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ACROBA

connect & produce through agile production

D5.5 Collaborative Assembly use cases

WP5

Lead Beneficiary: NUTAI

Delivery Date 31/10/2024

Dissemination Level: PU

Version V 1.0

nutai

The ACROBA project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 101017284.

Approval Status

	Name and Surname	Role in the Project	Partner(s)
Author(s)	Adrián Ripoll Moncho Andrés Ortega Giménez	Work Package Leaders, technical partners for the IKOR use case	NUTAI
Author(s)	Edoardo Giacheri Francesca Canale Andrea Pilloni	Technical partners for the ICPE use-case	STAM
Author(s)	Iñaki Gil Ganuza	IKOR's Use case Owner	IKOR
Author(s)	Costi Nicolescu	ICPE's Use Case Owner	ICPE
Reviewer	Alejandro Muñoz Espiago	WP4 Leader	STER
Reviewer	Iván Monzón	Technology Partner	AITIIP
Approved by	Norman Baier	Project Coordinator	BFH

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History of Changes

Version	Date	Description of Changes	By
1.0	29/10/24	First Version, general sections and IKOR's use case	Adrián Ripoll Andrés Ortega
1.1	30/10/24	Added sections regarding the ICPE use-case	Edoardo Giacheri Francesca Canale Andrea Pilloni

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1 Executive Summary

The objective of this document it is to describe the fully-operative solution found for both use case automatic stations, the one in IKOR and the two employed in ICPE. The whole project will be explained, starting with the requirements for the manufacturing process, then with the mechanical, pneumatical and electrical designs and installations, including also the description of the ACROBA implementation in the stations and finally explaining the Human-Robot Collaboration setups chosen for each case, and the required calculations to ensure compliance with the main safety norms.

2 Introduction

The starting point for this deliverable are the specifications and results from Deliverables 5.1, 5.2, 5.7 and 5.8, where preliminar studies about the feasibility of the collaborative robotic cells desired by the use case partners, IKOR and ICPE made possible to first have an idea on how to design stations that would fit in the processes of both partners.

This definition phase resulted in sketches of robotic cells that were yet to be designed and, finally, built into real prototypes that can be effectively installed into real industrial environments and improve complex manual processes.

The design of these robotic cells followed a similar approach for all the cells designed. IKOR's use case focuses on electronic components placing and consisted on just one cell, while ICPE's use case covers several steps of electric motors manufacturing, so it required two different stations and robotic operations that were complex to design and program.

The structure of this deliverable reflects both the design process carried out by all the partners of the project and the integration and refinement phase. NUTAI's contributions focused mainly in three different tasks: project management and supervision of the general progress of Task 5.2, engineering designs of IKOR's collaborative robotic cell, and supervising the compliance

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and coherence of the Human Robot Collaboration approach for all stations, as expert partners in the field.

The engineering designs for ICPE's use case were done by STAM, who followed ICPE's specifications just as NUTAI did. In the latter phases of design, where electrical designs and control concepts that integrated collaboration between humans and robots, there were more cooperation between all partners involved, especially BFH, BIBA, Sigma and IMR, to adapt the stations in a way that the main objectives of the project related to Human-Robot Collaboration could be checked in future tests (WP6).

Deliverable 5.3 showed partial progress in many engineering designs for all these use cases, although ACROBA integration was limited. In this Deliverable, further developments regarding physical installations and Software Integration is given.

3 Final Engineering Designs of Collaborative Cells

3.1 IKOR's Use Case Design Process

As explained by the results of the previous tasks, the starting point was the conceptual definition of the cell, which is the following:

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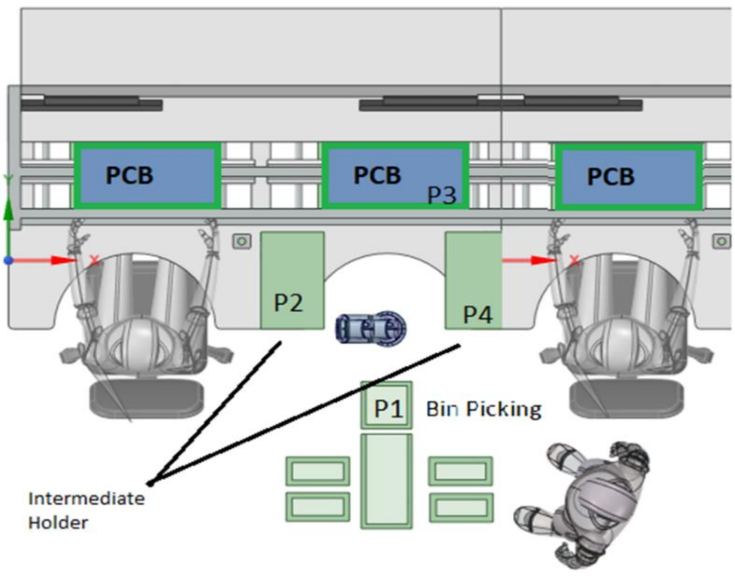

Figure 1: Conceptual design of IKOR's use case station

The idea is that in the electronics assembly line, the robot can perform simple operations such as picking and placing several components. The previous operations consist of preparing the PCBs and the subsequent operations consist of sticking the already placed components or place the rest of them.

These operations are still performed by human operators, so it is expected that the ACROBA platform allows to commission an agile robotic cell that improves the process overall efficiency and reduces the fatigue and errors from the operators. The expected flexibility of this station could allow easy modifications of the cell in case of small changes, such as a different PCB or different components.

As it can be seen in the diagram, the working space is shared by the human operators and the robot. Therefore, a collaborative solution is the most convenient and logic framework. If we consider the definition of Müller et al. [1] to classify the different methodologies in which humans and cobots can work together, we can consider that the operation is sequential, as

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there are both operations before and after the pick and place phase:

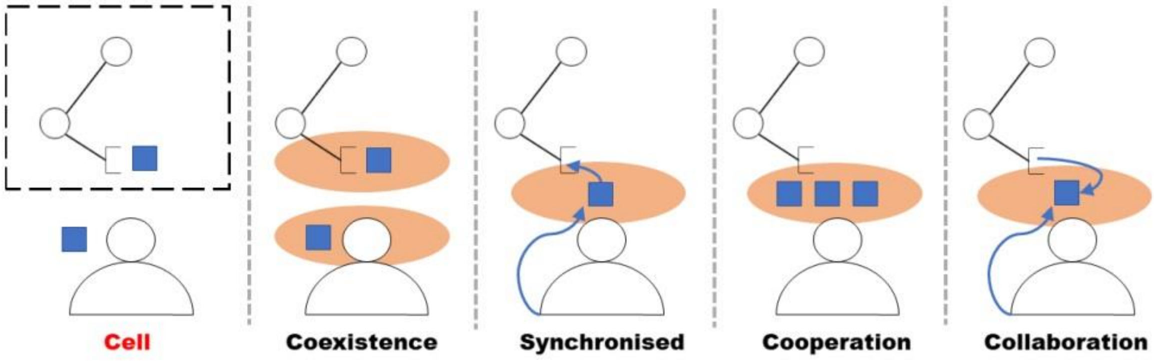

Figure 2: Classification of methodologies for human-robot shared working space

As the idea is to eventually set up the station in a real industrial environment, for all the designs there must be an additional requirement to be considered, that is the compliance with current industrial norms in force.

Some of these norms, as explained in more detail in section 3.1.4.1, include ISO15066, ISO 11161, ISO10218-2 and ISO10218-1.

Compliance with all collaborative standards to be applied in a real industrial environment is a complex task and it should be ensured in a normal collaborative project. These two conditions are essential for achieving a certification:

a) The safety devices and setups employed in these stations are already certified and they are suitable for these solutions.

b) The use and final implementation of these devices should also be certified. In order to obtain a certified design, we need the previous requirement, which is to use certified solutions, but the safety certification must also be demonstrated for every specific use case.

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NUTAI is the most suitable partner for providing knowledge and advice in this sense. As the scope of the project is limited to TRL7, and the designed stations are pilot lines, or prototypes, several specific devices or working modes that would comply with the standards are missing, but this allows a higher flexibility to test a wide variety of scenarios and KPIs.

For this reason, HRC designs and calculations are done according to these norms, resulting in a setup that can be considered collaborative according to all definitions.

The main components of the station are the collaborative robot, *Omron* TM5-900, a feeder for the electronic component, *Asyril* vibrating table, an intermediate table for the cobot to organize the different component and a PC that will work with the ACROBA platform. All these components will be further detailed in next sections.

Once the components were chosen, the mechanical tasks consisted on placing them in a logical and functional layout, considering aspects such as connectivity between components and avoidance of possible collisions. Besides, there were some doubts about the buffer (or intermediate surface) where the electronic components were placed before their final placement in the PCB. The shape this surface however had little effect on the final layout.

The initial idea for the buffer was based on the feasibility tests from previous tasks:

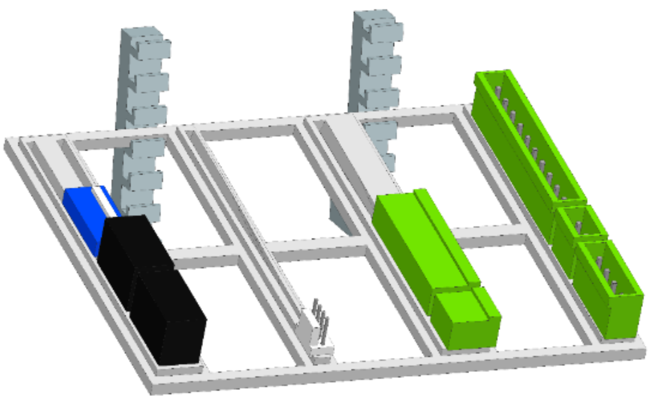

Figure 3: Initial design for the buffer

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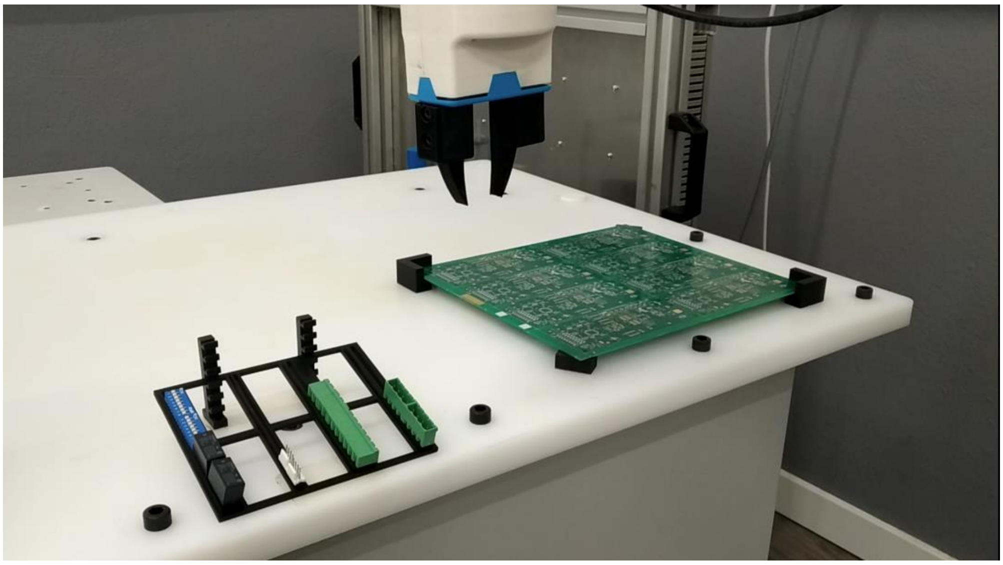

Figure 4:Preliminary Pick and Place test in NUTAI

The idea is that the different shape of the components matches different width and shapes of the keyholes. The slope of the surface ensures all components fall to the edge by gravity. However, some preliminary tests showed how the smallest components did not slide properly. This was one of the issues solved for the final deployment.

The layout has been defined to place the components in an efficient and productive way, also confirmed as optimal in simulations with the Virtual Gym. The cobot has two tasks to do, one where it picks the components randomly from the vibrating table and places them into a specific keyhole depending on the model, and the other where it places the components required for a PCB from the buffer. As those tasks must be done almost as fast as possible, all the elements must be as close as possible to the cobot, in a distribution where the presenters are in the most centric position. The final layout is the following one:

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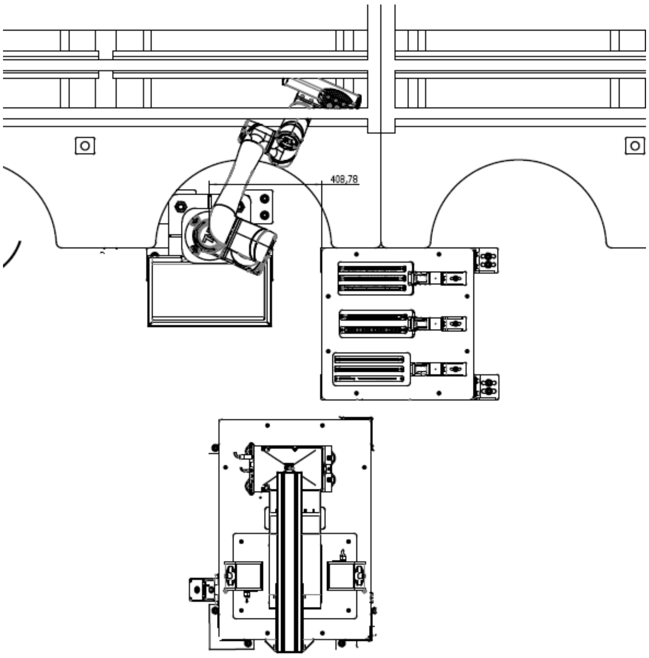

Figure 5: IKOR's Station final Layout

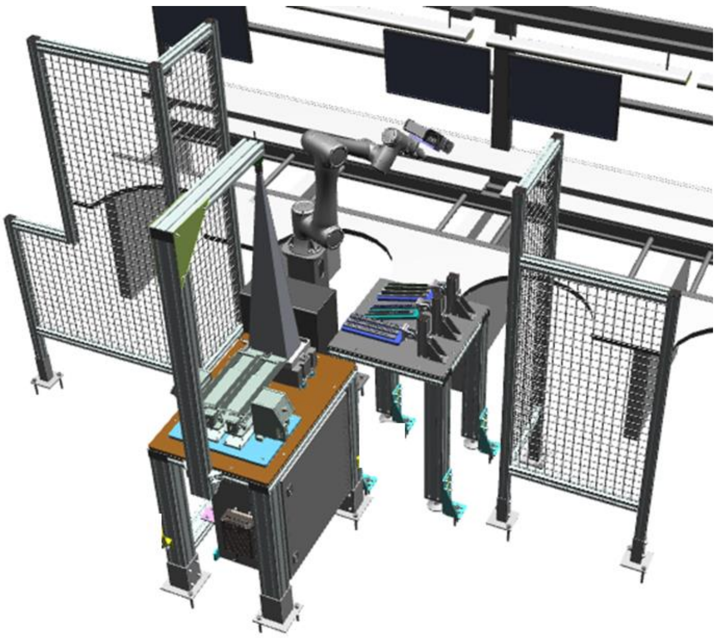

Figure 6: 3D Layout View

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3.1.1 Sequence of operation

The purpose of this operation is to assemble different elements of the PCB. Those elements will be mixed the cobot must organise them. The sequence intended for the station is the following one:

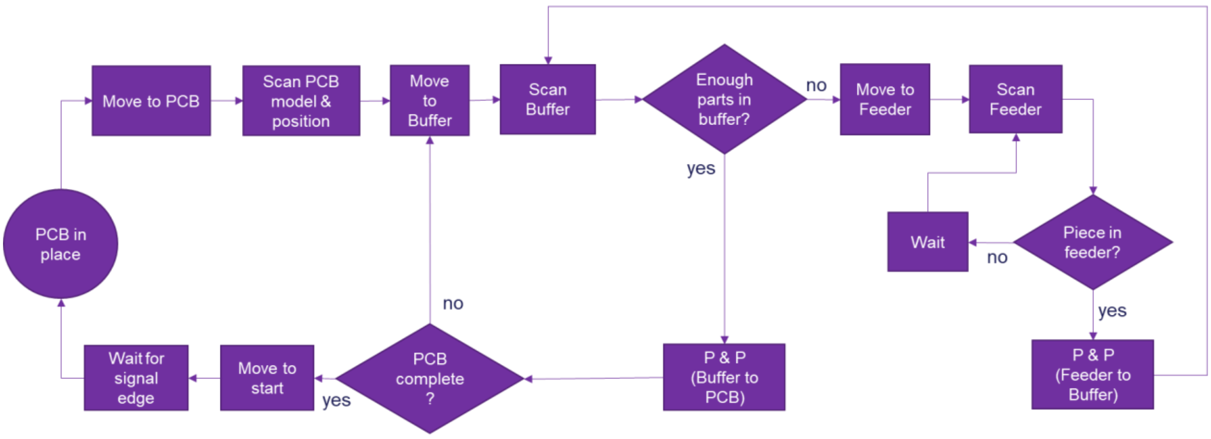

Figure 7: Sequence diagram for IKOR's use case

The first challenge is to pick the components from their initial mixed container and place them in a way they can be told apart and ready to pick again. The engineering team of *NUTAI* has come up with de idea of using a camera to identify the elements and pick the best placed one. In order to move the elements to find the next best-positioned one, the container will have a vibrating system that when being ordered, will vibrate in a determinate frequency that will flip over the components.

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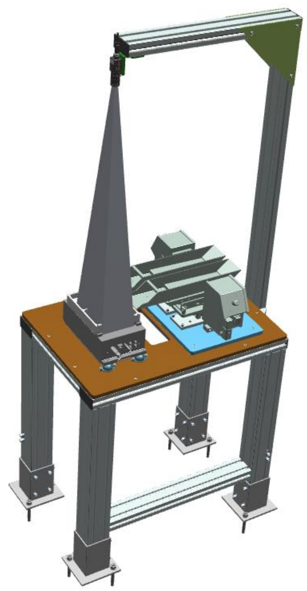

Figure 8: Vibrating Table 3D View

Once the system has identified the right element to be picked and the cobot has collected it, it will be placed in a presenter. Those presenters will be different for each component, in order to adapt their shape and inclination to them. The cobot will place the element in the highest edge of the presenter and it will slide.

Figure 9: Intermediate Table 3D View

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Lastly, the tool of the cobot has been designed with a gripper with the right shape and materials that allow to apply some pressure to the components in order to pick them, but not enough to damage them. There tool will carry a photoneo camera which will identify the PCB in the conveyor, which elements are missing and which are their place already. Once this information is given the cobot will pick from the presenter and place into the PCB.

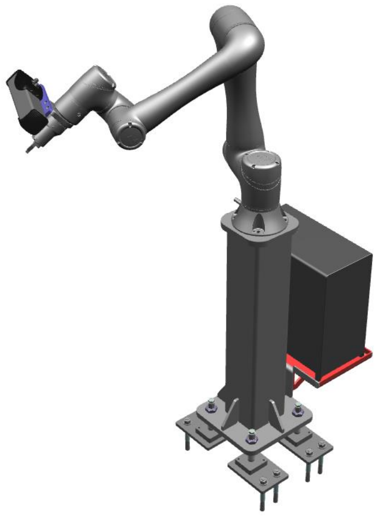

Figure 10: Cobot's Base 3D View

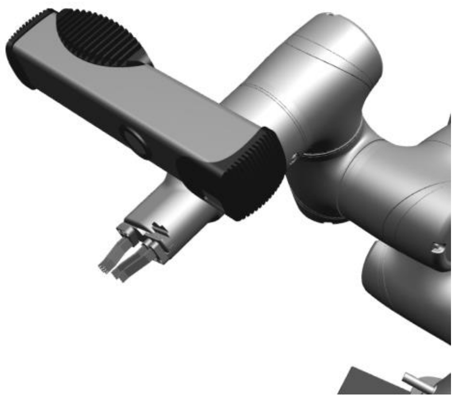

Figure 11: Cobot's Tool View

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3.1.2 Mechanical designs

The mechanical designs have been developed for IKOR by NUTAI. Weekly meetings have taken place to adapt to IKOR's needs and specifications and design an optimal collaborative robotic cell.

At first, the main components of the station were specified: a collaborative robot (OMRON), a PC that will host the ACROBA platform and command the whole station (model not specified yet), a feeder of electronic components (Asyril), an intermediate surface from which the robot will pick and place these components, and the secondary elements of the station (peripherals, laser scanner, electrical enclosure…).

The first decision it was made was the layout. The robot position was clear, but the position of the intermediate surface and the feeder was not. Besides, there were several models for the feeder and the best layout depended on which size was chosen: at first three possible solutions were considered:

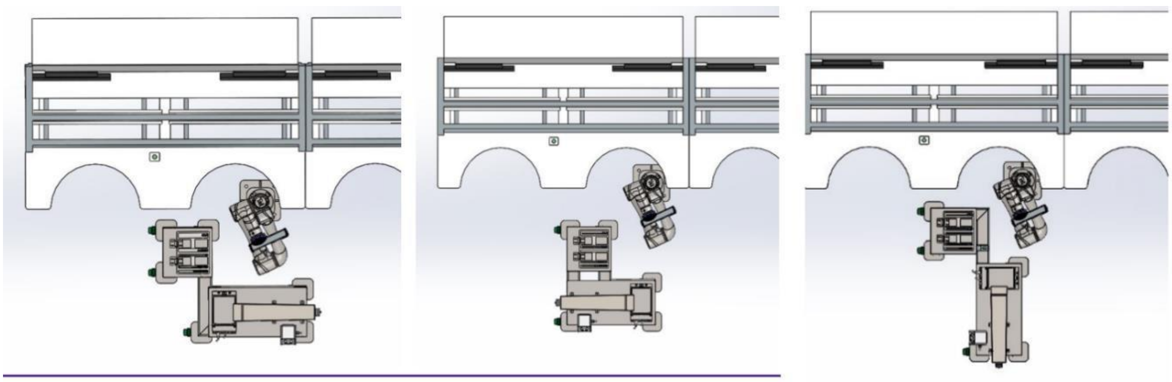

Figure 12: Layout proposals during the mechanical design phase. None of them was finally adopted

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For these choices, the bigger size of the feeder was considered, as it was the most restrictive. Each of them has pros and cons. Apart of the space, possible collisions needed to be taken into account.

When the final model of the feeder was chosen, the electrical designs began. Still, mechanical designs should continue with several problems in which the final version of the intermediate surface with different slopes was developed:

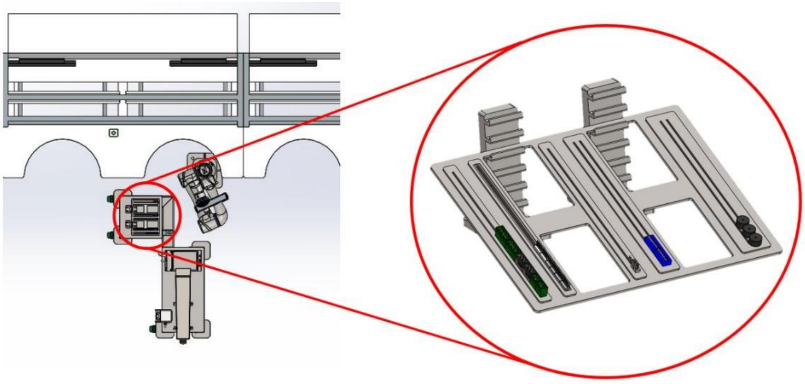

Figure 13: Intermediate buffer's first design

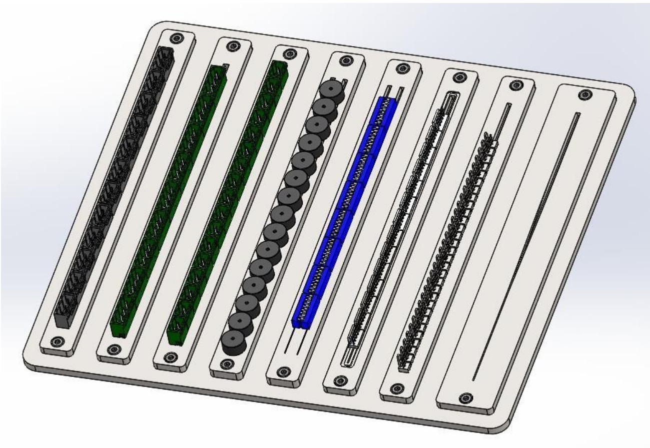

Figure 14: Intermediate buffer's second design

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This designs may be problematic for small components that have little surface to slide to the bottom part. If the robot is set to pick components from the lower part and components do not slide (because of friction or long usage) the system would not work properly.

Therefore, although it was a more complex mechanical design, through mechanical simulations it was determined that a set of three different slopes was the optimal way of distributing the electronic components. The ability to slide for a component depends mainly on the weight and the surface of friction (material is similar in all components). Therefore, the lowest slope is suitable for relatively larger components.

This design is also felixible, which is a main design criteria for the robotic cells concieved for ACROBA. If there was a sudden change of PCB model that requires different components, it would be easy to adapt again the slopes of this intermediate buffer, and re-programming and re-commissioning would also be easier with the ACROBA framework.

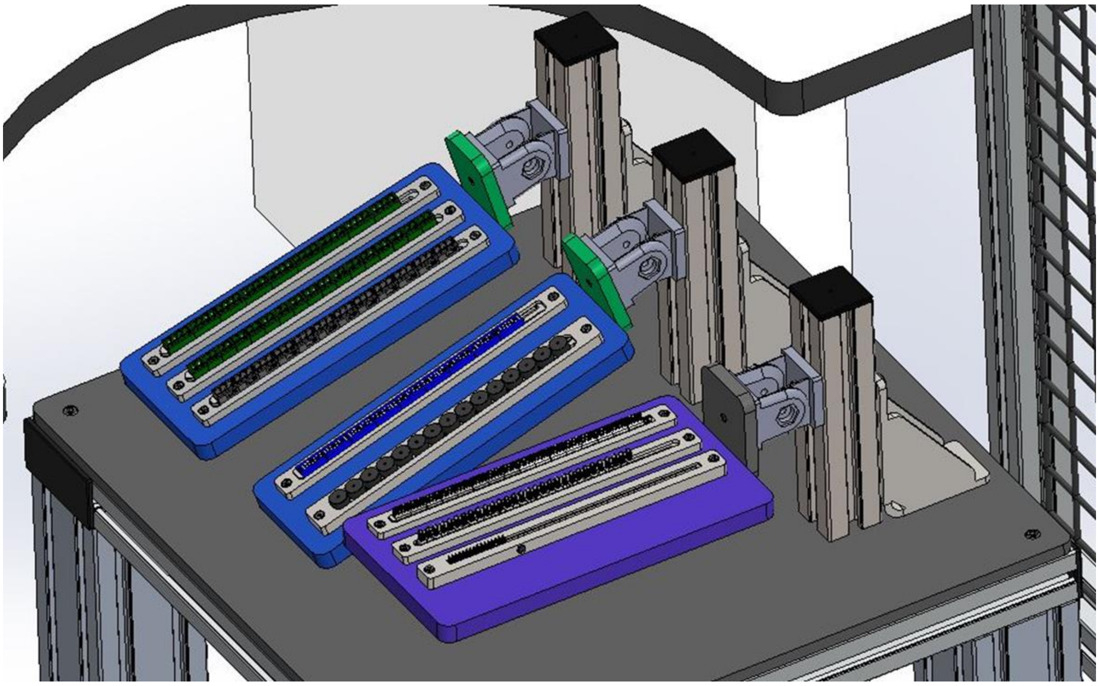

Figure 15: Intermediate buffer's final design

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3.1.2.1 Vibrating Table

The structure of the table itself is composed by anodised aluminium sections tied down to the floor, with an aluminium plate as a base for the other elements.

Under the main structure it is hosted the *Rittal* compact electrical cabinet. It has been placed there to save space for other stations and be close to the elements. Jointed to the cabinet there is the controller of the vibrating system.

Above the table the whole feeding system is placed. Following the process flow, first there are two *Asyril* 1L Hooper where the worker will deposit all the mixed components, with their specific controllers. The components arrive to the vibrating plate and table, laying over four silent blocks that prevent the system to move due to external factors.

Finally, the camera vision kit also from *Asyril* is hanging from a L shaped structure, placed right in the position where it will be able to see the components inside the vibrating table in order to identify those who have the right position to be picked.

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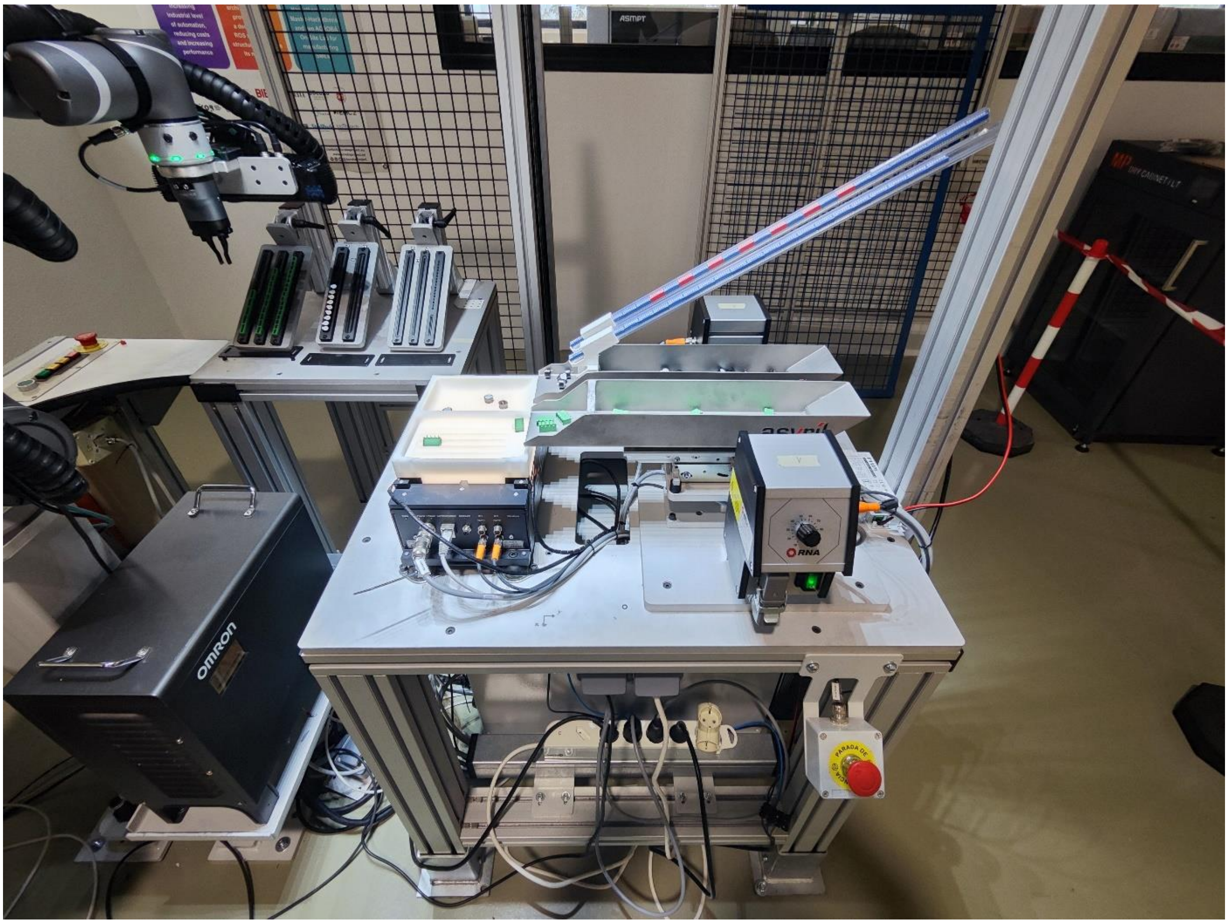

Figure 16: Asyril system and table installed at IKOR's facilities

3.1.2.2 Intermediate Table

The structure of the intermediate table is composed by anodised aluminium sections and a plate, much like the intermediate table.

Lying above it there are three presenter structures with three different slopes with adjustable joints to modify this slope if required. Each structure has several presenters, in total eight of them, specially designed to contain a specific electrical component in a specific position. They

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have been manufactured with materials chosen to let the component slide with the right speed to prevent them from turning over.

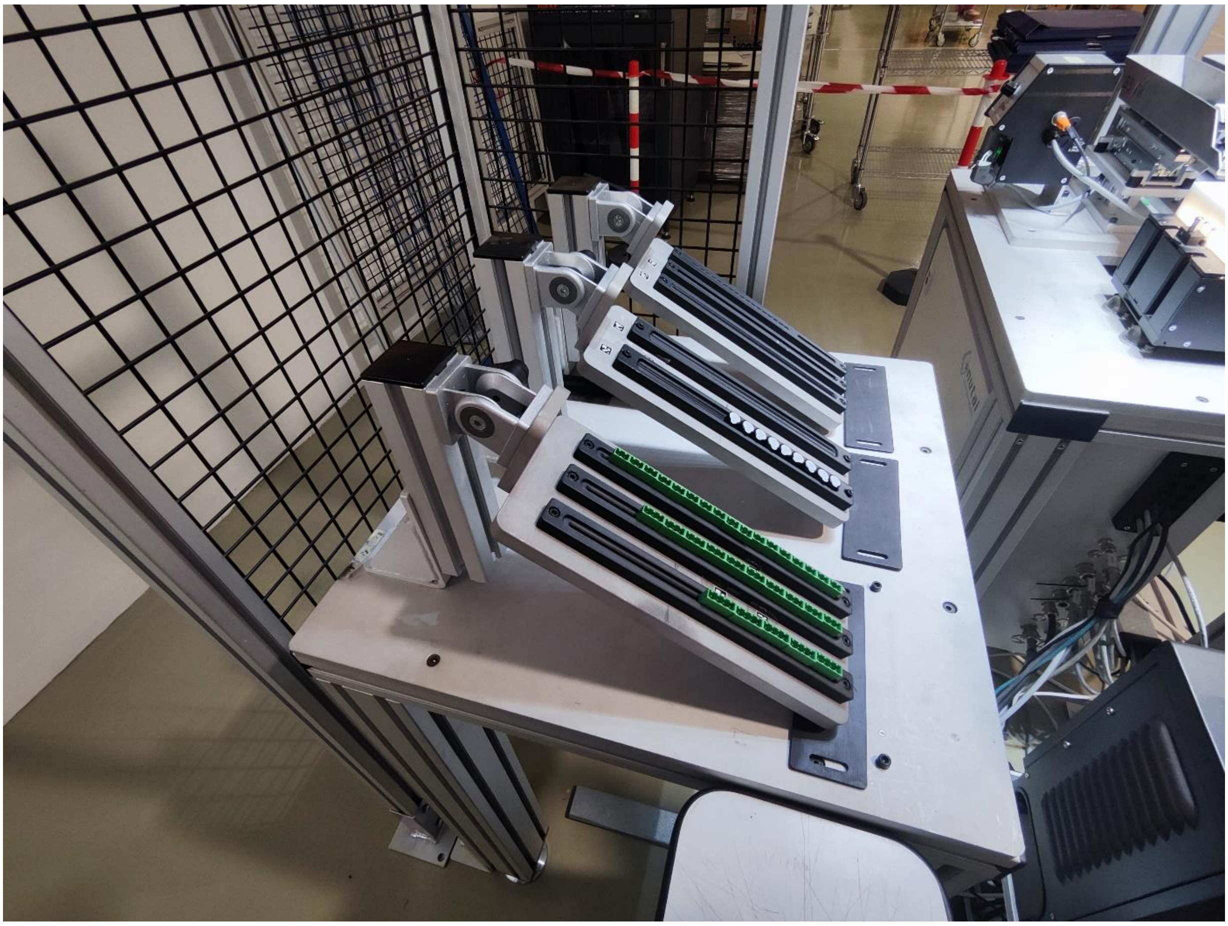

Figure 17: Intermediate buffer and table installed at IKOR's facilities

3.1.2.3 Cobot's Base and Tool

The *Omron* TM5-900 Cobot is standing on a steel base in order to have the right hight to operate. This base is at the same time is secured through four levelling spindles to four other levelling bases, which are tied down to the floor, giving the cobot the stability required. The controller of the robot is settled over a tray united to the base with a hole to pass all the cables.

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The tool of the cobot is a *DH Robotics* PCG-50 finger gripper to pick and place the different components.

The *Photoneo* camera, model *PhoXi 3D Scanner XS* is bridled next to the cobot's tool. It is used to determine the model of the PCB and the missing components, but also to detect in the presenter whether there are components ready to be picked or the cobot must do a refilling cycle.

Figure 18: Detail of the final tool of the robot and the Photoneo Vision System

The final drawings reflecting the exact designs of this stations are included in Annex A.

3.1.3 Electrical Designs

The architecture of the control system is defined in the following diagram:

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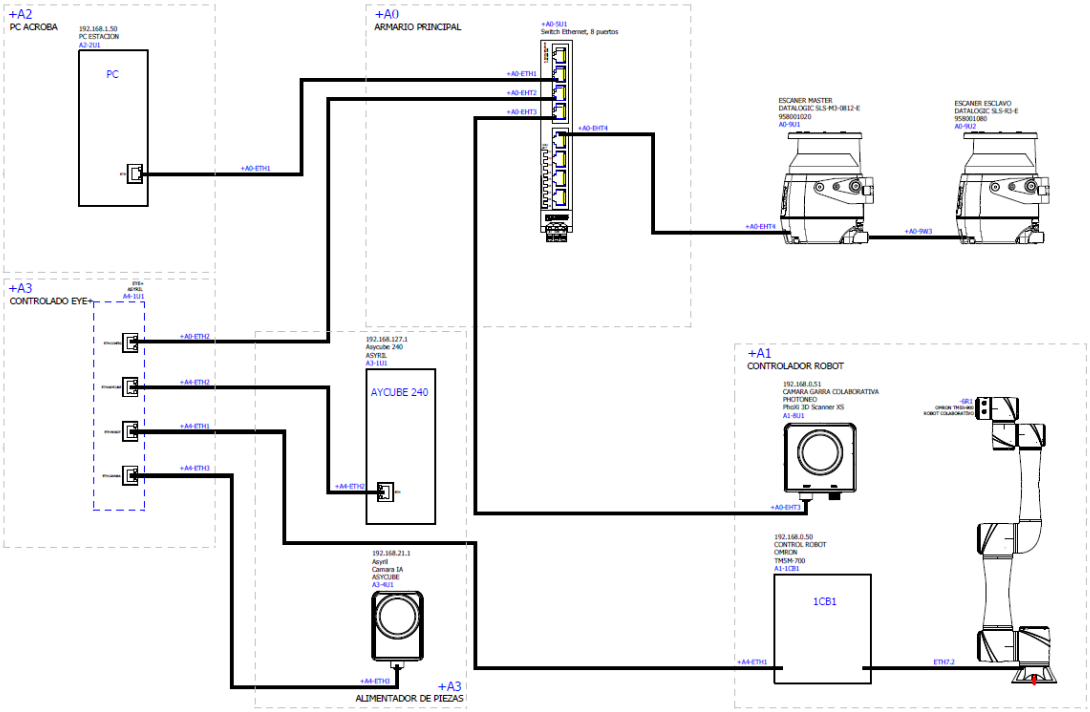

Figure 19: IKOR'S control architecture including scanners

The PC with ACROBA installed on it is connected through Ethernet with the switch installed in the main cabinet, which connects it with the other devices. From the switch it is connected the Photoneo camera installed in the robot. Also from the switch, it is connected the EYE+ Asyril controller whom stablishes the relation with the Asycube vibrating table, the Asycube camera and the Omron robot's controller. In case the installation of safety scanners in the station is required, they would be connected through the switch to the system.

These scanners would be strictly needed in case the station is finally deployed in a real industrial environment. For prototype purposes and ACROBA testing and demonstration, scanners will not be deployed, as the station is programmed to work at a collaborative safe speed that complies with the norms as confirmed by the impact test done.

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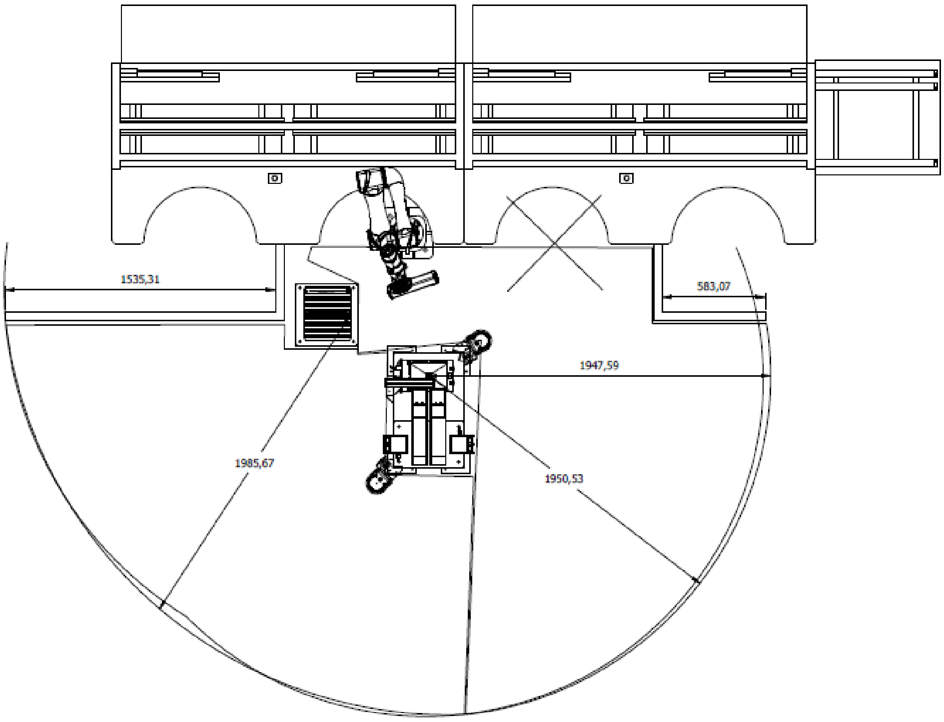

Figure 20: Safety Distances

In order to calculate the safety distance from the robot, the reaction time of the different components must be known. This information is provided by the manufacturer, and for this case the reaction time of the scanner is 62ms, for the safety CPU 10ms and for the cobot to stop its movement 466ms. This last value depends on the inertia of the robot, which is related to the relative payload of it. In this case, NUTAI has considered the worst possible working scenario of 100% extension, payload and speed. The total reaction time is 538ms, and applying the ISO 13855 norm an equation is given to obtain the minimum distance in which a human can be from the machine that ensures that if he decides to go straight to the cobot, it will stop before he arrives.

$$S = (K \times T) + C$$

Figure 21: Safety Distance Equation (ISO 13855)

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S = Minimum distance in millimetres between the detection zone and the dangerous zone.

K = 2 000 mm/s if $S \leq$ 500 mm, 1 600 mm/s if $S >$ 500 mm.

T = Reaction time in seconds.

C = 8 (d – 14), where the d is the detection capacity of the sensors of the dispositive in millimetres (given by the manufacturer).

t_scanner = 62ms
t_safety_CPU = 10ms
t_cobot = 466ms (payload 33%, speed 100%, extension 33%)
T = 538ms

S = 1600 * 0.538+1080 = 1940mm

Scanner Master: Datalogic Sentinel SLS-M3-0812-E
Scanner Esclavo: Datalogic Sentinel SLS-R3-E

Figure 22: Safety Distance Calculus

3.1.4 Human Robot Collaboration and compliance with safety standards

3.1.4.1 General Procedures and Compliance Tests

Nowadays the automatization of productive process in manufactures is increasingly high, and the authorities must ensure that this kind of cells are safe and any risk or potential danger that could appear is taken into account and addressed properly. The specific norm that stablishes requirements for automatic systems and industrial cells is the **ISO 10218**, which is divided in two parts.

The first part is the **ISO 10218-1:2011** norm. All directives for designing a safe industrial robot are stablished in it. It exclusively describes the basic risks associated to the robots and the requirements to eliminate or reduce those risks. The different kind of risks are related with the nature of the automatization process and the complexity of the installation. They depend on the kind of robot, its function, the way it is installed, programmed, operated and maintained.

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The second part is the **ISO 10218-2:2011** norm. In this norm the object of analysis is the whole industrial robotic system and cell when installed in automatized stations and production lines. The norm describes the basic risks and dangerous situations identified in those systems, and it provides the requirements to eliminating those risks properly.

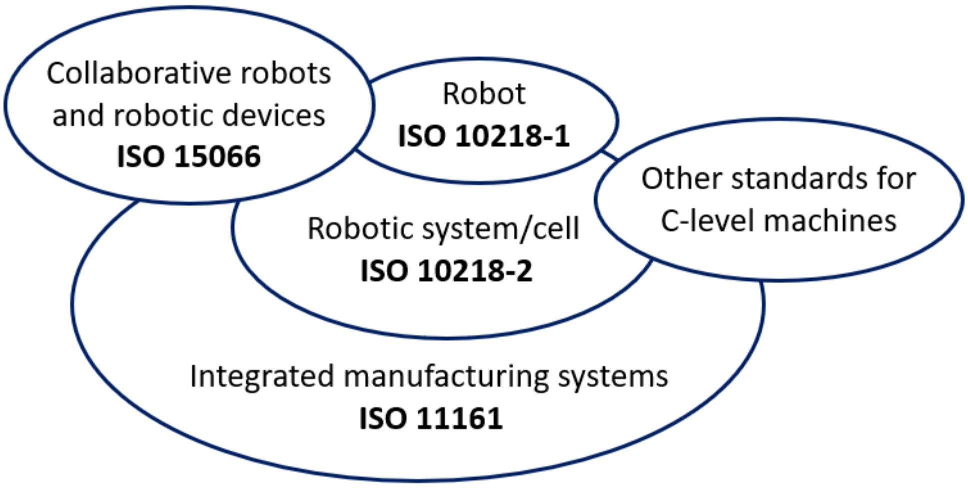

Figure 23: Diagram of relationships between standards for collaborative robotic system

Those norms previously presented are applicable for all kind of automatized cells, but the use of collaborative robot systems is increasing in industrial manufactories. Due to that, a specific norm has been stablished to apply in specific collaborative robotized cells. The **ISO 15066** standard outlines the steps that must be taken to incorporate industrial cobots into factories, including the use of protective measures when working next to operators, identifying potential hazards and assessing the level of risk to minimize harm.

This standard provides technical guidelines, safety measures, and recommendations for creating collaborative workspaces that are safe, such as risk assessments, hazard identification, and recommendations for the design process.

It specifies the maximum permissible collaborative force and pressure that different body parts can support without it being dangerous for the worker when he gets hit or entrapped due to

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automatic movements. It also defines safety requirements for different modes of collaborative robot operation, such as hand-guiding, power and force limiting, and speed and separation monitoring.

The norm also provides recommendations for safeguarding measures that can be implemented to ensure operator safety. These safeguards include safety mats, light curtains, and other devices to monitor operator proximity and ensure a safe operating environment.

The safe reduced speed gets determined through an impact test. The **ISO/TS 15066** norm explains the requirements than must accomplish any industrial collaborative cell. It is stablished the amount of force and pressure the different parts of the human body can resist, depending on the kind of hazard.

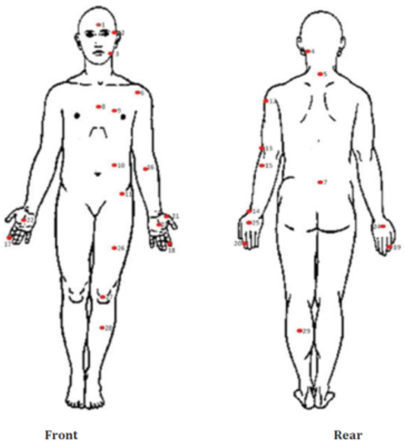

Figure A.1 — Body model

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 24: Pressure and Force Limits (ISO/TS 15066)

Due to those limits the speed of the robot cannot exceed the value that produces the highest admissible force. To verify the speed is not above the limit, an impact test must be taken. These tests consist of the following steps:

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a) Identify the dangerous parts of the station.

b) Stablish which parts of the body can get hurt and give the robot a collaborative speed.

c) Place piece of paper thar has ink inside of it is placed and recreate the dangerous movement. When pressure is applied to the paper, the ink gets freed and it stains the paper, the darker the stain the bigger the pressure.

d) The paper gets scanned and processed to translate the colour of the ink to pressure applied and obtain the maximum.

e) If the norm is not compiled the speed must be reduced and the whole test must be repeated until all dangerous movements are safe.

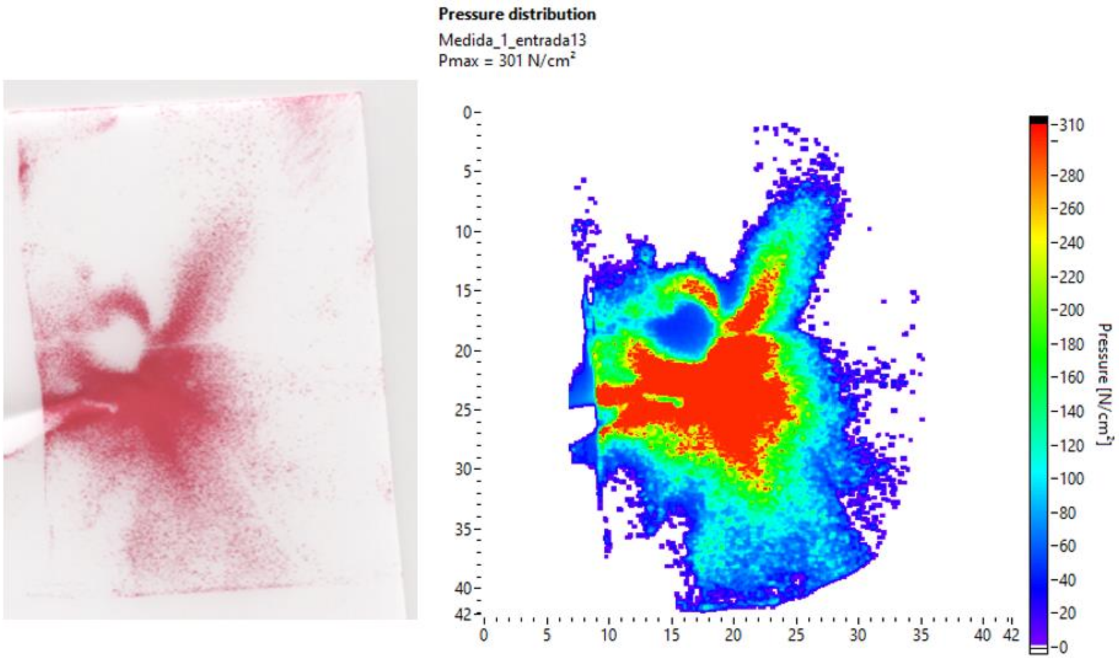

Figure 25: Example of an Impact Test

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3.1.4.2 Analysis of optimal HRC setup for IKOR's use case

An analysis of the best HRC modality for IKOR's use case has been done, explaining all the different configurations possible and how it would affect the ability to collaborate of the station.

At the end of the study, considering several items, concludes that the best option is to build a fully-collaborative cell where the cobot works all the time at a reduced speed. The worker can be all the time next to the cobot without it being any risk for his health and without any king of safety device.

The mark given is based on these criteria:

Table 1: HRC assessment criteria

	5	4	3	2	1
Cycle Time	Works at a fast speed, but it moves at a collaborative speed when safety area is invaded. The safety area is rarely invaded.	Works at a fast speed, but it stops when safety area is invaded. The safety area is rarely invaded.	Works at a fast speed, but it moves at collaborative speed when safety area is invaded. The safety area is usually invaded.	Works at a fast speed, but it stops when safety area is invaded. The safety area is usually invaded.	It always works at collaborative speed
Price	No devices	One standard device	2 standard devices or one atypical device	3 standard devices	4+ standard devices or 2+ atypical devices
Integration and Commissioning Time	Lowest: Robot working at a collaborative speed requires no devices	One or two standard devices connected directly to the robot. Robot stops when safety area crossed.	More devices connected to the robot or few standard devices connected to a PLC. Robot stops when safety area crossed.	One or two standard devices connected directly to the robot. Use of safety PLCs mostly. Robot stops and reduces speed to collaborative when safety area crossed.	More devices, including atypical (cameras), connected to a safety PLC or more complex setups. Robot stops and reduces speed to collaborative when safety area crossed.
Accessibility	Station open and easily accessible.	Station open, warning signs required.	Station open and accessible by most sides. Safety fences or equivalent required for closed sides.	Station mostly surrounded by safety fences. Accessibility very limited.	Station closed and access only possible when station completely disabled.
HRC	Totally collaborative. The operator can work at any distance to the robot.	Very collaborative. The robot works at a reduced speed when the operator is close. The operator can access the robot from most directions.	Quite collaborative. The robot works at a reduced speed when the operator is close. The operator can access the robot from few directions.	Kind of collaborative. The robot stops when the safety area is crossed. The operator can access the robot from few directions.	A little collaborative. The robot stops when the safety area is crossed. The robot needs to be reset manually. And operator has difficulty in accessing the robot.

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Table 2: Assessment for IKOR's use case in mode 3 collaboration

CASE: 3			
Description: Robot working at a reduced speed, humans can work next to it at any time, no safety devices are needed.			
Item	**Punctuation (1-5)**	**About:**	
Cycle Time	1	It always works at reduced speed.	
Price	5	No safety device must be bought.	
Integration and Commissioning Time	5	No safety device must be installed.	
Accessibility	5	There is no obstacles or safety zones.	
HRC	5	The robot is 100% collaborative.	
Overall Mark:	**21**	**Safety:**	**OK**

The advantages of this mode are that the station is totally accessible, workers can cross and rest inside the station without interrupting its normal behaviour. No safety devices must be installed and no safety areas must be designed, so the installation is the easiest one in terms of devices required. The main obstacle is that the cycle time is longer and that can affect the productivity of the station, so in case the main design criteria is to achieve the highest production rate (equivalent to the lowest cycle time), other kinds of collaboration modes would be a better choice.

Other results of different HRC choices were the following:

Table 3: Overall marks and comments resulting from the HRC analysis applied to IKOR's use case

CASE	DESCRIPTION	COMMENTS	OVERALL MARK
1	Robot working at a fast speed but when someone is detected by the	Good compromise between HRC and cycle time, high costs	17

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	scanners it stops and restarts at reduced speed.	because of the need of bareers and scanners to be certified.	
2	Robot working at a fast speed but when someone is detected by the scanners it stops.	Easier to program, but same cost as the previous case and lower cycle times.	14
3	Robot working at a reduced speed, humans can work next to it at any time, no safety devices are needed.	Lower cycle time, but the most economic and safe choice. Besides, it suits a high accuracy application.	21
4	Robot working at a fast speed, humans can work next to it but if they enter the safety zone the robot will stop and move at a collaborative speed. Light curtains used as safety elements.	Very flexible, easy to adapt to other applications, but even higher costs and harder to program, due to the need to connect both laser scanners and light curtains to the robot.	15
5	Robot working at a fast speed, humans can work next to it but if they enter the safety zone the robot will stop and move at a collaborative speed. Protection by 3D camera	Not suitable for a real TRL9 industrial application because cameras cannot be used to these kinds of collaborative robotic cells in a legal way.	16

Therefore, the final layout of the station was agreed as the following one:

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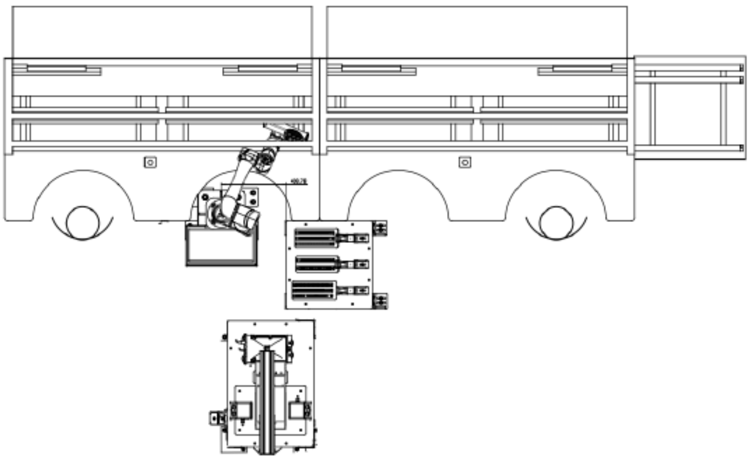

Figure 26: Layout Case 3 HRC Analysis

However, the IKOR’s use case cell that has been built is a prototype and some changes have been made in order to adapt the design to a less collaborative and more productive one. The cell works at a fast speed, and some fences have been installed with the aim of protecting the operators that could possibly work in those places.

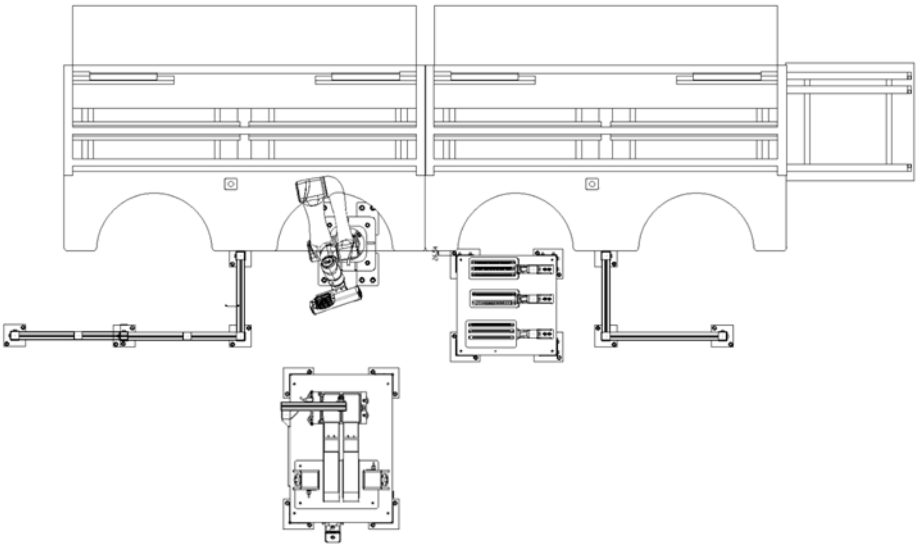

Figure 27: IKOR's Prototype Layout

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As the cell will be tested in a restricted and confined space, we can assume that professionals present during the evaluation will be aware of the dangers that are led by approaching the robot when it is working at a fast speed. This is consistent with the Technology readiness Level established in the project (7 - System prototype demonstration in operational environment).

In order to define the characteristics of the cell in a situation where it is working inside a real productive process, the first iteration has taken place to define the collaborative speed of the cobot. The cobot planner website's role is to help within this task (https://cobotplaner.de/).

The specifications of IKOR's use case, the tool, the configuration and the possible risks identified have been defined and introduced in the website and some tests have taken place. The results obtained are summarised in the following table:

Table 4: Cobot Planner Results

TEST Nº	KIND OF HAZARD	MOVEMENT DIRECTION	BODY PARTS AFFECTED	MAXIMUNG SPEED RECOMENDED
1	Impact	rotational movement over joint 1	Hand / Arm / Trunck	395 mm/s
2	Pinching	vertical movement downwards	Hand / Arm	198 mm/s
3	Impact	vertical movement upwards	Hand / Arm	909 mm/s
4	Impact	horizontal forward movement	Trunck	395 mm/s

Accordingly, when defining the cobot's speed a useful start point is the minimum 198 mm/s speed. The next step is to perform the impact test with the corresponding equipment, and it is the responsibility of the engineer to analyse the results obtained and to obtain conclusions, whether if the speed must be reduced, can be increased still compiling with safety but speeding up the process, or it is already correct.

3.1.4.3 Impact test applied to IKOR's use case

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The impact test consists on empirical measurements of the force applied by the robot in several critical positions that are considered the most dangerous for the operators. This test is done when the final application is completely defined.

When the sequence described in previous sections for picking and placing components was operative, three steps were considered as the most dangerous for operators:

Figure 28: First critical risk.

This first risk is when the robot performs a pick operation. It is considered equally dangerous for picking from the feeder and for picking from the intermediate surfase, so just a measurement is enough to ensure the force in this step is low enough.

In the photo, the force sensor can be seen placed where the operator could put a hand, to simulate what force and pressure could be applied.

The same procedure was applied when considering the placing operation:

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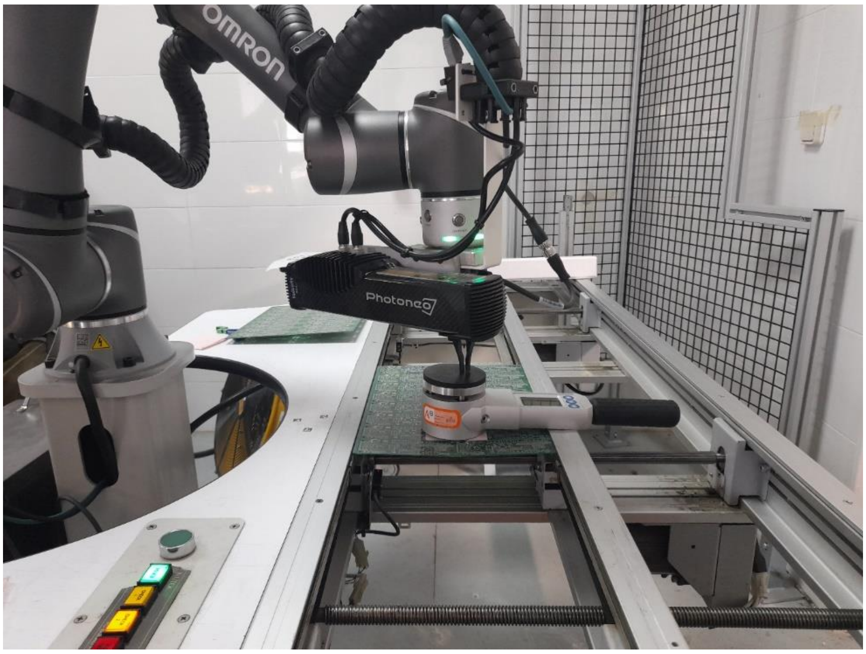

Figure 29: Second critical risk

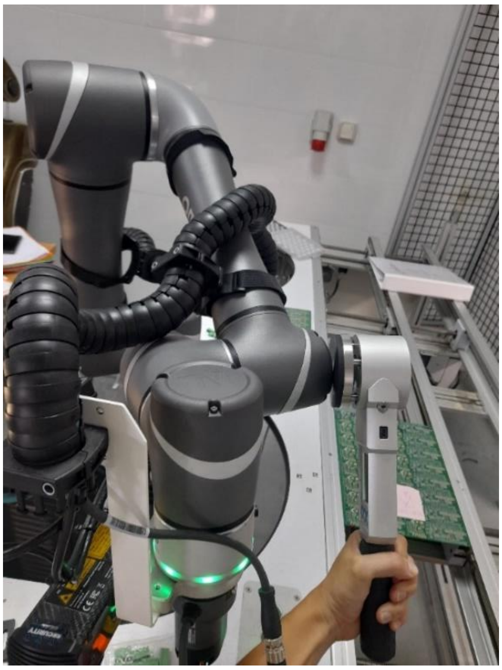

Figure 30: Third critical risk.

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And the third risk is generally considered in all stations that use cobots, that is the impact force when the robot is moving between points that are at a high distance.

This resulted in four different measures. The results of these tests were the following:

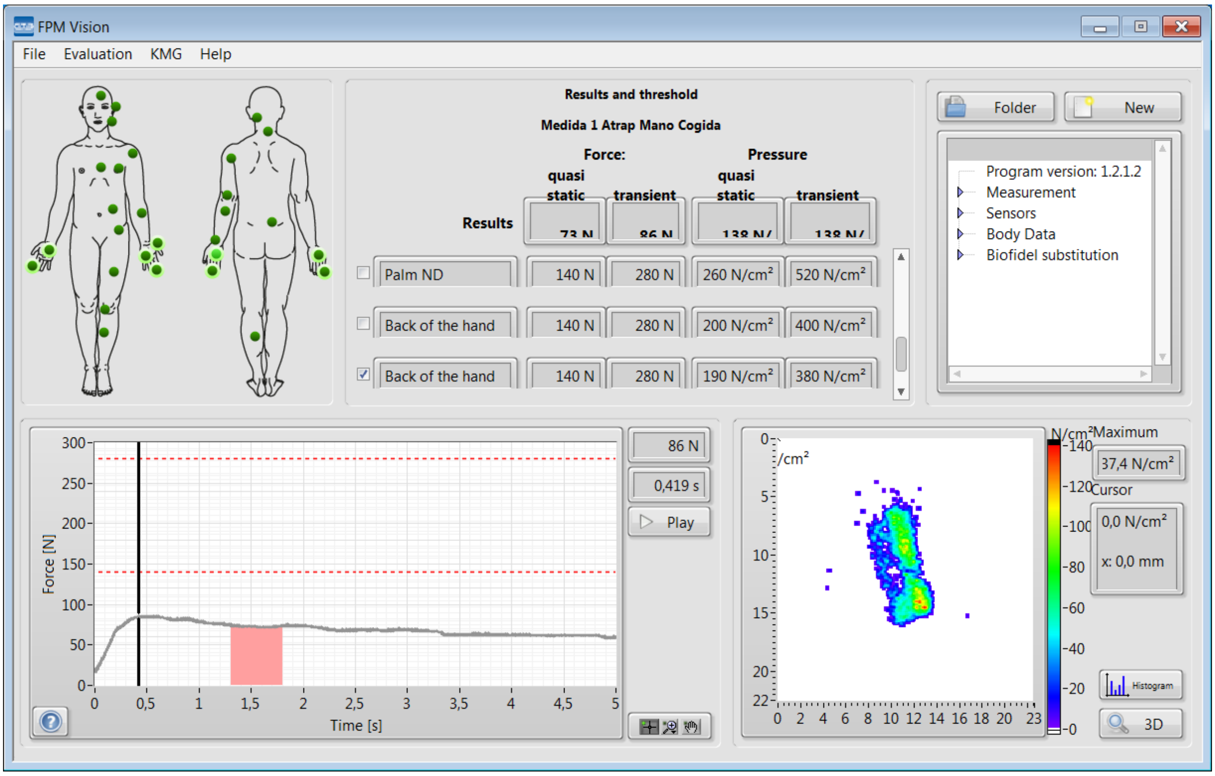

Figure 31: Results of first measurement

In this first test, the force of the robot applied to the hand is evaluated. In the graphics, we can identify the side of the hand evaluated, (back side, in this case), then, the limits and measurements taken, and also, on the bottom right side, the digitalized image of the pressure distribution of the impact.

We can clearly check that the measurements are well below the limits defined by the norms. In this case, the limits are 280 N for the transient impact and 140 N for the static impact. Both limits can also be seen in the graphic with dotted red lines. The black line marks the point of

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maximum transient force, that is 74 N, and the red square the value considered static, 63 N, as appreciated in the center squares. If the frame of any of the squares would be yellow, then the impact test would be not valid, needing to reprogram the robot to a lower speed or include a mechanical element to reduce the force and pressure of the impact.

The second measurement is considered when the robot hits the operator while moving. The shoulder would be in this case the body part affected and needs to be assessed:

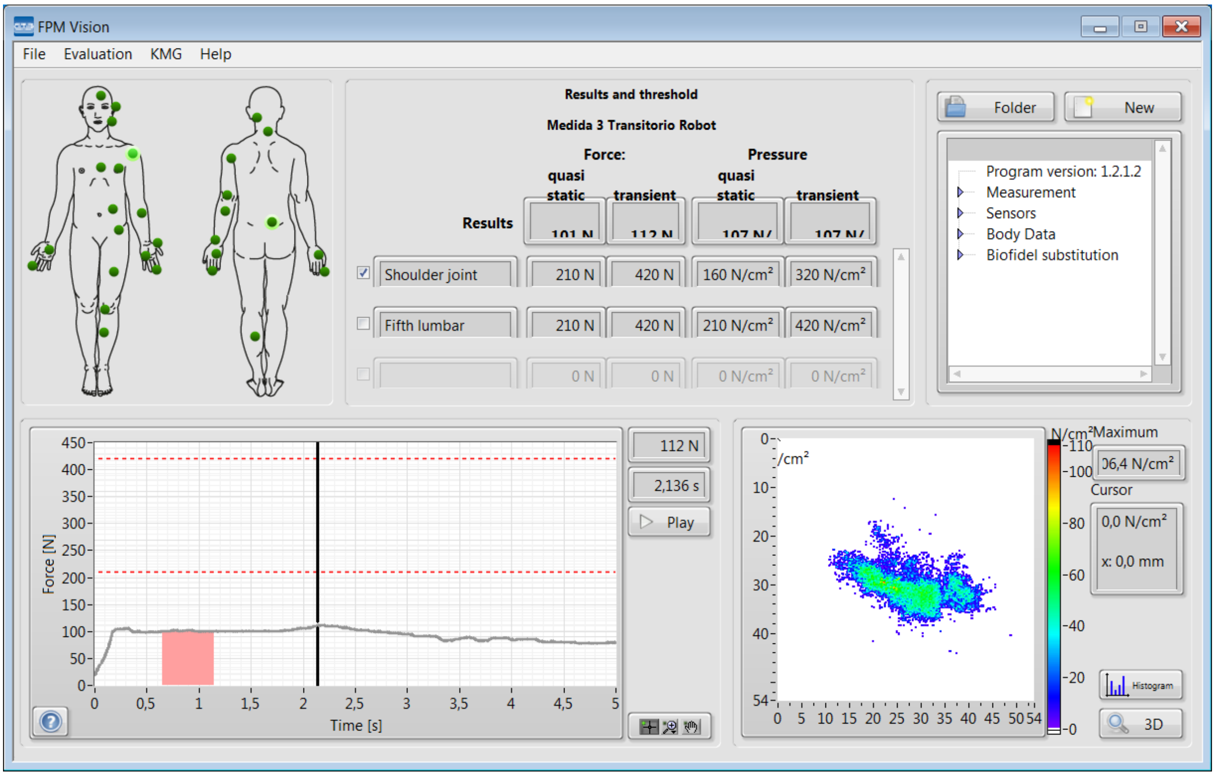

Figure 32: Results of second measurement

We appreciate that the limits are higher and the difference between the transient force and pressure and the static value is not so high. Again, it is confirmed we are way below the limits.

Finally, the third impact is measured, assuming the gripper opened, as we can see from the force distribution image:

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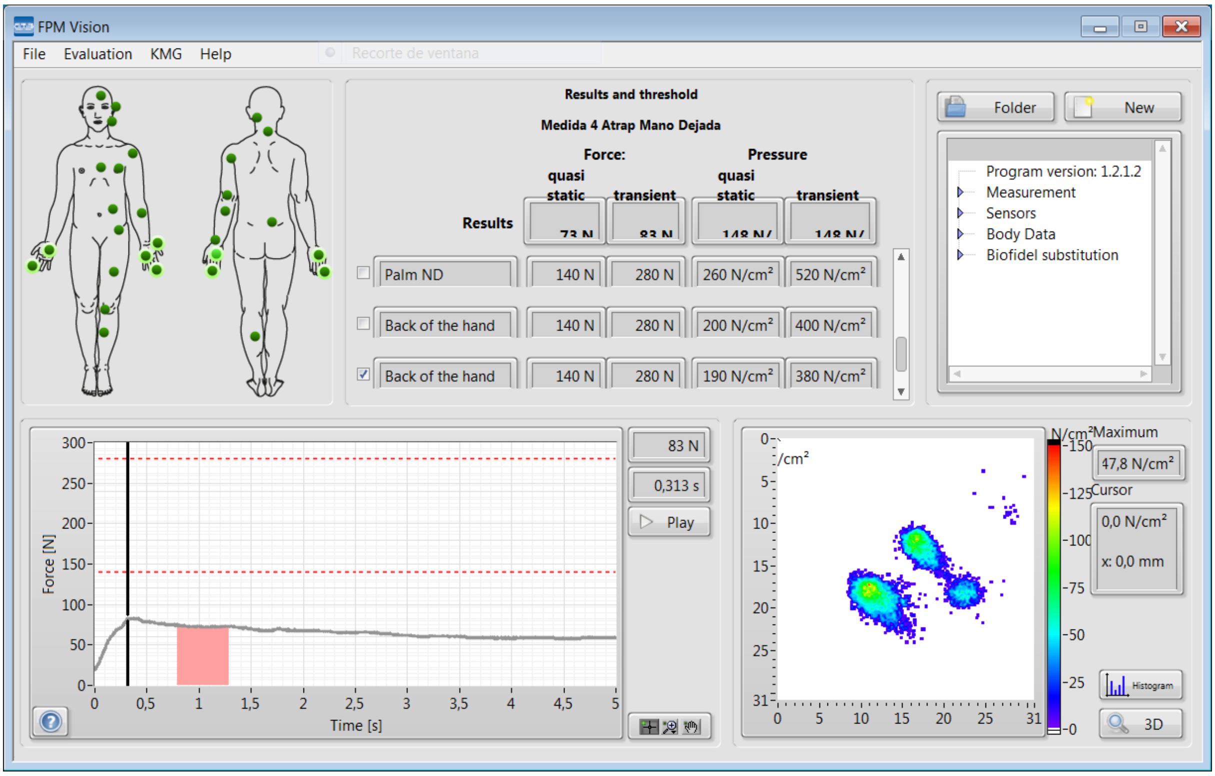

Figure 33: Results of third measurement

As we are again evaluating an impact on a hand, the limits are the same as in the first measurement. Here, the impacts show a little bit higher values of force, but below the limits anyway.

With all the potential risks assessed and confirmed below the limits, we conclude that the station is collaborative.

3.2 ICPE's Use Case

3.2.1 Requirements and specifications (including HRC)

The ACROBA project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 101017284.

The aim of ICPE is to set up a collaborative pilot line infrastructure for electric motor assembly. Two different robotic cells will be prototyped, one for the coils winding task and the other for the bonding operations. Even if the two cells present a similar structure, two independent cells will be prototyped. The aim is to increase the production, while improving the general working conditions and the ergonomics of the operators, without replacing their decision-making role. A high safety level in each phase of the collaborative production process will be assured by specific hardware and software solutions.

3.2.1.1 Winding process

The winding cell will perform coil winding on different type of stator, aiming to increase the production rate and to relief operators from the most repetitive tasks. The cell presents two different working zones, allowing the operator to extract the finished stator while the robot is performing the winding operation in the clear zone. The stators are installed on two motorized rotatory table, whose ensure a precise positioning. This is an important specification since some stators have a very small gap between the teeth where the end-effector needs to access. The tables are driven by two stepper motors coupled with two orthogonal gearboxes with a backlash < 5 arcmin. There are a total of 9 stators to be wounded as shown in the next table below. Each stator has different geometric parameters such as diameter, height, and number of teeth.

Table 5: Specifications of stator models

Test Name	Model Name	Diameter [mm]	Height [mm]	Number of teeth
TC_3001_1_1	KSO152010	153	18	24
TC_3001_1_2	KSO230010	230	25	36
TC_3001_1_3	KSO284010	284	10	72
TC_3001_2_1	KSO152100	153	100	24
TC_3001_2_2	KSO230100	230	100	36

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TC_3001_2_3	KSO284100	284	100	72
TC_3001_3_1	KSO230025	230	25	24
TC_3001_3_2	KSO230050	230	40	36
TC_3001_3_3	KSO230075	230	75	72

Before the winding operation starts, the robot must detect the first tooth to be wound. A laser sensor is mounted on the end-effector for this purpose. The first tooth is highlighted with a special sign and the robot is set to assume a process initialization position, bringing the sensor led close to the stator mounted on the rotary table. The operator manually adjusts the table to align the sign of the stator and the led. Once the alignment is achieved, the operator activates the rotatory table, which starts rotating until the sensor detects the absence of the tooth, indicating a gap between teeth. The tooth which follows the detected gap is the first to be wound.

3.2.1.2 Bonding

The robotic cell will perform magnet bonding on different type of rotors, aiming also in this case to improve the productivity and the working conditions. The robotic cell presents one spot for bonding operation, the tray containing the magnets to be bonded and a rotary table where the bonding will be performed. A two-component glue is used to bond the magnets on the rotors. The operator applies the adhesive on the rotor with a specific tool, while the robot positions the magnets under a spray that applies the activator. After the glue is applied, the magnets are placed on the rotors by the robot and the bonding occurs.

The robot is equipped with a pneumatic gripper which presents three different types of vacuum pads to grasp different magnets. Due to the strong magnetic force exerted by the magnets, the pads are sized not to lose the grip before the magnets are positioned on the rotors. There are a total of 6 different rotors and magnets to be bonded, each of them with different geometric parameters as shown in **Error! Reference source not found.**. The end-effector is designed to ensure the possibility of installing a camera, needed for skills such as CAD matching.

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Table 6: Specifications of rotors models

3.2.1.3 HRC

Test name	Model name	Rotor diameter [mm]	Rotor length [mm]	Magnets size [mm]
TC_3002_1_1	KSO056057	25	57,3	18,5 x 10,3
TC_3002_1_2	KSO082076	43,3	77	18,5 x 17,1
TC_3002_1_3	KSO170025	107,2	25,9	13 x 12,6
TC_3002_2_1	KSO095015	48	32	15 x 14,8
TC_3002_2_2	KSO095030	48	47	15 x 14,8
TC_3002_2_3	KSO095045	48	62	15 x 14,8

To guarantee safety in both cases, laser sensors to detect human presence are implemented. The robot operates at fast speed, but when a worker enters the safety zone from any side of the cell, the robot immediately stops. Once the robot is stationary, if the worker is still inside the safety zone, it switches to collaborative mode with reduced speed. As soon as the safety sensor no longer detects the worker's presence, the robot returns to its fast speed. This design offers the robot both a collaborative and a non-collaborative mode, which adds flexibility to the station.

3.2.2 Mechanical and pneumatical designs

3.2.2.1 Winding cell

The ACROBA project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 101017284.

The robotic cell is composed of aluminum profiles, with a footprint of 1560x1700 mm. Inside the cell are installed: two winding spots, a robotic arm, a wire tensioning system and safety equipment.

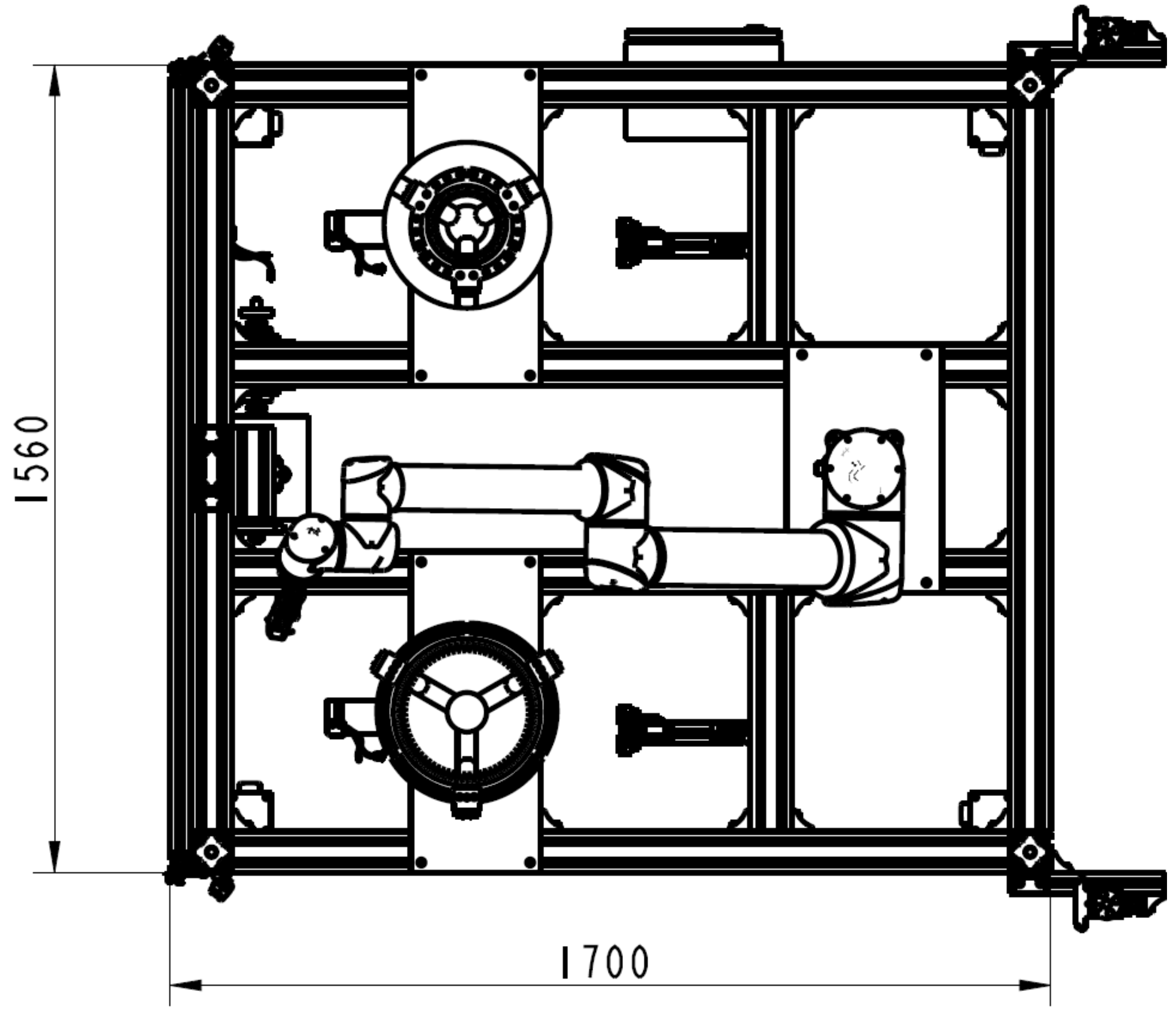

Figure 34: Winding cell layout

During the winding operation, the end-effector turns around the teeth as shown in Figure 35, the needle that brings the copper filament passes through the narrow gaps between the teeth.

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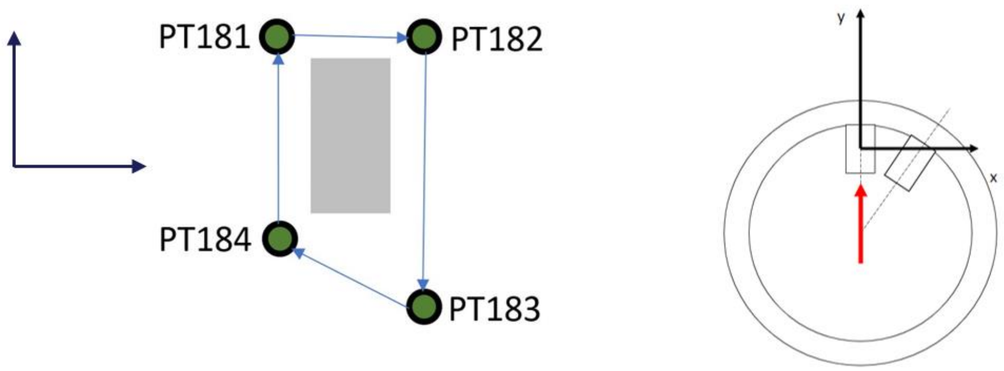

Figure 35: Winding path

Stators are attached to chucks driven by stepper motors coupled with right-angle gearboxes with a backlash <5 arcmin, allowing a precise positioning of the stators during the process. In fact, due to the large diameters of the stators, even a small error in the angle position can lead to a collision of the end-effector on the stator teeth.

The final configuration of the rotatory table is shown in Figure 36: to have a zero-backlash coupling between the gearbox and the chuck, it was adopted a bellow joint with keyhole.

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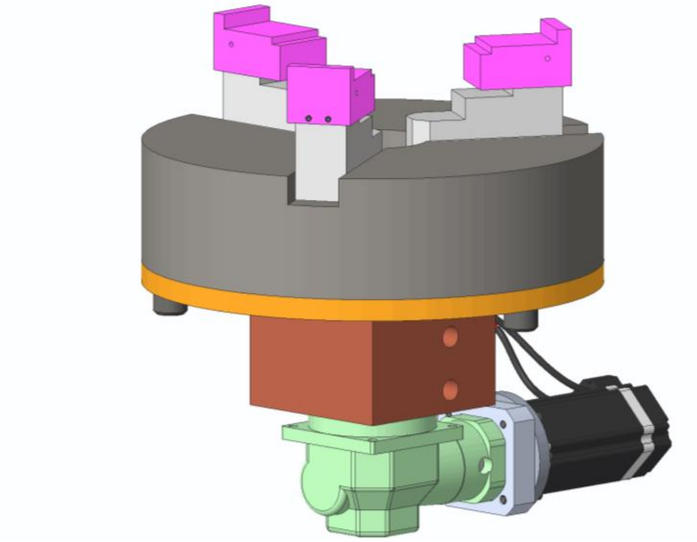

Figure 36: Rotatory table model

The chuck chosen has a jaws stroke of 320mm-185mm, allowing to grasp all the different types of stators required within the project. In Figure 37 is shown an example of two different stators installed on the chucks.

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Figure 37: Different stators installed on the spindle

To fix the stator, 3D printed fingers are mounted on the chuck claws, as shown in Figure 38. The design of these elements was made in order to use just one type of finger for all the stator and to not occlude the gap between the stator teeth.

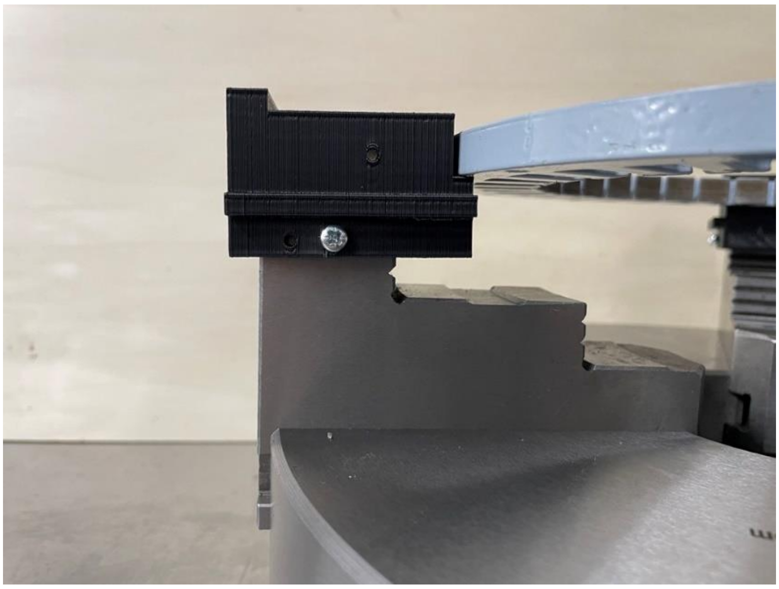

Figure 38: 3D printed finger

The winding is performed by a special end-effector, which presents pulleys to slide the wire into a needle able to pass through the gap between stators teeth. On the end-effector is also mounted the laser sensor for the first tooth detection described before.

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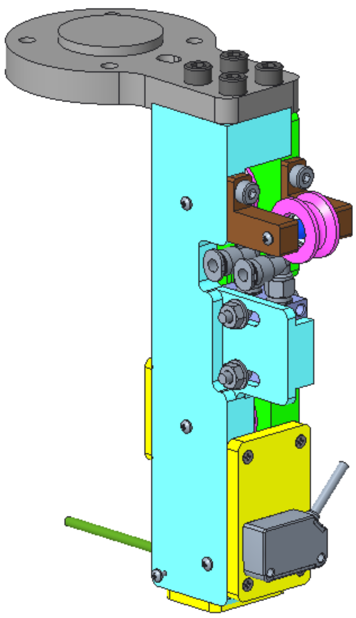

Figure 39: Winding end-effector

On each finger are mounted the three blue elements shown in Figure 40, to fix **n** metal pins, where **n** is the number of teeth of each stator. Pins are used to hold the wire when the end-effector finishes the winding of one tooth and needs to operate on the following one.

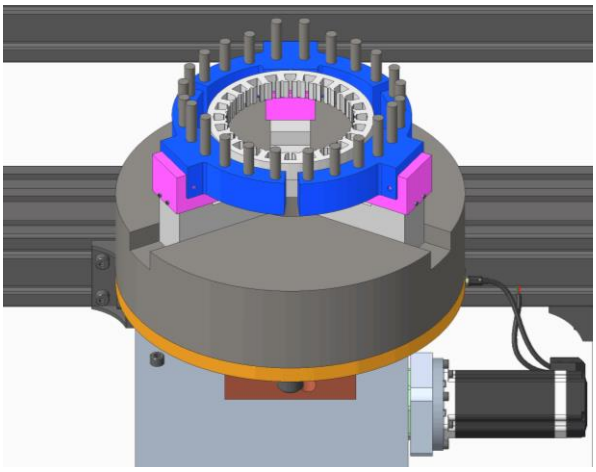

Figure 40: Metal pins to hold the wire

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A system to have constant wire tension has been integrated in the cell. The tool shown in Figure 41 is a commercial tensioner, that keeps the wire tight at a certain value, in order not to let it get stuck inside the end-effector sliding system.

Figure 41: Wire tensioner

The wire is rolled into a motorized coil, and its unwinding is performed according to the tension detected by a special tool under the tensioner. If the tension detected is too low the motor retrieves wire in the coil and vice versa.

Once the winding of a polar pair is completed, the wire is gripped and cut by the tool shown in Figure 42. Both the cutter and gripper are driven by two single-acting cylindrical pistons with return spring.

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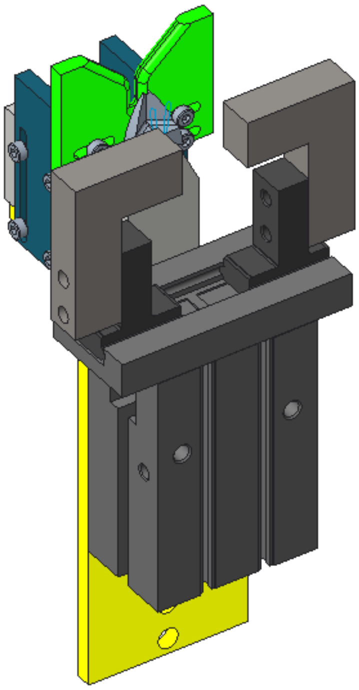

Figure 42: Tool for wire cutting

In Figure 43 is shown the pneumatical design of the winding cell. There is a total of 5 electrovalves and 4 single effect actuator and 1 double effect one.

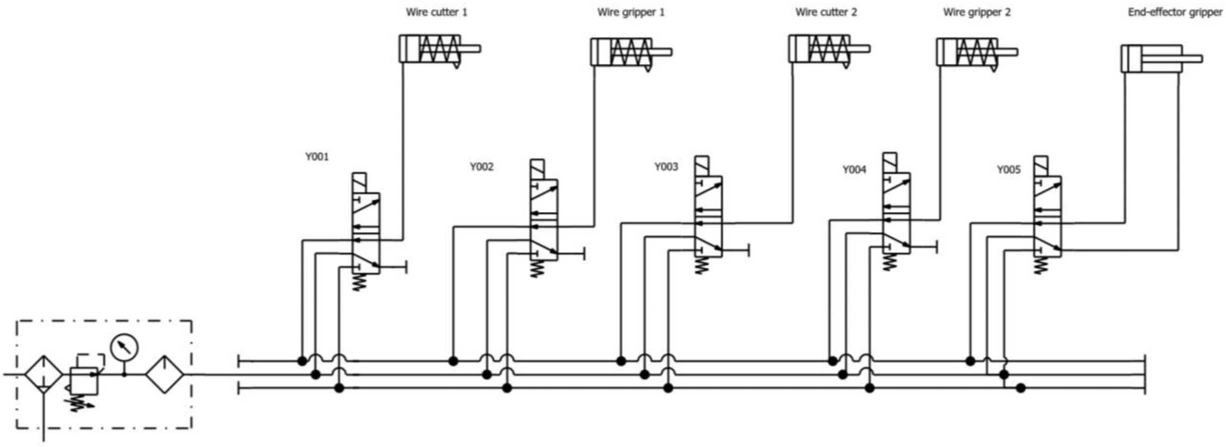

Figure 43: Winding cell pneumatical scheme

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3.2.2.2 Bonding cell

The bonding cell is composed by aluminum frame, with a footprint of 1000X1705 mm. The cell is separated in two different zones: a first one where trays for magnets are allocated and a second one where the bonding is performed.

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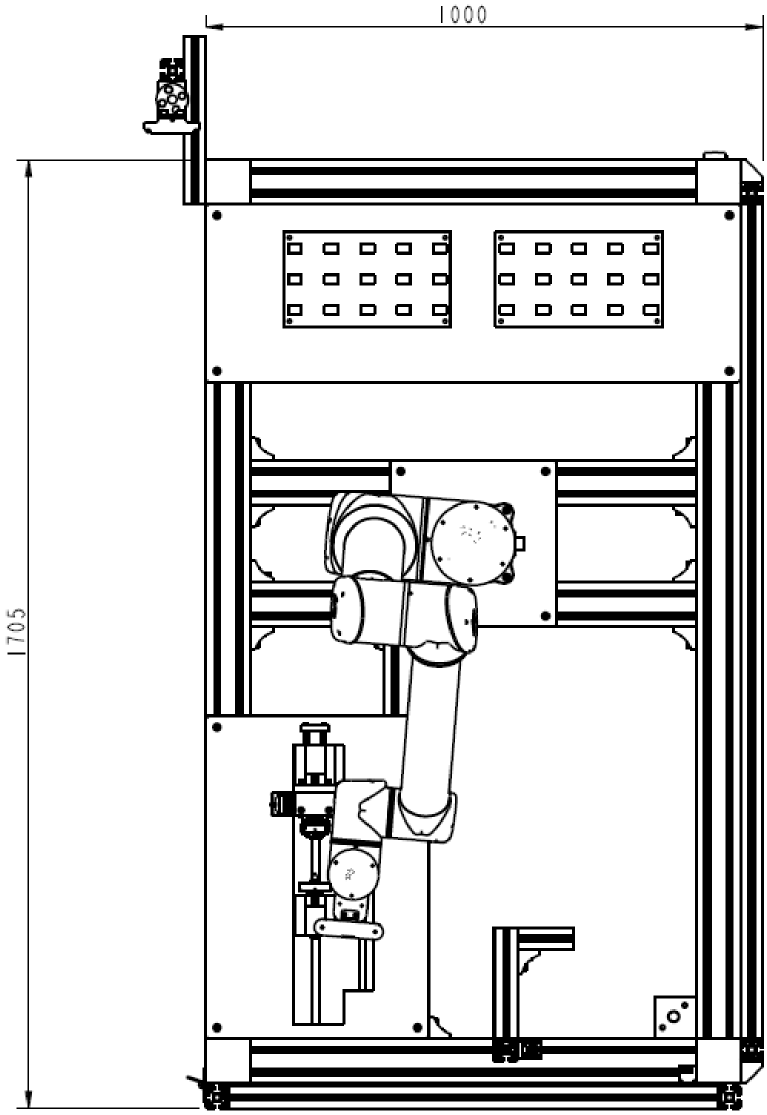

Figure 44: Bonding cell layout

Magnets are stocked on trays positioned on the opposite side of the bonding spot, therefore their coordinated are fixed and known. However, it will be also evaluated the use of the “CADMatching” skill of the ACROBA platform, to localize the different type of magnets, thus ensuring a higher flexibility.

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The rotors are fixed on a spindle that holds the components with a system, shown in Figure 45, composed of a chuck and a lathe-like tailstock.

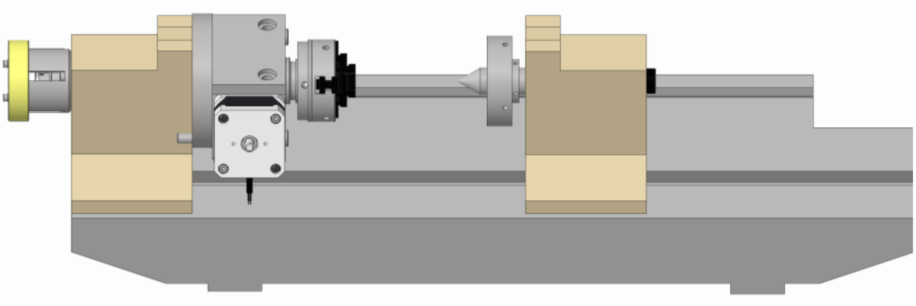

Figure 45: Bonding rotatory table

The rotatory table is motorized by an electrical motor, and it rotates of a certain angle each time a row of magnets is completed, offering a free spot to the robot that will bond the following magnet as shown in Figure 46.

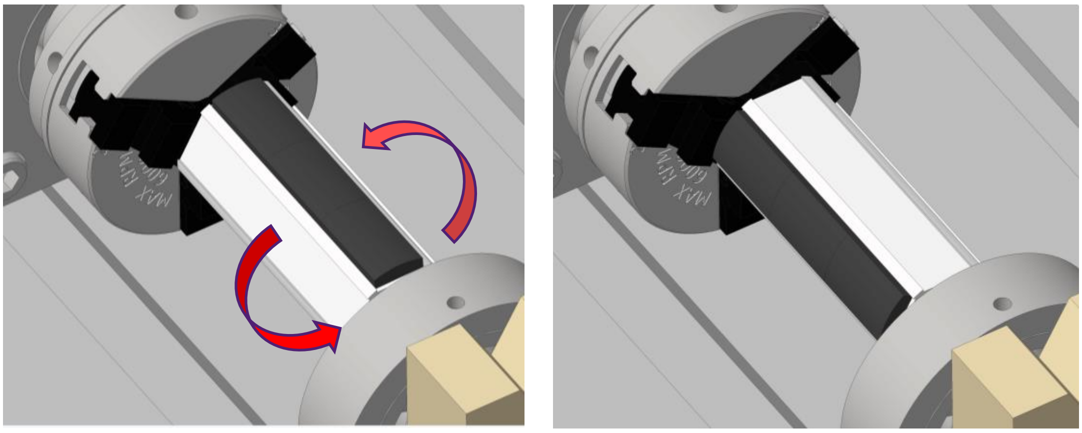

Figure 46: Rotatory table working

The end-effector is a vacuum gripper equipped with different pads and able to host the camera needed for the CAD matching skill, allowing the robot, if required, to identify the magnet and its position. The different vacuum pads are implemented due to the various dimensions of the magnets to be gripped. It is important to stress that, due to the strong magnetic force exerted

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between the magnets and the rotors, having specific vacuum pads dedicated to certain type of magnets will offer a better gripping condition.

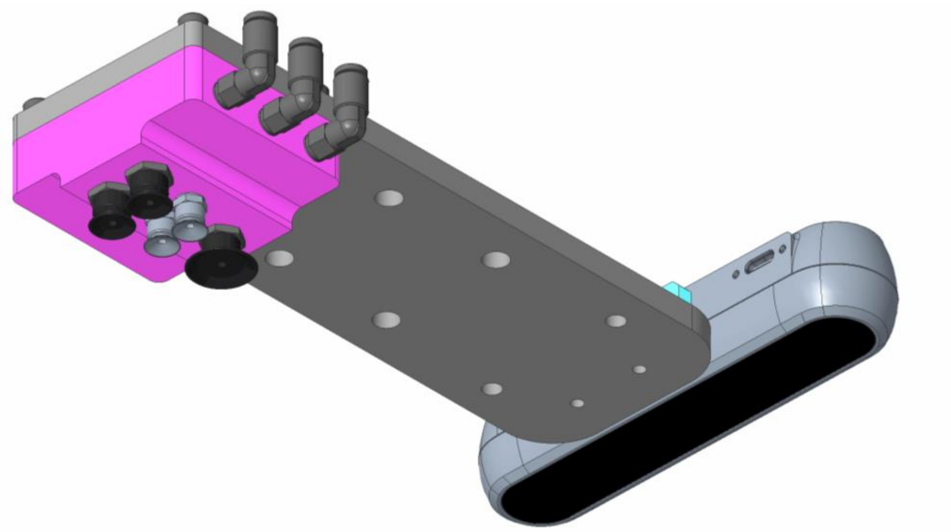

Figure 47: Bonding end-effector

In Figure 48 is shown the pneumatical design of the bonding cell. An electrovalves actuates an ejector which commands three separate vacuum pads.

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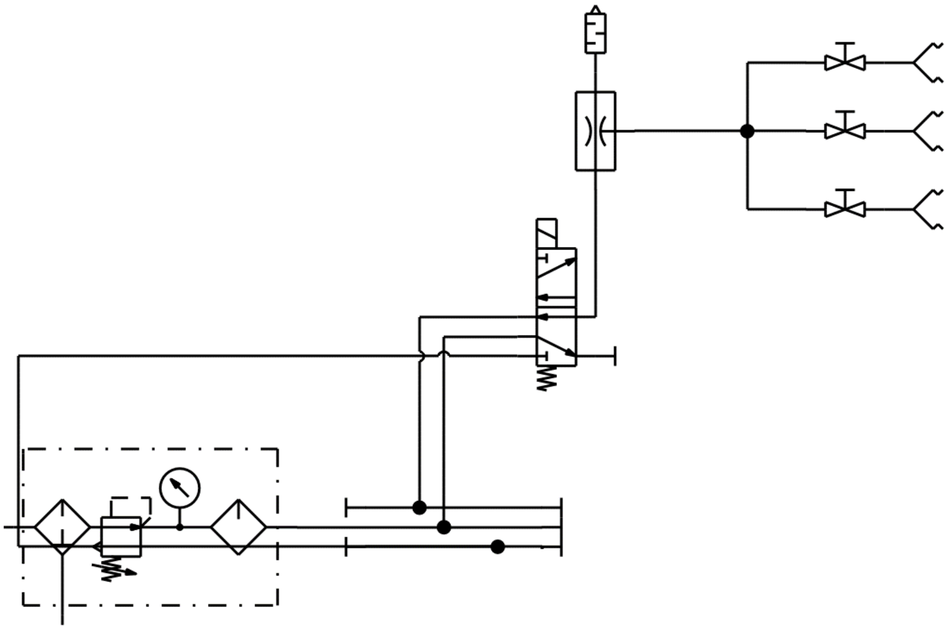

Figure 48: Bonding cell pneumatical scheme

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3.2.3 Electrical Designs

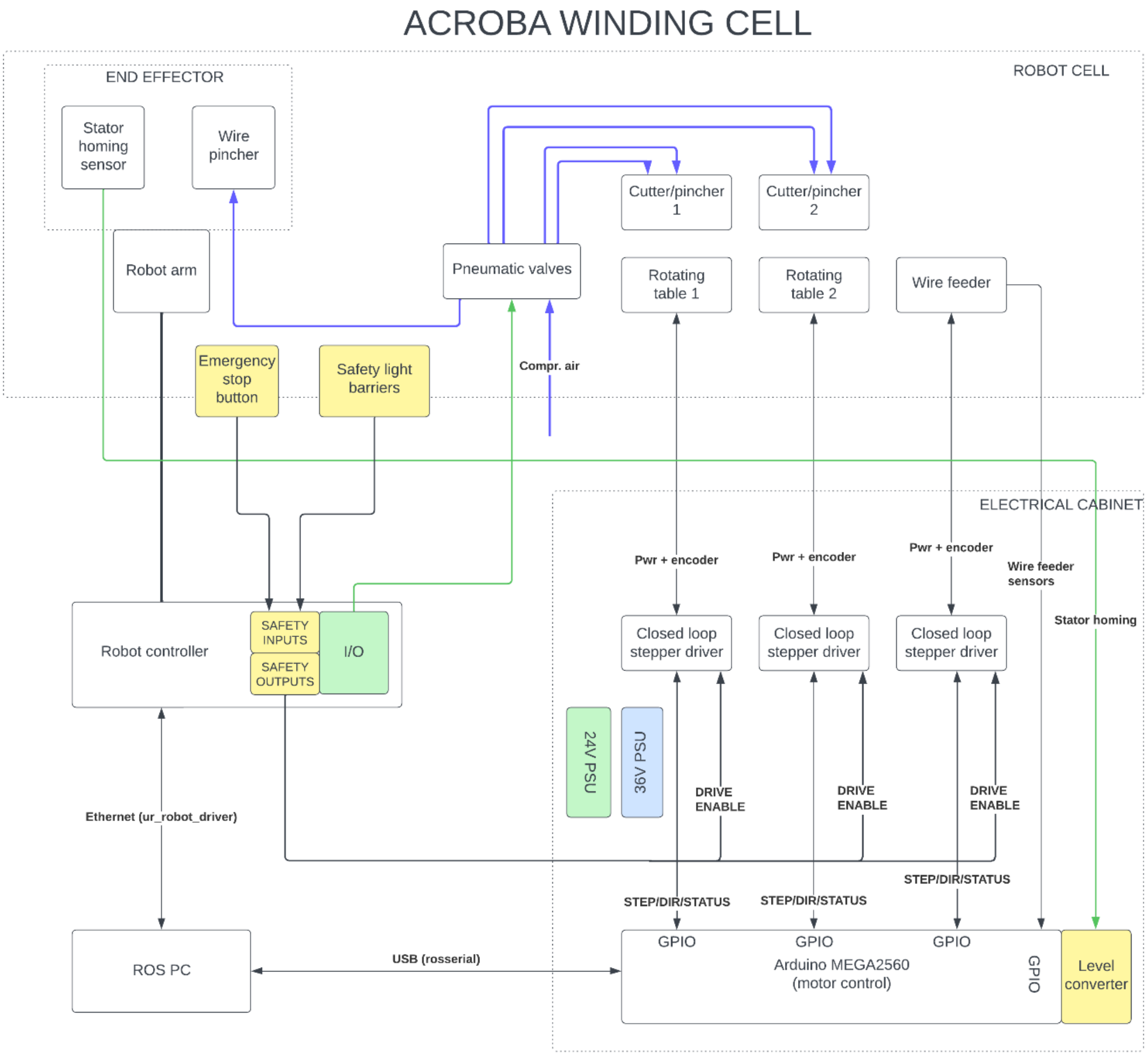

Figure 49: Winding electrical design

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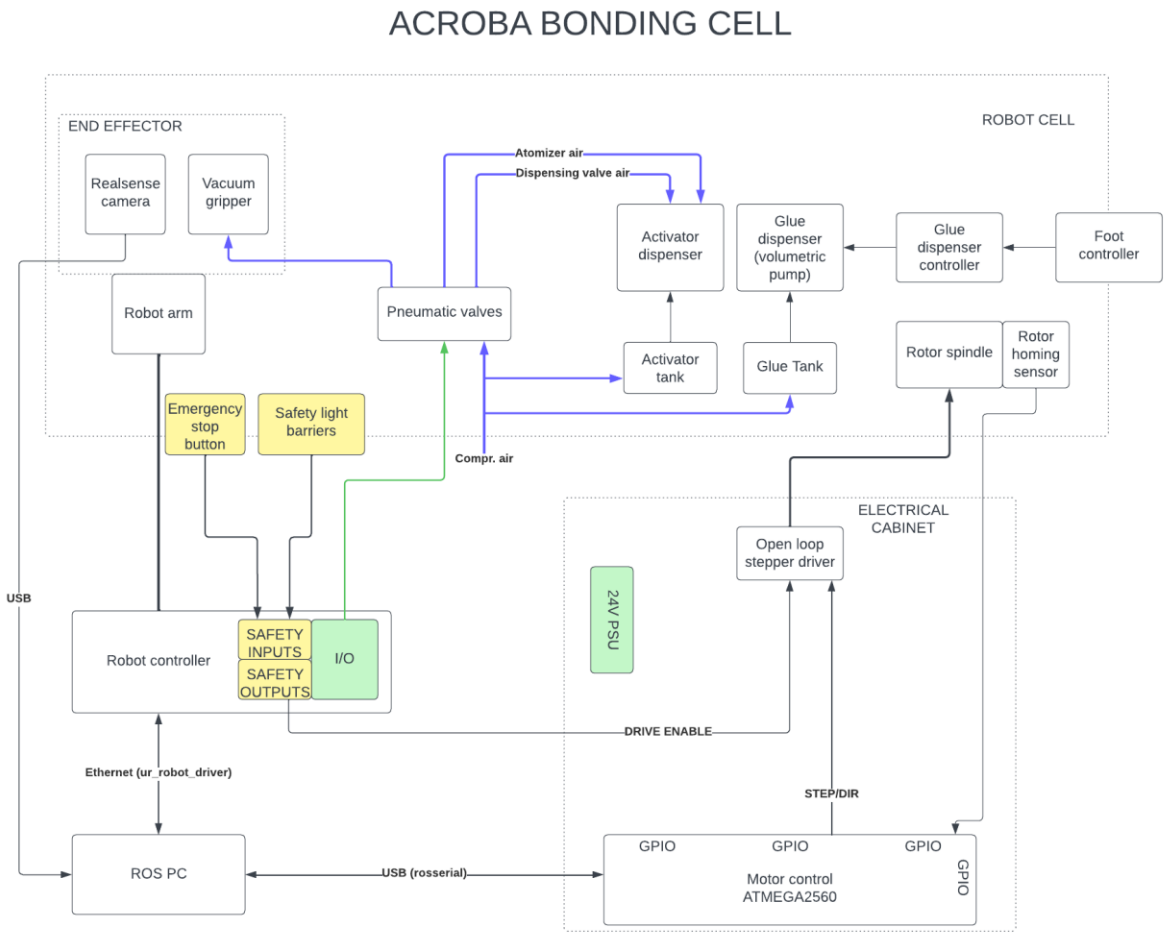

Figure 50: Bonding electrical design

3.2.4 Human Robot Collaboration and compliance with safety standards

For both ICPE's robotic cells, several options for human-robot collaboration have been considered in order to select the optimal design. The safety aspect have been assessed evaluating five different factors:

1. **Cycle Time:** The station must accomplish and minimize de cycle time of the operation.
2. **Price:** It is important to make sure the safety modality it is not overprized in relation to its budget and the future client's budget.

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3. **Integration and Commissioning Time:** It refers to the time it would take to integrate the different elements that the modality requires.
4. **Accessibility:** The station should be as open as possible to ease the operator's mobility and avoid having lots of fences or any other kind of obstacles.
5. **HRC:** It is important to maximize the collaboration between the workers and the robots.

The different options have been assessed in order to consider their strong and weak points and take into account the priorities for the stations, but comply the safety requirements (ISO 13855, ISO 13857, ISO 15066, ISO 12100) is mandatory.

In order to calculate the safety distance from the robot, the reaction time of the different components must be known. This information are reported below:

- **light curtain** 10 ms, wire synchronization system, single-line ON/OFF.
- **UR10 100ms**, considering the joint with the bigger stopping time with an extension of 66%, a payload of 33% and a speed of 66%

The total reaction time is 110 ms and applying the ISO 13855 norm an equation is given to obtain the minimum distance in which a human can be from the machine that ensures that if he decides to go straight to the cobot, it will stop before he arrives.

$$S = (K \times T) + C$$

Figure 51: Safety Distance Equation (ISO 13855)

$S =$ Minimum distance in millimetres between the detection zone and the dangerous zone.

$K =$ 2 000 mm/s if $S \leq$ 500 mm, 1 600 mm/s if $S >$ 500 mm.

$T =$ Reaction time in seconds.

$C = 8\ (d - 14)$, where the d is the detection capacity of the sensors of the dispositive in millimetres (given by the manufacturer).

$$t_{sensors} = 10\ ms$$

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$$t_{cobot} = 100ms\ (payload\ 33\%, speed\ 66\%, extension\ 66\%)$$

$$T = 110\ ms$$

$$S = 428\ mm$$

In the next sub-sections, the final safety layout chosen for the two ICPE's robotic cells are presented.

3.2.4.1 Winding cell

The final design includes a light curtain (highlighted in red in Figure 52) that covers the three free sides of the structure, ensuring that the entire hazardous area is covered by a single safety zone. It is possible to cover three sides with a single light curtain thanks to two mirrors placed at the corners of the structure that extend the range of the sensor. In this way, the robot operates at fast speed, but when a worker enters the safety zone from any side of the cell, the robot immediately stops. Once the robot is stationary, if the worker is still inside the safety zone, it switches to a collaborative mode with reduced speed. As soon as the safety sensor no longer detects the worker's presence, the robot returns to its fast speed. This design offers the robot both a collaborative and a non-collaborative mode, which adds flexibility to the station.

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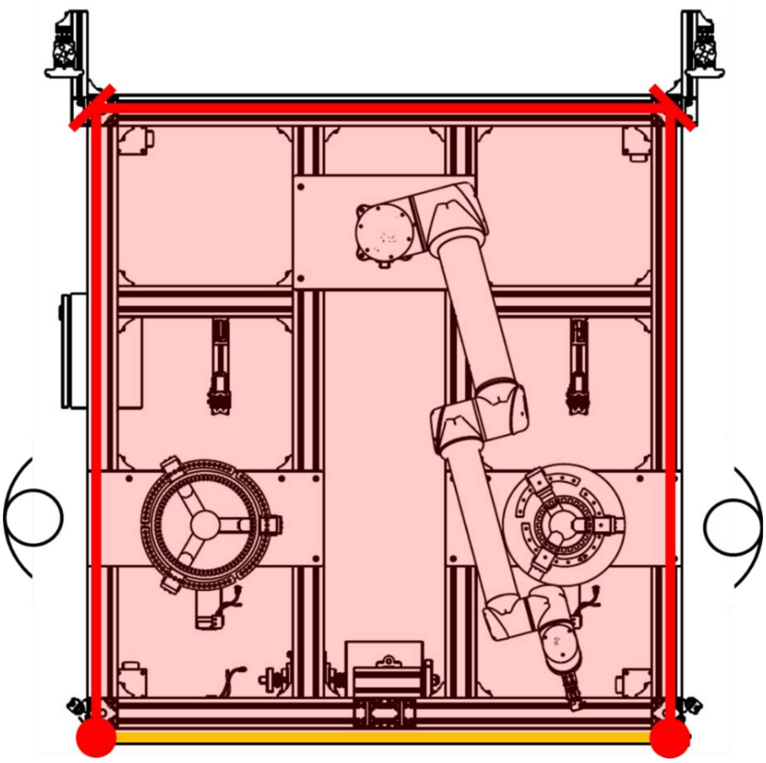

Figure 52: Safety scheme winding cell

In Table 7 the main aspects of the solution adopted are summarized. Each aspect has a mark that goes from 1 to 5.

Table 7: Main safety aspects of the winding cell

Winding cell		
Description: Robot working at a fast speed but when someone is detected by the light curtain it stops and restarts at reduced speed.		
Item	**Punctuation (1-5)**	**About:**
Cycle time	4	Usually, the robot works at a fast speed but at some moments it must work at reduced speed (not optimized version).
Price	4	One light curtain is needed to cover the safety zone.

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Integration and commissioning time	4	The installation of the light curtain requires no special procedures.	
Accessibility	4	The worker has easy access to the entire cell, except for where there is the fence (area not of interest for the worker).	
HRC	4	It can be collaborative, but at its normal behaviour it works in a non-collaborative mode.	
Overall Mark:	**20**	**Safety:**	**OK**

To summarize, this configuration offers two modalities: one where the robot and the human are not interacting, and the other where they can be in close proximity, but the robot speed is reduced. This approach results in a shorter cycle time compared to the other considered configurations, but it is not optimized since the robot is set to a reduced mode even if the worker enters the side of the cell opposite to where the robot is operating. This is because with a single light curtain it is not possible to understand if the operator is entering the safety zone from the right or the left side of the cell. On the other hand, including more than one light curtain would result in a excessive increase of the overall price.

3.2.4.2 Bonding cell

The final design includes a light curtain (highlighted in red in Figure 53) that covers the two free sides of the structure, ensuring that the entire hazardous area is covered by a single safety zone. It is possible to cover two sides with a single light curtain thanks to a mirror placed at the corner of the structure that extends the range of the sensor.

In this mode, the robot operates at fast speed, but when a worker enters the safety zone from one of the two free sides of the cell, the robot immediately stops. Once the robot is stationary, if the worker is still inside the safety zone, it switches to a collaborative mode with reduced speed. As soon as the safety sensor no longer detects the worker's presence, the robot returns to its fast speed. This design offers the robot both a collaborative and a non-collaborative mode, which adds flexibility to the station.

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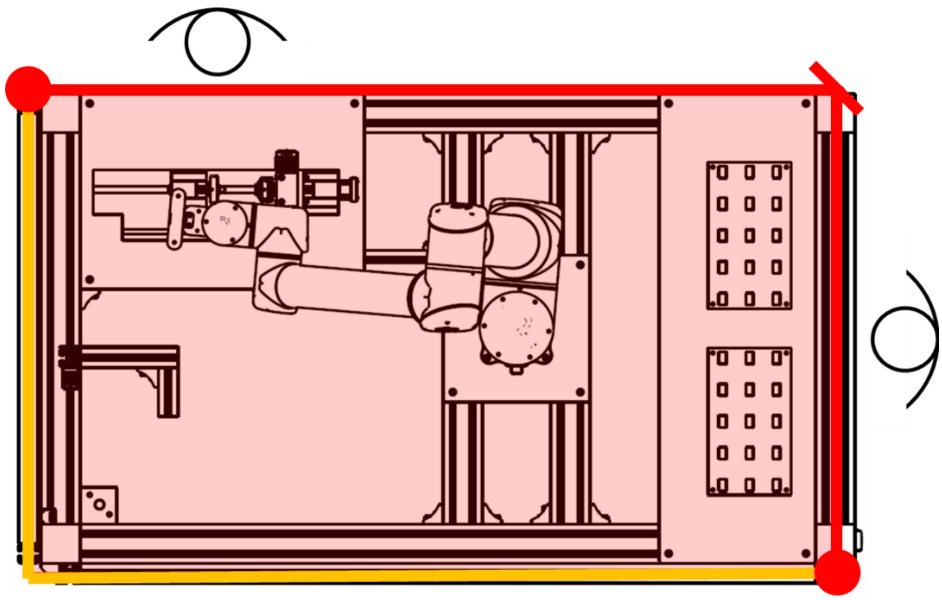

Figure 53: Safety scheme bonding cell

Also in this case, the main aspects of the bonding cell are reported in *Table 8*.

Table 8: Main safety aspects of the bonding cell

Bonding cell – Case 2		
Description: Robot working at a fast speed but when someone is detected by the light curtain it stops and restarts at reduced speed.		
Item	**Punctuation (1-5)**	**About:**
Cycle time	4	Usually, the robot works at a fast speed but at some moments it must work at reduced speed (not optimized version).
Price	4	One light curtain is needed to cover the safety zone.
Integration and commissioning time	4	The installation of the light curtain requires no special procedures.
Accessibility	4	The worker has easy access to the entire cell, except for where there is the fence (area not of interest for the worker).
HRC	4	It can be collaborative, but at its normal behaviour it works in a non-collaborative mode.

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Overall Mark:	20	Safety:	OK

To summarize, this configuration offers two modalities: one where the robot and the human are not interacting, and the other where they can be in close proximity but the robot's speed is reduced. This approach results in a shorter cycle time compared to the other considered configurations, but it is still not optimized since the robot is set to a reduced mode even if the worker enters the side of the cell where the robot is not operating. This is because with a single light curtain it is not possible to understand if the operator is entering the safety zone from the top or the right side of the cell. On the other hand, including more than one light curtain would result in a excessive increase of the overall price.

4 Hardware Integration

4.1 List of Materials and provider selection

4.1.1 IKOR's Use Case

4.1.1.1 Materials

The materials required to build the vibrating table, with the manufacturers chosen based on the trust and experience *Nutai* has with them, and selecting the cheapest option that accomplishes the minimum quality requirements is the following one:

Table 9: Vibrating Table Materials

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DROWING NO. / ITEM REF.	PART DESIGNATION	MANUFACTURER	UNITS
	VIBRATING TABLE SET		
050.20.05.00.001	VIBRATING TABLE PLATE	FASTEN	1
050.20.05.00.008	FEEDER PLATE	FASTEN	1
050.20.05.00.006	CAMERA BRACKET	GIMETAL	1
050.20.05.00.013	POSTER	GIMETAL	2
TI221123.01.001	SCANNER SUPPORT STRUCTURE	GIMETAL	2
TI220804.01.002	SICK BARRIER BRACKET	GIMETAL	2
TI220804.01.003	SICK BARRIER	GIMETAL	2
050.20.05.00.002	LIGHT PORFILE 90x90	FASTEN	4
050.20.05.00.005	BASIC PORFILE 45x90	FASTEN	6
	SCREWS	CLISER	
5502	COVER 45x90	FASTEN	6
5420	FLOOR ANCHORING 45x90	FASTEN	8
5330	BRACKET 42x42x42	FASTEN	2
5332	BRACKET 86x86x88	FASTEN	2
27750-03502060	SILENT BLOCK TIPO H2	NORELEM	4
6882512110	RING-MALE ANCHOR SNZ M-12x110	CLISER	8

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The elements that compose the intermediate table, both structure and presenters are detailed in the following table:

Table 10: Intermediate Table Materials

DROWING NO. / ITEM REF.	PART DESIGNATION	MANUFACTURER	UNITS
	INTERMEDIATE TABLE SET		
050.20.03.00.011	SUPPORT PLATE 1	MEDIMEC	2
050.20.03.00.012	UNION PLATE	MEDIMEC	3
050.20.03.00.015	SUPPORT PLATE 2	MEDIMEC	1
050.20.03.00.010	PPOFILE BRACKET	TECAM	3
050.20.03.00.002	LEOCO COMPONENT BASE	3D PRINT	1
050.20.03.00.003	PHOENIX COMPONENT BASE	3D PRINT	3
050.20.03.00.004	DB PRODUCT COMPONENT BASE	3D PRINT	1
050.20.03.00.005	ECE COMPONENT BASE	3D PRINT	1
050.20.03.00.007	MOLEX COMPONENT BASE	3D PRINT	1
050.20.03.00.008	SAMTEC COMPONENT BASE	3D PRINT	1
050.20.03.00.009	LIGHT PROFILE 45x45	FASTEN	3
	SCREWS	CLISER	
5501	COVER 45x45	FASTEN	3
53242	ADJUSTABLE JOINT 45x45	FASTEN	3
	INTERMEDIATE TABLE STRUCTURE		
050.20.04.00.001	INTERMEDIATE TABLE PLATE	TECAM	1
050.20.04.00.008	PROFILE RACKET	TECAM	4
050.20.04.00.002	LIGHT PROFILE 90x90	FASTEN	4
050.20.04.00.003	LIGHT PORFILE 45x90	FASTEN	2
050.20.04.00.004	LIGHT PORFILE 45x90	FASTEN	2
	SCREWS	CLISER	
5502	COVER 45x90	FASTEN	4
543116	BASE PLATE 90x90_M16	FASTEN	4
540690161	STEEL BASE STAND D90_M16x100	FASTEN	4
6882512110	RING-MALE ANCHOR SNZ M-12x110	CLISER	8

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The presenters for each component are manufactured with 3D print technology, as each one is specially made to host one component. They have been designed in order to let de components slide until they arrive to the final part of the presenter, ready to be picked, but with the resistance enough for not letting them turn over during the slide.

The materials needed to build the cobot's scructure are specified in the next table:

Table 11: Cobot Structure Materials

DROWING NO. / ITEM REF.	PART DESIGNATION	MANUFACTURER	UNITS
	ROBOT STRUCTURE		
TI220802.00.004	LEVELLING SPINDLE	TECAM	4
050.20.02.00.002	CONTROLLER TRAY	TECAM	1
TI220802.00.003	LEVELING BASIS	TECAM	4
050.20.02.00.001	STRUCUTRE	TECAM	1
	SCREWS	CLISER	

The components that are integrated in the cobot, such as the photoneo camera, the electric clamp, the accessories of the cobot, the elements needed to support them and the cobot itself are detalied in the following table:

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Table 12: Cobot & Cobot Accessories

DROWING NO. / ITEM REF.	PART DESIGNATION	MANUFACTURER	UNITS
OTHER			
050.20.00.00.002	COBOT FLANGE	MEDITERRÁNEA	1
050.20.00.00.003	PHOTONEO BOARD	MEDITERRÁNEA	1
050.20.00.00.004	BUTTON SUPPORT	METAL-CRIS	1
050.20.00.00.006	CASING SUPPORT	METAL-CRIS	2
050.20.00.00.007	SUPPORT BRACKET 1	METAL-CRIS	2
050.20.00.00.	SUPPORT BRACKET 2	METAL-CRIS	2
TRE.40.058.0.B	TRIFLEX ENERGY CHAIN R TRE.B	IGUS	1
TR.COB.01.40.30.0	TRIFLEX FASTENING WITH VELCRO STRAP AND PROTECTOR	IGUS	4
TL.40.01.Z2	LIGHTWEIGHT TERMINAL WITH TRIFLEX FIXING COMB	IGUS	2
023.22.03.00.001_C	TOOL FINGER, REWOEK WITH 0,5mm REBATE	MEC. RAFELBUÑOL	2
23.22.03.00.001_D	TOOL FINGER, REWOEK WITH 2,5mm REBATE	MEC. RAFELBUÑOL	1
	PHOTONEO CAMERA PhoXi SCANNER XS	PHOTONEO	1
	ELECTRIC CLAMP PGC-50	DH-ROBOTICS	1
2M5X-900 HW3.2 RT6-0019021	COBOT TM5 900	OMCRON	1

The materials needed to build the fences around the station to protect the workers are the following ones, some of them provided by Nutai itself:

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Table 13: Fences Materials

DROWING NO. / ITEM REF.	PART DESIGNATION	MANUFACTURER	UNITS
	FENCES		
050.20.06.01.001	LIGHT PORFILE 45x45	FASTEN	2
050.20.06.01.002	LIGHT PORFILE 45x45	FASTEN	2
050.20.06.01.003	LIGHT PORFILE 45x45	FASTEN	2
050.20.06.01.006	LIGHT PORFILE 45x45	FASTEN	2
050.20.06.01.004	WIRE MESH 1	NUTAI	1
050.20.06.01.005	WIRE MESH 2	NUTAI	1
050.20.06.02.001	LIGHT PORFILE 45x45	FASTEN	2
050.20.06.02.002	LIGHT PORFILE 45x45	FASTEN	2
050.20.06.02.003	LIGHT PORFILE 45x45	FASTEN	1
050.20.06.02.006	LIGHT PORFILE 45x45	FASTEN	1
050.20.06.02.007	LIGHT PORFILE 45x45	FASTEN	1
050.20.06.02.008	LIGHT PORFILE 45x45	FASTEN	1
050.20.06.02.009	LIGHT PORFILE 45x45	FASTEN	1
050.20.06.02.004	WIRE MESH 3	NUTAI	1
050.20.06.02.005	WIRE MESH 4	NUTAI	1
	SCREWS	CLISER	
5502	COVER 45x45	FASTEN	7
543112	GROUND ANCHOR BRACKET 45x45	FASTEN	6
6882512110	RING-MALE ANCHOR SNZ M-12x110	CLISER	12

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Finally, the electronical materials that will be installed are described above. It is not included the materials that must be provided by IKOR, such as the *Omron* cobot, the *DH Robotics* tool, the *Asyril* vibrating table, the *Asyril* camera and the Photoneo.

Table 14: Electrical material

DROWING NO. / ITEM REF.	PART DESIGNATION	MANUFACTURER	UNITS
	ELECTRICAL MATERIALS		
EATOELLIPSE PRO 1200DIN	UPS - 1200VA Power with overload protection surge	OMNIELECTRIC	1
TRIO-PS-2G/1AC/24DC/20	Switched Mode Power Supply Primary Trio Power	OMNIELECTRIC	1
FL SWITCH 1008N	Industrial Ethernet Switch	OMNIELECTRIC	1
FL SWITCH 1008NT	Industrial Ethernet Switch Wide Range Temperature	OMNIELECTRIC	1
	Eco-Rail-2 20-100-240/24	OMNIELECTRIC	1
5SL4516-7	PIA 1P+N 16A 10/10kA C	OMNIELECTRIC	1
5SL4506-7	PIA 1P+N 6A 10/10kA C	OMNIELECTRIC	6
5ST3010	Auxiliar Contact 1NA+1NC	OMNIELECTRIC	7
5ST3640	Bar Col. 2x(2F+HS/FS) 16MM2	OMNIELECTRIC	10
6EP4438-7EB00-3DX0	SITOP SEL 1400 10A 8X2	OMNIELECTRIC	1
5TE6800	B-PLUG 16A SUCKO	OMNIELECTRIC	1
VCF0	Int. Disconnected VARIO 3P 25A Control	OMNIELECTRIC	1
VZ8	Protective Cover for VARIO 12	OMNIELECTRIC	2
XAPD1201	Empty Grey Box 1 Orifice	OMNIELECTRIC	1
ZB4BS844	Emergency Button 40mm	OMNIELECTRIC	1
ZB4BSZ009	Electric Block Fixing Base	OMNIELECTRIC	2
ZBE102	Contact Block 1NC	OMNIELECTRIC	2
ZBY9460M	Circular Sticker 60mm "Emergency Disconnect"	OMNIELECTRIC	1
1651160000	Connector HDC-HDD-24-FC	OMNIELECTRIC	2
1651150000	Connector HDC-HDD-24-MC	OMNIELECTRIC	2
RITT1360000	AX Compact Cabinet 600x600x350, Ral 7035	OMNIELECTRIC	1

4.1.2 ICPE's Use Case

In this section the list of Materials and provider selection is given:

- Fervi m049/320 self-centering chuck.
- Homberger orthogonal gearboxes DE-DG55.
- Stepper-online Nema 23 ST-M2.
- FIPA GR04 122-20S air gripper.

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- FIPA BC GT NF05 + FIPA BC NY05BJ pneumatic cutter.
- Bianchini 5x E521-16-10-K13 electrovalves.
- Bianchini 1x Manifold E52C.
- KEYENCE Light curtains gl-r18l +brackets GL RB01.
- KEYENCE LR-XH50-XH100-XH250 laser sensor.
- Rittal AX 1034.000 electrical cabinet.
- PC Processor: Intel Core i9 11900 11th gen with integrated video Intel UHD Graphics 750
- Motherboard: ASUS Z590
- RAM: 16GB DDR4, 3200 MHz
- Storage: Solid-State Drive (SSD) SAMSUNG 870 QVO, 1TB, SATA3, 2.5"
- GPU: NVIDIA RTX 3060 12 GB
- ARDUINO MEGA 2560 X CONTROLLO 3 ASSI.
- Ringfeder DKN-100-47-20-19 metal bellow coupling.
- Ringfeder DKN-045-41-08-15 metal bellow coupling.
- DAV Tech spray valve DAS 100 EV, activator dispenser.
- DAV Tech volumetric pump manual glue dispenser.
- DAV Tech pressurized tanks PT, pressurized tank for glue and activator.
- DAV Tech controller for PCP pumps, microprocessor-control

4.2 Installations at NUTAI's facilities

The following preliminar tests were successful at NUTAI's facilities. These tests consisted on movements following several predefined trajectories that are similar to the ones that will be performed in the pick and place final application.

As seen, two different trajectories are executed. Communications have been successful.

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Figure 54: First preliminar testing at NUTAI's facilities

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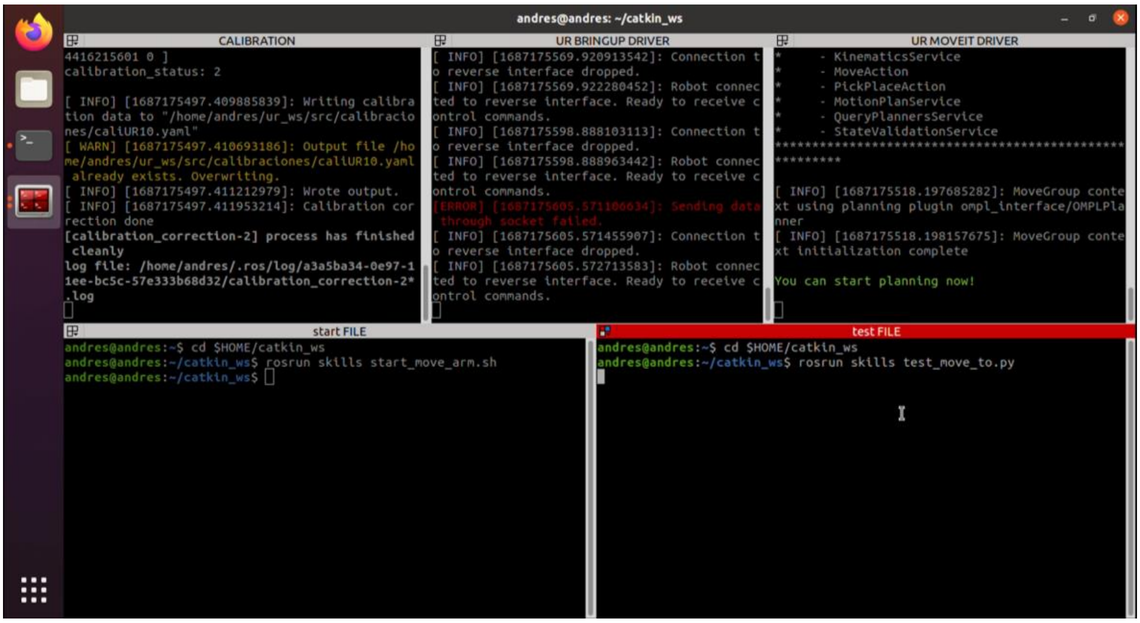

Figure 55: Detail on first Software Testing at NUTAI's facilities

These tests were preliminar and, as it can be seen in the installation image, were performed using a UR10e cobot available. They allowed NUTAI to get the most familiar possible with the

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ACROBA framework and communications among devices, until being able to program under the ACROBA structure basic instructions to be performed.

These basic orders are named “basic skills”, that many Use Cases should use, and therefore should be directly developed by Sigma. The testing proved valid, although in further phases the pretesting with all the equipment of the cell was required.

NUTAI received the rest of the equipment from IKOR and installed it in its facilities with the idea of refining the basic skills and developing some specific skills needed for the proper operation of the cell.

Figure 56: Installation of IKOR’s cell at NUTAI for integration and development

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A mong the skills developed by NUTAI, IKOR, Sigma and Vicomtech, we must list the following:

- **Read/Write I/O:** A skill to enable the conveyor and move the different PCBs to be assembled.
- **Count Components:** A skill to analyse an image obtained with the Photoneo to count the components in the intermediate surface. If they are not enough, the buffer should be first filled.
- **Locate PCB:** Also analyses the image obtained by the Photoneo vision system, but intended to accurately determine the position of the PCB, essential for placing operations.
- **Asyril control system:** Configures the vibrating system for a specific component under the ACROBA framework. Includes both the vibration parameters and the camera to chech the position of the components that can be brought to the intermediate surface.

A timeline was established for these three entities to coordinate the work. The steps followed for integration were the following:

Table 15: List of Tasks for Integration with the equipment in NUTAI

TASK DESCRIPTION	RESPONSIBLE
Make Omron robot move with cartesian moveit skill	NUTAI
PCB locate Skill	NUTAI
To finalize the specific skill to monitor the 3D force while *move_to* skill is running	NUTAI
To adapt gripper driver to ACROBA skill architecture	Vicomtech
Test with real hardware at Nutai	NUTAI
To incorporate (Vicomtech self routine to fine insertion of parts) instead of “Alfons’s” DRL *Difficult component place skill*	Vicomtech
To finalize the skill to count components developed by Sigma	NUTAI
Calibration of all equipment	NUTAI

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Run all the steps to complete the assembly of the PCS (according to test definition) Please, do not wait to Task planner!	NUTAI
To create a Skill to read MongoDB and connect it to GUI	IKOR
To create the sequences in the GUI according to our process flow	IKOR
To incorporate the DRL picking skill created by Deusto.	Deusto-IKOR-Vicomtec
Implement DRL skill to pick a part from Asyril system	Deusto-IKOR-Vicomtec
Creation of the URDF file of the robotic cell	Vicomtech
Capture demonstration videos of each relevant achievement of the project, so that they can be used in the justification of the project and in the video to be edited by the consortium.	All of us
Delivery of all equipment back to ikor.	NUTAI

When all the milestones regarding integration and development were complete in NUTAI, all the equipment was transferred back to IKOR to perform final testing and refinement there, as it is explained below.

4.3 Installations at IKOR's facilities

In order to advance with preliminar testings without waiting for all materials to be available. The best choice first was to install the pick and place part in IKOR's facilities. The vibrating feeder and the OMRON cobot used are present here, while at NUTA's facilities the intermediate surface, the robot pillar and the fences were installed.

This separation bassically allowed independent testing at both facilities at the same time. While IKOR focuses on pick and place skills, NUTAI can test movement and communications at the same time.

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On the design of a tailored fingers attachable to the robotic gripper to be customized for all identified components.

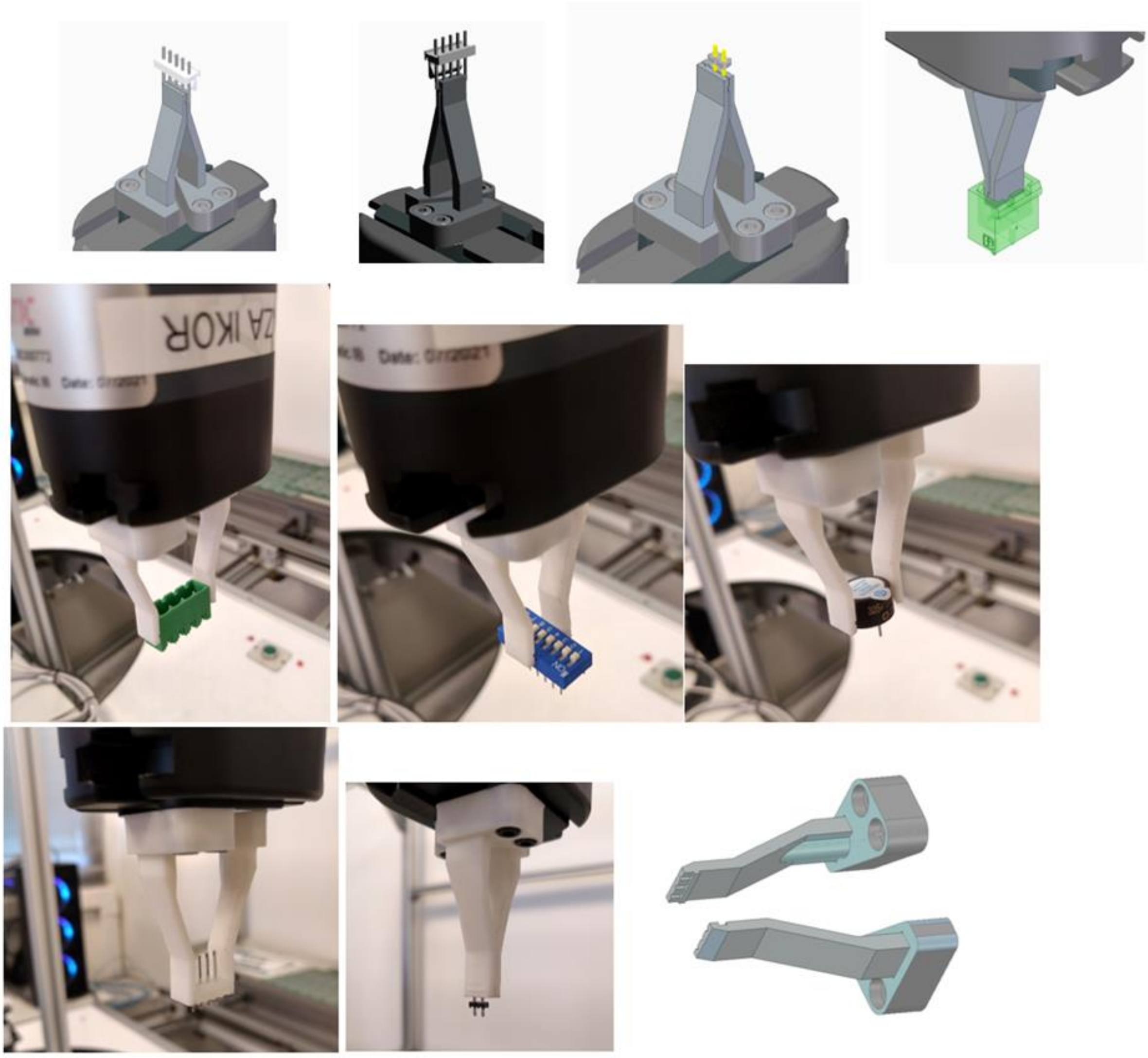

Figure 57: Images of the final design created at IKOR to handle electronic components

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On the installation and commissioning of the ASYRIL component dispensing system so that it could be delivered to Nutai pre-configured to work with the identified target parts. Ikor received all the necessary equipment and created the provisional mechanical structure. It commissioned the system and is working on the calibration of the optical vision system, and the calibration of the robot reference systems and the dispensing system.

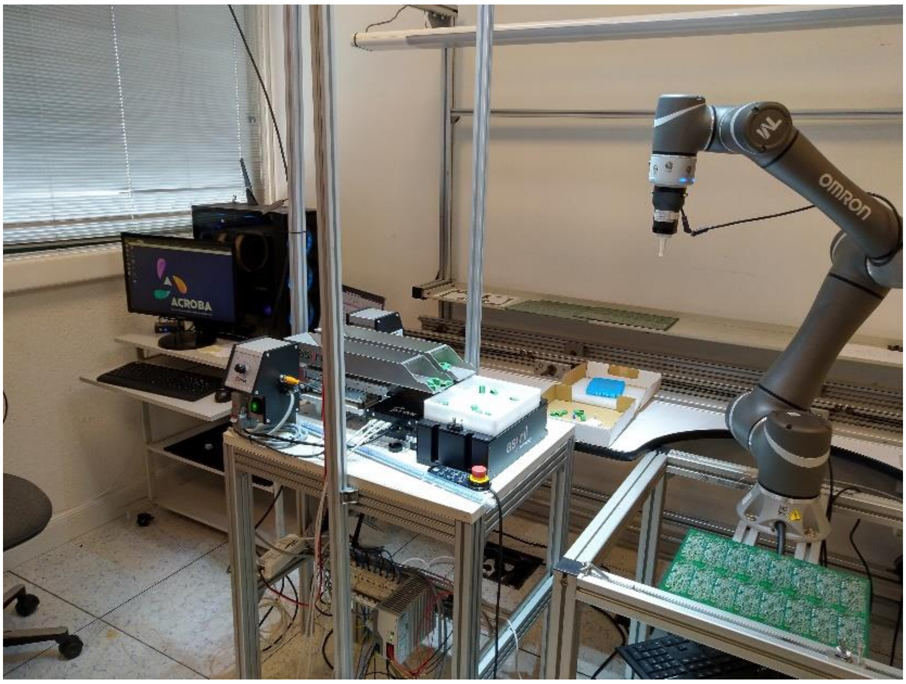

Figure 58: Image of the provisional robotic cell created at IKOR

A delivery of the equipment to NUTAI was done for month 35, which and consisted of the entire component dispenser system functional for a set of the components identified in IKOR use case.

The developments in NUTAI consisted on refining the generic skills and developing the specific ones needed for the proper operation of the cell. Meanwhile, IKOR progressed defining the

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user interface for an easier operation of the cell. This user interface will be detailed in the software part of this deliverable.

When the tasks in NUTAI concluded, the equipment was transferred back to IKOR to perform many of the final installations. The layout follows the exact final designs.

Figure 59: General View of the cell

This layout follows the HRC setup that works with a reduced safe speed. However, as it is not working in an industrial setup, some KPIs can be measured with a higher speed when the convenient barriers are placed.

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In the left part, the human interface can be appreciated. These devices are intended for setting up the configuration of the cell with the software developed by IKOR. They also allow to modify some core parameters of the station, such as communications, speed of the robot…

Figure 60: Detail on the robot and the PCBs to be assembled

In the station itself there is also a place for the operator, in the left side, who can prepare the PCBs and put them in the conveyor, so that the robot can pick and place all the components.

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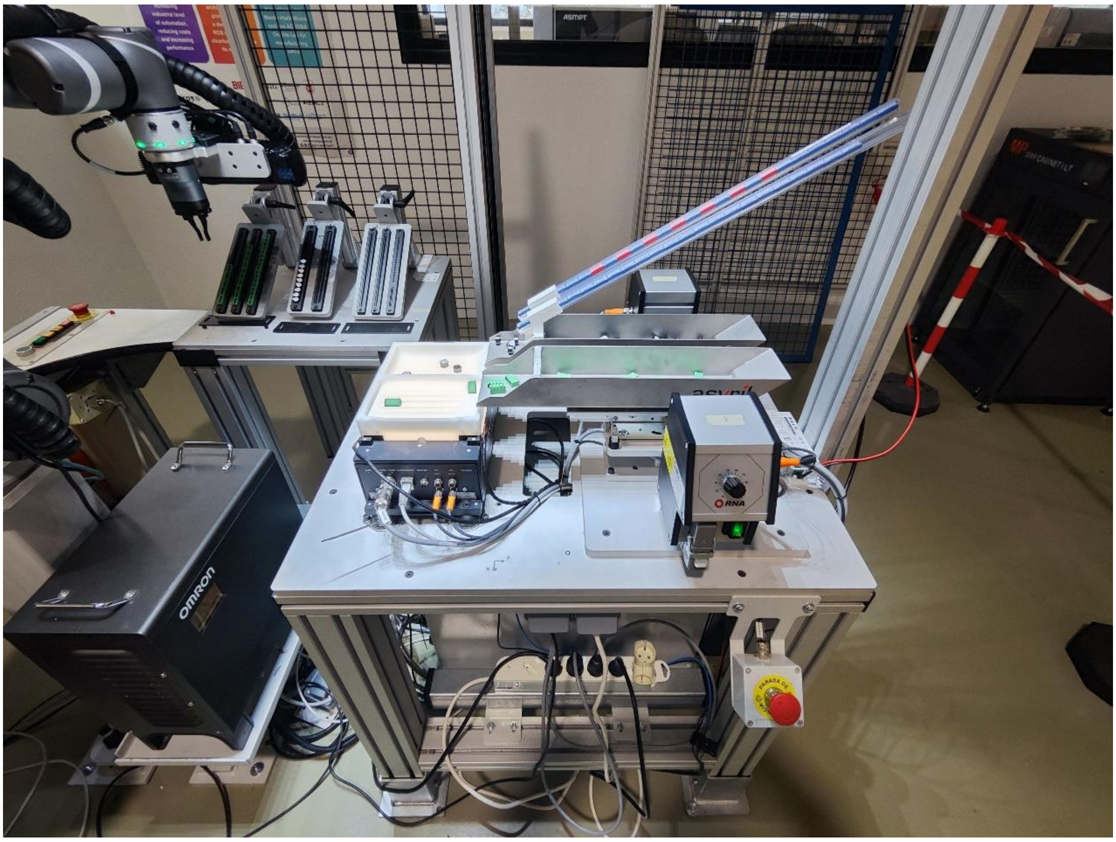

Figure 61: View of the rest of the main elements: vibratory system and intermediate surface

The operator can also access the cell from the rear side, in order to fill the Asyril system with components. With all the elements operative, the cell is completely functional and this operation is reflected in D5.6 and also in the videos of WP6.

The ACROBA project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 101017284.

Figure 62: Detail of the robot picking a component

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4.4 Installations of ICPE's Use Case

The two ICPE robotic cells have been installed at STAM laboratories.

4.4.1 Installation of the winding cell

Figure 63 and Figure 64 report two pictures of the complete winding cell for the ICPE use-case.

Figure 63 - ICPE use- case winding cell

The ACROBA project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 101017284.

Figure 64 - ICPE use- case winding cell

In Figure 65 is shown the end-effector of the winding process installed on the robot. In the picture, the wire correctly passes through the mechanism of the end-effector and its needle.

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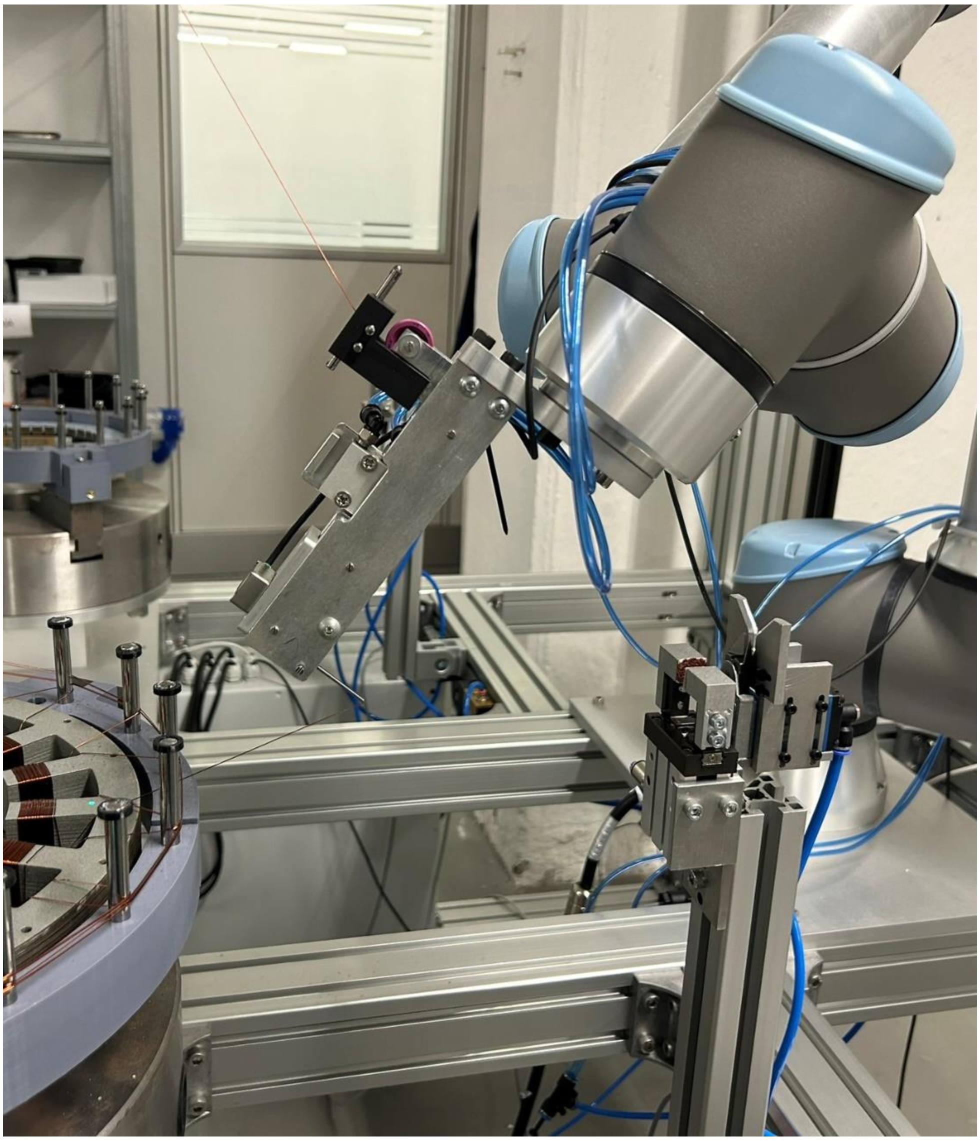

Figure 65 – ICPE winding end-effector

Figure 66 reports a picture of the pincher tool for fixing the wire. In the figure, the closed pincher is holding the wire exiting from the end-effector.

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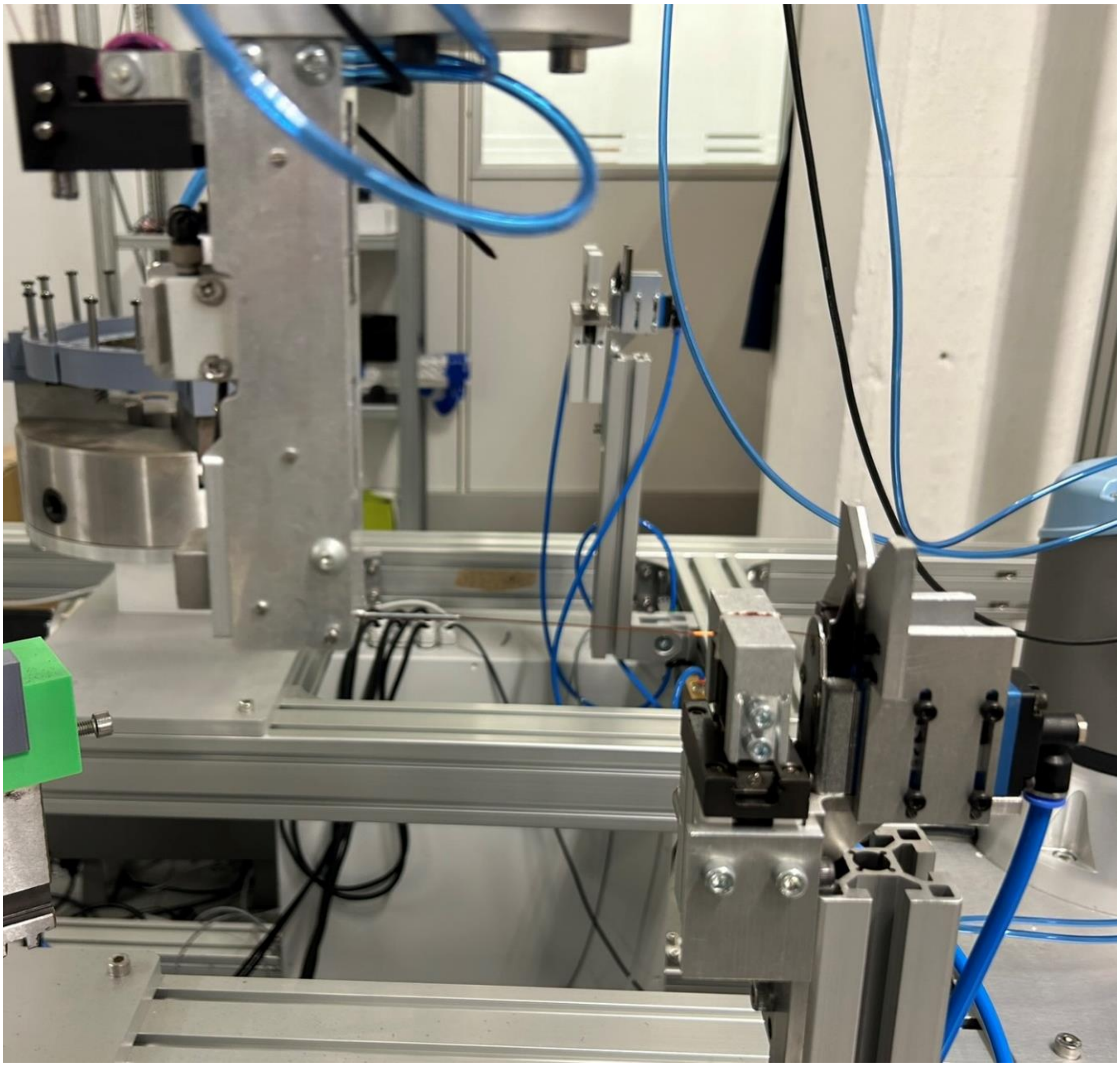

Figure 66 – ICPE winding pincher

In Figure 67, the tool for wire cutting operation is shown. In the picture, the needle of the end-effector is guiding the wire through the pneumatic cutter.

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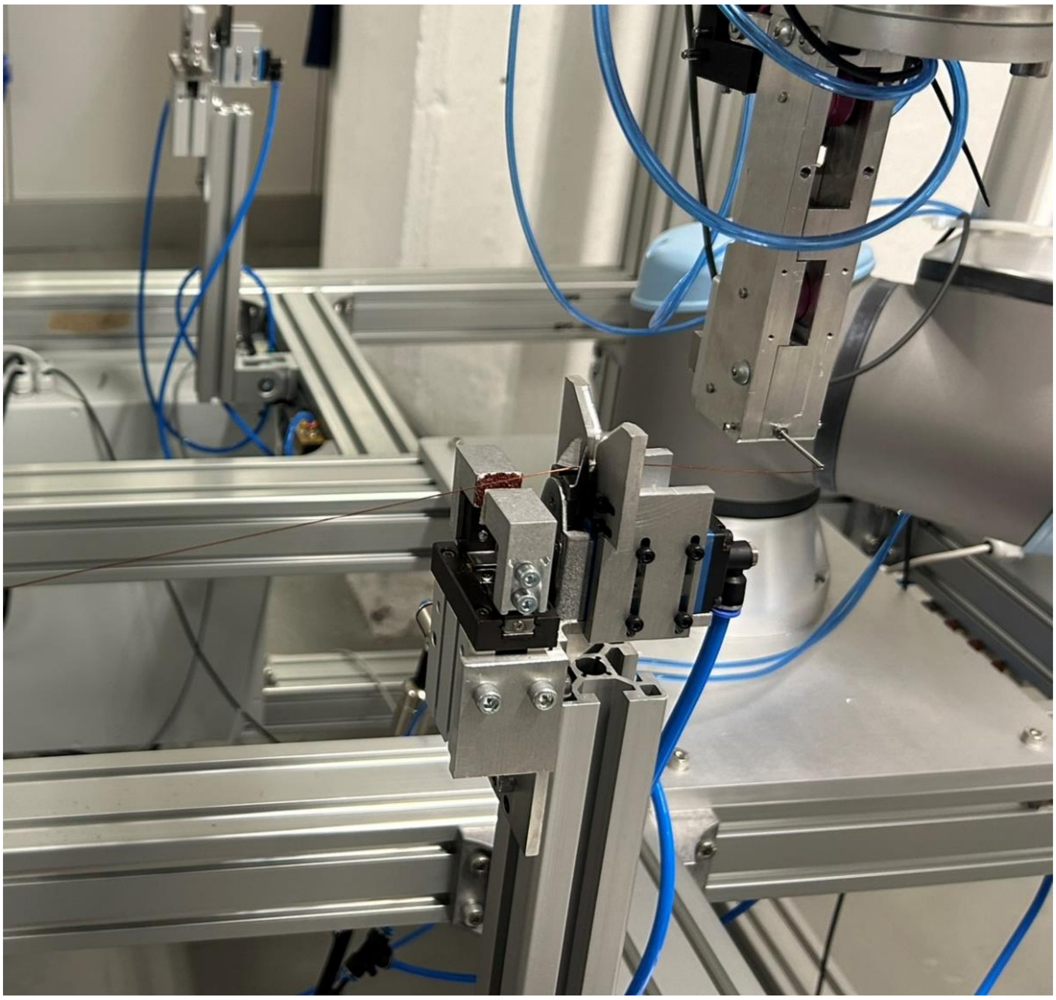

Figure 67 - ICPE winding cutter

Figure 68 shows two pictures of the rotary table of the winding cell hosting a stator. In the picture, the 3D printed fingers are visible, together with the metal pins used to hold the wire when the end-effector finishes the winding of one tooth and needs to operate on the following one.

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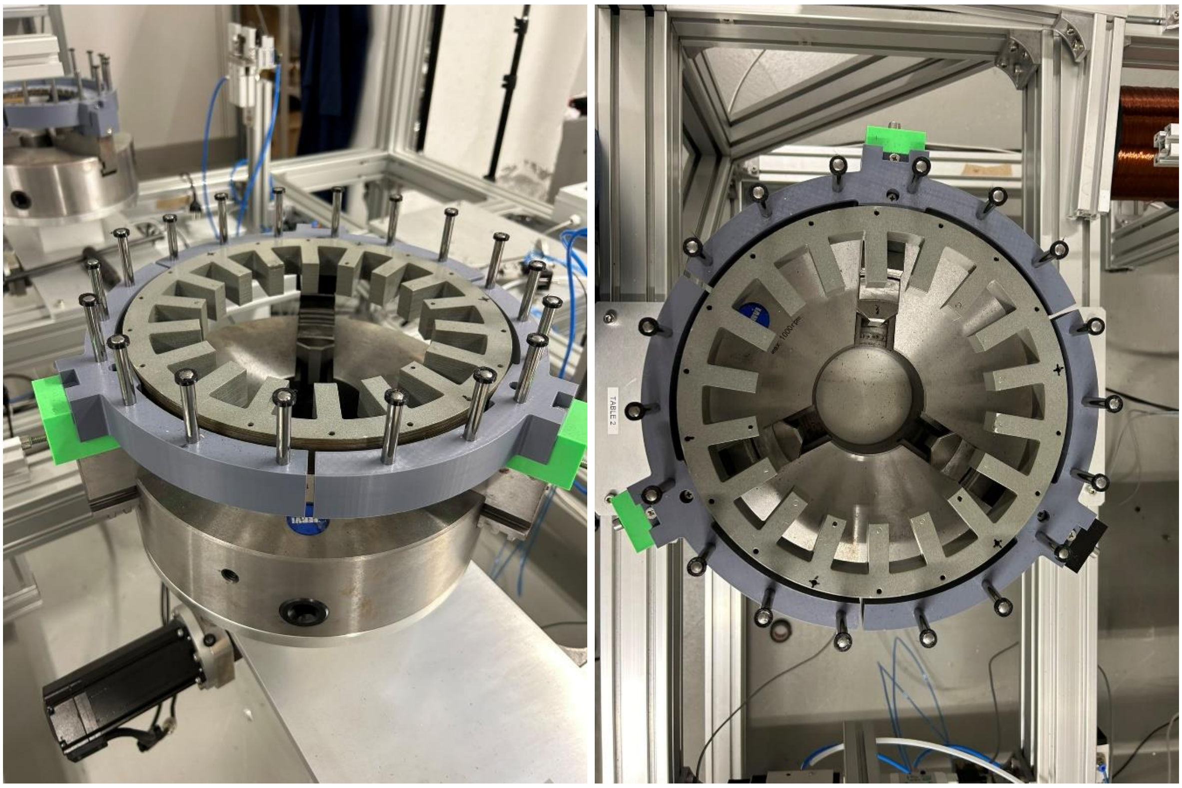

Figure 68 – ICPE winding rotary table

Figure 69 reports a picture of the tensioner installed on the winding cell.

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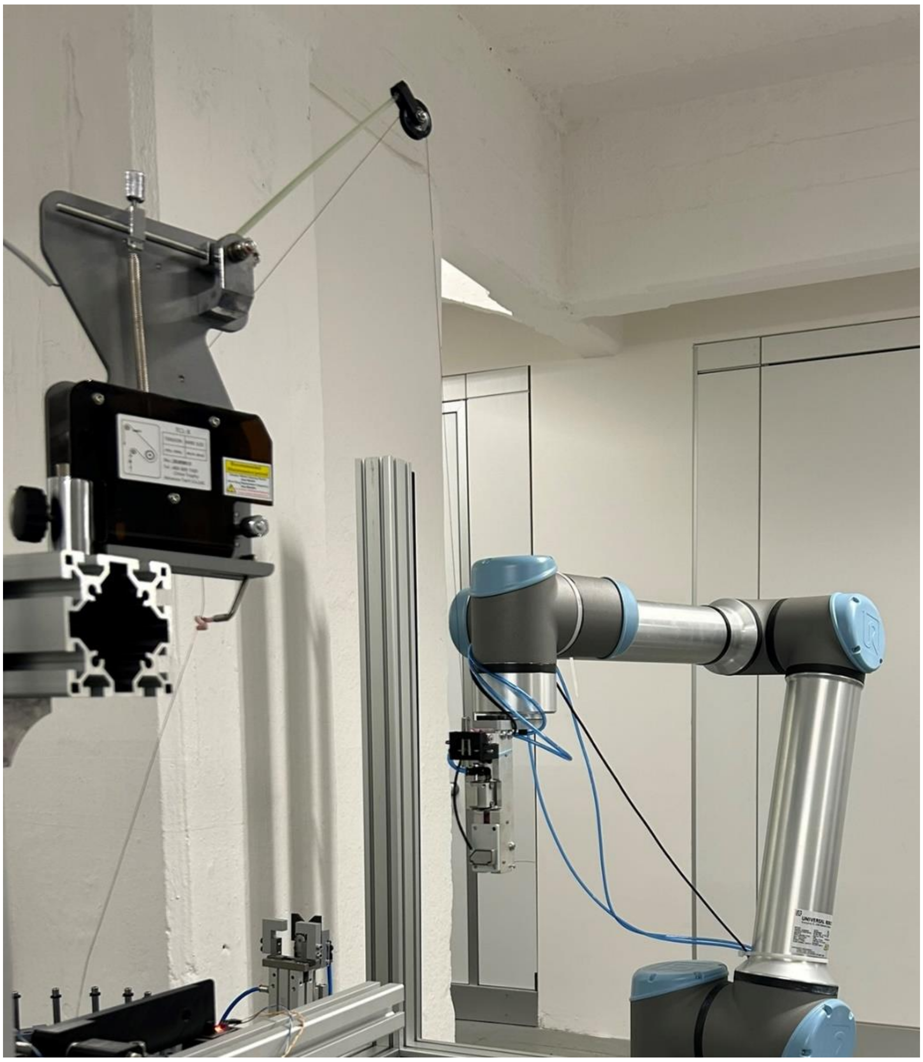

Figure 69 – ICPE winding tensioner

Figure 70 and Figure 71 show two pictures of the safety system installed for the winding cell. In the first picture, the light curtain is emitting green lights, meaning that no one is inside the safety zone. In the second picture, the presence of someone inside the safety zone is detected by the safety sensor, which is now emitting red lights.

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Figure 70 – ICPE winding safety light curtain (green mode)

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Figure 71 - ICPE winding safety light curtain (red mode)

Figure 72 provides a picture of the buttons installed on the cell to allow the operator to start the robotic winding process on rotary table 1 or rotary table 2.

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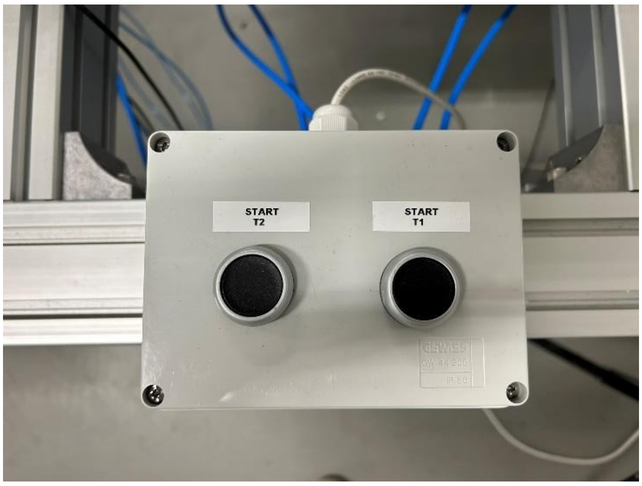

Figure 72 – ICPE winding buttons

4.4.2 Installation of the bonding cell

Figure 73 and Figure 74 report two pictures of the complete bonding cell for the ICPE use-case.

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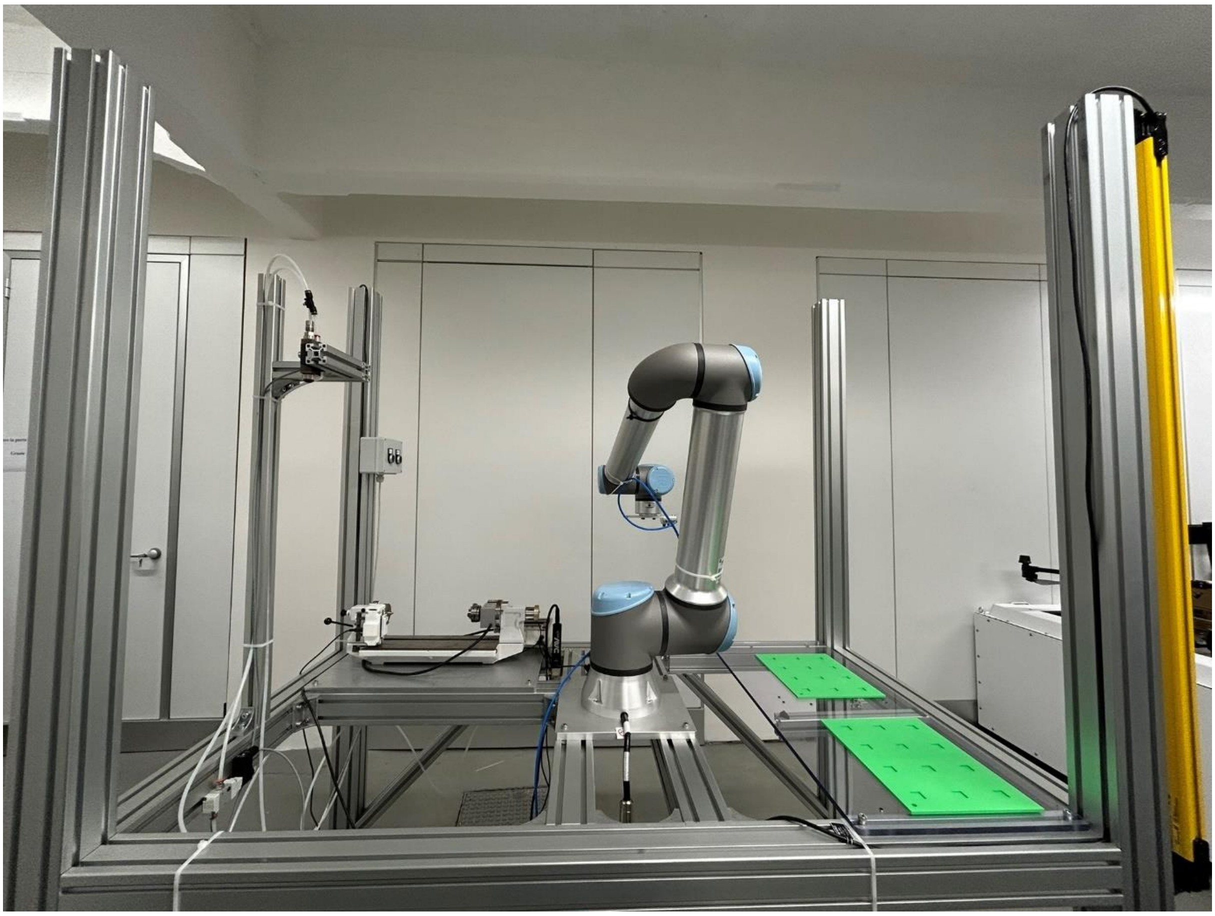

Figure 73 - ICPE use case bonding cell

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Figure 74 - ICPE use case bonding cell

Figure 75 shows a picture of the trays for the magnets of the bonding cell. They are 3D printed, and the polycarbonate transparent base on which they are installed, is designed such that it can host different sizes of trays.

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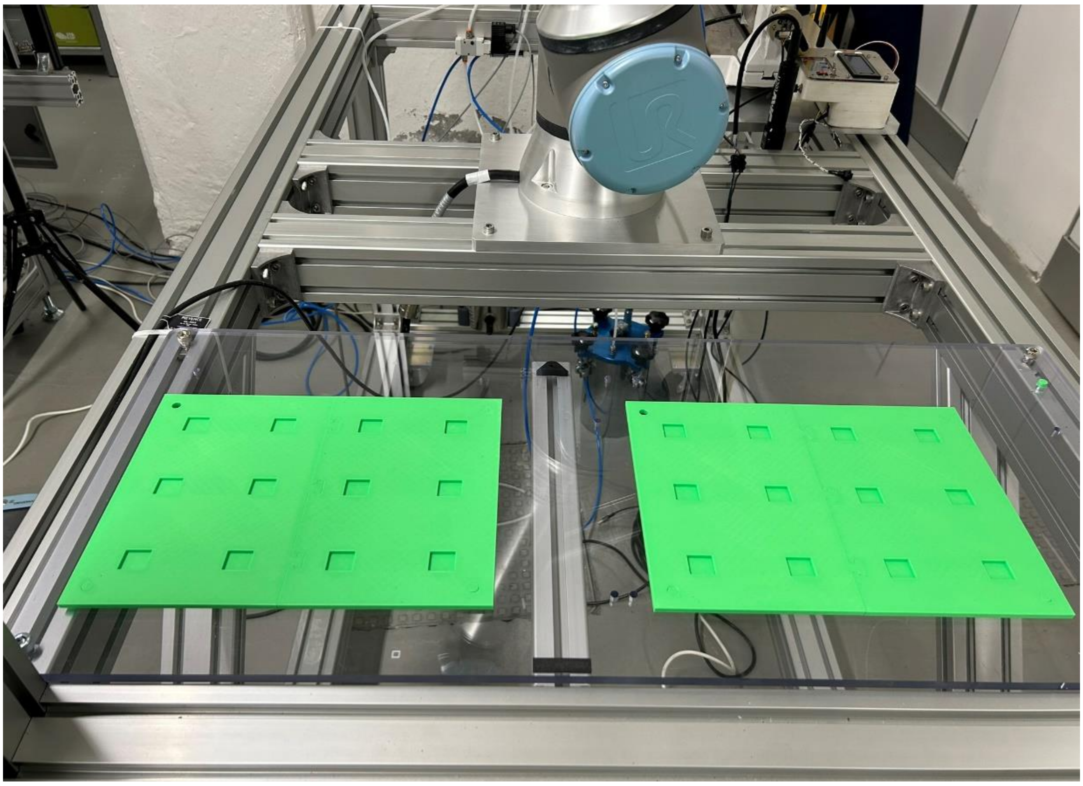

Figure 75 – ICPE bonding trays

In Figure 76, two pictures of the end-effector of the bonding cell are reported. The end-effector hosts three different configurations of vacuum pads, to allow the robotic picking of different sizes of magnets.

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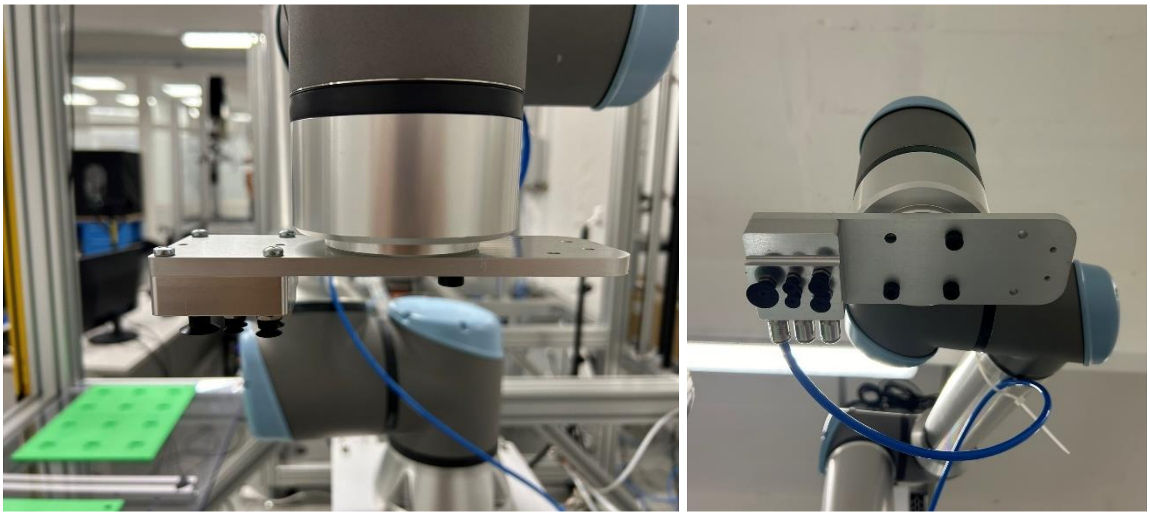

Figure 76 – ICPE bonding end-effector

Figure 77 show two pictures of the spindle of the bonding cell. In the one on the right, the spindle is holding a rotor during the magnet bonding operation.

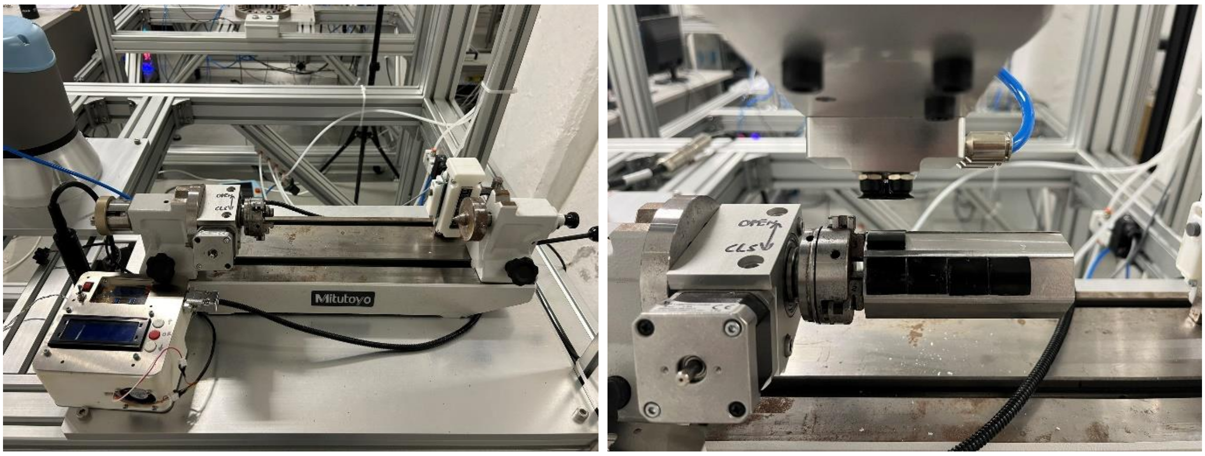

Figure 77 – ICPE bonding spindle

Figure 78 provides two pictures of the spray of the activator for the bonding process.

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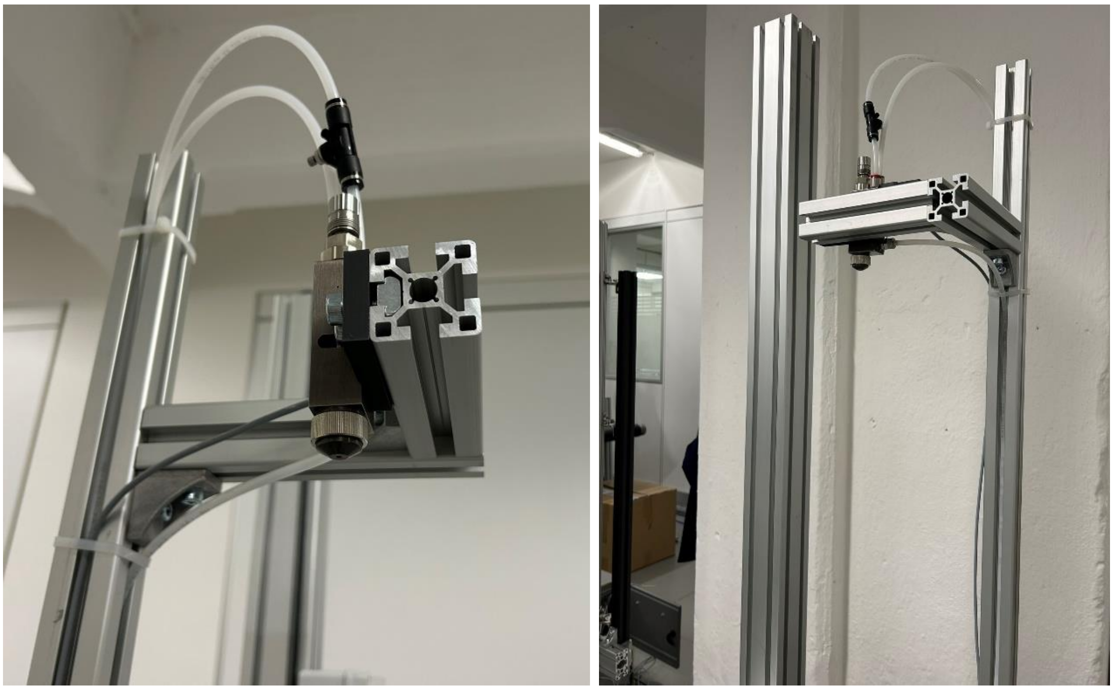

Figure 78 - ICPE bonding activator's spray

Figure 79 provides a picture of the buttons installed on the cell to allow the operator to start the robotic picking of the magnets and placing process of the magnets on the rotor.

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Figure 79 – ICPE bonding buttons

Figure 80 shows the safety system for the bonding cell. It consists of a light curtain with the emitter and receiver bars placed at two opposite corners of the cell, with a mirror placed in the corner in between them to allow the system to cover the entire entrance area, creating a comprehensive safety barrier across multiple sides of the cell.

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Figure 80 – ICPE bonding safety system

5 ACROBA Customization and Software Developments

5.1 Process and Flow Charts

5.1.1 IKOR's Use Case

IKOR's station has two main tasks to accomplish, one where the Cobot must pick the components from the presenter and place them into the PCB, and the second one where the Cobot reloads the presenter with components form the vibrating table.

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The steps to assemble the PCB are the following ones:

1. PCB arrives to position.
2. Cobot moves to PCB.
3. Photoneo camera scans PCB model and position.
4. Cobot moves to buffer.
5. Photoneo camera scans buffer.
6. If there are not enough components, the reloading cycle starts.
7. If there are enough components, the Cobot picks a component.
8. Cobot moves to PCB.
9. Cobot places the component.
10. If PCB incomplete, repeat from point 4.
11. If PCB complete, Cobot to start point.

And the steps to assemble the buffer are:

1. Not enough components in the buffer.
2. Cobot moves to feeder.
3. Asyril camera scans feeder.
4. If there are no well-placed component, table vibrates and repeats from point 3.
5. If there is a well-placed component, Cobot picks it.
6. Cobot moves to presenter.
7. Cobot places component into presenter.
8. Cobot continues with P&P cycle.

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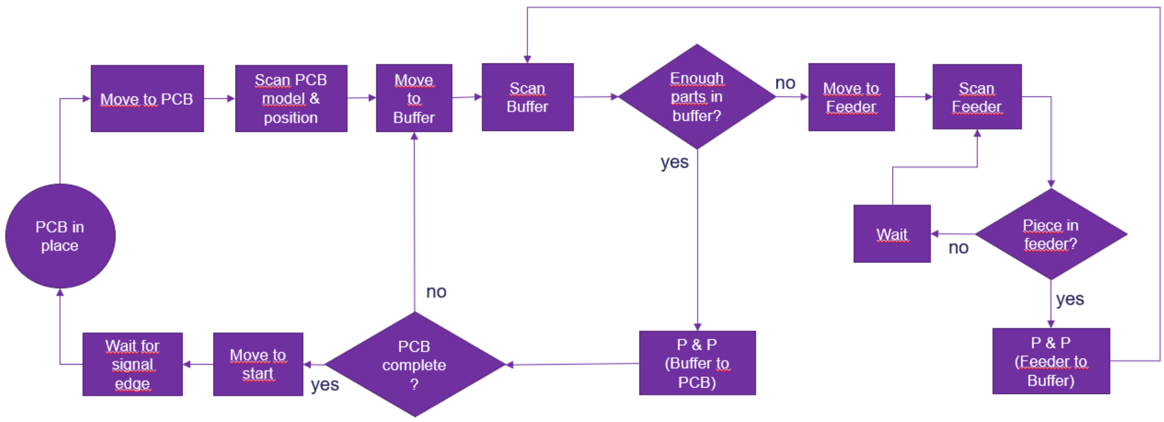

Figure 81: Diagram of IKOR's Sequence

5.1.2 ICPE's Use Case

In this section of the document the flowcharts of the three ICPE operations are presented, and the ACROBA skills required to program the stations are selected. Software Integration

In this section of the document the flowcharts of the three ICPE operations are presented, and the ACROBA skills required to program the stations are selected.

5.1.2.1 Coils winding process

The flowchart in Figure 82 illustrates the high-level sequence of human and robot tasks involved in the coils winding process. This collaborative process takes place simultaneously at two distinct spots, referred to as A and B in the figure, but the order of tasks remains consistent across both spots.

The process starts with the operator placing a new stator on the rotary table and performing the preparatory operations. Subsequently, the actual robotic winding process controlled by the

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ACROBA platform is executed. Once the winding of all teeth of the stator is completed, the process ends with the finishing operations carried out by the operator.

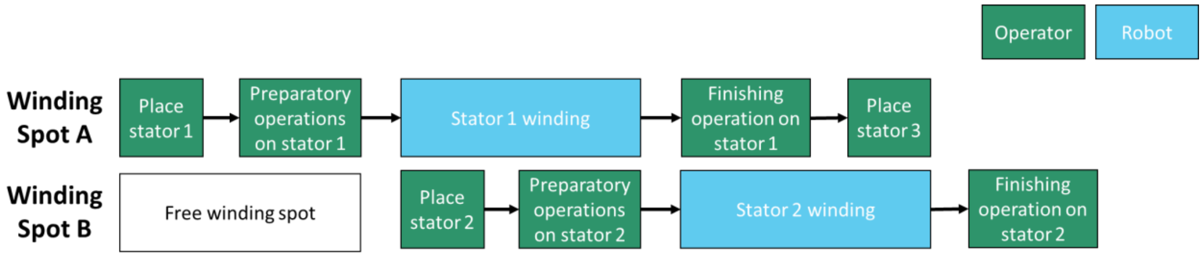

Figure 82: Flowchart of the high-level order of tasks of the Coils winding process

5.1.2.2 Magnets bonding process

Figure 83 shows the high-level sequence of human and robot tasks involved in the magnets bonding collaborative process. The process begins with the operator placing the magnet trays and loading the shaft onto the rotary table, followed by performing the angular position detection and correction procedure. Subsequently, the pick and place process for the magnets starts. The magnet with the correct polarity is picked from its fixed position on the tray, is placed under the activator spray for the activator deposition and then it is placed onto the shaft, which has been previously coated with adhesive by the operator. This process is repeated until all rows of the rotors are filled with magnets.

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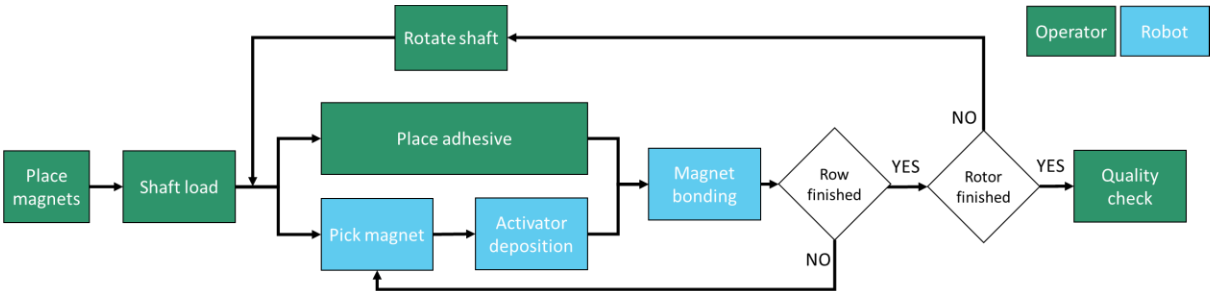

Figure 83: Flowchart of the high-level order of tasks of the Magnets bonding process

5.1.2.3 Primitive and skills

All ACROBA skills/primitives needed to execute the two collaborative processes of the ICPE use-case have been identified.

Table 16 reports the complete list of primitives identified for the two processes, highlighting whether these are general primitives available on the ACROBA platform or specific ones of the ICPE use-case, specifying who has been the partner responsible for its development, and indicating in which of the two processes are used. For each primitive, a brief description is provided.

Table 16 - Primitives list for the ICPE use-case

Primitive name	General / Specific	Resp. partner	Winding process	Bonding process
GenerateTrajectory	G	SIGMA	✓	✓
Given a desired goal pose for the robot, it generates the robotic trajectory to move the robot from the current pose to the goal one.				
ExecuteTrajectory	G	SIGMA	✓	✓

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Given a robotic trajectory generated by the GenerateTrajectory primitive, it executes it, making the robot move until the desired goal pose.				
GenerateWindingWaypoints	S	SIGMA	✓	
Given the geometrical parameters of a stator's tooth, it generates the complete list of waypoints for the robot to wind the tooth.				
ComputeRotorPositions	S	SIGMA		✓
Given the geometrical parameters of a rotor and of the corresponding magnets, it computes the placing poses for the magnets on the rotor.				
ComputeMagnetPositions	S	STAM		✓
Given the geometrical parameters of the magnets, it computes the picking poses for the magnets on the trays and list them in the correct order.				
ControlGripperWinding	S	STAM	✓	
It controls the opening and closing of the gripper inside the end-effector of the winding cell.				
ControlGripperBonding	S	STAM		✓
It controls the activation and de-activation of the vacuum of the bonding cell's end-effector.				
ControlPincher	S	STAM	✓	
Selecting which pincher of the winding cell (1 or 2), it controls its opening and closing to fix the wire.				
ControlCutter	S	STAM	✓	
Selecting which cutter of the winding cell (1 or 2), it controls its opening and closing to cut the wire.				

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ControlSpray	S	STAM		✓
It controls the activation and de-activation of the activator's spray of the bonding cell.				
ControlTensioner	S	STAM	✓	
It controls the mode of operation (feed wire or rewind wire) of the tensioner of the winding cell.				
LoadRotor	S	STAM		✓
Given a json file of a rotor including its geometrical and bonding information, it loads its parameters.				
LoadStator	S	STAM	✓	
Given a json file of a stator including its geometrical information, it loads its parameters.				
LoadWindingInfo	S	STAM	✓	
Given a json file of a stator including its winding information, it loads its parameters.				
RotateTableWinding	S	STAM	✓	
Given a goal position in milliradians and selecting which rotary table of the winding cell (1 or 2), it rotates the corresponding table to the desired position.				
TableWindingInplace	S	STAM	✓	
Selecting which rotary table of the winding cell (1 or 2), it "zeroes" the corresponding table, setting its current position as zero value.				
TableWindingReferencing	S	STAM	✓	

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Selecting which rotary table of the winding cell (1 or 2), it activates its referencing procedure of detecting the edge of a stator's tooth by reading the laser sensor values while rotating the table.				
ButtonWinding	S	STAM	✓	
It detects if the buttons of the winding cell have been pressed.				
ButtonPickBonding	S	STAM		✓
It detects if the pick button of the bonding cell has been pressed.				
ButtonPlaceBonding	S	STAM		✓
It detects if the place button of the bonding cell has been pressed.				

The selected primitives have then been grouped into skills, to create complete sub-tasks. These are listed in Table 17, indicating for each skill which actions it includes, specifying who has been the partner responsible for its development, and providing a brief description.

Table 17 - Skills list for the ICPE use-case

Skill name	**Included actions**	**Resp. partner**	**Winding process**	**Bonding process**
MoveTo	GenerateTrajectory	SIGMA	✓	✓
	ExecuteTrajectory			
Given a goal pose, it moves the robot to the desired pose.				
WindSingleTooth	GenerateWindingWaypoints	SIGMA	✓	

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	MoveTo			
Given the geometrical parameters of a stator’s tooth, it moves the robot to the generated list of waypoints, completing the winding of the tooth.				
FirstToothProcedure	LoadStator MoveTo TableWindingReferencing RotateTableWinding TableWindingInplace	STAM	✓	
It performs the first tooth procedure of the winding process, by moving the end-effector of the robot to the designated position and activating the referencing procedure of the rotary table. When the edge of the stator’s tooth has been detected, then the table is rotated backwards of half-tooth. At the end of the procedure, the end-effector of the robot is positioned exactly at the centre of the first tooth to be wound.				
FixWireProcedure	MoveTo ControlPincher	STAM	✓	
It performs the wire fixing procedure of the winding process, by moving the end-effector of the robot, which is holding the wire, to the pincher position, and then closing the pincher. At the end of the procedure, the wire is correctly fixed inside the pincher.				
CutWireProcedure	MoveTo ControlGripperWinding ControlCutter ControlTensioner	STAM	✓	

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It performs the wire cutting procedure of the winding process, by moving the end-effector of the robot, which is holding the wire, to the cutter position, and then closing the cutter. The tension of the wire is controlled in the meanwhile. At the end of the procedure, the wire has been correctly cut.				
PickMagnet	MoveTo ControlGripperBonding	STAM		✓
It performs the magnet picking procedure of the bonding process, by moving the robot to the correct magnet position on the tray and then activating the vacuum of the end-effector. At the end of the procedure, the magnet is attached to the end-effector of the robot.				
SprayMagnet	MoveTo ControlSpray	STAM		✓
It performs the activator spraying procedure of the bonding process, by moving the end-effector of the robot, which is holding a magnet, to the spray position and then activating the spray. At the end of the procedure, the magnet is covered with activator.				
PlaceMagnet	MoveTo ControlGripperBonding	STAM		✓
It performs the magnet placing procedure of the bonding process, by moving the robot to the correct placing position on the rotor and then deactivating the vacuum of the end-effector. Once the magnet is placed on the rotor, a procedure to push the magnet next to the previous one is performed, until the bonding is complete. At the end of the procedure, the magnet is correctly bonded to the rotor.				

The flowcharts of primitives and skills for the two ICPE processes have been outlined. These are reported in Figure 84 and Figure 85, which highlight in blue the blocks corresponding to robotic/system task, and in red the human ones. These flows include both general

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primitives/skills available on the ACROBA platform and ones that are specific for the ICPE use-case.

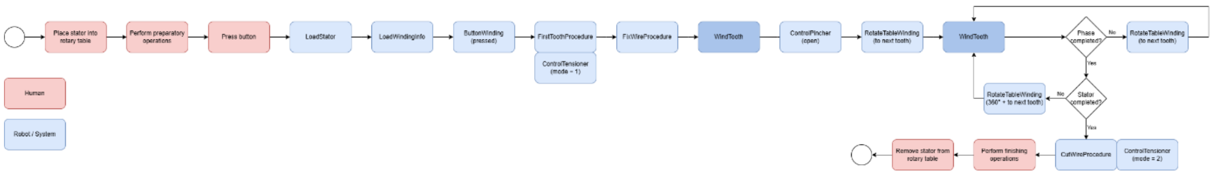

Figure 84 – Skills/primitives flow of winding process

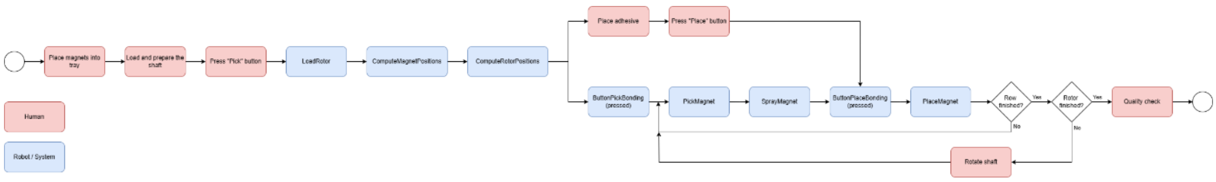

Figure 85 – Skills/primitives flow of the bonding process

5.1.2.4 Generation of JSON files

The first step of the software integration is to gather manufacturing information and provide it to the ACROBA platform in a condensed, summarized form in single file format. The information is given as outputs from various software used in the design phase and varies between the two main use cases.

Stator winding use-case

For the stator use case, these outputs are geometry (CAD) and winding information and the first step starts with modifications made to the CAD file made in Autodesk Inventor and parameterize key dimensions which are needed by the stator winding cell. They must be named exactly as below in order to be correctly interpreted in the next step.

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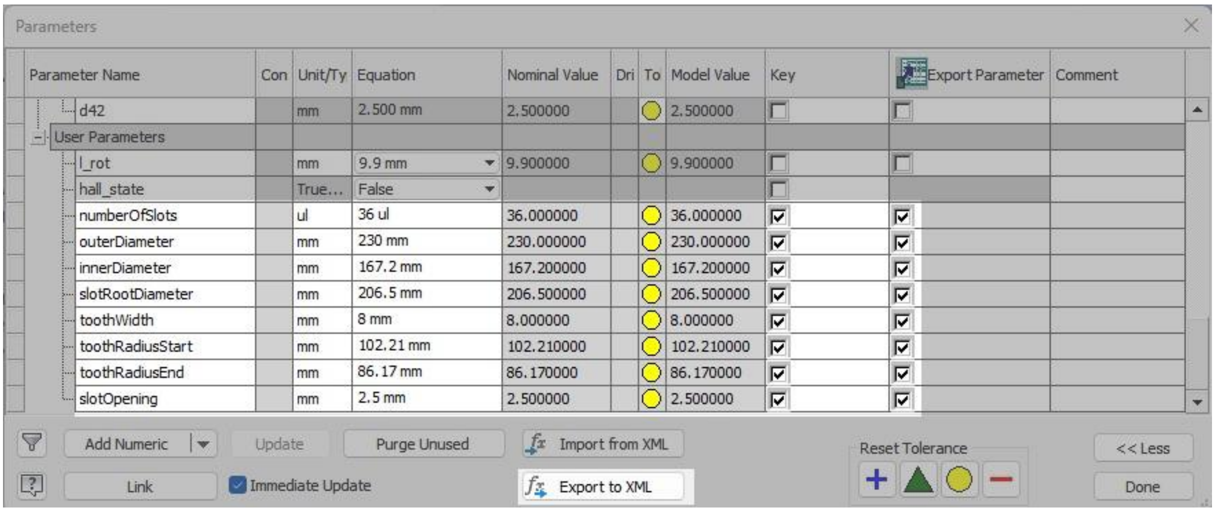

Parameters

Parameter Name	Con	Unit/Ty	Equation	Nominal Value	Dri	To	Model Value	Key	Export Parameter	Comment
d42		mm	2.500 mm	2.500000			2.500000			
User Parameters										
l_rot		mm	9.9 mm	9.900000			9.900000			
hall_state		True...	False							
numberOfSlots		ul	36 ul	36.000000			36.000000	☑	☑	
outerDiameter		mm	230 mm	230.000000			230.000000	☑	☑	
innerDiameter		mm	167.2 mm	167.200000			167.200000	☑	☑	
slotRootDiameter		mm	206.5 mm	206.500000			206.500000	☑	☑	
toothWidth		mm	8 mm	8.000000			8.000000	☑	☑	
toothRadiusStart		mm	102.21 mm	102.210000			102.210000	☑	☑	
toothRadiusEnd		mm	86.17 mm	86.170000			86.170000	☑	☑	
slotOpening		mm	2.5 mm	2.500000			2.500000	☑	☑	

Figure 86 - Parameters window in Autodesk Inventor

From this screen they are exported to an XML file which contains only the selected dimensions. When opening the xml, the raw values look like this:


```
▼<parameters>
  ▼<ParamWithValue>
     <name>numberOfSlots</name>
     <typeCode>ul</typeCode>
     <value>36 ul</value>
     <comment/>
     <isKey>true</isKey>
   </ParamWithValue>
  ▼<ParamWithValue>
     <name>outerDiameter</name>
     <typeCode>mm</typeCode>
     <value>230 mm</value>
     <comment/>
     <isKey>true</isKey>
   </ParamWithValue>
  ▼<ParamWithValue>
     <name>innerDiameter</name>
     <typeCode>mm</typeCode>
     <value>167.2 mm</value>
     <comment/>
     <isKey>true</isKey>
   </ParamWithValue>
```


Figure 87 - Snippet of XML file with stator geometry

The winding information is exported to txt file and the format is more or less in table form:

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```
Custom winding table
  54  0     BDC
  36  slots
  32  poles
1        BalWdg=TRUE
   3  Offset
   3  phases
  12  coils/phase
```

Ph	Go	Ret	Trn
1	1	2	10
1	8	9	10
1	10	9	10
1	10	11	10
1	17	18	10
1	19	18	10
1	19	20	10
1	26	27	10
1	28	27	10
1	28	29	10
1	35	36	10
1	1	36	10

Coil	Go	Ret	Span	Turns
1	1	2	1	10
2	8	9	1	10
3	10	9	-1	10
4	10	11	1	10
5	17	18	1	10
6	19	18	-1	10
7	19	20	1	10
8	26	27	1	10
9	28	27	-1	10
10	28	29	1	10
11	35	36	1	10
12	1	36	-1	10

Figure 88 - Snippet of TXT file with winding information

In the picture above you can see a summary of the contents of the .txt file exported by the finite element motor design software and contains at start some basic information such as number of slots (of the stator) and number of poles (number of magnets radially positioned on the rotor), the offset (in number of slots) between phases, the number of phases and number of individual coils per phase.

Then, the first table contains basic winding information for the first phase from which all the other information can be calculated.

The second table is a detailed version of phase 1 winding information which contains information for each coil of phase 1. For example, the winding of coil 1 of phase 1 starts in slot number 1 (Go) and ends in slot 2 (Return) and the winding is made in clockwise direction from slot 1 to slot 2 (Span=1) and the number of turns is 10. When span is -1, the winding is made counterclockwise (Go slot number is bigger than Ret slot).

The txt file continues with detailed information for phase 2 and phase 3: for example coil 1 of phase 2 starts in slot 1+3=4 and ends in slot 2+3=5 (offset=3).

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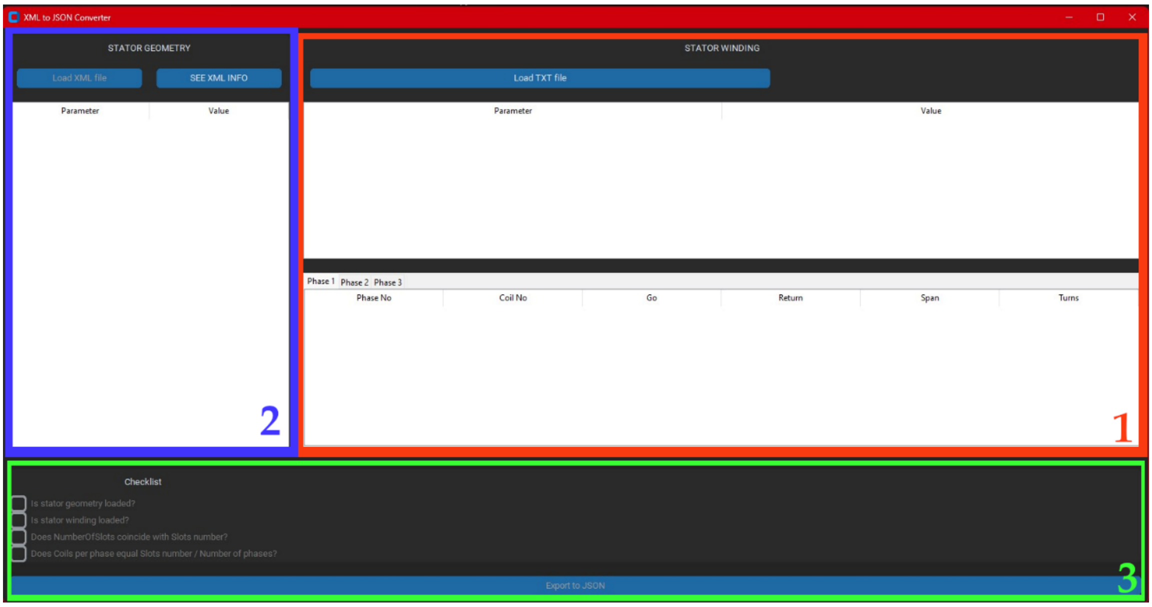

Figure 89 - Stator app with no information loaded

In order to parse both XML file and TXT file into a single JSON file, an app made using python code has been developed (Figure 89). The app has 3 main areas 1) stator winding information, 2) stator geometry, and 3) checklist before export.

First, the txt file must be loaded in the app and the GUI updates and shows the processed txt file. It is made in such a way that it can load both simple and detailed version of exported txt file (see video from Figure 90). Once the txt file is loaded, the button used for loading the xml file gets enabled.

Secondly the XML is loaded and geometry is interpreted. Additionally, 2 values are computed which might be useful for stator rotation as they describe the angle between the external mark of the stator and first slot and angle between two adjacent slots.

Once the checklist is complete, the export button gets enabled and the resulting json file contains all the required information for the next step.

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This order is made in order to check in the background if the number of slots from the TXT file corresponds to the number of slots in the geometry XML file.

Video showing the process can be found at this link:

Figure 90 - Video describing the stator app usage - no commentary

Additionally, the TableWindingReferencing primitive developed by STAM, required one of 3 possible points on the edge of the tooth for calibration, but because of the limited time the calculation of this angle was not made inside the app, but a function to calculate it was developed by ICPE for STAM to use.

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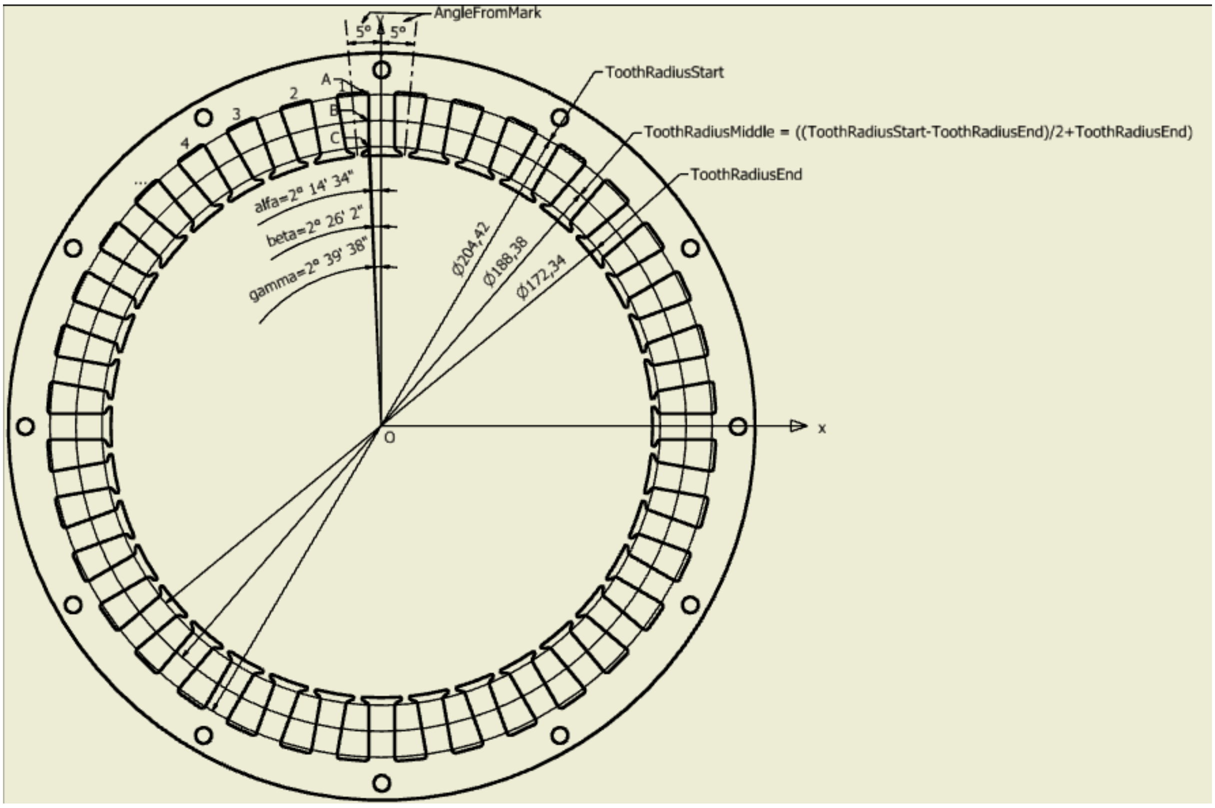

Figure 91 - Angle from mark. Angle between slots. Tooth edge angles - measured on 3D model.

Equation of circle: For any point $X(x_0,y_0)$ on the circle: $x_0^2+y_0^2=R^2$

This means:

$x_A=x_B=x_C=-4$ (Quadrant 2 => x is negative, y is positive; x= - (ToothWidth/2))

y_A=sqrt(ToothRadiusStart^2-16) = 102.13169978

y_B=sqrt(ToothRadiusMiddle^2-16) = 94.10502696

y_C=sqrt(ToothRadiusEnd^2-16) = 86.07711019

Thus: Angle of sector made by X point is $\theta = \left(\frac{|x_0|}{y_0}\right)$

Calculated edge angles:

α= arctan(4/102.13169978)= 0.0391451105 radians =2.24284962 deg = 2° 14' 34.25863"

β= arctan(4/94.10502696)= 0.0424801284 rad=2.43393207 deg=2° 26' 2.15545"

γ= arctan(4/86.07711019)= 0.0464365548 rad=2.66061861 deg=2° 39' 38.227"

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So you need the function: $\theta = arctan\left(\frac{|ToothWidth/2|}{\sqrt{R^2 - \left(\frac{ToothWidth}{2}\right)^2}}\right)$ where R is either ToothRadiusStart, ToothRadiusMiddle or ToothRadiusEnd; answer is in radians.

Or the function: $\theta = arctan\left(\frac{|ToothWidth/2|}{\sqrt{R^2 - \left(\frac{ToothWidth}{2}\right)^2}}\right) * \left(\frac{180}{\pi}\right)$ where R is either ToothRadiusStart, ToothRadiusMiddle or ToothRadiusEnd; answer is in degrees.

Below you can see a summarized diagram for generating the stator json file:

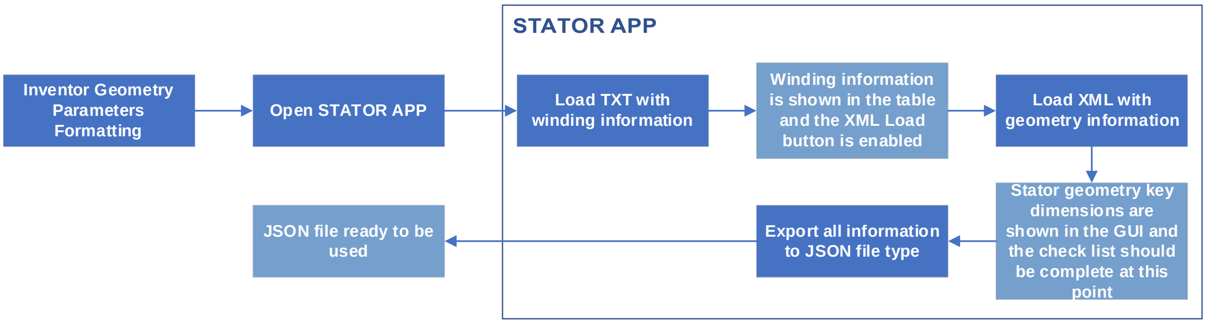

Figure 92 - Generating Stator Winding json file

Magnet bonding use-case

In this case, the required information is only about geometry and any rotor is represented by only 3 CAD files: one for the magnet, one for the rotor shaft and one for the assembly of rotor shaft and magnets.

The CAD file for the magnet contains the magnet dimensions, length, width and height.

The CAD file for the rotor shaft contains information about whether the rotor shaft is round or milled(slots made for the magnets), the number of poles (number of magnets placed radially),

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outer radius (if the shaft is rounded) or distance from the shaft center to the bottom of the milled slot for the magnet (if the shaft is milled) and the rotor width.

The CAD file for the complete rotor (shaft with magnets) contains information about the number of magnets per row (for example a shaft with a width of 50 mm might have 2x25mm magnets or 5x10mm magnets), about the polarity of starting magnet (the first placed magnet if it is North or South), about the offset of the first magnet (for example, a rotor might have a width of 52mm and the magnets are 2x25mm, then they might require to be placed with offset of 1mm from the side of the shaft in order to be placed in the middle of the shaft lengthwise) and two additional values which allows future development to bond magnets for hall sensors as well (one value states the presence of magnets for hall sensors and the other value is a distance between the last magnet placed and the magnet for the hall sensor).

In this case as well, a python app was developed in order to parse and format to a json file the 3 XML files exported from the 3 CAD files. The Rotor app has 3 sections to load them and the information is displayed in the GUI once they are loaded. As a failsafe, all the 3 xml files must be loaded before the Export to JSON button is enabled. There is no particular order for loading the files. Below you can see a screenshot of the Rotor app with example files loaded:

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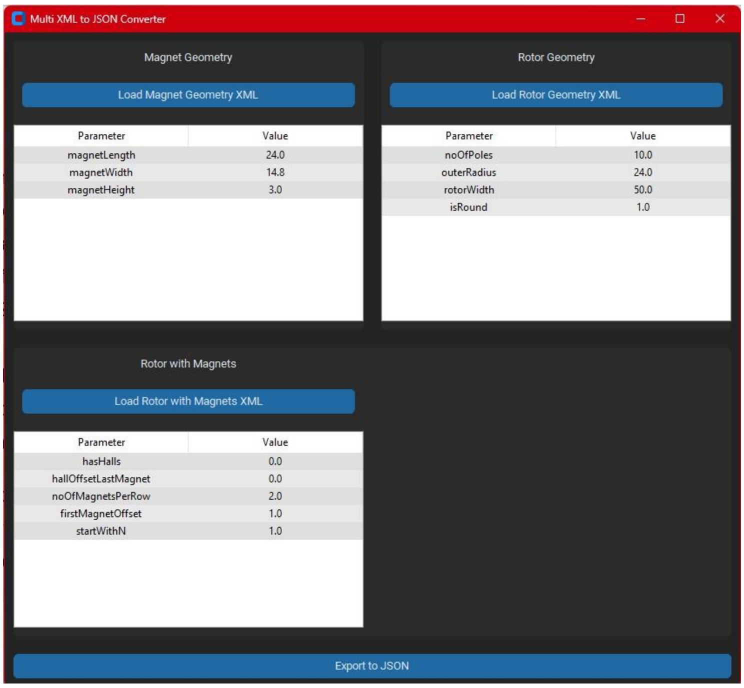

Figure 93 - Rotor app with loaded example files

A video of its usage can be found at the qr code below:

Figure 94 - Video describing the rotor app usage - no commentary

Below you can see a summarized diagram for generating the rotor json file:

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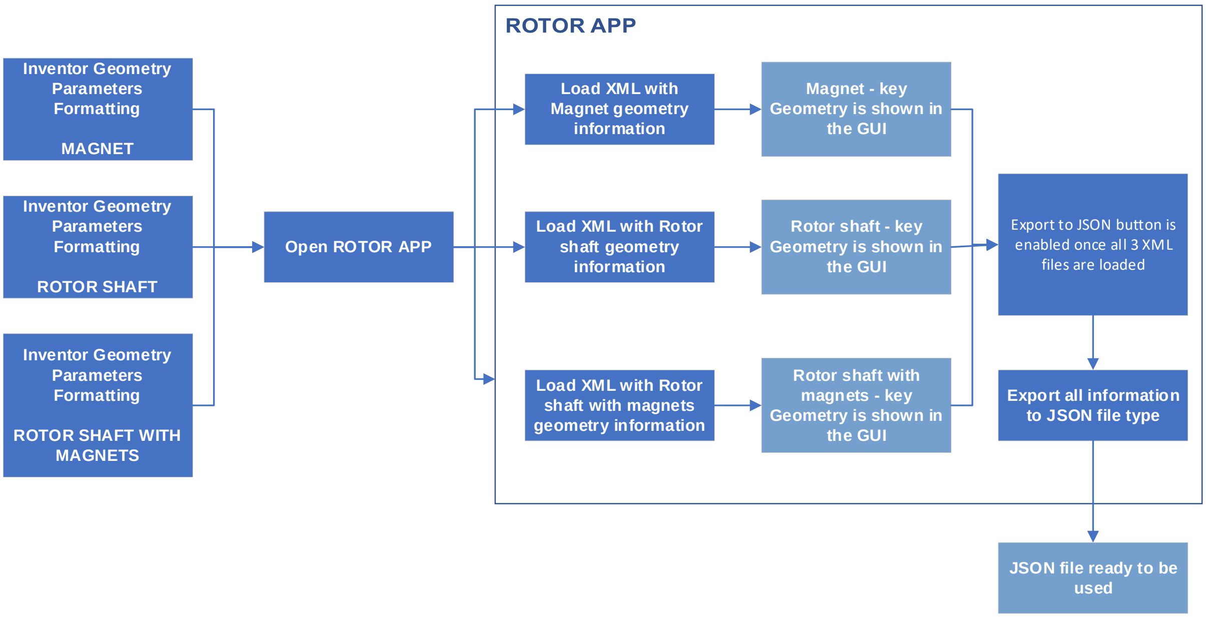

Figure 95 - Generating Magnet Bonding json file

5.2 Software Integration

5.2.1 IKOR's use case

The ACROBA platform applied to this use case is intended for the operator of the station, so it is easily reprogrammable to a different pick and place setup of electronic components.

The system architecture used in the IKOR robotic cell is based on the standard ACROBA architecture, along with the Ikor_Config_Cell component. This latter component includes several additional Docker containers.

Firstly, the use of Photoneo hardware, whose ROS driver is only compatible with Linux Kinetic, required us to deploy a dedicated container for this device.

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A second container houses all specific skills, such as those needed to interact with the Asyril component feeder system, Modbus RS485 control of the DH robotic gripper, the Omron robot itself, and the digital input/output control skills, among others.

A final third container was deployed to host the web interface and the MongoDB database. This interface functions as a ROS node, publishing various topics. Additionally, several skills were developed to facilitate interaction with the MongoDB database.

In this section, the basic structure and working of this application is shown.

This first window we can see when running the application is the following one:

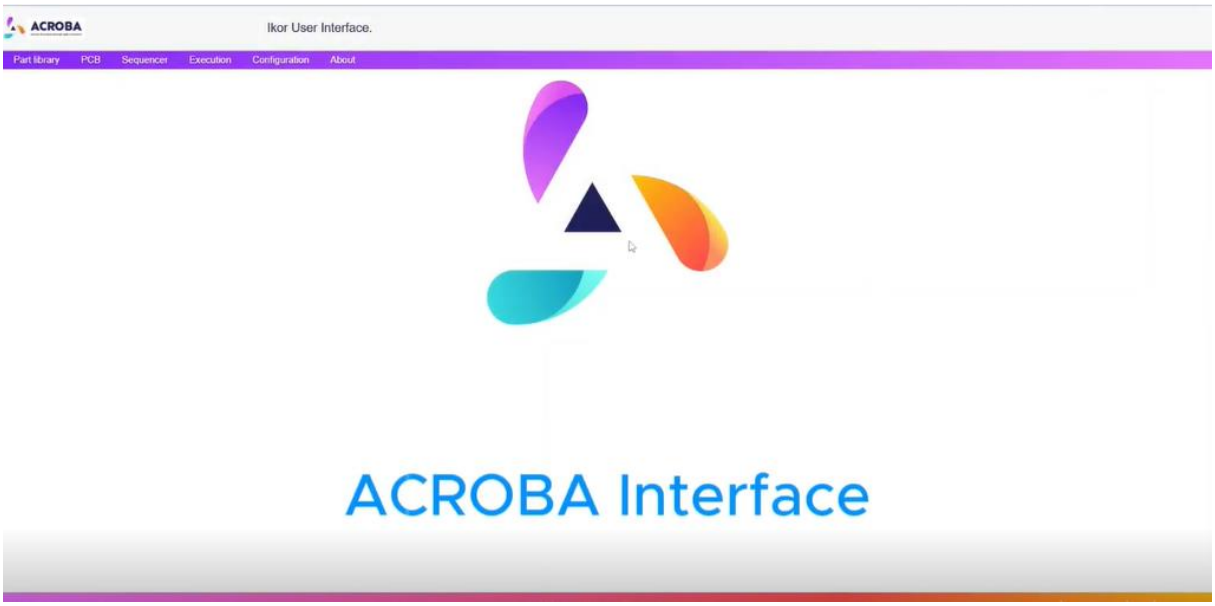

Figure 96: Main window of the application

In the upper part, five different operative sections can be deployed. They will all be explained. The "About" section gives information about the application itself.

The first window we see is the list of components and their values. Before the application works, all of the electronic components used should be properly included and set up in this database.

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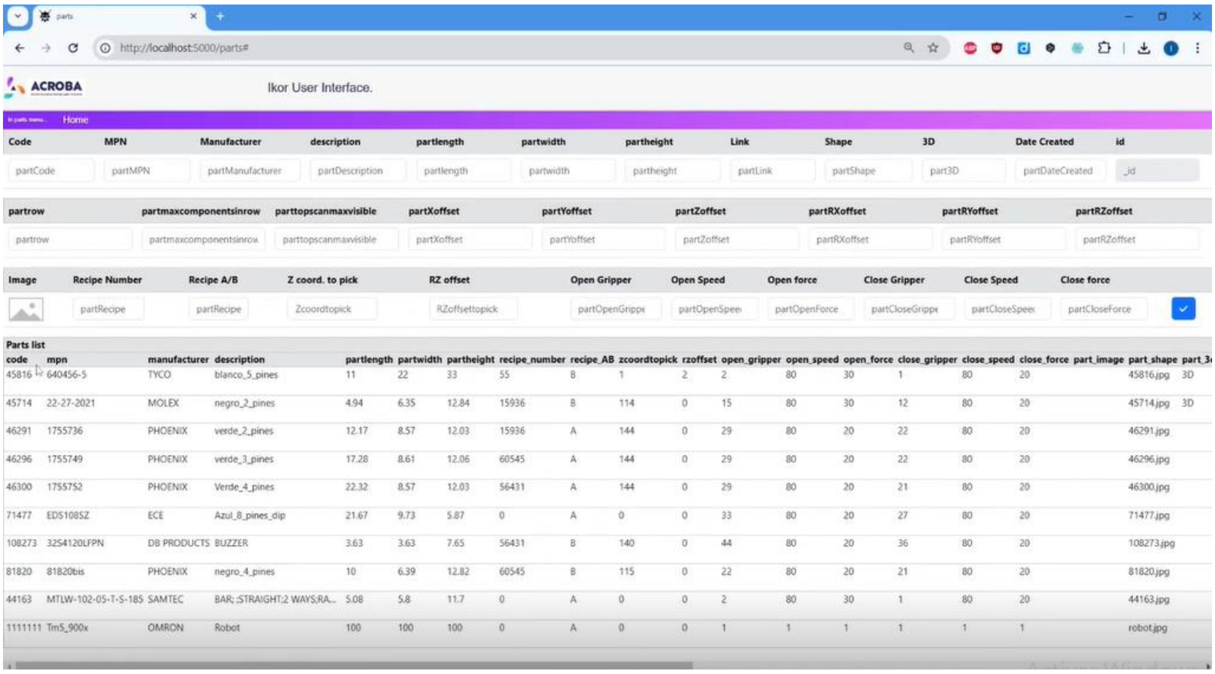

Figure 97: Part Library Window

We can change or configure any of the parameters of all these elements if we click on any of the components. The following window will appear:

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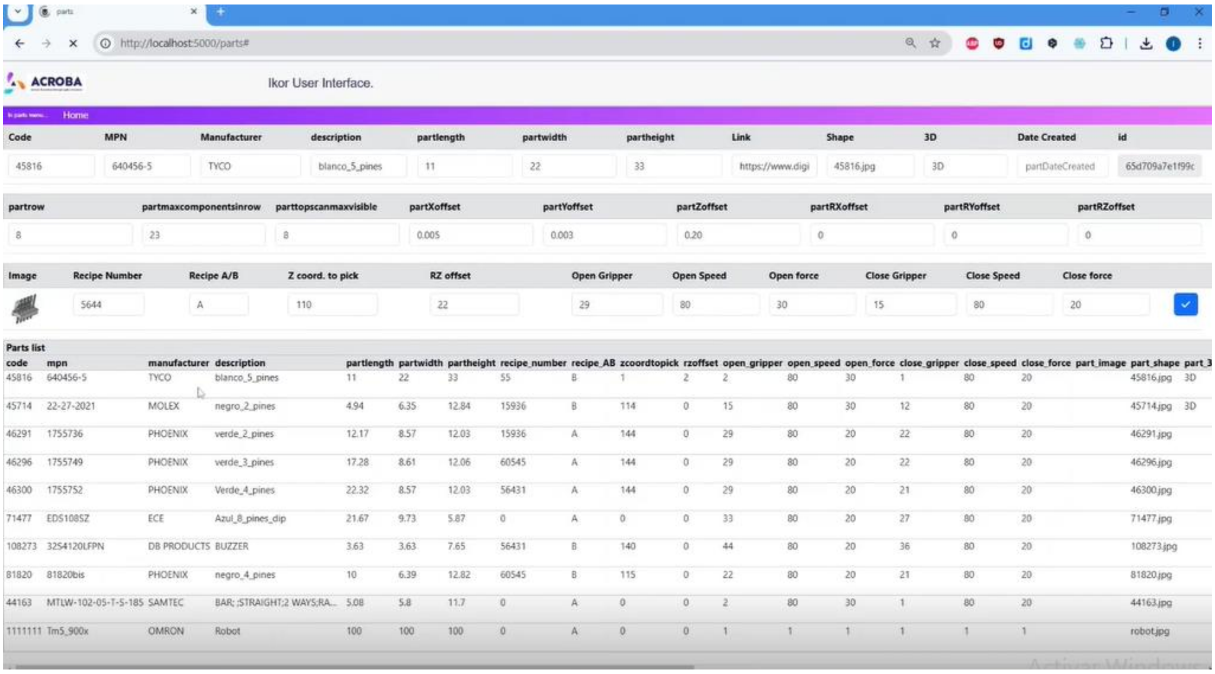

Figure 98: Detail on the configuration of each component within Part Library section

This configuring window allows the user to customise several key aspects of the component, such as the offset position (both in position and rotation) essential for piking, the recipe number, which affects the vibratory configuration so that the vibration effectively moves the components, and the dimensions and force to be used by the gripper.

The next tab that can be accessed is the PCB section, that enables loading different PCB models. In order to load any PCB model, they should be in a CAD format and then have the exact place of the components:

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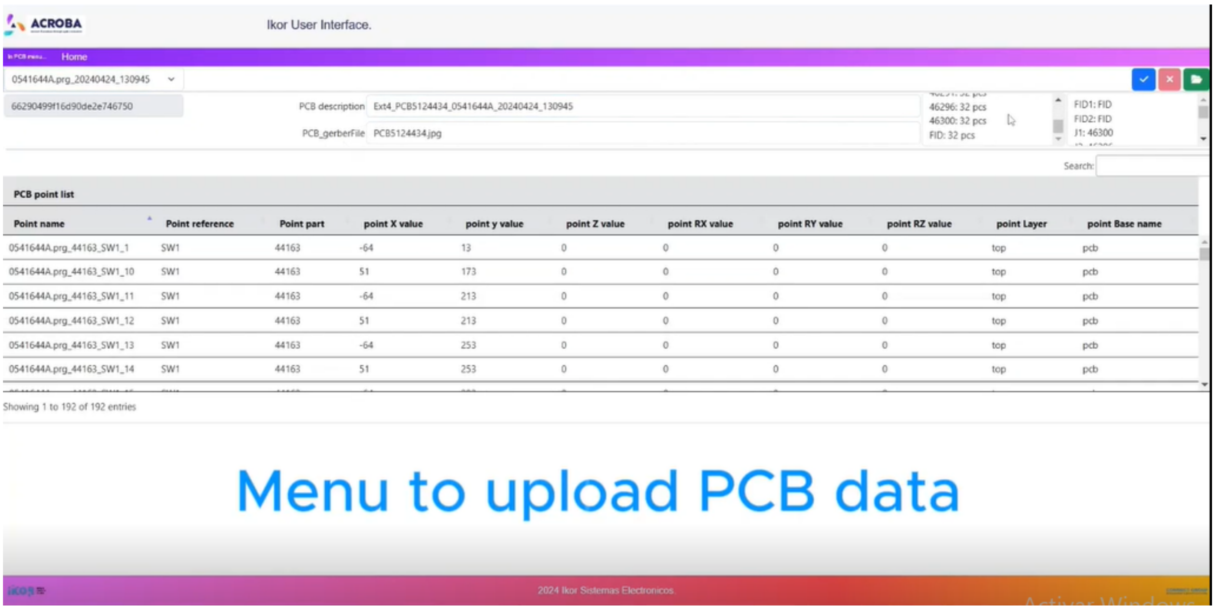

Figure 99: PCB Window

We can also check how many components of each kind has a PCB, with their positions:

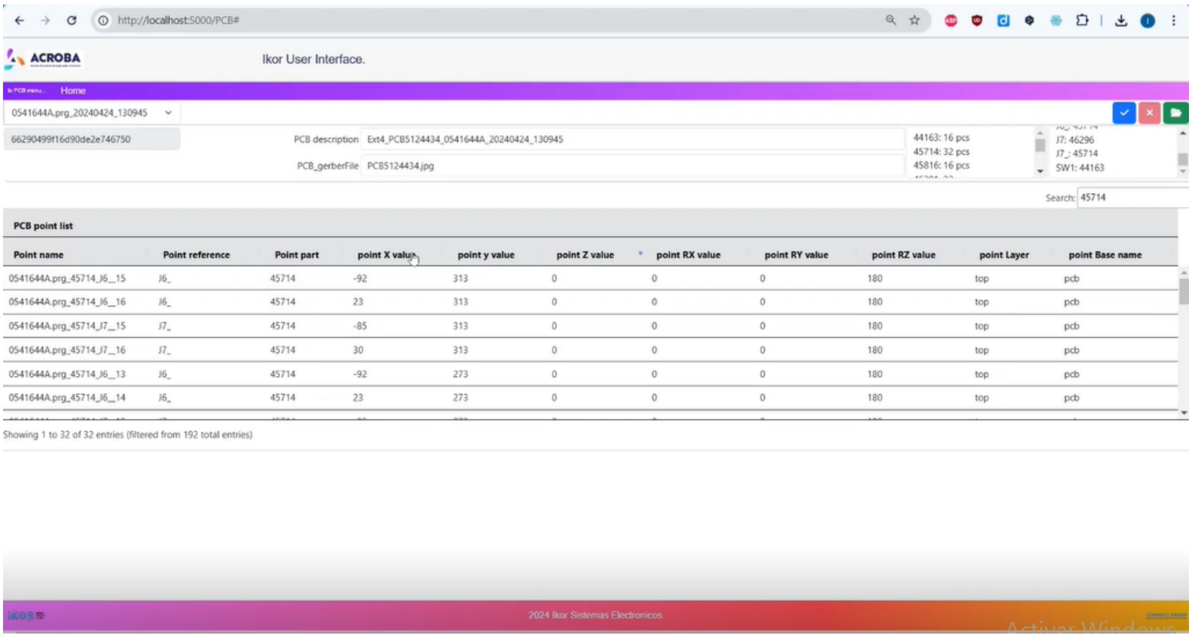

Figure 100: Search for components within PCB window

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The Configuration window is used to add, edit, or delete auxiliary robot positioning coordinates that are essential for process automation, such as the theoretical coordinates where the PCB stops on the conveyor, or the locations of certain ARUCO markers used for robot calibration.

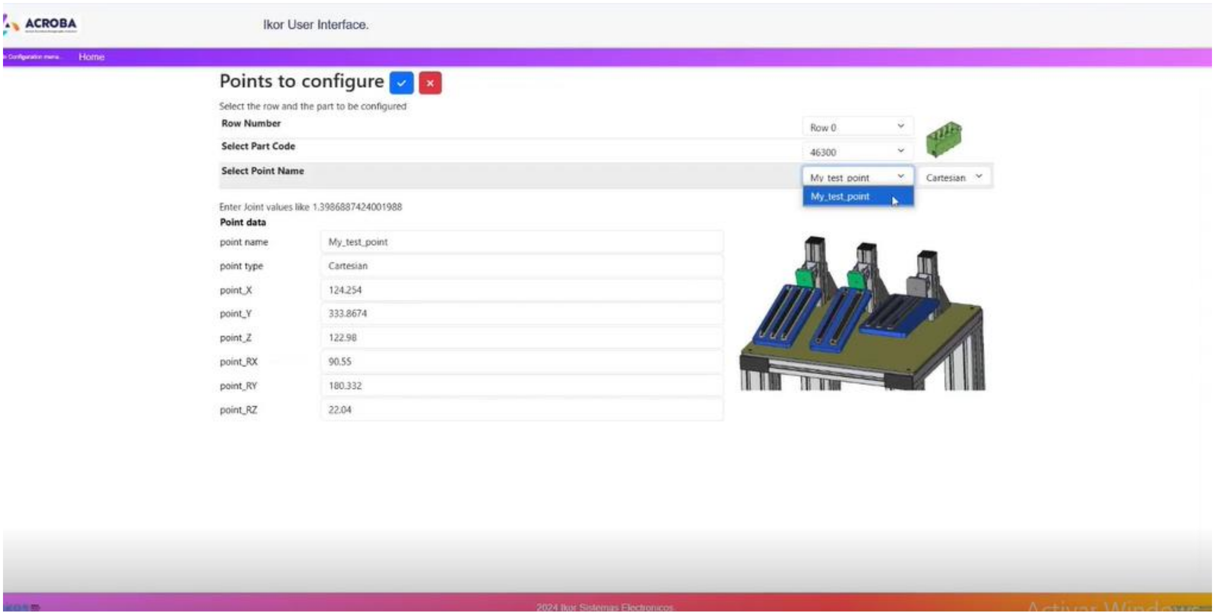

Figure 101: Configuration Window

And, finally, in the “Sequencer” window, we can program the sequence of components to be assembled in the PCB, determining how many elements and their respective order of assembly:

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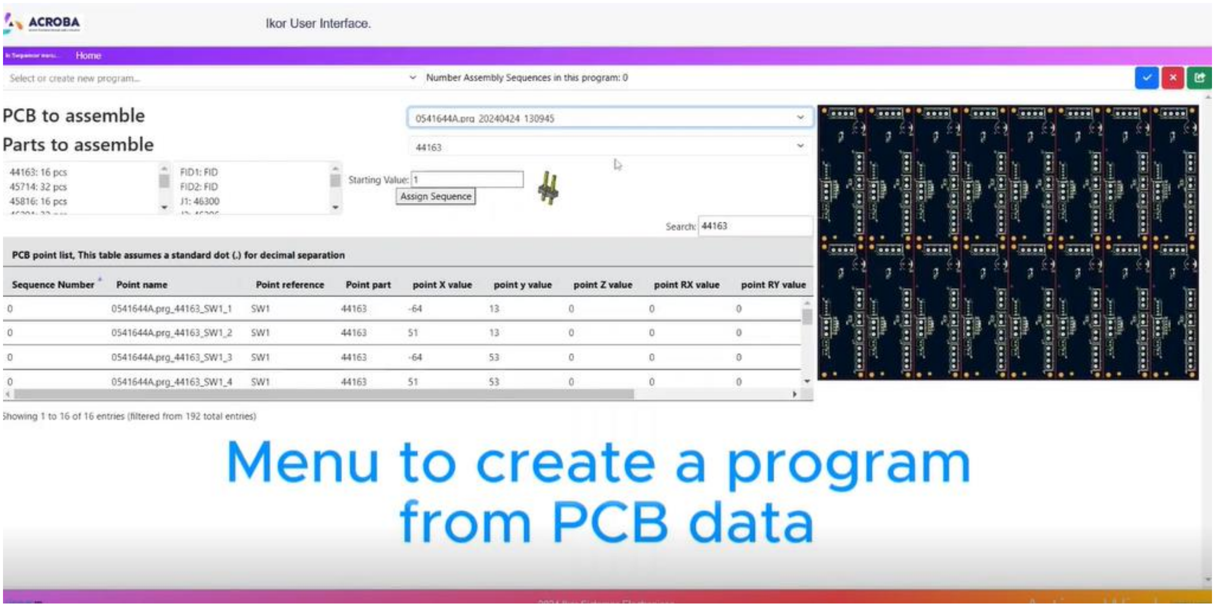

Figure 102: Sequencer Window

A program is an ordered selection of PCB points that need to be assembled in a specific sequence. The video quickly shows how a program can be created by first selecting one of the two PCBs targeted in this project, choosing components as desired by the operator, assigning sequence numbers (i.e., assembly order), and even modifying assembly coordinates. These features ensure the flexibility of the ACROBA system in an IKOR production environment. Once the points are selected, the program can be named and saved to the database.

Having everything configured, the user is able to control and monitor the process in real time with the execution window. This window shows the interface connection to the ROS system. Through selection widgets, the operator can select the program created in the previous tab and specify the starting sequence for the robot’s operation. The video in D6.6 demonstrates how pressing an action button triggers the publication of a topic containing the program name and sequence name. These names are then used by a directing script to query the MongoDB database.

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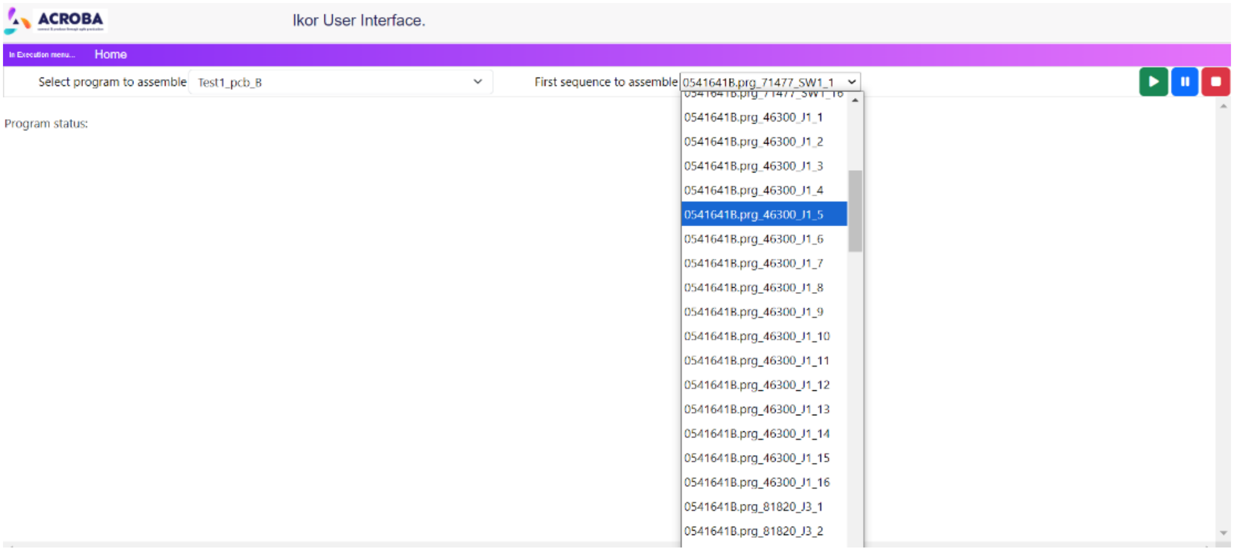

Figure 103: Execution Window

Having all these tools for setting up a pick and place collaborative application of electronic components, the underlying logic follows these steps:

1. The operator selects the program and sequence.
2. The web interface publishes this information to a topic.
3. A script subscribed to the topic receives this information and initiates the process.
4. It runs the *Get_program_data* skill and receives a list of ordered assembly sequences.
5. It runs the *Get_sequence_data* skill and receives the assembly coordinates and the component code to be placed at those coordinates.
6. It runs the *Get_part_data* skill and retrieves all configuration parameters for that component.

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With all this data, the script is ready to execute the assembly sequence. If it does not receive any pause or stop signals, the script will repeat the same querying process for each of the sequence names received initially until the list is completed.

5.2.2 ICPE's use case

For integrating and testing the primitives and skills of the ICPE use-case, a dedicated computer has been purchased, which has the following specifications:

- I9 8x8 5.0 GHz processor cores.
- 16 GB Ram memory.
- 1TB GB of free hard drive space.
- Minimum NVIDIA 940M or similar embedded Graphics.
- Network access.
- Ubuntu 20.04.3 LTS 64-bit.

Once the PC was available in STAM, the installation of the appropriate version of Ubuntu and of the ACROBA platform took place.

For the two robotic cells, the software integration parts foresaw the creation of the “cell config” GitHub repository, which includes all the information required to properly integrate a robotic cell into the ACROBA platform.

In particular, the repository contains:

- All the hardware ROS drivers packages: in the ICPE use-case this mainly consists in the Universal Robots ROS Driver, to communicate with the UR10e robot.
- A “Resources” package which gathers all the different data inputs which are needed to design a robotic cell on the ACROBA platform, in particular meshes, CAD files, URDF scenes, and test launch files to display scenes in Rviz.

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- The MoveIt! configuration package for the robot's motion planning and control.
- Some docker files listing the dependencies and giving instructions on how to build the repository.
- A ROS entrypoint file which provides environment setup instructions and the commands to launch the setup of the cell, on the real robot but also in simulation.

Figure 104 and Figure 105 show the scenes of the two cells displayed in Rviz.

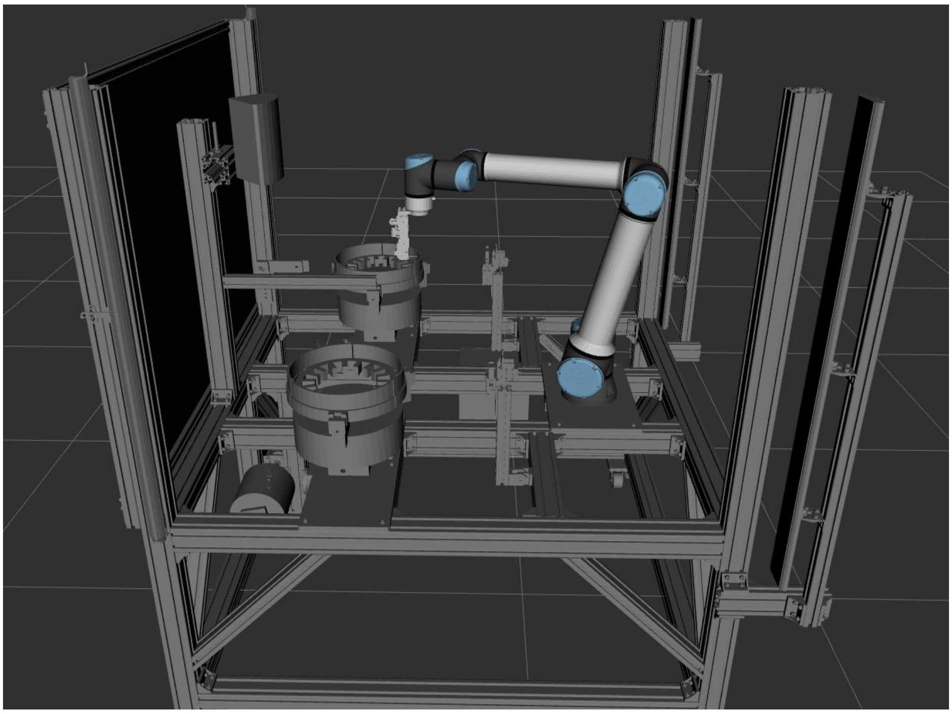

Figure 104 - Rviz scene of the winding cell

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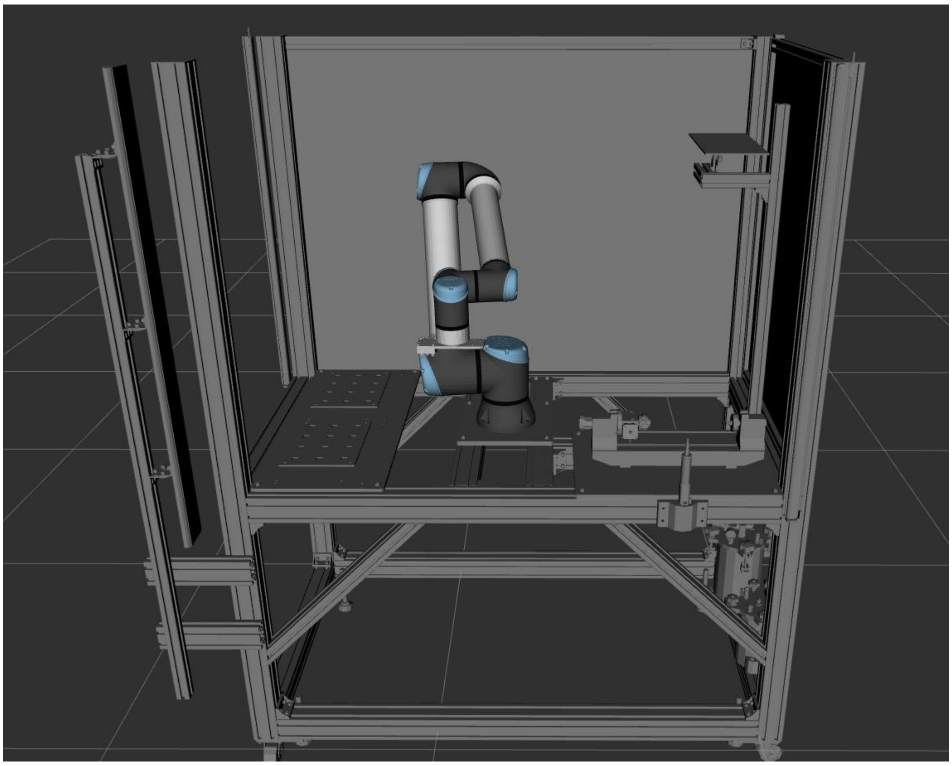

Figure 105 – Rviz scene of the bonding cell

Once the environment was fully set up, it was possible to proceed with testing and fine-tuning the developed robotic primitives and skills. This involved iterating between simulated and real-world environments to refine the capabilities and ensure optimal performance. At first, the simulation environment within Rviz was used, where it was possible to safely model and observe the system's movements, responses, and interactions. Testing in Rviz allowed to make preliminary adjustments to the robotic behaviors without the risks associated with the physical setup.

After achieving stability and confidence in the simulated environment, testing within the actual cell started. Here, it was possible to observe real-world variables, such as sensor feedback and environmental interactions, that might not have been fully captured in simulation.

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Through this meticulous process of testing and fine-tuning, the system's ability to perform the two complete collaborative processes was successfully developed and validated. Videos showing the two robotic processes have been submitted within deliverable D6.5.

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6 Conclusion

This Deliverable has shown the developments regarding the ACROBA customization and implementation into real robotic cells, for which an extensive process design has been carried out.

The main designers have adapted to the requirements of the use case owners and the resulting robotic stations comply with their main goal and the collaborative standards specified for this work package.

The ACROBA customization has consisted in selecting the required software developments to program the stations according to the processes of the use case owners. This has resulted in several real collaborative use cases completely operative under the ACROBA framework, and are easily reprogrammable, thus, agile.

The functionality of these cells can be seen in deliverables 5.6, 6.5 and 6.6.

7 Bibliography

[1] Müller, R.; Vette, M.; Geenen, A. Skill-based dynamic task allocation in Human-Robot-Cooperation with the example of welding application. Procedia Manuf. 2017, 11, 13–21. [CrossRef]

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