Cooperative human-robot polishing for the task of patina polishing on high-quality leather shoes

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Research Article

Keywords: Robotics, Industry, Human-robot, Collaborative robot, Shoe

Posted Date: August 2nd, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1857636/v1

Cooperative human-robot polishing for the task of patina polishing on high-quality leather shoes

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Abstract:
A patina is essentially the weathered look a piece of leather takes on as it ages. The patina finishing aspect can be also generated or grown artificially by scrubbing the leather surface with specific products. This research proposes a novel solution for bringing over automation to grow patina on leather footwear manufacturing using a new co-creative method based on cooperative robotics. These kinds of manual finishing operations on small objects are delicate and regularly need slight modifications carried out by skilled artisans, which adds complexity to the process automation and implies various key aspects to consider. This novel solution includes the design and implementation of a collaborative tool specially designed to grow patina finishing on shoe surface. The system accelerates the process in pursuit of time-saving without disregarding the work finishing quality. For this purpose, the use of a collaborative robot with a built-in constant contact force control is used in this research, together with an existing software function for manual path recording. The use of both tools in complementarity with the knowledge of the craftsman leads the robot end-effector adaptation to the inherent curved-surfaces over the shoe. Besides, some path corrections and tool orientation improvements are suggested based on data from a CAD model for the task to be accurately accomplished. This work presents a novel approach for automatic and semi-automatic shoe patina growing in the footwear industry. The solution has been successfully integrated in a real production line and it is currently in use.

Keywords: Robotics, Industry, Human-robot, Collaborative robot, Shoe.

1 Introduction

Bespoke shoes belong to the world of custom shoes and luxury footwear manufacturing, that stands out for being a carefully crafted process. The so-called patina [1] is personalization technique result of many steps for colouring and bleaching leather, through the generation of a process usually called in the industry as “patina growing” [2]. Due to the harsh effects that colour products have on leather, it is important to conclude the patina with a full leather care treatment to maintain its depth. The result is a soft sheen over the leather surface of the shoe, and it requires high skilfulness and dedication for achieving a great gleam. It could be fairly said that bespoke shoes production is more about art than industrial manufacturing [3][4], as it can be seen on images of Figure 1.

Massive shoe manufacturing is nowadays part of the factory industry. After discovering the potential of footwear mass customisation, traditional shoe producers have been integrating modern equipment and methodologies through information and communication technologies (ICT) to capture a much wider range of consumers, as described in preliminary studies [5]. However, in the fashion footwear industry, many operations are still handcrafted due to the high product variability and the need for ensuring the best product quality. A great number of sizes, colours, and leather qualities of footwear models are handled in complex manufacturing and assembly processes. In the particular case of bespoke shoemaking, which is grounded on the expertise of the artisan, the shining procedure consists of an iterative process of the addition of different proportions of water and wax, and specific drying times during several stages. In this context, the integration of automation-based solutions finds various limitations. Moreover, despite the evident benefit of modernizing the handmade approach to the customers using autonomous robotized systems, artisan businesses within the fashion footwear industry still offer some reluctancy to bringing automation to their production lines. The backbone of these small to medium artisan business is not always capable to invest large amounts of capital or willing to take risks that may interfere with the production flow [6].

The high added value shoe manufacturing is strongly characterized for giving the human-touch to their products, to guarantee the excellent quality in the final result, which make them very unique and elitist. This factor should be taken into account and thus, the integration of a cooperative solution for the human-robot interaction becomes very meaningful when designing an automatic system for this kind of industry. This paper describes a practical approach for soft polishing in a collaborative environment with the craftsman and a robotic system.

Figure 1: Shoes provided of a shiny handmade patina finishing (courtesy of Bespoke Factory Group)

1.1 Related works

Polishing processes can be encountered in many applications all across the industrial field, from car body polishing in the automotive industry [7] to mould manufacturing [8]. Several studies considering path planning [9], CAD systems and force control [10][11] have been developed with the aimed purpose of performing polishing tasks over complex geometry workpieces.
Footwear manufacturing is not exempt from specialized machinery or automated operations including robotic solutions [12][4] with a rising need for production monitoring [13]. In the last two decades, several projects for the footwear industry have emerged supported by the European Commission to transform a mass-produced product to a mass-customized one [14]. In 2010 arises the IDEA-Foot project aimed at the introduction of new methods for shoe standardization and the transfer of the geometrical information from the design to the production process in a digital standard data format [15].
Nevertheless, in the fashion footwear industry, most production is still mainly handcrafted, and short-production runs are generally handled as required by customization. Due to the complexity of the manufacturing process and the importance of the final quality, few operations can be completely automatized. In this context, a group of Robotic solution providers and Research institutes, along with Shoe manufacturers formed in 2010 the ROBOFOOT consortium [16][17]. It was conceived to promote the implementation of new manipulation strategies and devices for non-rigid parts, sensor-based robot programming and controlling tools through the introduction of smart robots. Within the scope of ROBOFOOT project, some of the initial results achieved [18] were the design and implementation of robotic cells that can combine roughing and gluing or inking and polishing processes. Previous studies have also provided robotic solutions for custom finishing operations in the same cell [19] using computer-aided design (CAD) system for automatic generation, optimization and validation of motion trajectories. Concerning roughing processes or shoe surface treatments, several experimental results have been obtained through computer vision techniques [20][21], cooperative robot control approaches [22], or specific control strategies [23].

In this work, the design of a collaborative environment using sensor-based robot force controlling for real-time adaptation of the trajectory, and optimization with automatic path planning based on CAD/CAM systems have been addressed. Similar approaches in the scope of shoe manufacturing have been described in many studies, especially about cooperative solutions [24], CAD-CAM generated tool paths and the use of a force-controlled head [25].

1.2 Objective of the research

The goal of this work is to give an automated functional and reliable solution to shoe patina application in the stage of the shining process. This task is performed by a 6DOF robot in collaboration with the craftsman, resulting in an improvement of the working conditions along with the productivity, and without disregarding the quality of the final product. Thus, a robotic cell is designed, implemented and tested in an artisan-based production. The selection of a collaborative robot accounts for the coexistence of manual operations with robotized ones: the operator interacts cooperatively with the robot during recording and supervision tasks and both share the same working area. To this end, an easy and intuitive way for manual path recording performed by the artisan while guiding the robot in sensitive motion is provided, and complemented with other automatic and partially automatic path generation alternatives based on a CAD model. Following this purpose and based on [7][26], a novel and ergonomic cooperative tool design has been developed to allow access to small concave areas of the shoe, maximizing human-robot cooperation. The tool has been designed specially for this application by a trial and error procedure to adjust the shaft length, the size, shape, separation and angle of handlers, accomplishing safety regulations and following a practical orientation focused on installing the final robotic cell in a real production line.

The polishing tool is intended to maintain the orthogonality with the shoe surfaces when applying the abrasive force, following the polishing techniques used by the experts. In the handmade process, the craftsman makes pressure on the leather moving the hand in circles with respect to the shoe surface and maintaining the relative movement parallel, so the applied force of their fingers is always orthogonal. The use of CAD/CAM data is suggested to improve the accuracy of the path generation and robot performance, introducing modifications in the orientation of the cooperative tool to maintain it orthogonal to the surface. The system can also re-calculate the paths to reduce the gaps or unnecessary overlaps in the recorded trajectories. Tool adaptation to the complex geometry of the shoe is achieved using a constant predefined force between the polishing tool and the leather. The force control is accomplished by the robot utilizing a built-in force-torque sensor mounted in the last wrist. This integrated solution exempts from buying or adding external force controller devices on the robot end-effector, meaning an economic and straightforward alternative.

Because of the lack of robotic programming background of the operators is expected, the system is provided with a graphic user interface (GUI) designed specifically for this polishing application. The process parameters and constraints can be intuitively configured from the robot screen. Another particular aspect to be considered in a collaborative environment is the safety for the operator, but it is also important to ensure that the product leather is not damaged during the process. In these terms, a rubber covering is set around the proposed tool to keep this application collaborative, and a leather-friendly material is used for the polishing task. Moreover, vision-based 3D shoe recognition and model matching is contemplated to ensure the correct location of the target shoe, avoiding potential damage. The proposed system is conceived after a depth analysis of the manual strategies used by qualified workers in fashion footwear polishing. The overall robotic solution has been designed for easy set-up and maintenance. The implementation of the functional prototype of the robotic cell not only increases visibly the capacity production of bespoke shoemaking in a real business, but it accomplishes such a challenging task in partnership with the artisan. The results demonstrate the feasibility of this approach since quality requirements are fulfilled without missing the valued "human-touch". Nonetheless, the real novelty of the presented approach essentially lies in the mere fact that automation in the fashion footwear industry is still, to a certain extent, an unexplored field that needs innovative focuses to continue making technological progress. This work, therefore, aims to propose a methodology for the development of shoe polishing or patina generation systems that can be extrapolated to any other similar application, in the footwear industry or any other leather related industry (e.g. automotive industry, fashion and complements, etc.).

The paper is structured as follows. Section 2 describes de design of the patina generation cell, including the process flow and the novel collaborative tool. Section 3 describes how the shoe is 3D located by the vision system. Section 4 describes how the trajectory is manually or automatically generated. Section 6 presents the experiential setup, its implementation in a real production line and system validation tests. Section 6 shows usability tests performed based on NASA-TLX and SUS questionnaires. Finally, Section 7 summarizes the novelties presented in this work and its final conclusions.

2 Design and implementation of the System

The design and implementation of the systems is basically focused on two steps: The collaborative tool to apply patina on leather shoe surface and; The robot setup where all elements required are integrated. Both of them are presented in the following subsections and elements' connections can be seen in Figure 2, where physical devices (i.e. robot&controller, F/T sensor, cooperative tool, patina cream holder, 3D camera or depth sensor, HMI pad, …) and software developments (i.e. trajectory database, trajectory controller, force control, …) are depicted. Figure 2 shows that the robot has been inverted mounted to reach all required positions and orientations. Doing so, shoulder axis is just over the shoe and access to the object is maximum.

Invert mounting is a very effective way to make the most out of robot's reach. With a robot mounted traditionally on a pedestal, the arm can be outstretch in one direction to polish one side of the shoe. But the workspace is limited to only positive or negative X and Y (relative to robot base). This mounting configuration is the most common in the industry but in this project, the robot is placed over the work piece, increasing the reach by allowing the robot to work in (+/-) X and Y. However, there are some cons to use this configuration. The main one is the need of a mounting structure that fits in the work environment. The structure must consider not only the weight of the robot but the polishing force and the interaction with the operator. All of them usually mean an expensive and bulky support for the robot.

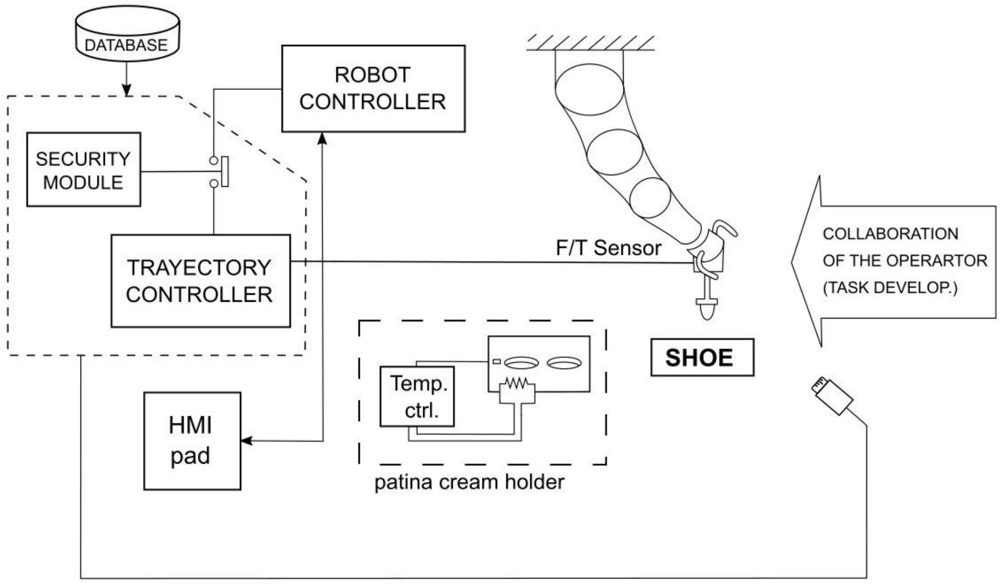


Figure 2: Conceptual design of the robotic cell designed as a novel approach in the shoe industry

2.1 Design and implementation of the Collaborative Tool

Following the guideline described in [27] and previous experience of authors [7], the collaborative tool must gather several requirements: Ergonomic, Lightweight, Collaborative, Tool designed to avoid wrist robot singularities, Easy installation and maintenance and Appropriate for leather treatment.

The tool must be ergonomic and light for better handling and smoother path recording operations. For this purpose, a handlebar made in plastic is integrated into the tool with a pair of knobs where the buttons are placed at the height of the thumbs. Figure 3 shows an exploded view of tool elements meanwhile Figure 4 shows a rendered view with elements description.

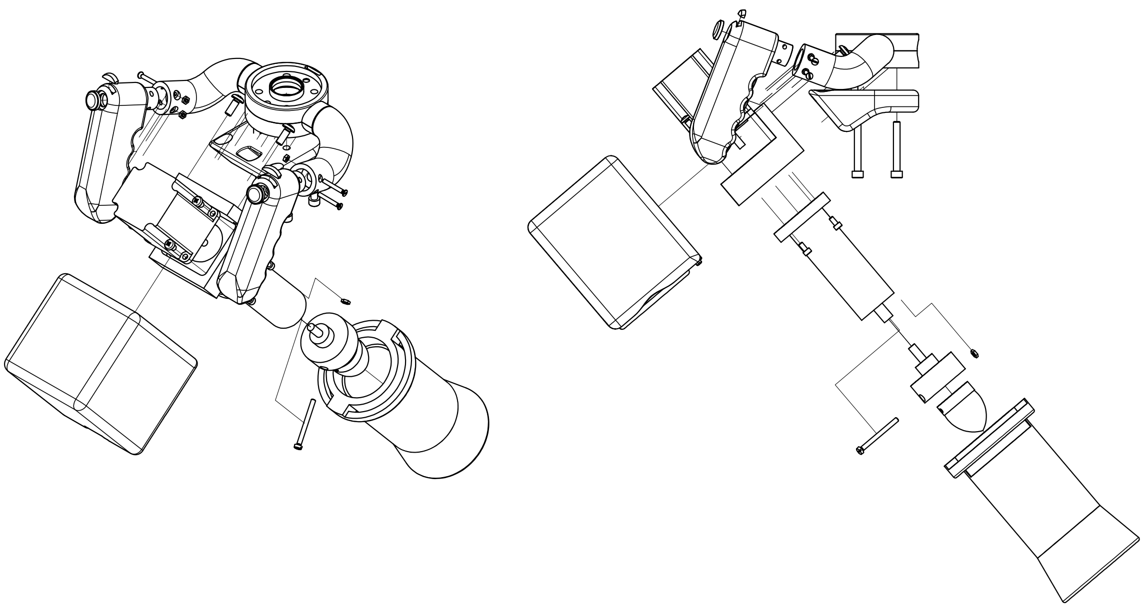


Figure 3: Design process of the collaborative tool for manual patina application

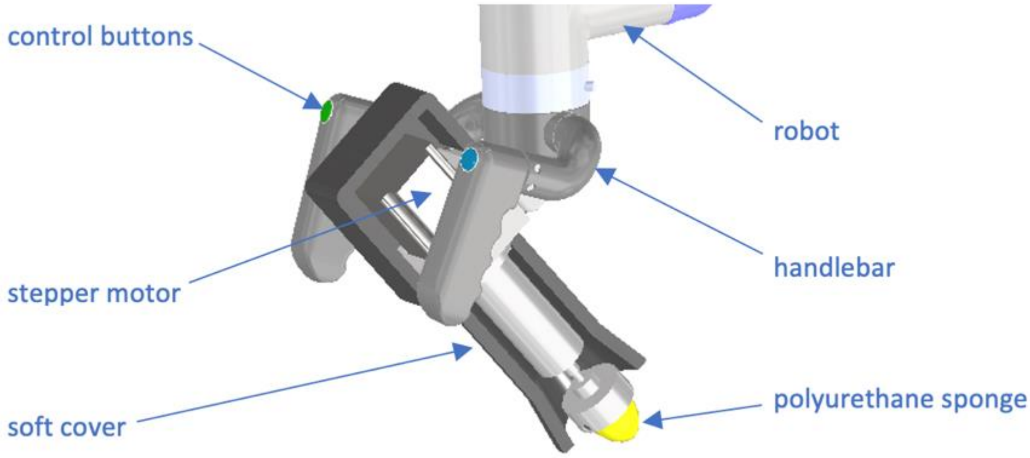


Figure 4: Assembled and rendered collaborative tool with element description

When considering a collaborative application, it is needed to ensure that any device is potentially harmful to the human being. This means that the tool should not contain any dangerous part exposed to the operators to guarantee that they work under safe conditions. Therefore, a rubber housing is designed to cover the metal pieces of the tool. This covering has been 3D printed using *Filaflex* material [28] with a 30% of density getting successful results.

The task of the robot and its position implies to reach some workpiece surface points close to wrist robot's singularities. To avoid this singularity, the polishing tool has been designed turning its Tool Centre Point (TCP) with 45 degrees inclination, following ideas presented in [29][30]. The wrist singularity appears when the axis 4 and the axis 6 become aligned. The TCP would remain stationary but the axis would move rapidly. With the proposed design, alignment of axis 4 and 6 is avoided and therefore the singularity also. In [31], the significance of singularities in the design and control of robot manipulators is described. This review tackles methods in robot kinematics that have been used in this applied research. This 45 degrees inclination design, allows to tackle the application using an UR5e instead of a bigger and more expensive robot like an UR10e. Moreover, it increases ergonomics for the operator due to its relative position related to robot's last link.

The collaborative tool contains a stepper-motor that makes a soft sponge turn to generate the patina over the leather surface. The tool is provided with two push-button as part of the path recording system. The input signal from the button is read by the robot to save the marked points by the user.

The first part of the tool is made in 3D printing with PLA plastic, which is in turn built in several pieces. The handlebar is connected directly to the core part as a single piece that counts with four holes to screw the whole tool to the end of the robotic arm. The knobs are bonded to the handlebar ends by a pair of screws and strong adhesive. The buttons are embedded in the knobs and fixed by a threaded ring (see Figure 3 and Figure 4). The wires pass through an internal hole of the handlebar up to the exterior wall of the core part and then are plugged into the robot connector.

Regarding the motorized system, the second part includes the stepper motor and the mechanical coupling devices, as well as the polishing tool. The casing is fixed through screws to a wedge-shaped piece also made of PLA plastic and screwed directly to the end of the robotic arm through the core part. The motor casing is built in aluminium, except for the critical parts that have to endure radial forces and mechanical stress, which are made in steel. For the same purpose, the motor coupling incorporates two bearings. The polishing tool consists of a polyurethane sponge attached by adhesive to a thin sheet of metal that works as a quick changeover (see Figure 3). When the sponge service life has expired it can be removed from the metal sheet, which can be cleaned with acetone.

Concerning motor selection, several aspects have been taken into account. For this application, the suitable working turning speed for the polishing tool ranges from 200 rpm to 600 rpm. Attending to the motor torque in this particular case, the required torque is not very high. However, some considerations have to be made. On one hand, the system needs a minimum of motor torque to overcome the friction forces to which the polishing tool is exposed. On the other hand, the motor weight increases considerably when looking at robustness with a higher torque motor. The tool weight hampers the smoothness of the path recording functionality. Therefore, there is a trade-off between torque and weight. The selected motor belongs to the line of Nema23 and the model reference is SY42STH47-1684. It has a maximum torque value of 18,9 kg·cm and an approximate weight of 1 kg. The overall weight of the tool is 2.90 kg.

The tool is mounted at the end of the robotic arm through four screws. The maintenance of the sponge has to be done after each shift or working day. The residual wax needs to be removed from the sponge if the robot has finished the task. The disassembly and reassembly of the sponge are fast and straightforward using a clamping bolt. When the sponge has reached its service life, it must be removed from the quick changeover.

The contact with the shoe surface materials considered were cotton lining and polyurethane foam. Cotton lining is currently used by the craftsman when shining the footwear. Polyurethane foams are usually provided to the customer along with the product for the same purpose. The use of polyurethane foam in the make-up market is widespread also. Different make-up foams or sponges were tested presenting excellent results. Moreover, the shape that many of these already manufactured sponges have is ideal for creamy products application and in special, for respectfully treat the leather. Also, because of the properties of the selected polishing material, the system can absorb vibrations and adapt better to the surfaces of complex geometry work pieces, while the fine control of the value of pressure between the tool and the leather becomes less critical.

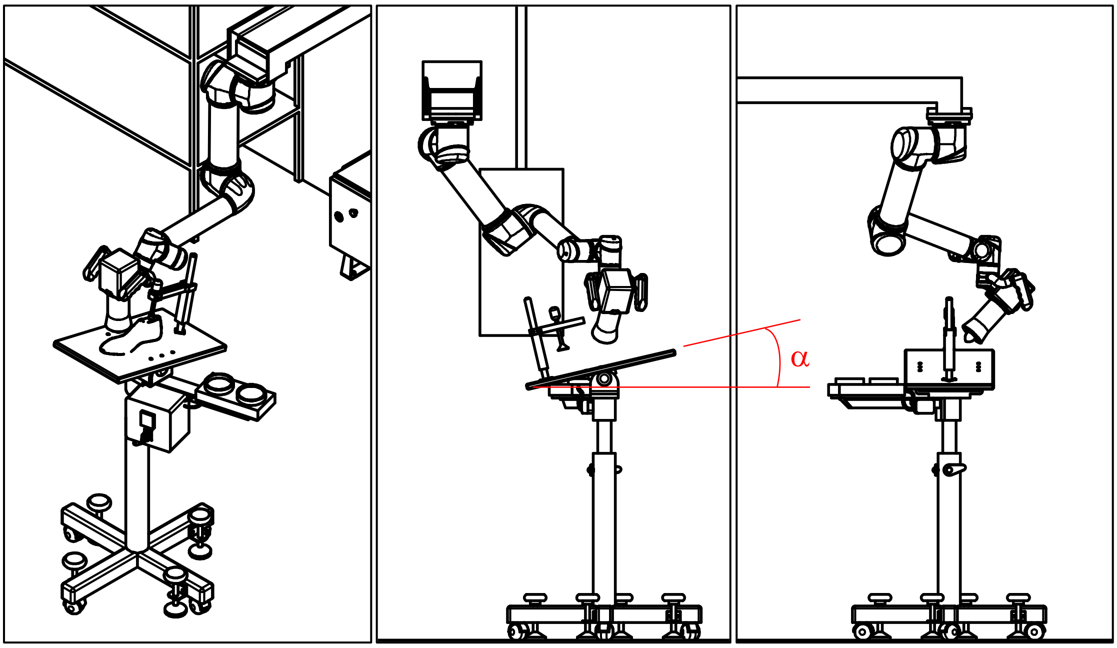
Figure 5 shows the implementation of the collaborative tool attached to the end effector of a robot in an industrial environment. The system is currently installed in Bespoke Factory Group production plant in Almansa, Spain.

Figure 5: Implementation of the collaborative tool attached to the end effector of a robot in an industrial environment

2.2 Design, implementation and operation of the Robotic Cell

The collaborative robot that is used in this work is an UR5e from Universal Robots. This 6-axis robotic arm incorporates a built-in constant contact force control, necessary for the tool surface adaptation and the correct polishing process accomplishment. This robot has been selected due to strategic reasons of the costumer. Collaborators of the company are already users of Universal Robots and the use of the same platforms make easier maintenance, development and modification tasks.

After analyzing the application and considering robot's reach, size of the shoe and the human-robot interaction, it was decided to place the robot upside down, attached to a support structure. Subsequently, the location and use of the rest of the elements related to the process is decided. Figure 6 shows part of the system layout, where the mounted on ceiling robot, the collaborative tool and the shoe stand are shown. The robot must spread the wax with a motor-driven sponge over the shoe surface while the work piece is at a fixed position on a stand. The shoe is placed on an inclined and height-adjustable structure that is accessible for the robot and the operator. This structure has been inclined around 30 degrees (value of α shown in Figure 6) to allow the tool to reach the whole shoe upper. The inclination is required due to the surface features of the heel and the toe.



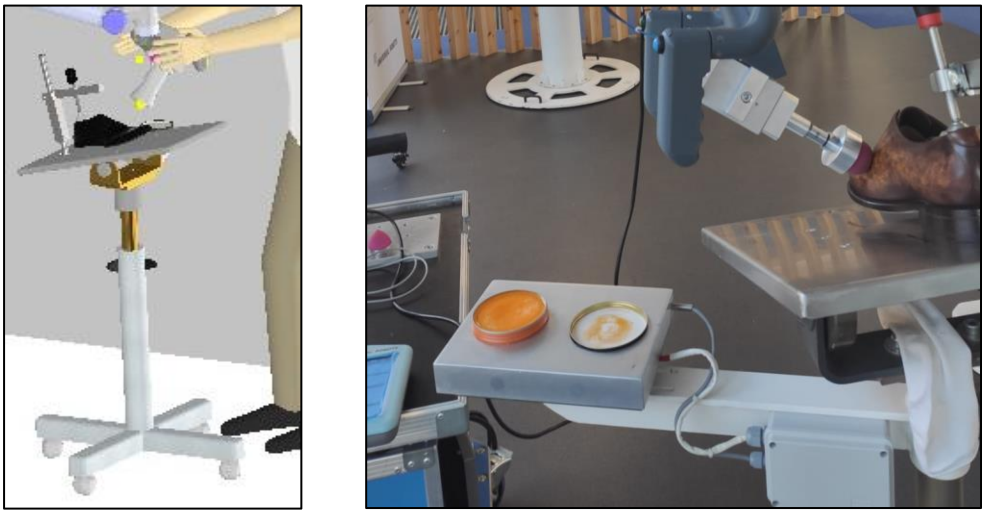
a) Perspective b)Front view c) Lateral view

Figure 6: Partial system layout. Collaborative robot, polishing tool and shoe stand

The cell also includes an electric panel located next to the robot that hosts the logic programmable controller (PLC) in charge of motor-driven system actuation. The PLC uses two digital inputs to set the direction of the motor spin through a three-position switch. The motor speed can be regulated through an integrated analogue input of the PLC coming from a potentiometer. An output pulse signal is generated to control the stepper motor of the patina tool.

The shoe rests on a flat tray with a variable inclination and positioned on a vertical metal structure designed to hold the work piece. The stand can be adjusted in height and comes with a heated steel platter of easy positioning around the column of the structure, where the wax is placed. A temperature controller is mounted next to the wax platter with an on-off switch.

Figure 7a shows the CAD representation of the shoe holder and Figure 7b shows its implementation. The heated plate allows maintaining the wax at a stable temperature during colder seasons. The user can choose the set point temperature from the controller screen to work with the ideal wax texture. To achieve an adequate base is necessary to have certain control over the amount of wax to apply. Wax temperature is directly correlated with its texture, the applied force and the sponge turning speed. The shoe stand also comes with a manual clamping system for comfortable mounting and gripping.



a) Shoe stand representation *b) Wax heating system attached to the shoe stand (image obtained during the lab tests)*

Figure 7: CAD representation of the shoe stand and implementation of the system

The design of the robotic cell has been made considering the operations that must be performed by the robot and by the operator. These operations are described as follows:

(1) Given a shoe model, the operator records the trajectories over the surfaces. To this effect, the operator moves the robot through the tool handlebar using a software function that lets the robot move in "sensitive" motion, that is, with hardly any resistance. This special function compensates the applied forces on the tool, resulting in a smoother robot motion that facilitates the user path recording. Path recording is done in three steps: frontal, left, and right. The flexibility for recording each path lets the operator decide the areas to be treated. It can be avoided, for instance, those parts with straps, buckles, or decorative elements. Then, saved paths are available for further optional modification and optimization.

(2) Optimization functions for trajectories can be done off-line based on a CAD/CAM system. Loading the saved paths over the work piece surface, it is possible to readjust specific points to solve inaccuracies in the path specification or keep the desired orthogonality between the tool and the surface. Optimized points data set can be used for later program executions.

(3) The GUI guides the operator in the definition of the process parameters, such as force values, speed, and other restrictions. Using computer vision, the system can recognize the presence of a shoe and its model. Once the shoe presence is verified, the robot can start the program execution.

(4) The program starts with the robot approximation to the heated wax to get the sponge smeared. Consecutively, the robot proceeds to spread the wax addressing each part of the shoe respectively. According to the process parameters that have been tuned by the operator, the wax application is performed several times on selected surfaces with defined force and speed. The axial force that the robot applies on the shoe surfaces is internally controlled to remain constant along the trajectories. The result is an appropriate layer on which the craftsman can work afterwards, saving him significant labour.

(5) The development of a mirroring software function allows the robot to reproduce the same saved trajectories for the other side of the pair of shoes, resulting in time-saving. In other words, the system offers the possibility of repeating the polishing task in the symmetric pair of a shoe model, once the former is completed in the station. If the mirror function is selected, the robot will stop and wait until operator validation.
(6) When the robot has finished the task, it follows the program flow defined by the operator and aims the next process or returns to home.

Once the robot path has been generated manually or semi-automatically, the robot performs the task autonomously. At any time, the operator can hold the collaborative tool to leave the pre-programmed trajectory and center the patina pad on a specific area. This is done by pressing one of the buttons on the tool. Once the operator has finished the operation in the specific area, the robot can return to the path it was making at the point where it left off and continue until the job is finished. In this way, it is guaranteed that the entire surface of the shoe has been covered in the production process, avoiding leaving open pores in the material.

Due to the system configuration, the expertise of the craftsman is combined with automatic tasks that not only allow the worker to save time and physical effort but can also help unskilled ones with the robot movement programming. These are important working advantages that add value to the system.

Figure 8 shows the flow chart of the system. Figure 9a) depicts the main behaviour of the robotized cell. Figure 10b) shows the approaching process of the tool and the patina application. Finally, Figure 11c) shows the manual path recording flowchart.

3 Computer Vision

The appropriate task performance is strongly determined by adequate shoe detection and positioning [24]. Following the previously defined paths over the surface like presented in [32] and [33], the robot moves with the polishing tool according to data provided in the demonstration step. The shoe is located in a stand equipped with a manual clamping system. Given the small and complex geometry of the workpiece, the high accuracy while addressing the pre-defined target points (teaching step) in the three-dimensional space is a critical aspect to be guaranteed. Therefore, the need for introducing a 3D computer vision technology for autonomous position and orientation recognition is developed.

The proposed vision system consists of a LiDAR camera [34][35] installed at a fixed position in the robotic workspace which maps the environment to detect the presence of a specific shoe model and provide information about its position and orientation [36][37]. The system can recognize the type of shoe and verify if it is placed in the right position or has slight displacements from the original location with a high level of accuracy [38]. The solution identifies the geometrical features of each type of shoe precisely, giving a model match according to the shoe model, size, and left/right shoe [24]. The presented approach of model matching and shoe position recognition provides to the system a validation before the robot program execution.

3.1 3D Shoe Recognition and Model Identification

One of the main features in computer vision inspection is the effect that the environmental light can cause on the material surface of the objects. In this research, an appropriate selection external lighting source is required to work in an open environment shared by operators [39]. The fashion footwear shows significant gleams and work pieces are individually shaped and curved, so the incident light is susceptible to reflections and shades. Moreover, the shoe geometry features must contrast with the background to get an evaluable image by the vision system, so the tray where the shoe is placed must have a matte finishing. To design an effective and robust illumination solution, a *dome illumination* [40], featured by being free of reflections, has been used. *Figure 12* shows the 3D vision system and the whole set-up at CFZ Cobots lab. In this case, the camera, the robot and the shoe can be seen. Figure 13 shows the detection of both shoes (left and right) with its visual features marked by colour. The computer vision package has been developed using ROS (Robot Operating System) [41]. A LiDAR camera connection is done through a node definition, where the footwear location data within the workspace is obtained after scanning the environment. A special library called ObjectNet3D [42] has been used to perform the object recognition. ObjectNet3D has been selected after comparing it with other libraries: *Principal Axle Descriptor*, *G3DNet* and *FusionNet*. Based on accuracy comparation performed in [43], ObjectNet3D has been chosen.

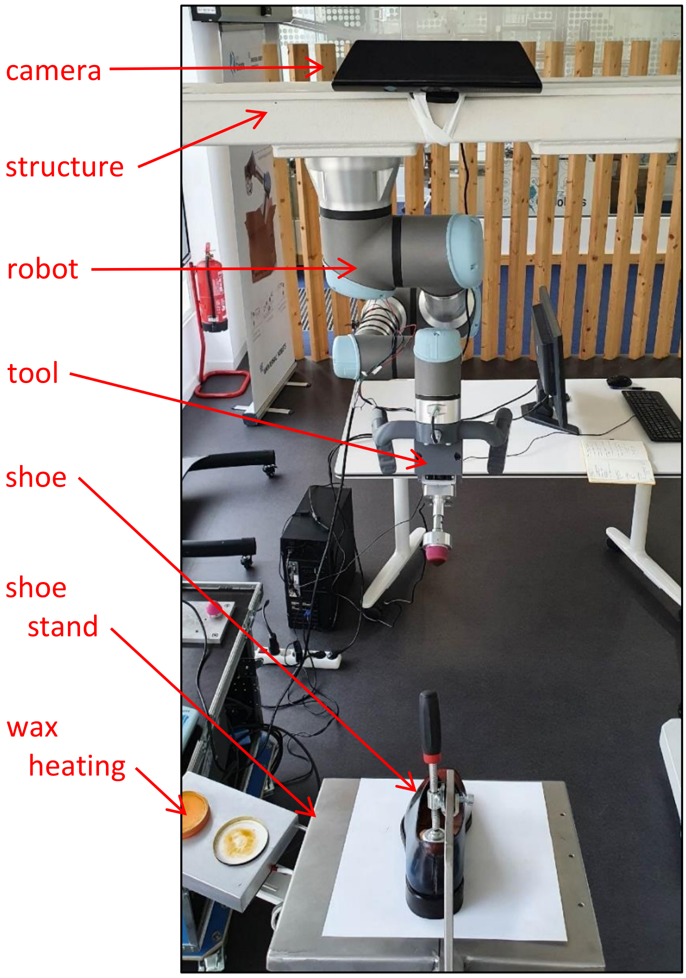
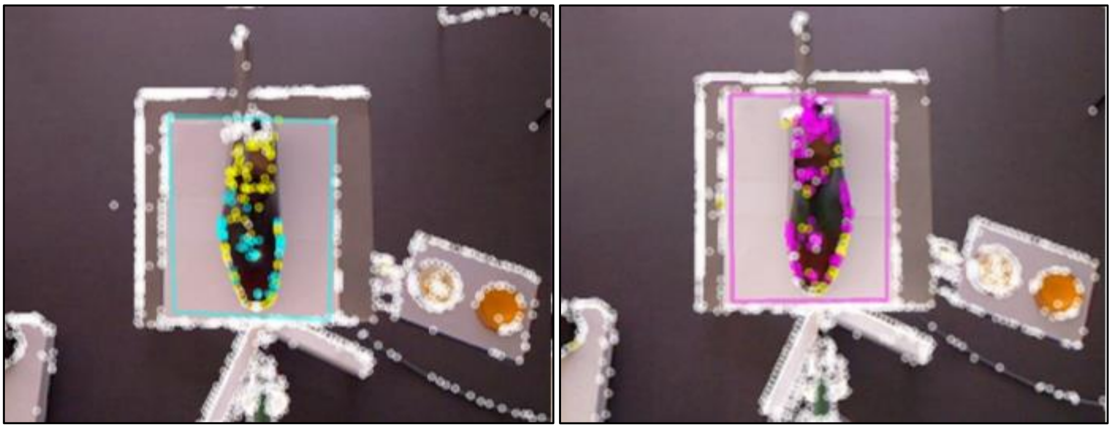


Figure 12: 3D vision system: Laboratory tests



a) Left shoe *b) Right shoe*

Figure 13: Detection and positioning in space of different models of shoes detecting left and right shoe.

The system allows the identification of relative position errors and identify the shoe model, size and foot. The robot starts the program once it has received the verified data from the LiDAR camera. Otherwise, the robot raises a notification to the operator asking for further checks. The design of the computer vision solution is also used to improve the path definition and tool orientation to fulfil the application requirements. Through the introduction of CAD information, paths can be re-calculated automatically while modifying the orientation of the points to have the polishing tool orthogonal to the shoe surface.

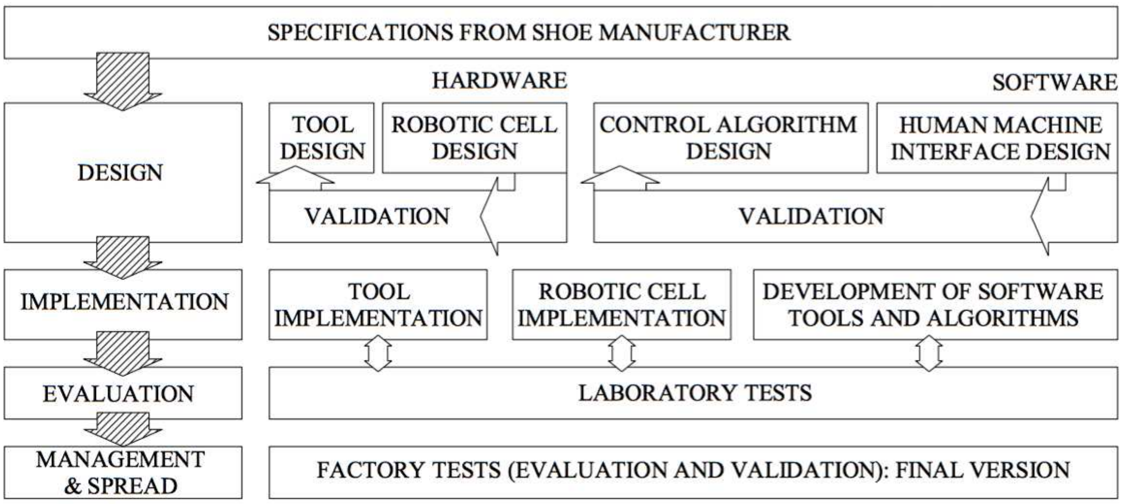


Figure 14: Methodology followed to design, implement and validate the robotized patina finishing application.

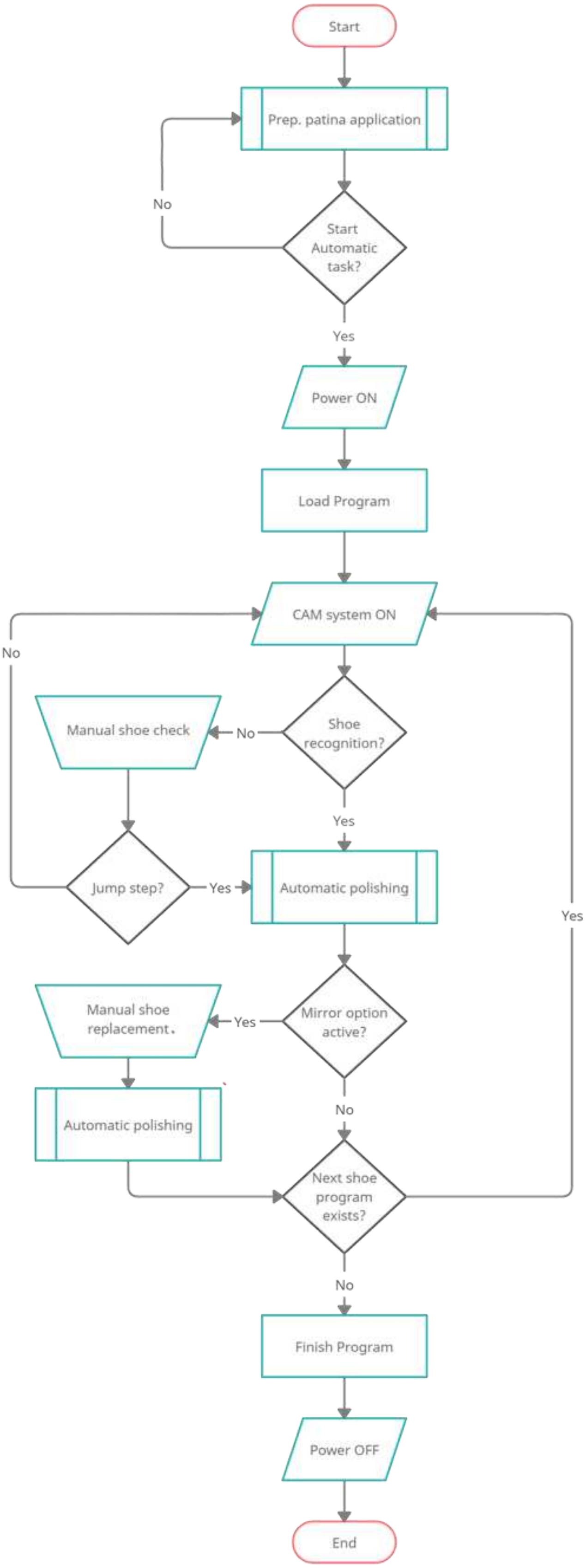
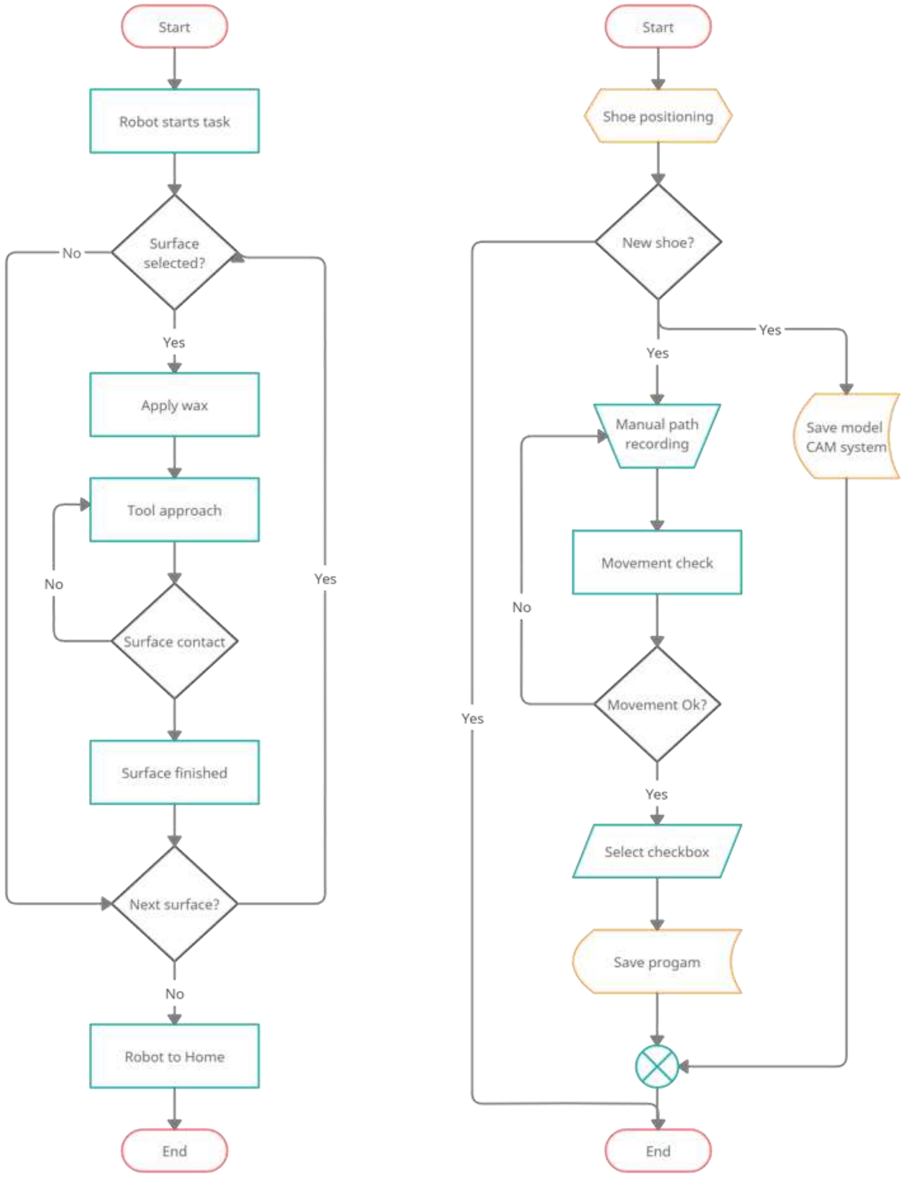


Figure 15: Flow chart of the robotic cell main behaviour



a) *b)*

Figure 16: Sub-charts of the system:
a) Sub-chart 1 – Approach and patina application;
b) Sub-chart 2 – Manual path recording.

4 Operation Description

Figure 14 summarizes the steps followed to design, implement and evaluate the proposed patina growing system. First, a study about the application requirements has been conducted based on interviews with specialized workers. Secondly, a laboratory mock-up has been designed and implemented and finally, experts on robotics and production line workers have validated a factory version of the system. Steps to operate the system are described in Figure 15 flowchart. This flowchart shows the sequence to use the robot in normal operation, when data of the shoe to be polished is stored in the system. A mirror function can be selected to polish a left-shoe having only the trajectories of the same right-shoe model or *vice versa*. Figure 16 shows: a) the patina growing procedure that is executed by the robot and; b) the manual path recording operation that is performed by the operator (teaching).

These flowcharts have been created in collaboration with experienced patina artists, specialists on product industrialization and experts in robotics following the guidelines presented in [44] and they can be extrapolated to any other leather polishing system based on path recording. To grow patina over the leather shoe, the tool has to apply the wax in several layers on small concave and convex surfaces. When addressing complex geometries with the direct use of paths, the helpfulness of a contact force control that enables the sponge to adapt to the changing surfaces avoiding path inaccuracies becomes apparent. Furthermore, for the different sizes of the same model of shoe, the use of a controlled force allows the robot tool to realign with the new body contour and keep the same path plan saved for the model at issue. The force control is a robot's built-in function that allows controlling the applied force in the direction of the tool Z-axis. The robot adjusts its position along the compliant axis to achieve the specified force.

4.1 Manual Teaching

Generating trajectories by hand is an intuitive and easy way of saving paths over the object's surface without the need for learning and using external complex software [45]. In some cases, it can produce greater results versus automatic path generation since they are based on the human experience [46]. The operator can selectively avoid areas that need any or special treat and plan a better trajectory for a specific model driven by its expertise. The robot function for path recording also lets the operator make quick and immediate corrections afterwards to improve the precision in the desired paths [47].
Although the advantages of using manual path recording over the workpiece are well known, the system would be susceptible to human errors since the suitability of the results is dependent on the operator level of experience [48]. It should be noted the importance of maintaining the tool closely perpendicular to the surface at every time during the path recording for an appropriate force control performance. The operator can eventually miss this consideration due to lack of skills or simply by mistake [49]. Additionally, an accurate completely automatic path generation based on machine learning technics could be by far much efficient. In this context, different approaches are described hereafter in which manual teaching is combined with automatic orientation and path generation.

4.2 Manual Teaching with Automatic Orientation

The direct use of the polishing tool for saving the set of points over the surfaces gives an approximate visual notion of the spatial movements that the robot has to perform during the polishing task as it can be seen in previous works like [50]. Although tool position and orientation can be easily set up by hand, an optimization strategy is considered because of possible operator mistakes. Works like [51] show a deep review of automated industrial robot path planning for spray painting process, where the orientation of paint source is particularly relevant. The tool orientation can be readjusted using the data from the CAD model identified by the 3D camera to fit the desired angles for better force control. This orientation based on CAD is used in [52], where an automatic teaching for welding tasks is developed using a laser vision sensor. Likewise, some points can be modified or added off-line to avoid gaps between trajectories and improve the definition of the task. This approach is a simplification of [53], where a teaching-free robot system utilizing three-dimensional CAD product data is developed to perform welding operations.

4.3 Fully-automatized Trajectory Generation

Complete automatic path generation can be performed in simplified robots like in [54], where sub-optimized trajectories can be obtained for 4 degrees of freedom mechanisms (excavators). An automatic collision-free trajectory generation for a 6 degrees of freedom robotic car-painting is presented in [55] where the task is defined as collaborative but the implementation is proposed with industrial robots. The automatic orientation of the tool can be performed using the Force/Torque signal [56] or using the CAD model of the surface like in [57], where a CAD model is used to generate automatically the path of a laser cladding robot in additive manufacturing.

This work has been inspired in [58], where a robot–based flexible manufacturing with intelligent sensing is presented. The article presents a sensor-based concept to carry out short series production with robots. Intelligent sensing extends the previously proposed by the authors approach towards a flexible robotic production. In the approach proposed, trajectories can be drawn from a standard template with defined restrictions such as percentage of overlap, shape-related offsets, or turning radios. The possibility of introducing machine learning for estimated path proposals is also considered. Using data from a set of manual path recordings, the system could generate an appropriate trajectory projected over the object surface like [59].

5 Real implementation of the system in a production line

The results of this project come from a contract signed between *Bespoke Factory Group* (BFG) enterprise and the authors of this article to design and implement the robot at its factory in Almansa (Spain). The company CFZ Cobots SL has collaborated in the development of the project providing software functions and development support. The system has been completely implemented and can be seen in Figure 17. The robot has been positioned at the end of the production line, next to the manual patina section, which occupies an area of around 40 square meters.

5.1 Human-machine interface and task process

Given a shoe model, the operator places it manually and save the initial point for the first trajectory. The user interface (see Figure 19 and Figure 20) shows how to save the starting point and provides the operator with an example of a trajectory to follow (See Figure 18). The ending point must match with the starting point since the approximation position to address the surface is automatically calculated from the defined point. Then, the operator starts the path recording through an available software function that allows the user to start, stop or cancel the path recording from the robot screen. The points over the surfaces are saved using a push button located in the knob of the tool. The operator will follow the same procedure for the separate three surfaces: front-side, left-side and right-side. Next, the operator can configure the parameters of the process, such as specific surface-related features like the tool translational speed, applied forces to surfaces, number of layers, or general functions like enabled surfaces to treat and mirror function activation. The user needs to verify the system before executing the program. The system verification consists of reproducing the resulting robot movements after automatic calculation from the user-defined points in slow motion, to prevent from possible collisions during the process. Once the program counts with the safety check, the operator can run the robot program. The flowchart of this process is depicted on Figure 19 where all steps and situations are considered. The flowchart also contains all options that can be selected in the Graphical User Interface (GUI). This GUI has been designed considering other industrial applications like automotive [60], furniture [61] and porcelain [62] to generate a general flowchart useful in other applications.

Figure 17: Prototype of functional robotized cell for patina application.

a) GUI trajectory guide menu *b) Parameter configuration screen*

Figure 18: Development of the system GUI

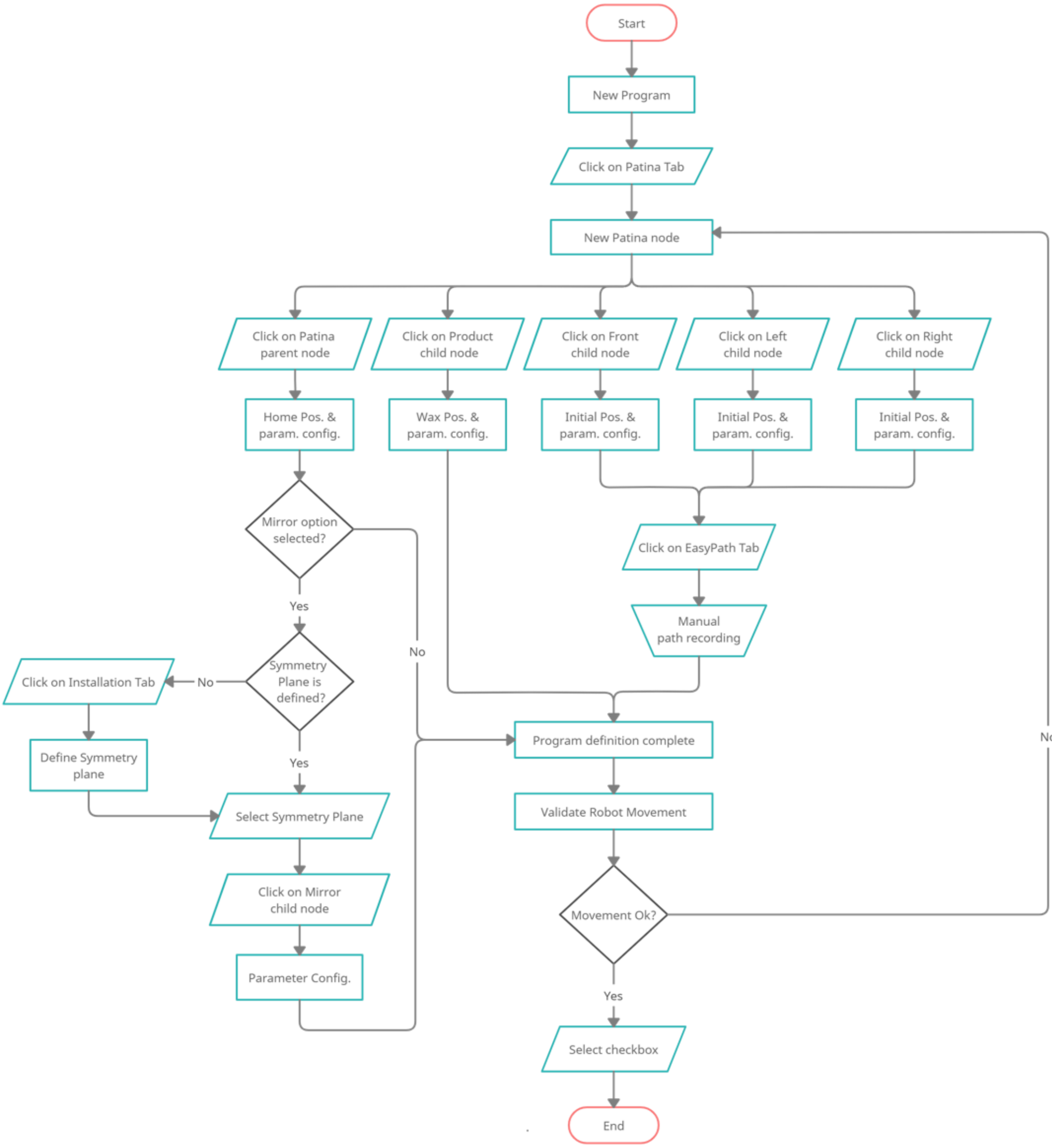


Figure 19: GUI flowchart description

a) Left side view *b) Front view* *c) Right side view*

Figure 20: The GUI provides the user information of the starting point and an example of a trajectory to follow

5.2 Validation Tests

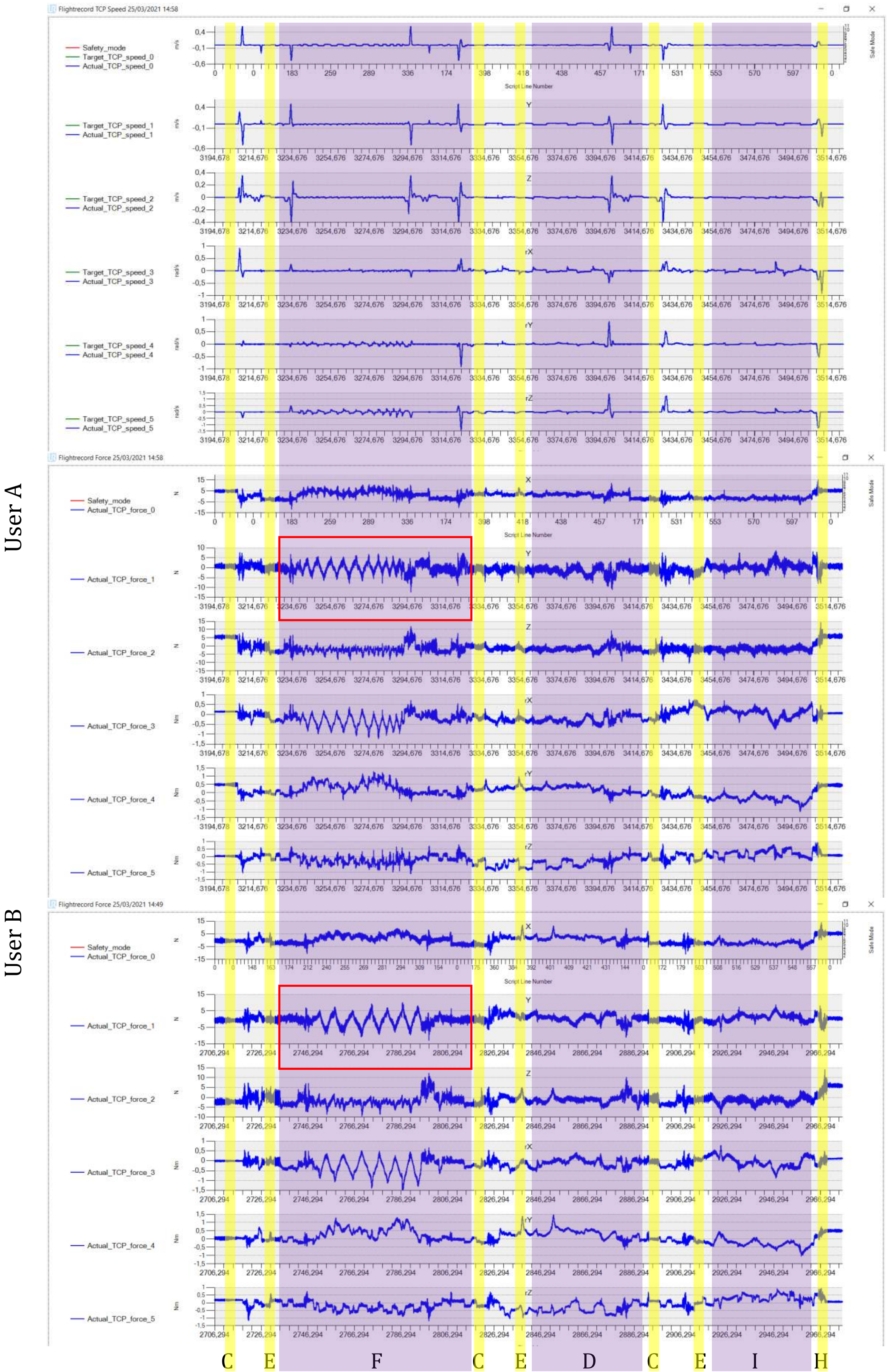
Current time process for handcrafted footwear varies a lot depending on the shoe model. Normally, the first shining layer takes the craftsman about 7 minutes on average. For achieving an appropriate result, one shoe needs between two and four layers of treatment, with approximately one hour of drying time between layers application. Generally, the craftsman deals in first place with the initial layers of the entire amount of shoes for daily delivery. After the initial layer application, the former shoes have completed their drying time and the craftsman starts the next round. The production volume is around 7 or 10 pair of shoes each day. In particular seasons, the demand exceeds the capacity production and the employees are required to work extra hours to handle the number of orders.

First layers are the briefest since the finishing stages need more dedication and finest performance. Typically, the first shining layer application takes one worker at least 3 hours in total for the daily production volume. From this perspective, the robotic cell is formulated to undertake the initial layer development. Further layers are left for the craftsman that gives the last finishing.

The system approach for the prototyped robotic cell is semi-autonomous since the operator has to replace the shoe manually at the stand. Nevertheless, the application can occasionally work to complete further layer treatment under operator supervision in a collaborative performance. The average times for cycle time are directly related to the selected system speed and the number of repetitions configured for each trajectory. The allowed system speed has been customized inside a range of values that safeguards the quality of the finishing and the safety of the operator. For the fastest allowed speed and two repetitions for each trajectory, the system fulfils the quality specifications and takes 10 minutes to complete one shoe. That means that the system is able to practically duplicate the productivity in the first stages. Also, positive assessments from workers highlight that the physical effort that implies eventual production loads diminishes by using the application. These results are analyzed in Section 7.

Figure 21 shows the guiding force associated to two different users performing the same test (user A and user B): Teaching the robot how to polish a whole shoe. This figure contains 10 different areas marked with yellow, for short duration events, and marked in violet, for patina application tasks. The first patina application area corresponds to the front area of the shoe (F), the second area corresponds to the right side of the shoe (D) and the third area corresponds to the left side of the shoe (I). User A is a highly trained in the use of the robot operator and user B is a very little trained in the use of the robot operator. The figure contains two red rectangles showing the smaller force values for the case of user A, while for user B, the applied force is of higher magnitude and more oscillatory.

In the following link: https://www.youtube.com/watch?v=oG_IbJJKNug, a demonstration video can be seen. This video briefly shows how the task of patina creation is manually performed, how the tool is initially introduced testing an actuator and it is also shown lab tests and factory implementation. The system is currently be used at Bespoke Factory Group factory in Almansa, Spain.



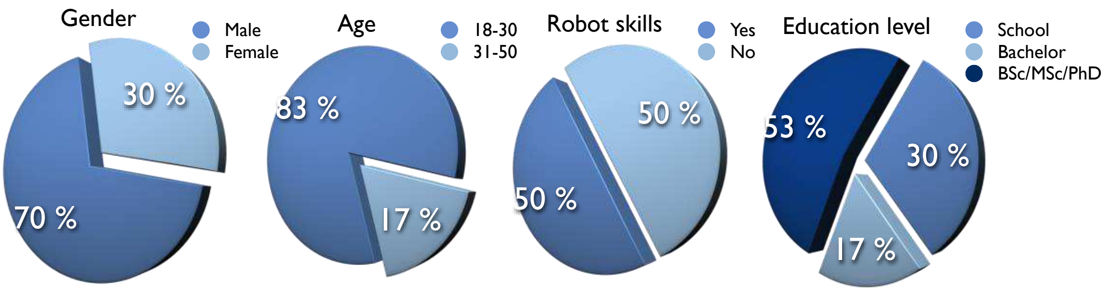
C: Wax application, E: Removal of wax excess, F: Front area patina, D: Right side area patina, I: Left side area patina

Figure 21: Real experiment of two users teaching the robot how to polish a shoe

6 Usability tests

In a similar way to other works [24], several usability tests have been used to validate a system by using user interviews. In particular, two standard questionnaires have been used in this project: the NASA Task Load Index (NASA-TLX) [63] and the System Usability Scale (SUS) [64]. On the one hand, the NASA-TLX questionnaire is considered, as it is commonly used to assess digital and physical experiences in work environments. On the other hand, the SUS questionnaire is considered to assess the usability of the proposed approach, as it is concise and is considered an industry standard.

The system has been installed in the factory and it has been tested by a group of 6 people. Two of them are patina operators of the company (BFG). One of them is an expert patina operator (male) with more than 15 years of experience in performing the task. The other patina operator (female) is a 3 years of experience full competence operator. On the other hand, four experts on engineering (without previous experience on patina handwork) have tested the system. Three of them have advanced knowledge in robotics (one female and two males). The fourth tester has any knowledge on robotics but he (male) is a specialist in mechanical engineering. With this group of people, the aim is to validate the functioning of the system in terms of usability and execution. Figure 22 and Table I show the main features of participants involved in the usability tests, gender, age, patina skills and education level are represented.



a) b) c) d)

Figure 22: Representation of participant features involved in the usability tests

	Gender		Age		Operating robot skills		Level of education				
	Female	Male	18-30	31-50	Yes	No	School	Bachelor	BSc	MSc	PhD
User 1	□			□	□					□	
User 2		□		□	□					□	
User 3		□		□		□		□			
User 4	□		□			□	□				
User 5		□		□		□	□				
User 6		□		□	□						□

Table I: Users that tested the system during the development

A particularly relevant aspect when using SUS or other usability tests is the minimum acceptable sample size [65]. Technically only two users are needed to have some measure of variability (standard deviation) and to generate confidence intervals [66]. Such a small sample size is not normally used to analyze usability tests, however, reliable data can be extracted using only five users [67].

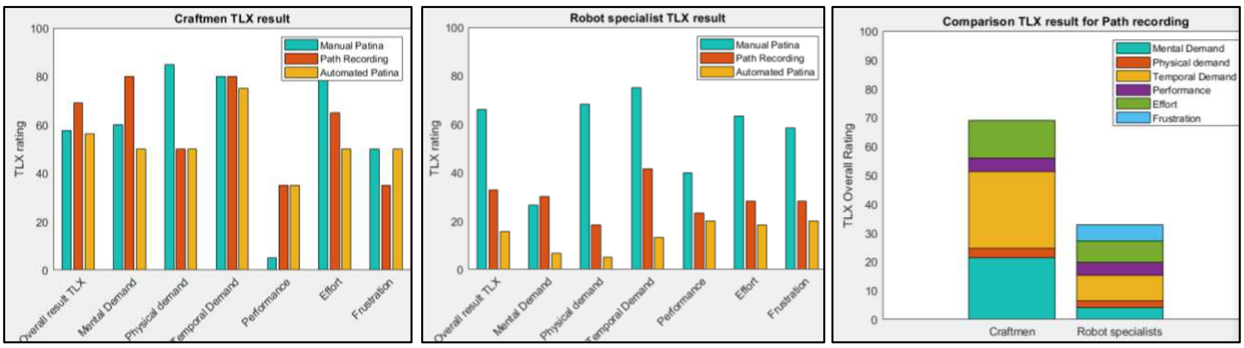
Often (only) 5 or more users are analized for early stage usability studies. The confidence intervals are wide enough and the average SUS score are surprisingly stable. In the state of the art, several computer simulations have been performed showing that with a sample size starting at 5, the sample mean is within six points of the SUS score of a very large sample 50% of the time [65].

Nicholas Pappas summarized in 2010 [68] that if the actual SUS score was a 74, average SUS scores from five users will fall between 66 and 80 half of the time. Seventy-five percent of the time, the score differed by 10 points and 95% of the time, by about 17 points.

Methodology to conduct the test:

- The participant fills in a first form with relevant data: gender, age, operating robot skills and education level.
- The participant practices with the robot to be more confident with its use and maneuvering.
- The participant carries out the test performing the patina task.
- The participant fills in the NASA-TLX and SUS questionnaires related to the experience of performing the test with the task.
- The participant makes comments about his/her global perception and answers some additional general questions.

Additional considerations of the test: The first practice with the robot to be more confident with its use and maneuvering took 10 minutes in all cases (experts and non-experts on robotics); The test includes the whole patina process and it takes between 10 and 15 min; Each user has tested the system three times and information registered is the average punctuation given by the user.

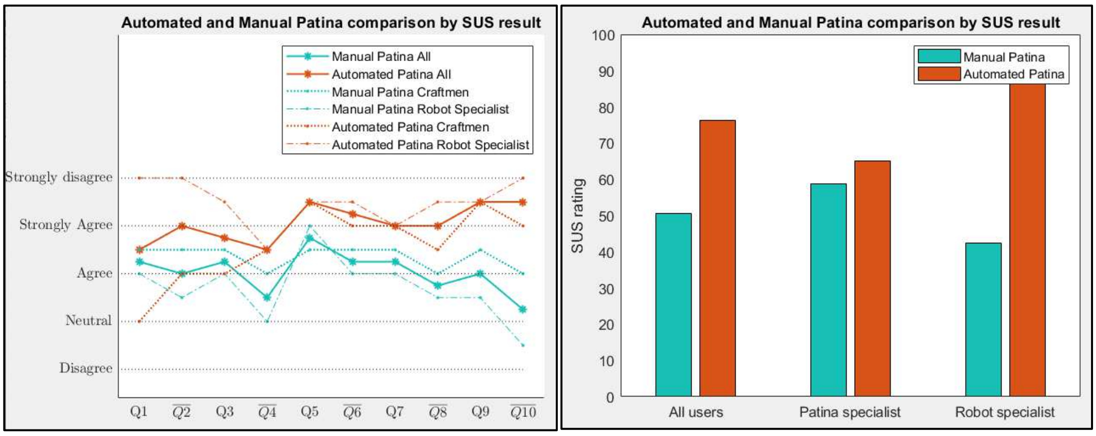


a) Craftsman perception using the robot

b) Robot specialists perception using the robot

c) Perception of demand for path recording task

Figure 23: Results of NASA-TLX [63] usability tests



a) Perception of path recording task *b) Feasibility using the robot*

Figure 24: Results of SUS [64] usability tests

Figure 23a shows that in all cases the effort of manual patina operators is greater when using the robot than when performing the task manually. The only two exceptions to it are the overall effort and frustration in performing the task. This is because path recording takes less time and requires less physical effort in both cases. Figure 23b shows the perception of effort that robotics users have when performing the task manually versus automatically. In this case, and as expected, the perception of effort perceived by the user is much higher when performing the task manually. Figure 23c shows that the perception of effort to perform the path recording is much higher in the case of craftsmen than in the case of robotics specialists.

Figure 24a shows the SUS technique applied to perform the same task. Perception of effort in performing the task is higher when using the robot in almost all cases. This effect is also shown in Figure 24b, because performing the task manually is faster and easier than performing it using the robot, the level of concentration and effort is higher in all cases.

The robot has been used on BFG current production line for 3 months. During this time, it has been possible to validate its behaviour, modifying the robot programme when required to adapt it to the company's needs. The robot is currently being used on BFG factory to support a patina operator who has increased his productivity by around 25%. Although, as previously mentioned, productivity in some stages practically doubles (100% productivity increment), the operator has to put on and take off the shoe manually from the stand and has to access the HMI menus among other tasks, its productivity is reduced to 25%. This reduction in productivity is significant and the team is currently working on automating some tasks to increase this figure.

7 Conclusions

In this paper, a novel collaborative robotic system for handcrafted shoe polishing has been designed. This application of cooperative co-creation is completely new in the footwear industry. The proposed solution focus on trajectory generation and its replication by the robotic arm to accomplish the polishing task. Regarding the type of trajectory generation, three approaches have been suggested according to the degree of autonomy of the final application. The first approach consists of manual path recording by a qualified operator through the straightforward use of the robot tool. The second approach combines the manual path recording with a CAD/CAM system for trajectory optimization. Finally, the last method is based fully on the CAD/CAM digital data for automatic trajectory generation.

The first approach has been considered for experimental validation of a working functional prototype. For this purpose, a complete robotic cell has been implemented in a collaborative environment, where the robot performs the first stage of the polishing task for a shoe located in a static position. Considering the complexity of the work piece geometry, the need for controlling the polishing tool contact force is assumed. With this aim, the collaborative robot UR5e from Universal Robots with a built-in force control function has been selected for this application. Force control is done in the direction of the surface normal, hence the importance of keeping the tool oriented orthogonal to the surface at any time. Taking these factors into account and because of the presence of small concave surfaces in a shoe, a novel cooperative tool focused on this specific application has been designed and implemented maximizing operator's ergonomics and factory needs. An intuitive graphic user-interface has been developed to enable the configuration of process parameters. Versatility in the definition of the tool trajectories and the possibility of customizing the process parameters allows the craftsmen to apply their knowledge, according to the special characteristics and requirements of each area of the shoe. Using computer vision, the 3D shoe recognition and model matching is also addressed. The system is equipped with a LiDAR camera that scans the environment and detects the presence of the footwear, its correct position and the model variant.

The application has been tested by professional staff in the footwear industry giving successful results in terms of quality for the first stages of the process. The system can achieve a suitable base on which the craftsmen can work in subsequent stages, and notably improving their productivity. Therefore, it can be claimed that the application has a positive impact on the initial requirements. Furthermore, the implementation of the described system introduces an innovative solution for this type of industry, both regarding the used materials for polishing and general process design. Still, among the system handicaps it should be underlined the fact that given the great diversity of shapes and styles of footwear, it is not always possible to satisfactorily undertake the polishing task in all of them. Obtaining feasible and reliable solutions when dealing with the automation of complex polishing tasks requires deep research of the whole process. Even so, the proposed solution is potentially suitable to be used in other manufacturing industries due to the methodological procedure presented in this paper, where task flow charts and HMI description are described in depth.

The next steps consist of using up to four shoe stands to get full cell capacity production. In future works, the implementation and validation of the other two presented approaches are contemplated, not only to increase the reliability and robustness of the system by optimization strategies but also the degree of automation of the robotic system. The integration of finer computer vision technology is meant to add more autonomy to the system while introducing an intermediate verification step for process safety conditions. These improvements in the design of the overall robotized solution are expected to enhance the efficiency of the process and contribute to reducing retouching operations.

Acknowledgements

Authors want to thank Bespoke Factory Group (bespokefactory.com) for funding this project, CFZ Cobots (cfzcobots.com) for their technical support on robotics and mechanical design and DESINOPE (desinope.com) for their technical support on process design related with the shoe industry.

Declaration

a. Funding: This work was supported by Bespoke Factory Group (bespokefactory.com)

b. The authors have no relevant financial or non-financial interests to disclose.
c. Availability of data and material: There are not more data.
e. Ethics approval: Not applicable
f. All authors contributed to the study conception and design. Material preparation, data collection and analysis
g. Authors give the consent for publication

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