13849-1
C	ISO 10218-1	ISO 10218-2
Supportive	ISO TS 15066	ISO TR 14121-2

Supportive- type of standards consist of Technical Specification (TS) and Technical Report (TR) which provide more detailed information according to the subject discussed in the standards. ISO TS 15066 is introduced better later in this thesis and ISO TR 14121-2 are giving practical guidance for risk assessment for a wide variety of machines. It could be used with ISO 12100 when implementing various tools and methods for each step of the risk assessment and risk reduction process.

2.4 Safeguarding devices

This section covers typical devices which are used for safeguarding hazardous areas in manufacturing machines.

2.4.1 Light curtains

With a light curtain, user putting hands, fingers or feet to a hazardous area could be prevented, because distances between light beams are short. This is called resolution. Resolution limit for the fingers is 14mm, for the hands 30mm and for the body protection 40mm. (Malm 2008, 19-20.)

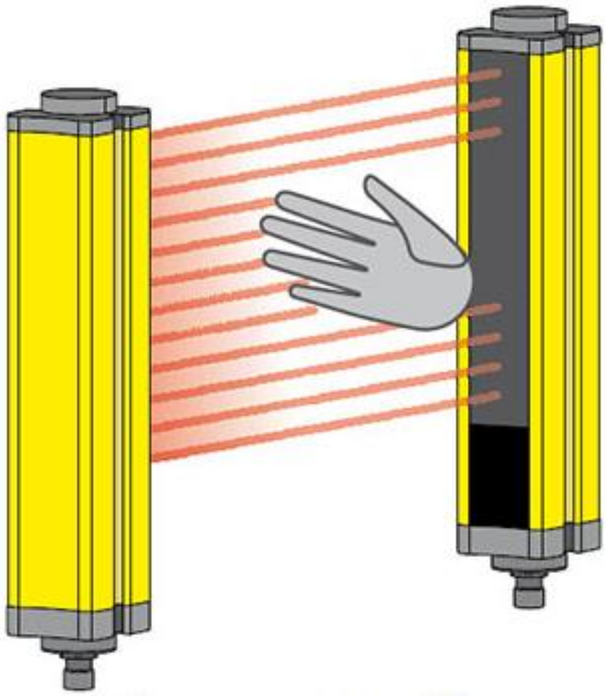

Figure 3: Principle of the light curtain
(Clearwater Tech 2016.)

For basic principle, the light curtain consists of several photoelectric sensors. Assembling several transmitters and receivers close to each other requires some consideration of interruption errors between light beams. To eliminate this error usually only one transmitter receiver pair is activated at the time. The frequency in activation between the light beams is high and reaction time is some milliseconds. (Malm 2008, 19-20.)

2.4.2 Safety mats

The working principle of this safety device is mechanical. The output from the mat is generated when the operator steps on it. The technology in the mat is based on compressed air, optical fibre or electromechanical solutions. Mats are usually made of industrial rubber with a thickness between 10 and 15mm. (Malm 2008, 20-21.)

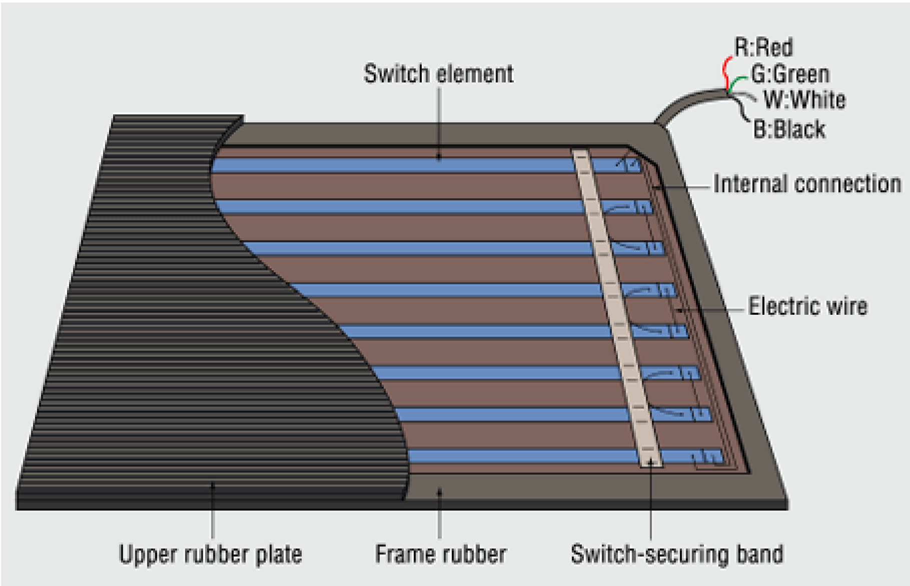

Figure 4: Principle of the safety mat by Tokyo Sensor (T.J. Solution 2012.)

2.4.3 Safety limit switches

Whenever safety fences are applied, it is necessary to ensure that a human is able to trespass the hazardous zone only when the machine is stopped or the risk inside the hazardous zone is not exceeding the measured limits. There are lot of options for safety limit switches in the market (Malm 2008, 22.)

Solenoid interlock switches prevent the gate opening by using a lock key, which is attached to the frame of the door. The switch could be set to open after a determined delay or signal. (Malm 2008, 22-23.)

Coded magnetic switches are compact solutions for gate monitoring. The device consists of a small magnet and a reading device which detects if the magnet is not in its perimeter and sends a stopping signal to the machine. The coding is implemented to make the bypassing of the switch harder. (Malm 2008, 23.)

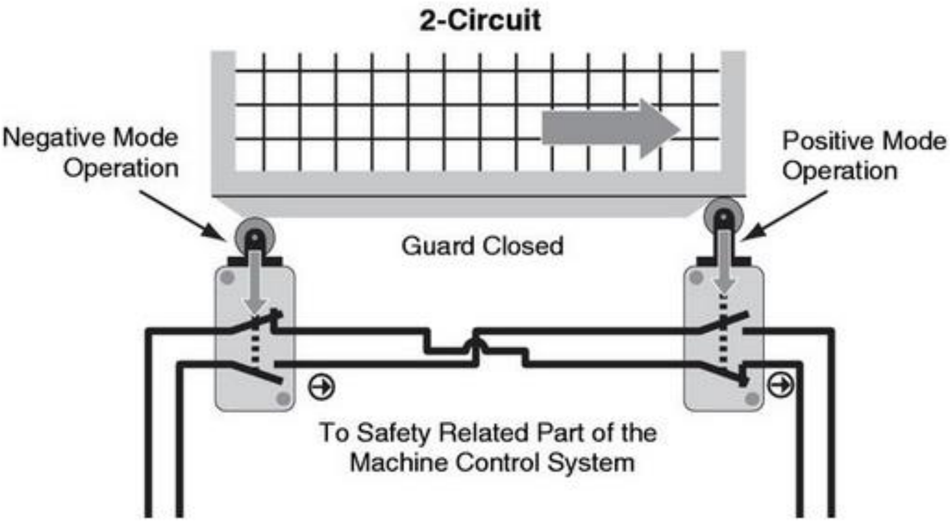

Figure 5: Example application executed with safety limit switches (Rockwell Automation 2016.)

2.4.4 Enabling switch

Enabling switch, also known as a ’dead man switch, uses a 3-state pressing switch to recognize and cut the signal if not pressed at all or if pressed too hard. It is used to gain access to the work cell’s hazardous zones when the machine is running with a reduced speed. Teach pendants used to program an industrial robot’s movement are equipped with enabling switches. (Schneider Electric 2009.)

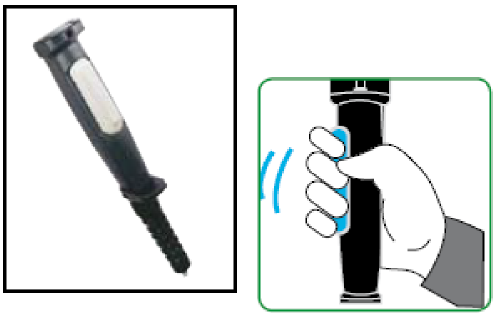

Figure 6: Example of an enabling switch (Schneider Electric 2009, 26.)

2.5 Standards regarding safety in collaborative robotics

Regarding safety in robots there are three standards to implement;

ISO 10218-1 concentrates on safety precautions in design and the functionality of the robot itself and concerns more the manufacturer than the commissioner. The main points of the standard regarding this thesis are:

4 Hazard identification and risk assessment

5.3.5 Single point of control

5.4.2 Performance requirement

5.5 Robot stopping functions

5.6.2 Reduced speed control operation

5.10 Collaborative operation requirements

5.10.4 Speed and separation monitoring

5.10.5 Power and force limiting by inherent design or control

5.12.2 Mechanical and electro-mechanical axis limiting devices

5.12.3 Safety-rated soft axis and space limiting

Annex A: List of significant hazards

Annex F: Means of verification of the safety requirements and measures

ISO 10218-2 is giving guidelines for integrating robotics to manufacturing. Considered main points regarding this thesis are:

4.2 Layout design

4.3.2 Limits of the robot system

5.4.2 Establishing safeguarded and restricted spaces

5.5.1 Perimeter safeguarding

5.5.2 Access for interventions

5.6.3.4 Manual reset, start/restart and unexpected start-up

5.7.4 Hand guiding of robot systems (collaborative robots)

5.10 Safeguarding

5.10.3 Minimum (safety) distances

5.11 Collaborative robot operation

6 Verification and validation of safety requirements and protective measures

Annex B: Relationship of standards to related protective devices

Annex C: Safeguarding material entry and exit points

Annex E: Conceptual applications of collaborative robots

Annex G: Means of verification of the safety requirements and measures

ISO TS 15066 is a technical specification which was released in February 2016 to fulfil and specify the collaborative safety with more detailed information of designing collaborative application in entity.

Also biomechanical limits of the human are tested in the University of Mainz in Germany and the results cover the maximum force and pressure limits for 29 body areas. (Robotiq.)

Table A.2 — Biomechanical limits

Body region	Specific body area		Quasi-static contact: Maximum permissible pressure [a] p_s N/cm²	Quasi-static contact: Maximum permissible force [b] N	Transient contact: Maximum permissible pressure multiplier [c] P_T	Transient contact: Maximum permissible force multiplier [c] F_T
Skull and forehead [d]	*1*	*Middle of forehead*	*130*	*130*	*not applicable*	*not applicable*
	2	*Temple*	*110*		*not applicable*	
Face [d]	*3*	*Masticatory muscle*	*110*	*65*	*not applicable*	*not applicable*
Neck	4	Neck muscle	140	150	2	2
	5	Seventh neck muscle	210		2	
Back and shoulders	6	Shoulder joint	160	210	2	2
	7	Fifth lumbar vertebra	210		2	2
Chest	8	Sternum	120	140	2	2
	9	Pectoral muscle	170		2	
Abdomen	10	Abdominal muscle	140	110	2	2
Pelvis	11	Pelvic bone	210	180	2	2
Upper arms and elbow joints	12	Deltoid muscle	190	150	2	2
	13	Humerus	220		2	
Lower arms and wrist joints	14	Radial bone	190	160	2	2
	15	Forearm muscle	180		2	
	16	Arm nerve	180		2	

Figure 7: Biomechanical limit values (ISO TS 15066:2016, 24.)

Table A.2 *(continued)*

Body region	Specific body area		Quasi-static contact: Maximum permissible pressure [a] p_s N/cm²	Quasi-static contact: Maximum permissible force [b] N	Transient contact: Maximum permissible pressure multiplier [c] P_T	Transient contact: Maximum permissible force multiplier [c] F_T
Hands and fingers	17	Forefinger pad D	300	140	2	2
	18	Forefinger pad ND	270		2	
	19	Forefinger end joint D	280		2	
	20	Forefinger end joint ND	220		2	
	21	Thenar eminence	200		2	
	22	Palm D	260		2	
	23	Palm ND	260		2	
	24	Back of the hand D	200		2	
	25	Back of the hand ND	190		2	
Thighs and knees	26	Thigh muscle	250	220	2	2
	27	Kneecap	220		2	
Lower legs	28	Middle of shin	220	130	2	2
	29	Calf muscle	210		2	

Figure 8:Biomechanical limits values continued (ISO TS 15066:2016, 25.)

2.6 Used safety technologies with collaborative robots

In this section the usual safety measures from the current market are introduced with example applications.

2.6.1 Safety laser scanner

A laser scanner is meant to detect an approaching object by optical sensing and to send a stop signal to the machine before the object reaches the hazard zone. (Malm 2008, 23)

For example the *PHARO-* safety laser scanner manufactured by ReeR is based on the principle of time-of-flight- measurement. It sends out very short pulses of light (S in the picture below). At the same time an electronic stopwatch is started and it measures when the light it is reflected and received by the safety laser scanner (E). Based on the time between sending and transmitting (Δt) the scanner calculates the distance to the object. The mirror rotates at constant speed (2) that directs the light pulses for cover an arc of 190°. By the mirror angle value, the scanner measures the object's direction. Based on the distance and direction of the object, the scanner determines the objects' position. (ReeR 2015.)

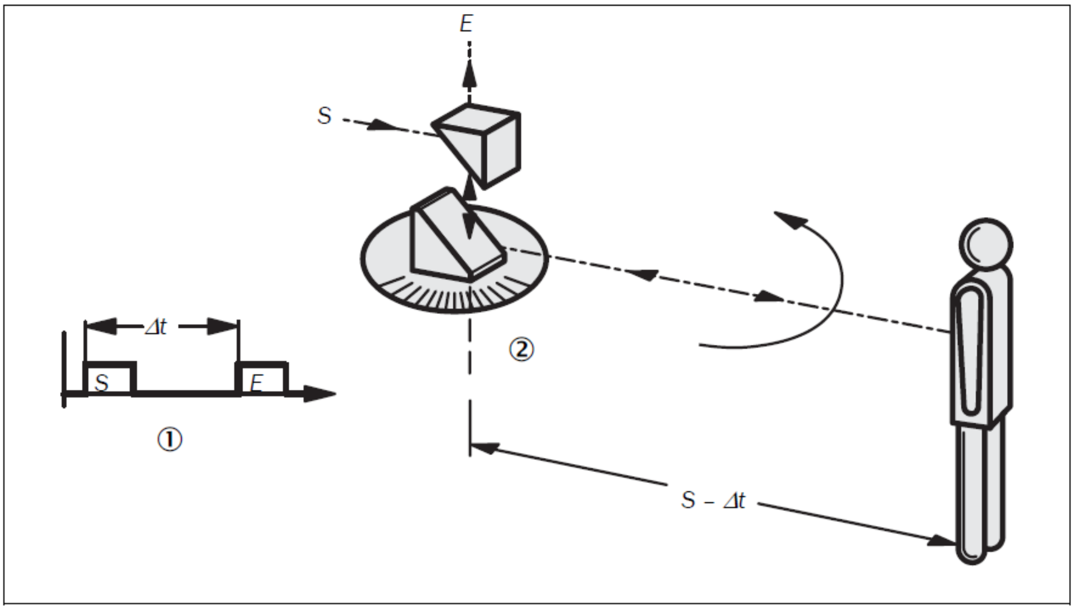

Figure 9: ReeR PHARO function principle (ReeR 2015, 14.)

There is a different number of field sets and field configurations available within the scanners in the market. *ReeR PHARO* is equipped with two fields, which are a Protective field (1, in the picture below) and a Warning field, stated as number 2 in the Figure 10 below. (ReeR 2015.)

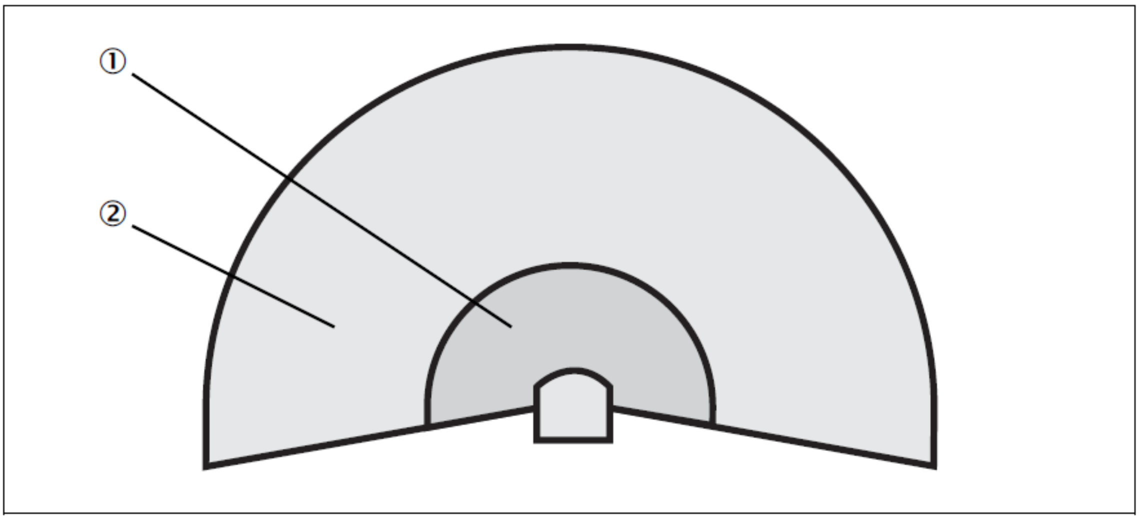

Figure 10: Fields of ReeR PHARO (ReeR 2015, 15.)

The scanner’s functionality is described in more detail in the section *Technical investigation*.

2.6.2 Tactile skin

This method uses the layer built on the robot which is consisting of sensors. These sensors could be used to measure pressure and proximity. In the following picture the tactile skin is used at the same time to control the robot arm and ensure safety. Fraunhofer’s application consists of pressure and capacitive sensors which are used to measure location, strength and area of contact. (Fraunhofer 2014b.)

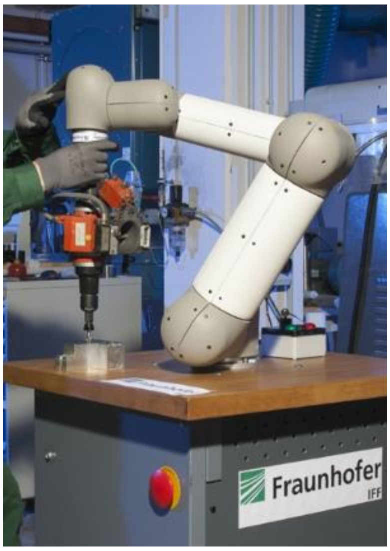

Figure 11: Tactile skin application by Fraunhofer (Fraunhofer 2014b.)

2.6.3 Axis monitoring

In most force limited robots in the market, for example models manufactured by KUKA, Universal Robotics, Rethink Robotics, there are sensors installed straight into the joints of the robots' arms to monitor forces and torques. The sensor values can be compared to the limit values and robot will be stopped if the values exceed enough. One implemented method is the overcurrent measurement. (Robotiq. 2015.)

An example of a robot representing this technology has been manufactured by KUKA and introduced later in the section *Safety methods for collaborative robots* .

2.6.4 Machine vision

One basic principle with safety devices is that they react to changes in a continuous signal. The safety device's machine vision is based on reacting to changes in the picture of the camera and then giving out a stopping signal. In situations when the lens is gathering dirt or the system starts to get inaccurate, the functionality of safety system can be ensured. (Malm 2008, 30-31.)

SafetyEYE manufactured by Pilz is based on this technology. The system consists of three CMOS cameras and the device is able to provide a 3D perception. (Pilz 2006.)

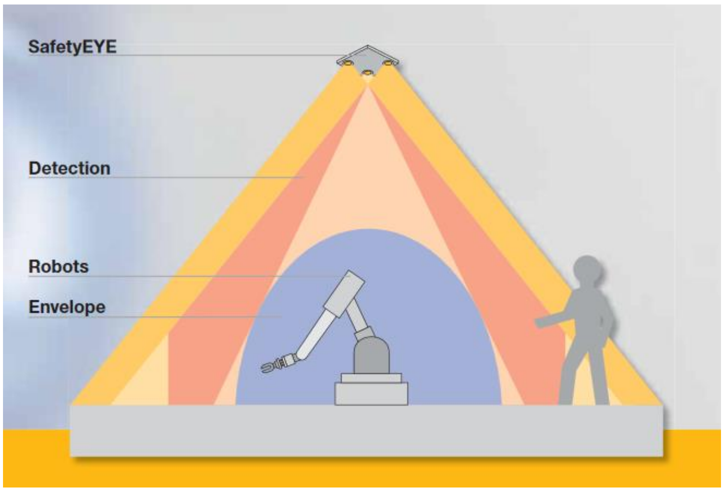

Figure 12: Areas of SafetyEYE. (Pilz 2006.)

2.6.5 Safety methods for collaborative operations

In the technical specification ISO TS 15066 are stated 4 different possibilities to ensure safety during collaborative situations. The methods are *safety-rated monitored stop*, *hand guiding*, *speed and separation monitoring* and *power and force limiting*. The methods can be used separately or the collaborative solution can be constructed of a combination of these methods. (ISO TS 15066:2016, 8.)

The *Safety-rated monitored stop*- method means ceasing the robot's motion before an operator enters the collaborative workspace to interact with the robot system and complete the work cycle's task. If the operator is not present in the collaborative workspace, the robot may operate non-collaboratively. When the robot is in the collaborative workspace, the safety-rated monitored function is active and the robot is stopped, and the operator is permitted to enter the collaborative workspace. The robot can resume the work cycle without any additional intervention only after the operator is no longer present in the collaborative workspace. (ISO TS 15066:2016, 8.)

The logic is illustrated in the following figure:

Robot motion or stop function		Operator's proximity to collaborative workspace	
		Outside	Inside
Robot's proximity to collaborative workspace	Outside	Continue	Continue
	Inside and moving	Continue	Protective stop
	Inside, at Safety-Rated Monitored Stop	Continue	Continue

Figure 13: Truth table for *safety-rated monitored stop operations* (ISO TS 15066:2016, 8.)

The technical investigation appearing later in this thesis is based on this collaborative method.

In the *Hand guiding*- method a hand-operated device is used to transmit motion commands to the robot system by the operator. Before the operator is permitted to enter the collaborative workspace and conduct the task, the robot achieves a safety-rated monitored stop command. The task is carried out by manually actuating the guiding devices located at or near the robot's end-effector. (ISO TS 15066: 2016, 9.)

An example application of this method is introduced by Fraunhofer, which is aiming at robot-assisted sensitive hand-guiding of heavy workpieces. The concept is using a steering-wheel-like two hand enabling switch. The implemented tactile sensors permit 3-stage sensing to reduce hazardous situations. The device has been installed straight to the tool center point (TCP) of the robot. (Fraunhofer 2014a.)

Figure 14 Hand guiding device by Fraunhofer
(Fraunhofer 2014a.)

In the *Speed and separation*- method, the robot and operator may be at the same time in the collaborative workspace. The risk has been lowered by constantly maintaining at least the protective separation distance between the operator and robot. When in motion, the robot never gets closer to the operator than the protective separation distance. (ISO TS 15066:2016, 10-11.)

Example from Fraunhofer is using projector and camera technology for generation and monitoring safe areas. The area is directly projected into the environment. The safe areas are changing dynamically regarding to position, size and shape. Stop is initiated when the projector beam is disrupted. (Fraunhofer 2014a.)

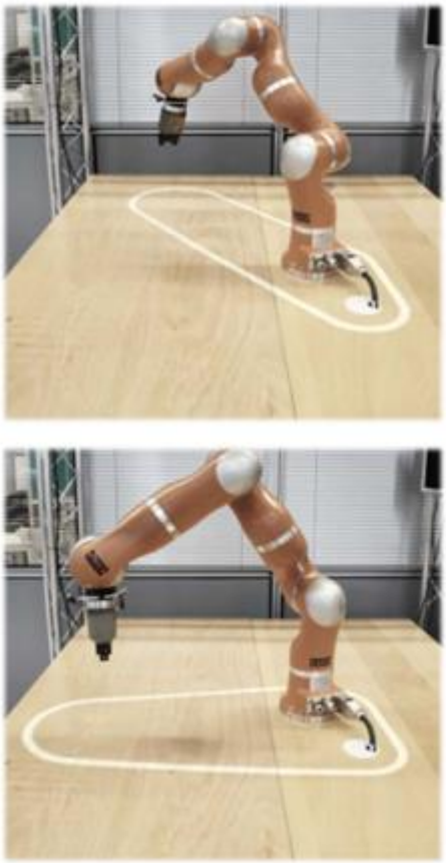

Figure 15 Example of Speed and separation monitoring by Fraunhofer (Fraunhofer 2014a.)

In the Power and force limiting- method, physical contact between the robot system and an operator can occur either intentionally or unintentionally. Power and force limited collaborative operation requires robots specifically designed for this particular type of operation. Either through inherently safe means in the robot or through a safety-related control system, risk reduction is achieved, by keeping hazards associated with the robot system below threshold limit values that are determined by the risk assessment. (ISO TS 15066:2016, 15.)

Figure 16 Collaborative robot based on Power and force limiting method by KUKA. (KUKA)

2.7 Safety functions for motions

Safety functions for the motion are different monitoring situations for example for the servomotor. By these functions the dangerous speeds and torques are avoided. (Schneider Electric.)

Safety functions used in application in this thesis are *Safe torque off, Safe Stop 2 and Safe limited speed.* (Schneider Electric.)

Safe torque off (abbreviation STO) is the most common safety function and are found most drives as standard. This function ensures that energy generating torque is eliminated and therefore prevents unintentional start of the motor. Drive free-wheels down to stop condition when STO is enabled. (Schneider Electric.)

Safe stop 2 (abbreviation SS2) is causing rapid motor stop safely and keeps monitoring the standstill position of the motor. The torque is ‘’kept’’ in the motor to enable it quickly again when necessary. (Schneider Electric.)

Safe limited speed (abbreviation SLS) function ensures determined speed limits of the drive. When the speed is reduced to the right level by the program, the SLS supervises, that the limit is not exceeded. Fault is activated if the limit is exceeded. (Schneider Electric.)

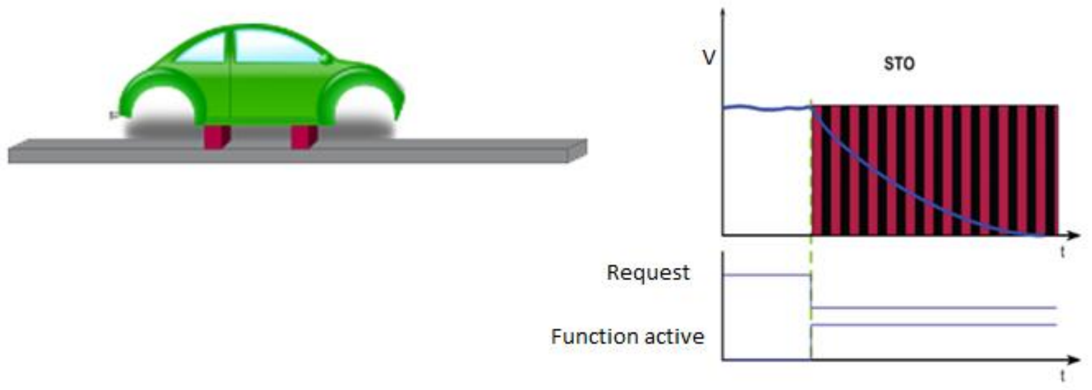

Figure 17: STO safety function

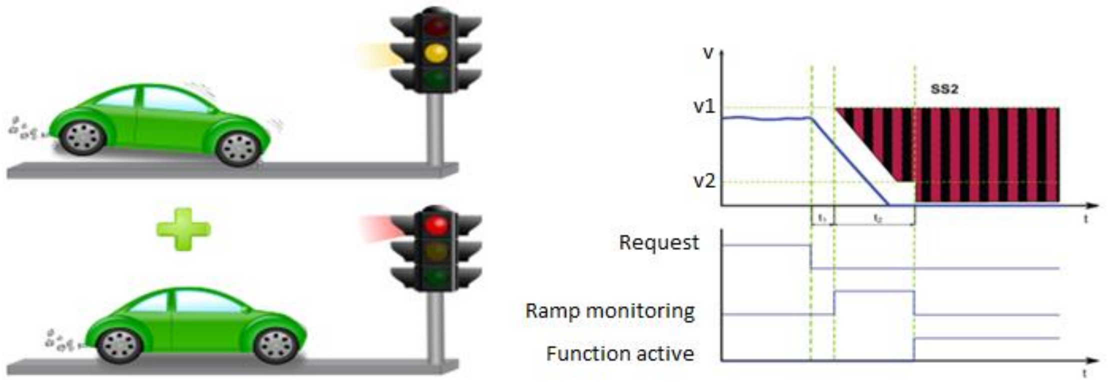

Figure 18: SS2 Safety function

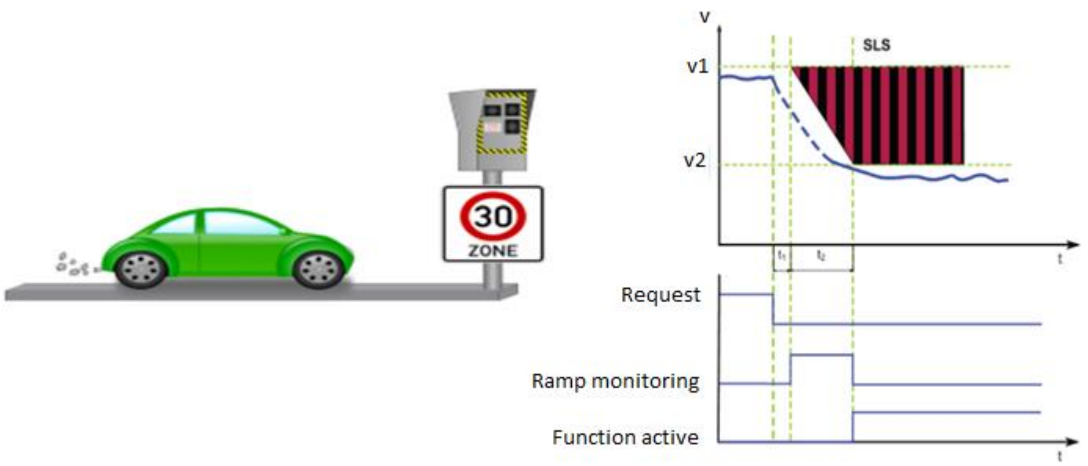

Figure 19: SLS Safety function

3 Technical investigation

3.1 Foreword

The technical investigation took place in Schneider Electrics factory in Marktheidenfeld from 21st of March to 21st of June. The main goals were to implement ReeR PHARO safety laser scanner with XPSMCM- programmable safety controller and TM5- safety logic, construct an example application basing on the Safety-rated monitored stop theory and to make a risk assessment example.

3.2 Constructed architectures

3.2.1 Components

Main components in the example architectures were *PHARO- safety laser scanner* and components manufacture by Schneider Electric; *Preventa XPSMCM- safety modular controller*, *PacDrive TM5- safety logic controller*, *PacDrive 3 Logic Motion Controller LMC* and *Thesys- contactor.*

ReeR PHARO PHR 332 is having 2 monitored safety zones and 2 monitoring cases available. The functionality of the safety zones and monitoring cases is introduced with example application later in this thesis. PHAROs Protective field could reach up to 4 meters. Warning field could reach theoretically 49 meters, but detection is dependent of the reflectivity. (for example objects with 20% reflectivity can be detected in radius up to 20m). Scanner is configured with the User Configuration Software (UCS).(ReeR 2015)

Figure 18: ReeR PHARO Safety laser scanner
(ReeR)

XPSMCM- safety modular controller is configurable controller for monitoring multiple safety functions as example emergency stop and guard monitoring. *XPSMCM* is configured via program called *SoSafe Configurable*. Controller is expandable and different modules are available for example to support fieldbus communication. (Schneider Electric 2015.)

Figure 19: XPSMCM safety modular controller with expansion modules
(Schneider Electric 2015.)

PacDrive TM5- safety logic controller is ‘’supervision’’ system for the output devices connected to the *LMC* and is used to create embedded safety systems. Also non-safety blocks could be attached, but they are not part of the safety system. Schneider Electrics program *SoMachine Motion* includes *SoSafe Programmable* which is used to configure *TM5*- system. (Schneider Electric 2010.)

Figure 20: Example of connected TM5 safety logic system

PacDrive 3 LMC Logic Motion Controller implements both PLC and motion functions and is used with PacDrive 3 robotics to control Schneider Electrics cartesian and delta robot models. *LMC* is programmed via *SoMachine Motion*.(Schneider Electric 2009.)

Figure 21: PacDrive 3 LMC (Schneider Electric 2016b.)

3.2.2 Example architecture 1

The first example architecture is consisting of *PHARO*- safety laser scanner, *XPS-MCM* and *Thesys*- contactor. Target usage is for simple applications. The output could be in example robot controller and the connection is done by hardwiring between *XPSMCM* and the controller.

The principle for safety function is the input, processing and output as in structure picture below.

Figure 22: Input - Processing - Output

The testing succeeded with both automatic and manual restart. When the object was in the Warning field the indicator light ''OBJECT IN THE WARNING FIELD'' was on and when object proceeded to the Protective field, the power was off from the contactor. Usage of automatic restart is prohibited in the situations where the user could exit from the detection zone to the hazardous zone.

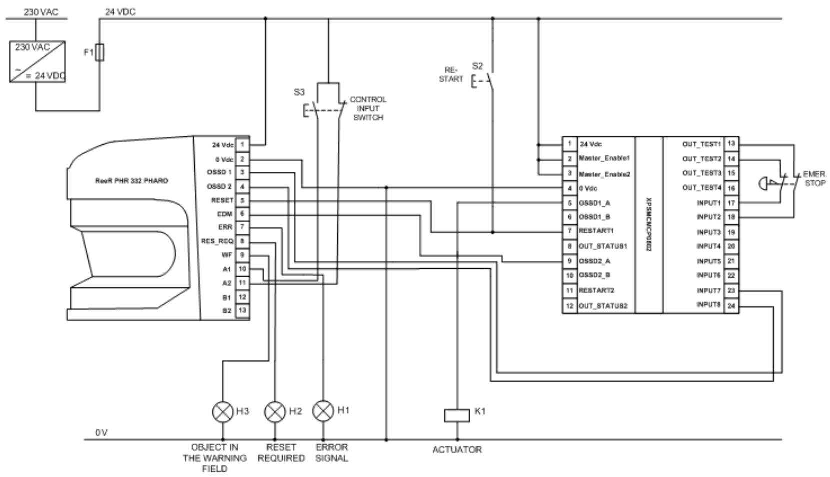

Figure 23: Wiring diagram of the architecture

3.2.3 Example architecture 2

The second example architecture is consisting of *PHARO*- laser scanner as the input device, *TM5* as the supervision device, *LMC* as the processing device and *Harmony XVMB1R6AG*- light tower as the output device. All other devices are communicating with Sercos 3 bus, except the connection between *PHARO* and *TM5*, which is hardwired.

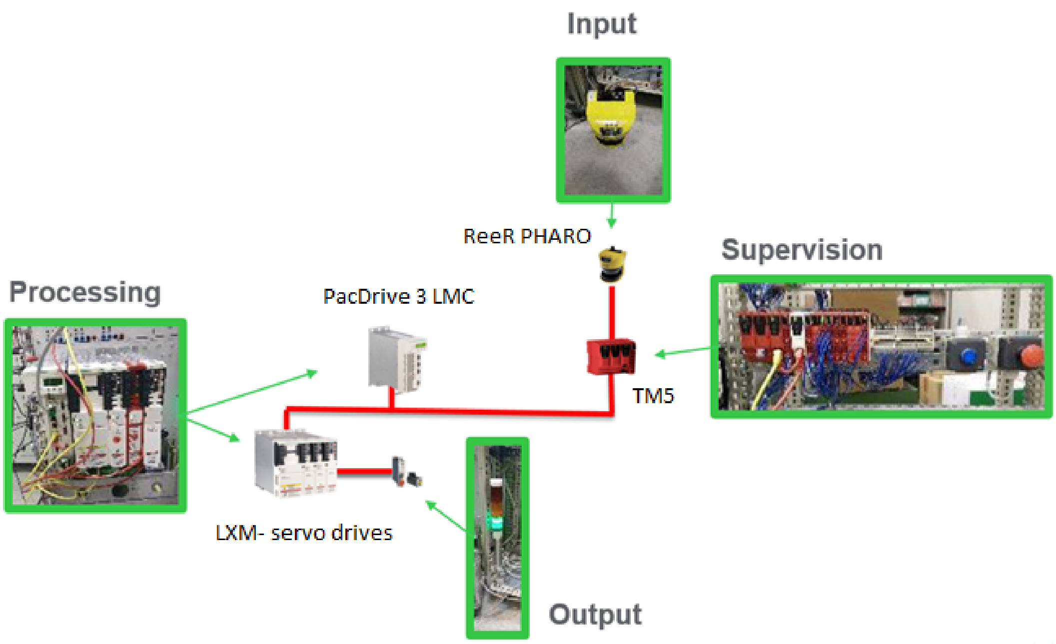

Figure 24: Example architecture 2

The picture below is demonstrating the functionality of the architecture from safety side of view. The full program block used in the architecture in SoSafe Programmable is found from the appendices.

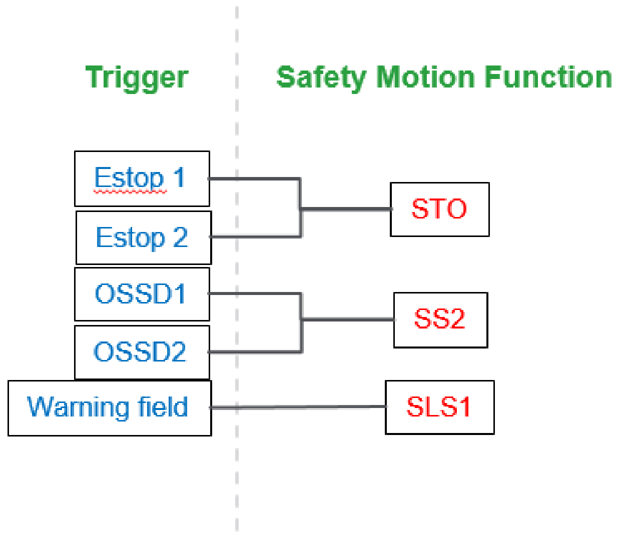

Figure 25:Simplified safety functionality of the architecture.

OSSD1 and OSSD2 in the picture are standing for the redundant output signals of the safety scanner. Emergency stop 1 (Estop1) and Emergency stop 2 (Estop2) are extra safety functions and connected for the testing purposes.

The architecture demonstration workflow was as follows;

1. The power is connected to the system. The scanner is in normal state and output needs to be restarted.

2. After restart, the output is also in the normal state.

3. When the operator or the object interrupts the Warning field of the scanner, the Safe Limited Speed (SLS)- safety function is activated for the output.

4. When the operator or the object interrupts the Protective field of the scanner, the Safe Stop 2 (SS2)- safety function is activated for the output.

5. When the object exits both the Protective field and Warning field, the scanner returns to the normal state and output needs restart.

6. After restarting the output the system returns to the normal operation.

3.3 Example application

In this section, the example application basing on the Example architecture 2 is demonstrated.

3.3.1 Layout

The picture of the example applications layout could be found below.

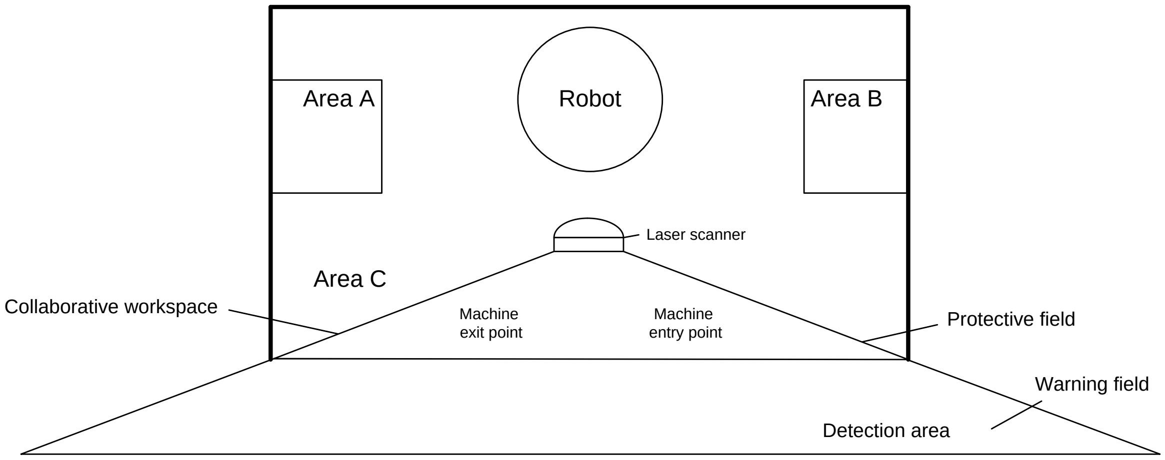

Figure 26: Application layout

Area A is standing for the conveyor which inputs material to the work cell, likewise *Area B* is the output conveyor.

Area C is standing for the *Collaborative workspace* as mentioned in the *Safety-rated monitored stop-* method. In *Area C*, the *Protective field* (coloured yellow in the 3D-picture) and *Warning field* (coloured red in the 3D. picture) of the safety scanner are active.

Machine exit point is standing for the area, where robot gives the object to the operator and *Machine entry point* is the area where operator returns the object to the task cycle.

The 3D- picture of the layout is found below.

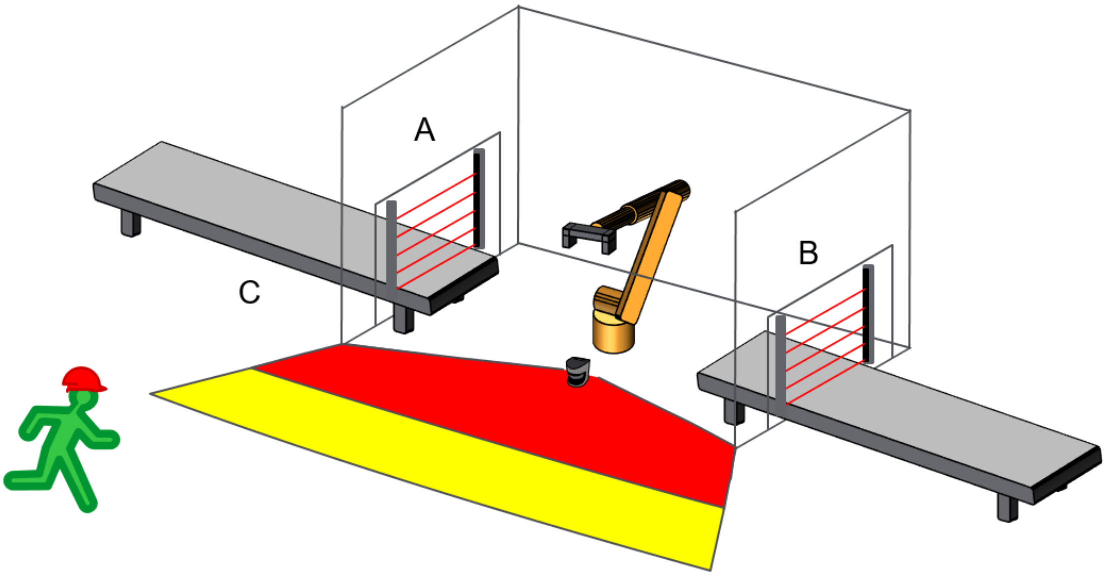

Figure 27: Application layout in 3D

3.3.2 Workflow demonstration

The work cycle starts normally after machine restarts and robot starts to move objects from *Area A* conveyor to the *Area B* conveyor.

The collaborative operation starts when the operator enters to the scanners *Warning field. The Safe limited speed (SLS)*- safety function is activated and robot speed reduced.

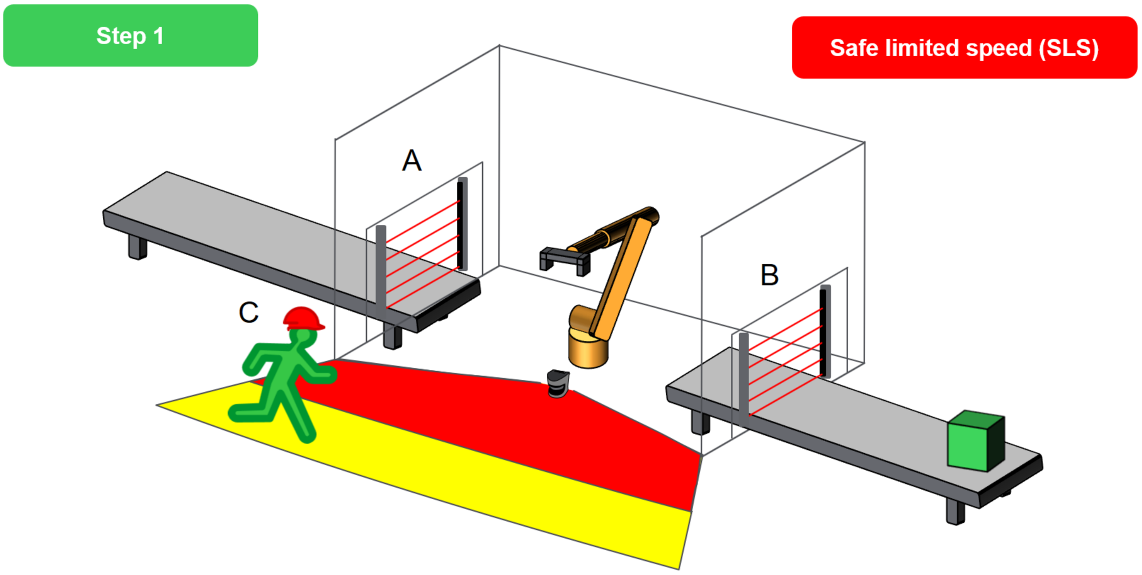

Figure 28: Example application: Step 1

In Step 2, after the robot is finished the work cycle by handling the object to the *Area B* from tool head, it picks up the object from *Area A* and transfers it to *Machine exit point*.

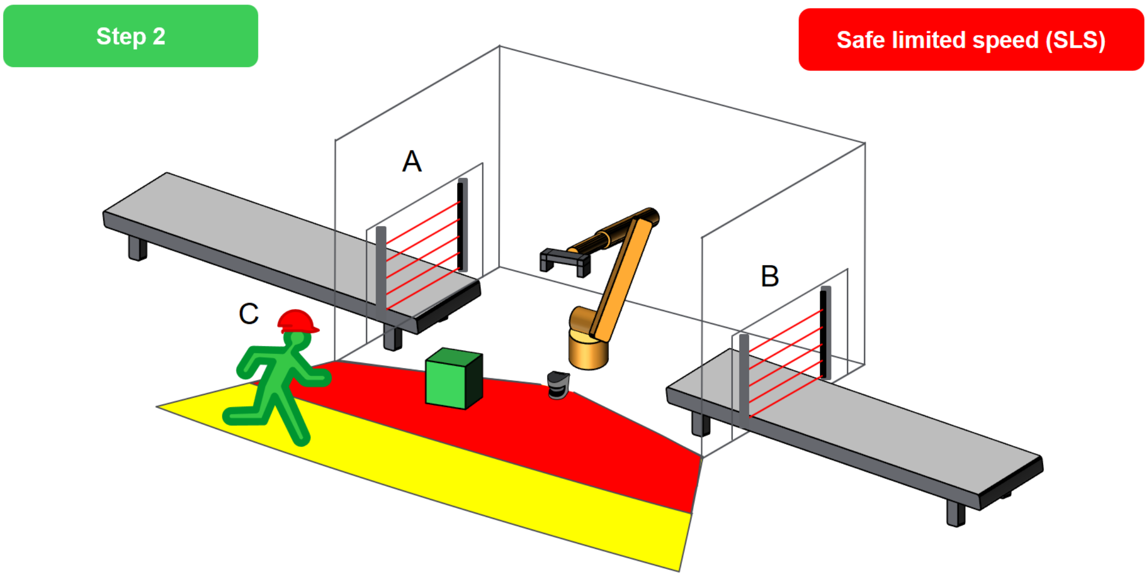

Figure 29: Example application: Step 2

In Step 3, when the robot is left from the collaborative area, the field set of the safety scanner switches and lets operator to go pick up the object without interfering the Protective field. The operator does the needed operations for the object, repair or inspection in the *Warning field* area while the robot continues the work cycle with reduced speed.

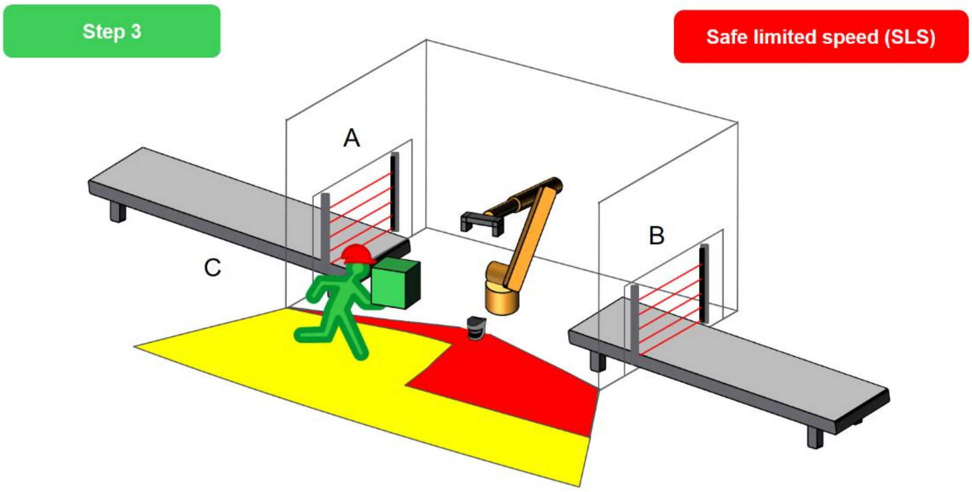

Figure 30: Example application: Step 3

In Step 4, the operator has finished the needed operation to the object and returns the object to the Machine entry point. During this step, the operator has to interrupt the Protective field and the Safe Stop 2 (SS2)- safety function is activated. This could be prevented by choosing safety laser scanner with more field sets available.

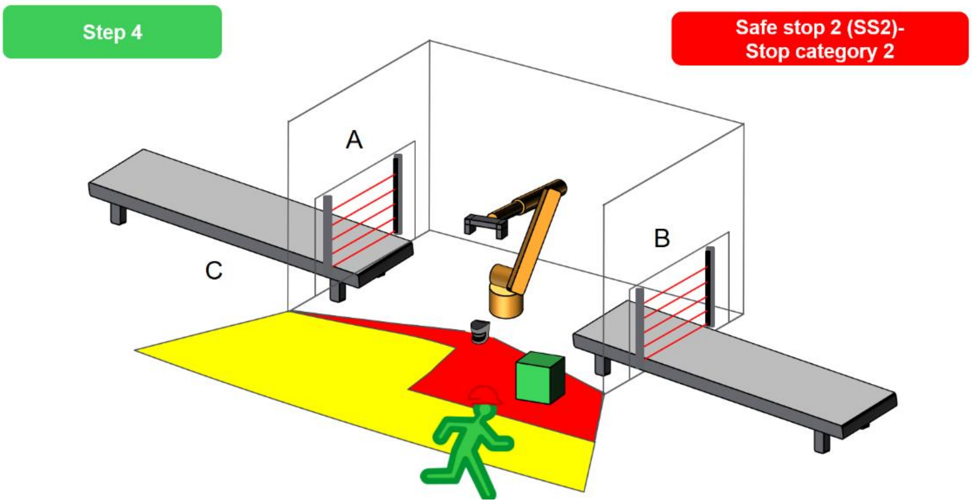

Figure 31: Example application: Step 4

In Step 5, after manual machine restart, the robot picks up object from the Machine entry point and puts it to the conveyor in Area B. After that the work cell is returned to the normal work cycle operation.

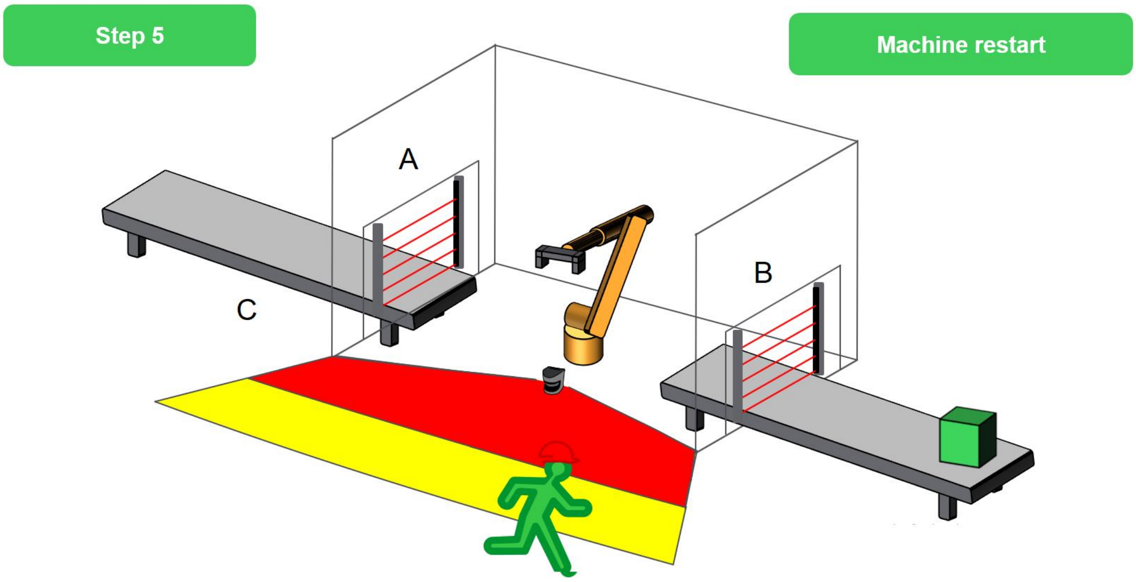

Figure 32: Example application: Step 5

4 Example of risk assessment

In this section, the general guidelines for the risk reduction process for example applications collaborative method are given.

4.1 General risk reduction process

The risk reduction structure is introduced in the ISO 12100- standard.

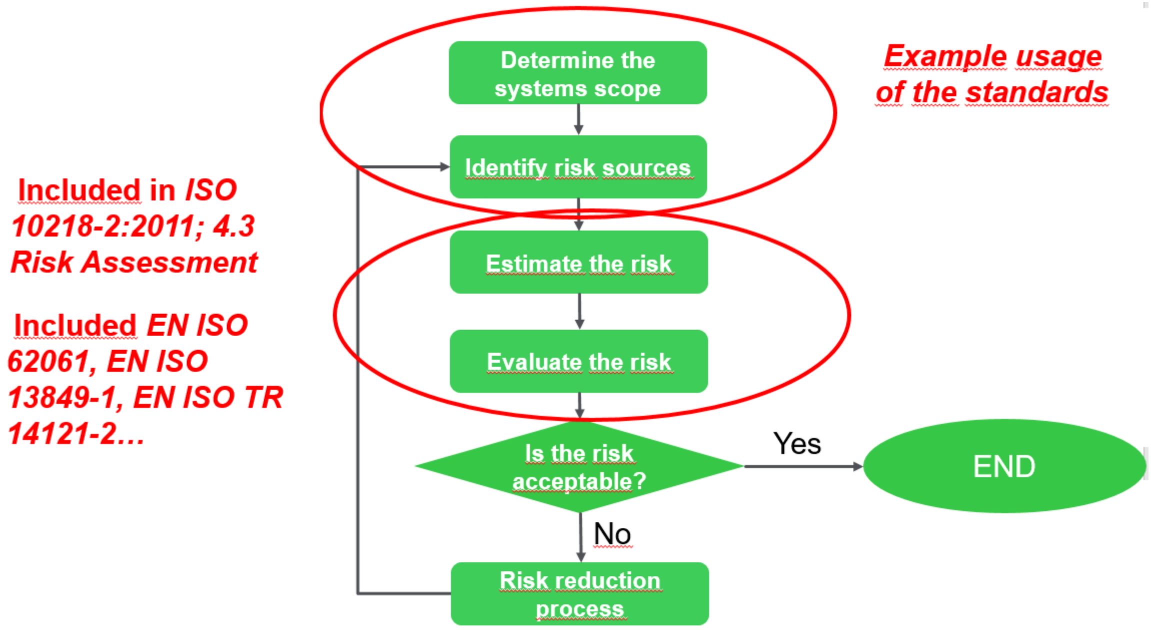

Figure 33: General risk reduction process structure with example usage of the standards

4.2 Determine system scope

The section 4.3. from ISO 12018-2 could be used to determine the systems scope. In this section Use limits and Space limits of the system are stated. For Use limits, the analysis of process sequences including manual intervention is executed. For the example application it is found from the *Workflow demonstration*- section. Also, the investigation to the required machine movement range, required space for operator tasks and other human intervention and required access for Space limits section is analyzed in the *Workflow demonstration*- section.

4.3 Identify risk sources

For example hazard identification there are 3 important points which are ISO 10218-2:2011; Annex A, ISO TS 15066; 4.3.2 Hazard Identification and ISO TS 15066; 4.3.3 Task Identification.

ISO 10218-2:2011 Annex A is including results from the hazard identification as executed in ISO 12100 and is giving guideline to recognize significant hazards.

ISO TS 15066; 4.3.2 Hazard identification is describing the structure and minimum requirements for the hazard identification execution.

ISO TS 15066; 4.3.3 Task identification is giving guidelines to identify the foreseeable task and hazard combinations and helps with structuring collaborative operations.

One risk in the example application is if the worker approaches too fast towards to the hazardous zone of the work cell and gets in the way of the moving robot as demonstrated in the picture below.

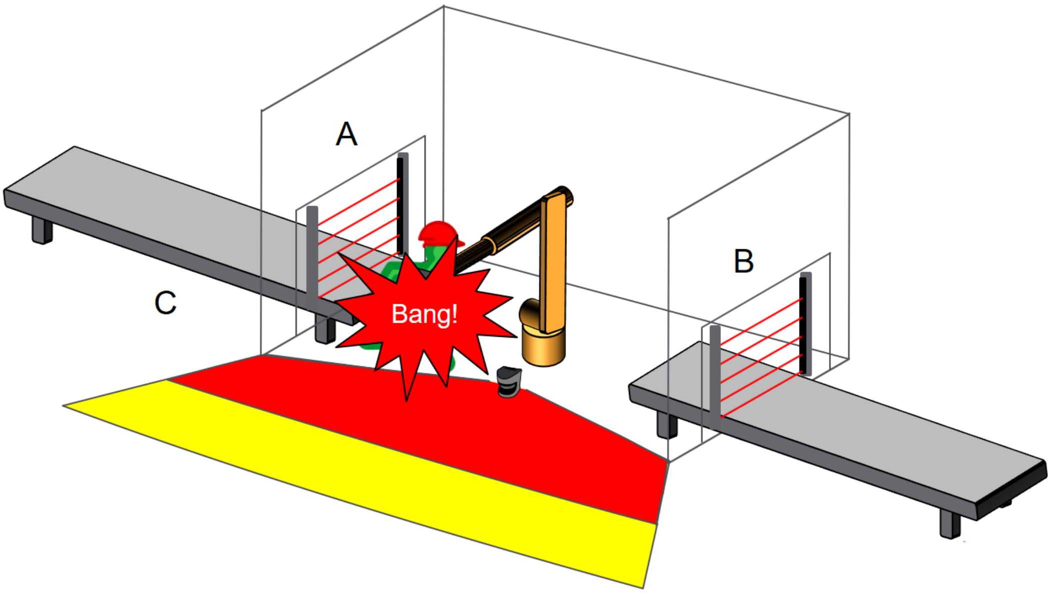

Figure 34: Too fast approach of the operator

4.4 Risk estimation and evaluation

For risk estimation and breaking the phenomena down to values, the following structure could be used as stated in the ISO 12100.

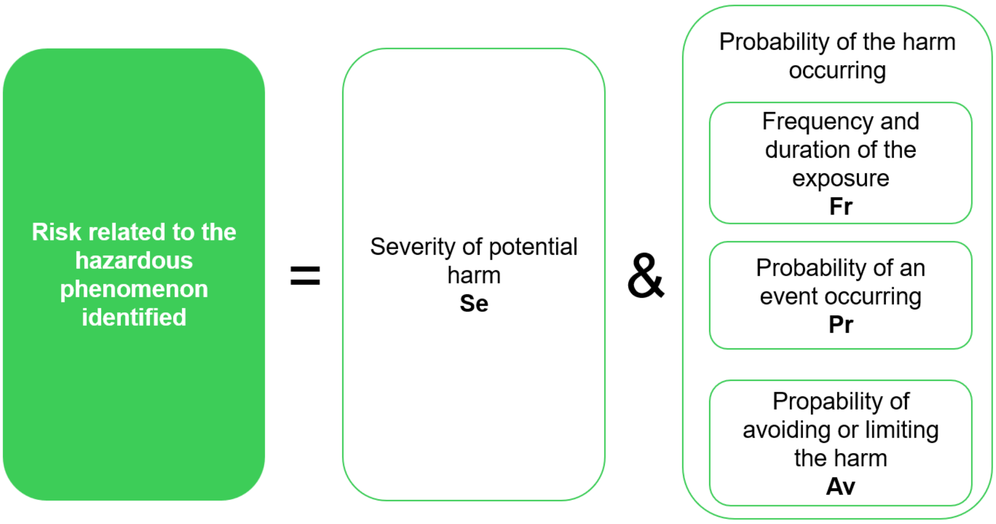

Figure 35: Risk Estimation structure form the ISO 12100 (Schneider Electric 2009.)

For numerical determination for example ISO 62061 could be used. In the following Figure the applicable points to the example hazard are pointed out.

Consequence	Severity Se
Irreversible: death, loss of an eye or an arm	4
Irreversible: shattered limb, loss of a finger	3
Reversible: requires the attention of a medical practitioner	2
Reversible: requires first aid	1

Frequency of dangerous exposure	Fr
≤ 1 hour	5
>1 hour... ≤ 1 day	5
> 1 day... ≤ 2 weeks	4
2 weeks... ≤ 1 year	3
> 1 year	2

Probability of occurrence of a dangerous event	Pr
Very high	5
Probable	4
Possible	3
Almost impossible	2
Negligible	1

Probability of avoiding or limiting the harm	Av
Impossible	5
Almost impossible	3
Probable	1

Figure 36: Risk analysis table (Schneider 2009.)

To continue risk estimation by ISO 62061 the determination of class of the probability (CI) of harm needs to be calculated. CI is calculated with the following formula;

$$Fr + \mathrm{Pr} + Av = CI$$

Equation 1: CI- class calculation (ISO 62061.)

With calculated values, the CI is 8. Together with the severity of the harm (Se), the value could be assigned to the SIL assignment matrix found from the standard. The red box is standing for the estimation result. (ISO 62061.)

Table A.6 – SIL assignment matrix

Severity (Se)	Class (CI)				
	3-4	5-7	8-10	11-13	14-15
4	SIL 2	SIL 2	SIL 2	SIL 3	SIL 3
3		(OM)	SIL 1	SIL 2	SIL 3
2			(OM)	SIL 1	SIL 2
1				(OM)	SIL 1

Figure 37: SIL assigment matrix (ISO

Also, the same kind of table could be found from the ISO TR 14121-2 without the SIL values, but giving out the level of risk as the table in ISO 62061.

Risk estimation

Document no.:
Part of doc. no:
☐ Preliminary risk estimation

Product:
Issued by:
Date:

Black area = High risk
Grey area = Medium risk
White area = Low risk

Consequences	Severity Se	Class CI (Fr+Pr+Av)					Frequency Fr		Probability Pr		Avoidance Av	
		4	5 - 7	8 - 10	11 - 13	14 - 15						
Death, losing an eye or arm	4						≥1 h	5	very high	5		
Permanent, losing fingers	3						< 1 h to ≥ 24 h	5	likely	4		
Reversible, medical attention	2						< 24 h to ≥ 2 w	4	possible	3	impossible	5
Reversible, first aid	1						< 2 w to ≥1 y	3	rarely	2	possible	3
							< 1 y	2	negligible	1	likely	1

Table 2: Risk estimation table. (ISO/TR 14121-2:2012, 18)

Also for the estimation diagram from ISO 13849-1 could be used. In the table, S stands for the severity of injury, F for frequency of and exposure to hazard and P for the possibility of avoiding the hazard or limiting harm. After conducting the Performance Level Required (PLr) indicates high-risk value. (ISO 13849-1:2008, 52.)

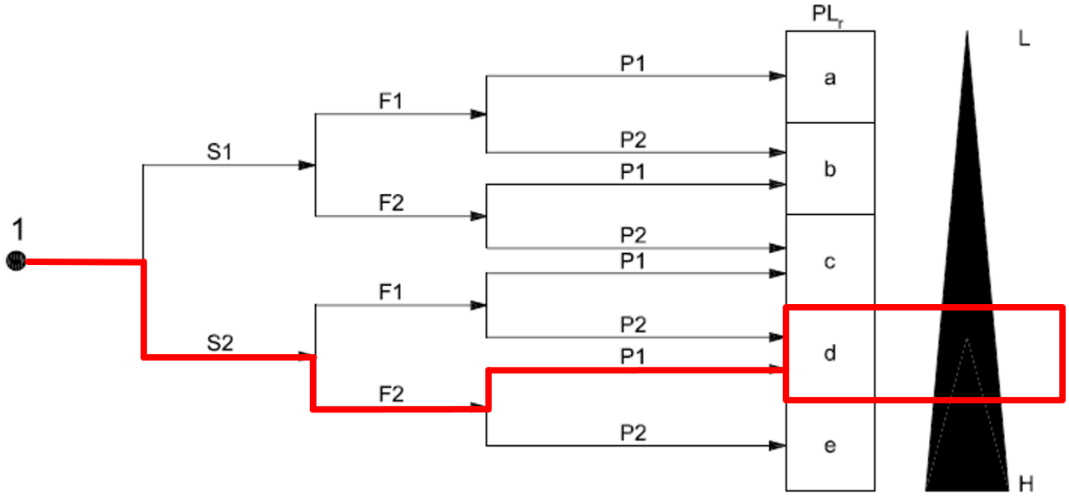

Figure 38: Risk estimation graph (ISO 13849-1:2008, 52.)

4.5 Risk reduction process

For the risk reduction to this type of risk, point b from the ISO TS 15066, 4.3.4 could be applied. ‘’Protective measures that prevent personnel from accessing hazard or control the hazards by bringing them to a safe state (e.g. stopping, limiting forces, limiting speed) before and the operator can access or be exposed to the hazard.’’ (ISO TS 15066:2016.)

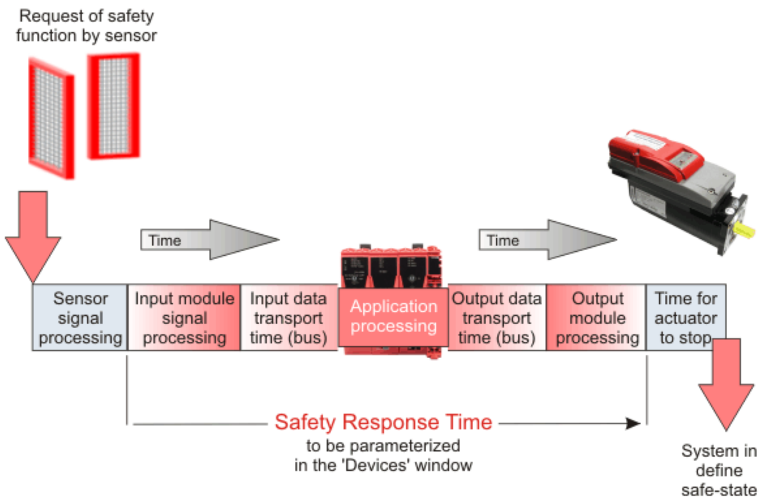

Figure 39: System stopping time (Schneider Electric 2010.)

To conduct the system stopping time needs to be calculated. For calculating the signal inside the example architecture 2, SoSafe Programmable is including Safety

Response Time Calculator, which is used to calculate signal processing time inside the modules.

For the TM5-input module, where *Protective fields* OSSDs were connected to the TM5- output module, the processing time was 49 milliseconds. The response time for the ReeR PHARO with a 150mm resolution is 0,06 seconds and for the example stopping time estimation for the robot with a payload of 10 kilograms it is 0,4 seconds. In total, the stopping time of the example architecture is 0,509 seconds.

For the safety distance (S) calculation the following formula could be used;

$$S = \left(K \times (T_m + T_s)\right) + Z_g + Z_r + C$$

Equation 2: Safety distance formula (ReeR 2015, 38.)

Here K is the approach speed, Tm is the stopping or run-down time of the machine, Ts is the response time of the PHARO, Zg is the general safety supplement (100mm), Zr is a supplement for a measurement error related to the reflection and C is a supplement for the prevention of reaching over. (ReeR 2015, 38.)

For given values, the result for the safety distance for risk is 2 114,4mm. By conducting this, the safety laser scanner could be used to prevent the fast approach to the hazardous area of the work cell, because the longest detection distance to the protective field is 4 meters.

5 Summary and cogitation

5.1 Future Prospects

Collaborative robotics is nowadays a trendy field in industrial manufacturing and continues to rise its potential because of the continuously more flexible and customizable production needs. The benefits of human-robot collaboration were introduced in the *Introduction*- section of this thesis. The developing and cheapening technology enables, for example, the broader implementation of machine vision.

With increasing industrial robot sales, inexpensive solutions with integrated safety will continue to be in the interest for small and medium sized companies. Integration of the most nowadays small force limited robots could be done by the workers by teaching the robot the motions by moving the robot's arm by hand. This kind of programming will also be interest with bigger payload robots.

Also, the development of ISO TS 15066 to a full standard is a foreseeable result from this direction of the technological development and the more generalizing applications in the market.

5.2 Results

This thesis gives the main guidelines for safety methods and introducesthe common technologies used for the safety of the human-robot collaboration in the industrial applications. Information was gathered from the newest standards and concepts and theapplications used by the manufacturers in the field of industry.

The overall workflow was kept consistent with good help from the host company, host university and the home university. The time was limited and the original plan to have a real robot in the demonstration application was not possible, due to the tight reservation schedule for a suitable delta- application, but the needed functionality was represented with satisfaction. The more dynamic workflow in the example application could have been reached, if the safety laser scanner had included more field sets.

When deriving the final feedback, the technical investigation seemed to have met the needs of the host company. The necessary research was done and the example application was established the way agreed. Also the example architecture had been tested successfully.

The thesis gives general information on the standards, technologies and example applications concerning the safety of the collaborative robotics in the industrial manufacturing.

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APPENDICES

List of standards appeared in the thesis:

ISO/TR 14121-2:2007 Safety of machinery – Risk assessment - Part 2: Practical guidance and examples of methods.

SS-EN ISO 12100-1:2003 Safety of machinery – Basic concepts, general principles for design – Part 1: Basic terminology, methodology.

DIN EN ISO 13849-1:2008-12 Safety of machinery – Safety-related parts of control systems – Part 1: General Principles for design.

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

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

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

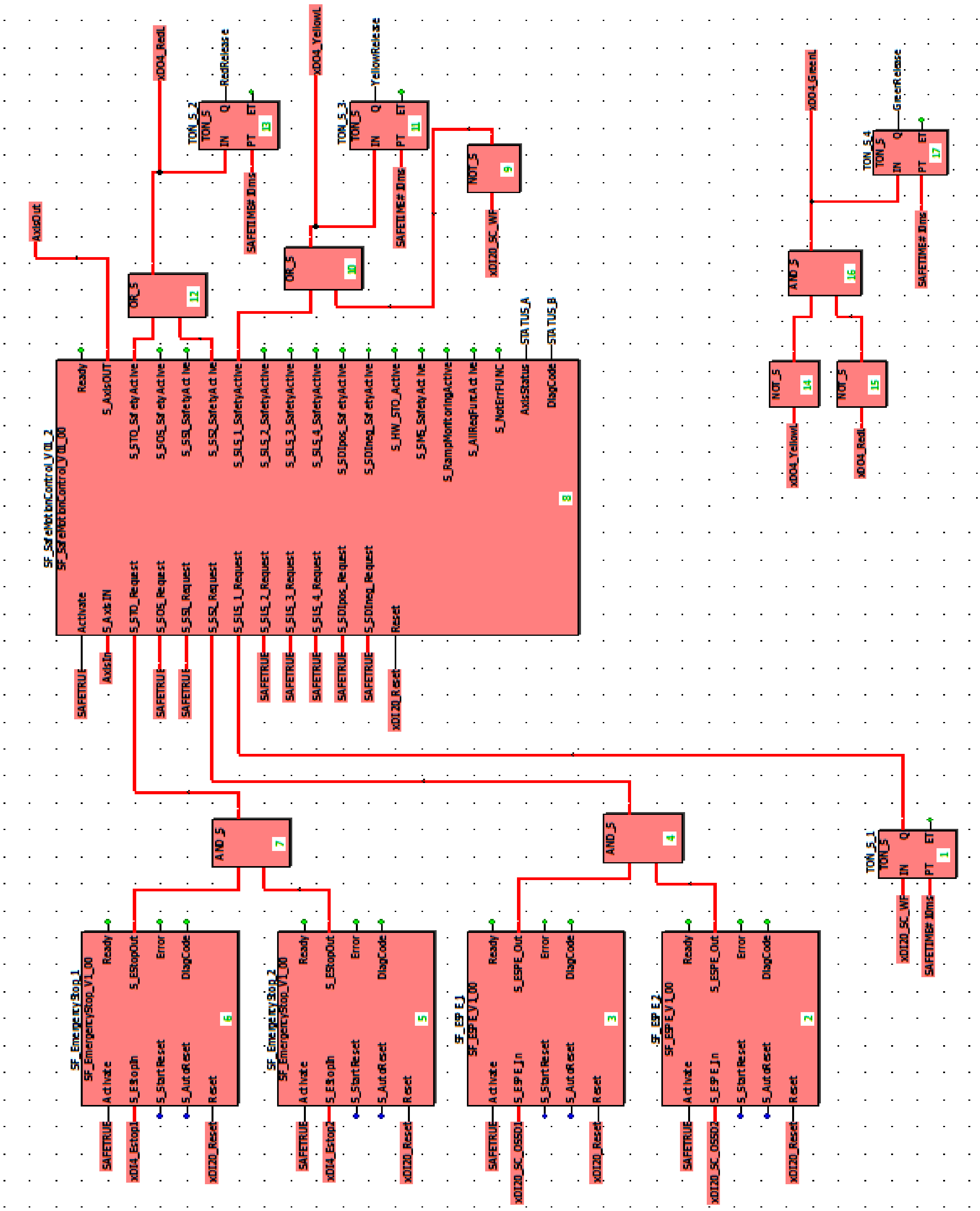

Figure 40: SoSafe Programmable: Example architecture 2 program block