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ACROBA

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D3.5 Safe Integration of Collaborative Robots

WP3

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1.5	2024.11.20	Final version	Zied Ghrairi

Disclaimer:

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Executive Summary

This document describes the approaches for the safe integration of collaborative robots. It contains the design of human robot collaborative applications resulted fromT3.3 and T3.4. The guidelines and safety procedures are presented in detail. In addition, the document describes how the performed effort (HRC model) in D2.5 is to be integrated at industrial level without affecting the safety of collaborative applications. A set of scenarios have been proposed, tested and validated based upon the implemented rule-based system (D2.5)

1 Introduction

The planning of industrial HRC applications involves a large number of individual tasks and is traditionally executed by a team with different areas of expertise. The design process of HRC applications, starting from the first sketch and finishing with the application running, requires a substantial engineering effort to fulfil the safety requirements as specified by the existing health and safety regulations and standards. The most relevant for industrial collaborative robotics include the ISO 12100 and the ISO 10218-1 and ISO 10218-2, as well as the technical specification ISO/TS 15066:2016, considering safety-related aspects of the application during the design phase. In particular, the ISO/TS 15066:2016 presents the safety requirements for each of the four basic types of collaborative operation (Safety-Rated Monitored Stop, Power and Force Limiting, Hand Guiding, Speed and Separation Monitoring). The basis for fulfilling these requirements is the concise process from process analysis until the selection and employment of adequate hardware and software technologies eliminating potential risks. Particularly when considering work situations where the workspaces of humans overlap with machines/robots/tools, a sound understanding of the process provides the key to an accurate safety requirements identification and technology selection. The collaborative pilot lines in ACROBA are prominent examples, where the interaction, productivity and safety issues have a significant relevance, thus technology choice is based on specific knowledge upon the industrial process.

2 Design of Collaborative Pilot Lines - Approach

Because the experience of the ACROBA use cases in designing safe applications with collaborative robots is limited, several workshops with different entities have been scheduled in order to design the ACROBA collaborative pilot lines. These consist of meetings with the experts from ACROBA industrial partners to gather relevant information and knowledge about the envisaged collaborative applications and meeting with associations such as the German entity DGUV – *Deutsche Gesetzliche Unfallversicherung* (Mr Bautz). The approach developed by ACROBA (Figure 1) has been evaluated by the DGUV and is considered as adequate for supporting collaborative environments. The comments, communicated from the DGUV, were related to:

- Checking the need to deploy such platforms as an additional safety layer, leading probably to affect productivity of the industrial company. DGUV has recommended the implementation of an additional layer enclosing the ACROBA platform. Due to the architecture of the ACROBA platform (use of ROS, skills, python programming language, Dockers), this layer should not be related to safety concerns/measures.
- Performing the mandatory risk assessment process to specify the adequate safety concept by eliminating potential hazards using the adequate mechanisms.
- Use of tools and toolkits (e.g. Cobot Planner) for estimating the maximum safe robot speed without exceeding the biomechanical limit values given in ISO/TS 15066:2016
- Enabling the changeability of the industrial system by selecting appropriate mechanisms

The recommendations of the DGUV have been reported and taken into consideration for the design of the collaborative pilot lines. The following figure illustrates the overall concept refined with the support of the DGUV safety expert. More details about the concept are given in D2.5.

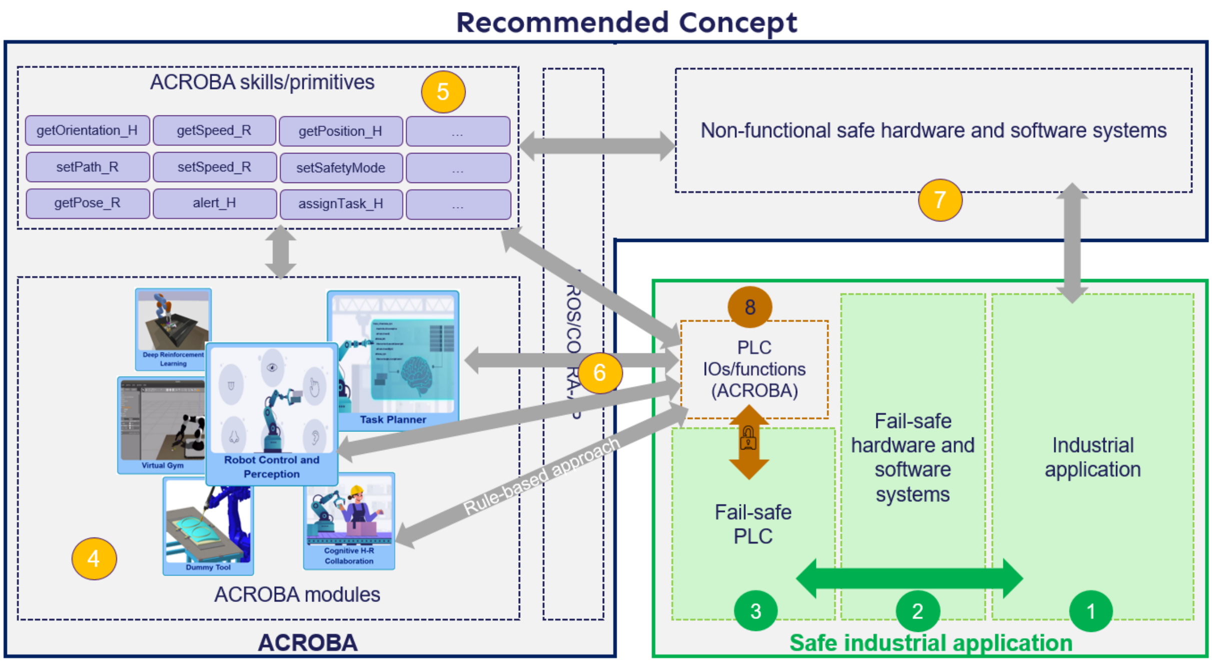


Figure 1: Recommended concept for interplay between safety and ACROBA collaboration capabilities

The worked-out concept overview includes eight sections, described as follows:

- Section 1, 2 and 3 represent the envisaged safe industrial application such as the IKOR and ICPE pilot lines including the industrial process and all required hardware and software components ensuring the safety of the collaborative robotic system.
- Section 4 and 5 represent the ACROBA platform components (modules and skills/primitives).
- Section 6 deals with the communication technologies that can be adopted to enable to exchange of data, information and knowledge (DIK) between the ACROBA platform and the safe industrial application.
- Section 7 constitutes the set of potential systems (sensors, actuators, software tools…) that could be used to support the provision of additional capabilities not only for enhanced human-machine interaction but also for monitoring and assessment of human factors (wellbeing, workload, ergonomics, …).
- Section 8 represents the required extension at PLC level to enable the exchange between ACROBA and the safe industrial application. It consists of set of variables (e.g. IOs) that need to be created and managed by the safety expert of the industrial application.

2.1 International standards relevant to Human-Robot Collaboration

When considering the proper implementation of collaborative applications, it is helpful to have an overview of the relevant standards. The hierarchy of standards of safety of machinery is shown below in Figure 2.

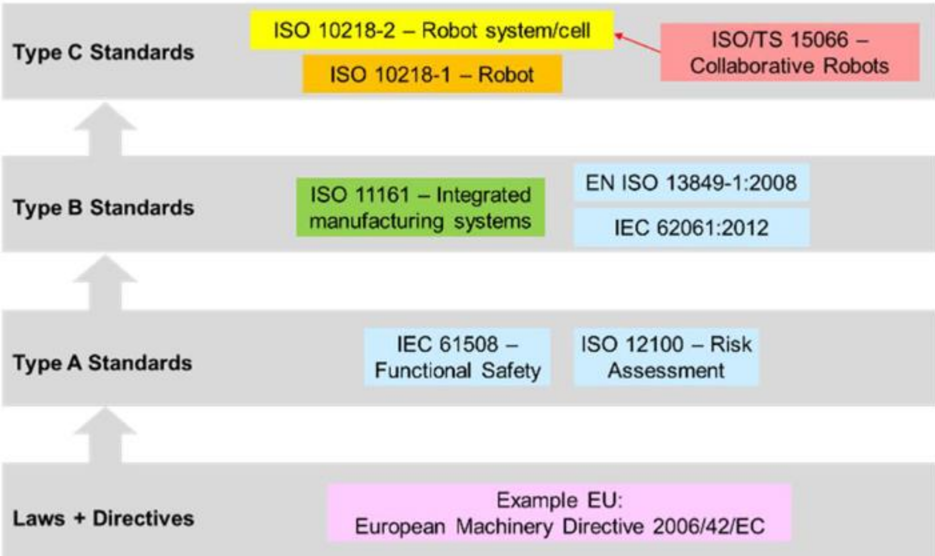


Figure 2: Overview of standards relevant to human-robot collaboration[1]

Following harmonized standards serves the ultimate purpose of utilizing the associated presumption of conformity with the European Machinery Directive. Since there is a product-level (type C) standard for the safety of industrial robots in ISO 10218-1, one can as a rule turn to this document for guidance in the design of the safety features for industrial robots and to ISO 10218-2 for the safety features of robot systems. Collaborative robots and collaborative applications, how- ever, have new properties for which there is insufficient guidance in the parts of ISO 10218. To fill this gap, the necessary additional information for designing safe collaborative applications has been compiled and included in ISO/TS 15066:2016. Since HRC applications can bring the human operator and the collaborative robot quite close to one another, a proper risk assessment conducted according to ISO 12100 is of utmost importance.

2.2 Recommendation Design Steps

For the implementation of new robot applications, as mentioned by the DGUV, risk assessment is considered a crucial process. In non-collaborative industrial applications, the risk assessment is typically created late in the implementation process, since fences and auxiliary

[1] https://wpo-altertechnology.com/es/functional-safety-nuevos-escenarios-de-implantacion-seguridad-funcional/

safety equipment eliminate most of the hazards. However, for the collaborative industrial robots (cobots) it is important to consider the safety-strategy early in the implementation process (safety-by-design), to secure that safety requirements are part of the overall requirement specification of the solution. Since cobots often operate without fences, contact situations with the operators are likely to occur. The safety standard ISO 10218-2:2011 describes three phases, which must be followed in the design process for safety. In prioritized order: Phase 1 - Eliminate hazards by design, Phase 2 - Mitigate risks by applying additional safety measures (safety functions, limit values, sensors, etc.) and Phase 3 - Inform and train the person that will work with the robot.

The following chart shows the general steps of a risk assessment. The description of each step is given in the next chapter, in parallel to the results achieved for the IKOR and ICPE pilot lines.

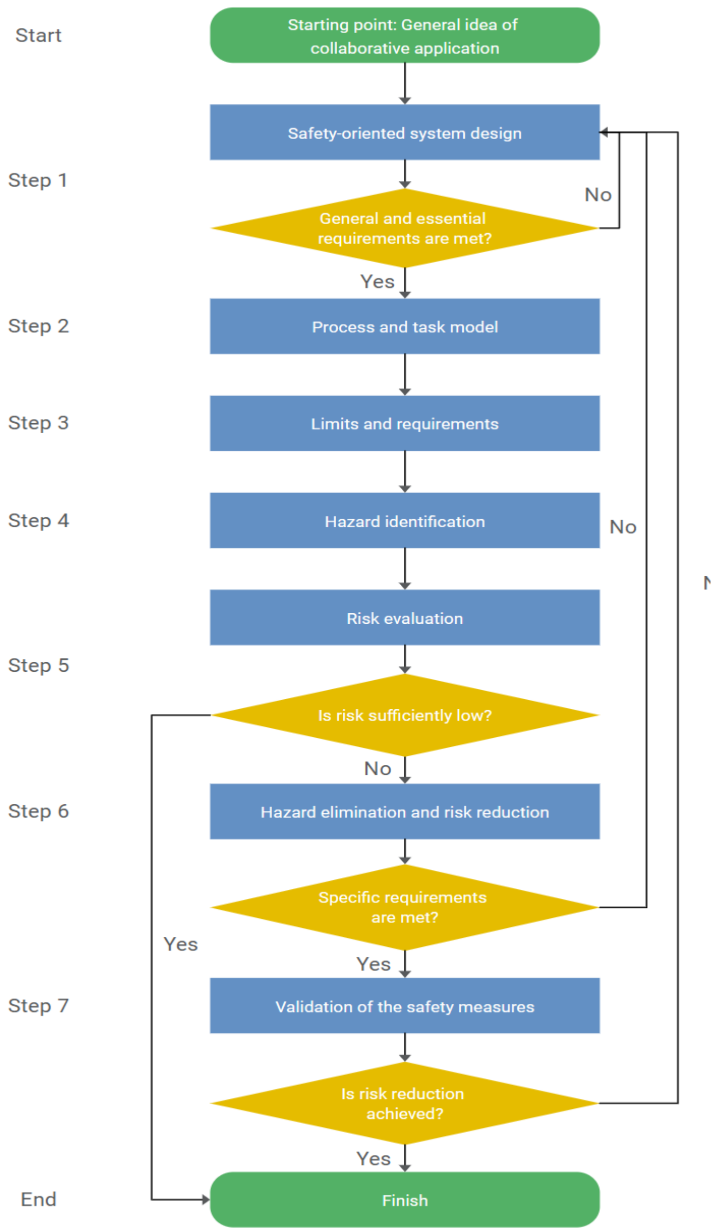


Figure 3: Steps of a risk assessment (Source: ISO 12100)

One of the comments from the meeting with the DGUV is related to the use of supporting tools such as the Cobot Planner. The cobot planner supports users of collaborative robots in estimating safe speeds. A safe speed is the maximum speed for a robot so that it does not exceed the biomechanical load limits in the event of unintentional contact with a human.

Depending on the hazardous situation, unintentional contact can mean jamming or impacting a part of the human body. In order to achieve the most accurate assessment possible by the Cobot Planner, it is necessary that the user describes the hazards of the HRC application under consideration with sufficient precision using the tools of the Cobot Planner. The safe speeds provided are estimated values that must be checked on the real robot using suitable methods. The use of the Cobot Planner requires that the users are familiar with the following regulations and standards:

- DIN ISO/TS 15066: Robots and robotic devices - Collaborative robots (ISO/TS 15066:2016)
- DGUV information: Collaborative robotic systems (FB HM 080[2])

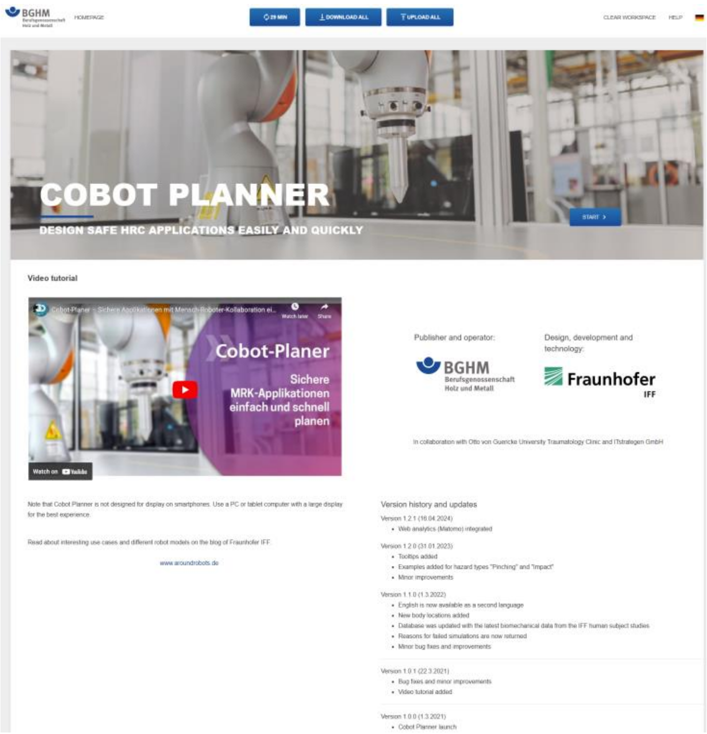


Figure 4: Recommended toolkit for safe (max) speed estimation[3]

[2]https://www.dguv.de/medien/fb-holzundmetall/publikationen-dokumente/infoblaetter/infobl_englisch/080_collaborativerobotsystems.pdf

[3] https://www.cobotplaner.de/

2.3 Safeguarding Modes

In order adequate safety measures to be identified, there is a need to focus on a formal description of the whole process. A detailed process description (Step 2) will support the decision-making phase. For Coexistence, safeguarding modes except hand-guiding can be applied because humans do not need access to the area around the robot. In sequential cooperation the workspace of the robot and the human overlap, which means that fences cannot be installed anymore. During parallel cooperation, a safety-rated monitored stop is not feasible because the robot should move while the human is in the shared workspace. In the highest interaction level: collaboration, physical contact between the robot and the human is required and therefore only the safeguarding modes Power and Force Limiting and hand-guiding are possible.

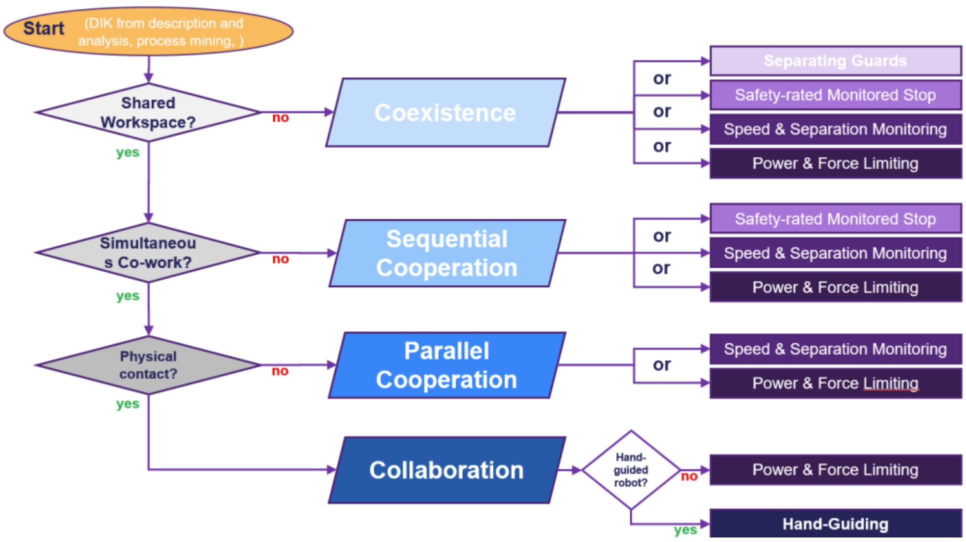


Figure 5: From Interaction Level Assessment to Safeguarding Modes Assignment (Behrens, 2015)

Table 1 presents the four basic types of HRC operations and the respective mains means of risk reduction.

Table 1: ***Overview of the four basic types of HRC operation***

Type of collaborative operation	**Main means of risk reduction**
Safety-rated monitored stop (SRMS)	Supervised standstill of robot when operator is in collaborative work space
Hand guiding (HG)	Robot motion only through direct guiding input of operator
Speed and separation monitoring (SSM)	Robot motion only when separation distance above protective separation distance. More details are given in chapter 2.4
Power and force limiting by inherent design or control (PFL)	In contact events, robot can only exert harmless levels of static and dynamics forces

2.4 Protective separation distance calculation

According to ISO/TS 15066:2016, the protective separation distance is defined as the shortest permissible distance between any moving hazardous part of the robot system and any human in the collaborative workspace. It can be calculated based on the concepts used to create the minimum distance formula in ISO 13855, modified to take into account the following hazards associated with speed and separation monitoring.

- In constant speed setting situations, the worst-case value for the safety-rated monitored speed of the robot is used. This value depends on the application and is validated by the risk assessment. The constant limit value shall be set as a safety-rated monitored speed according to ISO 10218-1:2011, 5.6.4, to ensure the constant limit is not exceeded.

- In variable speed setting situations, the speeds of the robot system and of the operator are used to determine the applicable value for the protective separation distance at each instant. Alternatively, the maximum allowed robot speed can be determined based on operator speed and actual separation distance between the robot and operator. The control function to accomplish this shall comply with ISO 10218-2:2011, 5.2.2.

- The stopping distance of the robot is determined according to ISO 10218-1:2011, Annex B.

The protective separation distance, S_p, can be described by following Formula:

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

Where

- $S_p(t_0)$ is the protective separation distance at time t_0; t_0 is the present or current time;
- S_h is the contribution to the protective separation distance attributable to the operator's change in location.
- S_r is the contribution to the protective separation distance attributable to the robot system's reaction time;
- S_s is the contribution to the protective separation distance due to the robot system's stopping distance;
- C is the intrusion distance, as defined in ISO 13855; this is the distance that a part of the body can intrude into the sensing field before it is detected;
- Z_d is the position uncertainty of the operator in the collaborative workspace, as measured by the presence sensing device resulting from the sensing system measurement tolerance;
- Z_r is the position uncertainty of the robot system, resulting from the accuracy of the robot position measurement system.

More details about the value estimation of the protective separation distance are given in the technical specification (ISO/TS 15066:2016, pages 11-14)

3 Execution of Recommended Steps and Results

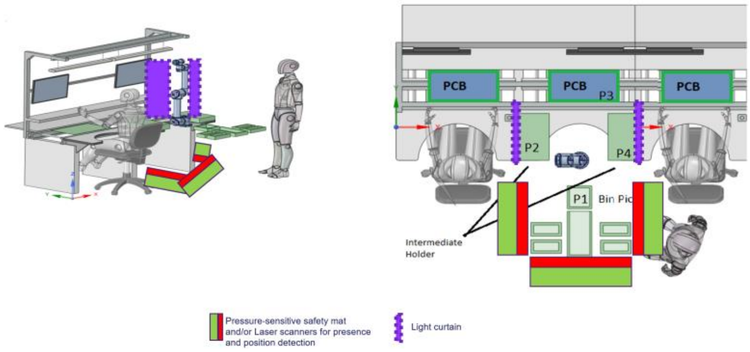
This chapter deals with the design of the ACROBA collaborative pilot lines. For that purpose, the recommended steps have been executed. It is important to note that all these steps including the final validation of the designed system need to be verified by the experts of the industrial partners in collaboration with professional safety consultants or accredited official bodies. The presented design results are experimental and require further validation before operational use.

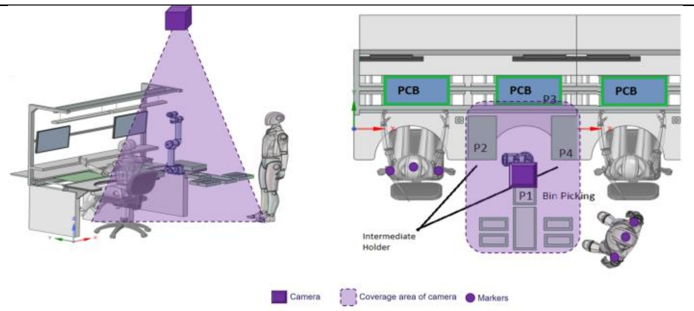
3.1 Safety-oriented system design

Step description: The objective of this step is to find a safe design for your collaborative application that satisfies the general, essential, and specific requirements given by the applicable directives and standards. As the workflow chart shows, it might be possible to return to this step during the entire process from different steps whenever the system does not meet the applicable safety requirements at several exit points of the process. For reducing the design effort, it is helpful to consider all applicable safety requirements from scratch. For instance, one should use only products for which the supplier can provide a declaration of conformity and/or of incorporation. In case the experience in designing safe applications with collaborative robots is little, reach out to professional safety consultants or accredited official bodies to achieve quick results and to reduce the number of design iterations. Once the system satisfies the general and essential safety requirements as specified by the directive to be used, proceed with the next step.

This step is an iterative process. After the first iteration, the partners started to check the feasibility of the generated/recommended safety concepts based upon best practices at industrial and at academic level as proof-of-concept. According to the performed analysis and based on the executed workshops with the industrial partners, the following safety concepts have been proposed and discussed in detail. The final setup and settings of the HRC workplace are described in detail in D5.5.

Table 2: Potential safety concepts for collaborative pilot lines – first iteration

Use-case	Technologies	Safety concept, graphical overview
IKOR	• Light curtains with safety mat/laser scanners	

<table>
<tr><td>IKOR</td><td>• Camera-based human detection and activity recognition:</td><td>
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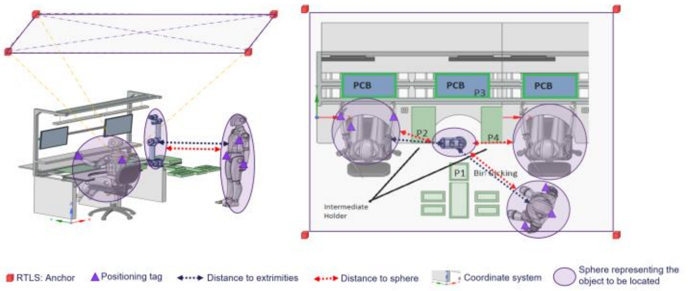
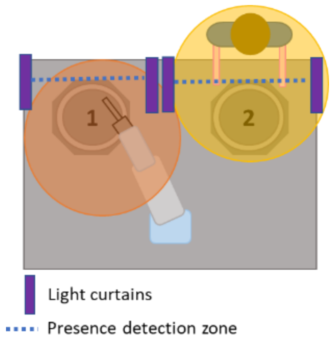
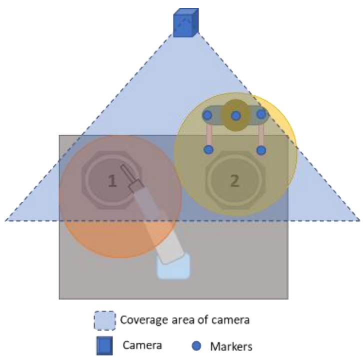
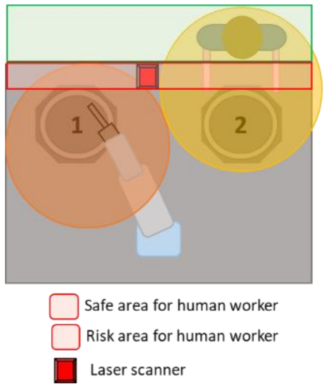
<tr><td>IKOR</td><td>• Indoor positioning sing RTLS</td><td>
</td></tr>
<tr><td>ICPE</td><td>• Light curtains
• Robot path control
• Robot speed control
• Alert mechanisms</td><td>
</td></tr>
<tr><td>ICPE</td><td>• Safe Camera
• Robot path control
• Robot speed control
• Alert mechanisms</td><td>
</td></tr>
</table>

ICPE	• Laser scanner (s) • Robot path control • Robot speed control • Alert mechanisms	

After several iterations of the recommended steps (Section 2.1) for the design of HRC applications and in collaboration with safety experts (accredited associations) from different participant partner's countries (Spain, Romania, Italy and Germany) following figures illustrates worked out layouts/safety concepts (source: D5.5). The electrical layout of the HRC systems is given in the Annexes (see the last sections of this document).

The partners IKOR and ICPE selected different safety measures based upon their needs and requirements. For the IKOR application scenario, the following figure illustrates the architecture and the selected technologies. According to the worked-out ACROBA overall concept (Figure 1), the two sections, ACROBA and safe industrial application and related components can be recognized.

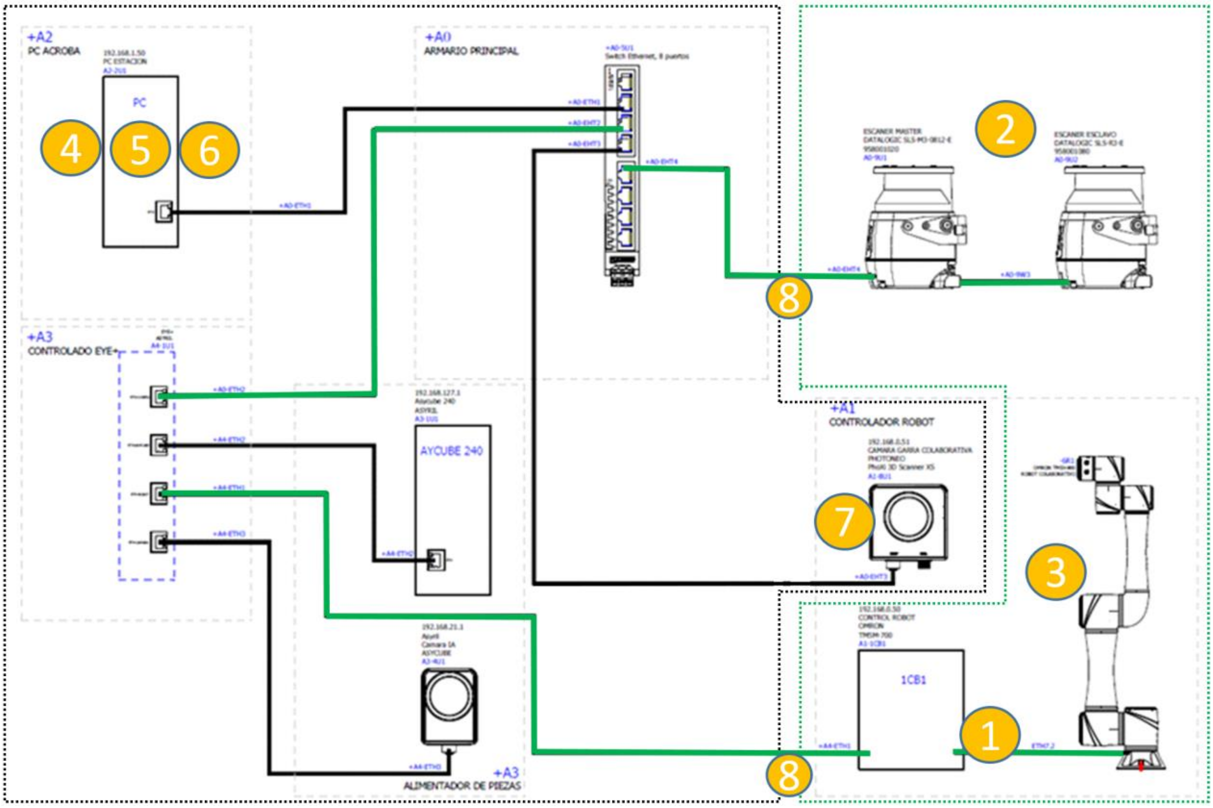


Figure 6: IKOR –control architecture including selected safety sensors (scanners)

The protective separation distance (also called safety distance) between human operators and robot systems is calculated based upon the formula given by the technical specification ISO/TS 15066:2016. This process has been executed by the partner IKOR and it is described in detail in D5.5, page 28.

The partner ICPE decided the use of light curtains to ensure the safety of the human operators and to enable human robot collaboration. The functional-safe Light curtains are installed to detect the intention of the human operators to enter the robot space.

Figure 7: Safety light curtains – bonding use-case (left), winding use-case (right)

The approach consists of reducing the robot speed to a safe threshold, enabling continued operation without fully stopping the process and fostering a collaborative environment between human and robot. report the installation of the light curtains in the bonding and winding cells.

Figure 8: ICPE winding safety light curtain – red mode: entering the robot space

3.2 Process and Task Model

Step description: Create a process description for all relevant life cycles of the application. Typical life cycles are but not limited to design, installation, normal operation, etc. It is necessary to consider each life cycle in a separate risk assessment. For clarity and simplification, it might be helpful to start with the life cycle normal operation. The process description for a life cycle should consist of a list with steps of a reasonable resolution that represents the process to its full extent, including a distinction of the actions done by the human, collaborative robot, and other machinery. For instance, set up the process model in tabular form, in which a row corresponds to a specific process step or action. Then, extend the table with two additional columns, the first for noting the form of interaction between robot and operator and the second to determine the role of the involved humans. Summarize all consecutive operations, which have the same form of collaboration operation into so-called task groups and assign a distinctive title to them.

Based on the requirements in ISO/TS 15066:2016, transitions between non-collaborative operation and collaborative operation are particularly critical parts of a collaborative application. These shall be designed such that the robot system shall not pose unacceptable risks to the operator during the transition.

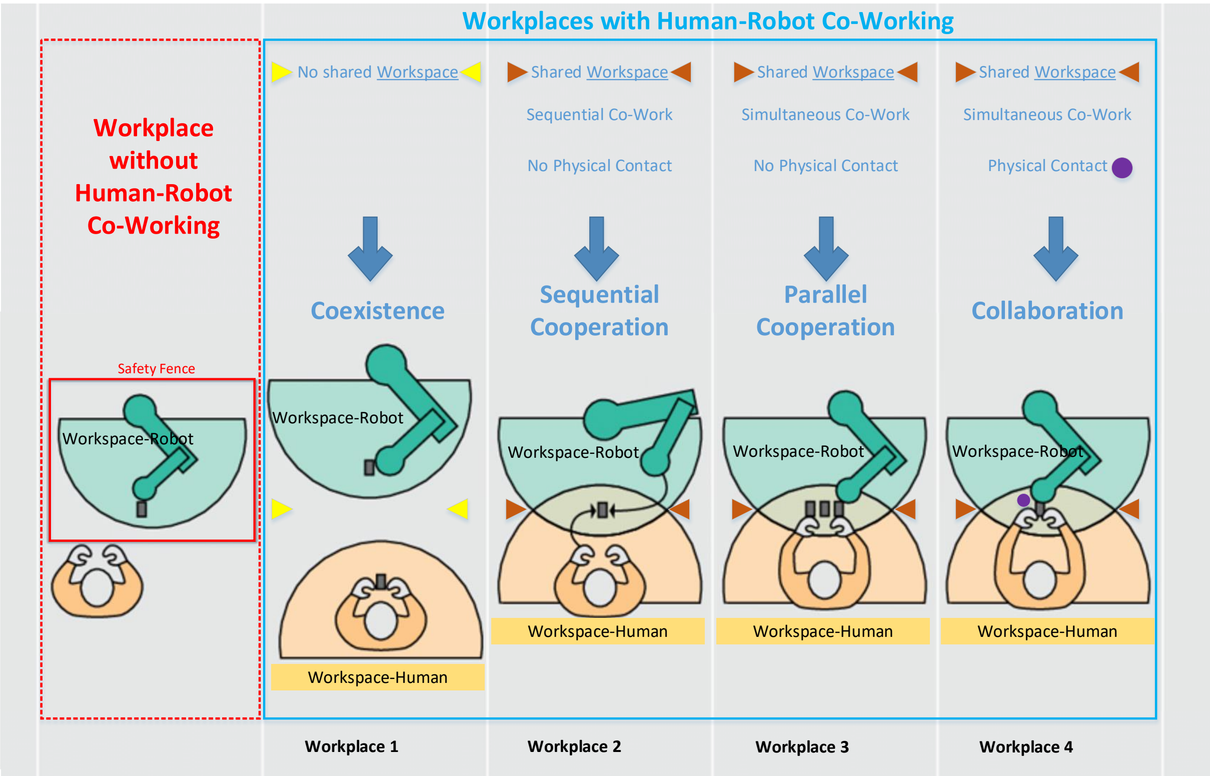


Figure 9: Workplace types - modelling approach (first iteration)

In order this important requirement to be addressed, the identification of the interaction type and of the steps in which a transition is taken place needs to be performed. For a detailed process modelling, the partner BIBA has adopted and extended the REFA method, widely used for the description of industrial processes, and worked out a document (guideline), helping the industrial partners to describe the processes/tasks.

Manual and automated Scenarios						Human-Robot Co-Working Scenarios			
• Task performed without human and robot	• Human operator waiting for next task	• Human operator is performing a task manually	• Human operator is performing a task manually • Robot is inactive	• Robot is performing a task	• Robot is performing a task • human operator is waiting for next task	• No shared Workspace	• Shared Workspace • Sequential Co-Work • No Physical Contact	• Shared Workspace • Simultaneous Co-Work • No Physical Contact	• Shared Workspace • Simultaneous Co-Work • Physical Contact
Automated (A0)	**Idle (I)**	**Manual (M1)**	**Manual (M2)**	**Automated (A1)**	**Automated (A2)**	**Coexistence (C1)**	**Sequential Cooperation (C2)**	**Parallel Cooperation (C3)**	**Collaboration (C4)**

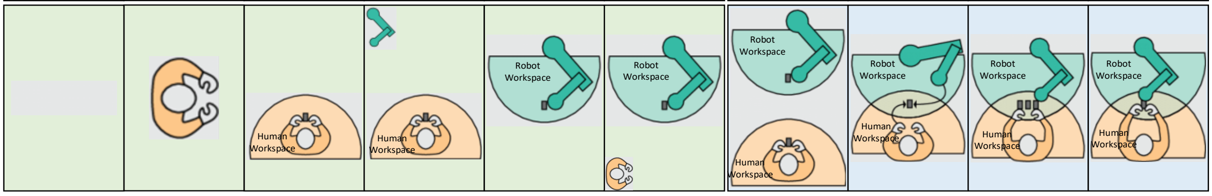


Figure 10: Workplace types - modeling approach (second iteration)

The collaborative pilot line partners have been asked to describe their future applications. Tasks (process steps) should be described in detail to extract relevant information related to:

- Interaction level: Onnasch et al. (2016) distinguish between coexistence, cooperation, and collaboration as forms of interaction between human and robot. The involved humans can take over the roles of supervisor, operator, collaborator, cooperator and bystander during the interaction. (Onnasch, Maier und Jürgensohn 2016). Identifying the interaction level helps to take corresponding decisions towards the safety strategy to be adopted at each task level, if possible.
- Safety issues: identification of potential hazards situations and hazard type
- Identification of adequate safety strategies: separating guards, safety-related monitoring stop, speed and separation monitoring, power and force limiting
- Requirements specification: which requirements should be taken into consideration and fulfilled?
- Technology selection: identification of potential technologies for ensuring human safety

- Process redesigning capabilities: e.g., tasks merging, task allocation (for human, for robot), …

The recommended process description approach requires three description forms: text, graphics, and symbols. The combination of all these forms will not only enrich the description but also the understanding of the ACROBA processes and the gain of findings towards collaborative operations and potential hazards.

IKOR pilot line

According to the approach presented by BIBA, several workshops have been initiated with the ACROBA partner IKOR. The outcomes of the workshops are illustrated in this chapter. The description (see Figure 11, Figure 12 and Figure 13) and the analysis of the IKOR pilot line reveals interesting findings (IKOR Fx) mainly related to the interaction of the humans (operator 1 and operator 2) with the robot system.

Tasks such as T3, T4, T7, T10, T11, T12, T13 and T15 are considered as tasks in which human operators and robots share the same workspace.

	ACROBA Partner	IKOR
	Use-case name	Assembly of electronic components
	Process detailed description (text)	The process described in this document aims to detail the assembly sequences of PTH components in a production process for the manufacture of electronic printed boards. Its particularity is that a robot takes part in the assembly of components in the same work line where human operators work, and must perform its operations sequentially, and at a balanced work flow.
	Process time (s)	TBD
	How many tasks in the process	21

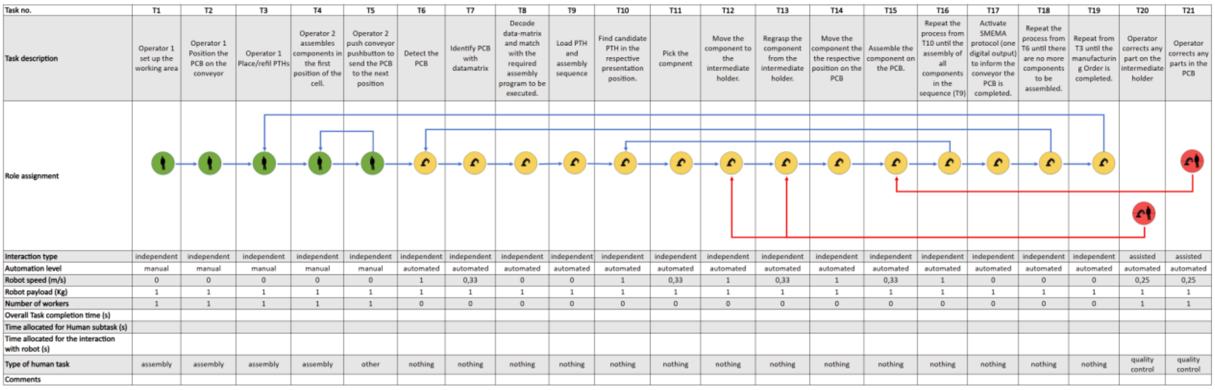
	Description item	**Description**
1	Work description	Assembly of THT components into a PCB
2	Workflow	Decode the assembly sequence of THT parts, Bin picking the parts from a vibratory hopper, placinf the parts into a regrasping intermediate holder, and assembling the parts into their respective position in the PCB.
3	Input	The bare PCB arrives from the conveyor. THT components are provided in bins to the vibratory hopper. The robot can access to a Database where the assembly sequence has been previously programmed.
4	Output	The PCB moves to the next station with all the THT components assemblled.
5	Human	Operator 1 : the one who is standing. He is in charge of seting up the cell and refilling of components when it is required. Operator 2 : the one seated on the left. He is in charge of assembling some PTH components and to feed the robotic cell.
6	Tools and equipment	The robot only needs one gripper with force control.
7	Environmental influences	The assembly line is located inside an industrial plant with regulated environmental conditions, humidity, temperature, lighting level, etc.

Figure 11: IKOR Process description - according to the REFA method

			No	Sequence phases	Remarks	Possible situations	BIBA recommendation
			T1	Operator 1 set up the working area	The robot should remain in a known rest position when not processing any assembly programs. This position should allow the operator to access common working areas without moving the robot, and should give the operator confidence that no action is being taken by the robot.	It may happen that the operator enters the robot work area and the robot state machine assumes that he is in a different execution cycle from the set-up. A third operator may be present to assist in set-up tasks.	
			T2	Operator 1 Position the PCB on the conveyor	Operator places PCB to be assembled at the entry of the conveyor	A failure of the PCB detector on the conveyor may occur, causing the PCB to move to the robot's working position before it is due. The operator may intercept the PCB as it moves along the conveyor in order to stop it or modify its position at any time.	Robot starts working as sson as the PCB reachs a specific position Pgo (quarantine area). OP1 has the ability to react until Pgo
			T3	Operator 1 Place/refil PTHs	Operator P1 places the raw material into the bins of the robotic Cell. P1 Operator places the raw material into the bins of the manual assembly position.	It may happen that the operator gets confused about the position of the electronic parts to be assembled by the robot, for example, interchanging by mistake a type of part in one of the component presentation mechanisms. It may happen that the operator fills in any of the presentation mechanisms with components during the robot's work execution time.	**Safety issue: sensor needed to detect the presence of the human (hands) in robot area. Camera / light curtains. Robot speed control**
			T4	Operator 2 starts production in the first position of the cell.	Operator 2 starts production by assembling the components that correspond to the first position of the cell, i.e. manually assembled components.	The robot can use this time to prepare material, i.e. take components from any of the unstructured presentation mechanisms and place them on the structured intermediate support.	**can:???** **Robot should avoid entering the OP working area. Speed and trajectory should be studied.**
			T5	Operator 2 push conveyor pushbutton to send the PCB to the next position	Conveyor moves the PCB to the robot assembly position P3	The transitions between previous task (material preparation) and the PCB assembly process would be conditioned by the detection of the PCB on the conveyor, which could startle the operator working next to the robot.	
			T6	Detect the PCB	The robot is informed through the SMEMA protocol (a digital input) that a new PCB is waiting to be assembled.	The PCB stop detector on the conveyor may fail causing the PCB to jump to the next workstation.	productivity issue: Redundancy-based approach in detecting a PCB at specific place
			T7	Identify PCB with datamatrix	The robot should look for a datamatrix on the PCB, what means the robot should move around the PCB area. P3	The robot may not be able to read the datamatrix code, for example due to glare or interference on the code, and therefore the intervention of operator 1 would be necessary to "present" a datamatrix code to the robot in a more favourable reading position.	**Set time limit for reading datamatrix code** **Hand guiding: the operator takes the PCB and places it at specific position, moves the robot to this position, places the PCB again in PCB area P3. Hand guiding reactivated manually**
			T8	Decode data-matrix and match with the required assembly program to be executed.	Robot doesn't move.	In case the execution time of this task takes too long or an error occurs that is not noticed by operator 1, he may misinterpret a different state of the robot execution cycle, and interact with it in a dangerous way, (e.g. by re-offering the datamatrix code in a more favourable reading position).	
			T9	Load PTH and assembly sequence	Robot doesn't move.		
			T10	Find candidate PTH in the respective presentation position. P1	The robot shall move to the presentation position of the respective component, i.e. to the vibratory bowl of the Bin Picking system. P1	It may happen that the robot collides with an operator who is refilling components.	**Human detection mechanisms (light curtains, camera), speed control**
			T11	Robot picks the compnent	From all the components that could be into the Bowl, the robot picks up the component proposed by the bin picking Skill. P1	It may happen that the **operator?** removes or relocates a component whose position may be hindering the robot's picking process, and this may occur at robot run-time.	**Human detection mechanisms (light curtains, camera), speed control**
			T12	Robot moves the component to the intermediate holder, P2 or P4.	Here, I am assuming that the robot can have two intermediate zones where components can be placed, P2 and P4.	It may happen that the robot collides with an operator who is realocating components to facilitate te job to the robot.	**Human safety consideration in Robot trajectories design.** **Human detection mechanisms (light curtains, camera), speed control**
			T13	Regrasp the component from the intermediate holder, P2 or P4.		It may happen that the **operator?** removes or relocates a component whose position may be hindering the robot's picking process, and this may occur at robot run-time.	**Human safety consideration in Robot trajectories design.** **Human detection mechanisms (light curtains, camera), speed control** **flexible robot run time (sequences): not necessary**
			T14	robot moves the component to the respective position on the PCB P3			
			T15	Assemble the component on the PCB. P3		It may happen that the robot collides with the PCB and a fragment of the PCB is ejected and hits one of the operators close to the robotic cell.	safety clothing (e.g. goggles, ...), no sensors needed
		c Iterations	T16	Repeat the process from T10 until the assembly of all components in the sequence (T9)		**Where is the robot stopped? P3-T15**	
			T17	Activate SMEMA protocol (one digital output) to inform the conveyor the PCB is completed.	Conveyor will move the PCB to the next station, and will also present a new PCB to be assembled if previous operator has already finished its task.	It may happen that the PCB derails or slips on the conveyor, not moving as it should.	Productivity issue
	b Iterations		T18	Repeat the process from T6 until there are no more components to be assembled.			
a Iterations			T19	Repeat from T3 until the manufacturing Order is completed.			
			T20	Operator corrects any part on the intermediate holder P2 or P4.	This task can be initiated by the operator 2 at any time during the operation of the robot. At his discretion, the operator can correct the position of the parts on the intermediate support to facilitate the robot pick-up.	Interruption at any time during the above-mentioned sequence of tasks.	already considerd during iterations, T11,T12,T13. This not a task that need to be described
			T21	Operator corrects any parts in the PCB P3	This task can be initiated by operator 2 at any time during operation of the robot. At his discretion, the operator can correct the position of parts on the PCB that is in the process of assembly, for example, to resolve the fact that a component has moved out of place undesirably.	Interruption at any time during the above-mentioned sequence of tasks.	

Figure 12: Tasks description and first analysis of IKOR process steps T1-T21 - according to REFA method

The following figure illustrates the outcomes of this step. The involved partners (BIBA, SIGMA, IMR, BFH and IKOR) have identified the need of safety measures to implement the envisaged application.



Task no.	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Task description	Operator 1 set up the working area	Operator 1 Position the PCB on the conveyor	Operator 1 Place/refil PTHs	Operator 2 assembles components in the first position of the cell.	Operator 2 push conveyor pushbutton to send the PCB to the next position	Detect the PCB	Identify PCB with datamatrix	Decode data-matrix and match with the required assembly program to be executed.	Load PTH and assembly sequence	Find candidate PTH in the respective presentation position.
Role assignment										
Interaction type	independent	independent	independent	independent	independent	independent	independent	independent	independent	independent
Automation level	manual	manual	manual	manual	manual	automated	automated	automated	automated	automated
Robot speed (m/s)	0	0	0	0	0	1	0,33	0	0	1
Robot payload (Kg)	1	1	1	1	1	1	1	1	1	1
Number of workers	1	1	1	1	1	0	0	0	0	0
Overall Task completion time (s)										
Time allocated for Human subtask (s)										
Time allocated for the interaction with robot (s)										
Type of human task	assembly	assembly	assembly	assembly	other	nothing	nothing	nothing	nothing	nothing
Comments										

Task no.	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21
Task description	Pick the compnent	Move the component to the intermediate holder.	Regrasp the component from the intermediate holder.	Move the component the the respective position on the PCB	Assemble the component on the PCB.	Repeat the process from T10 until the assembly of all components in the sequence (T9)	Activate SMEMA protocol (one digital output) to inform the conveyor the PCB is completed.	Repeat the process from T6 until there are no more components to be assembled.	Repeat from T3 until the manufacturing Order is completed.	Operator corrects any part on the intermediate holder	Operator corrects any parts in the PCB
Role assignment											
Interaction type	independent	independent	independent	independent	independent	independent	independent	independent	independent	assisted	assisted
Automation level	automated	automated	automated	automated	automated	automated	automated	automated	automated	automated	automated
Robot speed (m/s)	0,33	1	0,33	1	0,33	1	0	0	0	0,25	0,25
Robot payload (Kg)	1	1	1	1	1	1	1	1	1	1	1
Number of workers	0	0	0	0	0	0	0	0	0	1	1
Overall Task completion time (s)											
Time allocated for Human subtask (s)											
Time allocated for the interaction with robot (s)											
Type of human task	nothing	nothing	nothing	nothing	nothing	nothing	nothing	nothing	nothing	quality control	quality control
Comments											

Figure 13: Parameters and collaboration analysis of IKOR HRC use case

IKOR F1: During T3, it may happen that the operator gets confused about the position of the electronic parts to be assembled by the robot, for example, interchanging by mistake a type of part in one of the component presentation mechanisms. It may happen that the operator fills in any of the presentation mechanisms with components during the robot's work execution time.

IKOR F2: During T4, the robot can use this time to prepare material, i.e., take components from any of the unstructured presentation mechanisms and place them on the structured intermediate support.

IKOR F3: During T7, the robot may not be able to read the data matrix code, for example due to glare or interference on the code, and therefore the intervention of operator 1 would be necessary to "present" a data matrix code to the robot in a more favorable reading position.

IKOR F4: During T10, it may happen that the robot collides with an operator who is refilling components.

IKOR F5: During T11, it may happen that the operator removes or relocates a component whose position may be hindering the robot's picking process, and this may occur at robot run-time.

IKOR F6: During T12. it may happen that the robot collides with an operator who is reallocating components to facilitate the job to the robot.

IKOR F7: During T13, it may happen that an operator removes or relocates a component whose position may be hindering the robot's picking process, and this may occur at robot run-time.

IKOR F8: During T15, it may happen that the robot collides with the PCB and a fragment of the PCB is ejected and hits one of the operators close to the robotic cell.

Additional analysis efforts have been performed with a focus on the interaction between human operators and robot systems. For this purpose, a second data gathering process has been started. IKOR has been requested to provide a more detailed overview according to a scheme/template suggested by the ACROBA partner BIBA. This consists of a file in which the predefined process tasks/sequences must be described in more detail by answering specific questions (parameters). Every process task is considered independently. BIBA has selected specific parameters based on the complexity and the interaction level in the ACROBA collaborative pilot lines.

- How is the process task performed / which automation level? Manual, semi-automated, automated
- Which interaction type?
    - independent: human and robot operate independently on different work pieces into the same workspace.
    - synchronized: human and robot operate consecutively on one work piece. They are still separated, although this workplace can be designed very efficiently.
    - simultaneous: human and robot do not have physical contact during simultaneous operation on a mutual work piece
    - assisted: closest collaboration takes place if not only the same work piece is machined, but also when the workspace of the robot and worker overlap. This is the mode with the highest safety constraints.
- What type of task is the human operator performing? quality control, assembly, supervision, other (to be described) or nothing

- What is the speed of the robot (m/s) during each process sequence?
- What is the payload of the robot (kg) during each process sequence?
- How many human workers are involved in each process sequence?
- How long the sequence/task completion time take (s)?
- How much time is allocated for human operator's subtask achievement (s)?
- How much time is allocated for the interaction between human operators and robot systems?

ICPE pilot line

The analysis of the ICPE pilot lines reveals several findings (ICPE Fx) mainly related to the interaction level (low, high, too high), means of interaction (hands, entire body) and type of interaction (collaboration, coexistence, cooperation) of the human operator with the robot systems. The ICPE pilot line is divided into 3 sub use-cases: coils winding, magnets bonding and coils bonding.

Coils winding

ACROBA Partner	ICPE
Use-case name	Coils winding
Process detailed description (text)	The process aims at performing the stators coils winding of an electric motor. The robotic cell consists of two winding spot, a collaborative robot and a human operator. The workspace is shared between the two agents, which work in parallel
Process time (s)	To be evaluated
How many tasks in the process	3

	Description item	Description
1	Work description	Coils winding
2	Workflow	Preparatory operation on the stator, robotic coils winding, finishing operations on the stator.
3	Input	Stator, winding diagrams, CADs
4	Output	Wound stator
5	Human	
6	Tools and equipment	Pliers
7	Environmental influences	No environmental effects

Figure 14: ICPE Coils winding process description - according to the REFA method

The following table includes all the steps described by the use case owner according to the procedure provided by BIBA.

Table 3: Coils winding sequences description

No.	Sequence phases	Remarks	Possible situations
T1	Preparatory operations on stator	The human places the stator on a winding spot x and perform the preparatory operations. If it is the first step of the process, the robot waits until signal, otherwise robot go winding the stator on winding spot	
T2	Coils winding on a stator and human tasks on another stator	The robot performs the winding on a prepared stator, human places and prepares another stator on another spot	The human and the robot share the same workspace for the entire duration of the process.
T3	Coils winding on first stator Finishing operation on stator	The robot performs the winding on the second stator, human finish operation on the first stator and places/prepares a new one	
Tx	Iterations	Repeat T1, T2, T3	

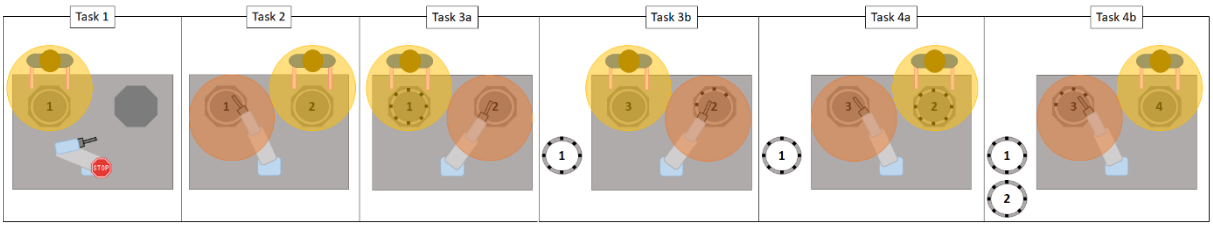


Figure 15: Coil winding sequences/tasks - graphical description

ICPE 1-F1: During T1, there is no need to consider safety issues since the robot is stopped

ICPE 1-F2: Between T2 and T3, it may happen that the human could be touched by the robot since human operator and robot and changing their working areas. Based on the workshops' outcomes, the worst case will be the collision of the robot with the human hands, since the human is almost behind a table on which all the assembly parts are placed, and the winding is taking place.

ICPE 1-F3: During all the tasks, the robot system will never reach the human body extremities (hands) in the case the human will not stretch his hands in the robot direction.

ICPE 1-F4: The coils winding process, based on existing process description, can be considered as a low level interactive (coexistence) workplace.

Task no.	Task1	Task2	Task3	Task 4
Task description	Preparatory operations on stator 1	Robotic coils winidng on stator 1	Finishing operation on stator 1 + preparatory operations on stator 3	Robotic winding on stator 3
		Preparatory operations on stator 2	Robotic coils winidng on stator 2	Finishing operation on stator 2+preparatory operation on stator 4
Role assignment				
Interaction type	synchronous	synchronous	synchronous	synchronous
Automation level	manual			
Robot speed (m/s)	0	0,1	0,1	0,1
Robot payload (Kg)	1	1	1	1
Number of workers	1	1	1	1
Overall Task completion time (s)	120	5040	5040	5040
Time allocated for Human subtask (s)	120	120	240	240
Time allocated for the interaction with robot (s)	0	0	0	0
Type of human task	assembly	assembly	assembly	assembly
Comments	There is not a real interaction, but the workspace is shared between the human and the robot			

Figure 16: Parameters and collaboration analysis of coils winding HRC use case

Magnets bonding

ACROBA Partner	ICPE
Use-case name	Magnets bonding
Process detailed description (text)	magnets on the rotor of an electric motor. The robotic cell consists of a robotic arm and a human operator
Process time (s)	To be evaluated
How many tasks in the process	8

	Description item	**Description**
1	Work description	Magnets bonding
2	Workflow	under the activator spray, adhesive deposition
3	Input	Magnets, adhesive, activator, rotor, CADs
4	Output	Rotor with magnets
5	Human	
6	Tools and equipment	N.A.
7	Environmental influences	No environmental influences

Figure 17: ICPE Magnets bonding process description - according to the REFA method

Analog to the previous processes, we start with a table including all the steps described by the use case owner ICPE according to the procedure provided by BIBA.

Table 4: Magnets bonding sequences description

No.	Sequence phases	Remarks	Possible situations
T1	Place magnets on tray	The human place the magnets on the correct tray	The human and the robot share the same workspace for the entire duration of the process.
T2	Shaft load	The human loads the shaft on the spindle	
T3	Place adhesive on the rotor	The human place the adhesive on the rotor	
T4	Pick magnet from the tray	The robot picks the magnet with the correct polarity from the tray	
T5	Activator deposition	The robot places the magnet under the activator spray	
T6	Magnet bonding on the rotor	The robot places the magnet on the rotor and waits for the reaction time	
T7	Rotate shaft	The human rotates the shaft, if needed	
T8	Quality check	The human visual check the quality of the rotor	

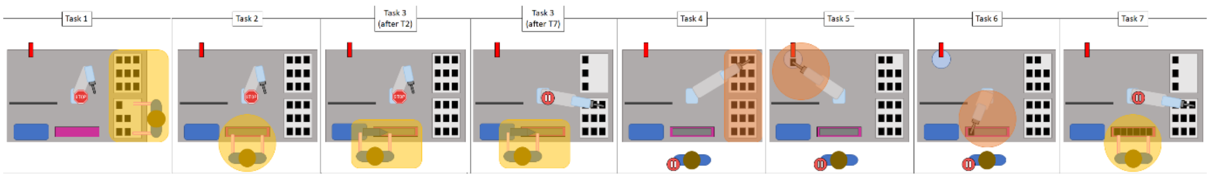


Figure 18: Magnets bonding sequences/tasks T1-T7 / graphical description

ICPE 2-F1: The only process steps in which humans are collaborating are T3 (after T7) and T7.

ICPE 2-F2: In the rest of the process steps, either the robot system or the human operator is doing a task. For these tasks a simple safety concept is able to ensure human safety, since there is no interaction expected.

ICPE 2-F3: the magnets bonding process as a whole can be considered as no critical scenario for safety point of view (BIBA). Nevertheless, HRC related primitives could contribute to avoid potential safety issues provoked by unexpected human behaviours.

Task no.	Task1	Task2	Task3	Task 4	Task 5	Task 6	...		Task 7	Task 8
Task description	Place magnets on tray	Shaft load	Place adhesive on the rotor	Pick magnet from the tray	Activator deposition	Magnet bonding			Rotate shaft	Quality check
Role assignment										
Interaction type	synchronous	synchronous	synchronous	synchronous	synchronous	synchronous		synchronous	synchronous	synchronous
Automation level	manual	manual	manual	automated	automated	automated		manual	manual	manual
Robot speed (m/s)	0	0	0	0,1	0,1	0,1		0	0	0
Robot payload (Kg)	1	1	1	1	1	1		1	1	1
Number of workers	1	1	1					1	1	1
Overall Task completion time (s)	100	200	30	20	5	20		5	120	120
Time allocated for Human subtask (s)	100	200	30	0	0	0		0	0	120
Time allocated for the interaction with robot (s)	0	0	0	0	0	0		0	0	0
Type of human task	assembly	assembly	assembly	assembly	assembly	assembly		assembly	quality control	quality control
Comments	There is not a real inetraction, but the workspace is shared between the human and the robot									

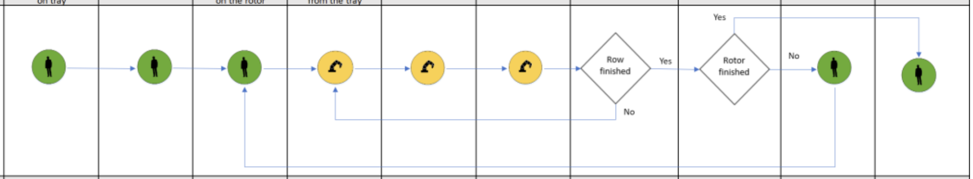


Figure 19: Parameters and collaboration analysis of magnets bonding HRC use case

Coils bonding

ACROBA Partner	ICPE
Use-case name	Coils bonding
Process detailed description (text)	The process aims at performing the bonding of coils on the stator of an electric motor. The robotic cell consists of a robotic arm and a human operator
Process time (s)	To be evaluated
How many tasks in the process	8

	Description item	**Description**
1	Work description	Coils bonding
2	Workflow	Preparatory operations, pick coil, place it under the activator spray, adhesive deposition on stator, place of coil on the stator
3	Input	Coils, adhesive, activator, stator, CADs
4	Output	Stator with coils
5	Human	
6	Tools and equipment	N.A.
7	Environmental influences	No environmental influences

Figure 20: ICPE Coils bonding process description - according to the REFA method

Table 5: Coils bonding sequences description

No.	Sequence phases	Remarks	Possible situations
T1	Place coils on tray	The human place the coils on the correct tray	The human and the robot share the same
T2	Shaft and tube load	The human loads the shaft and the tube on the spindle	

T3	Place adhesive on the tube	The human place the adhesive on the tube	workspace for the entire duration of the process.
T4	Pick coil from the tray	The robot picks the coil from the tray	
T5	Activator deposition	The robot places the coil under the activator spray	
T6	Coil bonding on the tube	The robot places the coil on the tube and waits for the reaction time	
T7	Rotate shaft	The human rotates the shaft, if needed	
T8	Quality check	The human visual check the quality of the stator	

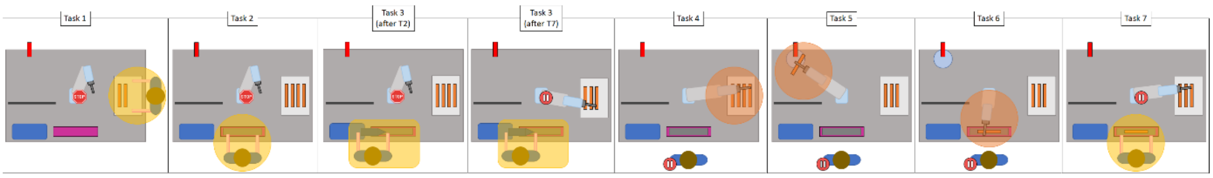


Figure 21: Coil bonding sequences/tasks T1-T7 / graphical description

ICPE 3-F1: The only process steps in which safety issues are raised are T6 and T7.

ICPE 3-F2: In the rest of the process steps, either the robot system or the human operator is doing a task. For these tasks a simple safety concept is able to ensure human safety, since there is no interaction expected.

ICPE 3-F3: The Coil bonding process as a whole can be considered as no critical scenario for safety point of view (BIBA). Nevertheless, HRC related primitives could contribute to avoid potential safety issues provoked by unexpected human behaviors.

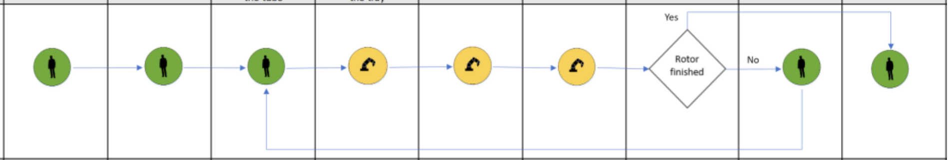
Task no.	Task1	Task2	Task3	Task 4	Task 5	Task 6		Task 7	Task 8
Task description	Place coils on tray	Shaft and tube load	Place adhesive on the tube	Pick coil from the tray	Activator deposition	Coil bonding		Rotate shaft	Quality check
Role assignment									
Interaction type	synchronous	synchronous	synchronous	synchronous	synchronous	synchronous		synchronous	synchronous
Automation level	manual	manual	manual	automated	automated	automated		manual	manual
Robot speed (m/s)	0	0	0	0,1	0,1	0,1		0	0
Robot payload (Kg)	1	1	1	1	1	1		1	1
Number of workers	1	1	1					1	1
Overall Task completion time (s)	100	200	30	20	5	20		5	120
Time allocated for Human subtask (s)	100	200	30	0	0	0		0	0
Time allocated for the interaction with robot (s)	0	0	0	0	0	0		0	0
Type of human task	assembly	assembly	assembly	assembly	assembly	assembly		assembly	quality control
Comments	There is not a real inetraction, but the workspace is shared between the human and the robot								

Figure 22: Parameters and collaboration analysis for coils bonding HRC use case

3.3 Limits and Requirements

Step description: Determine the limits of your application and summarize them in a single document. Limits describe the conditions and constraints under which the machinery (here the collaborative application) is intended to operate. The description of the limits should include a description of each machine, including the robot. Add a brief description of the key performance indicators given for your process (e.g., cycle time). Use the tabular process model and the application's floorplan from CAD to refer to the process steps and system components.

IKOR pilot line

The following table includes the list of requirements that have been worked out based on the generated findings for the IKOR pilot line.

Table 6: Summary of most relevant requirements for IKOR pilot line

Findings	Process tasks	Requirements
IKOR F1	T3	Collisions between the robot and human body extremities (hands) must be avoided
IKOR F2	T4	Robot should avoid entering the operator's working area. The distance between robot and human must be known in real-time

IKOR F3	T7	Ensure human safety during his support in moving the PCB
IKOR F4	T10	Robot should avoid colliding with the human during his work. The distance between robot and human must be known in real-time
IKOR F5	T11	Human operator should avoid hindering the robot picking process. The operator presence in robot area should be detected
IKOR F6	T12	Human detection mechanisms must be implemented, and collaborative tasks must be designed
IKOR F7	T13	Human operator should avoid hindering the robot picking process. The operator presence in robot area should be detected
IKOR F8	T15	Protect human operator against PCB fragment

For the implementation of the collaborative IKOR pilot line, the following capabilities should be offered. These consist of mechanisms ensuring:

- Detection of the PCB, which is performed by reading the data matrix
- Picking of the PTH components on the conveyor, and possibly its reorientation
- Placement of the PTH on the PCB
- Contact/force feedback (Fixing the PTH on the PCB)
- Control the final PCB board (Inspection and motion around the PCB)
- Monitoring of robot movement (joint position in the working area)
- Monitoring of robot speed
- Control of robot movement (e.g., path scheduling)
- Control of robot speed (e.g., path scheduling)
- Monitoring of the human position (in the working area)
- Monitoring of the human extremities (mainly hands, head) according to his position
- Alerting Mechanisms for the human operators
- manually moving the robot TCP to specific position

ICPE pilot line

The following table includes the list of requirements that have been worked out based on the generated findings for the IKOR pilot line.

Table 7: Summary of most relevant requirements for ICPE pilot line

Findings	Process tasks	Requirements
ICPE 1-Fx	all	Collisions between the robot and human operator body extremities (hands) must be avoided
ICPE 2-Fx	all	Collisions between the robot and human operator body extremities (hands) must be avoided
ICPE 3-Fx	all	Collisions between the robot and human operator body extremities (hands) must be avoided

For the implementation of the collaborative ICPE pilot line, the following capabilities should be offered. These consist of mechanisms ensuring:

- Control of the robot motion (Path planning for winding, placing parts at specific location)
- Detection of specific parts (CAD matching for stator)
- Manipulation of specific parts (Grasping/releasing magnets)
- Contact/force feedback (Pushing the magnet on the rotor)
- Monitoring of robot movement (joint position in the working area)
- Monitoring of robot speed
- Control of robot movement (e.g., path scheduling)
- Control of robot speed (e.g., path scheduling)
- Monitoring of the human position (in the working area)
- Monitoring of the human extremities (mainly hands, head) according to his position
- Alerting Mechanisms for the human operators

3.4 Hazard Identification

Step description: Analyze each component within the collaborative space and in the reach of the human carefully. Analyze the major components like robots, tool, work piece, and environment separately. Refer to the applicable directive to find out which general hazards are relevant for your case. Create a separate data sheet for each hazard. Go through the task groups of the process model to determine the foreseeable misuse of the application. The objective here is to anticipate what humans will do if a possible irregularity occurs. Any time at which the human interacts physically with the robot is often a viable source of potential misuse. Determine the corresponding specific hazards for each identified case of misuse. The standards for your application should provide a list of typical and relevant specific hazards. Record any hazard in a separate datasheet. Double-check the process model, whether other hazards can occur, and keep in mind that other hazards may not be necessarily related to the collaborative operation (e.g., electrical hazards).

According to ISO/TS 15066:2016, the list of significant hazards for robot and robot systems contained in ISO 10218-2:2011, Annex A, is the result of hazard identification carried out as described in ISO 12100. Additional hazards (e.g. fumes, gases, chemicals and hot materials) can be created by specific collaborative applications (e.g. welding, assembly, grinding, or milling). These hazards should be addressed on an individual basis through a risk assessment for the specific collaborative application.

The hazard identification process shall consider the following as a minimum:

- robot related hazards, including
    - robot characteristics (e.g. load, speed, force, momentum, torque, power, geometry, surface shape and material);
    - quasi-static contact conditions in the robot;
    - operator location with respect to proximity of the robot (e.g. working under the robot);
- hazards related to the robot system, including
    - end-effector and work piece hazards, including lack of ergonomic design, sharp edges, loss of work piece, protrusions, working with tool changer;
    - operator motion and location with respect to positioning of parts, orientation of structures (e.g. fixtures, building supports, walls) and location of hazards on fixtures;
    - fixture design, clamp placement and operation, other related hazards;

- determination as to whether contact would be transient or quasi-static, and the parts of the operator's body that could be affected;
- the design and location of any manually controlled robot guiding device (e.g. accessibility, ergonomic, potential misuse, possible confusion from control and status indicators, etc.);
- the influence and effects of the surroundings (e.g. where a protective cover has been removed from an adjacent machine, proximity of a laser cutter);

- application related hazards, including:
  - process-specific hazards (e.g. temperature, ejected parts, welding splatters);
  - limitations caused by the required use of personal protective equipment;
  - deficiency in ergonomic design (e.g. resulting in loss of attention, improper operation).

For the identified hazard, it is recommended to use the following template for each hazard description.

Table 8: Template for hazard description

No.	1
System	End-effector/tool and work piece
Reference	EN ISO 10218-2, ISO/TR 20218-1
Cause	**Falling work pieces**
Potential causes	Loss of work piece. Loss of power, Loss of pressure, Broken cables, …
Potential consequences	Crushing, Cutting or severing, Friction or abrasion, Stabbing or puncture
Notes	Work piece maximal weights ca. 500g and has sharp edges and corners.

The identification and recording of the hazard is an intensive process and need to be executed by the HRC application owner. For that purpose, many stakeholders need to be involved: process engineers, human operators, worker council, safety experts. For the ACROBA pilot lines, the industrial partners and their assigned technical partners are familiar with this required action and will execute it in iterative way until the hazard has been eliminated. A detailed hazard identification procedure has to be performed by IKOR and ICPE. The results of this process will be delivered within the D5.5.

3.5 Risk Evaluation

Step description: The procedure for evaluating the risk is straightforward and must be carried out for all recorded hazards. Go through each hazard and estimate the risk-relevant parameters. Use the chart (Figure 23) to determine the risk level that arises from the hazard considered. The risk chart distinguishes between a serious (red), moderate (yellow), and low risk (green). A serious risk (red) indicates that safety measures for risk reduction are mandatory. A recommendation to apply safety measures corresponds with moderate risk (yellow). If the risk is low, it is sufficient to inform the system operator about the risk in the manual or by using appropriate signs or signals. The implementation of safety measures using safety components or skills (functional safety) might require a different risk evaluation. The objective here is to determine the performance for the used safety component. Please refer to the standards for your application and check which performance is required and how the required level corresponds to the risk evaluation result.

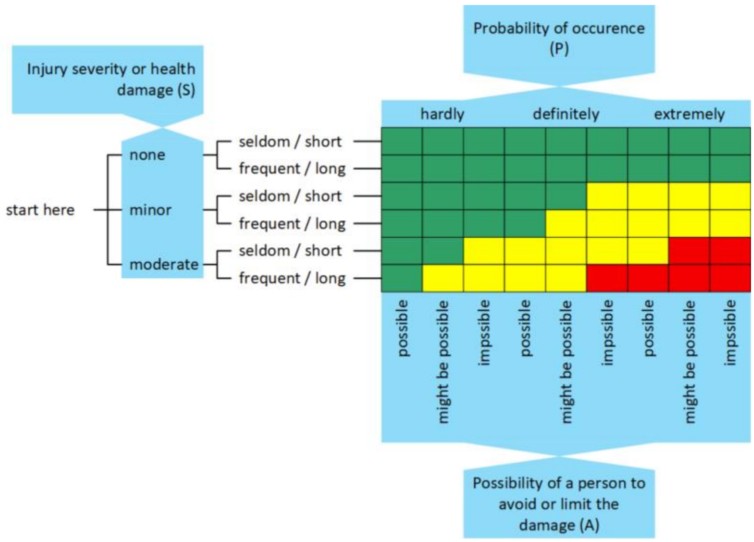


Figure 23: Chart for risk level estimation

The risk evaluation should be done for each hazard identified and using the suggested risk graph (Figure 24). Furthermore, the hazards have to be considered for the determination of the required safety integrity level (SIL) and performance level (PLr) for the adopted safety measures

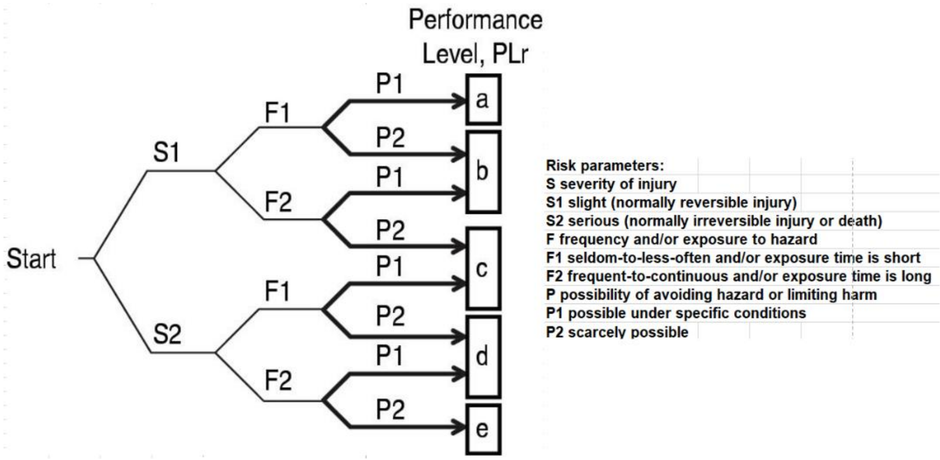


Figure 24: Risk graph for determining required PLr for safety function

The following definitions were used for risk evaluation. Regarding the "Injury severity or health damage (S)" the usual definitions from the PLr determination according to EN ISO 13849-1 were used:

Table 9: Definitions for risk evaluation

Term	Definition
None	No injury or health damage.
Minor	S1: minor (usually reversible) injury; i.e., any injury that is expected to heal completely without leaving permanent disease and/or damage. For example: scrapes, bruises, minor cuts, etc.
Moderate	S2: severe (usually irreversible) injury including death; Injuries, which are not expected to heal. For example: loss of limbs, irreversible bruising, loss of eyesight, and even death of persons.

An example for the evaluation of the risks is given in Table 10.

Table 10: Risk evaluation – an example

No.	S	F	A	P	Risk
1	Minor	Frequent	Possible	Hardly	Low
2	Moderate	Seldom	Possible	Extremely	Moderate
3	Moderate	Seldom	Mb possible	Extremely	Serious

The evaluation of the risk is a crucial process and need to be executed by the HRC application owner. Similar to the hazard identification process, many stakeholders need to be involved. For the ACROBA pilot lines, the industrial partners and their assigned technical partners are familiar with this required action and will execute it in iterative way until the related hazard is eliminated. A detailed hazard identification procedure has to be performed by IKOR and ICPE. The results of this process will be delivered within the D5.5.

3.6 Hazard Elimination and Risk Reduction

Step description: Reducing a specific risk can be achieved in two ways. The first way is to eliminate the hazard by design, which also eliminates the associated risk. This way is the preferred one, although it is only achievable by design measures. The second way is to reduce the risk by applying safety measures in terms of components or skills, which apply to all cases with moderate and serious. Check the applicable standards if the selected safety component or skill has further requirements to be met. If the selection does not meet a particular requirement, try to modify the design or to find a different measure that reduces the risk to a similar extent. The primary objective is, in any case, to reduce the risk to a low one (green in the risk evaluation chart). Specify at least one testing plan for each safety measure in the hazard datasheet. The testing plan must point out how to prove that the applied safety measures are capable of reducing the determined risk as expected.

3.7 Validation of the Safety Measures

Step description: Go through the hazard datasheet and carryout the testing plan. After the tests, re-evaluate each risk by repeating step 5. Once the tests proved that all safety measures are effective and reduce the risks appropriately, carryout a final safety check-up to ensure that all steps of the risk assessment were done and successfully reached. The result of this step is expected to be reported within D5.5.

4 HRC Meets Human-centricity

Expect for ensuring human safety in HRC applications, a requirement that need to be fulfilled by adopting the process described above, the design and planning of additional HRC capabilities, mainly related to human factors (see D2.5), can be implemented based upon the concept described in (D2.5). These capabilities are generated through the modules, primitives, skills and non-functional hard and software tools of the ACROBA platform. These capabilities can be provided and performed according to the principles of planning and scheduling strategies.

The safe industrial workplace, including the robot system and the human operators, takes benefits from the potential capabilities. The proposed capabilities in combination with the implemented rule-based toolkit will not affect the safety measures/concepts of the robotic application, implemented following the presented design process. This will be ensured through isolation/an access management strategy: the deactivation of writing the PLC safety-related parameters or through thresholds that must be not exceeded. For Example, if the maximum robot speed of in Task x must not be higher than a specific value (example 1m/s), the PLC will hinder a new robot speed update (suggested by a triggered event/rule) above this value. For the case a PLC value is not to be updated, any external try for editing this parameter value should/will be declined/avoided by the PLC. The setting of the PLC is to be managed and validated by the process safety experts.

Depending on the envisaged capabilities, the deployment of the rule-based system requires probably the integration of additional hardware technologies and the development of specific skills and primitives serving the gathering of required data, information and knowledge (DIK).

For example, to assess the fatigue or stress of a human worker, which could lead to new risks/hazards, specific parameter values through additional sensors (smart watches, eye tracker …) have to be gathered.

For testing and validating the rule-based system, BIBA has used the already integrated vison-based systems (cameras) and related skills/primitives/topics. Figure 25illustrates the model developed in D2.5. In order the model to be deployed, the user (process engineer) has to define adequate rules. The definition of the rules and their integration in the rule-based system are described in D2.5.

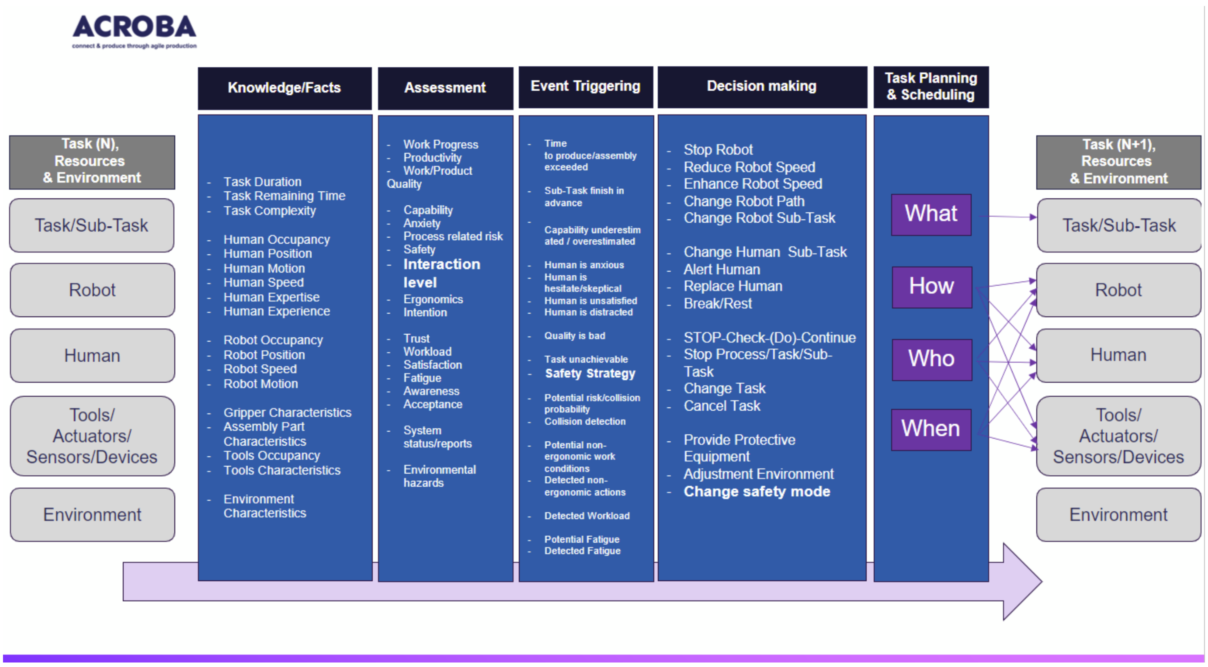


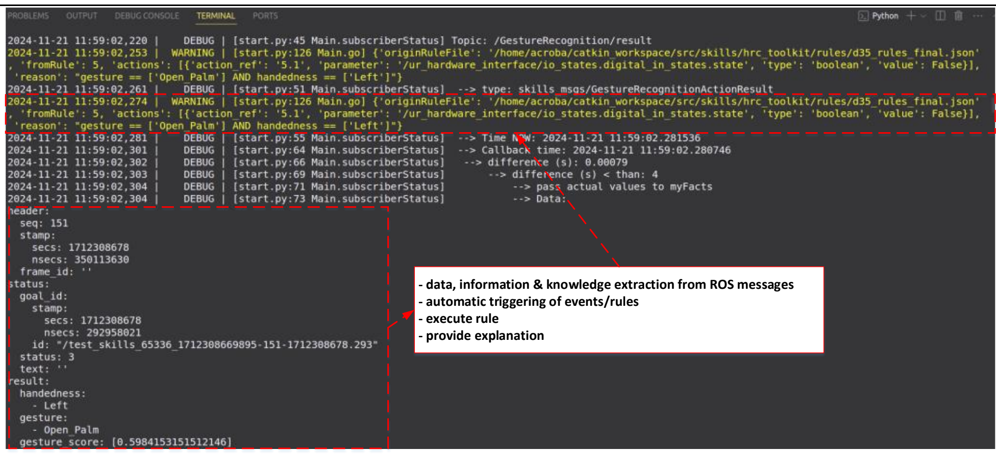
Figure 25: HRC model including human factors and behaviors, potential assessment and decision-making capabilities (Source: BIBA)

Here are some validated examples showing potential scenarios of the rule-based system in combination with the ACROBA platform:

Scenario 1	Human operator stops (temporary) the collaborative process task due to urgent issues.
User story	The human operator in the IKOR assembly process is performing task T20 (human operator corrects any part/component in the intermediate

	holder) while the robot is trying to execute task T13 (robot re-grasps the component from the intermediate holder). Human worker and before terminating this step wants to halt (temporary) the robot due to physical workload or stress situation.
approach	Human operator executes following gesture: An open palm gesture with the left hand
Rule definition	hrc_toolkit > rules > d35_rules_final.json > ...

```json
{
  "rules": [
    {
      "rule_for": "IKOR",
      "rule_ref": 5,
      "conditions": [
        {
          "condition_ref": "5.1",
          "source": "SIGMA",
          "topic": "/GestureRecognition/result",
          "data_in": "result",
          "topic_parameter_name": "gesture",
          "operator": "==",
          "value": ["Open_Palm"]
        },
        {
          "condition_ref": "5.2",
          "source": "SIGMA",
          "topic": "/GestureRecognition/result",
          "data_in": "result",
          "topic_parameter_name": "handedness",
          "operator": "==",
          "value": ["Left"]
        }
      ],
      "selection": "all",
      "actions": [
        {
          "action_ref": "5.1",
          "parameter": "/ur_hardware_interface/io_states.digital_in_states.state",
          "type": "boolean",
          "value": false
        }
      ]
    },
    {
      "rule_for": "IKOR",
      "rule_ref": 6,
      "conditions": [
```

<table>
<tr><td>Execution using ACROBA platform</td><td>
</td></tr>
<tr><td>STATUS in ACROBA</td><td>Validated scenario at lab-scale</td></tr>
</table>

Scenario 2	Human operator reduces the robot system speed for quality control purposes
User story	The human operator in the IKOR assembly process is performing task T21 (human operator corrects any part/component in the PCB) while the robot is executing task T15 (robot assembles/places the component on the PCB). Human worker suspects a defect (broken component) and wants to verify it. In order to avoid stopping the process, the safe speed of the robot should be reduced by 50% to enable quality control before robot starts assembling the next component.
approach	Human operator executes following gesture: A thumb down gesture with the left hand

Rule definition

```json
{
    "rule_for": "IKOR",
    "rule_ref": 6,
    "conditions": [
        {
            "condition_ref": "6.1",
            "source": "SIGMA",
            "topic": "/GestureRecognition/result",
            "data_in": "result",
            "topic_parameter_name": "gesture",
            "operator": "==",
            "value": ["Thumb_Down"]
        },
        {
            "condition_ref": "6.2",
            "source": "SIGMA",
            "topic": "/GestureRecognition/result",
            "data_in": "result",
            "topic_parameter_name": "handedness",
            "operator": "==",
            "value": ["Left"]
        }
    ],
    "selection": "all",
    "actions": [
        {
            "action_ref": "6.1",
            "parameter": "/speed_scaling_factor.factor",
            "type": "number",
            "value": 0.5
        }
    ]
}
```

Execution using ACROBA platform

```
2024-11-21 14:59:46,588 |    DEBUG | [start.py:45 Main.subscriberStatus] Topic: /GestureRecognition/result
2024-11-21 14:59:46,584 |  WARNING | [start.py:126 Main.go] {'originRuleFile': '/home/acroba/catkin_workspace/src/skills/h
rc_toolkit/rules/d35_rules_final.json', 'fromRule': 6, 'actions': [{'action_ref': '6.1', 'parameter': '/spped_scaling_fact
or.factor', 'type': 'number', 'value': 0.5}], 'reason': "gesture == ['Thumb_Down'] AND handedness == ['Left']"}
2024-11-21 14:59:46,590 |    DEBUG | [start.py:51 Main.subscriberStatus]  --> type: skills_msgs/GestureRecognitionActionRe
sult
2024-11-21 14:59:46,595 |  WARNING | [start.py:126 Main.go] {'originRuleFile': '/home/acroba/catkin_workspace/src/skills/h
rc_toolkit/rules/d35_rules_final.json', 'fromRule': 6, 'actions': [{'action_ref': '6.1', 'parameter': '/spped_scaling_fact
or.factor', 'type': 'number', 'value': 0.5}], 'reason': "gesture == ['Thumb_Down'] AND handedness == ['Left']"}
2024-11-21 14:59:46,602 |    DEBUG | [start.py:55 Main.subscriberStatus]  --> Time NOW: 2024-11-21 14:59:46.602156
2024-11-21 14:59:46,646 |    DEBUG | [start.py:64 Main.subscriberStatus]  --> Callback time: 2024-11-21 14:59:46.601793
2024-11-21 14:59:46,647 |    DEBUG | [start.py:66 Main.subscriberStatus]   --> difference (s): 0.000363
2024-11-21 14:59:46,649 |    DEBUG | [start.py:69 Main.subscriberStatus]       --> difference (s) < than: 4
2024-11-21 14:59:46,650 |    DEBUG | [start.py:71 Main.subscriberStatus]           --> pass actual values to myFacts
2024-11-21 14:59:46,651 |    DEBUG | [start.py:73 Main.subscriberStatus]           --> Data:
header:
  seq: 379
  stamp:
    secs: 1712308688
    nsecs: 705316543
  frame_id: ''
status:
  goal_id:
    stamp:
      secs: 1712308688
      nsecs: 661709785
    id: "/test_skills_65336_1712308669895-379-1712308688.662"
  status: 3
  text: ''
result:
  handedness:
    - Left
  gesture:
    - Thumb_Down
  gesture_score: [0.8585006594657898]
```

STATUS in ACROBA	Validated scenario at lab-scale

Scenario 3	Human operators interacts per voice with the robot system.
User story	A human operator is grasping tools and wants to control the robot. The tools are hindering the human operators to perform the envisaged gesture.
approach	For the definition of the scenario rule, additional topics should be made available/implemented on the ACROBA platform. These consists of voice-to-text translation mechanisms (e.g. based on OpenAI Speech-to-text). In addition to that, other hardware components need to be integrated such as microphone and light devices (scenario status). Here is an example (draft) how the rule can be defined
Rule definition	

```
"rules": [
  {
    "rule_for": "ICPE",
    "rule_ref": 7,
    "conditions": [
      {
        "condition_ref": "7.1",
        "source": "SIGMA",
        "topic": "/VoiceRecognition/result",
        "data_in": "result",
        "topic_parameter_name": "voice",
        "operator": "==",
        "value": ["robot you ar too fast, wait untill I finish my task"]
      }
    ],
    "selection": "all",
    "actions": [
      {
        "action_ref": "7.1",
        "parameter": "/speed_scaling_factor.factor",
        "type": "number",
        "value": 0.0
      },
      {
        "action_ref": "7.2",
        "parameter": "/light_status",
        "type": "string",
        "value": "blinking orange"
      }
    ]
  }
```

Execution using ACROBA platform	Not implemented
STATUS in ACROBA	N/A

5 Conclusions

The purpose of this report is to explain the mandatory steps to be executed in order to design a collaborative application. The steps have been described and approaches for some steps have been developed and integrated in the design phases of the pilot lines (e.g. REFA-based process description method for step 2). As recommended by the project reviewers, meeting with safety bodies have been organised to support the partners, to adopt the right methodology and develop the appropriate safety concepts for the industrial pilot lines. The outcomes of some steps (4, 5, 6 and 7) is provided by the pilot line owner and are described in D5.5. In addition, the report D3.5 presents the link to D2.5. This consists of adopting the rule-based system developed by BIBA to enable the integration of potential capabilities. This type of toolkits facilitate the enhancement of collaboration, demonstrated via some scenarios, and avoid the related mechanisms/programming effort at PLC level. The use of the rule-based toolkit has no effect on the safety of the industrial application. According to the KANO model, which categories the customer satisfaction into three fields, namely, "must be", "attractive" and "exciting", the design of the safety application in ACROBA is representing the must be category, while the deployment of the rule-based system can be considered as an attractive measure.

6 References

Behrens, Roland, José Saenz, Christian Vogel, and Norbert Elkmann. *Upcoming Technologies and Fundamentals for Safeguarding All Forms of Human-Robot Collaboration.* Königswinter, Germany: 8th International Conference Safety of Industrial Automated Systems, SIAS 2015, 2015.

ISO 10218-1:2011, "Robots and robotic devices – Safety requirements for industrial robots – Part 1: Ro- bots", ISO, Geneva (2011).

ISO 10218-2:2011, "Robots and robotic devices – Safety requirements for industrial robots – Part 2: Ro- bot systems and integration", ISO, Geneva (2011).

ISO/TS 15066:2016, "Robots and robotic devices – Collaborative robots", ISO, Geneva (2016).

ISO 12100:2010, "Safety of machinery – General principles for design – Risk assessment and risk reduction", ISO, Geneva (2010).

ISO 13849-1:2015, "Safety of machinery – Safety-related parts of control systems – Part 1: General princi- ples for design", ISO, Geneva (2015).

Onnasch, Linda, Xenia Maier, and Thomas Jürgensohn. *Mensch-Roboter-Interaktion - Eine Taxonomie für alle Anwendungsfälle.* baua - Bundesanstalt für Arbeitsschutz und Arbeitsmedizin, 2016.

Annex – IKOR

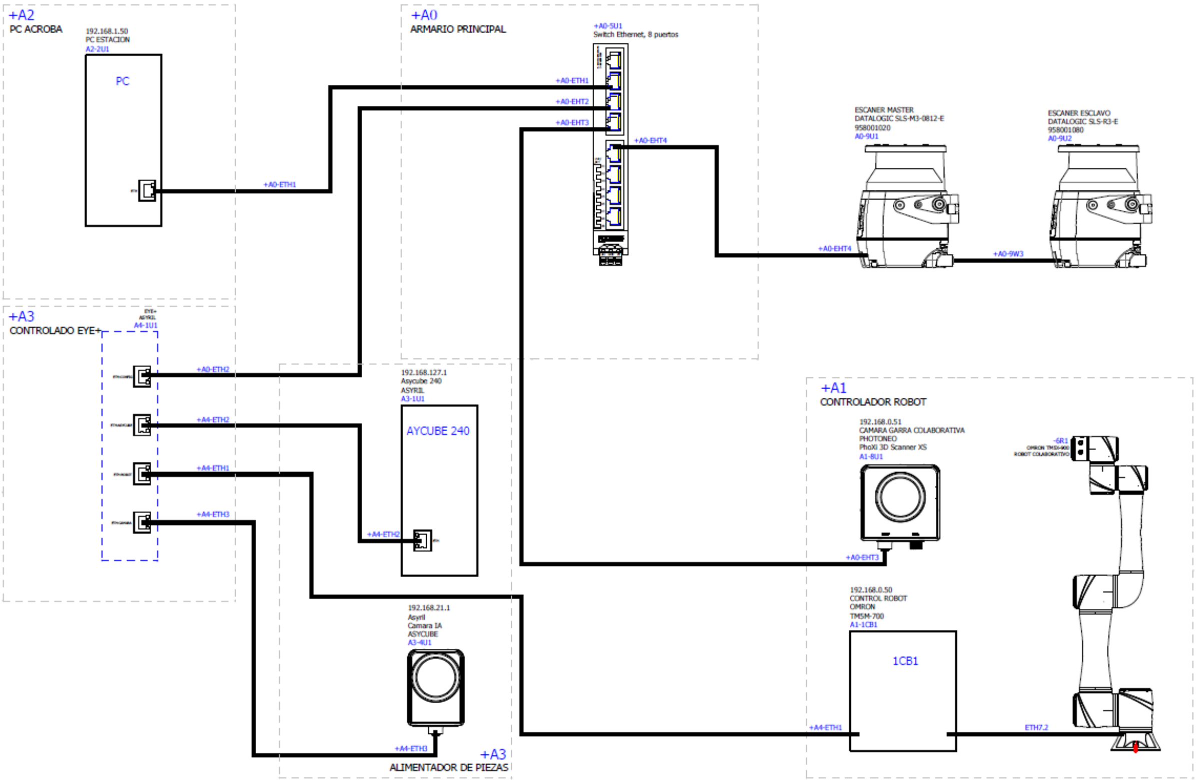


Figure 26: IKOR'S control architecture including scanners

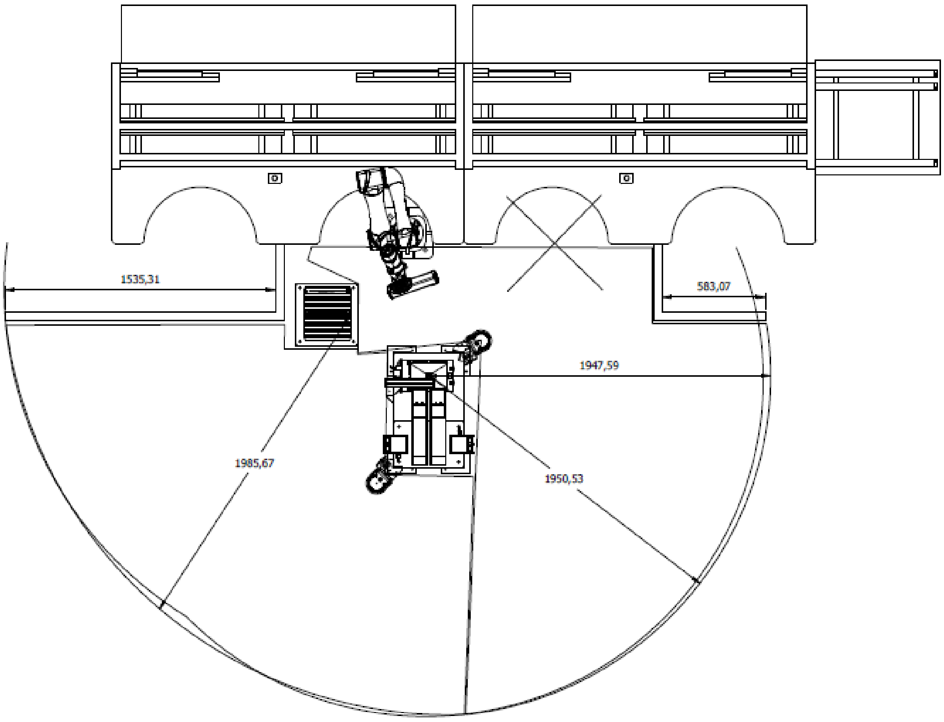


Figure 27: IKOR - Safety Distances

Annex – ICPE

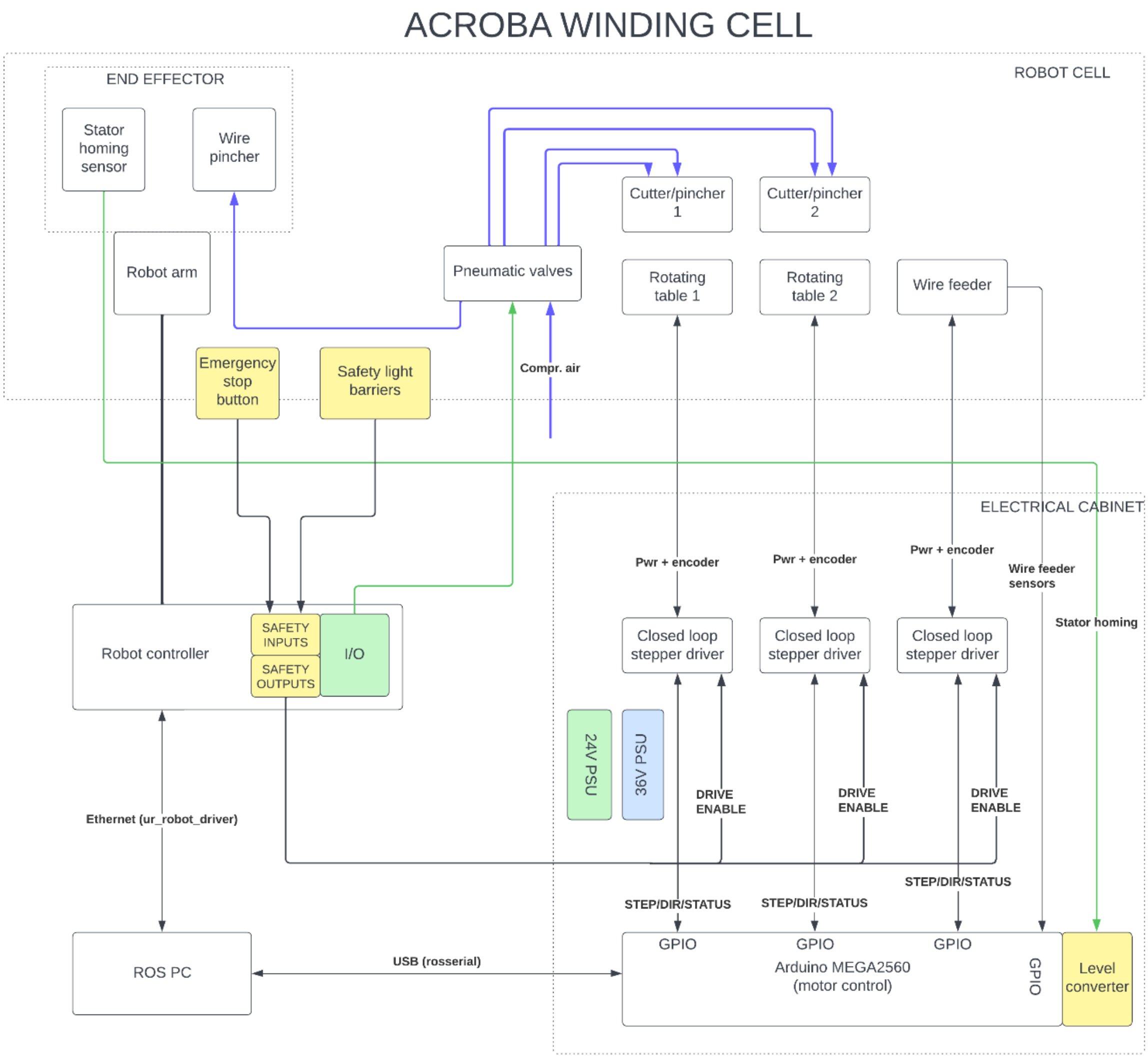


Figure 28: ICPE - Winding electrical design

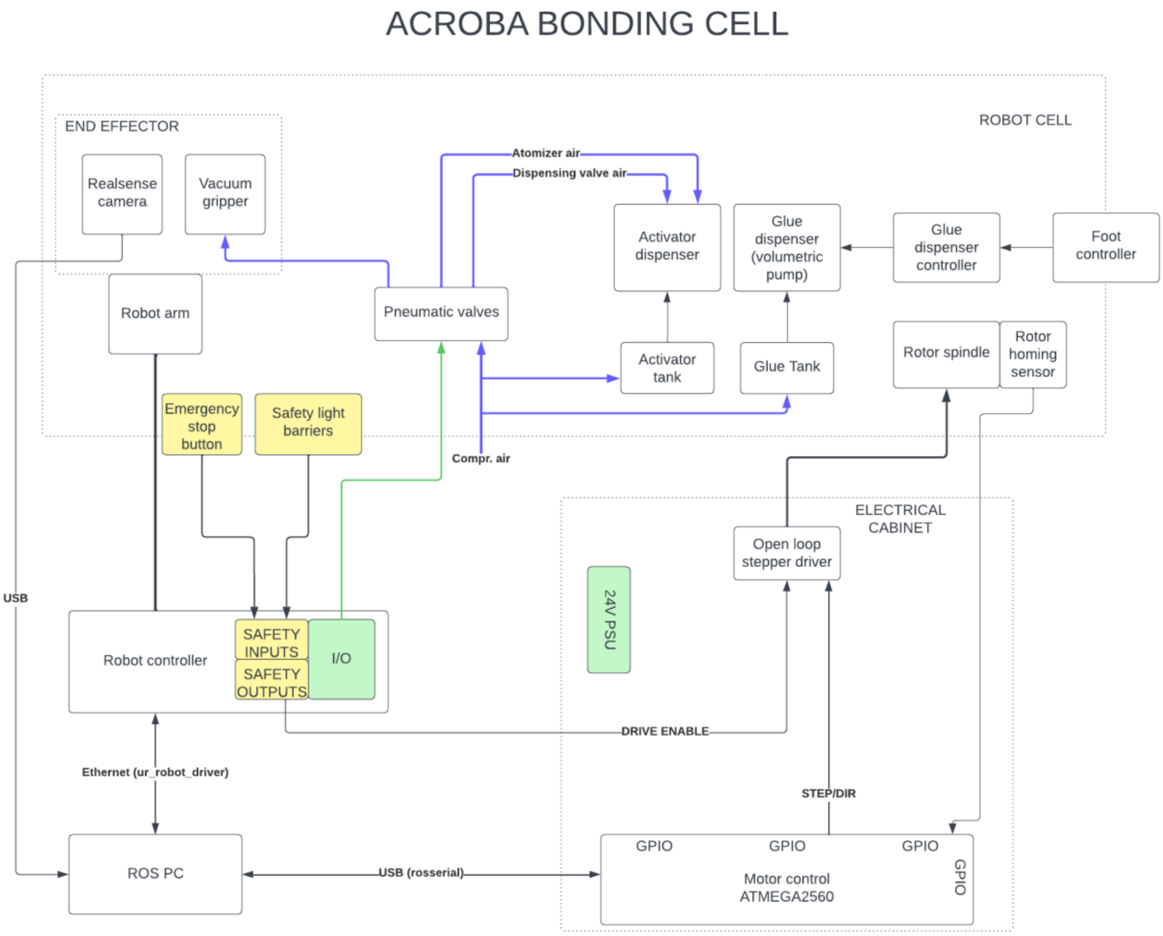


Figure 29: ICPE - Bonding electrical design