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Degree course:

MASTER IN INDUSTRIAL MECHANICAL ENGINEERING

Study Project: Integration of a Transfer System for Hybrid Assembly in the Smart Mini Factory Laboratory

by
Carlos Alonso Paz Rocha

Supervisor:
Dr.-Ing. Erwin Rauch

Second Supervisor:
Prof. Renato Vidoni

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1. Introduction

The present project was carried out in the Smart Mini Factory lab, a learning factory laboratory of the Free University of Bozen/Bolzano. The objective of this project is the integration of a transfer system into the Smart Mini Factory. The transfer system is intended to create a layout that is as universal as possible and allows maximum flexibility in the configuration of the line. This requires the investigation of the working areas of robot, transfer system and human in order to coordinate them with each other. In addition, the SCARA station is to be integrated into the project, if possible without housing. Finally, an automated demo of one of the robots will be created.

For this purpose, the project was divided into three different sections with their own methodology of work. The first section is aimed at analyzing the movement of the robots and their workspace. The second section was focused on designing safety measures for the SCARA robot. Finally, the third section was intended to create a demo of one of the robots, which forms part of the transfer system.

2. Movement and Workspace Analysis

The following section presents the results of workspace and movement analysis of the different robots of the Smart Mini Factory lab in relation to the Linear Transfer System (LTS) to be implemented.

The work methodology consisted of the following steps:

1) Elaboration of a workspace map in SolidWorks for every single robot that takes part in the LTS. This map was created according to the datasheet of each robot.
2) Proposal of a new position for each robot to maximize the reachable area of the end-effector over the LTS. This new position considers also the reduction or elimination of any probability of collision between robots.
3) Calculation of the total covered area of the initial layout and the proposed one and comparison of them to identify the improvement in terms of use of space.

The robots considered to calculate the total covered area were KUKA Kmr (1), KUKA Kmr (2), UR3, Scara and ABB IRB. The Adept Quattro, UR10 and the Parallel Robot TFO were not taken into account because the difference of areas in both scenarios do not really vary and to get any improvement of the workspace not only the design or height of the conveyor would have to be modified but probably also the housing or support of the robots.

For the proposal, the conveyor was not modified; only the position of the robots around the LTS was considered.

2.1. KUKA Kmr (1)

The first thing we can easily notice is that an important area is being wasted because of the position of the robot. It could be placed further to the left so that the robot's workspace could cover an additional section of the LTS. Moreover, the inner sphere of the robot is covering part of the LTS. The inner sphere represents the space that the robot's end-effector cannot access; therefore, this is a wasted space due to the proximity of the robot to the line. The actual area that the KUKA Kmr (1) [1] can reach is 2977.64 cm2.

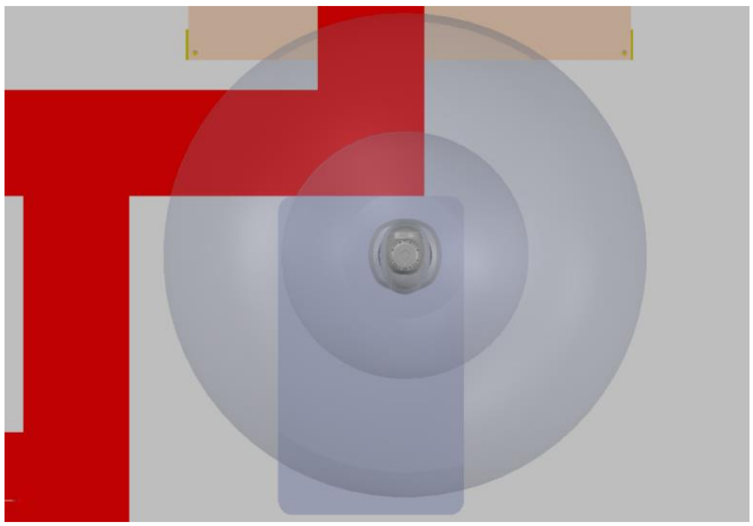

Figure 1. Scenario 1. Position of the KUKA Kmr (1) robot.

The proposal for this robot was to move it to the left so now it can cover two different sections of the LTS. Another decision with respect to the KUKA Kmr was to place its arm a little away from the LTS to avoid wasted spaces because of the inner sphere. With the changes, the workable area is 7050.92 cm2, which is 2.37 times higher than the initial one.

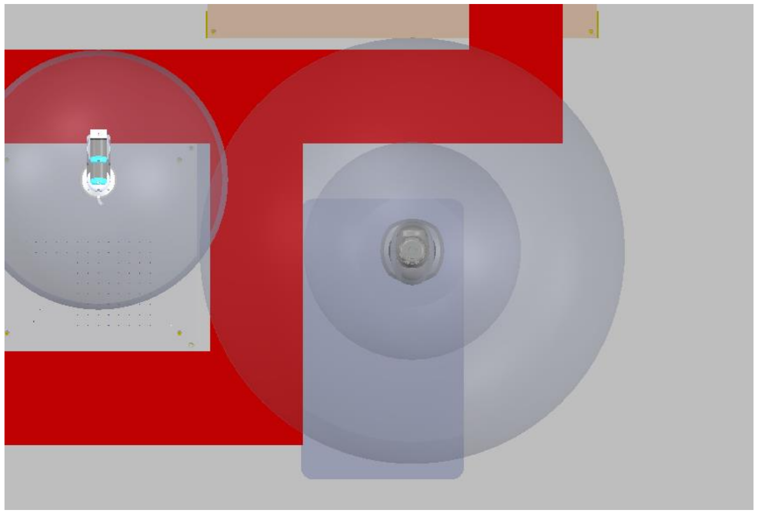

Figure 2. Scenario 2. Position of the KUKA Kmr (1) robot.

2.2. UR3 Robot

It can be appreciated that the UR3 robot [2] is already covering a big area, which includes two different sections of the LTS. Any other position of the robot on its own table would reduce its reachable area over the line. The problem emerges when we see that this robot shares a big space with the KUKA Kmr (2) [1]. We can consider the shared area like a wasted space because we have another robot that is already covering that spot; but also, and more important, that shared area might produce possible collisions between the two robots; this probability must be reduced or eliminated. The covered area of the UR3 robot is 3480.74 cm2; however, the workable area not considering the shared space is 1831.90 cm2, 47.37% lower.

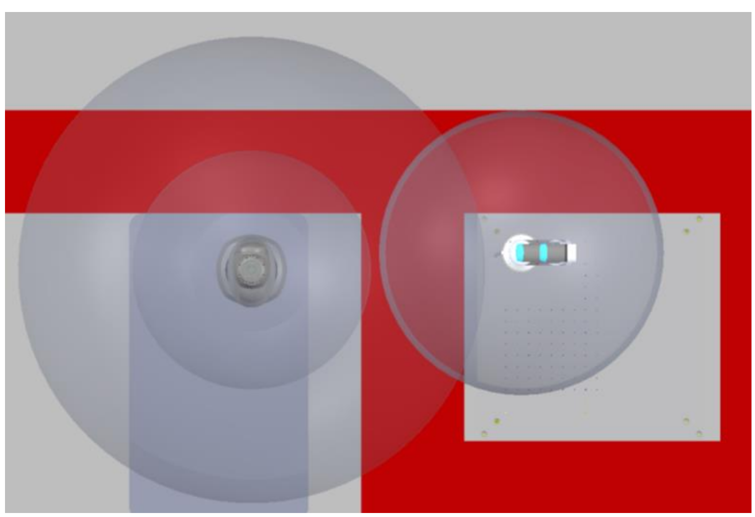

Figure 3. Scenario 1. Position of the UR3 robot.

As a proposal, the UR3 was moved a little to the right, occupying now a middle place on the table. While the accessible area has been reduced 35.63% in comparison with the initial position, the probability of collisions with the KUKA Kmr (2) has been practically eliminated. If we compare the two scenarios not considering the shared area in the first scenario, because that area is already covered by another robot, then the reachable space in the second scenario (2240.60 cm2), is higher than the first one in 22.31%.

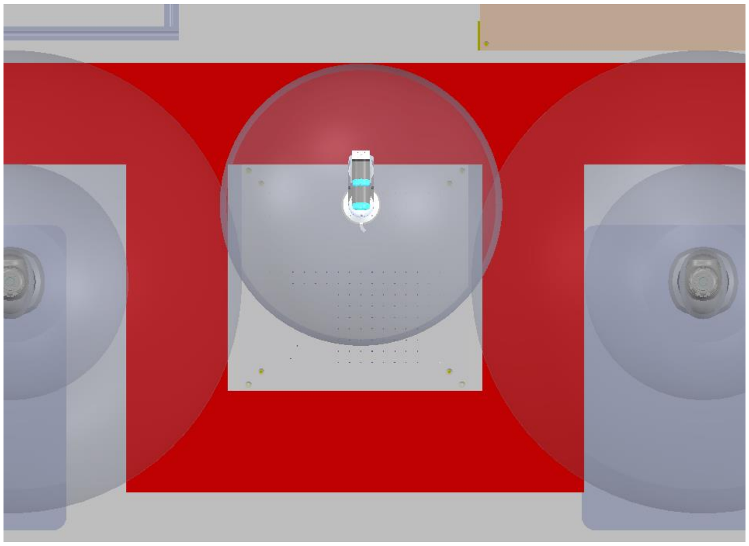

Figure 4. Scenario 2. Position of the UR3 robot.

It can be seen very small areas shared by the UR3 and the two KUKA robots. These areas are found in spaces where the UR3 robot is not supposed to operate, therefore the probability of collision is very low. Additionally, to get a collision between the robots, they would have to have their arms fully extended in a specific direction at the same time, fact that would be extremely unusual, therefore we consider the probability of collision as null.

2.3. KUKA Kmr (2)

Unlike the KUKA Kmr (1), in the initial scenario the KUKA Kmr (2) is covering a big space which includes two sections of the LTS; however, we find two problems that need to be considered. First, this robot shares an area with the UR3. As it has been explained before, this distribution of the space could produce collisions between the robots. This problem was solved in the second scenario by changing the position of the UR3 robot. The other issue we face is the inner sphere covering a section of the line near the robot. It can be assumed that the nearest parts of the LTS with respect to the robot are spaces where this operates the most; therefore, having an unreachable area in this position would generate problems while programming the robot.

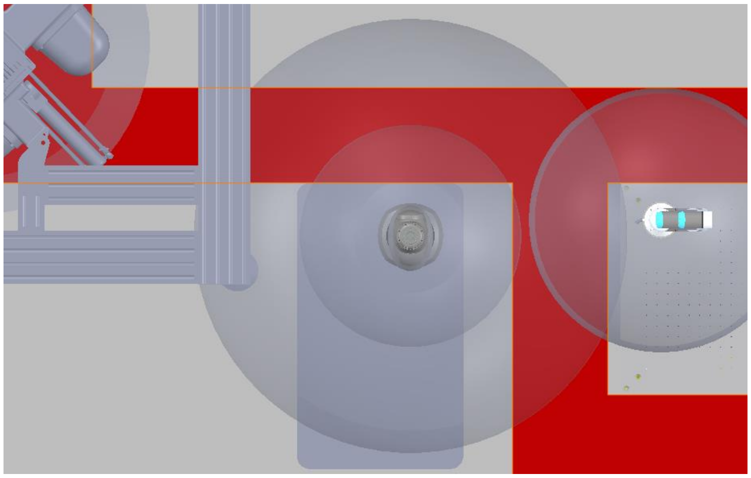

Figure 5. Scenario 1. Position of the KUKA Kmr (2) robot.

Again, as with the KUKA Kmr (1), the proposal for this robot is moving its arm a little away from the LTS so the inner sphere does not interfere with the reachable space of the line. The area in the first scenario, is 6699.02 cm2, while the area in the second scenario is 7276.59 cm2, which represents an increment of 8.62%. While this augmentation of the area is small, problems such as collision between robots and unreachable space because of the inner sphere were solved.

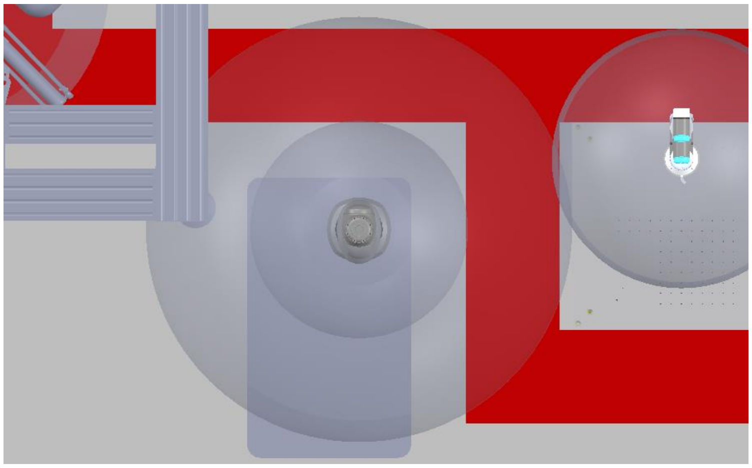

Figure 6. Scenario 2. Position of the KUKA Kmr (2) robot.

2.4. SCARA Robot

As shown in the Figure 7, the area covered by the Scara Robot [3] is very small; this is just 1462.44 cm2. The evident solution would be to move the robot to the left, but this movement is limited by the position of the ABB robot; we need to avoid any collision. For this reason, the ABB robot as well as the Parallel Robot TFO were moved to the left, what gives more space to the scara to be moved to a position which let it cover a bigger area over the LTS. The area covered by the Scara Robot in the second scenario is 3205.78 cm2, 2.19 times bigger.

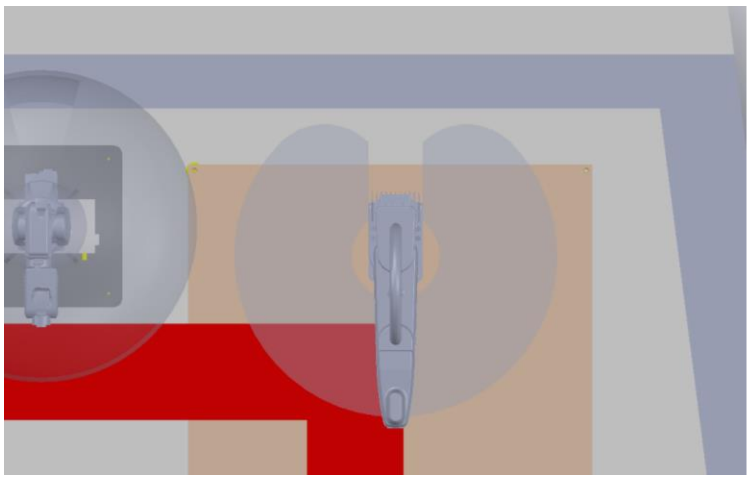

Figure 7. Scenario 1. Position of the Scara robot.

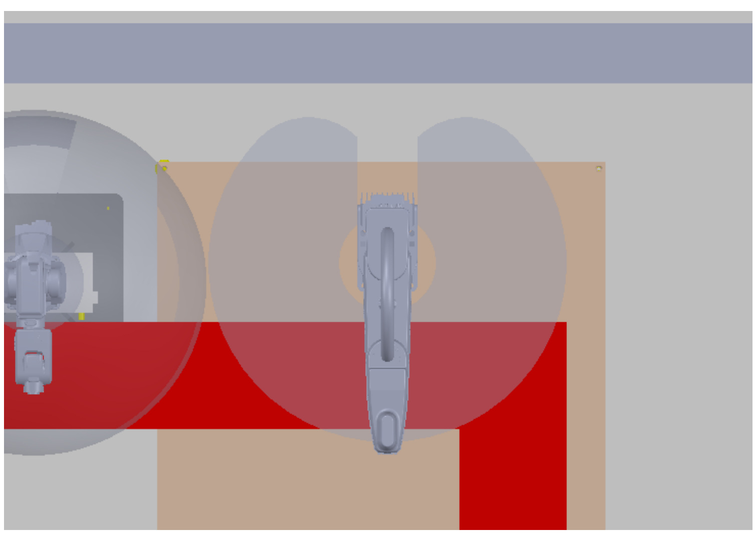

Figure 8. Scenario 2. Position of the Scara robot.

Something that needs to be taken into account is the fact that there is a gap (27.5 mm) between the limit of the scara robot and the LTS. There are three ways to avoid any problem produced by this separation. The first one is to reduce the height of the table where the robot is in 27.5 mm.

Another option is to use objects/pieces whose height is higher than 27.5 mm. Any piece below this measure will not be caught by the robot. The last solution would be to attach a gripper or another device to the robot, what would completely eliminate any gap between the robot's end effector and the line.

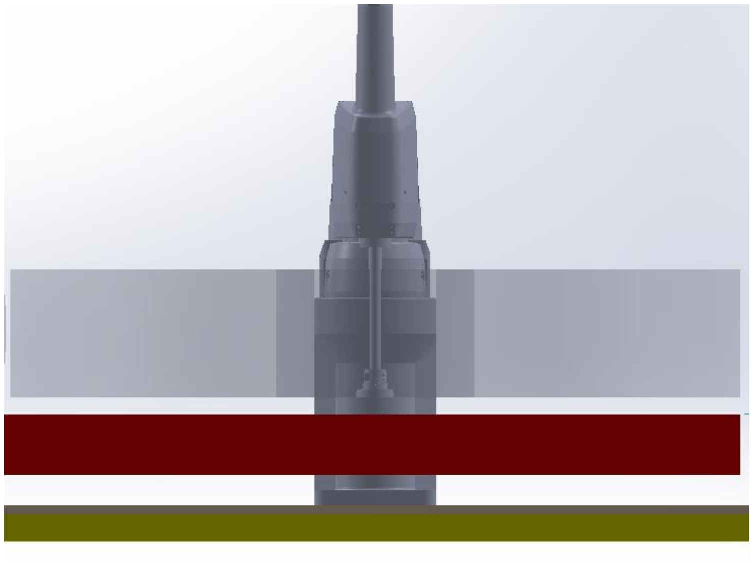

Figure 9. Gap between the Scara robot and the LTS.

2.5. ABB IRB Robot

Once the Parallel Robot TFO was moved to the left to give space to the Scara Robot, this was placed a little closer to the LTS so that the ABB robot [4] is capable to cover as much surface of the conveyor as possible.

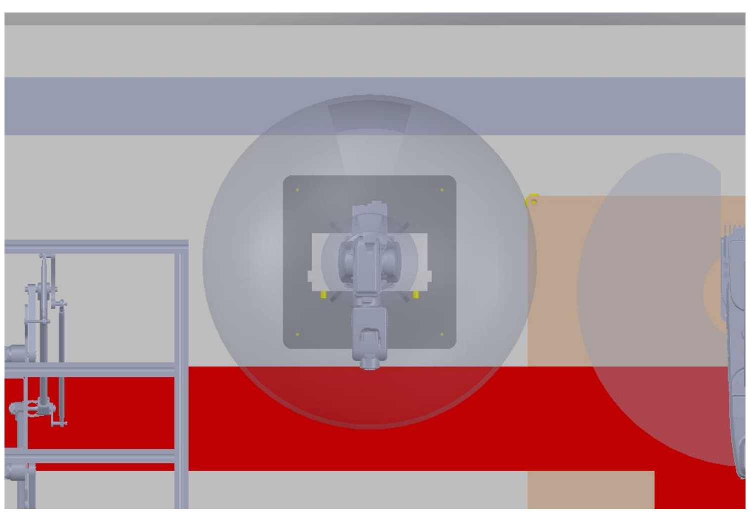

Figure 10. Scenario 1. Position of the ABB IRB robot.

The area in the first scenario is 1202.03 cm2, on the other hand, the area in the second scenario is 3188.59 cm2, 165.27% bigger than the initial one, an important increase. There is no possibility of collision with other robots.

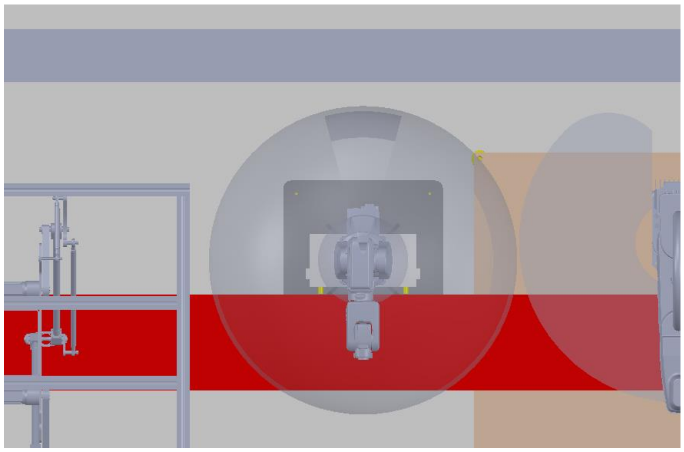

Figure 11. Scenario 2. Position of the ABB IRB robot.

The Table 1 summarizes the difference between the two scenarios in terms of use of space. The second scenario (proposed) takes better advantage of the given space. The total covered area by the first five robots that were evaluated is approximately 62% bigger than the initial layout.

Table 1

Robot	Area (in cm^2)		Increment
	Scenario 1	Scenario 2	
Kuka 1	2977.64	7050.92	137.0%
Kuka 2	6699.02	7276.58	8.6%
UR3*	1832.41	2240.60	22.3%
Scara	1462.44	3205.78	119.2%
ABB	1202.03	3188.59	165.3%
Total	14173.53	22962.47	62.0%

*Reachable area not considering the shared space with the KUKA Kmr (2) robot.

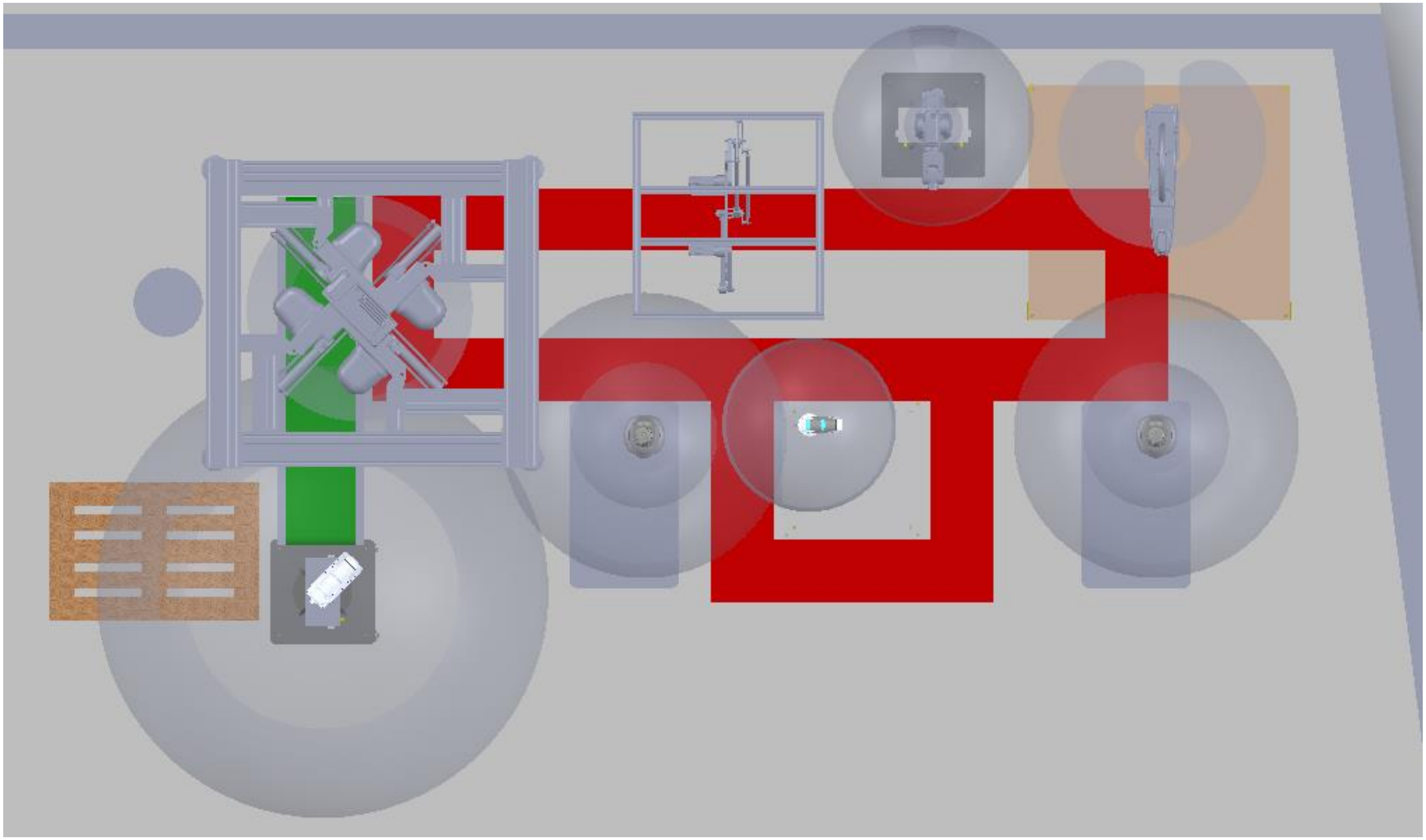

Figure 12. Scenario 1. Initial Layout.

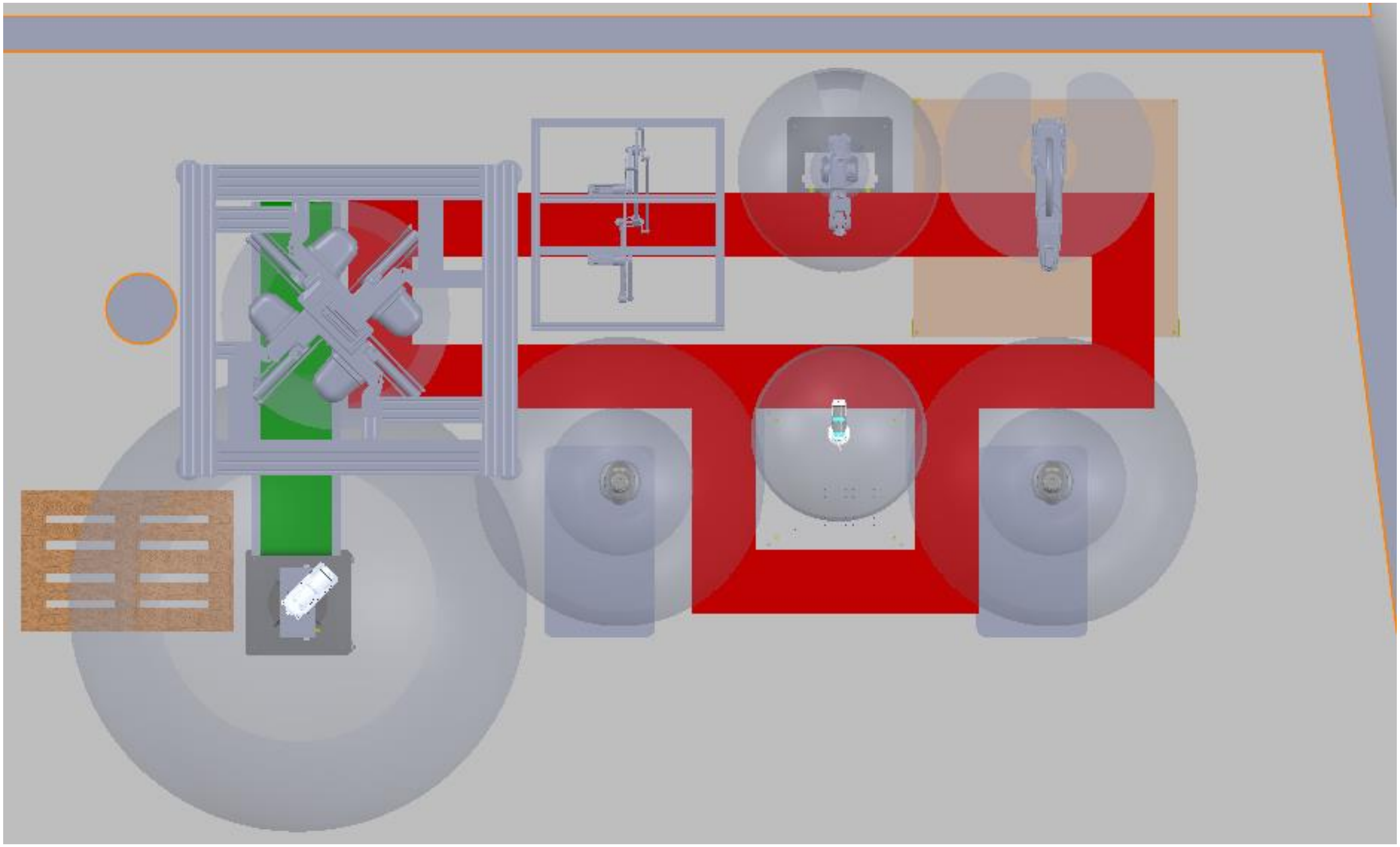

Figure 13. Scenario 2. Proposed Layout.

3. Safety Measures for the Scara Robot

The second section of the study project is aimed at analyzing and evaluating safety measures for the Scara Robot in the Smart Mini Factory lab.

The work methodology consisted of:

1) Identify the standards that stablish the positioning of safeguards with respect to the approach speeds of parts of the human body, and define the safety devices to be used in the lab environment.
2) Calculate the minimum safety distance to place the safeguards according to the safety standards.
3) Define the position of the proposed safety devices in the workspace and make a quotation.

3.1. Safeguard and Safety Standard

Among the principal safety devices, we can find light curtains, which are optoelectronic devices that are used to safeguard personnel near moving machinery with the potential to cause harm [5]. When an object or person crosses the sensing screen (curtain) with the body or part of the body, the device sends a signal to stop the operating robot. Light curtains are used where the result of an accident is only a slight injury [6] [7].

There are standards that let us determine the safety distance between the robot and the safety device. One of these standards is ISO 13855 [8], which provides a formula to calculate the minimum safety distance.

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

Where:

S: Minimum safety distance between the protection and the hazardous point

K: Approach speed of the body or parts of the body expressed in mm per second. The values of K can be

K = 2000 mm/s for safety distances up to 500 mm

K = 1600 mm/s for safety distances longer than 500 mm

T: Maximum stopping time (robot stopping time + light curtain response time ON to OFF)

C: Additional distance expressed in mm $C = 8 \times (d - 14)$ if $d \le 40$ mm

d: Detection capability

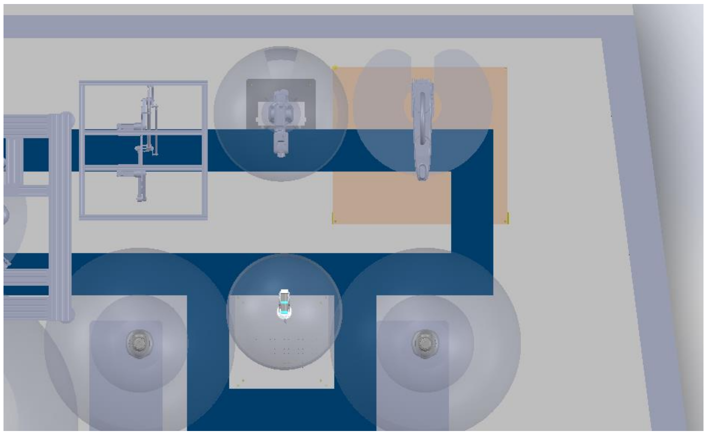

Figure 14. Layout of the Linear Transfer System

3.2. Comparison of Robots' Stopping Times

The Scara Robot i600 Cobra does not have any information in its data sheet about its stopping time; therefore, it was necessary to search available information about other Scara robots in the market and do an approximation.

The closest robot to ours is the Scara Robot e600 Cobra [3], which has the same length, rated and maximum payload, and the same manufacturer. In the following pictures, the stopping time of each joint is shown. We must consider the largest stopping time at the highest speed and payload among the joints to perform our calculations; in this case, 0.295 seconds of the joint 2.

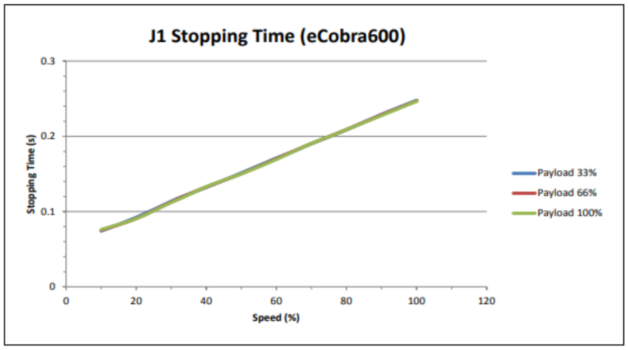

Figure 15. Joint 1 Stopping Time for eCobra 600, in Seconds

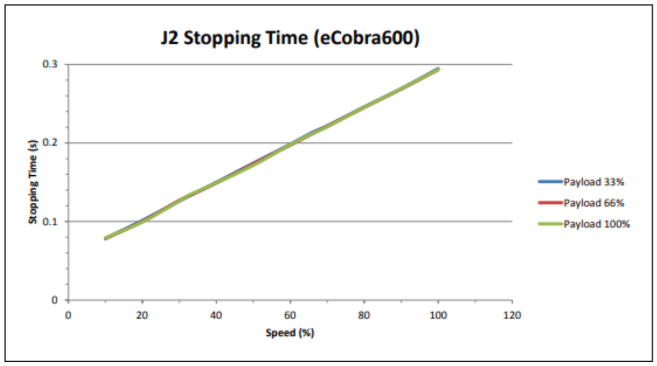

Figure 16. Joint 2 Stopping Time for eCobra 600, in Seconds

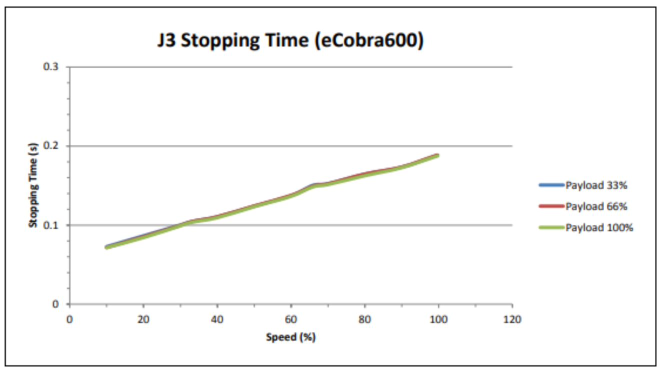

Figure 17. Joint 3 Stopping Time for eCobra 600, in Seconds

It can be noticed in the figures above, that the eCobra 600's stopping times do not depend on the payload, since their curves overlap each other.

Information about other Scara Robot in the market was collected in order to make a comparison between them, and also observe the usual effect of the payload over the robots' stopping time.

The YAMAHA SCARA Robot YK500TW [9] has the following XY-axis stopping time in seconds (Figure 18). The length of the robot is 500 mm. For a load of 4kg and 100% operation speed, the stopping time is approximately 0.29 seconds.

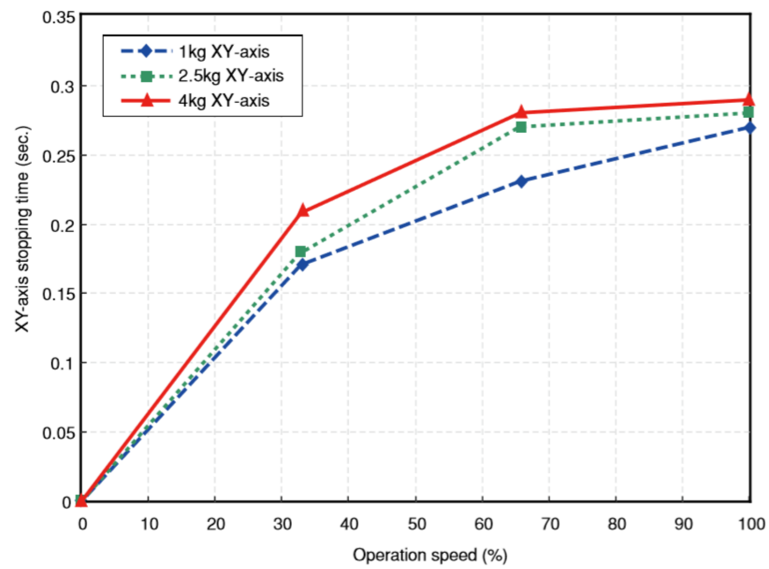

Figure 18. XY-axis stopping time for YK500TW

Another robot that served as reference was the R6YXH350 [10], which has a stopping time of 0.34 seconds approx. as the load is 3 kg and the operation speed is 100%. Some significant variations in the stopping time are evidenced when changing the payload.

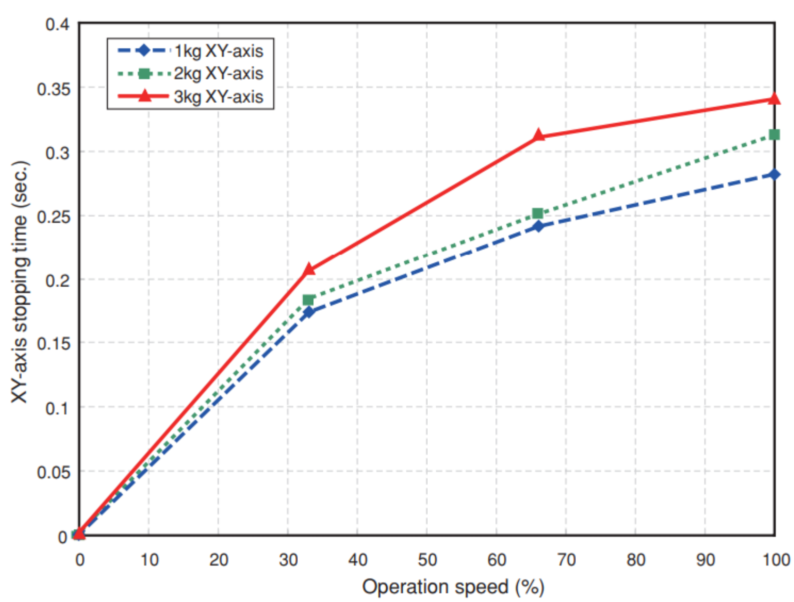

Figure 19. XY-axis stopping time for R6YXH350

3.3. Calculation of Minimum Safety Distance

Light curtains of F3SJ Series [11] were considered to do a first calculation. Among its main specifications, we find:

F3SJ-E

Detection capability: 25 mm

Maximum response time ON to OFF: 15 ms

Safety Distance = 2000 x (0.295 + 0.015) + 8 x (25 – 14) = 708 mm

The ISO 13855 indicates that if the safety distance is bigger than 500 mm, the approach speed to use should be 1600 mm/s. The resultant safety distance cannot be smaller than 500 mm.

Safety Distance = 1600 x (0.295 + 0.015) + 8 x (25 – 14) = 584 mm

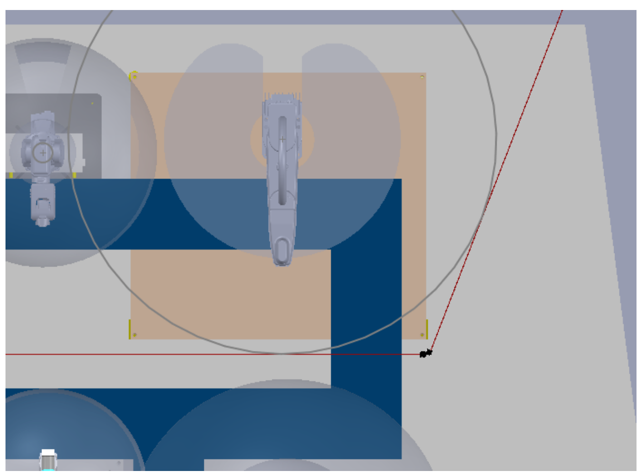

Figure 20. Light curtain with safety distance of 584 mm

The best detection capability of light curtains in the market is 14 mm; the F3SJ-A Series [11] possesses this feature; however, this series is much more expensive than the F3SJ-E's.

If we do calculate again the safety distance with this new value, the results are:

F3SJ-A

Safety Distance = 2000 x (0.295 + 0.015) + 8 x (14 – 14) = 620 mm

Since the distance is bigger than 500 mm, we can use once again an approach speed of 1600 mm/s.

Thus:

Safety Distance = 1600 x (0.295 + 0.015) + 8 x (14 – 14) = 496 mm → 500 mm

As mentioned before, if we consider an approach speed of 1600 mm/s, the minimum safety distance must not be lower than 500 mm. The 496 mm obtained cannot be applied but must be rounded up to 500 mm.

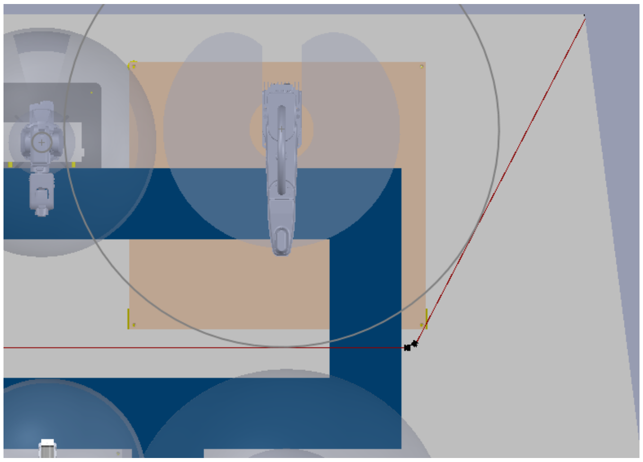

Figure 21. Light curtain with safety distance of 500 mm

The reduction of the minimum safety distance by using light curtains with better detection capability (14 mm) in this case is 84 mm. This means 14.38% shorter than the distance gotten utilizing the F3SJ-E Series.

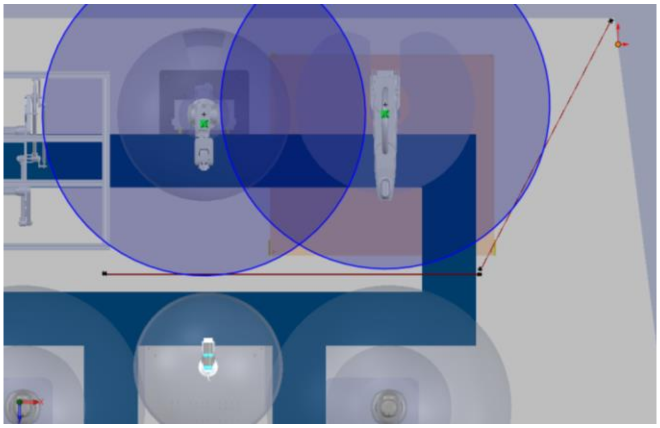

Figure 22. Light curtains distribution covering ABB and SCARA robots

It is important to highlight that we have made calculations based on the maximum robot speed. This would be necessary if the robot was part of a production line. In a factory where the lean-manufacturing is applied, the Scara robot would only use a maximum speed if it was either the bottleneck or part of a critical process. Since the Scara Robot i600 is used not for production but for study purposes, and its operation velocity is higher than the other robots' in the same line, the speed to be considered for a more suited calculation to the SMF could be 50% of its maximum value at rated payload. Thus, the stopping time of the robot would be now 0.17 seconds approximately. Of course, when programming the robot, it should not exceed 50% of the maximum speed.

F3SJ-E

Safety Distance = 2000 x (0.17 + 0.015) + 8 x (25 – 14) = 458 mm

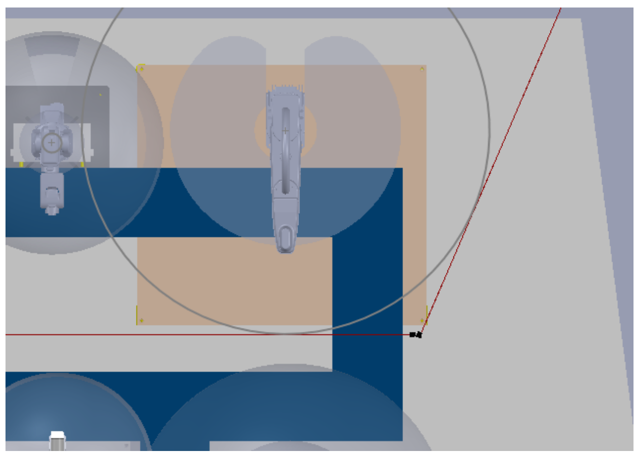

Figure 23. Light curtain with safety distance of 458 mm

F3SJ-A

Safety Distance = 2000 x (0.17 + 0.015) + 8 x (14 – 14) = 370 mm

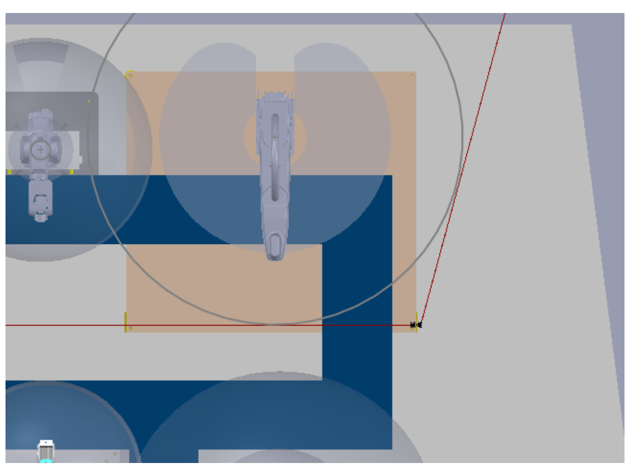

Figure 24. Light curtain with safety distance of 370 mm

An approach speed of 1600 mm/s cannot be applied because the safety distances in both cases are shorter than 500 mm. The difference of the minimum safety distance between the two cases is 88 mm. This represents a reduction of 19.21%.

Furthermore, we can see in this case that reducing the response time of the light curtains does not have an important additional effect on the calculations of the safety distance since it represents no more than the 8% of the maximum stopping time (Scara Robot + Light Curtain).

Table 2

	Minimum Safety Distance	
Devices	(at robot's full speed)	(at robot's half speed)
F3SJ-E	584 mm	458 mm
F3SJ-A	500 mm	370 mm
Difference	84 mm	88 m

3.4. Comparison of Cost of Light Curtains

The Table 2 summarizes the minimum safety distances obtained by the calculations considering a full and half speed of the robot and using light curtains of the F3SJ-E and F3SJ-A series. The difference between the two devices is 84 mm at full speed and 88 mm at half speed. Thus, the reduction of the safety distances is 14.38% and 19.21% respectively. This diminution of space is not justified in terms of costs because the total sum of prices of the F3SJ-A devices is 83.22% more expensive than the F3SJ-E series, as can be seen in the Table 3.

Table 3

Cost of Light Curtains					
F3SJ-E Series			F3SJ-A Series		
Device	Price		Device	Price	
F3SJ-E0705P25	€	1,627.96	F3SJ-A0695P14	€	2,946.55
F3SJ-E0865P25	€	1,832.09	F3SJ-A0875P14	€	3,392.85
Total	€	3,460.05	Total	€	6,339.40

The study proposes the implementing of two light curtains of the F3SJ-E series, both with different heights, the first one is 705 mm tall because it goes over the linear transfer system, and the second one has a height of 865 mm because it must cover an additional space. Considering the selection of the devices, the safety distance recommended is 584 mm because it fully satisfies the requirements stablished in the ISO 13855.

As can be seen in the Figure 25, the light curtains safeguard the work area around the ABB IRB 120 robot. This robot is not collaborative; therefore, it was important to include a safety area for this robot as well.

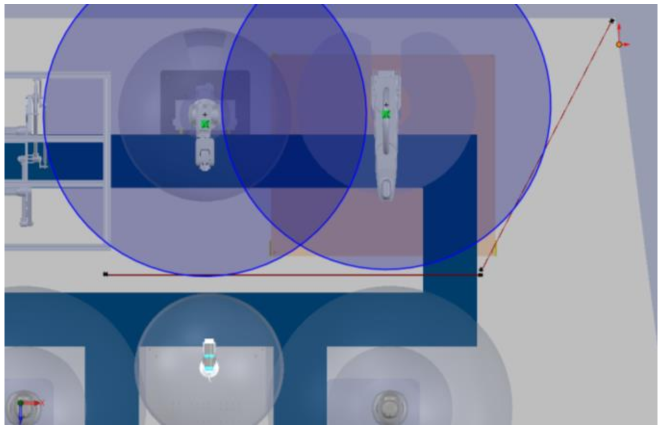

Figure 25. Light curtains distribution with safety distance of 512 mm

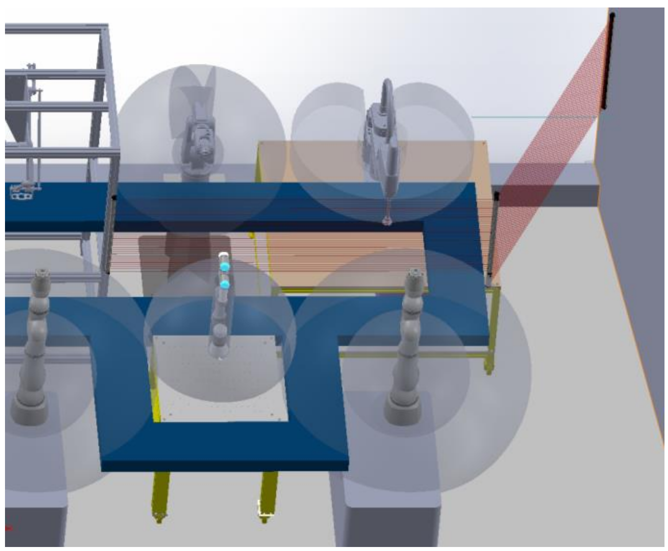

Figure 26. Layout of the LTS with light curtains

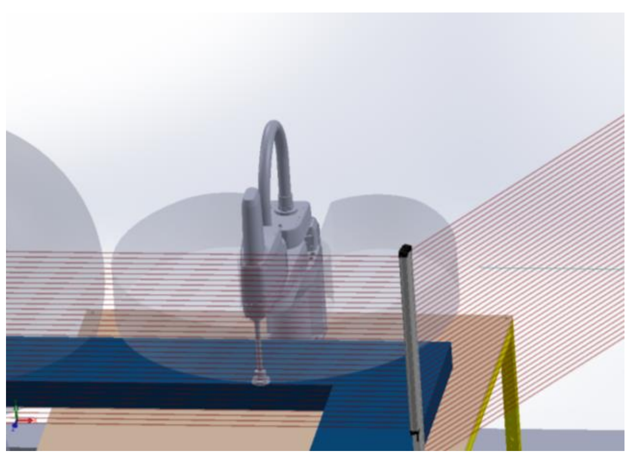

Figure 27. Light curtains and Scara robot

4. Palletizing with UR10 Robot

4.1. Support Evaluation

One of the processes in the Linear Transfer System to be performed is the palletizing of boxes and parts. This labor is supposed to be executed by the UR10 Universal Robot [12].

The objective of the last section is to evaluate the suitability of the support of the UR10 for palletizing purposes, as well as to develop a demo of palletizing with Universal Robots.

The steps to be followed were:

1) Analyze the center of mass of the robot and its support, considering additional variables like acceleration and position of the robot's arm.
2) Calculate if the support is suitable for the robot in static dynamic state.
3) Understand how Universal Robots work.
4) Program a demo of palletizing with the functionalities that Universal Robots interface offers.

4.1.1. Analysis of Center of Mass of Robot and Support

The height and weight of the support, as well as its center of mass, were taken into account. Furthermore, variables such as the length, mass, center of mass and inclination of the robot, the load and acceleration of the end-effector were considered.

Since the support was built mainly using an only material, its center of mass can be easily measured using its 3D model and applying tools of CAD software. The mass of the supports is 150 kg and its center in the x-axis is at 0 m (considering a centered position), and 0.304 m in the y-axis. The length of the support's base is 0.6 m long.

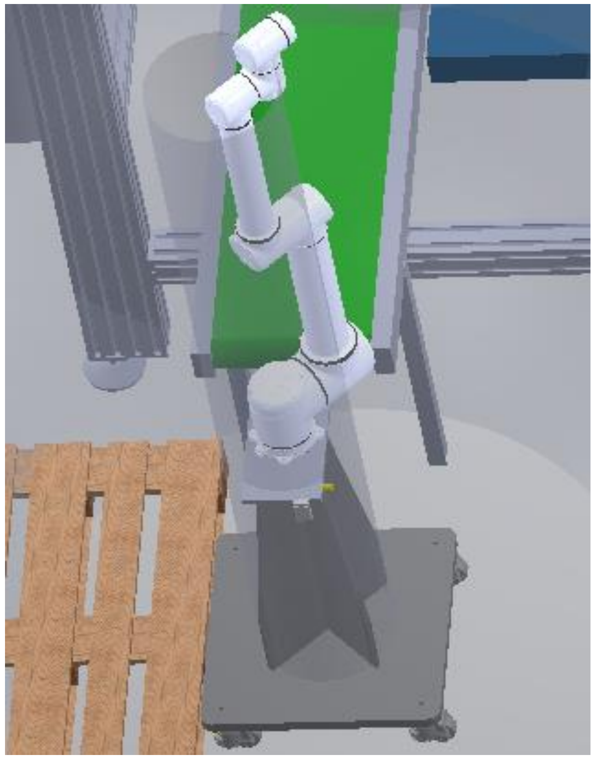

Figure 28. UR10 robot and its support

The table 4 provides information about the links that make up the UR10 robot. The center of mass of each link is expressed on its own coordinate system when the robot's arm is fully extended in an upright position as shown in the Figure 29.

Table 4

Measures of the UR10 Robot

Link	Mass (kg)	Length (mm)	Center of mass* (mm)	
			X	Y
1	7.1	128	27	21
2	12.7	612.7	158	380
3	4.27	571.6	68	240
4	2	115.7	18	0
5	2	0	18	0
6	0.365	0	-26	0
Total	28.435			

*Center of mass of each link

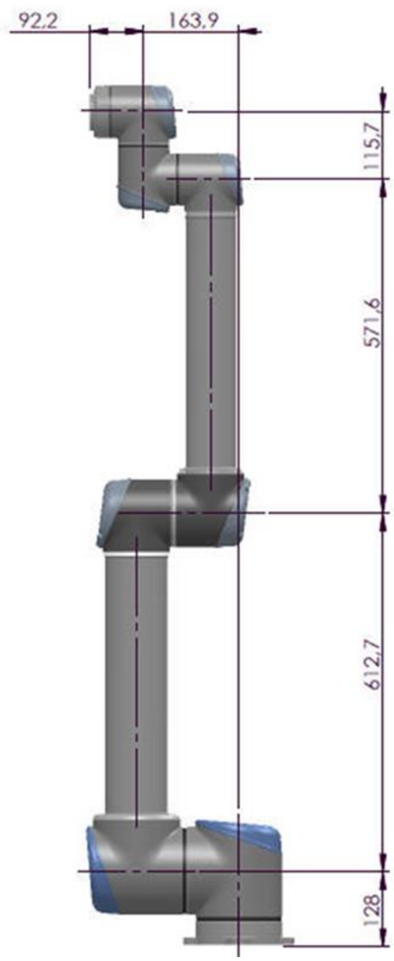

Figure 29. Measures of the UR10 robot

The table 5 displays the center of mass of each link of the robot when its arm is extended horizontally. In this case, the links share the same coordinate system, starting from the link 1, whose center on the x-axis is located at 0 mm.

Table 5

Measures of the UR10 Robot with arm fully extended 180°

Link	Mass (kg)	Length (mm)		Center of mass* (mm)	
		Accum. X	Accum. Y	X	Y
1	7.1	0	21	0	21
2	12.7	612.7	21	380	21
3	4.27	1184.3	21	852.7	21
4	2	1300	21	1184.3	21
5	2	1300	21	1300	21
6	0.365	1300	21	1300	21
Total	28.435				

*Center of mass in the reference system

The table 6 groups the center of mass of all the system's components. The link 1 of the arm is located on the support.; both centers of mass are placed at 0 m in the x-axis.

Table 6

Center of mass of the system			
Component	Mass (kg)	Center of mass (m)	
		X	Y
Support	150	0	0.304
Arm	28.435	0.489	0.925
Load	10	1.300	0.925
Arm+Load	**38.435**	**0.700**	**0.925**
Total	188.435		

4.1.2. Calculations for the Evaluation of Suitability of the Support

The first case sets out the evaluation of the center of mass when the arm of the robot is fully extended in the horizontal axis and holds a load of 10 kg (maximum load according to the specifications of the robot). The wheel (pivot) of the support is located at 0.3 m in the x-axis; this point cannot be exceeded; otherwise, the whole system will turn over. By means of simple calculations shown below, it was found that the center of mass of the system in the previously described position and orientation is 0.158 m in the x-axis. This value is smaller than the maximum “allowed”, therefore we conclude that the support is suitable to the robot and load in a static situation.

Nevertheless, this analysis is not enough because motion of the robot is required. Thus, internal forces as the acceleration of the joints must be also considered in this study. We also need to determine the maximum linear acceleration that can be applied in the load and in the center of mass of the arm by the joint 2 (shoulder).

Doing some calculations based on the D'Alembert's principle of inertial forces [13], we arrive until the formula shown below. All the variables are expressed as well.

$$Z = \frac{x * g * (m1 + m2) \pm (y * a1 * m1 + y * a2 + m2)}{g * (m1 + m2 + M)}$$

x: Center of mass in the x-axis
y: Center of mass in the y-axis
m1: Mass of the arm
m2: Mass of the load
M: Mass of the support
a1: Acceleration of the arm (center of mass)
a2: Acceleration of the load
g: Gravity

x	0,7782
y	0,925
m1	28,435
m2	10
M	150
a1	0
a2	0
g	9,81

Z = 0.158 m

x: Center of mass in the x-axis
y: Center of mass in the y-axis
m1: Mass of the arm
m2: Mass of the load
M: Mass of the support
a1: Acceleration of the arm (center of mass)
a2: Acceleration of the load
g: Gravity

x	0,7782
y	0,925
m1	28,435
m2	10
M	150
a1	5,503784
a2	12,58
g	9,81

Z = 0.3 m

If the movement of the arm is guided by the joint 2, the load and the arm have the same angular velocity, therefore, the a2 is related to a1 in a ratio of 2.2857.

The linear acceleration of the load at which the system turnover is 12.58 m/s2. Thus, the angular acceleration of the joint 2 cannot exceed the 5.5 m/s2.

It is important to know the linear acceleration of the end effector because it is possible to restrict this value in the programming software when it exceeds the limits.

4.2. Robot Programming

To teach our universal robot to perform a routine of palletizing, we need first to click on Program Structure Editor, select the Wizards button and choose the pallet routine template.

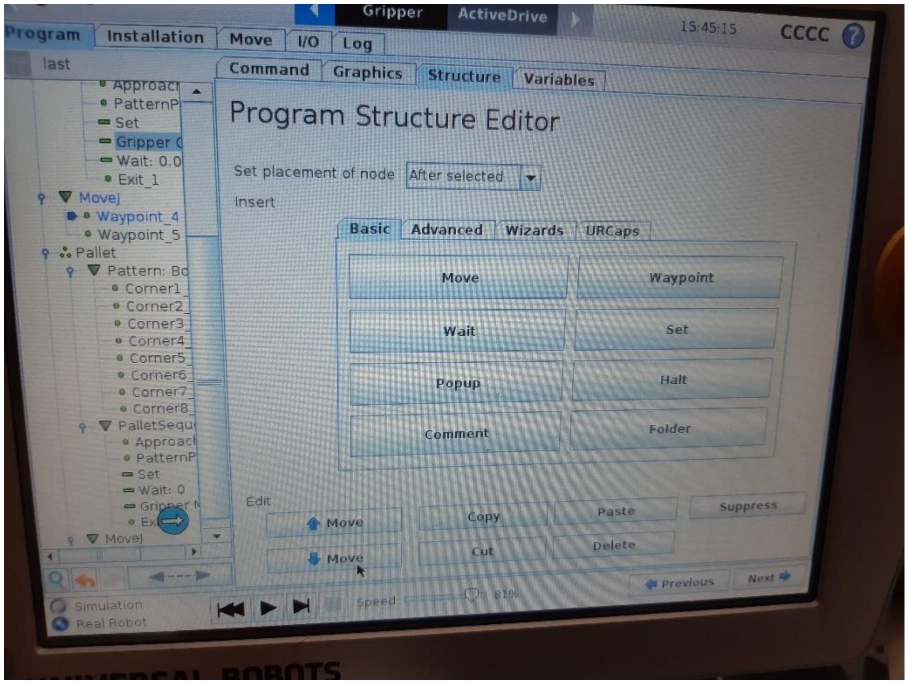

Figure 30. UR10 Program Structure Editor - Basic

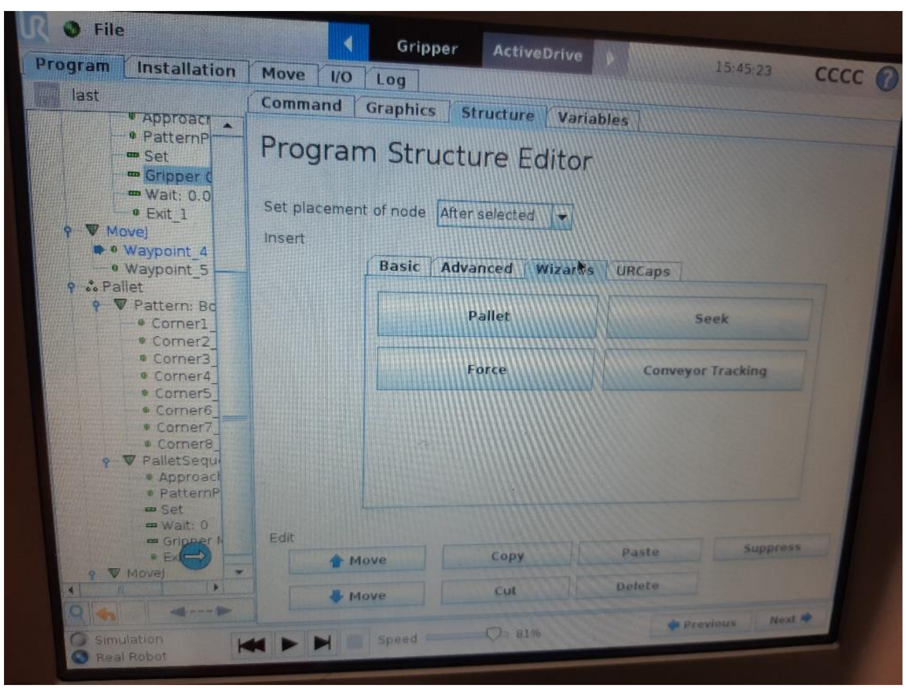

Figure 31. UR10 Program Structure Editor - Wizards

Now it is necessary to define the pattern to be followed by the robot. There is list of four different patterns. We are interested in the box option instead of the square option because the pallet will have a 3d configuration.

Once we have clicked on the box button, we need to define the number of units (interval count) for each row, column and level that make up the box.

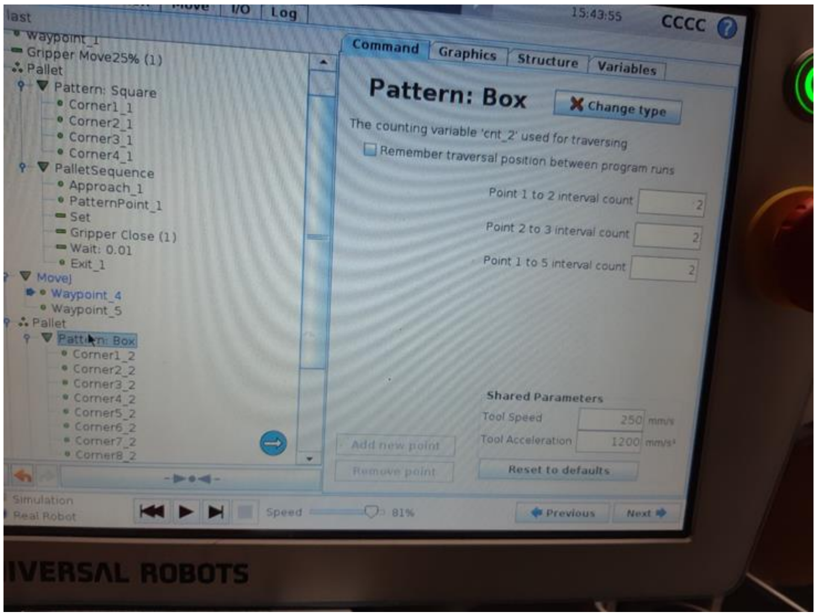

Figure 32. Palletizing Pattern - Box

Now we need to teach the robot all the corners of the box starting from the first level. We need to select eight corners in total.

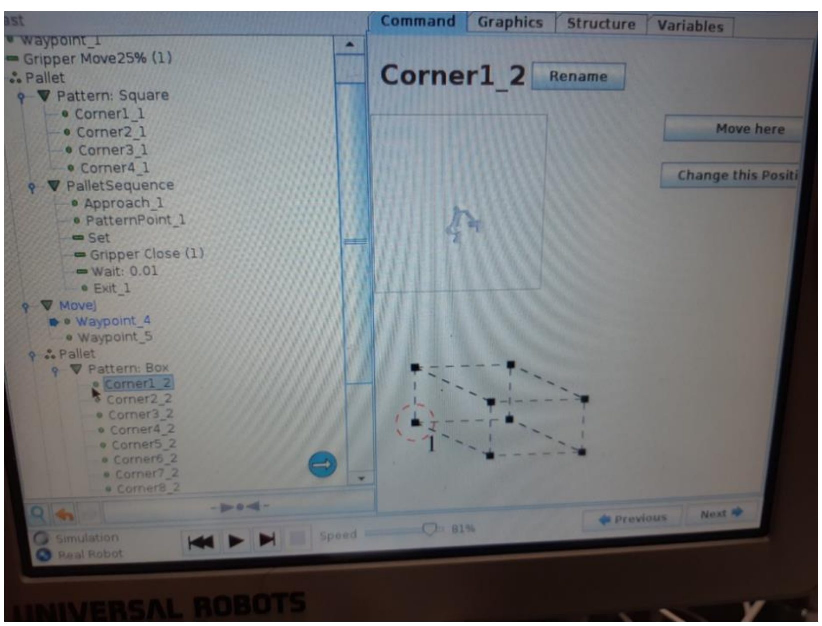

Figure 33. Selection of the corners of the box

The next step is to show the robot how to pick up the first part of the pallet and then replicate that motion for the rest of the parts

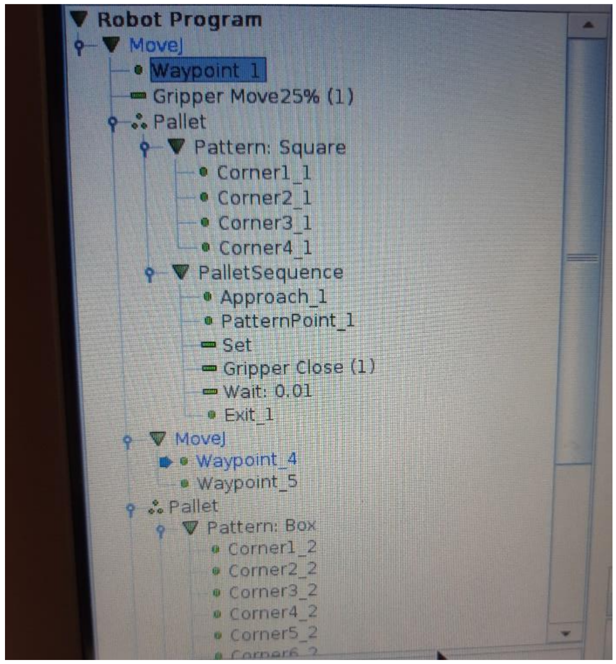

Figure 34. Robot Program

Approach is the position the robot will go to before it places the part down the pallet. It is important to give it an enough clearance, so we do not have any collision with the other parts of the pallet. Pattern point is the actual location where we are going to place the first part in the box.

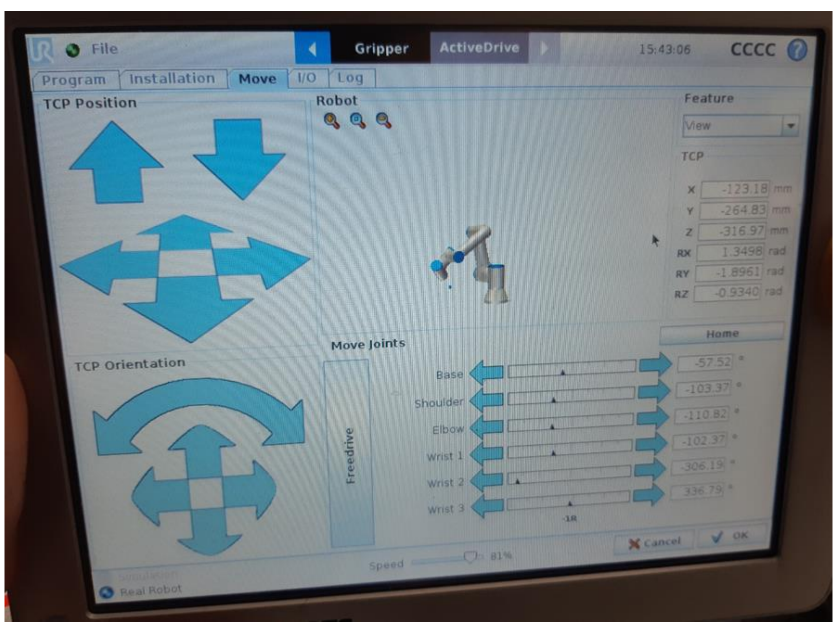

Figure 35. Selection of the Position and Orientation of the Robot

We can select the set command to turn off the vacuum and release the part. Since in this study we are using a gripper instead, we need to add a step in the cycle in order to open the gripper and release the piece in the predetermined position.

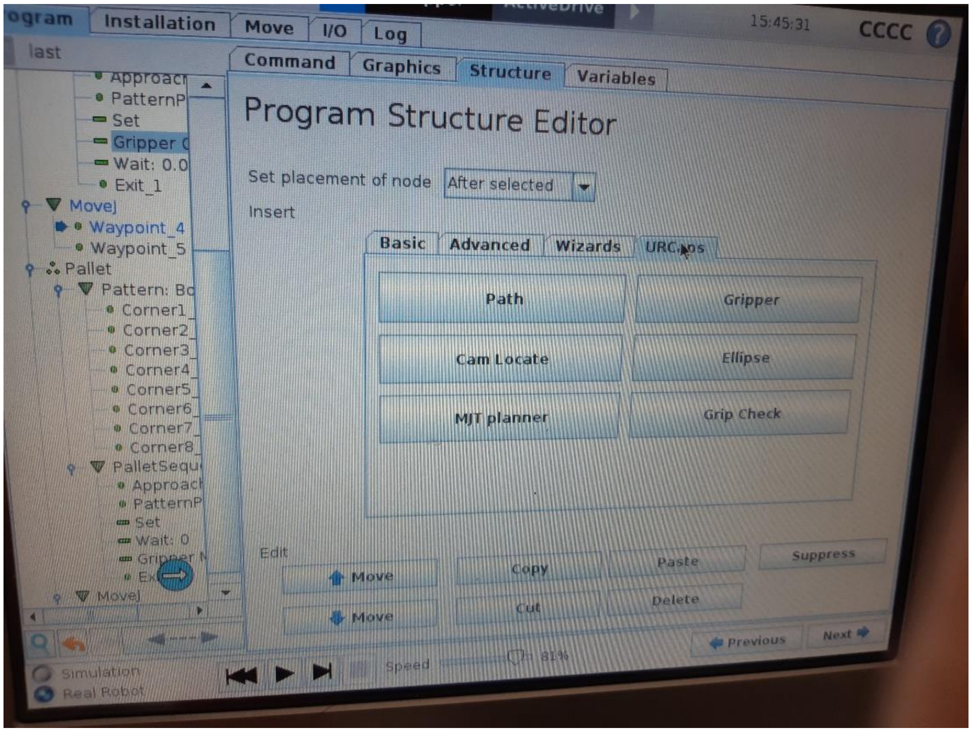

Figure 36. UR10 Program Structure Editor – URCaps

Figure 37. Selection of the Gripper Action

The video of the palletizing demo was displayed in oral presentation of the project.

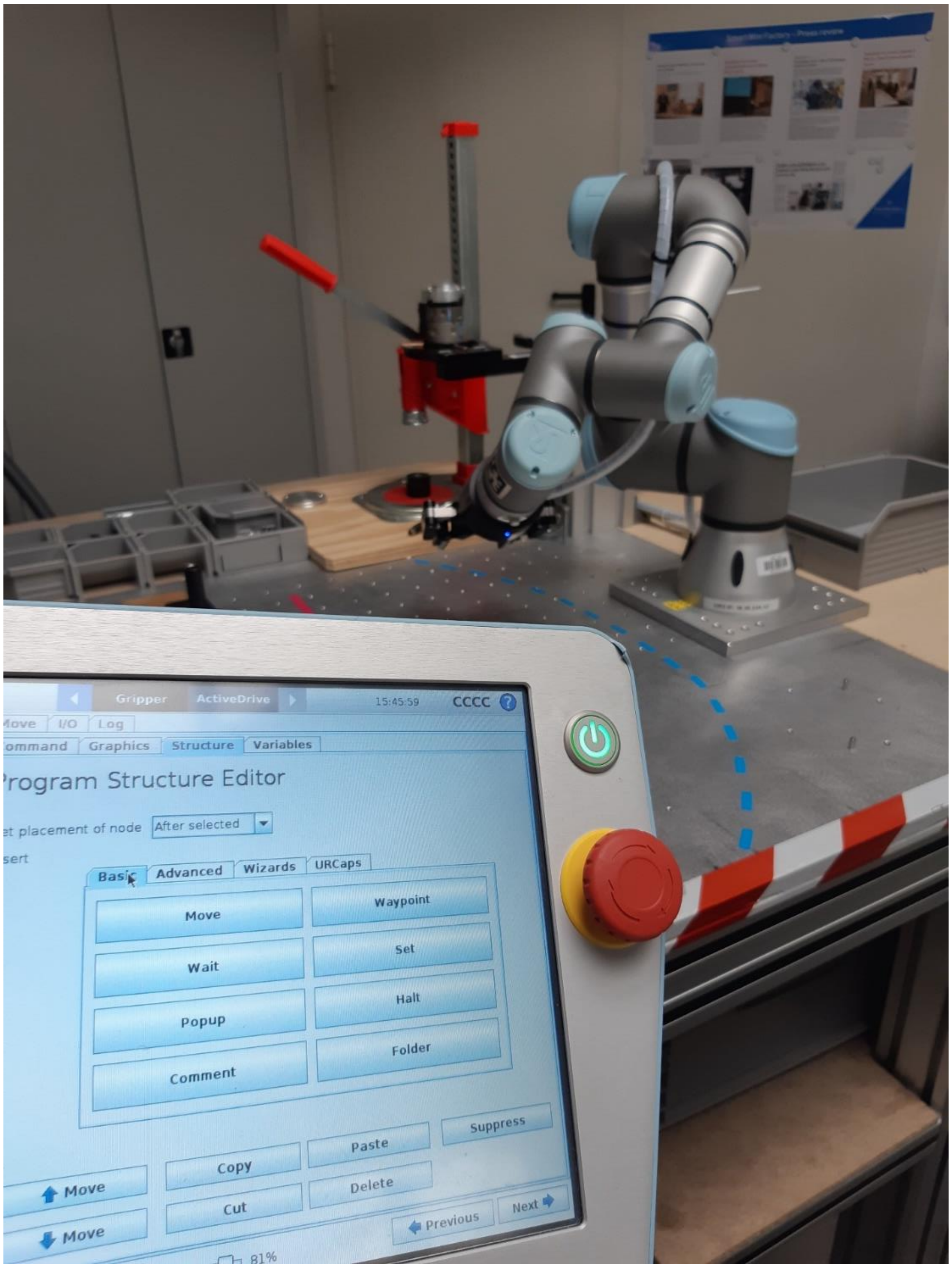

Figure 38. Programming a Universal Robot

5. Conclusions

The development and implementing of a hybrid assembly concept that integrates a flexible linear transfer system should consider and analyze a set of diverse factors such as workspace, workforce and industrial and collaborative robots. The addition of the workspace of the robots is fundamental for the design of a layout that maximizes the given space, minimizes the probability of collisions between robots and enables flexibility.

Likewise, the safety of workers must be ensured since the hybrid assembly includes industrial robots that do not stop themselves as collaborative robots do when they impact on the human body. For that reason, light curtains were selected, thanks to their capacity to rapidly detect the presence of any part of the body of the operator or visitor, besides the fact that they do not disturb the visualization of the processes of the system, what is important for teaching purposes. The use of safety standards to define the minimum safety distance for the positioning of the safeguards is crucial to prevent any accident that could harm people.

Finally, it is also important to evaluate the suitability of the robots for the tasks that were assigned to them. In the case of the project, the suitability of the UR10 and its support for palletizing purposes were analyzed through mathematical calculations. This analysis corroborates that the support is suitable in any static situation. However, there are certain values for linear and angular acceleration that must not exceed the limits established in the present study.

6. References

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