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Author	TEKNIKER,AYCN
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Abstract	Summary of the tests developed to assess the results achieved during the first 24 months of the project.

Document History			
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1.0	07.09.2012	Version submitted to EU	TEKNIKER

Content

1 List of figures and tables

1.1 Figures

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2 Introduction

According to the roadmap defined in deliverable D1.2, Chapter 6, the evaluation process was divided into three different steps that had to be reported in the following deliverables:

D5.1 Basic pilot implementation and evaluation

Object of evaluation and responsible

- Individual operations:
  - Milling (QDESIGN), roughing (CNR-ITIA), gluing (QDESIGN)
  - Inking (AYCN, INESCOP), polishing(AYCN, INESCOP)
- Other operations:
  - Visual inspection (TEKNIKER)
  - Last pose identification (TEKNIKER)
- Component evaluation
  - Last manipulation (ROBOTNIK)
  - OFF-Line Programming (INESCOP)
  - OFF-path adjustment (CNR-ITIA)
  - On-line path adjustment in roughing CNR-ITIA)

Deadline

Month 18: February 2012

D5.2 Intermediate pilot implementation and evaluation

Object of evaluation and responsible

- Individual operations:
  - Last removal (AYCN)
- Combined operations:
  - Roughing+gluing (QDESIGN, CNR-ITIA)
  - Inking+polishing+last removal(AYCN, INESCOP)
- Component evaluation
  - Safety (CNR-ITIA)
  -

Deadline

Month 24: August 2012

D5.3 Final pilot implementation and evaluation

Object of evaluation and responsible

- Individual operations:
  - Packaging (QDESIGN)
- Component evaluation
  - Manual guidance (COMAU, TEKNIKER)
- Component evaluation
  - Shoe manipulation (ROBOTNIK, DFKI)
  - Visual inspection: shoe identification (TEKNIKER)
- System evaluation
  - Manufacturing metrics (TEKNIKER, QDESIGN/ROTTA, AYCN/PIKOLINOS)

   - Easy to use and maintain (TEKNIKER)

Deadline

Month 30: February 2013

However the first two deliverables have been merged into one (this document) as the real implementation has not followed a clear division into individual and combined operations.

In this document we report the evaluation both at operation level and at component level. In the both cases the scheme is:

- Short introduction: the operation or the object of evaluation
- Evaluation: Test description and results

As it is explained in the corresponding chapter, some evaluations have been reported in the technical deliverables and some others will be finally reported in D5.3.

3 Single operations

3.1 Last Milling

3.1.1 Operation introduction

Last milling is an auxiliary operation that was selected by the consortium to allow shoemakers to have a last prototype very quickly, using the robot used in roughing during idle periods (at night, for instance). The mass production of lasts will remain being made by conventional means.

The proposed solution for Robotized Last milling (described in D2.2) is as follows:

- There is a workstation where there is an spherical tool mounted in a spindle.
- The workpiece is hold by a gripper attached to the flange of the robot.
- The robot has to move the workpiece following the trajectory generated by a CAM software to obtain the desired shape (the last).
- Robomove software is used to control the robot variables (pose, positioning of the part/tool in the cell), to simulate the behaviour of the robot and check for collision/unreachable points in trajectory and to convert the NC file in a runnable program in the robot, in our case in PDL2 language.
- The QDHMI software is the Human Machine Interface which allows managing the files generated by Robomove and to send them to the robot in a piece-wise fashion in order to not saturate robot’s memory.

Below some drawings of the layout of the cell:

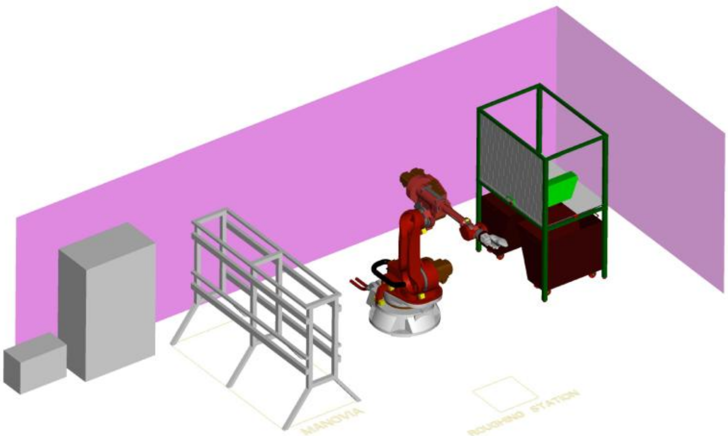


Fig. 1 Last Milling cell layout, 3D

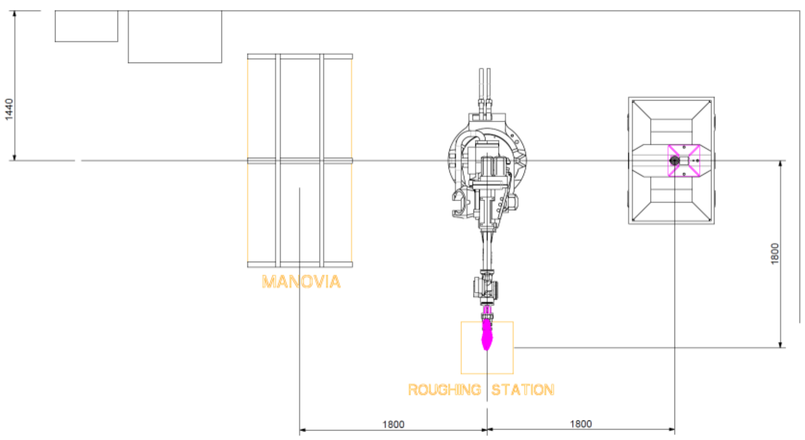


Fig. 2 Last Milling cell layout, drawings

3.1.2 Evaluation

All programs were executed with a tool of ∅20mm, feed rate 3000mm/min (theoretical) and passes of 1.5mm depth.

The main parameters in this milling application are the milling *time* and the *quality* of the geometries and surfaces of the last obtained.

Time

It is the amount of time required to mill one single last (left or right) starting from the raw material. The process consists in the following 4 steps:

1. roughing of the first half;
2. roughing of the second half;
3. finishing of the first half;
4. finishing of the second half.

The order of the last two operations may be the reverse in order to save time in the rotation of the shoe. Some models of shoe, may require some other finishing phases if, for some reason, it's more convenient using a separate finishing program for the bottom of the workpiece.

We assume that the grasping device is already attached to the workpiece, i.e., the time required for this operation has not been taken into account.

Roughing programs are the most time critical in the whole milling operation: while in finishing programs, the CAM should know how much material has to cut, in roughing operation this information may be not available or not reliable. Of course it is possible to do a 3D scan of the raw piece, but it is time consuming as well and the mounting of the grasping device may introduce each time a little angular difference, and this may become a large linear difference in the tip of the shoe (>3mm). If the tool encounters more material than expected, the robot may lose the trajectory and both the spindle and the robot have to support a heavy stress.

One solution is to virtually scale the raw piece of a small positive amount: in this way the tool will not be in touch with the raw material in the first steps, this will compensate small mismatches form real raw piece and the model used in CAM. However, the roughing program will result longer, and the tool may perform some passes in the void.

Depth of the pass, the radius of the tool and the feed rate (speed) are other important parameters in this process. The smaller depth of each pass and radius of the tool, the finer quality of the surfaces is. But if the passes are closer and the tool is smaller, the execution time will be longer as more passes will be required.

On the other hand, if the speed is high, this will generate more vibrations and side effects in the dynamic of the robot.

We summarize some results in the following table:

Operation\Size	37	44
Roughing first half	12’	11’
Roughing second half	12’	11’
Finishing first half	10’	11’
Finishing first half	10’	11’
Total	44’	44’

Table 1: Roughing and finishing milling operations, time required

Quality

The geometrical quality of the finished pieces depends on many factors:

- accuracy of the robot;
- dynamic of the robot;
- accuracy in the measurement of the TCP;
- repeatability of the grasping device;
- feed rate of the tool, RPM of the spindle, depth of pass and other tradeoffs on technological parameters;
- quality and status of the tool.

In the following images, there are some measurements taken on a finished workpiece (size 37):

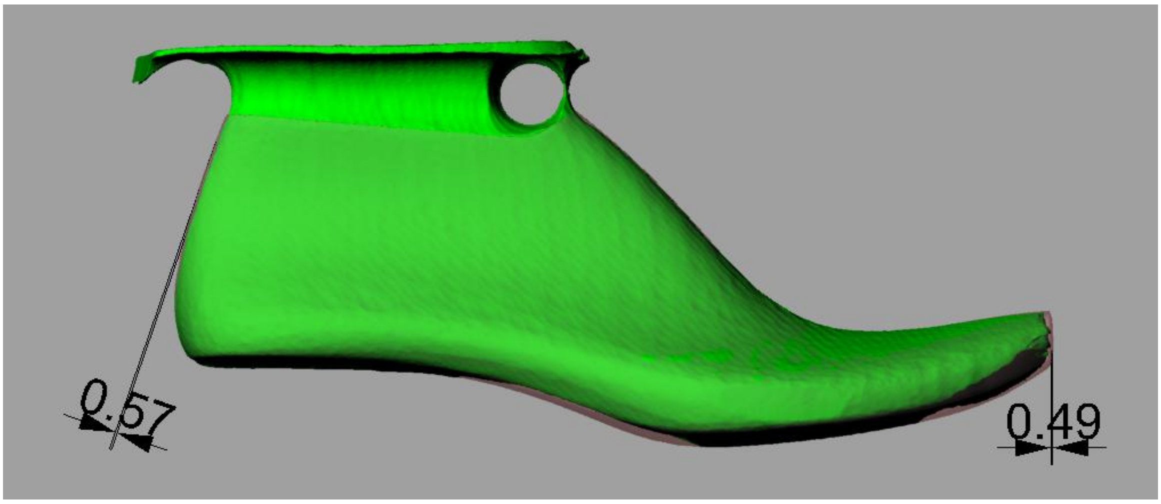


Fig. 3 Scanned milling last, dimensional errors

The green shape is an acquisition of the finished part taken with an optical 3D scanner (Manufacturer: Open Technologies; model: Optical revenge; serial num: Opterev 000055). The pink transparent shape is the original STL file, used as source in CAM. The fixture in the upper part of milled part was not cut.

In **Fig. 3** it is possible to appreciate that the whole length of the shoe is good, there is a small error in the back of about 0.57mm. The tip of the shoe presents some bumps, because there was little material here and the tool created some vibrations. The difference with the model is below 0.5mm the maximum admissible.

In **Fig. 4** and **Fig. 5** it is presented a comparison between the scanned mesh of the milled part and the 3D source model. The different colours represent the deviation from the model:

- dark blue 0mm;
- green 1mm;
- yellow 2mm;
- orange 3mm;
- red >4mm.

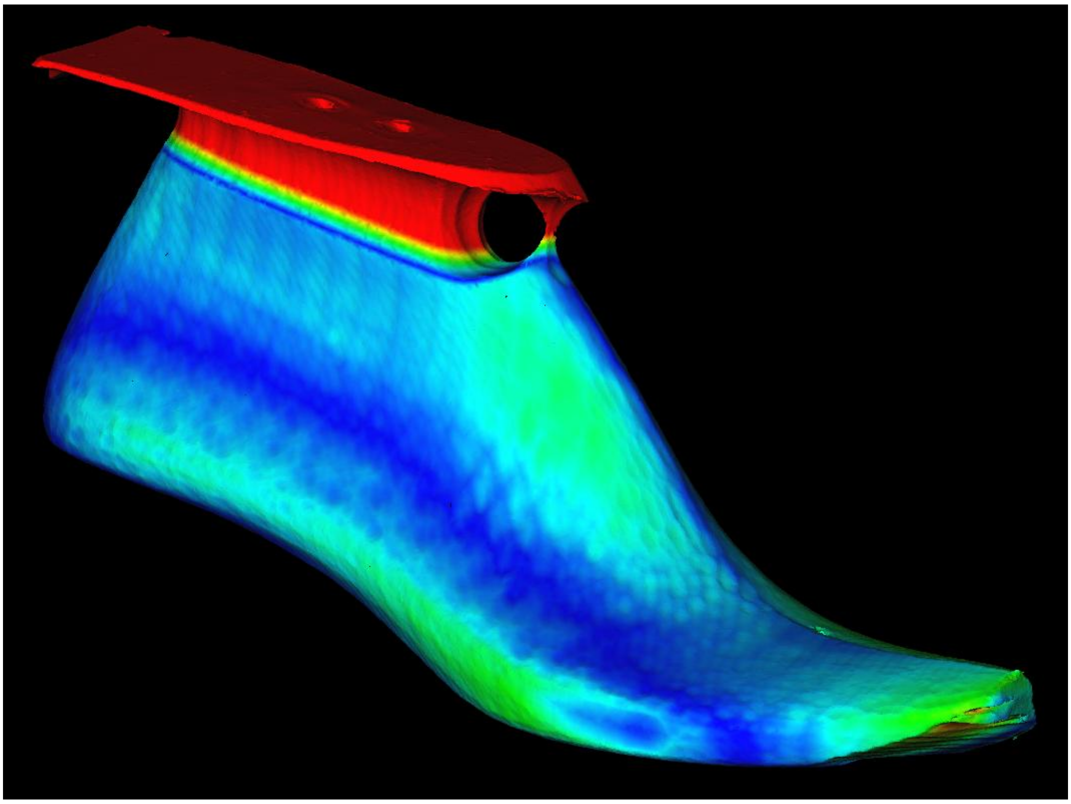


Fig. 4 Scanned milling last, cloud of dimensional errors (right)

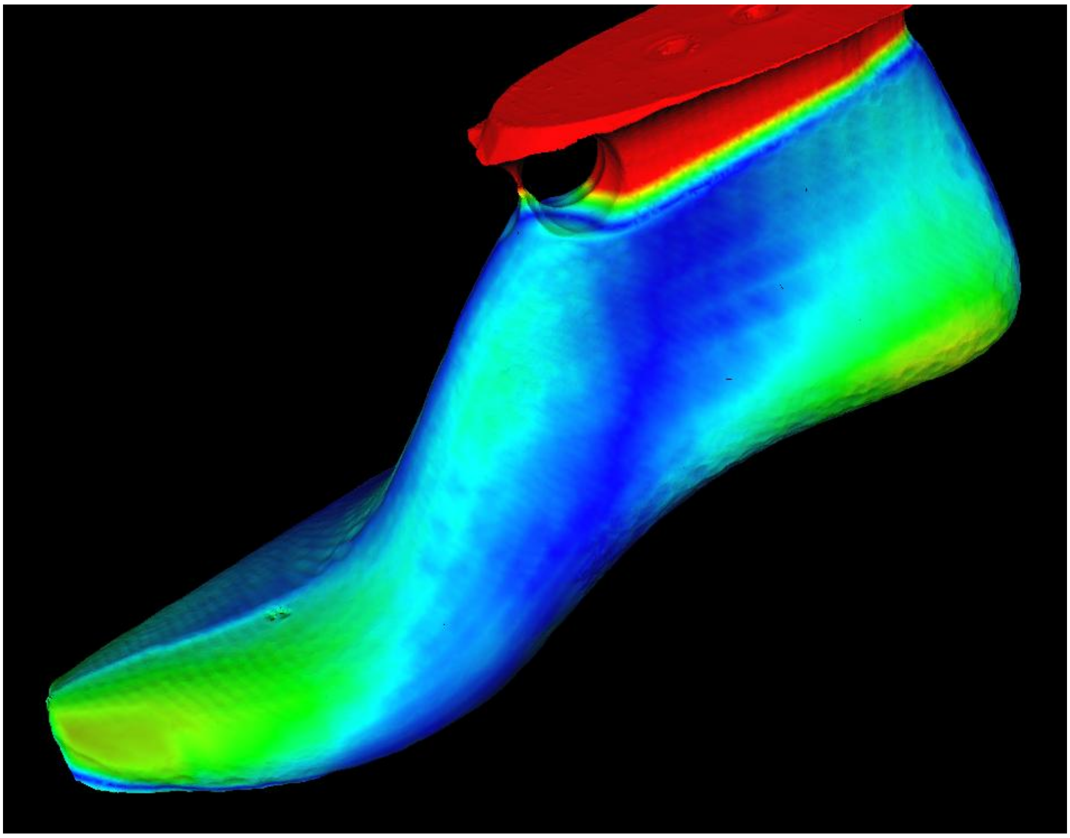


Fig. 5 Scanned milling last, cloud of dimensional errors (left)

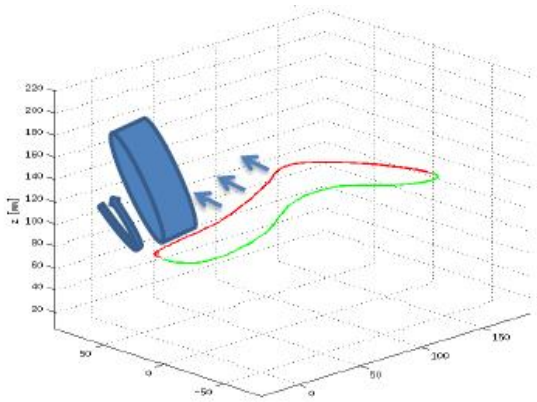
In the last picture it is possible to see the line where the two finishing programs overlap. The tip of the shoe presents more deviation from the model due to the fact that in the tip the force of the tool is applied on a longer arm, so there is a flexion of the material. The other factor is that the measured TCP of the tool was slightly shorter than the real length, so more material has been cut.

3.2 Roughing

3.2.1 Description

A special machine was designed for roughing operations. The main objective was to install a force sensor for closing a force control loop during roughing operations (see Deliverable D4.3 “Advanced sensor based robot control Solutions” and D2.2 “Engineered solution for Robot assisted footwear manufacturing”).

(a) Roughing Station



(b) Robot and Roughing Station @ ITIA's labs

(c) Direction of rotation of the tool with repsect to the execution path

Fig. 6 Intermediate Roughing Prototype

The robot has to perform a 6-axes interpolated trajectory, and a control strategy has been developed in order to deviate from the nominal path in order to guarantee a correct control of the interaction force between the shoe (mounted on the end-effector) and the tool (fixed to the ground). Control strategy is described in D4.3.

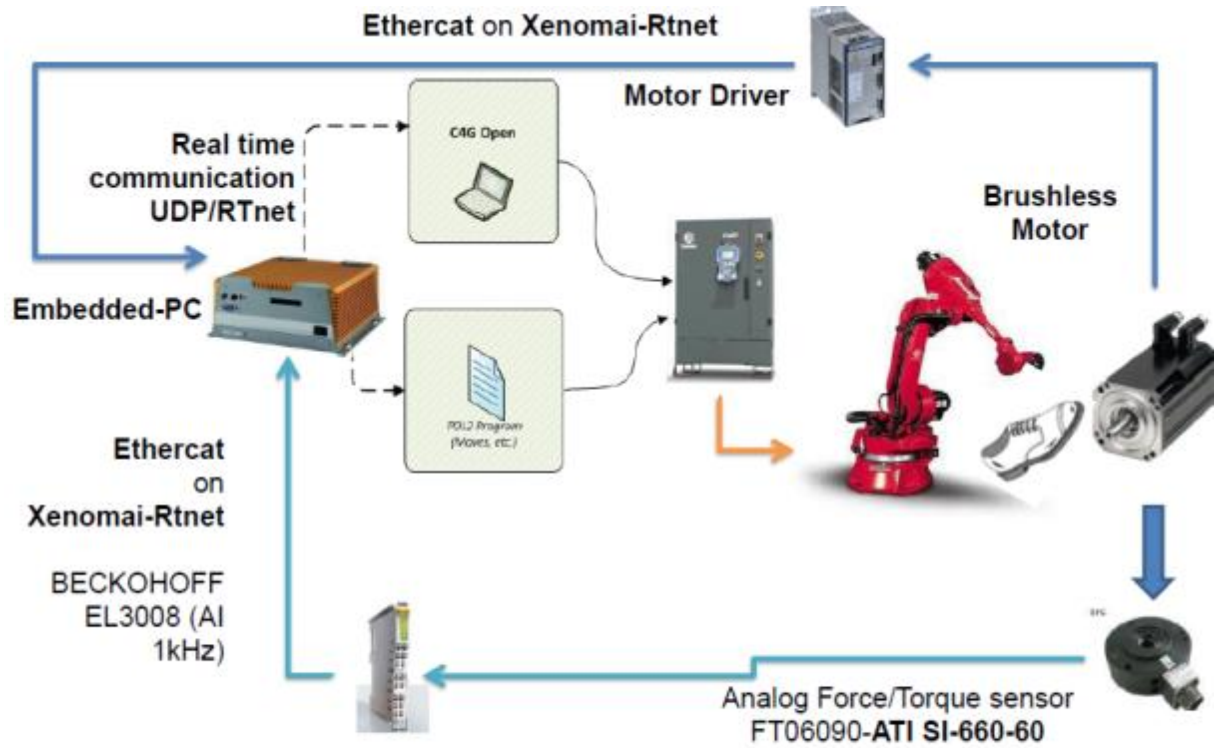
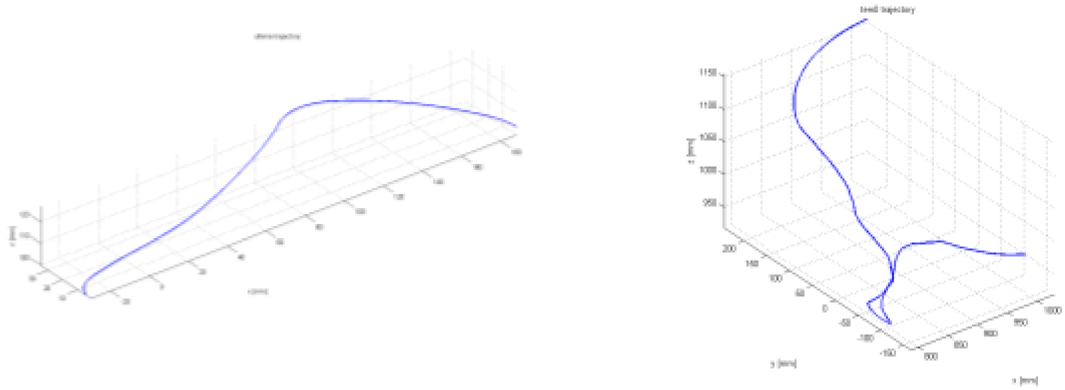


Fig. 7 Schema of the set-up

It is worth underlining that the interpolation of the motion is done by the COMAU robot controller (the standard interpolator is used) and the embedded PC modify the trajectory by imposing a deviation each instant time (500 Hz).

First experiments have been performed on samples given by ROTTA and depicted in Figure below.

Fig. 8 Sample Shoe for first-roughing experiment



(a) Trajectory of the tool on the shoe (shoe is moving and tool is fix)

(b) trajectory of the flange centre

Fig. 9 Executed Path

The roughing of this kind of shoes is challenging since:

- Extremely soft-leather imposes an extremely accurate force control;
- The trajectory is characterized by a hard 6-axes interpolation for the robot since the curvature of the sole is extremely variable. Furthermore, in order to follow the imposed trajectory the robot has to pass through the wrist singular configuration.

3.2.2 Evaluation

Fig. 10 Unsatisfactory roughing results

Experiment didn't achieve satisfactory results due to the integral behaviour of the C4Gopen modality 7.

In detail, the C4Gopen communication channel sends two set of data to the external PC:

- The set-point of the internal interpolator (at motor level);
- The actual position of the robot (at motor level);

The modality 7 used in the experiment provides an integral behaviour, that is, the deviation imposed in the previous step is maintained also in the next steps.

Hence, **the set-point sent by the robot interpolator to the external PC is the nominal point calculated by the robot interpolator at that instant plus the deviation of the previous instant time. As a consequence, the external PC has none information about the nominal trajectory.**

The deviations to the motors velocities are imposed by the external PC at 500 Hz, and they are sent to the internal robot micro-interpolator that runs at 2 kHz. The micro-interpolator applies to the deviations a low-pass filter at low frequency.

This micro-interpolation step implies that the deviation imposed is slightly modified, and as a consequence, if the external PC imposes a deviation after a time, and it subtracts the same quantity at the following step, the robot does not come in the nominal path, but a little deviation is still present.

In order to overcome this problem, an interpolator has been developed also in the external PC, and a heuristic algorithm tries to identify at each instant time what should be the nominal position on the nominal path on the basis of the information received from the C4Gopen channel.

Unfortunately, the heuristic algorithm does not performs correctly when deviation is quite fast (around 10 mm/s) and the deviation is more than 5 mm.

Due to these limitations, the consortium agrees that modality 7 of the C4Gopen does not fit the application requirement, and a new modality will be integrated in the final prototype.

The new idea consists on using the modality 4 of the C4Gopen. In this modality the motion interpolator is in charge of the external PC, and the robot interpolator is not used.

The results of this new approach will be reported in D5.3

3.3 Gluing

The operation has not been implemented yet. From the technological and robotic point of view the process is similar to the inking operation, so we considerer that the results obtained in inking can be extrapolated to gluing.

If finally ROTTA purchases the inking machine in the timeframe of the project, the evaluation will be performed for the sake of confirmation of that hypothesis, and reported in D5.3.

3.4 Inking

3.4.1 Description

The inking process is done by means of a conventional cabinet, inside of which, an spraying gun has been implemented. This gun can be controlled by means of digital signals from the robot controller.

The process is done by moving the shoe around the gun following the trajectory created using BasicCAM.

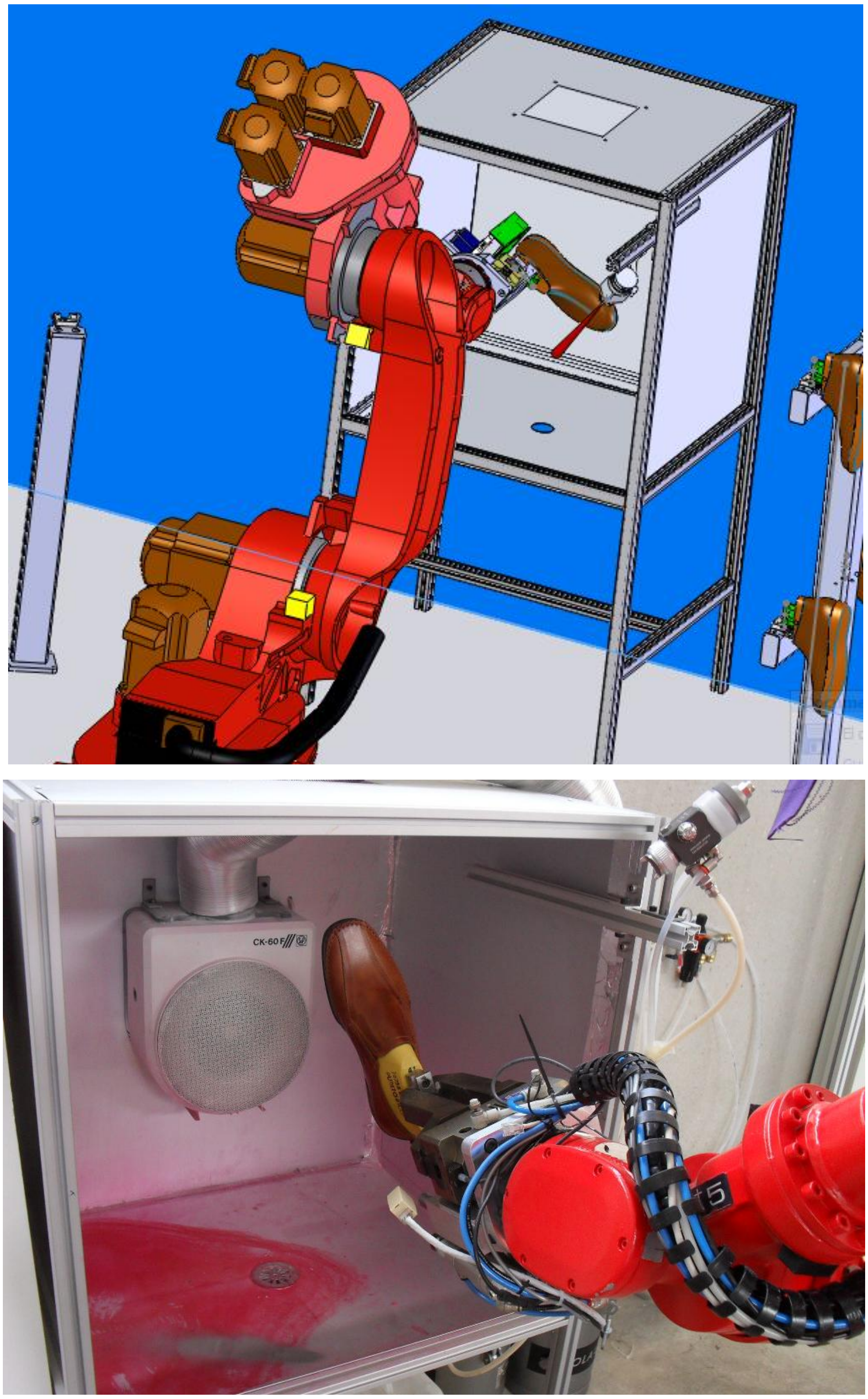


Fig. 11: Inking process

3.4.2 Evaluation

After discussing with shoemaker experts it was decided that it was not possible to evaluate the inking and polishing operations as isolated operations; on the contrary they considered that it was important to evaluate the final result after the completion of both operations. This combined evaluation can be found in Section 4.2.

3.5 Polishing

3.5.1 Description

The polishing process is done using a conventional polishing machine. The machine is equipped with an inverter to control the velocity according to the features of the shoe.

The robot moves the shoe on the rollers (first on the right roller later on the left one) following the path calculated in the CAM.

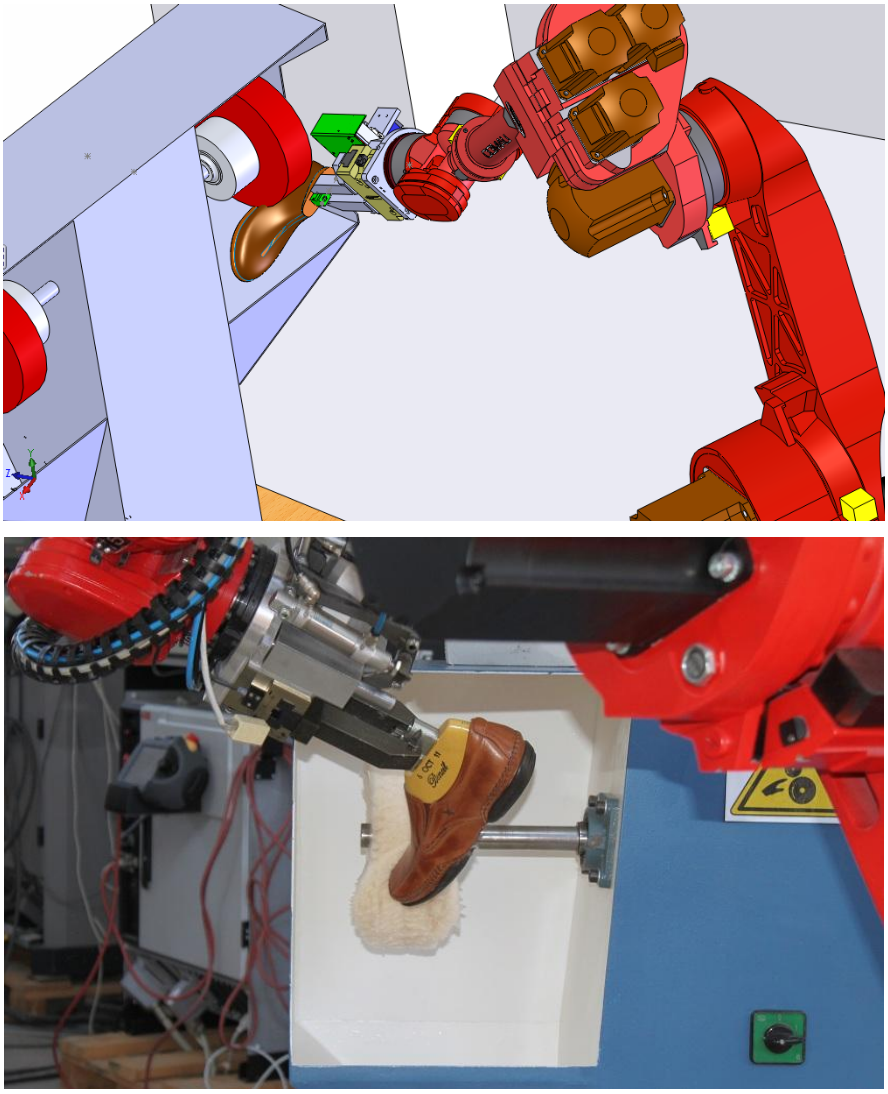


Fig. 12: Polishing process

Due to the constraints introduced by the fences of the standard machine a specific polishing machine has been designed and developed for the SIMAC demonstrator fair, as it is reported in D6.1.

3.5.2 Evaluation

As explained in the case of inking, after discussing with shoemaker experts it was decided that it was not possible to evaluate the inking and polishing operations as isolated operations; on the contrary they considered that it was important to evaluate the final result after the completion of both operations. This combined evaluation can be found in section 4.2.

3.6 Visual inspection

The evaluation of the visual inspection system has been included in D2.4.

3.7 Last opening

3.7.1 Description

To remove the shoe from the last it is completely necessary to open it. In previous deliverables it was already reported that operators have to exert around 30kg of force to do this operation. ROBOFOOT proposes using the robot and an auxiliary station that has been designed by AYCN (see pictures below) to do this operation.

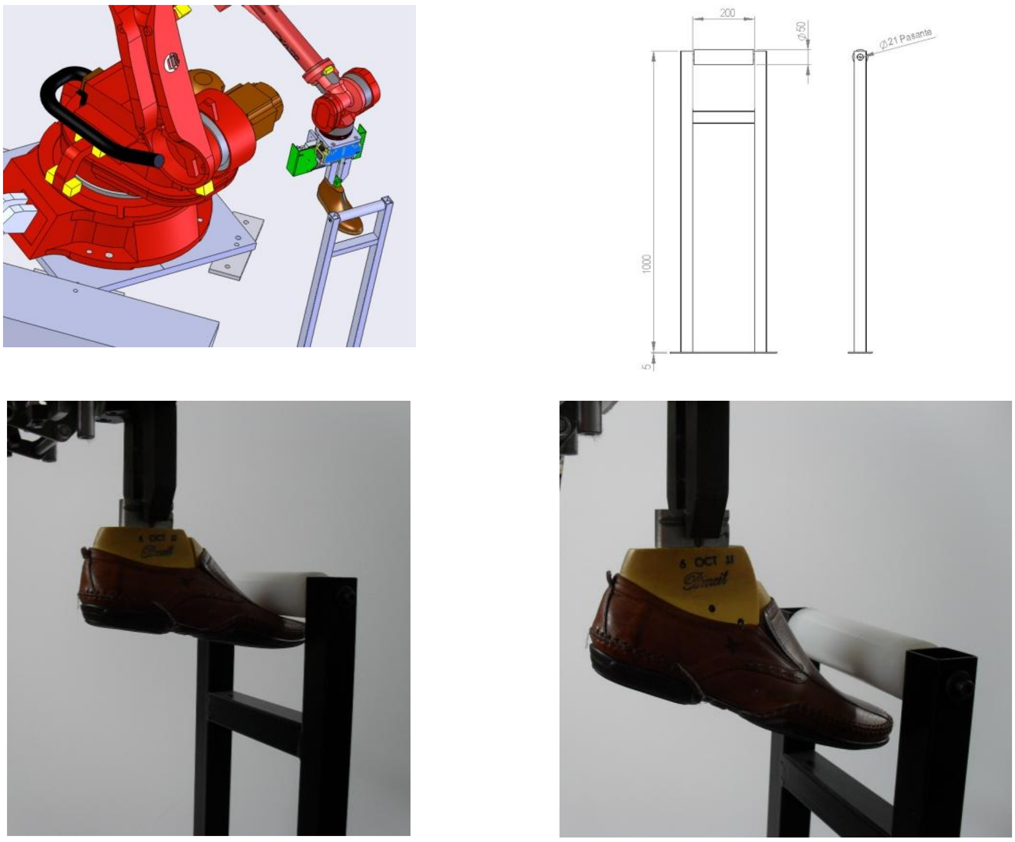


Fig. 13: Last opening station and operation

Once the last has been open, the robot leaves the open last (with the shoe) on a conveyor. An operator is in charge of removing the shoe from the last.

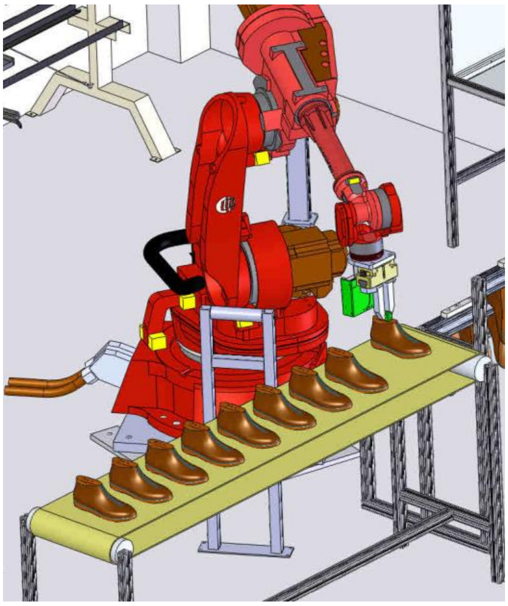


Fig. 14: Leaving the open last on the conveyor

3.7.2 Evaluation

Two features have been assessed in the cell set-up at INESCOP facilities:

- Force applied
- Damages on the leather

No specific experiment has been carried out for this evaluation, but as for the testing of the rest of operations in this cell (inking and polishing) multiple (several hundred) cycles have been done, we can consider the results valid. These results can be summarized in:

- The force applied has **never** been higher than the maximum allowed by the robot controller
- The leather of the shoes has not suffered any damage at all

4 Combined operations

4.1 Roughing & gluing

The combined evaluation has not been carried out for the reasons explained before.

4.2 Inking & Polishing & last removal

4.2.1 Description

The initial prototype of this combined cell has been implemented at INESCOP facilities for tuning and experimentation.

The individual operations have been already explained. They have been integrated in the cell presented in next picture.

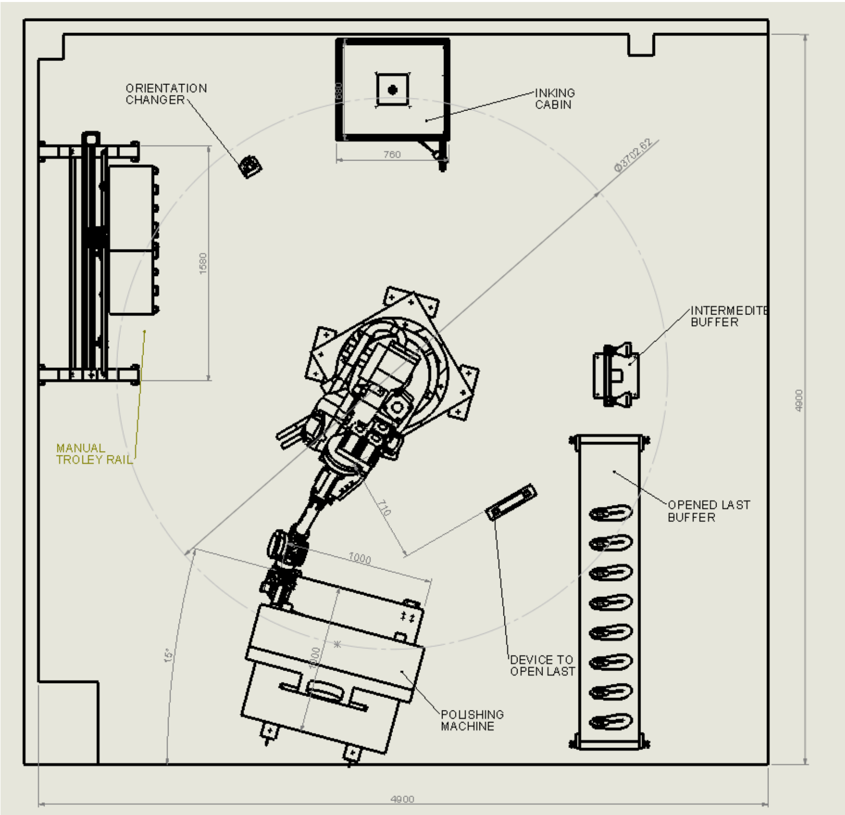


Fig. 15: Combined operations layout set-up at INESCOP: 2D drawing

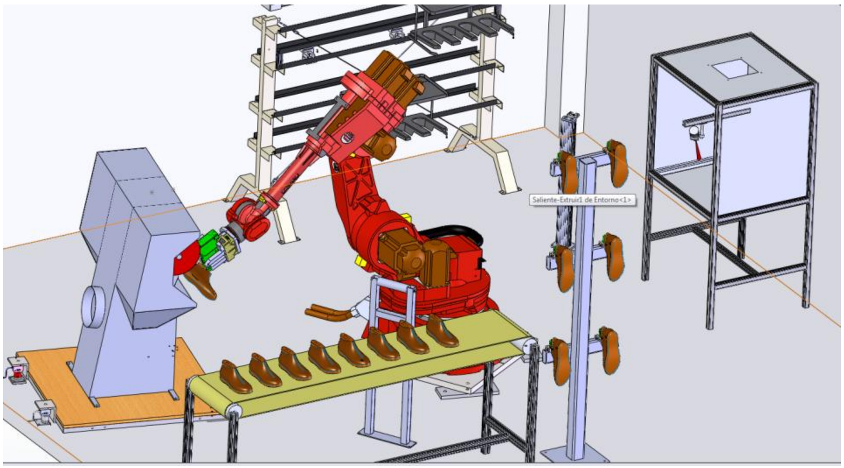
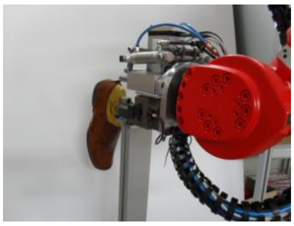


Fig. 16: Combined operations layout set-up at INESCOP: 3D drawing

The sequence of operations is the following:

1- Shoe Grasping from the Manovia • The robot performs the visual servoing procedure to identify the pose of the last • The robot takes the shoe from the manovia		
2-Grasping orientation change • The robot goes to the rotating station • Leaves the last • Rotates the wrist • Takes the last (90º) from the station		
3-Inking operation		

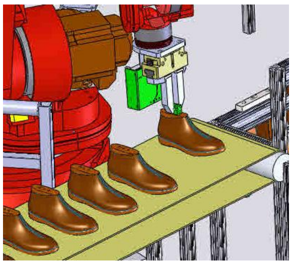
4-Ink Drying • The robot leaves the inked shoe in one of the free positions in the buffer • After a period of time (around 8 minutes) it takes the last again to carry out the polishing operation		
5-Polishing		
6-Last opening		

Table 2: Sequence of operations: inking / polishing / last removal

4.2.2 Evaluation

Two different features have been analyzed:

- Time employed
- Quality of the operations

4.2.2.1Time employed

It was measured the time employed by an expert operator at PIKOLINOS facilities with the time employed by the robot in doing the same process at INESCOP.

It has to be taken into account that in the case of robotized operations there are some manipulations that are not present when the operations are done by human operators.

Inking / Polishing / Last opening		
Operation	**Time**	
Taking the shoe from the manovia	5	
Grasping orientation change	10	
Inking	**11**	
Subotal inking		26
Placement on the buffer	20	
Drying in the Buffer	11	
Subotal drying		31
	Tiempo	
To move to the polisher	3	
Polishing (I)	**10**	
Polishing (I), front part	**10**	
To move to the second roller	5	
Final polishing (II)	**10**	
Final polishing (II), front part	**11**	
Subotal polishing		49
Last opening	9	
Leaving on the conveyor	3	
Subotal last opening		12

Table 3: Time employed in the robotic cell: inking / polishing / last removal

On the other hand, the mean time of key operations when done by expert operator was:

- Inking: 9s (24s)
- Polishing: 26s (49s)

The difference is high; however, it seems that there is room for improvement that can be achieved by several means:

- Improving the inking process: nowadays the spraying seems to be too much directional; a 'rough' spraying, opening the gun may reduce the process significantly.
- Increasing the speed of the movements of the robot when going from one station to other
- Increasing the movements of the polishing operation: the fences introduce a constraint in the speed of the operation.
- The mechanism to leave the shoe in the buffer positions and the grasping rotation station can be re-designed to make it faster if finally this time cannot be reduced by tuning the program.

4.2.2.2Quality of the operation

To assess the quality of the operation the following experiment was carried out.

Description of the experiment

- 26 pairs of shoes were used in the experiment:
  - 13 pairs were inked and polished at INESCOP facilities in the robotized cell, using the ROBOFOOT system

- 13 pairs were introduced in the production line of PIKOLINOS and were inked and polished by human operators
- It is important to emphasize that operators were not informed about the experiment
- All pairs were taken to PIKOLINOS plant:
  - The pairs were labeled with a random number.
  - The pairs were randomly put in order on a shelf
- Three persons belonging to PIKOLINOS' staff take part in the evaluation of the quality of the inking+polishing of the 26 pairs.
  - The evaluators did not know if the shoe was operated at PIKOLINOS (human operator) or at INESCOP (robot)
  - Each 'inspector' did the evaluation without knowing the result of the evaluation of the others
- The three inspectors were:
  - An skilled operator
  - Quality manager at VABENE plant
  - Quality manager of PIKOLINOS Group
- Inspectors had to classify the shoes as:
  - Correct
  - Average
  - Bad
- In case of Average or Bad classification, inspector had to explain 'why'
- During the evaluation, a person from TEKNIKER reported the results and comments in a form

Fig. 17: Inspector analysing the shoes and experiment reporteur

<u>Results achieved</u>

After the experiment, it was decided to group the shoes classified as BAD and AVERAGE in the same group, as the limits between both was difficult to establish by the inspectors and in all cases the shoes were going to be reworked in the same way (after that, they can be delivered to customers without any problem).

The results achieved are shown in the next table:

		PIKOLINOS Quality Manager		VABENE Quality Manager		Skilled Worker		Majority	
		Items	%	Items	%	Items	%	Items	%
INESCOP	GOOD	8	31%	6	23%	16	62%	8	31%
	BAD	18	69%	20	77%	10	38%	18	69%
	Total	26		26		26		26	
PIKOLINOS	GOOD	14	54%	14	54%	12	46%	14	54%
	BAD	12	46%	12	46%	14	54%	12	46%
	Total	26		26		26		26	

Table 4: Experiment results to assess the quality in inking / polishing

Some comments:

- The ‘majority’ column has to be understood as the score provided by the majority of the three inspectors that evaluated each shoe.
- The results of both quality managers (PIKOLINOS and VABENE) is similar and rather different from the score given by the operator
- This last inspector, the operator, scored better those shoes worked by the robot
- The coincidence between the majority and Inspector 1 is just by chance. In fact 22 times there were such a coincidence and 4 times not
- In ALL shoes classified as BAD the reason was the excess of ink. This seems very easy to correct and might be related with the size of the open flow used during the experiment that is also one of the reasons of the amount of time employed

In summary, we consider that the quality achieved is satisfactory (after some minor adjustments).

5 Component evaluation

5.1 Visual servoing: last pose identification

5.1.1 Description

It has been already explained in different deliverables that with the objective of not modifying the existing production means, it was decided to develop a system that allowed identifying the pose of the last in the manovia. To achieve it, a visual servoing system has been developed.

Details of this system can be found in D4.2 and D4.3 as well as the performance achieve with the system.

Besides that, and additional evaluation process has been carried out to assess the robustness of the system. This evaluation took place during the industrial trade fair on Machine-tools, BIEMH12, that was held in Bilbao from 28th May to 2nd June. This is the most important industrial fair in Spain.

During the fair a simplified ROBOFOOT prototype has been set up by TEKNIKER. The components of this prototype were:

- COMAU robot
- A segment of manovia with a trolley where 2 pairs of shoes were placed
- The visual servoing system
- A visual inspection station
- A polisher.

Fig. 18: Prototype presented during BIEMH12

During the fair, the robot had to identify the pose of the last using the visual servoing system, grasp the last, and finally to take it to the inspection station and the polisher to perform the operations.

5.1.2 Evaluation

The performance is explained in D4.3 and its Annex I of this document. Besides that, the system has been tested during the whole duration of the above mentioned trade fair: six days, 8 hours per day (a total of 48 hours). Taking into account the context of the fair, the system (including the visual servoing part) has not been used with the full speed of the robot like in the experiments carried out in TEKNIKER (explained in D4.3), therefore the process time are not relevant. What is worth emphasizing is that around 1000 complete cycles of the process were completed and the visual servoing system achieved a 100% of success (pose correctly identified) during the fair.

On the other hand, it is important to say that the system has been setup in a very simple way, only changing the robot frame, without changing either visual parameter or code line.

5.2 Last manipulation

5.2.1 Description

As described in chapter 6.1.1 of D1.2, two different categories have been considered:

- Manipulation of the last.
- *Manipulation of the shoe (without last).*

In this deliverable it is explained the evaluation of the first category, while the second one will be reported in D5.3.

Also in chapter 6.1.1 of D1.2, three different tests were scheduled:

a) Pick: To measure the picking process two benchmarks proposed in EURON[1] for Visual Servoing were used as well as another one related with the accuracy:

- The capability of grasping (pass/fail). Several tries had to be done placing the shoe in the pick area with different positions and orientations. The difference between these positions/orientations and the theoretical picking point will be the same that in a normal manufacturing process, that it is expected to be of a few millimetres/angular degrees.
- Time and computational cost. The seconds elapsed in the whole picking process are measured as well as the computational cost of the position corrections.
- Position/orientation repeatability. Once the robot moves the Last to the Measurement place, position and orientation are measured. To measure this position error, the lasts used for the tests has calibrated surfaces, so the measure is done by dial gauge touching the surfaces, what is evaluated is the deviation between the different measures. This resulting repeatability will include the error due to robot repeatability in the related work area. To measure the orientation error a Laser pointer is attached to a Last so it points to a perpendicular surface, this surface has a 1mm square grid so it is possible to mark the deviations between different measures.

b) Hold: The grasped Last is moved in different directions with high accelerations rates. After a set of movements the Last is returned to Measurement Place again to check the position and orientation.

c) Operation: It is also necessary to measure the impact of the different operations in the holding process. To this end different forces and torques, equivalent to the one applied in the different operations selected, will be applied to the last grasped by the robot. This test will measure the stiffness of the grasping when forces are applied in the last.

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1 http://www.robot.uji.es/EURON/en/visual.htm

Additionally to those described in D1.2, a new test has been considered:

d) Last opening: At the moment of the redaction of D1.2 it was not decided if this process was performed by the robot. This is the operation that considerably produces more effort in the Last/Gripper joint and the repeatability is not important because after Last removal the shoe is released, so it is tested apart from test c). It is a pass/fail test consisting on opening different Lasts and see that they are correctly opened and not released from the gripper. See chapter 1.9 Last removal for further details.

5.2.2 Evaluation

Test A: pick

The evaluation of Pick pass/fail test and the time consumed in the pick operation is detailed in chapter 5.1.

To measure the Repeatability, the values are calculated according to UNE-EN ISO 9283 [ref]:

- Being *n* measurements called Value(x)
- It is obtained the average value AVG of all the measurements:
  AVG = Average(Value(0-n))
- All the errors are obtained as Error(x) = (value(x) – AVG)
- Repeatability = Average(Error(0-n)) +3*Stdev(Error(0-n)))

Fig. 19: Test Desk

Fig. 20: Repeatability test using the dial gauge

The Repeatability of the grasping system was done in the Test Desk (see picture **Fig. 19**). The laser pointer attached to the Last was projected in a perpendicular surface at a distance of 4012 mm, so a difference of 4 mm between two measures means:

angle_error = asin(4 / 4012) = 0,06º

After 10 measures the average error was 0,028 and the standard deviation 0,026, i.e. the **repeatability was 0.11º**.
The Test Desk did not allow a reliable measurement with the Dial Gauge.
With the test in the robot the Dial Gauge deviations were around the resolution of the device (0,025mm), the repeatability obtained was 0,022mm, better than robot repeatability.
The angle measurement was made with 2 laser pointers attached to the Last in the robot, at a distance of 1305mm to the first surface (floor) and 2960 to the second one (wall). The worst angle result is result was a repeatability of 0,038º

Fig. 21: Projection of the laser on the square grid surfaces

<u>Test B: hold</u>

Holding test was performed using the same measurement positions and the repeatability achieved was equal than in previous test.

<u>Test C: operation</u>

Last was pulled with a dynamometer from the toe and then measured the angle, resulting a permanent deformation in the range of the previously measured repeatability. In a Second test the Laser was pulled again and the Laser deviation was measured in the instant of maximum force applied (around 4-5 Kgf), the resulting values provide an idea of stiffness of the system.
The minimum values of stiffness for every axis were:

Axis	Kg	angle deviation	Force/angle
z	4.5	0.3512340953	125.68540636
y	4	0.2195229853	178.75121347
x	4.3	0.1756186976	240.19651998

Table 5: Minimum values of stiffness for every axis

They include the elasticity of the robot, the gripper and the Last. In a worst case scenario, when receiving a vertical force of 2Kg during an operation, the toe of the shoe (assuming a length of 250mm) will be 0,66mm away of its calculated position due to system elasticity.

5.3 Off-line Programming

One of the problems that we found, and that the virtual simulation could not fully resolve was that simulations can provide lots of information about axis dynamics, collisions, etc. but always in a virtual environment, so they do not provide information about the possible deviations that mechanical elements may suffer, which can only be checked through real testing.

As a solution to this problem, it has been developed a new technology that allows assessing the matching between virtual geometry and real geometry.

This system consists of the following elements:

- A camera that captures all the sequence, so the user can see all the process in the computer and detect all possible deviations.

Fig. 22: Two lasers and camera

- Two laser projectors that generate beams of different shape, one has a circle and a point and the other one has only a point

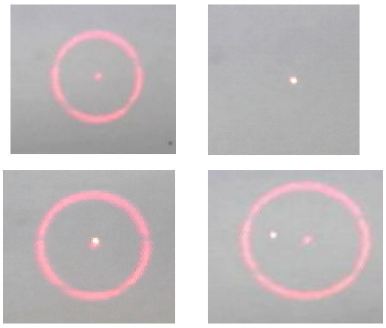

Fig. 23: Circle and point laser (top), laser matching and mismatching (below)

Both lasers are arranged forming an angle and coincide on a work plane on which the camera focuses as well. This focus plane is located at 250 mm, and the circle diameter is at 10mm distance. As we know the angle formed by the circular laser and the point laser, the relative deviation of the point laser from the centre of the circle can provide information relative to the path deviation.

The absolute allowed deviations are below 0.5 mm.

As both lasers are located in a specific place they come into contact with the sole surface and the user can easily see if there is any deviation either in the work plane or the path that the robot does.

Fig. 24: Laser beams at different plane configurations

Figure **Fig. 24**-A shows the expected profile if everything is correct. A positive or negative deviation gives rise to Figure B or C. Since the diameter of the circle is known, it is possible to quantify the error vector of the deviation.

The combination of these two different beams gives the user two different types of information, one defines the plane on which the robot is working and lets the user knowing exactly if the path is going to be good. The other one indicates if there is an inclination on the plane that the robot is working on, allowing the user to modify the shoe and put it in the right place.

5.3.1 Evaluation

INESCOP has carried out the following test to validate this system:

- A path was generated using the BasicCam software on the sole area of a previously digitized last. The path was drawn at 10 mm from the edge of the last.

  The path was subdivided into four parts, each one making approaching movements to the starting point. The path was performed on the work plane. By making the movements one after another, it was possible to check if any deviation was produced in the work plane and in the performance of paths.
- The LaserCam system was fixed on a support and the TCP was defined on the system's workong point and plane.

In this basic prototype, it was possible to capture the frame sequence for later analysis. The resulting error was below 0.5 mm.

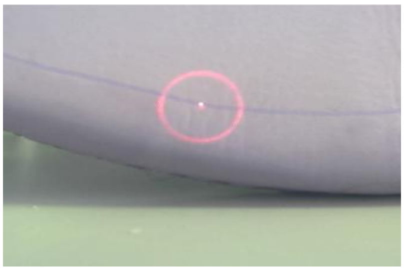

Fig. 25: One of the frames acquired during the test

5.4 Off-path adjustment

5.4.1 Description

As detailed in D1.2 (section 6.1.2), the off-line path adjustment is needed since:

- the path generated using off line programming techniques has to be adjusted to account for geometric differences between the digital data and the actual physical scenario (inaccuracies in the grasping device fixation on the last)

- there should be the possibility to change the path e.g. for a new, almost identical work piece.

The solution developed consists on a laser scanning acquisition system with the following features:

- Working volume equal to 300x300x600 mm;
- Accuracy equal or less than 0.1 mm;
- Acquisition time equal or less than 30 sec;
- Four laser scanner modules (see figure below), and each laser scanner module is provided by
    - one camera (752 x 480 pixels)
    - one laser emitter (Class 3R)
- 1 linear axis that moves the target (last coupled with the gripping device)

The target motion and the acquisition are synchronized and managed by the same PC embedded.

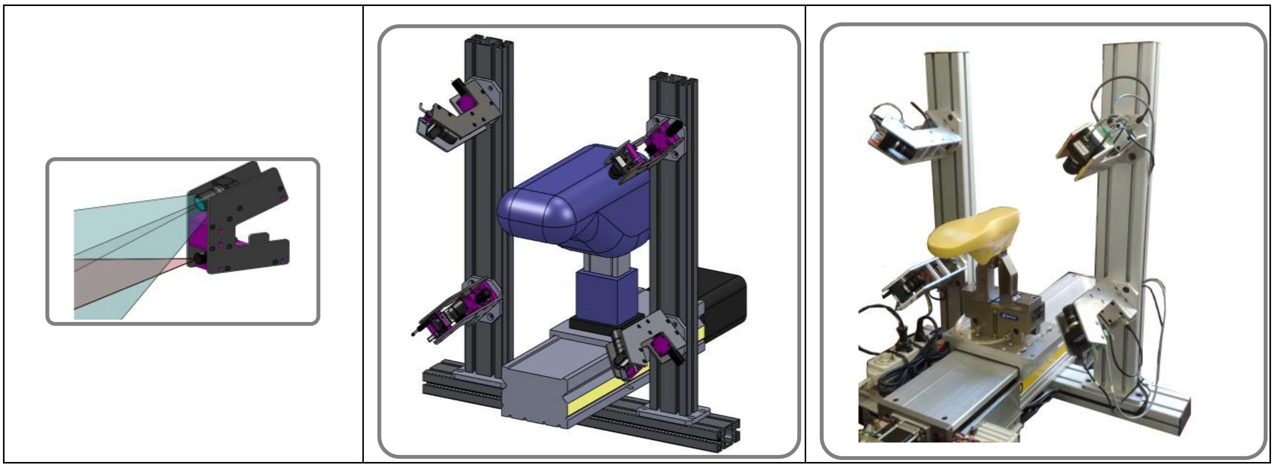

Fig. 26: Laser scanner 3D single module and Laser Scanning Station

Detailed description is reported in D4.2 and D6.1.

5.4.2 Evaluation

The objectives related to the off-line path adjustment have been declared in Deliverable 1.2 (Section 6.1.2).

To reach these challenging goals, the Laser Scanning Station has been designed modular. In fact, thanks to this feature, the accuracy problem can be faced and solved simply by scaling the modules and adding the number of necessary laser scanning modules.

The number of laser scanning modules, the camera resolution, and the laser scanner power have been selected on the basis of an iterative process.

The optimization cost-function has been defined on the basis of

- **economic cost of prototype;**
- **measurement accuracy of the laser scanning system.**

The alignment procedure consists of identifying (registration process) the 3D rigid between the CAD nominal model and the 3D object reconstructed by the LSS (each point is expressed in the same Cartesian frame).

The developed iterative algorithms allows an easy and cost-efficient solution:

Target accuracy can be fixed by defining a user-selected tolerance threshold τ>0 that identify the exit condition for the algorithm (iteration finishes when the mean-square error is below the threshold).

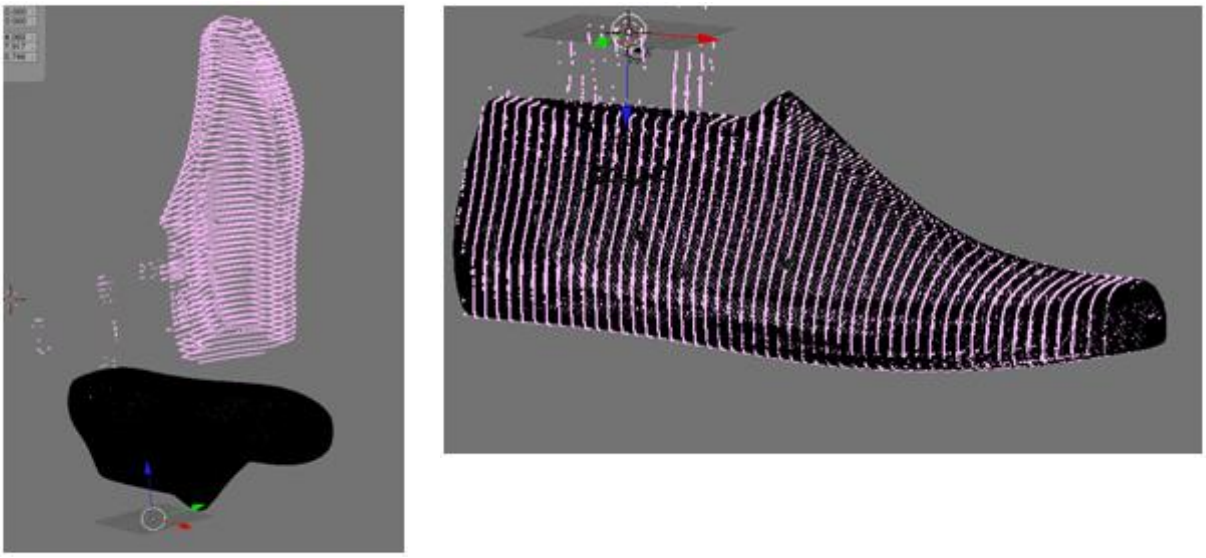

Fig. 27: Point clouds on CAD reference system (black) and on scanner reference system (pink) before and after registration procedure

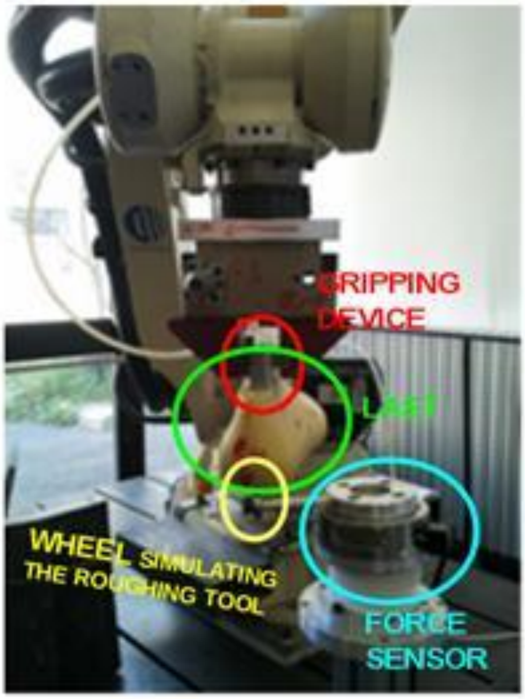

Fig. 28: set up of robot cell for validation tests

The experiment simulates the shoe-roughing application. The experiment consists of three different phases:

- An appropriate gripping device has been mounted on the last manually, such that errors in the device-alignment are introduced.
- A roughing trajectory is calculated by CAD/CAM and expressed in a frame centered nominally in the centre of the gripping device.
- The shape of the last coupled with the gripping device is acquired by the LSS
- The compensation i.e. the 3D rigid roto-translation is calculated
- The robot is asked to bring the last in contact with a wheel simulating the roughing tool.
- The operation is performed twice, with and without compensation; interaction forces between the last and the wheel are measured by means of a force sensor

The figure below reports the experiment results. Without correction, the path followed by the robot is erroneous: zero-forces between time 11s to 16s means that contact is lost, while a high force peak of more than 4N is achieved at time 18s. Considering the repetition with the part program correction, the last is always in contact with the wheel. However, an increasing of the contact forces is still present when the robot moves towards the shoe tip. This is due to a valuable difference from the CAD model and the actual last.

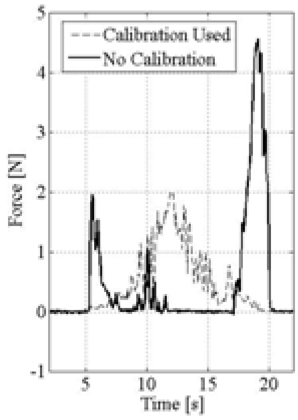

Fig. 29: Results of validation tests

5.5 On-line path adjustment in roughing

As explained in section 3.2, this evaluation will be reported in D5.3

5.6 Safety

5.6.1 Description

New technologies, devices and standards are posing challenging design and implementation shift in the usage of Industrial Robots (IRs hereafter).

The introduction in standard EN-ISO10218 of collaborative workspaces where humans and robots can simultaneously work, sharing the workcell without physical fences, has deeply modified the way to think about the integration of robots in shop-floors.

Nevertheless, safety options provided by basic suppliers of IRs are still quite limited or unavailable.

In such a complex context, ROBOFOOT has focused on how to safely monitor and track the position of users within a collaborative IR workspace, and how to assure a safe collision avoidance strategy in such workspace.

This work shows how these two problems correspond to a new approach in robot cell design, where the HW/SW architectures have to assure the *functional safety* of the plant and the cell-controller must be provided with intelligent computational nodes where *algorithms for safety* run and modify the robot behaviour during the movement.

The solution investigated and developed introduces a new concept based on ***a safe-network of unsafe devices*** where the network architecture should allow the achievement of high-safety standards in terms of functional performance, and of the necessary versatility and expandability in order to integrate nodes devoted to the elaboration of collision avoidance algorithms.

Furthermore, in ROBOFOOT project, efforts have been spent on the development of a particular collision avoidance strategy that can be easily implemented in standard IR controllers.

This set-up developed (see Figure below) demonstrates the feasibility of the suggested approach, and the experimental results show that safe-collaborative workspace can be guaranteed also with current standard industrial robot and IR controllers (see Deliverable D2.3).

The SafeCPU is a COTS PLC by B&R Automation whose functional safety is certified SIL3/PL-e according to IEC61508. The SafeCPU provides two communication channels allowing interfacing with external devices: a safe-certified Ethernet protocol (POWERLINK Safety® by B&R, proprietary standard) that allows the communication with certified safe digital I/O like electromechanical switches; a non-safe Ethernet port allowing communication through TCP/IP and UDP/IP protocol (POWERLINK, open source standard).

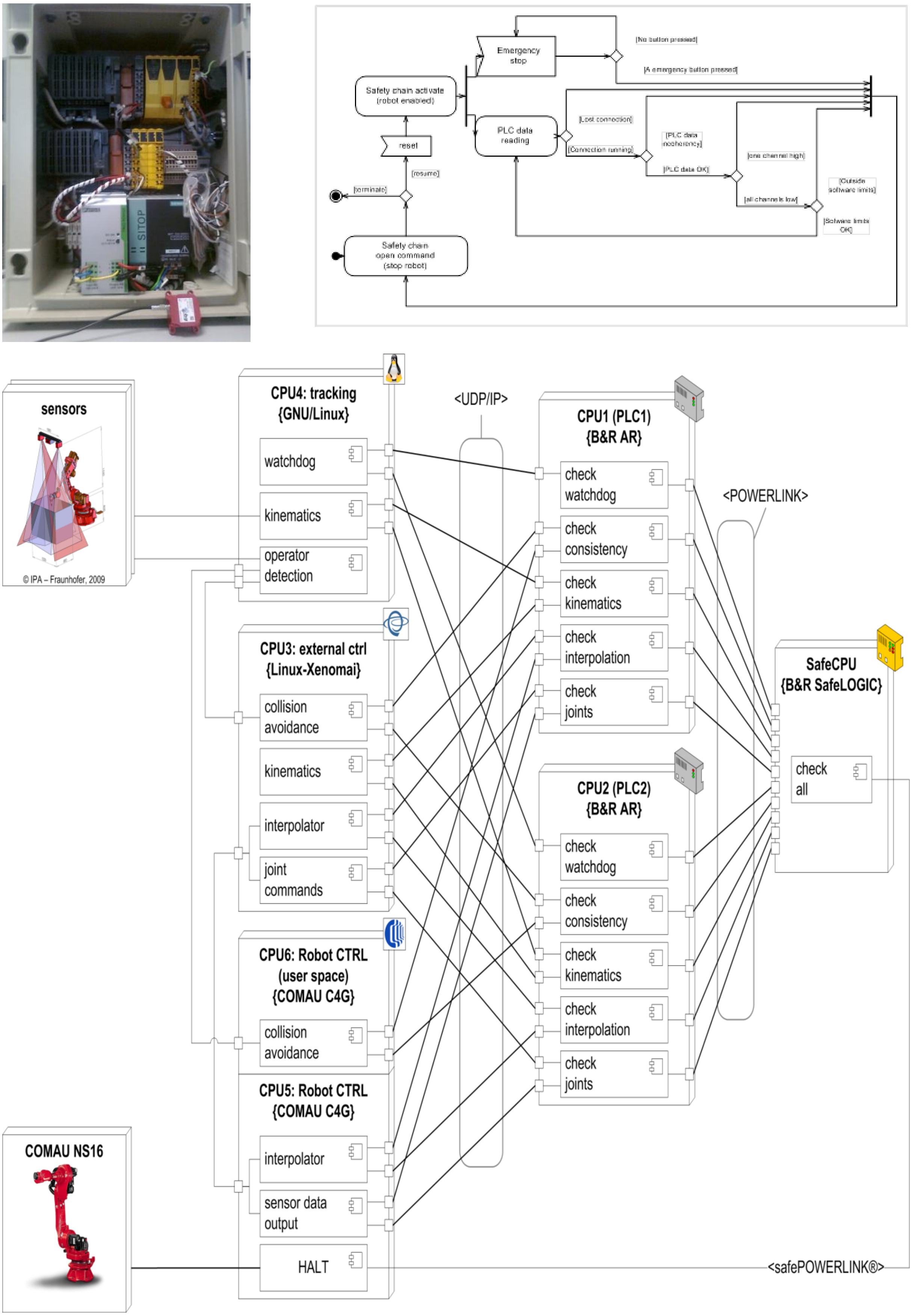

Fig. 30: Experimental set-up developed by CNR-ITIA

Safe-communication channel (*i.e.*, POWERLINK Safety®) assures that any halt-event command, issued by the logic implemented in the SafeCPU, safely opens the emergency circuit. Conversely, data coming from unsafe communication channels (*i.e.*, POWERLINK) are redundantly computed and redirected by two standard PLCs, namely CPU1 and CPU2. As displayed in the figure above, each PLC implements different consistency checks on redundant-data transmitted through standard UDP/IP through the Ethernet physical layer. Boolean results of data comparisons are sent to SafePLC that in case of incoherence, or negative occurrence received, safely opens the emergency circuit. Programs running in the two PLCs provide equivalent functionalities, but are implemented by different programmers in order to fulfill the requirements of IEC61508. The implementation of the safety framework in **¡Error! No se encuentra el origen de la referencia.**displays a functional box containing the SafePLC, the safe I/O and the two PLCs, which are actually 3 different nodes in the physical system. Thanks to the redundancy of functionalities, the “box” can be therefore considered as a safe-observer of the data passing through the network.

Considering the left side of the Deployment Diagram, the functionalities necessary to guarantee a supervised workspace sharing have been implemented in 4 different CPUs: 2 CPUs (namely CPU5 and CPU6) are the PCs available for the NS16 robot, one PC, namely CPU4, is devoted to the acquisition of data coming from sensors in the working cell. Tasks in CPU4 are watchdog-monitored on sensors data acquisition, and are used for tracking both humans and robot positions, since COMAU NS16 does not provide redundancy measure of joint positions. The robot motion control, running in CPU6, communicates only with the real-time external PC, namely CPU3, through the C4GOPEN high-rate communication channel. In order to obtain a complete calculation redundancy, CPU3 integrates a library that virtualize the actual robot interpolator, and computes the forward kinematic in order to enable the collision avoidance strategies and to compare the robot position with measures coming from sensors (CPU4). Collision avoidance algorithms have been developed both in the user-programming language of the robot interpreter (that runs in CPU5) and in the external real-time PC (CPU3). Both CPUs send the results of the implemented strategy to the PLCs, that verify the consistency of the data calculated, while, only the output of the algorithm running in the user-space of the robot is used by the robot motion controller. In addition, a second user-program in the robot controller sends cyclically through UDP/IP communication channel to CPU1 and CPU2 the actual position of the robots, the motion targets.

Since data payloads exchanged among the PLCs and the different nodes of the network is quite limited, UDP/IP connection has been preferred to TCP/IP because it guarantees higher frame-rate, the probability of packet loss is limited due to dedicated local network and the data transfer acknowledge is not required in presence of fault-tolerant applications on redundant consistency checks.

More details on our Safety proposal can be found in D2.3.

The prototype designed and developed in CNR-ITIA labs is compound by the following elements:

Node id	Description	Company	Safe	Communication Protocols	OS	Language
Safe CPU	SafePLC	B&R	Yes	X20 Powerlink	Proprietary	FB
CPU1	PLC-1	B&R	No	UDP, Powerlink	VxWorks	C
CPU2	PLC-1	B&R	No	UDP, Powerlink	VxWorks	C
CPU3	PC-Embed	AAEON	No	TCP/IP,UDP, c4gopen	Linux/Xenomai	C++
CPU4	PC	HP	No	TCP/IP	Linux	Python
CPU5	c4gopen	COMAU	No	c4gopen	N.A.	N.A.
CPU6	Teach Pen-dant	COMAU	No	TCP/IP,	WinCE	PDL2
CPU7	PC	OEM	No	TCP/IP	Win	Python

Table 6: Elements of the prototype developed by CNR-ITIA

NOTE: Sensors have been simulated, none real sensor has been connected to the developed set-up.

5.6.2 Evaluation

Communication Time features:

From	To	Type	Real Time	Cycle Time (nominal)	Latency (mean)	Jitter (mean)
CPU1/2 SafeCPU	**SafeCPU CPU1/2**	Round-trip	YES	800 us		5 us
CPU3	**CPU1/2**	One-way	NO	(sync) 5 ms	50 us	10 us
CPU3 CPU5	**CPU5 CPU3**	Round-trip	YES	(sync) 1 ms		10 us
CPU4	**CPU3**	One-way	NO	50 ms (minimum)	1.8 ms	250 us
CPU4	**CPU1/2**	One-way	NO	50 ms (minimum)	50 us	10 us
CPU4	**CPU6**	One-way	NO	50 ms (minimum)	1.2 ms	150 us
CPU6	**CPU1/2**	One-way	NO	20 ms	800 us	100 us
SafeCPU	**Safe-Relay**	--	YES	--	50 ms	10 s

Table 7: Communication performance of elements in the system

Considering the timing features of involved nodes, it is possible to compute the nominal time among the detection of an emergency event and the actual emergency circuit reaction, taking into account the following constraints:

i) incoherence between data coming from CPU-3 and CPU-6 requires a reaction time equal to 20 ms (max communication time between CPU6 and CPU-1/2) plus the communication between the PLCs and the SafeCPU equal to 0.8 ms, plus the SafeCPU execution time plus 0.010 ms, plus 50 ms that is the time spent from electro-mechanical relay to be opened. Hence, the total latency is about **72 ms**.

ii) Incoherence in target generation is equal to the C4GOPEN communication time (1ms) plus calculation time (less than 20 microseconds) plus communication time between CPU-3 and the two PLCs (0.8 ms), plus the communication time among the PLCs and the SafeCPU (0.8 ms) plus the safe-relay reaction time (50 ms). Hence, the event total latency is about **52 ms**.

iii) Incoherence in following error calculation is equal to c4gopen communication time (1ms) plus communication time between CPU-3 and the two PLCs (0.8 ms), plus the communication time among the PLCs and the SafeCPU (0.8 ms) more the safe relay reaction time (50 ms). Hence , the event total latency is about **50 ms**.

iv) Identification that an operator is inside the *Danger-Area* requires: tracking sensors data elaboration (different on the basis of the eligible hw/sw), plus the communication time among the CPU-4 and the CPU-3/6, plus the elaboration data time equal to time calculated in point (i).Under such hypotheses, the measurement system assures the object identification in **50 ms**, and the maximum latency time for the emergency circuit reaction is about **102 ms**.

In summary, taking into account a watchdog on the data coming from sensors, a reasonable reaction time of the system is about **100 ms**.

Economic Costs:

Node id	Description	Company	Safe	Costs (€)
Safe CPU	SafePLC	B&R	Yes	**1,200**
CPU1	PLC-1	B&R	No	**600**
CPU2	PLC-1	B&R	No	**600**
CPU3	PC-Embed	AAEON	No	**700**
CPU4	PC	HP	No	**500**
CPU5	c4gopen	COMAU	No	**N.A.**
CPU6	Teach Pendant	COMAU	No	**N.A.**
CPU7	PC	OEM	No	**400**
TOT. COSTS OF THE CALCULUS NODES				**3,900**

Table 8: Cost of computing modules

NOTE:

None sensor has been purchased or integrated in the set-up, however it is worth to note that any kind of sensor can be integrated easily in the set-up (analog/digital/usb/ethernet-based etc).

Costs of Safe Sensors (lists of some products available in the market):

ID	Type	Company	Category	**Costs (€)**	Off-the-shelves
1	Capacitive Sensor	KUKA	Cat. 2 DIN 954-1	**> 2,000**	**NO**
2	Laser scanner	Leuze ROTOSCAN	Type3 (EN 61496-1, 61496-3)	**> 4.000**	Y
3	Laser scanner	Schmersal LS 30	Type3 (EN 61496-1, 61496-3)	**> 4,000**	Y
4	Laser scanner	Sick 3000	Type3 (EN 61496-1, 61496-3)	**> 4,000**	Y
5	Laser scanner	Sick PLS	Type3 (EN 61496-1, 61496-3)	**> 5,0**	Y
6	Laser Scanner	Sick RLS 100	Type3 (EN 61496-1, 61496-3)	**> 4,000**	Y

7	Laser scanner	Siemens SIEGUARD	Cat. 3 DIN 954-1	**> 4,000**	Y
8	Positioning Switch	Telemecanique	Cat. 1 DIN 954-1	**< 100**	Y
9	Proximity Switch	Euchner	Cat. 3 DIN 954-1	**< 100**	Y
10	Safe Edges	Mayser	Cat. 4 DIN 954-1	**< 500**	Y
11	Safety Barriers	Techno GR SB4	Cat. 3 DIN 954-1	**> 2000**	Y
12	Safety Bumper	Mayser	Cat. 3 DIN 954-1	**< 500**	Y
13	Safety Bumper	SSZ Systeme Zimmermann GmbH	Cat. 3 DIN 954-1	**< 500**	Y
14	Safety Light Grids	various	Cat. 3 DIN 954-1	**> 5000**	Y
15	Safety Lock	Banner	--	**< 500**	Y
16	Safety Lock	Schmersal	Cat. 3 DIN 954-1	**< 500**	Y
17	Safety Mat.	Mayser	Cat. 3 DIN 954-1	**< 500**	Y
18	Safety Mat.	SSZ Systeme Zimmermann GmbH	Cat. 3 DIN 954-1	**> 500 €/m2**	Y
19	Safety Timer	Piltz	Cat. 3 DIN 954-1	**< 500**	Y
20	Safety Relay	Piltz	Cat. 3 DIN 954-1	**> 500**	Y
21	Safety Camera	Piltz	Cat. 3 DIN 954-1	**> 12000**	Y
22	Physical Fences	various	Cat. 3 DIN 954-1	**> 120 €/m**	Y

Table 9: Cost of safe sensors

Comparison between the benefit of the safe-net of un-safe sensors and a cell build by the means of standard solution is not easy to be done and it depends on the number of the sensors that the actual implementation provides.

Furthermore, the cost of the certification process of the solution is not easy to be estimated in a general situation.

However it is worth underlining that only collaborative solution would allow the use of robots in traditional shoe-factory shop-floors