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ACROBA

connect & produce through agile production

D5.3 Report on integration and customization of generic ACROBA solution

WP5

Lead Beneficiary: NUTAI

Delivery Date 30/6/2023

Dissemination Level: PU

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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

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History of Changes

Version	Date	Description of Changes	By
1.0	6/06/2023	First Version, general sections and IKOR's use case	Adrián Ripoll Mar Gracía
	6/06/2023	Added sections regarding the ICPE use-case	Edoardo Giacheri Francesca Canale Andrea Pilloni
2.0	30/06/2023	Updated software testings and hardware installations	Adrián Ripoll

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Executive Summary

The objective of this document it is to describe the development of the fully operative solution found for both use case automatic stations, the one in IKOR and the one in ICPE. The whole project will be explained, starting with the requirements for the manufacturing process, then with the mechanical, pneumatical and electrical design and last with the ability to collaborate of the station, making sure the safety norm is complied.

1 Introduction

The starting point for this deliverable is the specifications and results from Deliverables 5.1, 5.2, 5.7 and 5.8, where preliminary 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 mirrors the design process carried out by all the partners of the project. 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 and coherence of the Human Robot Collaboration approach for all stations, as expert partners in the field.

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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).

In the last part of this deliverable, information about the installation of the hardware and software where the ACROBA can be tested is given, taking into account several non-critical elements are not present due to extended delivery times or delays from other Work Packages.

2 Engineering Designs of Collaborative Cells

2.1 IKOR's Use Case

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

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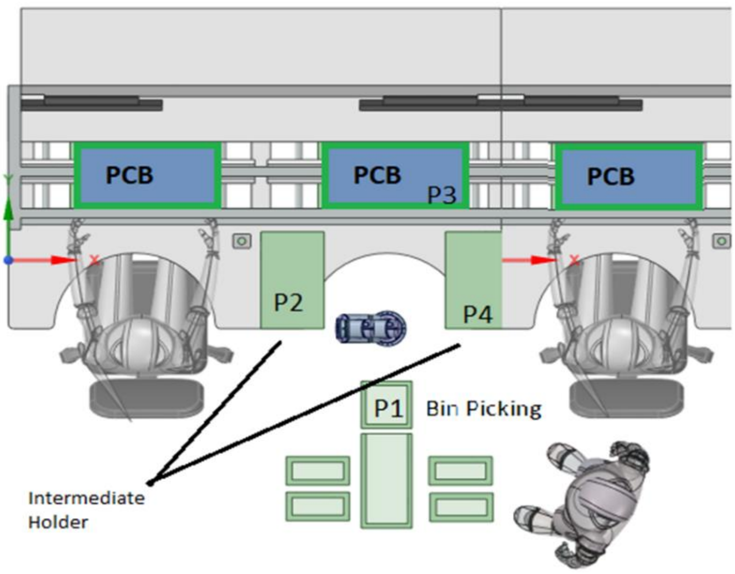

Figure 1 Conceptual design of IKOR's use case station

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.

As 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:

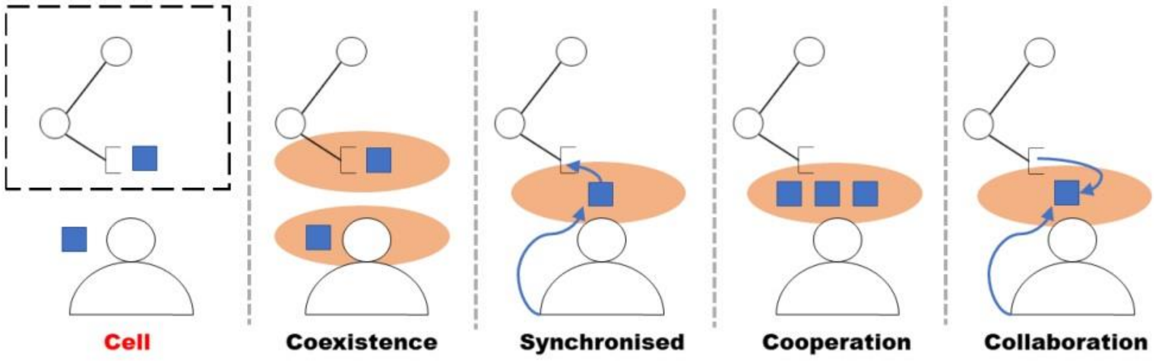

Figure 2 Classification of methodologies for human-robot shared working space

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, some HRC designs and calculations are done according to these norms, but they differ slightly from the final design that is installed.

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.

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:

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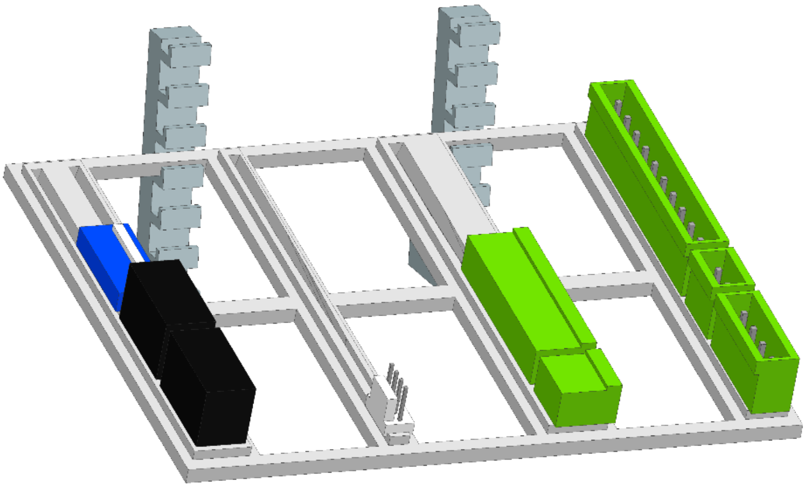

Figure 3 Initial design for the buffer

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 that has been solved in this task.

The layout has been defined to place the components in an efficient and productive way. 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 of 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 such as the following one:

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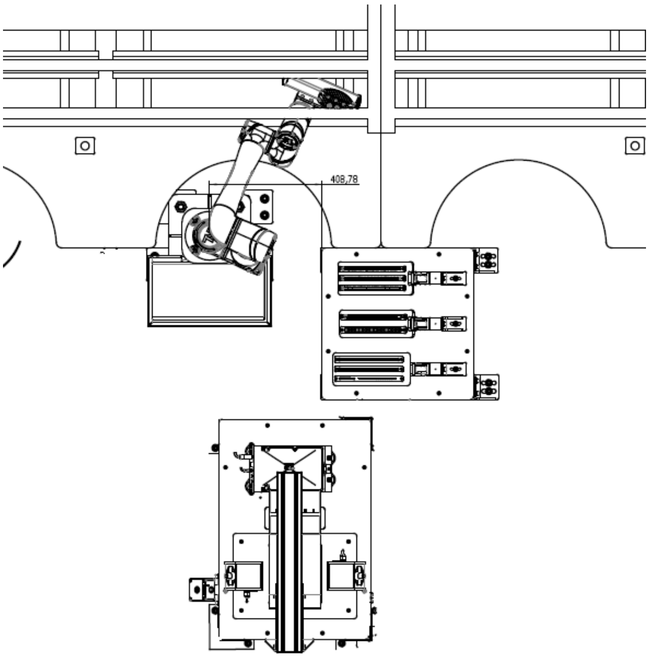

Figure 4 IKOR's Station final Layout

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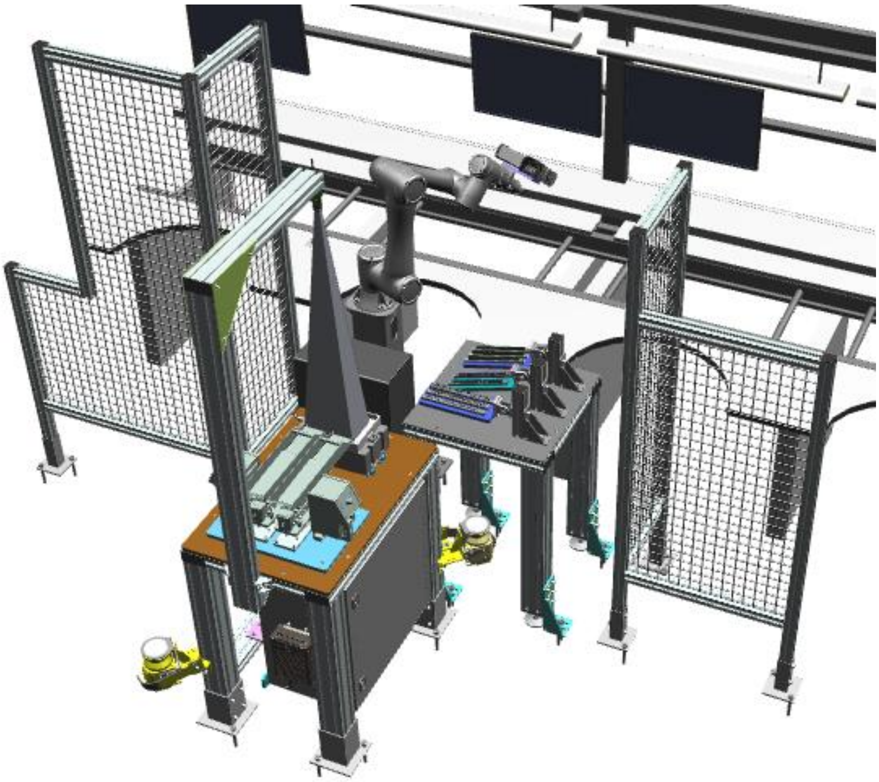

Figure 5 3D Layout View

2.1.1 Requirements and specifications (including HRC)

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:

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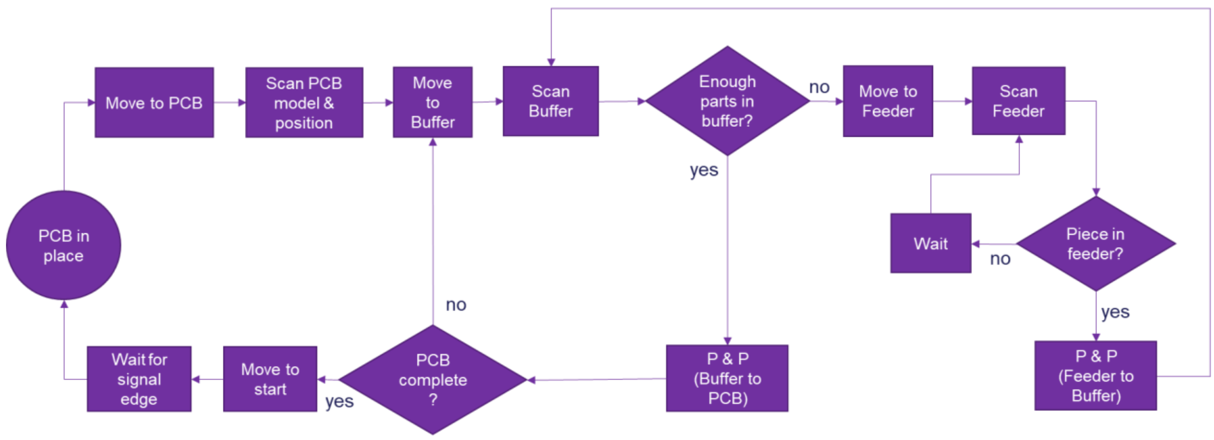

Figure 6 Sequence diagram for IKOR's use case

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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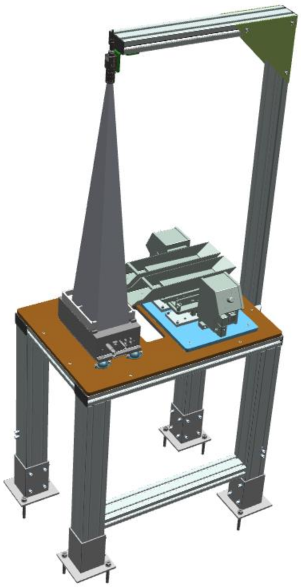

Figure 7 Vibrating Table 3D View

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 8 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 9 Cobot's Base 3D View

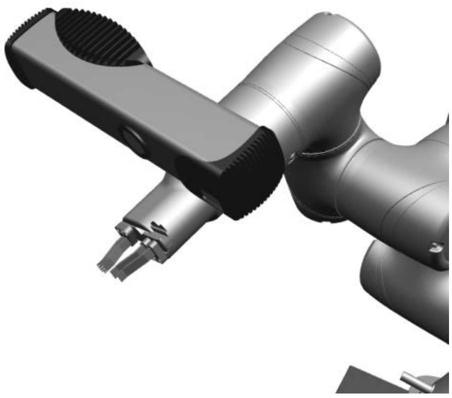

Figure 10 Cobot's Tool View

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2.1.2 Mechanical and pneumatical designs

IKOR's use case design is being carried out mainly by NUTAI. Weekly meetings currently take 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:

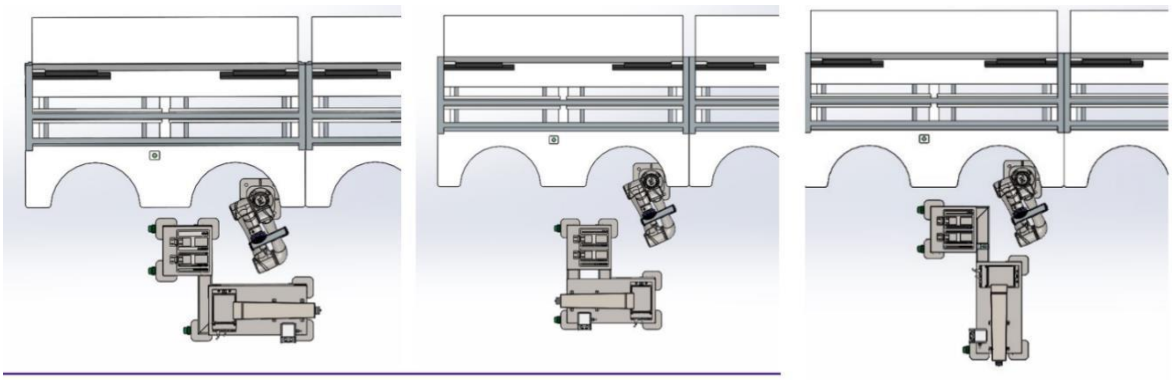

Figure 11 Layout proposals during the mechanical design phase. None of them was finally adopted

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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 considered.

When the final model of the feeder was chosen, the electrical designs began. Still, mechanical designs should continue with several problems:

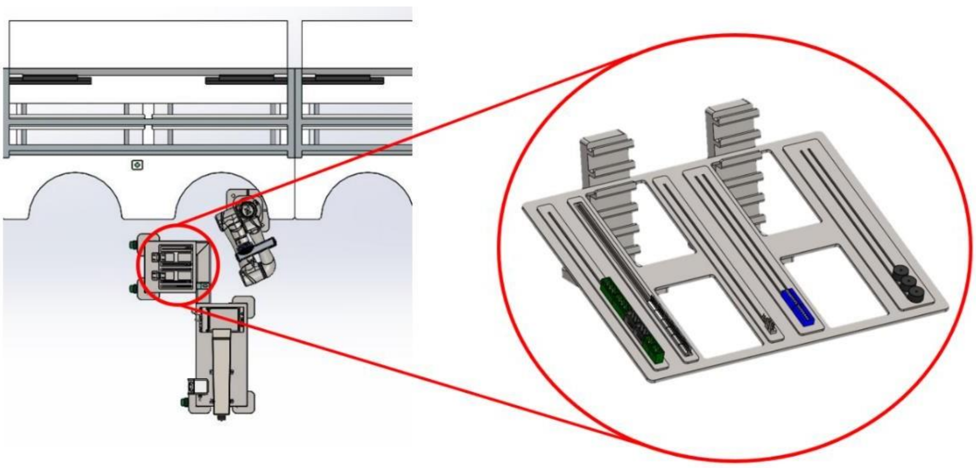

Figure 12 Intermediate buffer's first design

The slope of this surface is not easy to determine, because it should guarantee that the components fall, but if it is too steep, the friction between components may be too high and when the robot picks one, the next one is misplaced or falls.

Apart from that, in this shape of surface, several components with identical dimensions would be on the same slot. The idea was that a camera installed in the robot would recognize the component and pick it, with additional software logic to choose between components. However, it was determined the space and mechanical cost saved with this idea did not compensate the software design complexity when compared to a wider surface with one slot per component.

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Therefore, the final design adopted is similar to this one. The width of the slots is slightly higher at the top part, to ease the placement of a component by the robot:

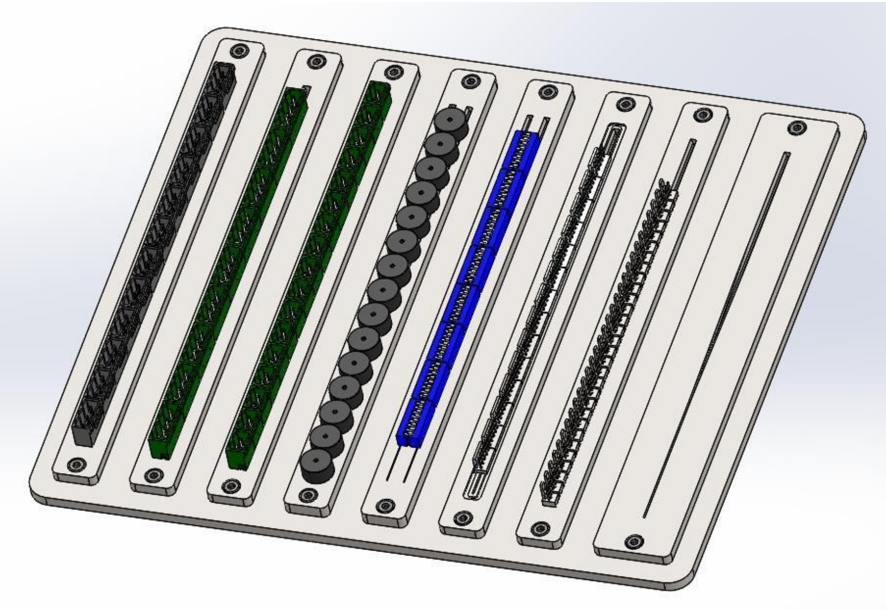

Figure 13 Intermediate buffer's second design

This design 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

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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.

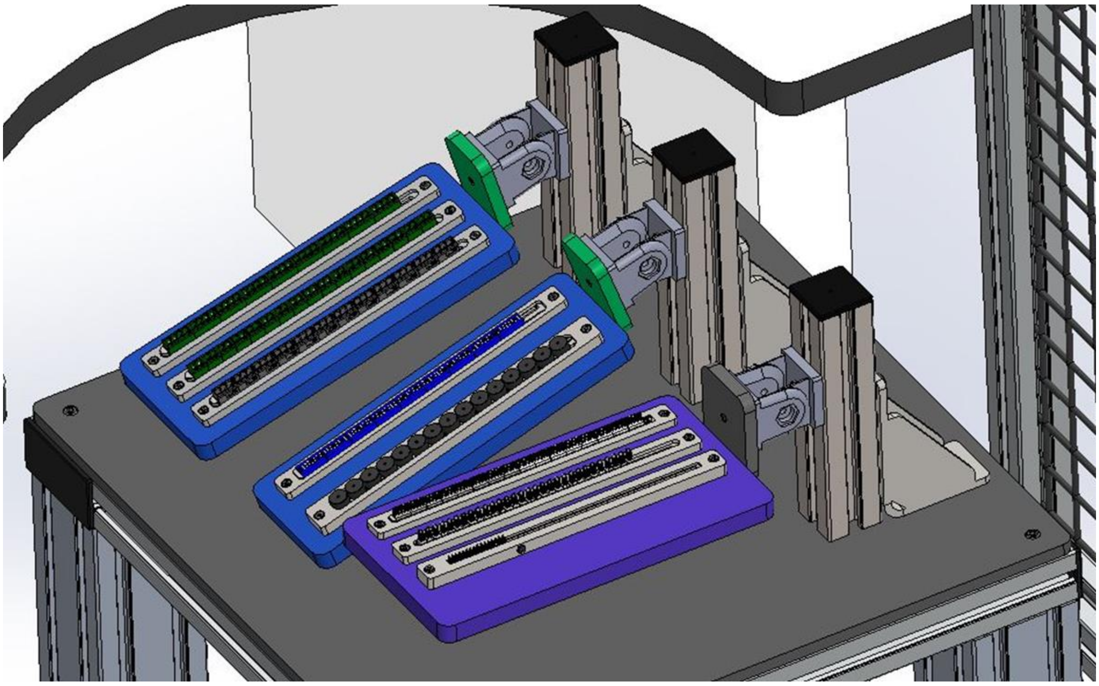

Figure 14 Intermediate buffer's final design

2.1.2.1 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.

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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.

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

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

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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.

2.1.3 Electrical Designs

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

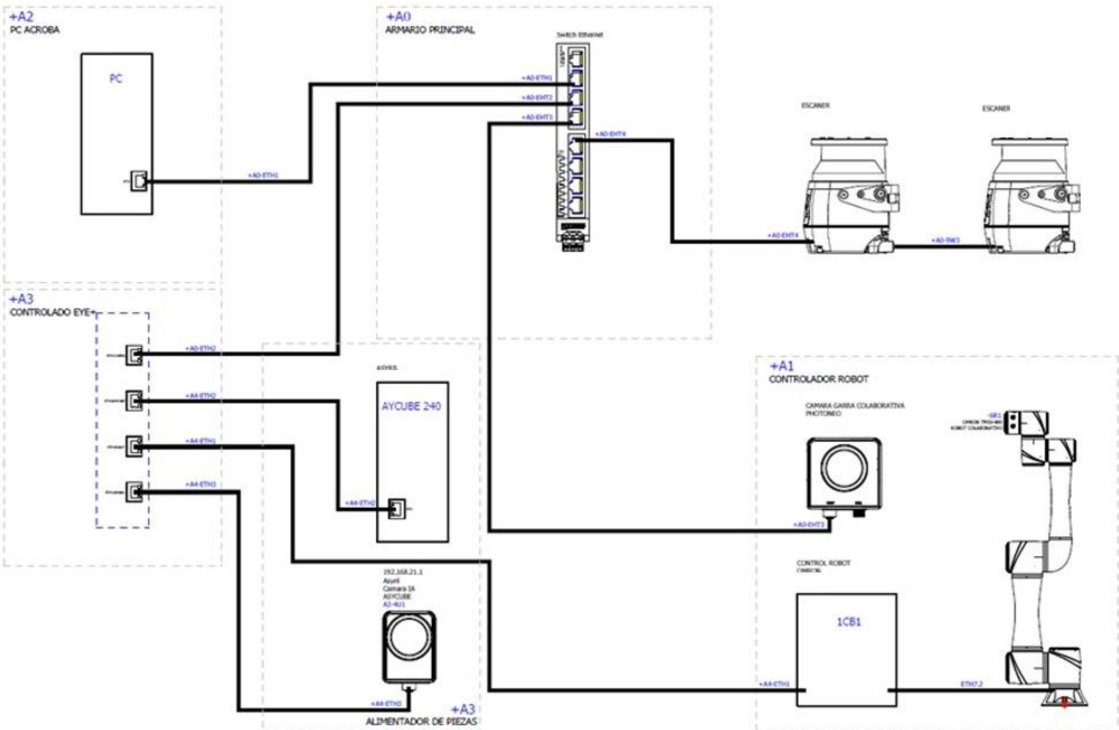

Figure 15 IKOR'S control architecture

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

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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.

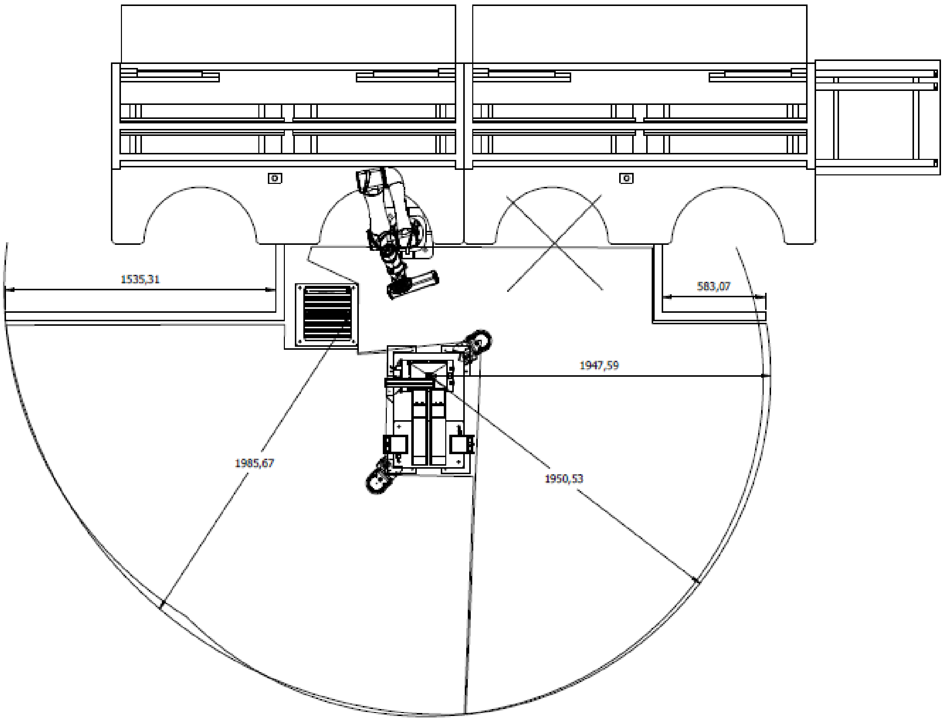

Figure 16 Safety Distances

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

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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 17 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_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 18 Safety Distance Calculus

2.1.4 Human Robot Collaboration and compliance with safety standards

2.1.4.1 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

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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.

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.

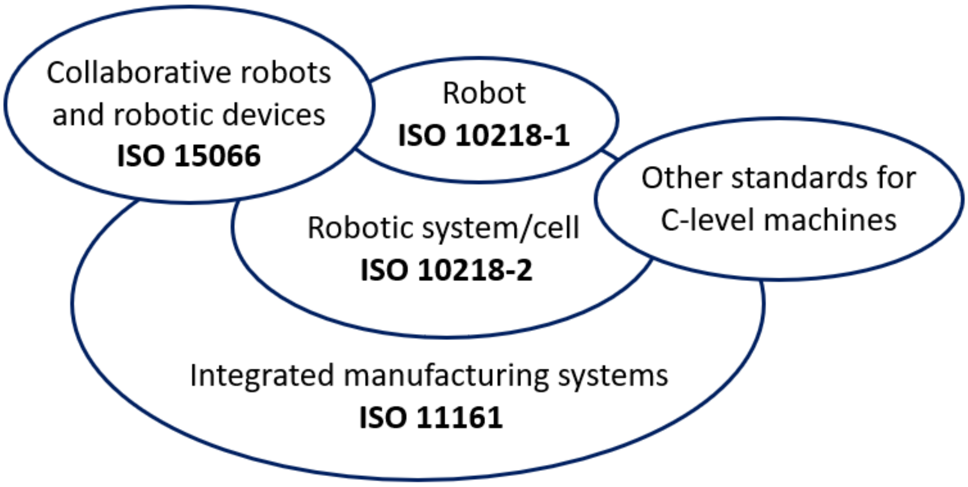

Figure 19 Diagram of relationships between standards for collaborative robotic system

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**

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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 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.

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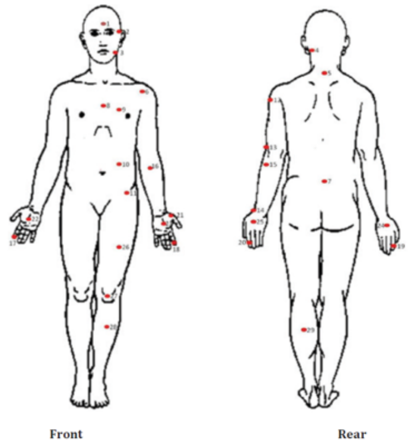

Figure A.1 — Body model

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 20 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:

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.

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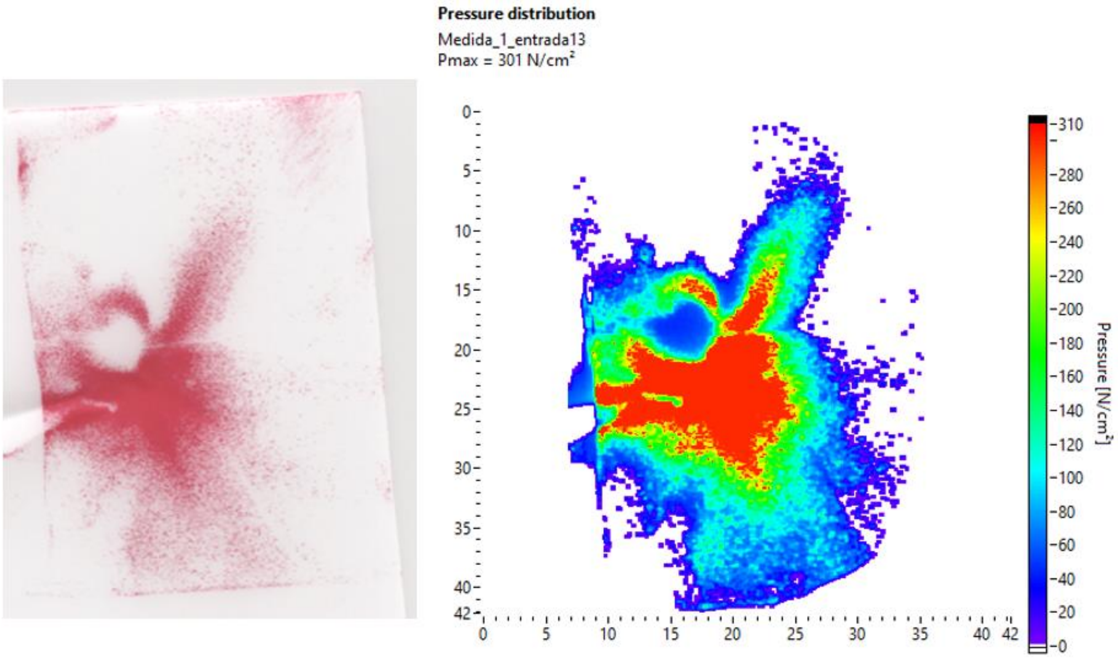

Figure 21 Example of an Impact Test

2.1.4.2 Application to IKOR's Use Case

An analyse 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, it has been stablished 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.

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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.

The advantages of this modality are that the station would be totally accessible, workers could cross and rest inside the station without interrupting its normal behaviour. No safety devices would be installed, and no safety areas should be designed, so the installation would be the easiest one. The main obstacle is that the cycle time would be longer and that could affect the productivity of the station. The layout would be such as the following one, without any kind of safety elements:

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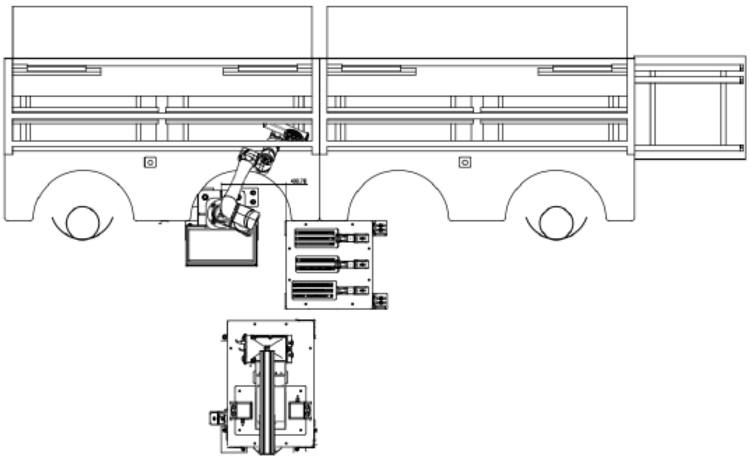

Figure 22 Layout Case 3 HRC Analysis

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.

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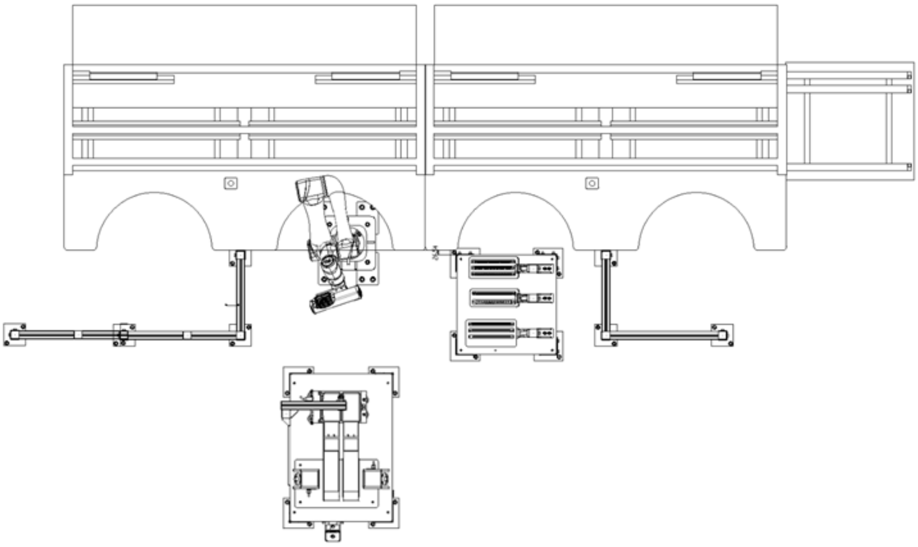

Figure 23 IKOR's Prototype Layout

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 on the website and some tests have taken place. The results obtained are summarised in the following table:

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Table 3 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 will be performing 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.

2.2 ICPE's Use Case

2.2.1 Requirements and specifications (including HRC)

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.

2.2.1.1 Winding process

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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 **Table 4**. Each stator has different geometric parameters such as diameter, height, and number of teeth.

Table 4 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
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,

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indicating a gap between teeth. The tooth which follows the detected gap is the first to be wound.

2.2.1.2 Bonding

Table 5 Specifications of rotors models

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

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 **Table 5**. The end-effector is designed to ensure the possibility of installing a camera, needed for skills such as CAD matching.

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2.2.1.3 HRC

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.

2.2.2 Mechanical and pneumatical designs

2.2.2.1 Winding cell

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.

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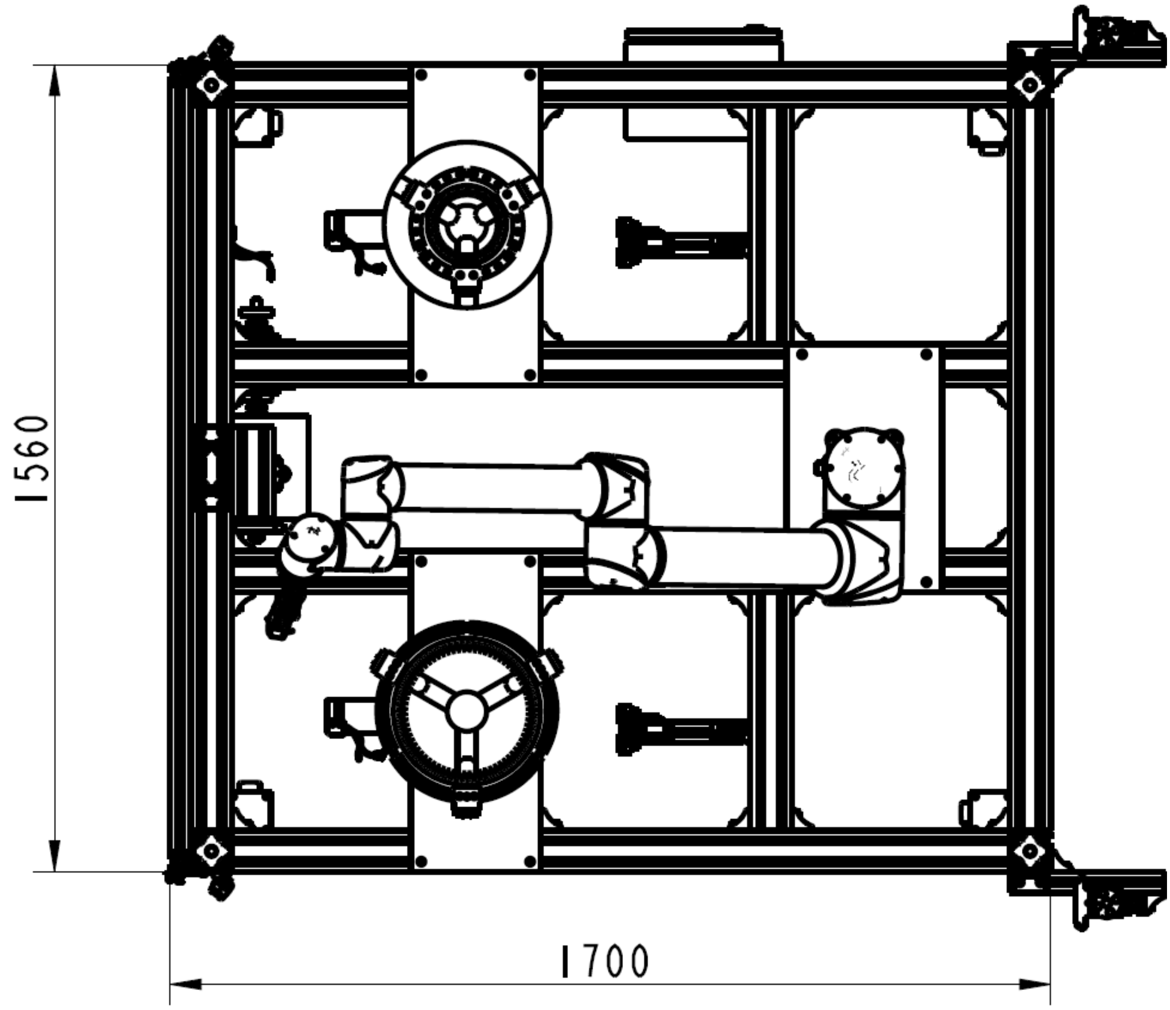

Figure 24 Winding cell layout

During the winding operation, the end-effector turns around the teeth as shown in **Figure 25**, the needle that brings the copper filament passes through the narrow gaps between the teeth.

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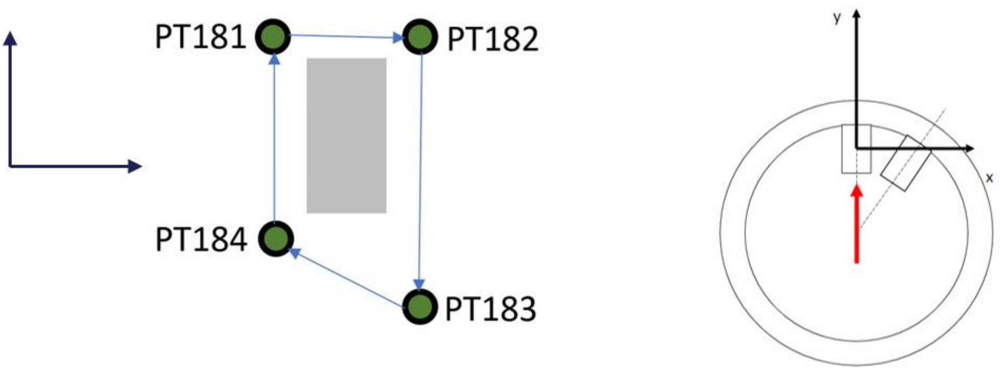

Figure 25 Winding path

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 26**: to have a zero-backlash coupling between the gearbox and the chuck, it was adopted a bellow joint with keyhole.

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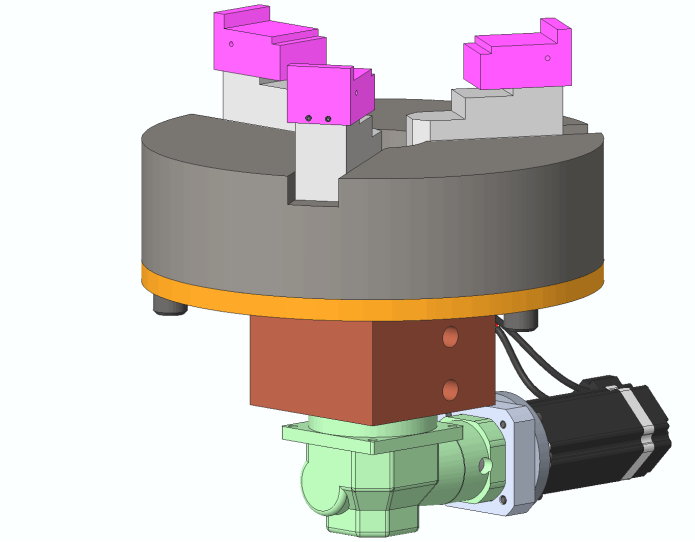

Figure 26 Rotatory table model

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 27** is shown an example of two different stators installed on the chucks.

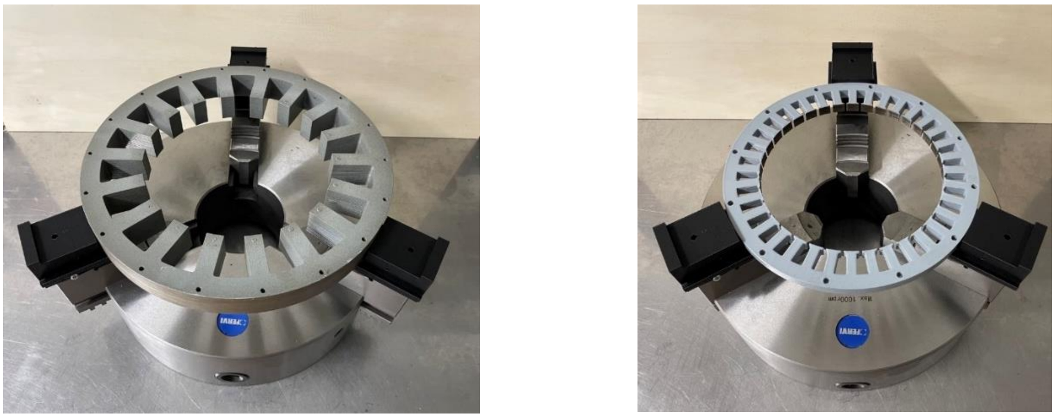

Figure 27 Different stators installed on the spindle

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To fix the stator, 3D printed fingers are mounted on the chuck claws, as shown in **Figure 28**. 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.

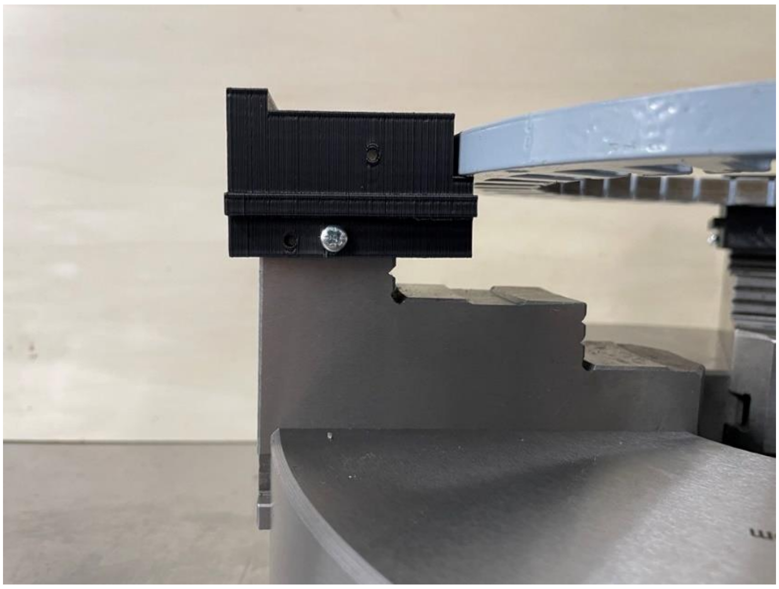

Figure 28 3D printed finger

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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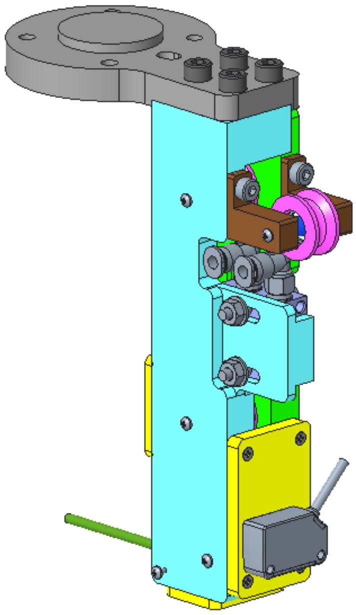

Figure 29 Winding end-effector

On each finger are mounted the three blue elements shown in **Figure 30**, 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.

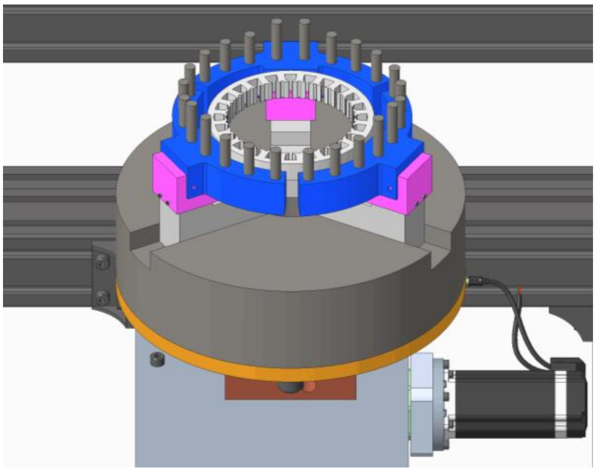

Figure 30 Metal pins to hold the wire

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A system to have constant wire tension has been integrated in the cell. The tool shown in **Figure 31** 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 31 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 32**. Both the cutter and gripper are driven by two single-acting cylindrical pistons with return spring.

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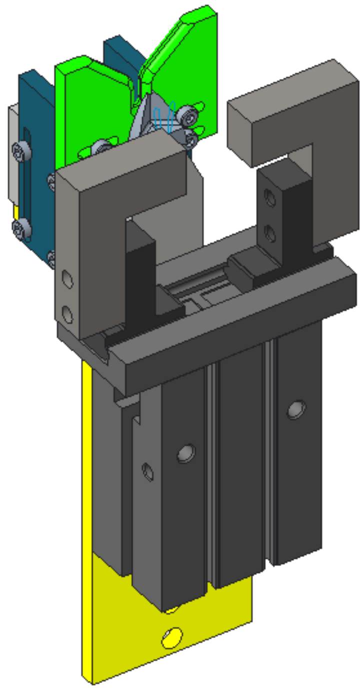

Figure 32 Tool for wire cutting

In **Figure 33** 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.

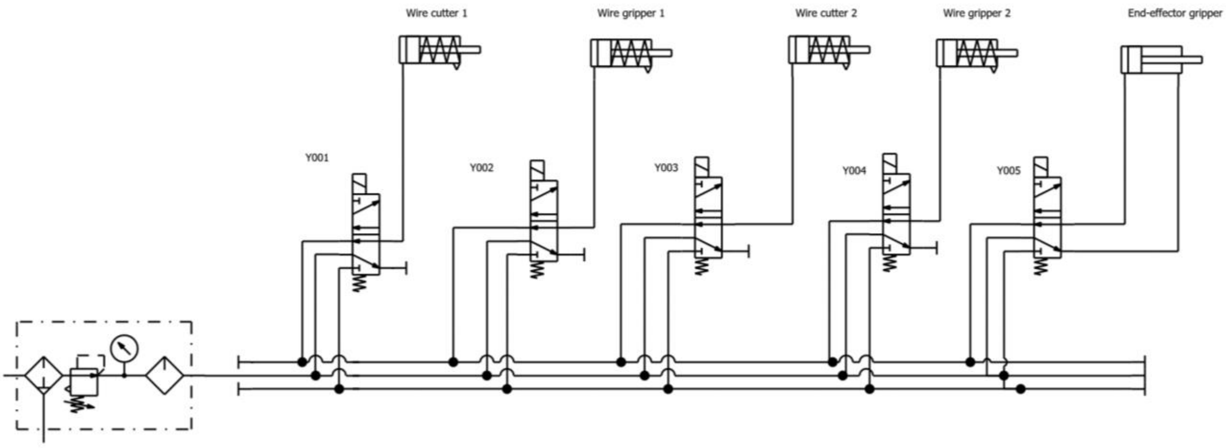

Figure 33 Winding cell pneumatical scheme

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2.2.2.2 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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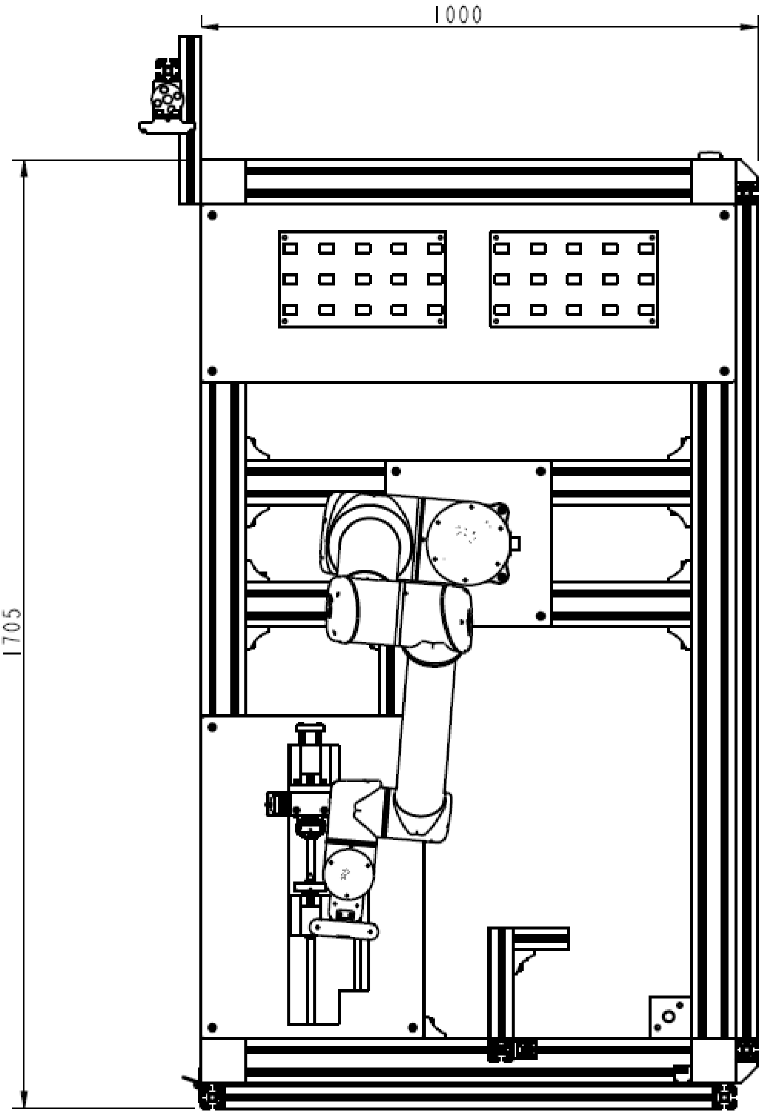

Figure 34 Bonding cell layout

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 35**, composed of a chuck and a lathe-like tailstock.

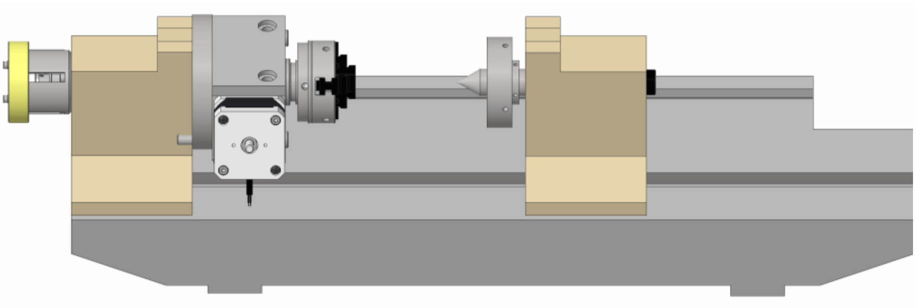

Figure 35 Bonding rotatory table

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 36**.

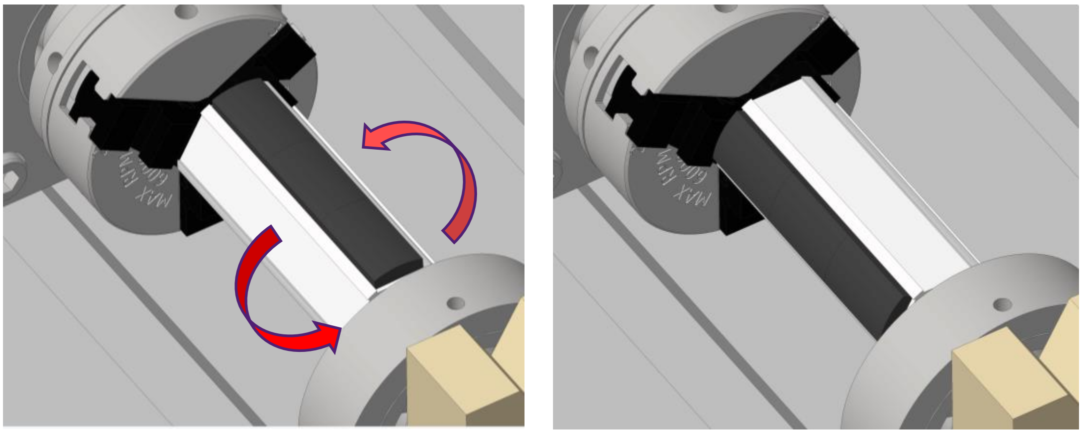

Figure 36 Rotatory table working

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

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

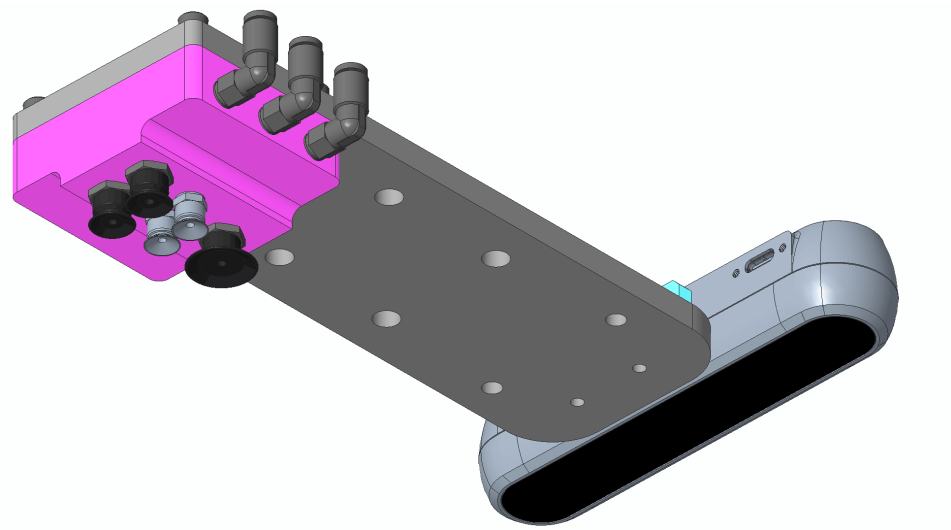

Figure 37 Bonding end-effector

In **Figure 38** is shown the pneumatical design of the bonding cell. An electrovalves actuates an ejector which commands three separate vacuum pads.

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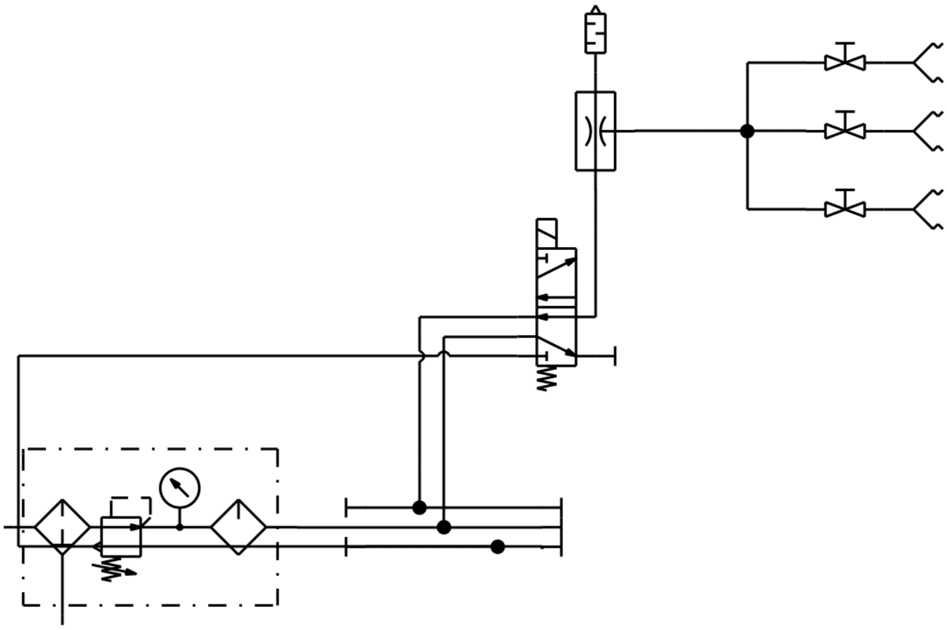

Figure 38 Bonding cell pneumatical scheme

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2.2.3 Electrical Designs

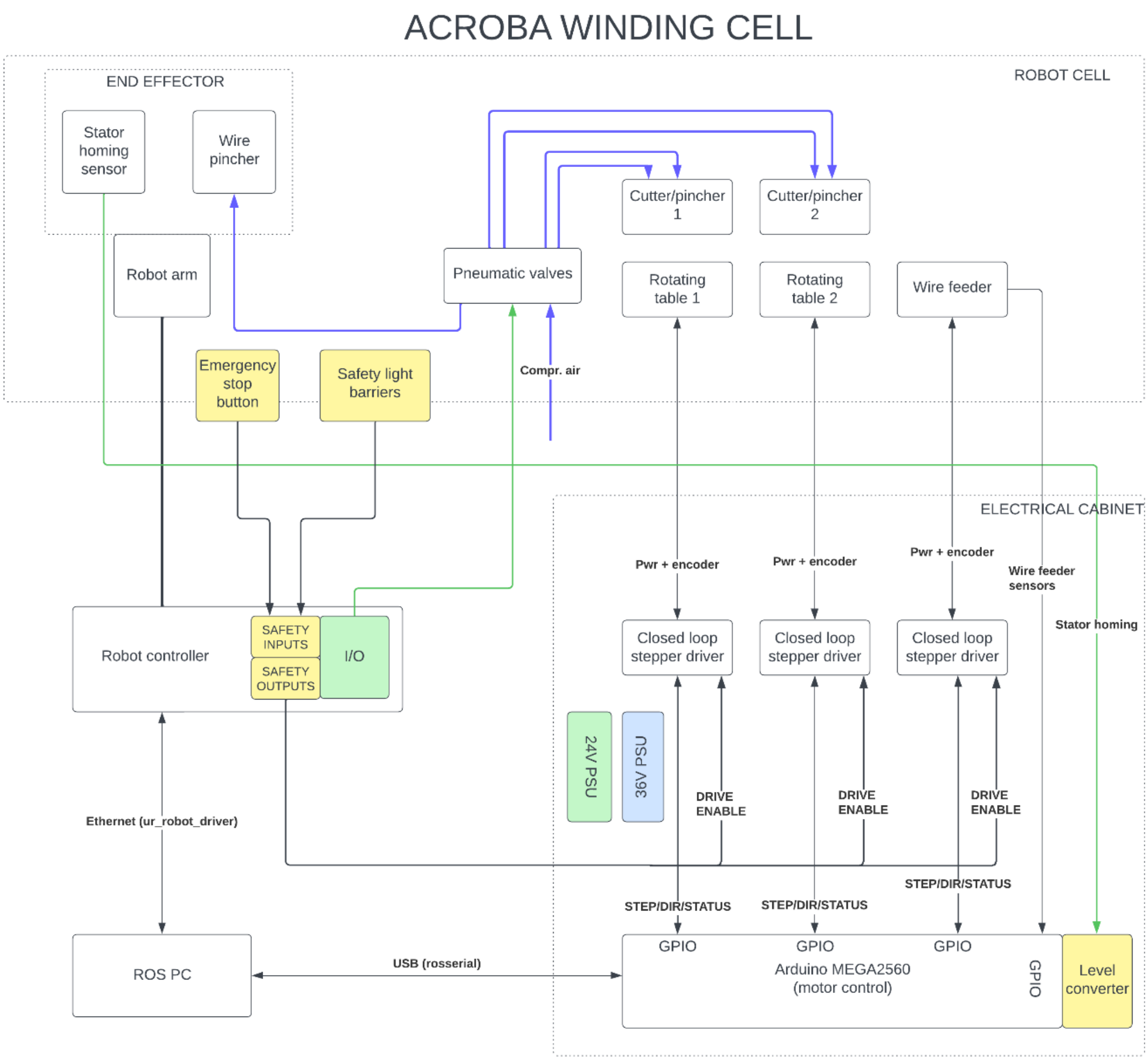

Figure 39 Winding electrical design

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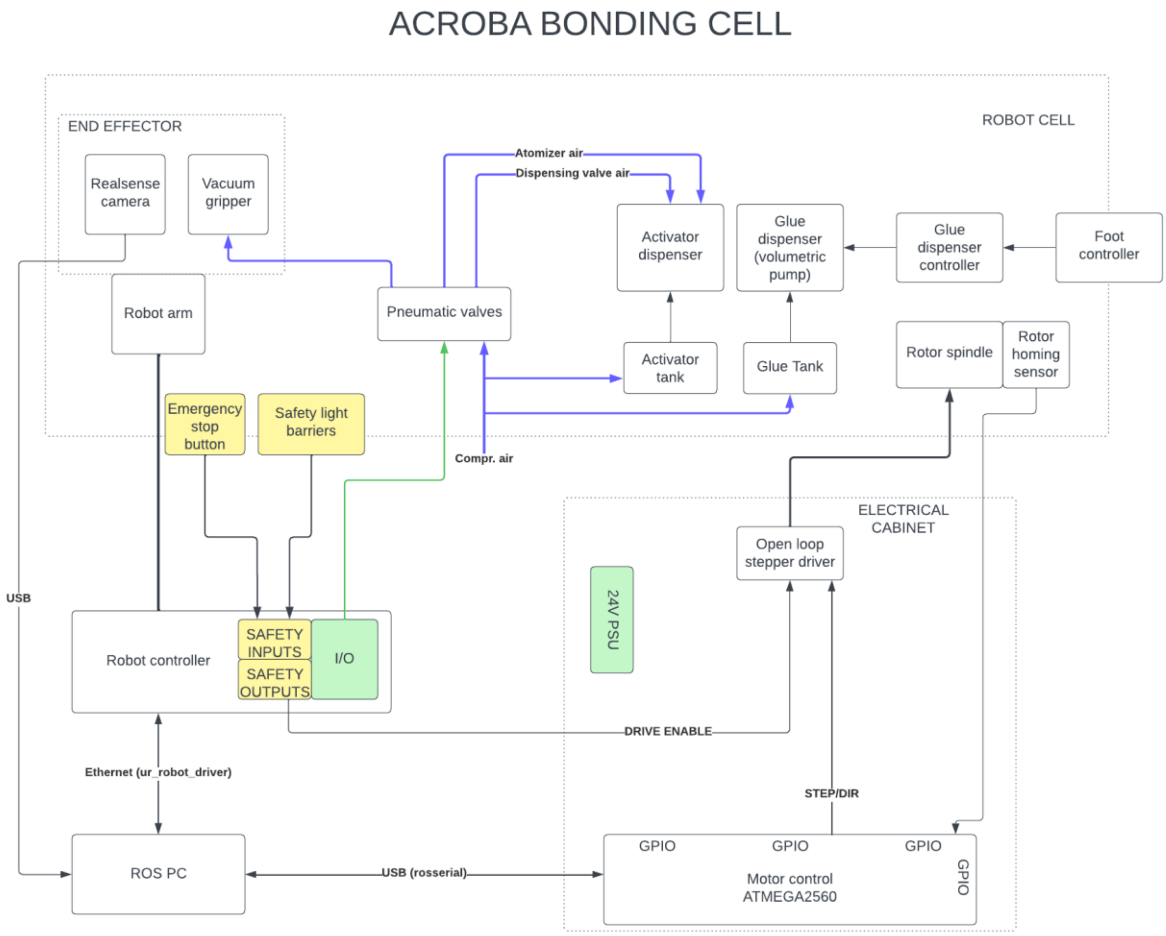

Figure 40 Bonding electrical design

2.2.4 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.

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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.
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 41 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).

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

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

$$T = 110\ ms$$

$$S = 428\ mm$$

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

2.2.4.1 Winding cell

The final design includes a light curtain (highlighted in red in **Figure 42**) 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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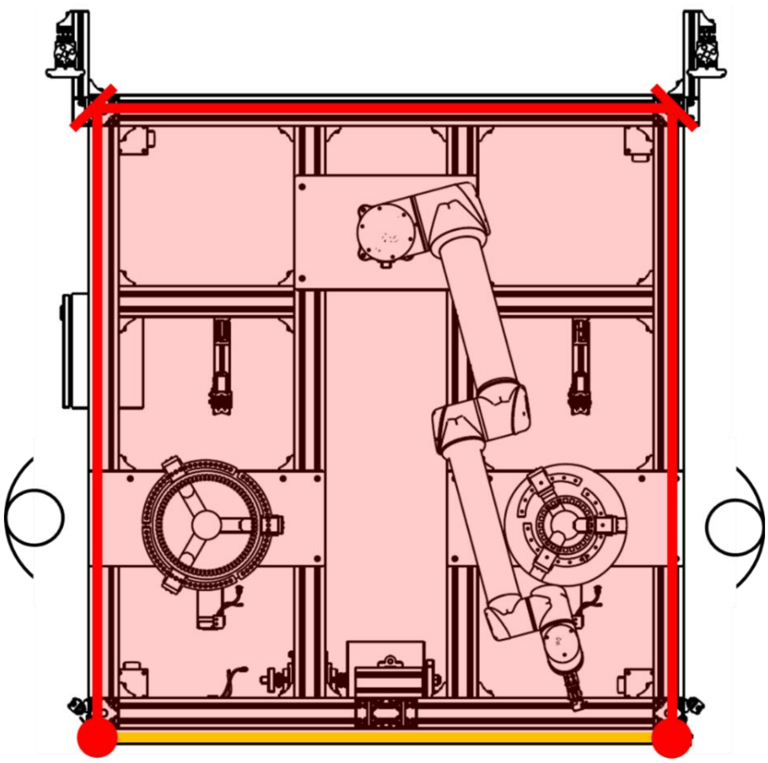

Figure 42 Safety scheme winding cell

In **Table 6** the main aspects of the solution adopted are summarized. Each aspect has a mark that goes from 1 to 5.

Table 6 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 an excessive increase of the overall price.

2.2.4.2 Bonding cell

The final design includes a light curtain (highlighted in red in **Figure 43**) 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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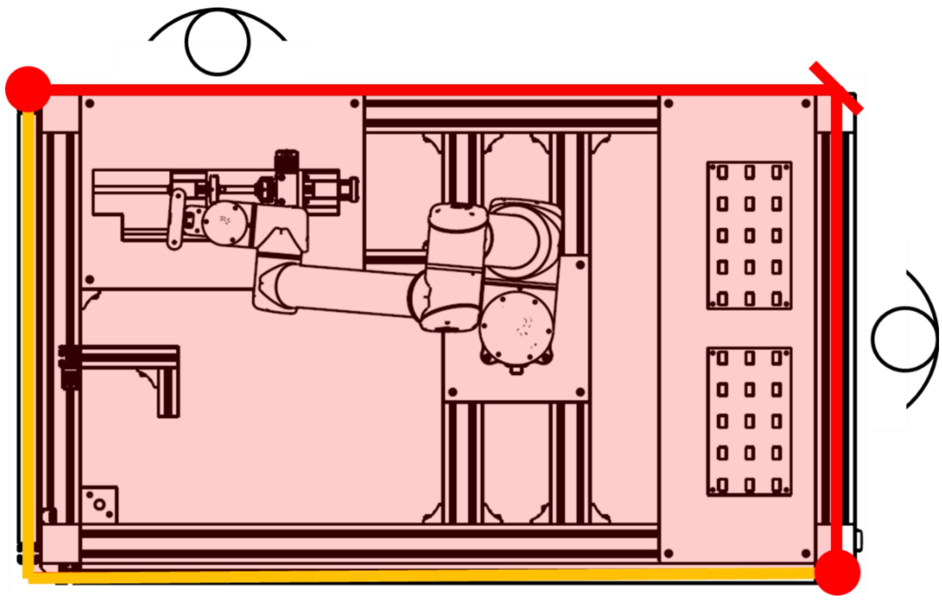

Figure 43 Safety scheme bonding cell

Also in this case, the main aspects of the bonding cell are reported in Table 7.

Table 7 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 an excessive increase of the overall price.

3 Hardware Integration

3.1 List of Materials and provider selection

3.1.1 IKOR’s Use Case

3.1.1.1 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:

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Table 8 Vibrating Table Materials

PART DESIGNATION	MANUFACTURER	UNITS
VIBRATING TABLE SET		
VIBRATING TABLE PLATE	FASTEN	1
FEEDER PLATE	FASTEN	1
CAMERA BRACKET	GIMETAL	1
POSTER	GIMETAL	2
SCANNER SUPPORT STRUCTURE	GIMETAL	2
SICK BARRIER BRACKET	GIMETAL	2
SICK BARRIER	GIMETAL	2
LIGHT PORFILE 90x90	FASTEN	4
BASIC PORFILE 45x90	FASTEN	6
SCREWS	CLISER	
COVER 45x90	FASTEN	6
FLOOR ANCHORING 45x90	FASTEN	8
BRACKET 42x42x42	FASTEN	2
BRACKET 86x86x88	FASTEN	2
SILENT BLOCK TIPO H2	NORELEM	4
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 9 Intermediate Table Materials

PART DESIGNATION	MANUFACTURER	UNITS
INTERMEDIATE TABLE SET		
SUPPORT PLATE 1	MEDIMEC	2
UNION PLATE	MEDIMEC	3
SUPPORT PLATE 2	MEDIMEC	1
PPOFILE BRACKET	TECAM	3
LEOCO COMPONENT BASE	3D PRINT	1
PHOENIX COMPONENT BASE	3D PRINT	3
DB PRODUCT COMPONENT BASE	3D PRINT	1
ECE COMPONENT BASE	3D PRINT	1
MOLEX COMPONENT BASE	3D PRINT	1
SAMTEC COMPONENT BASE	3D PRINT	1
LIGHT PROFILE 45x45	FASTEN	3
SCREWS	CLISER	
COVER 45x45	FASTEN	3
ADJUSTABLE JOINT 45x45	FASTEN	3
INTERMEDIATE TABLE STRUCTURE		
INTERMEDIATE TABLE PLATE	TECAM	1
PROFILE RACKET	TECAM	4
LIGHT PROFILE 90x90	FASTEN	4
LIGHT PORFILE 45x90	FASTEN	2
LIGHT PORFILE 45x90	FASTEN	2
SCREWS	CLISER	
COVER 45x90	FASTEN	4
BASE PLATE 90x90_M16	FASTEN	4
STEEL BASE STAND D90_M16x100	FASTEN	4
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 10 Cobot Structure Materials

PART DESIGNATION	MANUFACTURER	UNITS
ROBOT STRUCTURE		
LEVELLING SPINDLE	TECAM	4
CONTROLLER TRAY	TECAM	1
LEVELING BASIS	TECAM	4
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:

Table 11 Cobot & Cobot Accessories

PART DESIGNATION	MANUFACTURER	UNITS
OTHER		
COBOT FLANGE	MEDITERRÁNEA	1
PHOTONEO BOARD	MEDITERRÁNEA	1
BUTTON SUPPORT	METAL-CRIS	1
CASING SUPPORT	METAL-CRIS	2
SUPPORT BRACKET 1	METAL-CRIS	2
SUPPORT BRACKET 2	METAL-CRIS	2
TRIFLEX ENERGY CHAIN R TRE.B	IGUS	1
TRIFLEX FASTENING WITH VELCRO STRAP AND PROTECTOR	IGUS	4
LIGHTWEIGHT TERMINAL WITH TRIFLEX FIXING COMB	IGUS	2
TOOL FINGER, REWOEK WITH 0,5mm REBATE	MEC. RAFELBUÑOL	2
TOOL FINGER, REWOEK WITH 2,5mm REBATE	MEC. RAFELBUÑOL	1
PHOTONEO CAMERA PhoXi SCANNER XS	PHOTONEO	1
ELECTRIC CLAMP PGC-50	DH-ROBOTICS	1
COBOT TM5 900	OMCRON	1

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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:

Table 12 Fences Materials

PART DESIGNATION	MANUFACTURER	UNITS
FENCES		
LIGHT PORFILE 45x45	FASTEN	2
LIGHT PORFILE 45x45	FASTEN	2
LIGHT PORFILE 45x45	FASTEN	2
LIGHT PORFILE 45x45	FASTEN	2
WIRE MESH 1	NUTAI	1
WIRE MESH 2	NUTAI	1
LIGHT PORFILE 45x45	FASTEN	2
LIGHT PORFILE 45x45	FASTEN	2
LIGHT PORFILE 45x45	FASTEN	1
LIGHT PORFILE 45x45	FASTEN	1
LIGHT PORFILE 45x45	FASTEN	1
LIGHT PORFILE 45x45	FASTEN	1
LIGHT PORFILE 45x45	FASTEN	1
WIRE MESH 3	NUTAI	1
WIRE MESH 4	NUTAI	1
SCREWS	CLISER	
COVER 45x45	FASTEN	7
GROUND ANCHOR BRACKET 45x45	FASTEN	6
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 13 Electrical material

PART DESIGNATION	MANUFACTURER	UNITS
ELECTRICAL MATERIALS		
UPS - 1200VA Power with overload protection surge	OMNIELECTRIC	1
Switched Mode Power Supply Primary Trio Power	OMNIELECTRIC	1
Industrial Ethernet Switch	OMNIELECTRIC	1
Industrial Ethernet Switch Wide Range Temperature	OMNIELECTRIC	1
Eco-Rail-2 20-100-240/24	OMNIELECTRIC	1
PIA 1P+N 16A 10/10kA C	OMNIELECTRIC	1
PIA 1P+N 6A 10/10kA C	OMNIELECTRIC	6
Auxiliar Contact 1NA+1NC	OMNIELECTRIC	7
Bar Col. 2x(2F+HS/FS) 16MM2	OMNIELECTRIC	10
SITOP SEL 1400 10A 8X2	OMNIELECTRIC	1
B-PLUG 16A SUCKO	OMNIELECTRIC	1
Int. Disconnected VARIO 3P 25A Control	OMNIELECTRIC	1
Protective Cover for VARIO 12	OMNIELECTRIC	2
Empty Grey Box 1 Orifice	OMNIELECTRIC	1
Emergency Button 40mm	OMNIELECTRIC	1
Electric Block Fixing Base	OMNIELECTRIC	2
Contact Block 1NC	OMNIELECTRIC	2
Circular Sticker 60mm "Emergency Disconnect"	OMNIELECTRIC	1
Connector HDC-HDD-24-FC	OMNIELECTRIC	2
Connector HDC-HDD-24-MC	OMNIELECTRIC	2
AX Compact Cabinet 600x600x350, Ral 7035	OMNIELECTRIC	1

3.1.1.2 Installation at NUTAI's facilities

The following preliminary 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 44 Testing at NUTAI's facilities

3.1.1.3 Installation at IKOR's facilities

In order to advance with preliminary testings without waiting for all materials to be available. The best choice is 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 are installed.

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This separation basically allows 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.

On the design of a tailored fingers attachable to the robotic gripper to be customized for all identified components. This task is well advanced. The design is finished, and it is now the time for functional validation.

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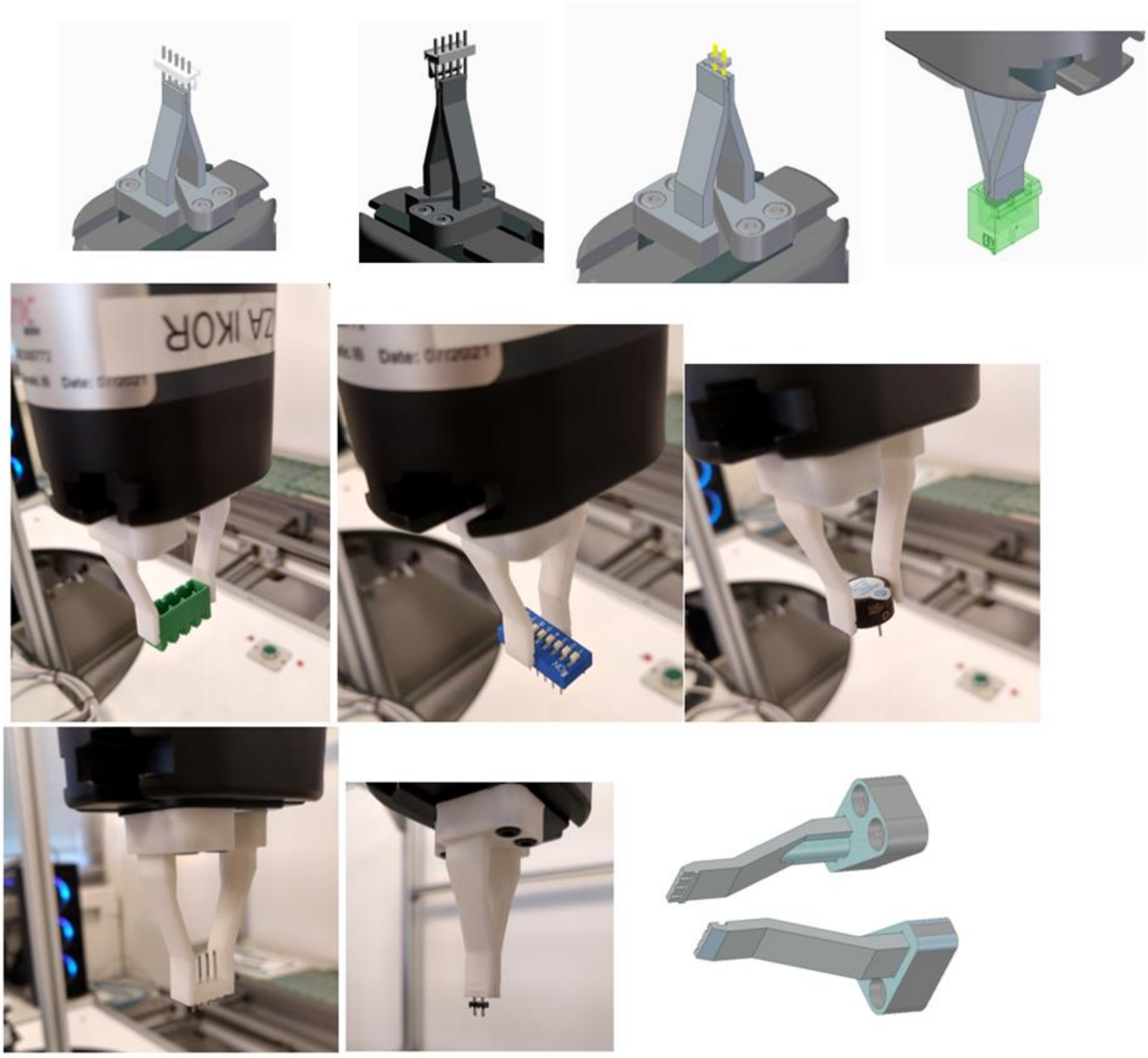

Figure 45 Images of the final design created at IKOR to handle electronic components

On the installation and commissioning of the ASYRIL component dispensing system so that it can be delivered to Nutai pre-configured to work with the identified target parts. This task has just begun. Ikor has received all the necessary equipment and has created the provisional mechanical structure. It has commissioned the system and is working on the calibration of the

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optical vision system, and the calibration of the robot reference systems and the dispensing system.

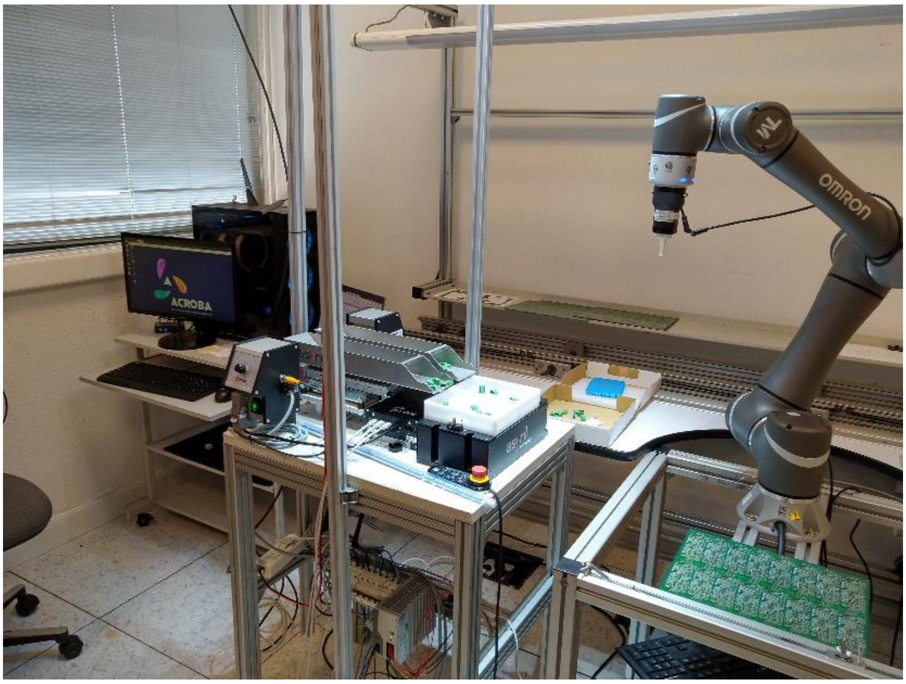

Figure 46 Image of the provisional robotic cell created at IKOR

A delivery of the equipment to NUTAI is planned for month 35, which will consist of the entire component dispenser system functional for a set (not yet determined) of the components identified in IKOR use case. As of that date, the following development and integration work will be carried out at NUTAI.

3.1.2 ICPE's Use Case

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

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

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3.2 Installation Developments

In Figure 47 and Figure 48, the frames of the ICPE use case cells are shown. All the other tailored designed components will be installed inside the cells in the next few days.

Figure 47 ICPE use case winding cell.

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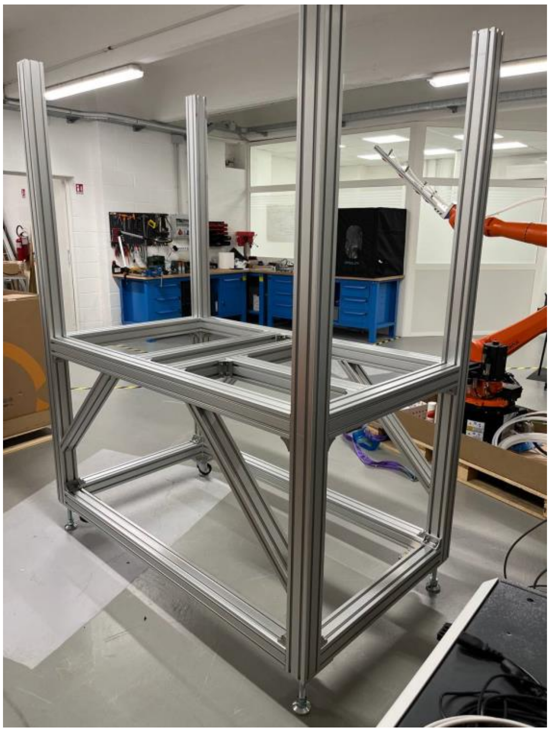


Figure 48 ICPE use case bonding cell.

In **Figure 49**, the end-effector of the winding operation is shown.

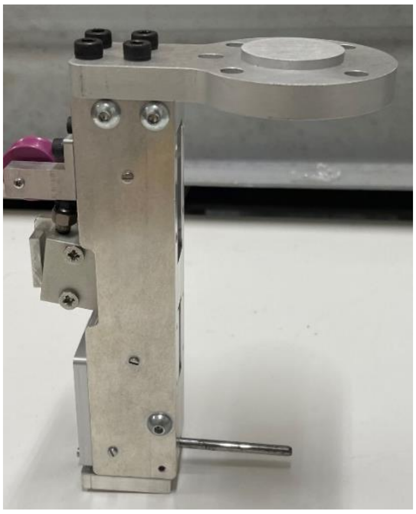
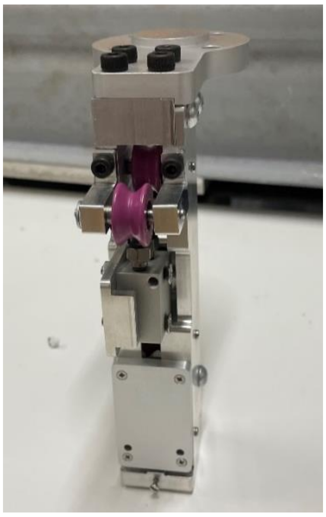

Figure 49 winding end-effector

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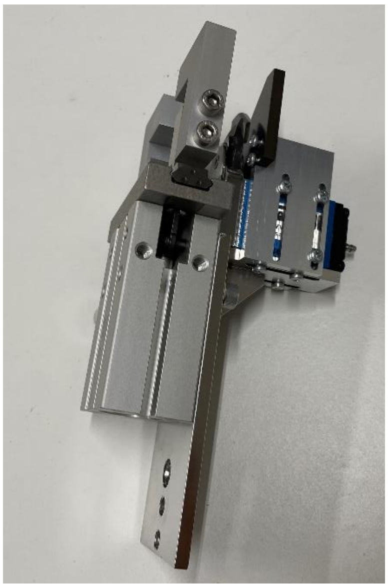
In Figure 50 the tool for wire cutting operation is shown:



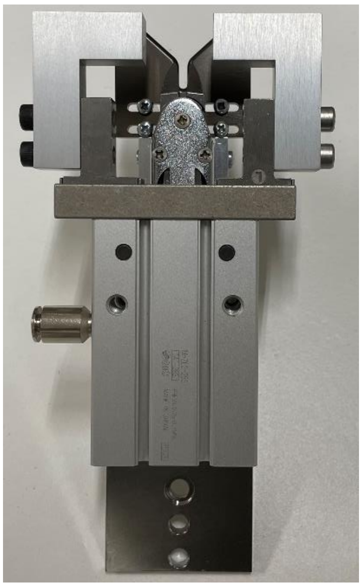


Figure 50 Tool for wire cutting operation.

In **Figure 51** the motors of the winding cell are shown.

Figure 51 Rotatory table stepper motor

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In Figure 52 the end-effector of the bonding cell is shown.

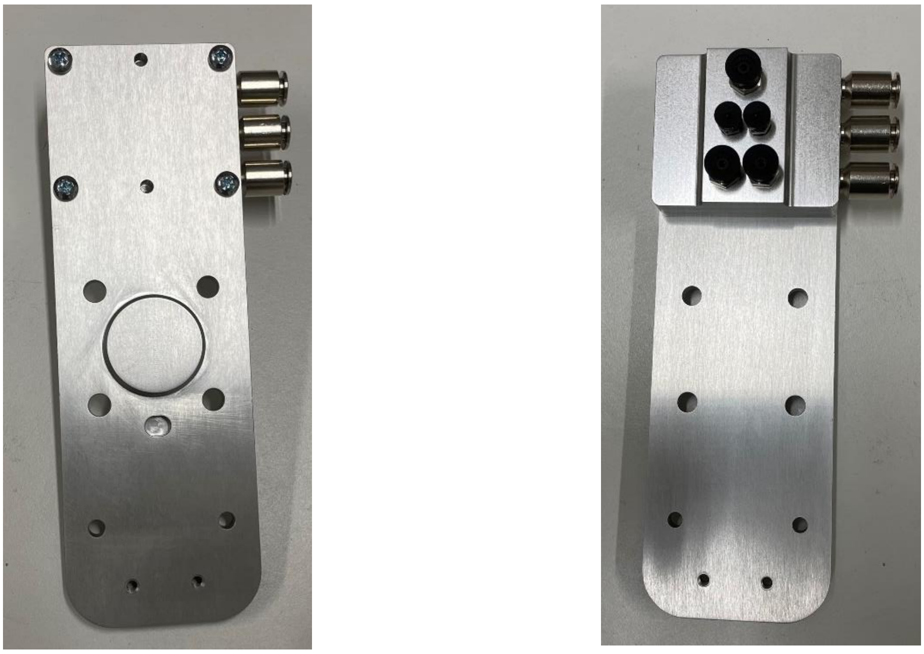

Figure 52 Bonding end-effector

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4 ACROBA Customization

4.1 Process and Flow Charts

4.1.1 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.

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.

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7. Cobot places component into presenter.
8. Cobot continues with P&P cycle.

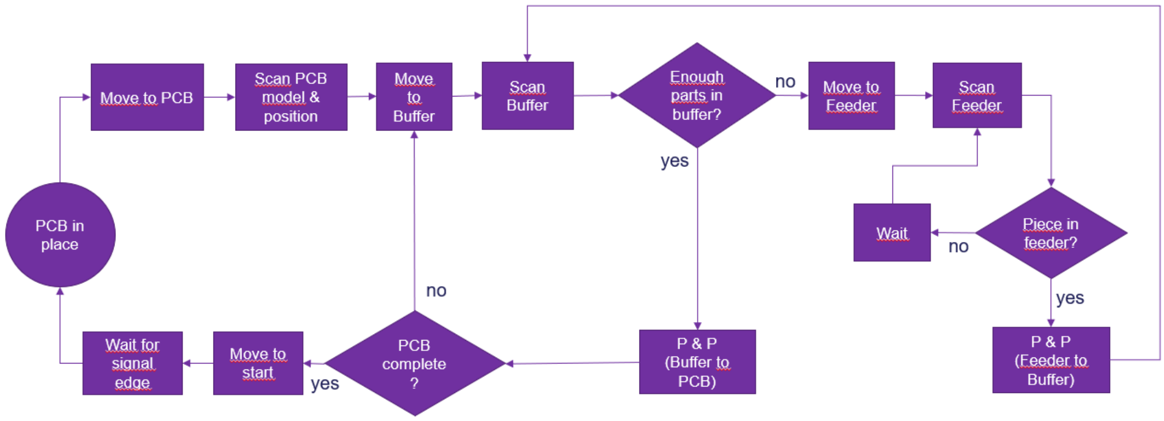

Figure 53 Diagram of IKOR's Sequence

4.1.2 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.

4.1.2.1 Coils winding process

The flowchart in **Figure 56**. 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.

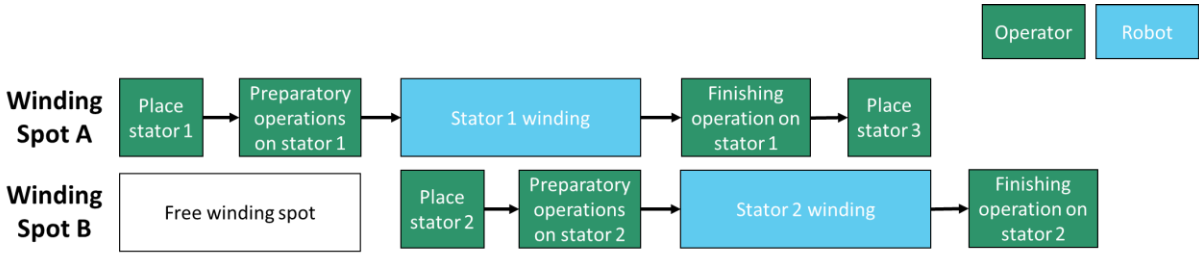

Figure 54 Flowchart of the high-level order of tasks of the Coils winding process

In Figure 54 a more detailed flowchart of the actual logic behind the “Stator winding” block is reported.

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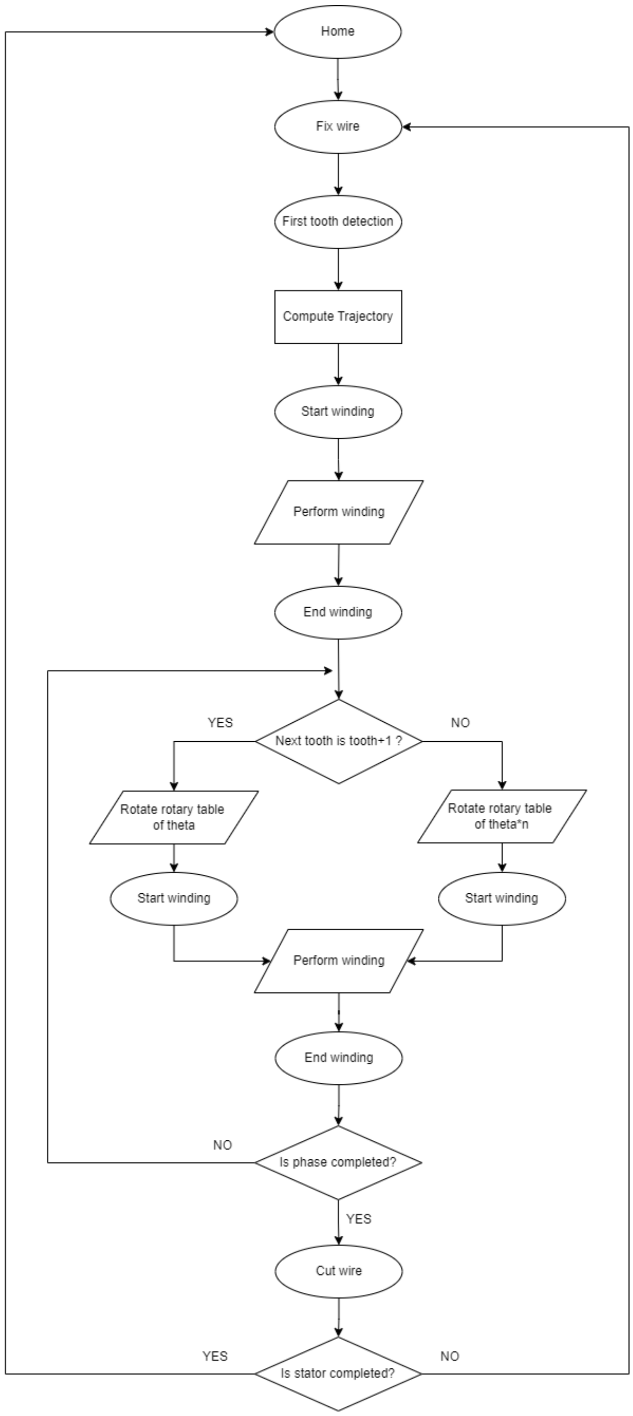

Figure 55 Stator winding flowchart

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The ACROBA skills required to carry out the winding process have been selected and are reported in **Table 14**. In the table are highlighted:

- In green, the tasks carried out by the operator.
- In light blue, the ACROBA skills.
- In yellow, the customized primitive specific of this ICPE operation.
- In red, the drivers responsible for controlling the external hardware components.

Table 14 ACROBA skills schema of the Coils winding process

Placing the stator on the rotary table			
Preparatory operations: stator clamping, fix wire into end-effector, etc			
Wait for human "continue"			
For n° of phase in the stator	Gripper End-Effector	Activate	
	MoveTo	Cutter position	
	Gripper Cutter	Activate	
	Gripper End-Effector	Deactivate	
	MoveTo	Zero position	
	TableRotation	Until border of tooth detected	Clockwise
	TableRotation	Half of teeth	Counter-cl.
	GetWindingWaypoints		
	For each tooth	MoveTo	Waypoint positions
		Gripper Cutter	Deactivate
		MoveTo	Exit position
		TableRotation	Angle to next tooth
	MoveTo	Cutter position	
	GripperCutter	Activate	
	Cutter	Activate	
Finishing operations: stator unclamping, quality control, etc.			

In this first operation considered in the ICPE use-case the main involved ACROBA skill is the "MoveTo" which is responsible of the robotic arm's movement to specific locations within the station. These locations include:

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- The cutter position, where it is installed the tool for fixing and cutting the wire shown in Figure 32.
- The zero position, a location above the stator where the "first tooth detection" procedure described in Section 2.2.1.1 of this document is initiated.
- The waypoint positions, intermediate points located around the stator tooth forming the robot's trajectory for winding the tooth.
- The exit position, situated outside the stator pins (illustrated in **Figure 30**), where the end-effector should move before the rotary table begins rotating to present the next tooth to be wound, to hold the wire.

The "GetWindingWaypoints", is a specific primitive responsible of generating the waypoints of the winding robot's trajectory. These waypoints are generated based on the geometrical features of the stator, extracted from its CAD file, and are the ones reported in **Figure 25**. At the time of writing this document, this primitive has only been discussed between the technical team responsible of the ICPE use-case and the developers, but it has not been developed yet.

4.1.2.2 Magnets bonding process

Figure 56 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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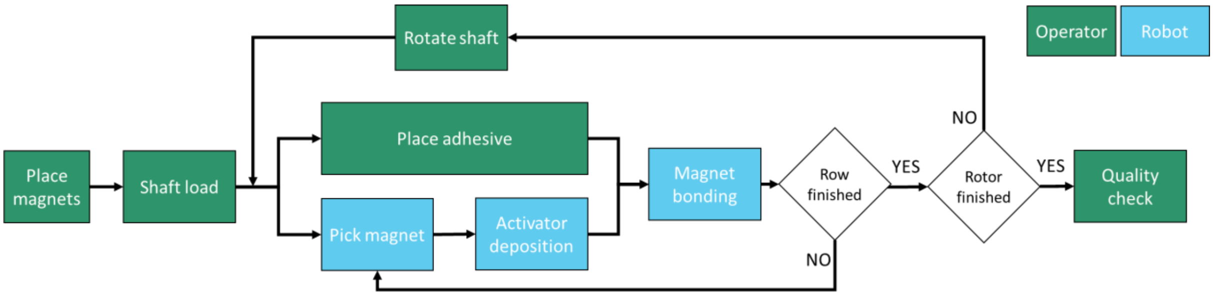

Figure 56 Flowchart of the high-level order of tasks of the Magnets bonding process

The ACROBA skills required to carry out the magnets bonding process have been selected and are reported in **Table 15**. In the table are highlighted:

- In green, the tasks carried out by the operator.
- In light blue, the ACROBA skills.
- In red, the driver responsible for controlling the external hardware component, which in this case is only the activator spray.

Table 15 ACROBA skills schema of the Magnets bonding process

<table>
<tr><td colspan="4">Preparatory operations: place magnets trays and shaft, tool for shaft angular position detection and correction</td></tr>
<tr><td rowspan="7">For n° of rows in the rotor</td><td colspan="3">Adhesive deposition on the shaft + "continue" button</td></tr>
<tr><td colspan="3">Wait for human "continue"</td></tr>
<tr><td rowspan="4">For n° of magnets in a row</td><td>Pick</td><td>Magnet from tray</td></tr>
<tr><td>MoveTo</td><td>Activator position</td></tr>
<tr><td colspan="2">ActivatorSpray</td></tr>
<tr><td>Place</td><td>Magnet on shaft</td></tr>
<tr><td colspan="3">Shaft rotation</td></tr>
<tr><td colspan="4">Quality check</td></tr>
</table>

In this second process of the ICPE use-case, three main ACROBA skills play a significant role:

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- Pick: this skill is responsible for moving the robot to the fixed positions of the magnets on the trays and picking them up, activating the vacuum end-effector.
- MoveTo: once the magnet is picked up, the MoveTo skill moves the magnet, held by the end-effector, under the activator spray.
- Place: it is responsible for accurately positioning the magnet onto the shaft in the correct position.

The possibility of adding the "CADMatching" skill before the "Pick" skill is currently being considered. This skill would allow to automatically compute the pose of the magnets on the trays. However, the evaluation process is still ongoing to determine whether the accuracy of the grasping pose computed by this skill is sufficient for our application. Indeed, since the magnets used are characterized by a limited surface, it’s crucial to have a highly accurate grasping pose to guarantee a powerful vacuum degree, allowing to effectively pick and securely hold the magnets.

4.1.2.3 Coils bonding process

The flowchart in Figure 48 illustrates the overall sequence of tasks involving humans and robots in the coils bonding process. The collaborative process begins when the operator positions the coils tray and loads both the shaft and the tube onto the rotary table. Following this, the operator carries out the angular position detection and correction procedure. Subsequently, the pick and place process for the coils begins. The coil is picked from its fixed position on the tray, is moved under the activator spray for the activator deposition. Finally, the coil is placed onto the tube, which the operator had previously coated with adhesive. This entire process is repeated until all rows of the stator are filled with coils.

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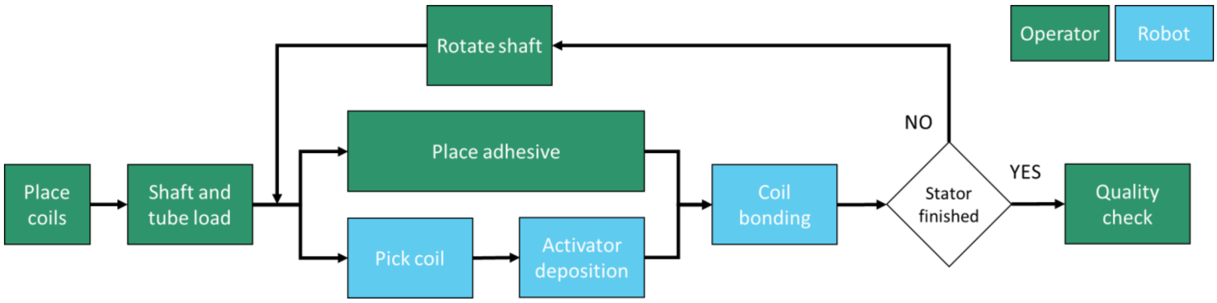

Figure 57 Flowchart of the high-level order of tasks of the Coils bonding process

The ACROBA skills required to carry out the coils bonding process have been selected and are reported in **Table 16**. In the table are highlighted:

- In green, the tasks carried out by the operator.
- In light blue, the ACROBA skills.
- In red, the driver responsible for controlling the external hardware component, which in this case is only the activator spray.

Table 16 ACROBA skills schema of the Coils bonding process

Preparatory operations: place tray, shaft and tube		
For n° of coils in the stator	Adhesive deposition on the tube + "continue" button	
	Wait for human "continue"	
	Pick	Coil from tray
	MoveTo	Activator position
	ActivatorSpray	
	Place	Coil on tube
	Shaft rotation	
Quality check		

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The ACROBA skills involved in this third process of the ICPE use-case and their role are identical to those described for the magnets bonding, being both processes based on a robotic pick and place activity.

4.2 Skill Pre-Integration

4.2.1 IKOR's use case

The features of the devices used by NUTAI to install the ACROBA framework have been the following:

PC specifications:

- Processor: Intel(R) Core(TM) i7-3520M CPU @ 2.90GHz 2.90 GHz
- Installed RAM: 16.0 GB (15.9 GB usable)
- System: Windows 10 Pro
- System type: 64-bit operating system, x64-based processor

Virtual machine:

- Software: Virtual Box 7.0
- Operating system: Ubuntu 20.04.3 LTS
- System:
    - o Base memory: 5120 MB
    - o Processors: 2
- Display:

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o Video memory: 128 MB

o Graphics Controller: VMSVGA

- Storage: 160 GB Dynamic Hard Disk Drive (currently 75 GB occupied)

- Network: Adapter configured as a bridge adapte

4.2.1.1 ROS Primitives testing

The following lines are samples of commands with results of running skills and primitives in ROS. The following steps were followed:

0) Enter the environment (env):
source $VENV_FOLDER/.pyenv/versions/bin_picking/bin/activate
1) Run pr_<name_primitive>.py
2) Run test_<name_primitive>.py

In case of a successful run for a primitive and skill, the ROS graph is showed. In it, the circles represent nodes, the basic unit for an action, and the squares represent the topics, which are a channel of information between nodes. Every node should be linked to a topic, at least, before connecting to another node. In case of error, there is no image.

-cad_loading

Error in pr_cad_loading.py

-cad_to_views

Error en pr_cad_to_views.p

-depth_to_pointcloud_vg

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Error en pr_ depth_to_pointcloud_vg.py

-detect_default

Error en pr_detect_default.py

-detect_markers

Seems to work fine. “Waiting for camera topics to be published”

-generate_grasp_pose

Error in pr_generate_grasp_pose

-generate_waypoints

pr_generate_waypoints seems to work fine (“server ready”) but this does not exist: test_generate_waypoints

-get_rgbd_vg

ModuleNotFoundError: No module named 'acroba_unity_msgs'

-get_robot_pose

Seems to work, possibly the mistake of pr_get_robot_pose after running test_get_robot_pose is due to not testing it with all real elements

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-grasp_vg

ModuleNotFoundError: No module named 'acroba_gym'

-matching

ImportError: cannot import name 'ParameterSource' from 'click.core'

-move_gripper_vg

ModuleNotFoundError: No module named 'acroba_gym'

-move_human

ModuleNotFoundError: No module named 'acroba_unity_msgs'

-outlier_removal

ImportError: cannot import name 'ParameterSource' from 'click.core'

-plane_filtering

ImportError: cannot import name 'ParameterSource' from 'click.core'

-reconstruction_3d

ImportError: cannot import name 'ParameterSource' from 'click.core'

-release_vg

ModuleNotFoundError: No module named 'acroba_gym'

-roi_selection

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ImportError: cannot import name 'ParameterSource' from 'click.core'

-save_intrinsics

Seems to work fine

-save_pointcloud

ImportError: cannot import name 'ParameterSource' from 'click.core'

-save_rgbd

Seems to work fine (“server ready” y “waiting for data”)

-spawn_human

ModuleNotFoundError: No module named 'acroba_unity_msgs'

-subsampling

ImportError: cannot import name 'ParameterSource' from 'click.core'

-visual_human_tracking

Seems to work fine (Waiting for camera topics”)

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-visual_human_tracking_depth

It is a .py file, but Linux detects it as NON EXECUTABLE

4.2.1.2 ROS Skills testing

Skills are made up of one or more primitives. Therefore, they represent more complex processes. The following steps were followed:

1) Execute start_<name_skill>.sh (not required to be in the environment)
2) Execute test_<name_test>.py

-cad_matching

start_cad_matching.sh It is NOT an executable according to Linux

-locate

Seems to work fine, “Waiting for servers”

-move_arm

It is not “test_move_arm.py”, but probably its name is “test_move_to.py”

-pick

Parece que funciona pero OJO: los nodos /Pick y /Grasp han tardado alrededor de 30 segundos (después de la ejecución de test_pick.py) en aparecer.

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-place

Seems to work.

-pointcloud_processing

Seems to work.

-scan

"Waiting for servers"

4.2.1.3 Problems and future steps

- After running rqt_graph, the active nodes and topics are displayed, but their relation is not show.

- After running rostopic list the /planning_scene is shown

- With rostopic info /planning_scene we see that it has Publishers like /GenerateTrajectory and /ExecuteTrajectory. It hasn't got any subscriber

- With rostopic echo /planning_scene (que devuelve los mensajes que se publican en ese topic) nothing appears, but the diagram changes with rqt_graph and the /planning_scene does appear

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- Generally, the delay when activating a Node or a Topic is about 20 seconds, but maybe it is due to the device used.

Future steps will focus on testing skills and primitives in ROS+URSIM

4.2.1.4 Task Planner testing

The task planner drag and drop application works fine, but it has no code linked. When linking blocks, they should carry some code, and this is not the case at the moment.

The whole pick and place task has been programmed using the application, but at the moment is incomplete due to this lack of code behind. It will be solved soon.

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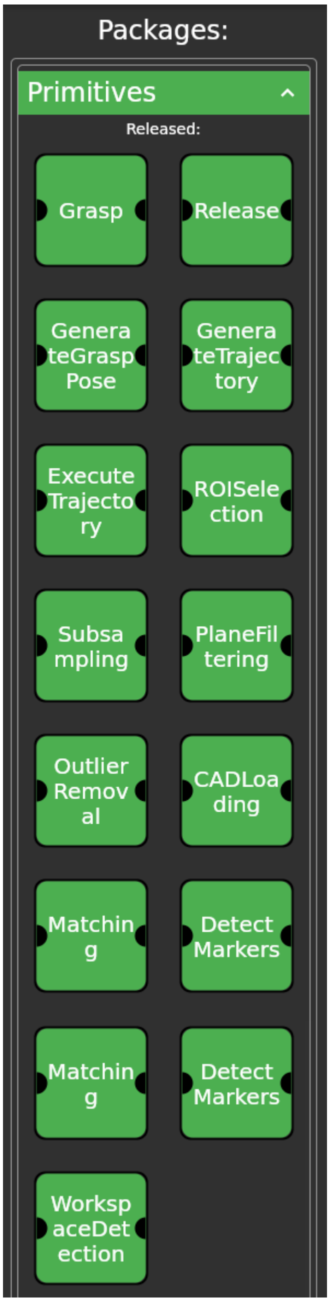

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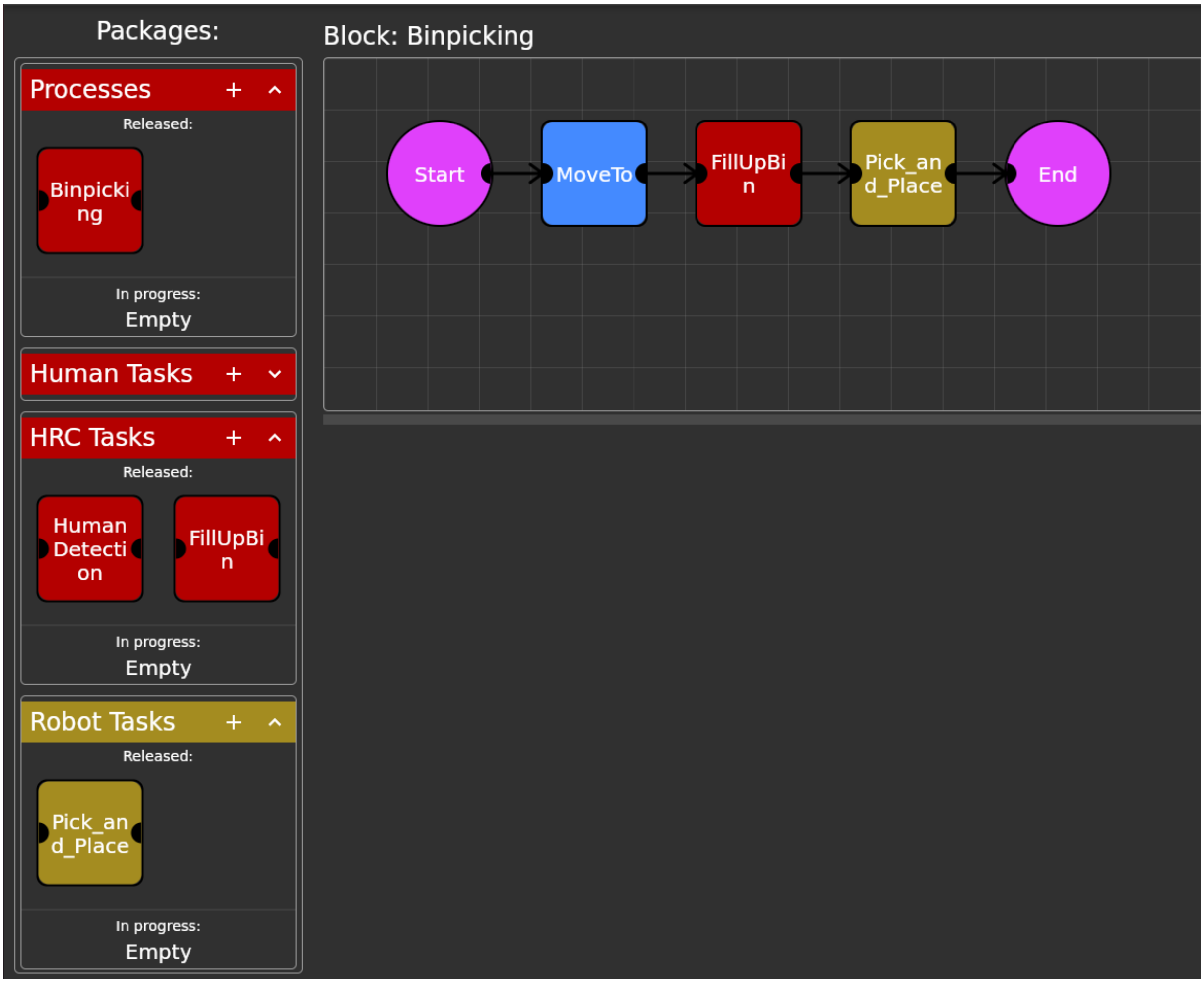

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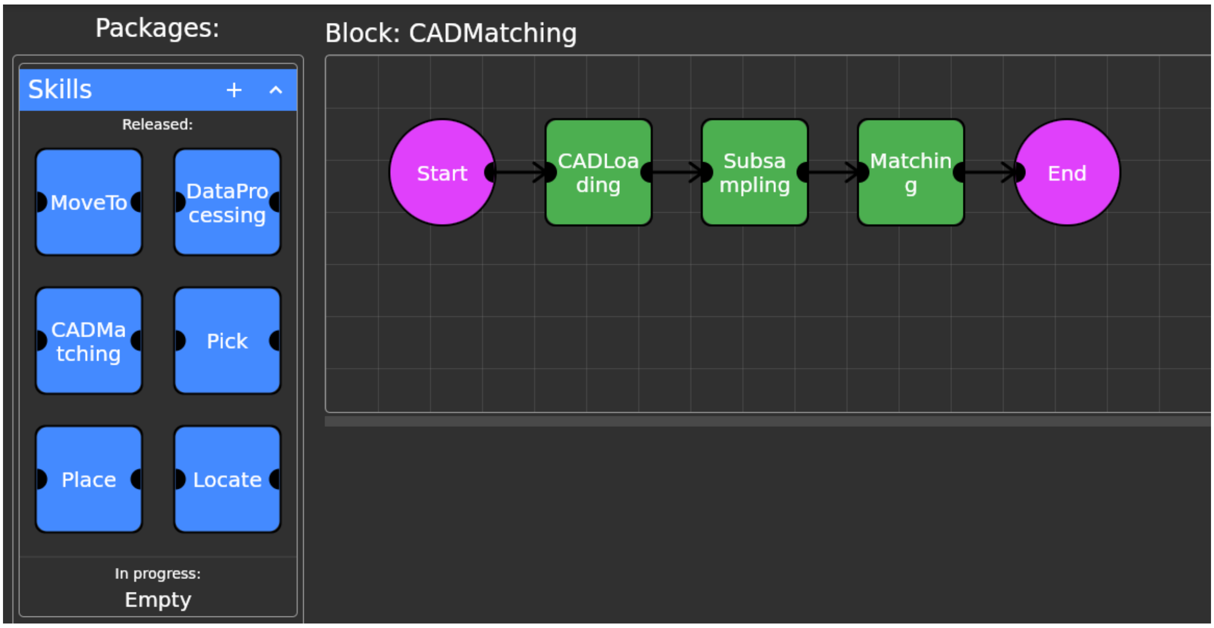

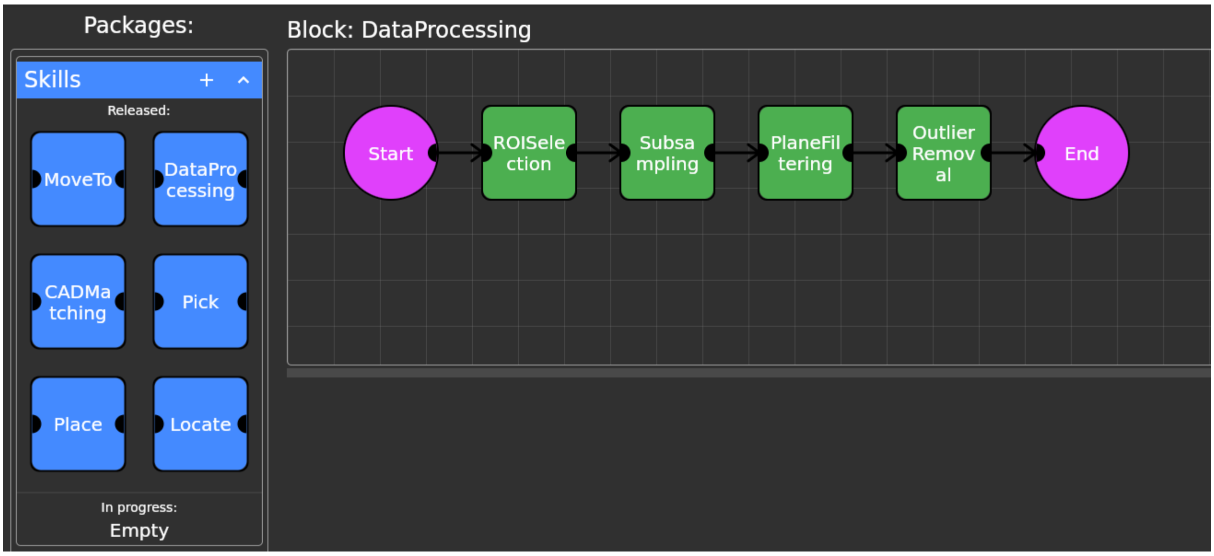

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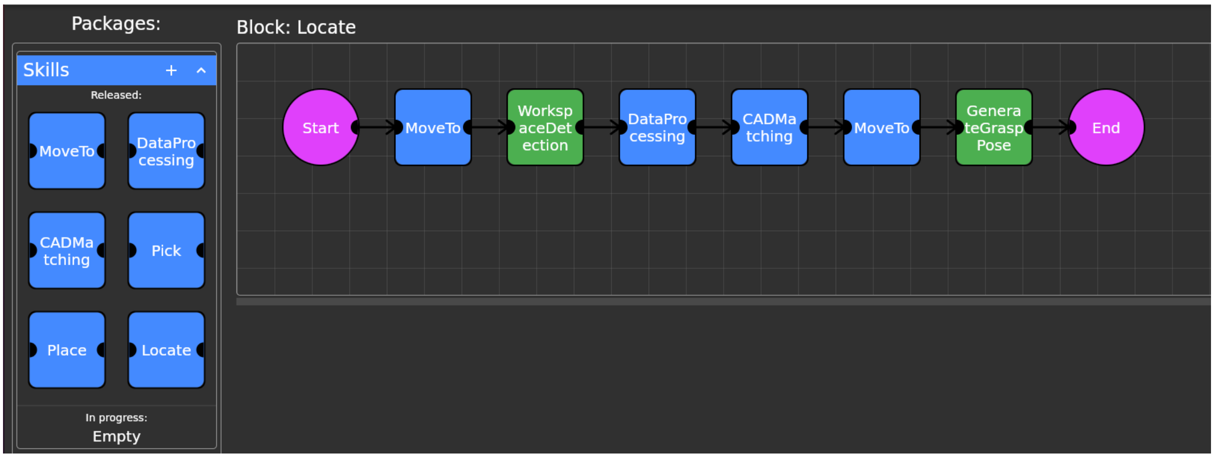
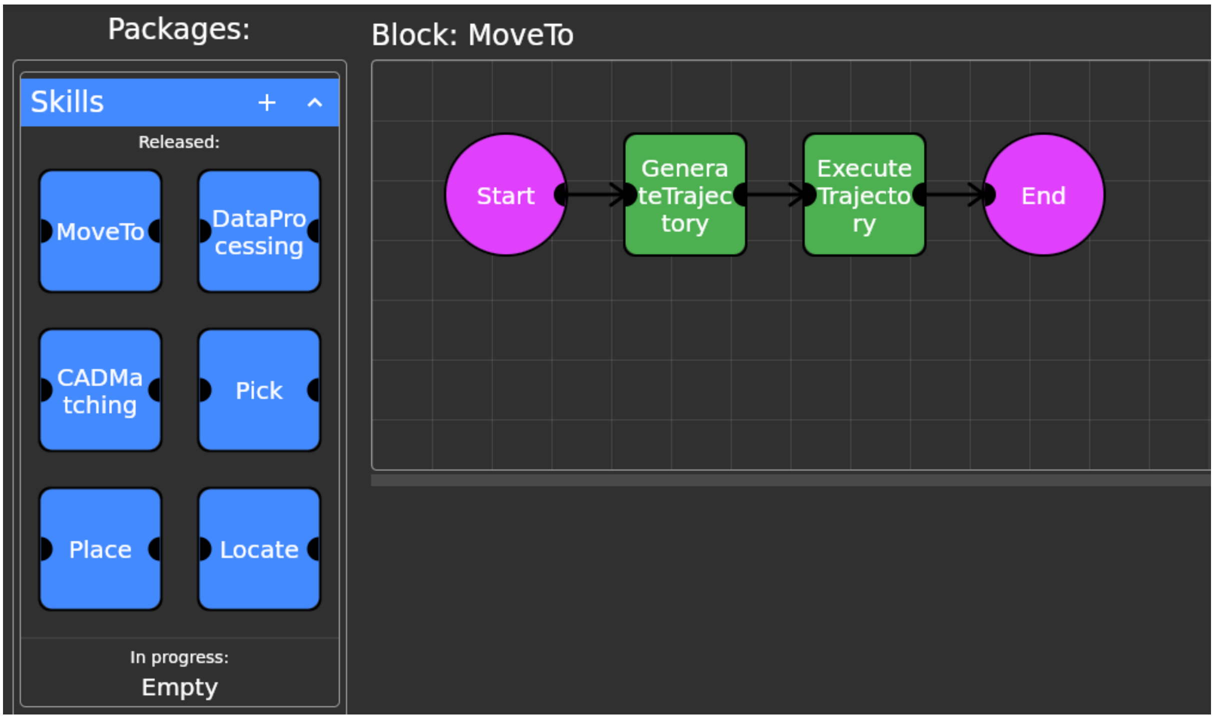
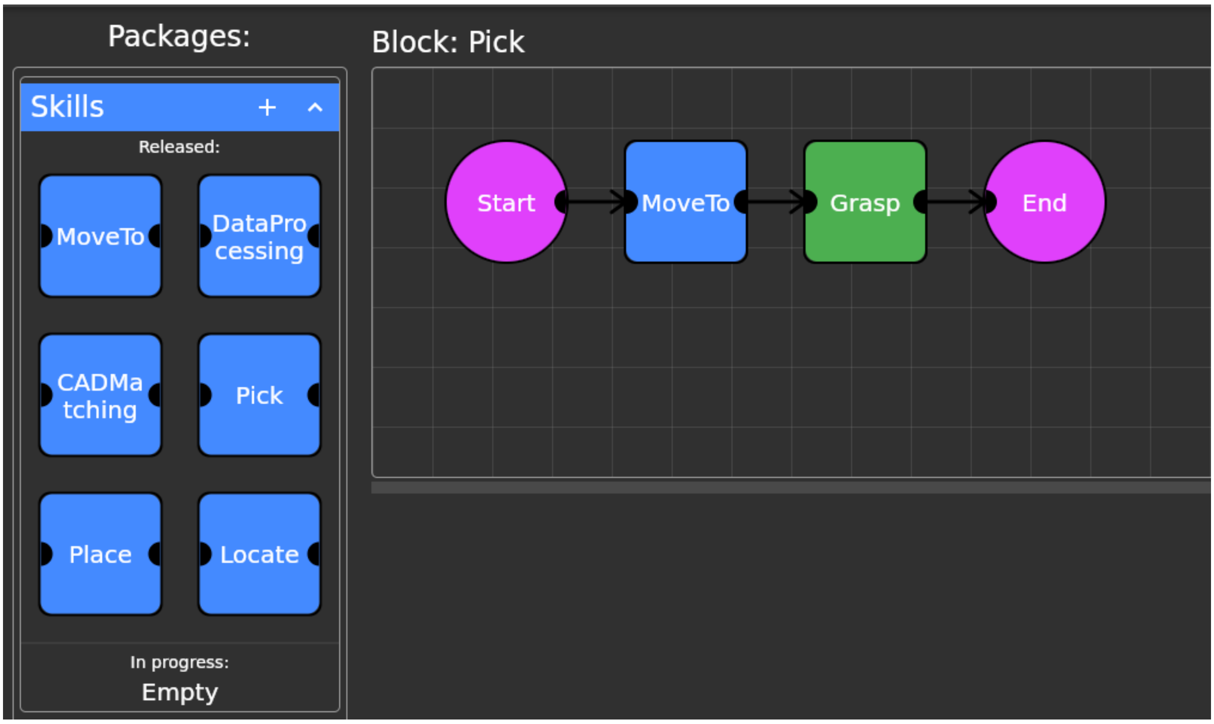
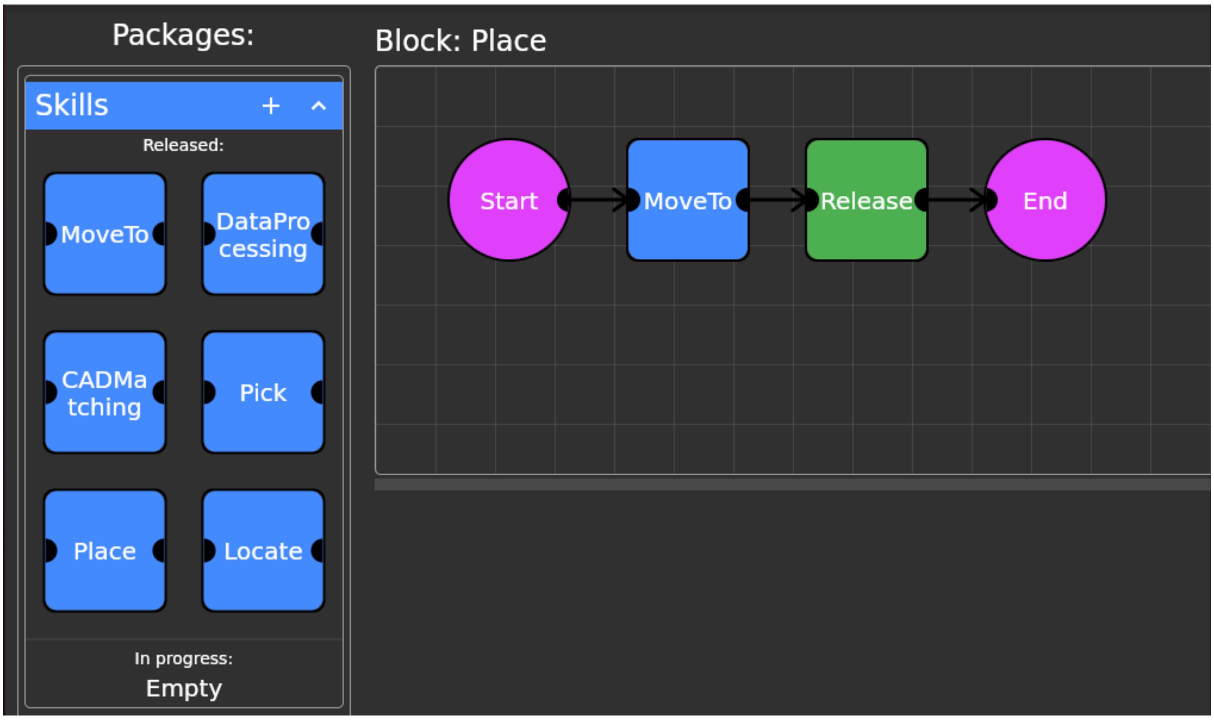


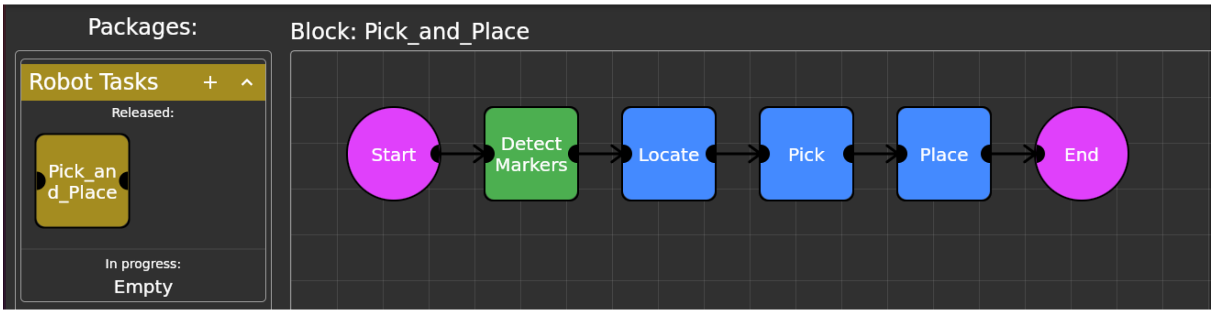


The ACROBA project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 101017284.





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



4.2.1.5 *Code Run with UR10e at NUTAI's facilities*

The only difference between the simulation using URSim and testing with UR10 is the IP input as an argument in the calibration and launch commands of the UR driver.

Due to the errors found, we are working with two different workspaces: catkin_ws and ur_ws. A workspace is a linux folder where files are stored and compiled independently, functioning as a virtual working environment.

The UR related commands need, as a previous step, to execute the command "source ~/ur_ws/devel/setup.bash" to activate the UR workspace in that command window, as it automatically loads the catkin_ws workspace (this is the problem of working with 2 workspaces, in the other virtual machine I could put all the files together without errors). This will be done in the calibration, in the UR-ROS connection driver and in the MoveIt driver for UR.

- **Calibration**

This command launches the file "calibration_correction.launch" corresponding to the ur_calibration folder (package). As arguments it is given the IP of the robot and the path (including the name) of the file that will be automatically generated with the calibration data.

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A file with the robot calibration will be needed to launch the UR-ROS connection driver (next step).

- **Connection driver UR-ROS**

This command launches the driver necessary for the UR-ROS connection and communication to be established. This file is "ur10_bringup.launch", corresponding to the ur_description folder (package). As arguments it is given the IP of the robot, the calibration file and the specific robot description file, which in this case is "load_ur10.launch". Both files must be included with their full path.

If successful, it will appear in the command window.

- **MoveIt Driver for UR**

This command launches the MoveIt driver for the specific UR. It is the file "moveit_planning_execution.launch", belonging to the "ur10_moveit_config" folder (package).

MoveIt is a set of open source software libraries and tools designed for robot motion planning and control. It is a high-level motion planning library commonly used in the ROS environment for robotic manipulators.

- **Connecting the URCap ExternalControl**

The Linux virtual machine must be started with the network adapter configured as a bridge adapter, selecting the Intel® Centrino® Advanced-N 6205.

With the URCap "ExternalControl" installed in the robot and configured with the IP of the Linux virtual machine, a program created only with the URCap is executed. In this case the URCap has been called "Control by ros vm".

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Once the Robot Program has been executed with the URCap, the following message will appear in the UR-ROS connection driver command window.

- **Start Archive (.sh)**

To use a primitive correctly, you must first launch its server "pr_<primitive_name>" and then the code "test_<primitive_name>.py". As the skills contain several primitives, to avoid having to start the server for each one manually, the "start_<filename>.sh" files are used.

This type of file triggers the execution of several primitive servers simultaneously. In this case, "start_move_arm.sh", belonging to the "skills" folder (package), is executed. The effect is to execute the primitives "pr_generate_trajectory" and "pr_execute_trajectory". In addition, the virtual environment "bin_picking" (where independently installed dependencies are located) and the programming code of the skill "sk_move_to.py" are also loaded.

- **Test File**

The execution of "test_<name>.py" activates the client node that will send the desired target to the server (previously started with "pr_<primitive_name>" or "start_<filename>.sh").

The client is an editable Python script that triggers the robot to perform the action. In this case the UR moves to a programmed point.

Another identical script has been programmed, but with another target point for the robot to go to:

```
rosrun skills test_move_to_2.py
```

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4.2.1.6 *Control of OMRON cobot and Asyril Vibrating table*

It has been a challenge to get this robot up and running on the one hand, because IKOR didn't have experience with robots and secondly, because Omron does not officially support ROS.

However, IKOR has managed to install the necessary drivers on the robot and configure them properly.

They have managed to install the drivers in the shared folder of the ACROBA workspace. It has been necessary to do a CMAKE of them and learn the sequence and the main executable that has to be launched to start the service, but in the end, the robot and ROS to communicate as can be seen in the following images.

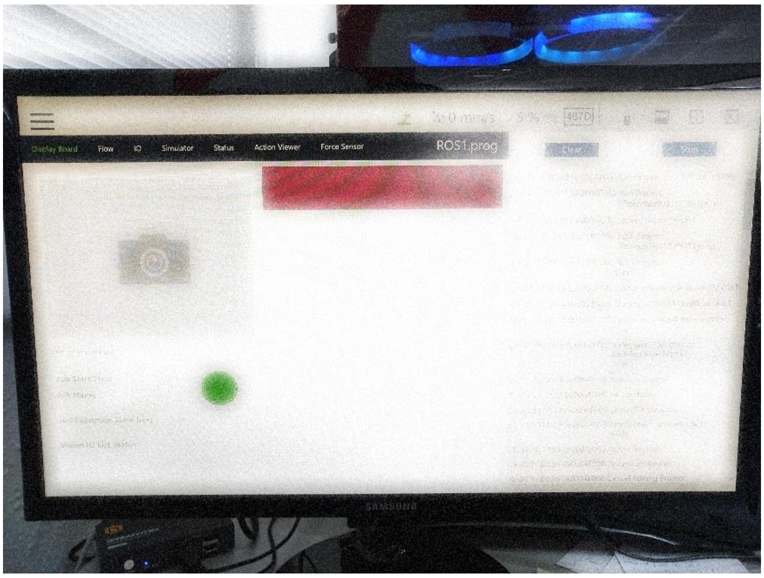

Figure 58 Image of the Robot Operating system while executing ROS1 listen node.

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Figure 59 Image of the ACROBA ROS workspace with TM_driver active and running

The main challenge in making this system work within the ACROBA platform has been to make the ASYRIL controller accessible from the workspace and to learn how to use the manufacturer's software. With the lessons learned from the previous configuration of the robot, it has only been necessary to configure the mapping of port 7171 in the Docker-compose.YML file and make the static IP and DHCP addressing configurations on the router. This done, we were able to reach the Asyril EYE+ controller from the ACROBA workspace and execute TCP commands on port 7171.

As an evidence, it is shown below the basic commands for working with ASYRIL, as viewed from the terminal in ACROBA.

They are in line with manufacturer documentation: Commands — EYE+ 4.0 documentation (asyril.com)

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Asyril controller is also accessible from the web browser in the ACROBA virtual machine, and all the system can be configured from there.

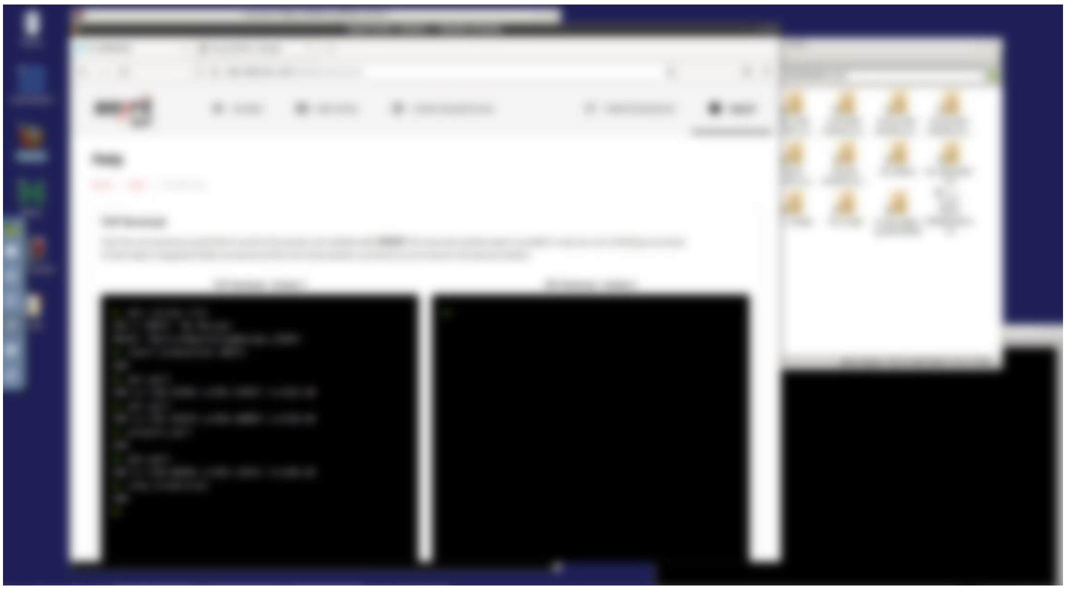

Figure 60 Image of the web browser at ACROBA workspace requesting TCP commands to ASYRIL

4.2.2 ICPE's use case

At the time of writing this document, the process of installation of the ACROBA platform on the PC for the ICPE use-case has not started yet. This is primarily due to a delay in the arrival of the PC, which was delivered to STAM in early June 2023.

Indeed, a dedicated PC for this activity 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.

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- 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 took place. However, the installation of the ACROBA platform has not yet been carried out: it will be performed in early July 2023 following the instructions provided by DEUSTO in Deliverable D1.3.

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5 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. With these preliminary tests, several problems have been found and the works to be developed in the following phases of the project will solve them in order to have fully developed collaborative pilot lines with the ACROBA environment.

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

6 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]

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