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RESEARCH ARTICLE

Development of an Integrated Robotic Workcell for Automated Bonding in Footwear Manufacturing

JOSÉ-FRANCISCO GÓMEZ-HERNÁNDEZ[1], **JOSÉ-MARÍA GUTIÉRREZ-HERNÁNDEZ**[1],
ANTONIO JIMENO-MORENILLA[2], **JOSÉ-LUIS SÁNCHEZ-ROMERO**[2],
AND MARÍA-DOLORES FABREGAT-PERIAGO[1]
[1]INESCOP—Footwear Technology Center, 03600 Elda, Spain
[2]Department of Computer Technology, University of Alicante, 03690 San Vicente del Raspeig, Spain

Corresponding author: José-Francisco Gómez-Hernández (jfgomez@inescop.es)

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ABSTRACT Traditional manufacturing industries are currently immersed in an automation process, integrating new techniques and tools, driven by the demands from producers to improve the manufacturing process as well as the working conditions of employees. For the footwear industry, bonding is a key operation in the manufacturing process where the outsole is assembled onto the lasted shoe. However, in this operation, workers are often subjected to hazardous substances (i.e., organic solvents) and perform repetitive tasks with limited added value. Against this background, this paper describes the results of a research project, whose aim was to obtain the maximum benefit from different technologies analyzed, such as collaborative robotics, artificial vision and multirobot control, for the manipulation of flexible/deformable objects. The main result of this project is a robotic workcell for shoe bonding that has been introduced in the production line to fully automate the operation. This workcell integrates three collaborative robots, one for (hot melt) adhesive application and another two, with two-finger electric grippers, to carry out the bonding synchronously. Different vision systems have also been embedded to conduct the various processes involved. The entire operation is controlled and coordinated through ROS (Robot Operating System). The key findings of this research showcase the automation of a process traditionally undertaken by humans. In this novel approach, two robots collaborate to manipulate flexible objects, liberating the operator from engaging in repetitive, non-value-added tasks and the handling of hazardous substances.

INDEX TERMS Bonding, footwear, fourth industrial revolution, robotics and automation, smart manufacturing, manufacturing automation.

I. INTRODUCTION

Industrial development stimulates a strong socioeconomic reactivation and improvements in the quality of life of the population. The 4th industrial revolution is a reality that begins to impact on the new forms of production, organization of companies and, of course, on the safety and health of workers. Incorporating technologies such as robotics into traditional manufacturing sectors with a strong presence in Europe can determine the difference between preserving the relevance of the European manufacturing sector and weakening it at the global level.

European footwear is recognized worldwide as a distinctive symbol of traditional values combined with high quality products. In 2018, the European footwear sector [1] (EU28) was represented by 19,856 companies and 260,309 direct employees.

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In terms of footwear total production, Europe is in a relative weak position compared to Asia, despite 7 EU countries being among the world's largest producers, with Italy at the top (10th position), based on 2018 data. Regarding footwear exports by quantity, the panorama improves considerably. Asia, and specially China, leads the ranking, with almost two thirds of all footwear exports. However, Germany, Belgium, Italy, Netherlands and Spain appear in the top ten [2].

Due to the Asian dominance in footwear production, Europe has had to focus on more expensive, higher quality, value-added footwear to face this competition. This can be clearly observed in the average export prices per country, where Italy is the unrivalled leader among the world's top 20 producers. Europe's position is therefore further improved when the value of footwear exports is considered rather than the quantity. From the value of exports in 2019, 9 of the top 15 exporters are European. Among the main exporters of footwear, focusing on the countries totally or partially integrated in the southwest European region (SUDOE), France occupies the 7th position, Spain the 9th and Portugal the 15th.

All these data highlight the importance of preserving and modernizing an industrial sector with such economic weight and prestige in the European industrial background, improving its technological level and sustainability. To fight against increasing competition, it is important to raise productivity to keep prices down, while maintaining the level of quality that differentiates European footwear.

Traditionally, the manufacture of footwear requires to perform several manual operations. These are precise operations, most of which involve the manipulation of flexible objects such as leather, insoles and outsoles of different materials and shapes. The automation of these operations is a key factor in improving footwear production in Europe, and hence, the productivity of companies. This is vital to ensure that they continue producing in Europe and that the jobs they generate survive, while becoming higher quality, knowledge-intensive and more technologically advanced. Technologies like robotics [3] and artificial vision [4] help in the automation of processes, which is one of the main ways to improve the efficiency of manufacturing chains and raise the productivity of traditional footwear industry.

Thus, protecting and improving the quality of existing jobs, and creating new ones is the main objective behind the knowledge and technologies investigated and developed in the research carried out. The sectors on which this study focuses may be impacted considerably by the results of the research due to their high employment rate and great importance in the economy of European countries.

II. BACKGROUND

Analyzing the state of the art about the automation of the bonding process in the footwear industry, different research works related to the operation can be found, mainly for gluing application systems, using cartesian robots and a vision system [5], [6], or anthropomorphic robotic arms to spray the outsole [7]. References can also be found about systems for applying adhesive to the shoe upper using adhesive extrusion systems [8], as well as about other systems to deposit glue so as to wet the shoe upper controlling the force between the glue extruder and the surface of the shoe upper during the application [9]. Different approaches can also be identified to automate footwear manufacturing plants from the 3D CAD information of the footwear model [10], but results are not particularly satisfactory or limited to the large-scale manufacturing; however, given the specific characteristics of this sector, where short series of shoe models are usually manufactured and different sizes and feet (right and left) must be considered, fully automating a plant is particularly challenging. Other systems apply adhesive onto the shoe upper and the outsole [11], but no reference has been found about robotic systems that perform the bonding operation of these two parts of the shoe after adhesive application.

When reviewing solutions for other sectors we observe operations executed with two robots to manipulate heavy objects [12]. However, these systems often lack the precision required for the proposed operation. In the automotive industry, numerous assembly operations can be automated using robots [13]. Nevertheless, the majority of components manipulated by these robots are rigid and lack flexibility. Over the past years, there has been significant development in the field of dexterous grippers, resulting in various robotic system designed to enhance the flexibility of industrial assembly operations [14].

Therefore, the aim of this paper is to present a robotic workcell for footwear manufacturing to apply glue and perform the bonding process between the shoe outsole and upper. This workcell has been built as a demonstrator of different technologies that could carry out together one of the most common operations in footwear manufacturing.

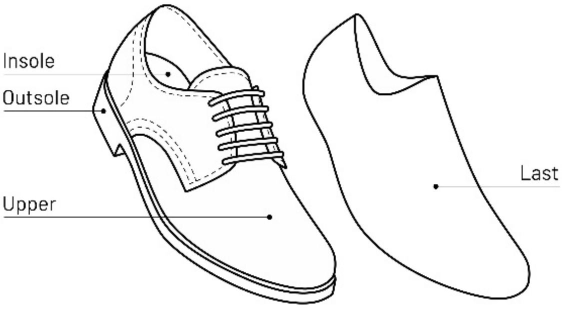

FIGURE 1. Shoe parts.

III. DESCRIPTION OF THE SHOE BONDING PROCESS

The bonding operation starts with the preparation of the pieces. Outsoles must be cleaned and treated physically or chemically so that the adhesive bonds perfectly. The upper also need to be prepared, which usually involves deburring and roughening [15] to remove bulky folds from the material and to improve adhesion. Once prepared, the adhesive [16] is applied, left to dry, then reactivated and the bond between the two parts is made. After bonding, the shoe is placed in a press designed for this purpose, where adhesion is consolidated.

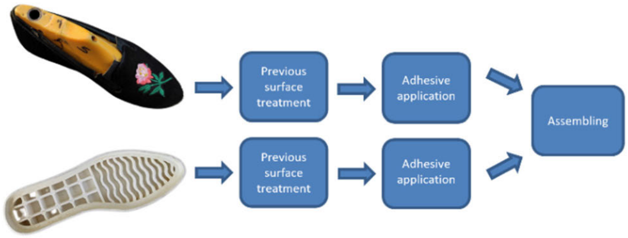

FIGURE 2. **Footwear bonding process.**

In the gluing process, adhesive has been conventionally applied to both parts, that is, the outsole and the upper [17]. However, in the process described in this paper, a reactive polyurethane (PUR) adhesive [18], [19], [20] is used, which only needs to be applied to one of the parts: the outsole, is used. This adhesive is, in addition, more environmentally friendly as it does not contain any solvents [21].

Once the adhesive has been applied, the operator brings both parts and performs the assembly operation joining the outsole to the upper. This process needs a high level of precision so that the outsole is perfectly aligned to the shoe. Subsequently, the operator introduces the shoe in a press to finish the bonding process.

IV. SYSTEM DESCRIPTION

The proposed system is the result of the integration of various interconnected elements.

A. SOFTWARE

In terms of software, the decision was to use ROS (Robot Operating System) [22] for the entire project, which is widely implemented in academic environments. ROS is a framework for the development of robotic applications, based on the distribution of processing in nodes that communicate by message passing. Its main advantages are being widely supported by most robots and devices and its large library of packages that provide necessary functionalities already implemented, such as simulation, motion planning and collision calculations.

The Kinetic Kame version of ROS, released in 2016, was employed in order to have a stable and tested version. In addition, ROS requires the use of Linux as the general operating system; specifically, Ubuntu 16.04 was chosen.

Working with ROS as the base framework implies that any piece of software used in the demonstrator workcell must run under this system to communicate seamlessly with the rest of it. If this was not possible, the software in question would be responsible for sending and receiving the information it manages under the ROS protocol, so that it can be interpreted by the rest of the system. RViz [23] is used as a primary visualizer in ROS and the MoveIt! [24] Motion Planning Framework [25] plugin is employed in ROS to perform the motion planning and robot trajectory calculation.

B. ROBOTS

For the proposed system, three robots are used: one Universal Robots UR3 for the adhesive application, and two Universal Robots UR10 for the rest of the process, including grasping, rotating and assembly. The outsole, being a flexible object, is difficult to manipulate and maintain the desired shape with a single grip point. This complicates movement and assembly onto the upper. The upper, assembled onto the last (see Figure 1: Shoe parts.), have a curved shape at the bottom, depending on the type of last and heel height. Thus, several grip points are needed on the outsole to adapt its shape to this curvature.

The movement of the robotic arms can be performed in several ways depending on the requirements of each task within the demonstrator. Each of the alternatives and their use cases are explained below:

1) MoveIt PLANIFICATION (ROS)

This is the most typical way for robot motion planning when working with ROS.

MoveIt is a ROS package in charge of planning and executing robotic arm movements. It receives, on the one hand, the geometric information of the cell environment, and on the other hand, the description of the robotic arm, with the size and shape of each segment and axis of the robot.

With this information, given an origin value for the robot axes and a final cartesian position for the end of the robotic arm, MoveIt plans the movement of the entire robot to reach its destination and avoid collision with obstacles in the environment. To this end, MoveIt calculates the value for each axis of the robot at each instant of the movement.

These features make MoveIt a good choice. However, it has several drawbacks:

- **Planning time:** The motion calculation is not as fast as desirable, which may involve delays in the execution of the operation that may be excessive in some cases.
- **Randomness:** MoveIt uses a random seed for motion planning, therefore, two executions of the tool with the same origin and destination may not result in the same path. This raises uncertainty in the robot movements, which in some cases is not desirable.

MoveIt planning will be employed either in most movements, except in those cases where the disadvantages mentioned above make it inadvisable, or to take advantage of the benefits of another type of movement.

2) SEND COMMANDS TO AXIS TOPICS (ROS)

In this way, the desired values for the robot axes are directly sent to the robot through messages in ROS. This avoids the two main drawbacks of MoveIt: delays and randomness.

The main problem of this system is that the desired values of the axes must be directly calculated, which is complicated to obtain in execution time, therefore, they must be obtained beforehand. In addition, it must be ensured that there will be no collision between the current position of the robot and the desired one, since the system will not check it.

For those reasons, this type of movement is suitable when the initial and final positions are predefined and when delays need to be prevented.

Furthermore, this system can also be used if randomness is to be avoided, as in a multi-robot synchronized movement, but the axis values cannot be obtained beforehand. In this case, the KDL (Kinematics and Dynamics Library) ROS tool must be incorporated. This tool offers functionalities for calculating axis values from cartesian positions, that is, the calculation of the inverse kinematics of the robot.

3) UR SCRIPT

Finally, ROS can be bypassed, and the robot can move by sending scripts with the desired movement directly to it.

The problem with this system is that it stops the execution of the ROS node on the robot and must be restarted when the scripted motion is completed. This process of stopping and restarting ROS on the robot generates a slight delay that is not desirable.

However, the advantage of using scripts on the robot is that they can react immediately to changes in the robot signals. This makes it the only option when it is required to achieve perfect synchronization of two hypothetical robots used to perform the operation, which have interconnected physical digital signals.

In a context where there are two robots simultaneously holding the same object, it is very important to ensure that they can be moved at the same time, that is, synchronously. There are two main ways to achieve this, depending on the needs of each movement:

a: SYNCHRONISING THROUGH MESSAGES IN ROS

With this system, both robots are coordinated through messages in ROS to start their movement at the same time. One of the benefits is that all the tools and information provided by ROS are available without having to leave the ROS environment. In addition, the delay associated with relaunching ROS once the movement has finished is avoided.

However, the synchronization with this system is not perfect, since it depends on the latency associated with the messages passing through the network as well as with the program itself when reading the message and executing the command.

Therefore, this synchronization will be used when the distance is small and the speed is slow, allowing for some flexibility in the timing and high precision provided by the ROS environment.

b: SYNCHRONISING THROUGH PHYSICAL SIGNALS

To obtain a perfect synchronization, the best option is to interconnect physical signals between both robots. In this way, any latency associated with communication over the network is avoided.

In addition, to read these signals and react as quickly as possible, combining this synchronization with movement through scripts is an advantageous approach.

This way, it is the robot itself that is waiting for the right signal to change in order to know when to move. This synchronization will be used with long fast movements but not necessarily precise.

C. GRIPPERS

For the manipulation of outsoles, two different grippers have been employed from two different companies. The first robot, with the highest workload, is equipped with a Robotiq 2F85 gripper, while an OnRobot RG2 gripper is integrated into the second robot.

FIGURE 3. **Left: Robotiq 2F85; Right: OnRobot RG2.**

To improve the grip with grippers, which sometimes have to hold the outsole by themselves, flexible thimbles were printed in 3D with flexible material and air bubbles inside. These thimbles make easier to grip different types of outsoles, adapting its shape to maximize contact surface and improve grip.

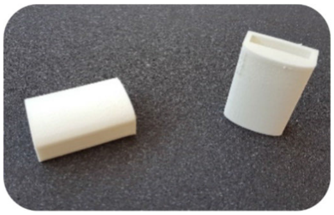

FIGURE 4. **Thimbles for the grippers.**

D. VISION SYSTEM

The vision system is composed of five 3D cameras Intel RealSense D415 [26], attached to the structure in different ways and positions to obtain the best representation of the environment. One of the cameras is used for grasping in the rotation station, described in the next section. The other four cameras (synchronized by hardware) are used for the reconstruction [27], [28], [29] of the environment and the control of the deformation [30], [31] in the assembly station.

For the adhesive application, a more precise digitalization system is required; a Gocator 2350D 3D Laser Line Profile Scanner is utilized for that purpose. This device provides a high quality and dense point cloud of the outsole, which is used for the reconstruction of the outsole surface and calculates the toolpath that the UR3 robot employs to apply the adhesive over the outsole.

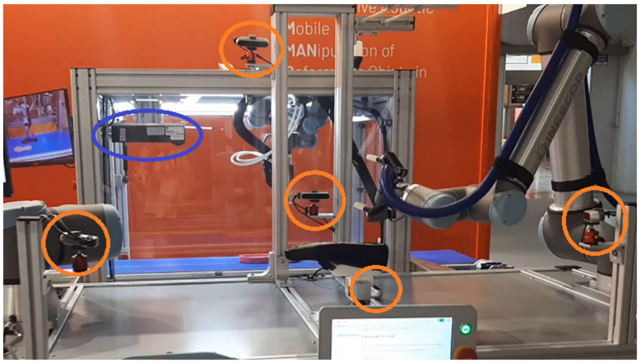

FIGURE 5. Distribution of the cameras of the vision system.

E. MODULES

The system has been divided into four modules or stations. The first module is the adhesive application station. The second is the grasping station, where the robot grasps the outsole. The third module is the rotation station, where the robot rotates the outsole to invert the outsole grasping. The fourth module is the assembling station, where two robots collaborate to place the outsole onto the upper and bond them.

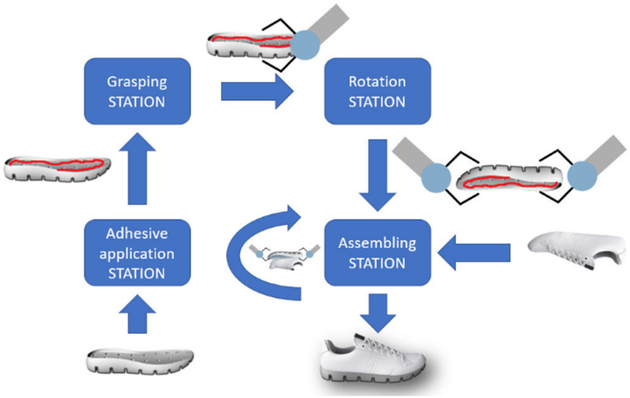

FIGURE 6. Workcell modules.

All these modules have been installed in a structure that integrates the different elements.

A modular scheme based on 4 stations has been devised to facilitate the design and construction of the workcell and to establish a clear division of the work to be performed. The final implementation of the system is illustrated in Figure 9, where the appearance of the different stations integrated in the final demonstrator can be observed.

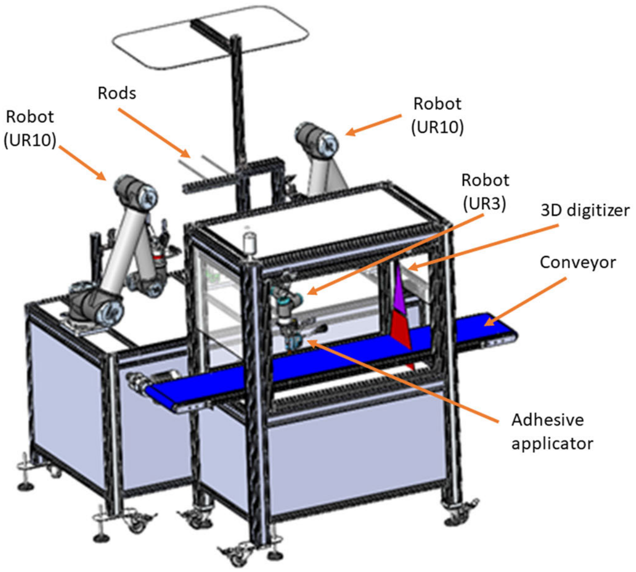

FIGURE 7. Structure view (from adhesive application station).

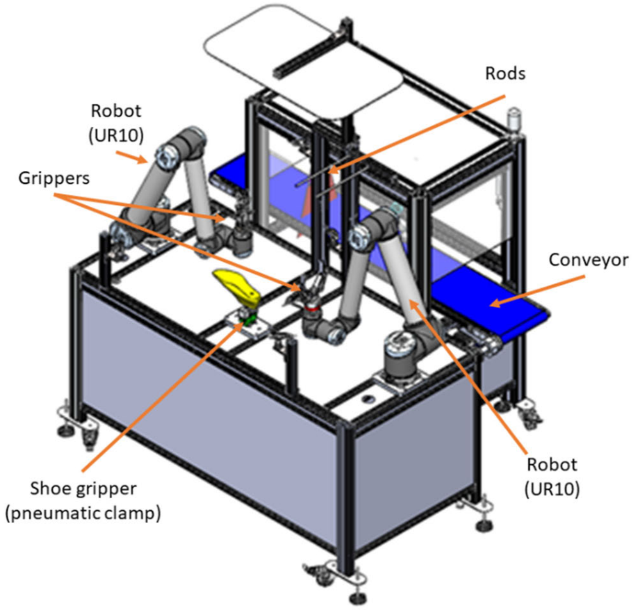

FIGURE 8. Structure view (from assembling station).

The conveyor grasping station can be identified at one end of the adhesive application station, which is in the background of the image. The entire structure of the final demonstrator is shown in the foreground, with the rotation station represented as a pair of rods at the top of the image, and the assembling station, with the shoe upper upside down and secured in the center of the demonstrator's workcell.

1) ADHESIVE APPLICATION STATION

This station is composed of a conveyor that moves the outsole from the input area to the output area, a digitizer that obtains a 3D point cloud from the outsole, a Universal Robots UR3,

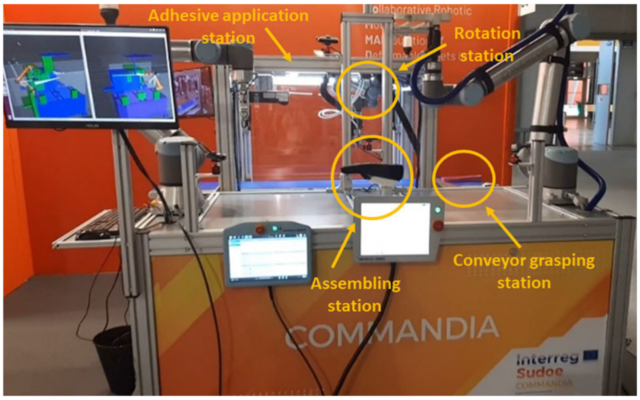

FIGURE 9. General view of the system.

and a hot-melt applicator for the application of the adhesive over the outsole.

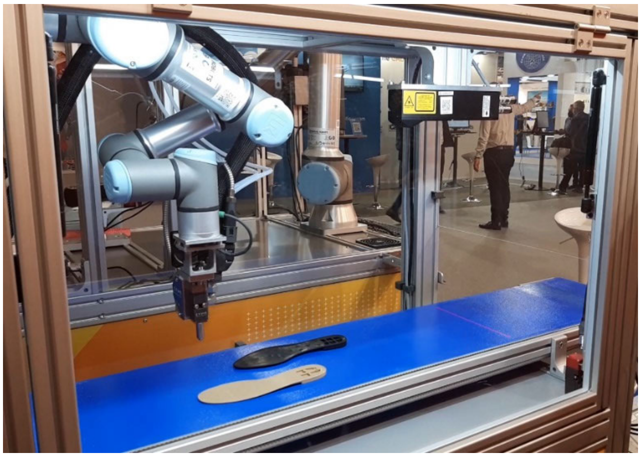

FIGURE 10. Adhesive application station.

During the operation, the user inserts the outsole in the system by placing it in the conveyor Subsequently, the scanner scans the outsole, and the system reconstructs the geometry of the outsole and sends the point cloud to ROS in order to start the calculation of the grasping point. With the configuration of the adhesive application, it calculates the toolpath for the adhesive application. This toolpath is, in most cases, a double parallel around the outside of the outsole, including start and end areas.

The robot follows the calculated toolpath, properly applying the adhesive to the outsole. The outsole then reaches the end of the conveyor belt, where it can be grasped.

This station could work independently from the rest of the workcell and has been developed in C#. To communicate this station with ROS, the library RosBridge [32] has been used. This communication is produced in three points (Figure 12):

- When the outsole is digitized, the point cloud is sent to start the calculation of the grasping point.
- At the end of the process, when the outsole reaches the grasping area, which is located at the end of the conveyor, the final position of the outsole is sent to start its grasping of the outsole. The message sent in this case contains the displacement of the outsole, over the conveyor, with respect to the point cloud sent previously.
- The last communication is produced when the grasping station grasps the outsole from the conveyor to indicate to the adhesive application station that it can resume the conveyor movement and continue with the process.

FIGURE 11. Adhesive toolpath, single (left) and double (right) parallel.

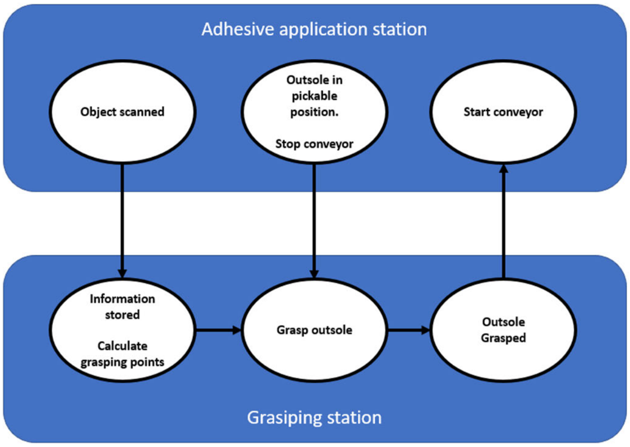

FIGURE 12. Communication protocol.

Within ROS, communication between nodes can occur in different ways, mainly: topics, services, and actions. Among them, actions are chosen at all three communications points, since it is necessary to have confirmation that information has been received and processed every time.

The adhesive employed, PUR (hot-melt), is applied by the robot as a bead on the outsole surface. The viscosity of the adhesive is crucial, as it enables us to invert the outsole without any spillage in subsequent stations. Hot-melt adhesives represent solvent-free organic adhesives utilized in the bonding stage of footwear production. This leads to a notable decrease in the emission of volatile organic compounds into the atmosphere. These adhesives, being 100% solids, bring about various technical and economic enhancements in the footwear manufacturing process. Notably, they eliminate the need for additives, are applied exclusively to one side (outsole only) and obviate the necessity for drying.

2) GRASPING STATION

This station uses one of the UR10 robots with a gripper; for this purpose, a Robotiq 2F85 gripper is used. The process starts when the station receives the message from the adhesive application station with the point cloud of the outsole. At this point, the station calculates the grasping antipodal points of the outsole, using the GeoGrasp [33], [34], [35] algorithm, without a previous recognition of the outsole. The method is based on the extraction of the outsole's outline using concave hulls and the measurement of the curvature in the contour areas. The process considers the different shapes, sizes, materials, and colors that outsoles can be featured with; these can be determined from the point cloud of the digitization of the object. Thus, antipodal points are calculated only with the information from visual data.

It must be taken into account that electric grippers are used and that the calculated points represent the position of the gripper fingers. Therefore, there should be two points placed on opposite sides of the outsole with a maximum distance of 100 mm.

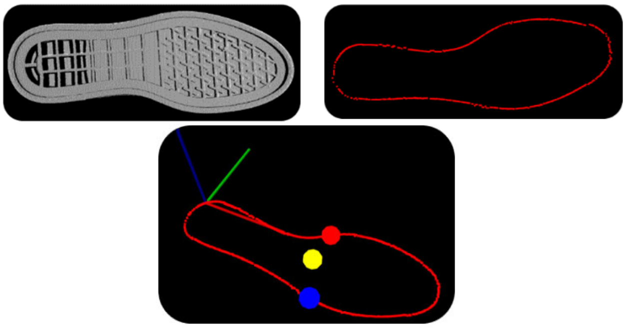

FIGURE 13. Top left: full point cloud; Top right: concave hull; Bottom: calculated grasping points.

From the two points obtained as grasping points, which represent the gripper fingers, the position of the gripper center is determined, and MoveIt is used to calculate the complete position of the robot.

In addition, the distance at which the gripper fingers must be closed for optimal grasping can be calculated by measuring the distance between the grasping points.

After grasping the outsole, the UR10 robot picks up the outsole, sends the message to continue to the adhesive application station, and moves the outsole to the next station.

3) ROTATION STATION

FIGURE 14. Robot grasping the outsole with the gripper.

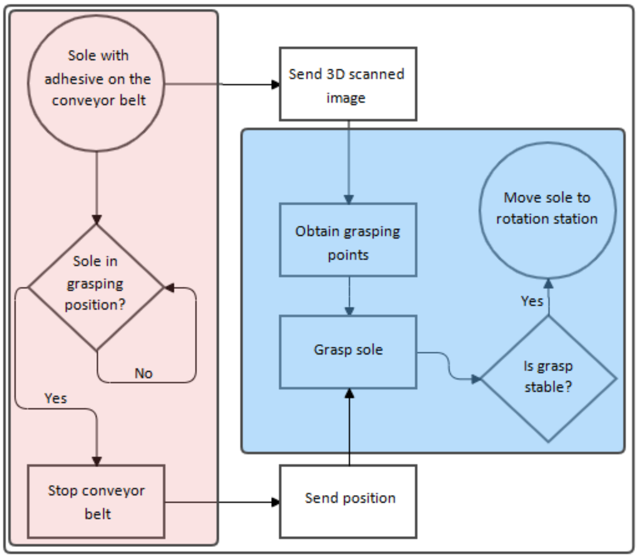

FIGURE 15. Grasping station schema. On pink background: adhesive application station. On blue background: grasping station.

Once the robot grasps the outsole from the conveyor, the outsole already has the adhesive on the upper side, which is why it must be grasped by the robot from the outside. Prior to assembling the outsole onto the upper, it is necessary to invert the outsole in order to put the adhesive in contact with the shoe upper.

FIGURE 16. Left: grasping the outsole from the conveyor. Right: grasping the outsole to do the assembly.

Multiple options have been tested to conduct this operation, resulting eventually in the use of two steel rods for reversing the robot's grip on the outsole. This is the most simple, effective, and cheap solution to perform the operation.

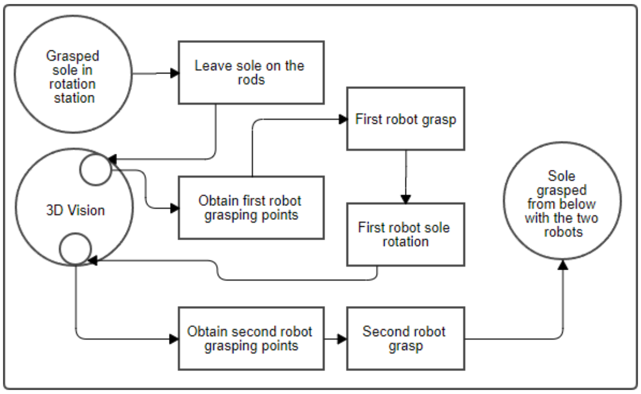

FIGURE 17. **Rotation station scheme.**

The process consists of leaving the outsole on the pair of rods that keep the sole in horizontal position, while providing enough mobility to grasp the outsole from the bottom, as it can be observed in Figure 18.

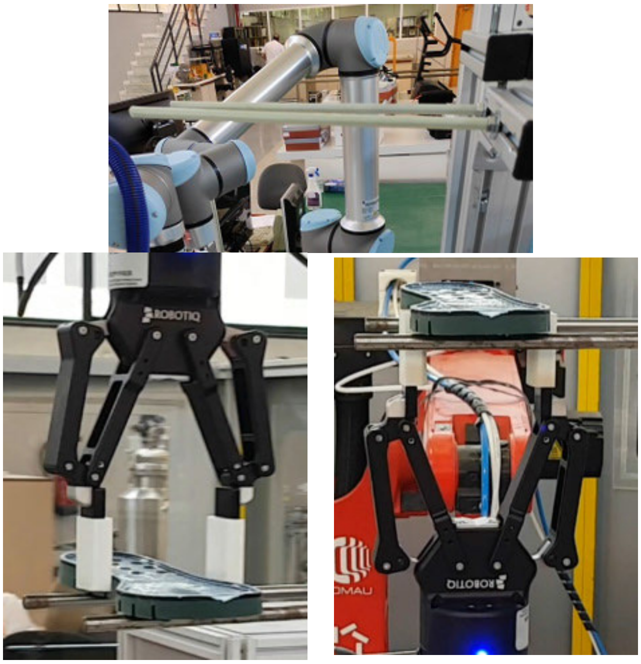

FIGURE 18. **Top: pair of rods of the rotation station. Left: leaving the outsole over the rods. Right: grasping the outsole from the rods.**

The process begins by placing the outsole on top of the rods. Subsequently, it is necessary to obtain the grasping points that will be used to pick the outsole up again from below. This is advisable, even if theoretically the position of the sole is known, as it is not possible to guarantee that the sole has not moved when it has been left on the rods.

For this purpose, the GeoGrasp tool is also used, with a point cloud captured by one of the 3D RealSense cameras integrated in the workcell, which is located directly below the rods.

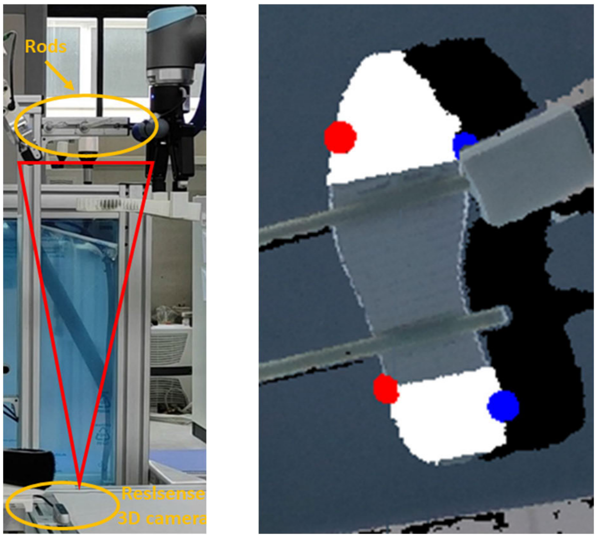

FIGURE 19. **Left: rods and 3D camera location. Right: calculated grasping points.**

The software calculates two pairs of grasping points: in the toe area and in the heel area. The points of the heel area are used for grasping with the first robot, leaving enough space for the second robot to grasp the outsole from the toe area in the next step, thus minimizing the risk of collision between them during the subsequent multi-robot manipulation.

Once the image from the RealSense camera is obtained, the robot is moved to the bottom part of the sole, and from the grasping points obtained and with the use of MoveIt, the position of the whole robot to reach these points is calculated. The movement is performed, and the gripper closes to grasp the outsole again, this time from below.

Once the outsole is grasped from the bottom part, the only step remaining is to rotate it 180°, in order to leave it in a suitable position to be grasped by the second robot and to perform the subsequent assembly onto the shoe upper.

After rotating the outsole 180°, the second robot has to grasp it from the other end, that is, from the toe area, as it can be observed in Figure 22.

To ensure that the grasping points for the second robot are correct, they must be obtained again, using the same RealSense camera located under the rods, but in this case, selecting the grasping points of the toe area.

Now, the outsole is grasped with the two robots, and they must be moved synchronously to carry the outsole to the assembly station.

4) ASSEMBLING STATION

This station performs the bonding process between the shoe outsole and upper. It starts with the outsole being grasped by the two robots and inverted, ready to be joined to the upper.

FIGURE 20. Sequence of grasping the outsole from below.

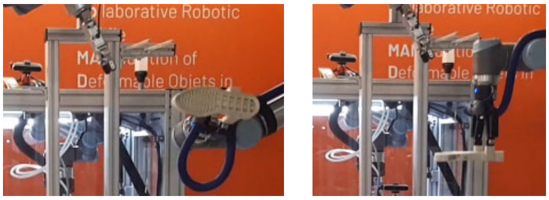

FIGURE 21. Rotating the outsole 180°.

FIGURE 22. Grasping the outsole with the second robot.

At this point, the two robots move in a coordinated way, transporting the outsole to the upper of the lasted shoe, which has been fixed upside down on the structure (see Figure 24). Once the outsole is located at a safe distance over the shoe, the assembly operation is performed, with the two robots moving more slowly to specific points calculated on the lasted shoe with a 3D vision system.

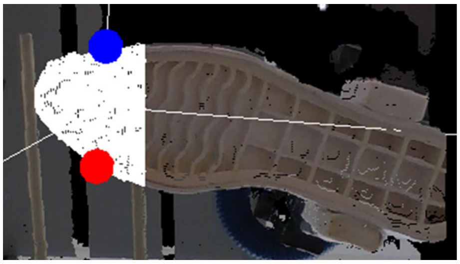

FIGURE 23. Calculated grasping points for the second robot.

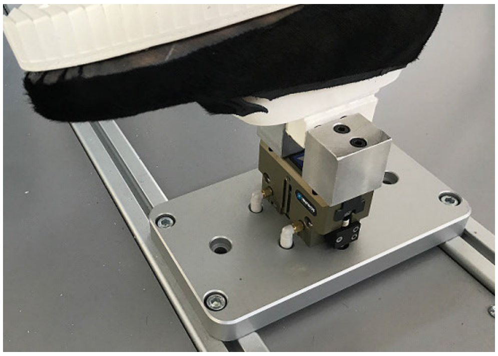

FIGURE 24. Pneumatic clamp for the last.

Once the shoe and the sole are joined together, a small pressing step is performed using the grippers, first with one robot, and then with the other, in order to ensure that the joint does not move during the process.

After this process, the shoe is ready to be inserted in the press to finish the bonding process correctly.

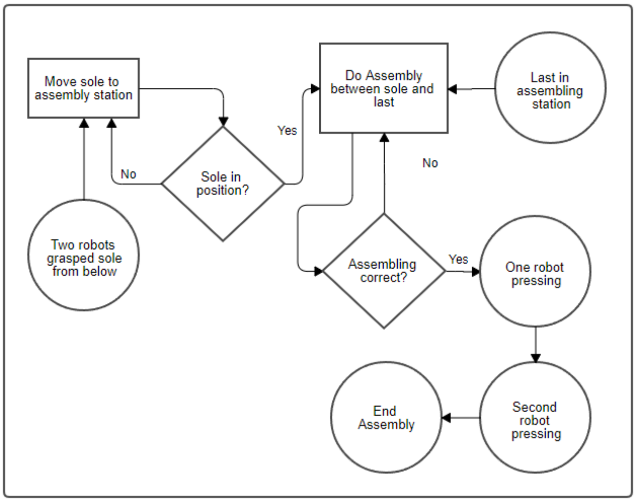

FIGURE 25. Assembly station scheme.

Movements in this station could be differentiated into two types. The first one is a movement of considerable distance and can be performed at high speed since the final position is predefined and great precision is not required. This requires a perfect synchronization between the two robots, therefore, this movement is performed using UR Script with synchronization through physical signals, as described previously.

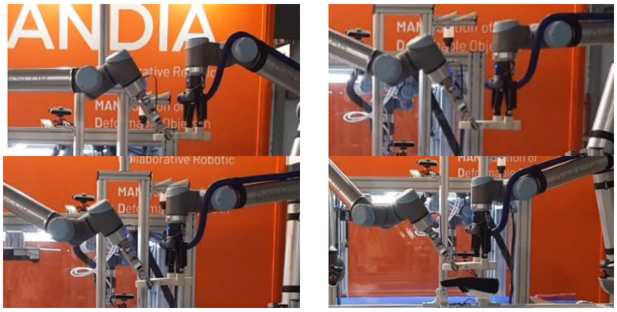

FIGURE 26. Moving synchronously from the rotation station to the lasted shoe.

Once the outsole has been placed on the shoe, the second type of movement begins. To perform this task, target points over the shoe upper for each of the grippers must be calculated, and the movement of both robots has to be controlled [36], [37], [38] with the help of the 3D vision system [39], [40] that has been installed in the structure of the system. This movement, despite requiring high precision in the target location, is a slow and short-distance movement, therefore, synchronization is not extremely relevant. This makes it a good choice for the movement sending commands to axis topics and synchronization through messages in ROS, as described previously.

To ensure that the outsole is correctly joined to the upper the system tracks [39] some points of the outsole using the 3D vision system to adapt the shape to the upper part of the shoe.

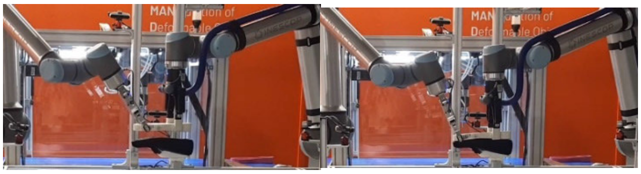

FIGURE 27. Assembling the outsole onto the lasted shoe.

When assembly is finished, and with the aim of strengthening the joint, a final pressing step is performed, using the robots' own grippers. To this end, first with one gripper, and then with the other, the following steps are carried out:

- Releasing the sole by opening the gripper.
- Raising the gripper approximately 15 cm.
- Closing the fingers to obtain a surface to press on.
- Moving the gripper downwards until it meets the sole and pressing.

The proposed systems manage different types of information and devices. In Figure 29 a general diagram about the software-hardware system can be observed.

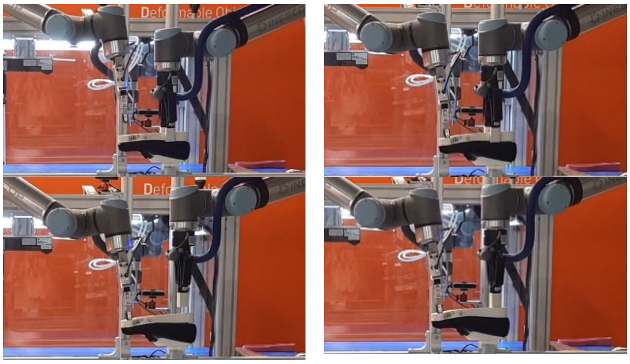

FIGURE 28. Pressing the outsole to the shoe.

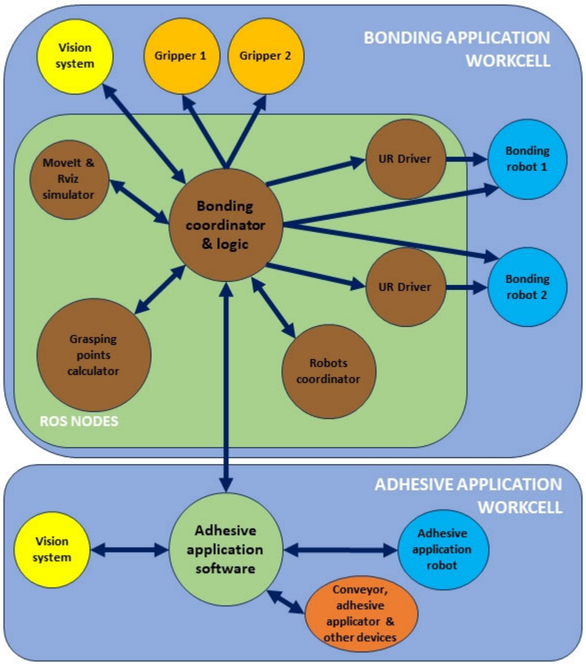

FIGURE 29. General schema.

The adhesive application workcell, composed of its corresponding software, which manages the robot for the adhesive application, the vision system, the adhesive applicator, and other devices. This workcell communicates with the assembly workcell through the ROS node responsible for coordination and logic.

This ROS node is the heart of the assembly cell, establishing direct communication with the grippers and the two robots in the cell using UR drivers for ROS embedded in their respective nodes or directly, depending on the desired movement type. Trajectories are computed using MoveIt and simulated in RViz through a separate node. To facilitate software coordination between the two robots, a dedicated node called the "Robot Coordinator" is employed.

Moreover, the second major node of the cell is responsible for calculating the grasping points, for which it communicates with the hardware of the vision system. The main node also communicates with the vision to carry out the assembly process itself.

V. RESULTS

The system is composed of multiple sub-systems that can be tested and evaluated separately. The overall performance of the demonstrator will depend on the results obtained in each of these areas.

First, and to evaluate the conveyor grasping station, the correct calculation of the grasping points is crucial, as well as the subsequent grasping of the soles. Many grasping point calculation tests were conducted with good results [35]. Regarding the grasping performance itself, multiple tests were carried out with different models of soles on the demonstrator.

FIGURE 30. **Grasping of different models of outsoles.**

The overall grasping performance is satisfactory, especially when the soles are thicker, as the grip is more stable. Flexible outsoles do not present a challenge unless they are also excessively thin, as this compromises the gripping ability.

Heeled soles are the most problematic as the heel is not digitized, which greatly affects the center of gravity of the outsole. This implies that the center of gravity calculated and used for the grasping points is not the real one, thus the grip is compromised. However, heeled soles do not fall within the scope of the project, where more emphasis has been placed on flexible soles for men's footwear.

Most of the tests were performed using casual outsoles without side wall or with a relatively small side wall. No test has been carried out with outsoles with a high side wall due the adhesive bead could not be applied optimally to the side wall of the sole. Alternative adhesive application methods, such as spray or spiral, valid for soles with side wall, were considered, but a clean application was not achieved without the outsole becoming stained on the outside, making it difficult to manipulate the sole later with robotic grippers.

In view of these results, a set shoes and outsoles with well-balanced thickness and flexibility were prepared in order to allow other aspects of the demonstrator, such as the synchronization and assembly of the outsole, to be tested reliably. The lasts for these shoes were printed in 3D, as a support to attach each of them to a pneumatic clamp is needed.

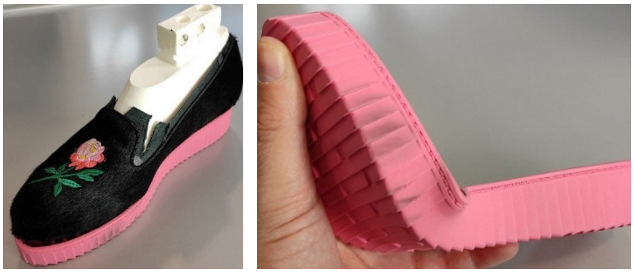

FIGURE 31. **Lasts, shoes and outsoles used for synchronisation and assembly validation.**

Regarding the rotation station, results were remarkably similar to those discussed in the grasping station, as both operations are quite similar. The rotation operation benefits from a thick outsole, which allows for better grip, as the outsole is only grasped from one side for a short time. In general, the rotation of the selected soles functions correctly as long as the grasping points are not too close to the end of the outsole. Optimum performance is obtained with the grasping points at about 32% of the outsole from its rear side.

The assembly station includes two important tasks: the synchronized movement with two robots and the outsole assembly itself.

As commented in the description of the assembling station, the synchronized movement tests conducted obtained the best performance and accuracy results using physical signal synchronization for the long movement to the assembly station and ROS message synchronization for the assembly movement.

To analyze the precision of the dual robotic arm collaboration, we can consider a set $N = \{1,\ 2\}$ of robots with the ability to move kinematically through several 3D points:

$$q_i = (x_i, y_i, z_i)\,, \quad \forall i \in N$$

where q_i denotes robot i's position. Our focus is on a scenario where both robots manipulate an outsole in 3D, each one grasping the sole rigidly in a fixed point of contact on the sole exterior. We can consider:

$$\begin{aligned} q_1 &= (x_1, y_1, z_1) && \text{as the desired position of robot 1} \\ q_2 &= (x_2, y_2, z_2) && \text{as the desired position of robot 2} \\ q'_1 &= \left(x'_1, y'_1, z'_1\right) && \text{as the real position of robot 1} \\ q'_2 &= \left(x'_2, y'_2, z'_2\right) && \text{as the real position of robot 2} \end{aligned}$$

where the desired position is the theoretical coordinate sent to the robot, and the real position is the coordinated read from the robot. So, we can calculate the distance d_d between q_1 and q_2 as the desired distance between robot 1 and robot 2; and d_r as the distance between q'_1 and q'_2 as the distance between the real position between robot 1 and robot 2:

$$d_d = d\left(q_1, q_2\right) = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$$

$$d_r = d\left(q'_1, q'_2\right) = \sqrt{(x'_1 - x'_2)^2 + (y'_1 - y'_2)^2 + (z'_1 - z'_2)^2}$$

The difference between d_d and d_r denotes the error between the desired position and the real position of the two robots:

$$\varepsilon = |d_d - d_r|$$

It is important that this error must be the minimum possible to avoid any distortion of the sole during the movement and to analyze this error we record 10 samples of movements of the assembly station differentiating between the two types of movements synchronization that the station perform, the first one (phase 1) for long and fast movement and the second one (phase 2) for a short, slow and more accuracy movement. The mean of collected data is shown in Figure 32.

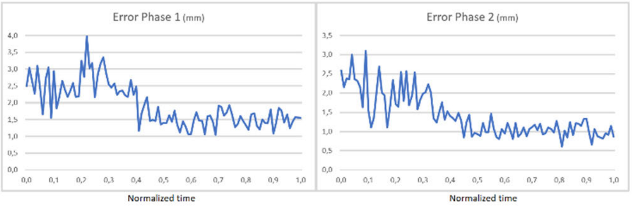

FIGURE 32. Accuracy in the synchronised movement of the robots.

Reviewing the data, we can see that the error for the movement of phase 1 is a bit bigger than phase 2, stabilizing the accuracy error around the middle of the movement at 1.5mm in phase 1 and 1.0mm in phase 2. Due to the flexibility of the outsoles the observed accuracy does not suppose a problem.

The accuracy of assembly is one of the crucial aspects of the whole process, which justifies the need for a complete vision system. This assembly consistently achieved good precision, both in the longitudinal and transverse axis of the outsole, as well as in its orientation. Minor deviations did occur in some cases, but they were not significant in either magnitude or frequency.

To assess the performance of the workcell as a whole, the implementation of the workcell feedback operation was considerably useful, since having the demonstrator running uninterruptedly allowed for an evaluation of its speed and failure rate easily. Tests were carried out using only one or two outsoles in the system at a time. With multiple soles, the second outsole waits at the end of the adhesive application workcell, without interfering with the system, but the process is accelerated to some extent by overlapping the first movements of the first robot with the last movements of the second one.

Both the operation time and the failure rate are an approximation measured at the last iteration of the demonstrator and provide an index of the level of robustness it has reached. These parameters could vary if different types of soles are utilized or if more time is invested in optimizing the robot's movements, which are committed to be safe and smooth rather than to maximize speed. Operation time at around 1 minute should be easily achievable.

TABLE 1. Failure tests.

	Average operation time	Average time without errors	Average failure rate
1 outsole in the system	1' 31''	64 minutes	2,36%
2 outsoles in the system	1' 25''	60 minutes	2,36%

The manual operation does not take longer than 30 seconds. Therefore, the robotic operation should be further optimized in order to make its introduction into a conventional production line feasible.

T-peel strength measurements were carried out to validate the bonding process using standard materials as representative of the upper and soling materials in the footwear industry. Adhesion was obtained from T-peel tests according to the standard EN 1392 [41]. A commercial reactive hot melt polyurethane adhesive was used to prepare the adhesive joints. Before the adhesive application each adherent was surface treated accordingly. After that, PUR adhesive was applied only to one of the adherents, in this case, onto the soling materials to produce the representative upper-to-sole joints. Manually, both adherents were immediately placed in contact and a pressure of 0.8 MPa was applied for 10s to achieve a suitable joint. After that, the adhesive joints are stored for 96h at room temperature to ensure that the adhesive is fully cured. Finally, the T-peel strength was measured in an Instron 1011 test machine using a crosshead speed of 100 mm/min. The values obtained were the average of five replicates (standard deviation was less than 5%). Furthermore, the adhesive joint failure was determined according to Table 2.

TABLE 2. Adhesive joints failure types.

Designation	Description of adhesive joint failure type
S1	Surface peeling of the upper material
S2	Surface peeling of the outsole material
M1	Deep tearing of the upper material
M2	Deep tearing of the outsole material
A1	Detachment of adhesive from the upper material
A2	Detachment of adhesive from the outsole material
N	Contact failure between adhesive films
C	Failure of adhesive cohesion

The validation tests were carried out with different upper-to-sole joints as representatives of the footwear industry. On the one hand, as upper materials, leather, patent leather, suede and a textile have been selected. On the other hand, as soling materials, commercial outsoles were used such as a thermoplastic polyurethane (TPU), a styrene-butadiene-styrene thermoplastic rubber (TR), leather and an ethylene-vinyl-acetate copolymer (EVA) have been selected.

TABLE 3. T-peel strength results.

Upper material	Outsole material	Adhesion value (N/mm)	Aspects (% designation)
Leather	TPU	5.4	100S1
Patent leather	TPU	5.2	100S1
Suede	TPU	4.4	100S1
Textile	TPU	5.3	100S1
Leather	TR	5.2	100S1
Patent leather	TR	4.8	100S1
Suede	TR	4.4	90S1/10S2
Textile	TR	3.6	90S1/10A2
Leather	Leather	6.3	100S1
Patent leather	Leather	5.0	100S1
Suede	Leather	4.2	100S1
Textile	Leather	8.7	100S1
Leather	EVA	5.3	60S1/40S2
Patent leather	EVA	3.6	60S1/20M2/10A2/10N
Suede	EVA	4.2	20S1/60S2/20M2
Textile	EVA	5.2	100S1

Table 3 includes the obtained results for the different upper-to-sole adhesive joints considered. As conclusion, all adhesive joints fulfill the technical requirements of the most demanding joints in the footwear industry.

However, as a research prototype, the workcell developed demonstrates the feasibility of automating the bonding operation and can be evaluated in its current state for introduction into automated production lines with limited human interaction.

VI. CONCLUSION AND FUTURE WORK

The knowledge generated in this project is extensive, covering a diverse range of typologies employed in the described demonstrator. The creation of this demonstrator required a coordinated research and development effort across various domains, including artificial vision, robotic manipulation, multi-robot synchronization, and deformation control of flexible materials.

The novelty of the proposed work lies mainly in the sector to which it is addressed, footwear. The system shown in the article is not intended for mass production, but rather for small and medium-sized footwear manufacturing factories, which do not manufacture more than 800-1000 pairs per day, frequently varying the model of footwear manufactured.

The final demonstrator developed performs a standard assembly operation between a flexible object (outsole) and a rigid object (lasted shoe). These types of joints occur continuously in many industrial operations and can partially or completely admit many of the techniques described in this paper.

The objectives proposed in this research have been reached, obtaining the automation of a manufacturing process where the manipulation of flexible and deformable objects has been achieved. The proposed solution improves the safety and health of workers, avoiding the manipulation of hazardous materials and the execution of repetitive tasks. Moreover, the obtained system could be extrapolated to other sectors such as meat, toys, furniture or textile, among others. These can benefit from technologies such as control of deformable/flexible objects, multi-robot control or artificial vision, helping thus in the automation of processes, which is one of the main ways to improve the efficiency of manufacturing chains and raise the productivity of the industry. Improving the productivity of these companies is vital to ensure they continue producing in Europe as well as the survival of the jobs they generate, which become higher quality, knowledge-intensive and more technologically advanced.

For future research, optimizing the whole process and improving the usability for a wide range of shoes and outsoles is proposed. The connection of the described operation with the required previous and subsequent step should be addressed. In the previous step, outsoles must be prepared for the application of adhesive, where a robot could apply atmospheric plasma treatment [42], [43]. In the subsequent step, the whole shoe must be inserted in a press to consolidate the bonding; this operation can be also conducted by a robot.

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JOSÉ-FRANCISCO GÓMEZ-HERNÁNDEZ was born in Spain, in 1975. He received the degree in computer science from the University of Alicante, Spain, in 1999. He began his professional career as a Researcher in CAD/CAM software focused on footwear design and manufacturing, including machining of footwear components and robotics. He is currently a Senior Researcher Fellow with INESCOP, Alicante, Spain and the Head of the Advanced Manufacturing Unit. His research interests include robotics and manufacturing. He also has participated in several research projects for the footwear sector. Specifically, he has worked in tasks related to the robotization of footwear productions tasks and machining process.

JOSÉ-MARÍA GUTIÉRREZ-HERNÁNDEZ was born in Spain, in 1984. He received the degree in computer science from the University of Alicante, Spain, in 2007. He began his professional career working as a Video Game Developer. After that, he transitioned to become a Researcher in software development for the footwear industry, including CAD technologies, computer vision, and robotics. He is currently a Senior Developer in the robotics department with INESCOP, Alicante, Spain, where he has worked on multiple projects focused on automating the footwear industry.

ANTONIO JIMENO-MORENILLA was born in Spain, in 1970. He received the Ph.D. degree from the University of Alicante, in 2003. He is currently a Full Professor with the Computer Technology Department, University of Alicante, Spain. His research interests include computational geometry for design and manufacturing, rapid and virtual prototyping, and high-performance computer architectures. He also has considerable experience in the investigation of the professional skills of computer engineers.

JOSÉ-LUIS SÁNCHEZ-ROMERO was born in Spain, in 1970. He received the Ph.D. degree from the University of Alicante, in 2009. He is currently an Associate Professor with the Computer Technology Department, University of Alicante, Spain. His research interests include computational geometry for design and manufacturing, parallel computing, optimization algorithms, and high-performance computer architectures.

MARÍA-DOLORES FABREGAT-PERIAGO was born in Spain, in 1963. She received the degree in industrial engineering from the University of Cartagena, Spain, in 1985. She began her professional career as a Researcher in electronics development focused on control and automation of industrial process related with footwear production. She is currently a Senior Researcher Fellow with INESCOP, Alicante, Spain, and the Head of the Automation and Robotics Department. Her research interests include robotics and manufacturing. She also has participated in several research projects for the footwear sector. Specifically, she has worked in tasks related to the robotization of footwear productions tasks and machining process.

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