International Journal on Cybernetics & Informatics (IJCI) Vol. 12, No.1, February 2023

A CYBER-PHYSICAL METHODOLOGY TO AUTOMATE ROBOTIZED FINISHING PROCESSES

Angel Dacal-Nieto[1], Rubén Paz-Cibeira[1], Carmen Fernández-González[1],
Juan José Areal[2], Pablo López-Beiras[2] and Víctor Alonso-Ramos[1]

[1]CTAG – Centro Tecnológico de Automoción de Galicia, O Porriño, Spain
[2]PCAE – Peugeot Citroën Automóviles España (Stellantis), Vigo, Spain

ABSTRACT

Finishing operations represent a crucial stage in manufacturing, where it is necessary either to remove unwanted material from a part, or provide aspect features to it. This includes smoothing, polishing and machining-alike solutions. In this paper, a new methodology to approach the automation of finishing processes in manufacturing, is presented. Four main steps are defined: part measuring, path creation, finishing operation, and part verification. Two use cases, belonging to real workplaces in an automotive factory of the Stellantis group, are presented as validation scenarios. One of these, a cyber-physical system to deburr a weld beam between two parts of complex geometry, has been successfully working in-line for the last ten years. This represents an improvement of the ergonomics of the operators and their working conditions, as well as a reduction of costs. This shows that the automation of finishing process means an opportunity to increase productivity, quality and efficiency in the factory.

KEYWORDS

Finishing, Cyber-Physical-System, Robotics, Automotive, Manufacturing.

1. INTRODUCTION

The execution of manufacturing processes sometimes provokes unwanted accumulations and additions of material on parts which must be removed or smoothed to avoid problems such as dimensional inaccuracies, interference upon assembly, safety hazard during handling of parts, etc [1].

The removal of this undesired material or defects can be labelled as finishing, and groups different types of actions such as smoothing, polishing and other machinings [2]. Although the prevention of the burrs is the best solution, many technologies have to unavoidably deal with the presence of burrs, and will have to in the next decades.

Finishing operations have traditionally been performed manually [3]. However, smoothing, as well as polishing, are unpleasant operations to be performed by a human. Manual smoothing and polishing are very labour intensive, highly skill dependent, expensive, error-prone, inconsistent in quality, and environmentally hazardous due to abrasive dust [4]. Therefore, several automatic smoothing and polishing approaches have been proposed in the past to allow a solution closer to near-net-shape philosophy, faster, safer, and which can produce repetitive results. This depends on several factors, including the kind of material to be deburred, as well as its size and location [5].

David C. Wyld et al. (Eds): NLDML, CCITT, EDUTEC, AUEN -2023
pp. 195-211, 2023. IJCI – 2023 DOI:10.5121/ijci.2023.120116

Under this context, this paper proposes a new methodology to automate finishing processes, as a framework to guide similar developments in manufacturing. Finishing usually involves mechatronics, mechanics, electronics, software engineering and an ad-hoc control engineering development, which allows to solve the problem using an adaptable but systematic procedure, guided by intelligent algorithms.

This methodology has been followed and applied in two use cases, both of them implemented in a Stellantis group automotive factory. One of them consists in the smoothing of a weld beam from the union of two parts of complex geometry, whereas the other use case consists in the polishing of the aforementioned weld beam. The first application is installed in-line since 2012, and has been uninterruptedly working since then (currently 2022).

The paper is organized as follows: Section 2 will present the State of the Art, reviewing the involved technologies. Section 3 will develop the proposed methodology, and Section 4 will present the use cases. Section 5 will show the results and Section 6 will present discussion and conclusions.

2. STATE OF THE ART

Undesired accumulations of material resulting from manufacturing operations have geometries and positions which are unpredictable and unknown. This means that it is necessary to recognize and inspect each part, and no assumptions can be made from one manufactured part to another. Knowing how each specific burr or weld beam is, allows to adapt a further operation using some tool and device combination. The natural way of acquiring those data is using any kind of sensor (Subsection 2.1). Using the information provided by sensors, an adapted finishing technology should be chosen (Subsection 2.2). Therefore, the finishing operation is performed according to a finishing strategy (Subsection 2.3) and control (Subsection 2.4). In this Section these technologies will be commented.

2.1. Sensoring Technology

A sensor is any device able to measure physical features, making them readable by an electronic instrument. The choice of the adequate sensor for such a large set of relevant dimensional measures can be performed using different points of view.

Depending on contact [6], there are contact and non-contact sensors. While non-contact methods, in which optical techniques are included, seem the most suitable in many cases (mainly because of speed, price and precision), contact methods can be useful in cases in which contact force control must be performed, such as the case of robotic polishing systems, as stated in [7], despite having some disadvantages as described in [8]. In the case of contact sensors, there are 6-axis force/torque sensors [9] that extend the sense of touch needed for some kind of processes to lightweight robots, bringing them closer to the capabilities of the human hand, and being able to detect the slightest exerted force and encountered resistance, and react accordingly in real time [10].

Depending on the activity perspective (whether a dynamic element is supplied for inspection), optical techniques are classified into passive or active methods [11]. In order to get a 3D model of the workpiece, samples of active methods are laser triangulation [12] and time-of-flight [13] technologies. The first one is based on projecting a known light pattern on the piece, so this pattern gets deformed by the geometry of the piece. Scanning a large set of profiles, the 3D shape of the piece is built. Time-of-flight sends and receives light pulses over the piece, so measuring the time between emission and reception, the distance to the object can be calculated, and so its shape. On the other hand, a passive method is stereo vision [14], which integrates two images obtained from two different perspectives. Stereo vision needs at least two cameras, which may involve a higher cost. Additionally, its calibration is more complex than the other options, and changing light conditions can produce undesired results. Time-of-flight technology does not usually obtain good results on shining surfaces. Besides, its accuracy and price are still not competitive nowadays. Therefore, in problems where a 3D profile needs to be measured along a piece, laser triangulation has been the most chosen and reliable option in the last years. Other methods, such as conoscopic holography or interferometry, could be more accurate in the future, but they are not currently as robust to be industrialized.

The next decision involves choosing between a smart sensor and a dumb sensor. The first option performs the processing of the image in the same device, meanwhile the second option needs of an external processing unit to process the image acquired by the sensor. According to [15], using an embedded system is a better option, since they are more robust, more efficient, and they allow to save itself other equipment, and minimizes the time of transfer information. One of the greatest advantages of using an integrated system is the elimination of 3D calibration process, which is very complex and sensitive.

The last step concerning sensoring is considering the image processing algorithms to be executed over the acquired images. Edge-detection techniques are among the best options to pre-process the image to perform dimensional calculations that provide all the data needed to guide the operation to be executed. The alternative is cloud processing, which demands fast communications to allow a real-time behaviour.

2.2. Finishing Technology

The first consideration of performing an automated finishing operation is the necessity of a six-axes robot, since other options could not usually deal with an irregular burr geometry. Friction during these operations produce severe vibrations, which forces to use a very robust equipment that saves the mechanic and electric devices involved in the process.

In case of performing a smoothing operation, the first step should be the choice of the rotary direction of the spindle in relation to the feed direction of the workpiece. According to [16], climb milling (Figure 1, left), in which the feed direction of workpiece and the direction of the milling cutter are the same, is much used nowadays than conventional milling (Figure 1, right), in which the milling cutter has the opposite direction of workpiece's feed direction, because it requires less power and the surface gets better results. However, climb milling is not suitable for materials where too much heat is generated, such as forged steel. Therefore, conventional milling or climb milling will be chosen depending on the material to be machined.

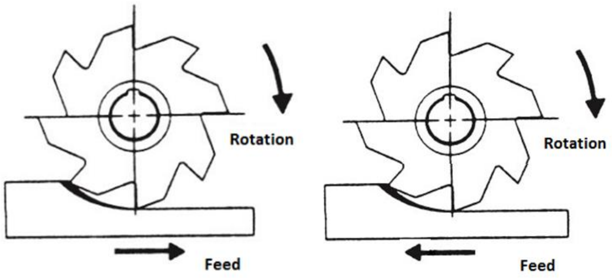

Figure 1. Left: climb milling. Right: conventional milling.

Another decision that must be made, depending on the geometry of the part, is whether to operate with the tool in a lateral or in a frontal position. Milling with the lateral tool presents advantages about the accessibility of the tool and the robot. Nevertheless, frontal milling needs a lower spindle power and causes less torque at the end of the robot. The main difficulty that arises in the first method is the torque transmitted to the robot in areas with a small radius, which causes to play with cutting conditions and strategies that involve an increase in cycle time. In addition, if the workpiece is very heavy and/or big, it allows to place it horizontally, thus making easier its manipulation.

Concerning polishing operations, according to [17], robotic polishing systems could be mainly divided into two types: the first one is a robot hand-hold polishing tool, where the workpiece is fixed to the worktable, suitable for polishing a workpiece with a larger volume or weight, and the second is a robot hand-hold workpiece near a polishing belt for polishing operations, which is suitable for polishing a small volume or weight workpiece. Hand-hold polishing tool is the most common polishing type in which the operation is performed with the tool frontal, as shown in Figure 2 on the right, in which the sanding tool could be a simple pneumatic grinder with adjustable speed in order to be as similar as possible to the grinders used by operators, which are relatively economical.

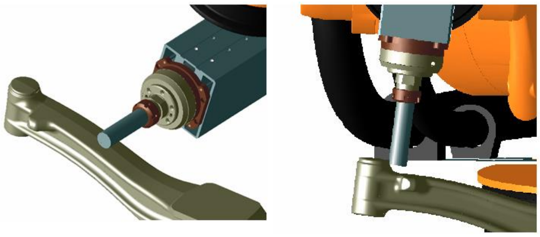

Figure 2. Left: Machining with the tool lateral. Right: Machining with the tool frontal.

2.3. Finishing Strategy

Two main strategies can be suggested depending on the simultaneity of the finishing operation and the necessary sensoring. A first option implies "first measuring, then performing finishing", in two stages. A second option implies "finishing while measuring", i.e. while the piece is being measured, the piece is also being milled at a security distance. Both options are presented in Figure 3.

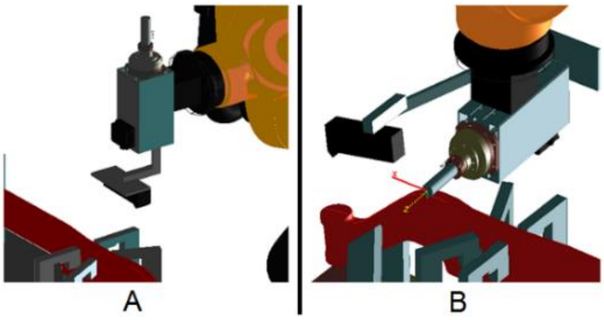

Figure 3. Sensor and milling system. A: First measuring, then milling; B: Finishing while measuring.

Material projections and vibrations could be solved in both methods using some protection and it is proven that vibrations affect equally on both approaches. In addition, some sub-strategies can be studied within option 1. On the one hand, two robots can be used, but this would require a greater economic investment, not always possible. On the other hand, the sensor can be placed on a wall, acting as the workpiece handle. This suggests robust equipment if it is a good-sized workpiece.

2.4. Control system

A robot-based smoothing system is usually composed of a spindle motor, a smoothing tool, and a tool holder, in which a spindle motor rotates the smoothing tool, oscillates the tool in the axial direction, and occasionally rotates the workpiece when it is small and lightweight [18].

Motors can be classified by speed, depending on their rpm rate. The material and the detail that the job requires determine the necessary speed of the spindle motor, being generally necessary higher spindle speed as the smaller the details are required, and as the smaller is the surface to be worked [19]. Pneumatic spindles are the most used, usually being their maximum speed 30.000 rpm with no load, and being relatively cheap, reliable, and with a high power versus weight ratio. According to them, high frequency motors are controlled by a converter to vary the speed between 5.000 rpm and 12.000 rpm, with a maximum horsepower of 0,74 kW and a maximum torque of 0,15 Nm.

Concerning smoothing tools, the most widely used tools in robot-based smoothing automation are solid smoothing tools, which are rotary files made from various materials that have many different shapes. The selection of the correct tools is based on geometry, material properties, location, and the volume of the burrs to be removed.

Finally, it is important to highlight that tool holders must be considered in a robotic smoothing system. Since solid burrs do not absorb the reaction during the burr removing operation, and the volume and the hardness of the burrs are not uniform, the results may also be not uniform, and the robot and spindle are exposed to unexpected shock. In such cases, the robot may stop running and provide an error message, so that, to protect the system from this situation, tool holders should be provided with certain compliance functions.

In terms of polishing, contact stress is influenced by the contact posture between the polishing tool and the workpiece surface, having the planning of the polishing path an important influence on the workpiece surface quality. Therefore, to achieve the desired requirements of surface dimension, precision and surface roughness, both force control and path control are required.
Polishing is a typical contact-processing approach, in which the contact state between the end-effector and the surface of workpiece is in need of real-time changes. This means that a robotic polishing system needs to be flexible to control contact stress. The two main methods to perform this control are passive compliance control and active compliance control. Passive compliance control without actuators during a robotic polishing process is only realized through various passive mechanisms, such as springs. However, although nominal contact stress between the polishing tool and the workpiece surface is maintained, the lack of actuators means that the contact stress cannot be adjusted in real time, due to workpiece's geometry variations and material characteristics of the elastic element, being therefore difficult to control the pose accurately. Thus, as contact stress determines the quality of polishing parts, the active compliance control method is the main research trend for a high polishing quality.

There are two main methods of active compliance through a hardware platform: through-the-arm system and around-the-arm system. The through-the-arm system is based on the constrained motion of each joint in a robot. However, it has an important drawback, since the system becomes unstable at high bandwidths [20], and polishing processes require a dynamic high frequency adjustment of the contact stress to adapt abrupt changes in the curvature of the workpiece surface. Thus, the around-the-arm technique, which employs an external active end-effector to control the contact stress, is the most common method used in active compliance control. In this method, the robot arm is called a macro robot, which mainly provides the surface posture and path tracking of the workpieces, and the force adjustment is performed using the end-effector, which is also called a mini robot [21]. The around-the-arm method enables higher bandwidth and accuracy for the polishing operations, due to the fact that contact stress control is only performed by the mini robot [22]. The main disadvantage of this design is that the auxiliary actuator moves the polishing motor, the polishing spindle, and the polishing head, being the loads of these items considerable. Therefore, considering that the holding force of the mini robot is expected to be relatively small due to its size limitation, if these loads are carried by the auxiliary actuator of the mini robot, the holding force of the mini robot needs to be increased and consequently its physical size and inertia will be increased. Thus, as the macro robot carries the mini robot, a larger macro robot is needed if the mini becomes heavier, and hence the total cost of the system is increased. As a result, the through-the-arm technique, which tracks the desired force by adjusting the whole robot's posture [23], is the one used in most automation tasks in which both position and force of the end-effector need to be controlled to complete the task. For example, when using a robotic arm to polish a car apron [24] [25], being frequencies adjusted by algorithms.

On the other hand, it is important to highlight that force can be controlled by mean of a control loop uncoupled from the robot position control loop. Using a force sensor, an uncoupled feedback control based on a sensor signal can modify gains for the position control loop of the robot arm. In line with the above, as the initial and final points are known, an algorithm can be developed to allow the robot to process the measurements from the force sensor, reacting thus to these values, so that the force exerted on the part could remain constant to modify the path depending on the position of the tool.

3. METHODOLOGY

The proposed methodology consists in four main stages that are flexible and generic enough to give support and orient any kind of finishing-alike operation in manufacturing. The flow chart of Figure 4 summarizes the 3.1) part measuring, 3.2) path creation, 3.3) finishing operation and 3.4) part verification phases, that should be executed in a loop until the part is acceptable (or a specific threshold of tries is reached).

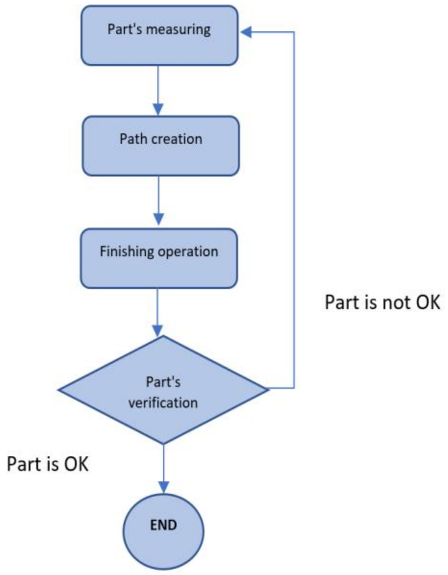

Figure 4. Methodology flow chart.

3.1. Part Measuring

Part measuring defines the first step of the methodology. This step consists in measuring the characteristics of the parts, as well as the characteristics of the undesired material to be removed. The shape and size of both part and unwanted material must be measured and studied in order to correctly define the path in which the operation must be performed. For this purpose, the necessity of a sensor is crucial. Therefore, depending on the type of the part and the operation to perform, a specific sensor must be selected to capture the information about the location and shape of the accumulated material to be eliminated. Thus, for instance, in some cases it could be used an intelligent sensor to perform an inspection using laser triangulation whereas, in other cases, the use of distance sensors or force sensors is more optimal due to the shape of the workpiece or the operation to perform. This stage acts as input for the stage 2.

3.2. Path Creation

Once the part and undesired material have already been detected by the sensor, this information must be processed to define the path in which the finishing operation must operate. This information could be processed either by the sensor itself, if it is intelligent, or by an external PC. This processing is key to correctly perform the operation. In some cases, for instance, it could imply the modification of a predefined reference route according to the data acquired by the sensor, whereas in other cases the processing could consist in the evaluation of the distance of the machining tool to the workpiece. Thus, a compensation system could be needed to adjust the path to adapt it to the workpiece's geometry. This compensation system adjusts the position of the tool using a robot program to ensure that the path is as perpendicular as possible to the surface of the piece. Besides the compensation system, a TCP (Tool Centre Point) calibration system [26] could be also needed for measuring the position of the tool. Its function is to readjust robot's TCP position to ensure that the tool operates at the right point and does not damage the workpiece.

3.3. Finishing Operation

Once all the information acquired during sensor inspection has been processed and the path has been defined, the finished operation itself needs to be performed. The data used to perform the tasks would be usually stored and kept in a PLC or external PC.

As mentioned in Section 2.2, a six-axes robot would be usually the best option in case that the position, size and nature of the unwanted material are unknown or irregular. In addition, equipment must be robust to withstand vibrations produced during finishing operations.

While smoothing, the type of milling to be performed will depend on the material to be machined, and depending on the geometry of the part, milling could be done with tool lateral or perform frontal milling. As stated in Section 2.2, milling with the tool lateral presents advantages about the accessibility of the tool and the robot, whereas frontal milling needs a lower spindle power and causes less torque at the end of the robot. However, frontal milling with small radius is not guaranteed.

On the other hand, in polishing operations, they are usually performed with the tool frontal, being the sanding tool fixed to the six-axes robot, as explained in Section 2.2. In this way, the sanding tool could be an angled grinder with adjustable speed through a solenoid valve, which is an operating tool commonly used by operators when performing polishing operations manually. However, as stated before, another possibility is that the robot could hold the workpiece and move it closer to a polishing belt to perform the polishing operation.

About the strategy used, two strategies have been suggested depending on the simultaneity of the finishing operation and sensoring, being one of them performed in two stages, called "first measuring, then performing finishing", and the other in one stage, called "measuring and performing finishing simultaneously". Its use will mainly depend on its control system, level of detail and cycle time. In addition, in these operations it is very important to select the right motor and converter, as well as the tool holder and the optimal tool.

In case of performing a polishing operation, as stated in Section 2.4, it is convenient to perform an active compliance control, either using a through-the-arm technique or an around-the arm technique, depending on whether both position and force of the end-effector must be controlled to complete the task, as well as the frequency adjustment needed of contact stress, polishing accuracy, and costs.

3.4. Part Verification

The verification stage aims to validate that the finishing operation has been properly performed. This means to obtain a quantifiable result above a quality threshold. If the finishing operation has been performed correctly, above this threshold, then the finishing process of the part has finished, and the part should be removed from the workstation. On the contrary, if the finishing operation has not been properly executed, then the part should be measured again by the sensor, and the cycle of Figure 5 starts again. In some cases, this cannot be repeated indefinitely, since removing the material can cause functional or structural problems, and the part has to be eventually discarded as trash or recycled.

This quality verification means to deal with measuring, at least, the thickness of the part after the process, and the rugosity or surface inspection. The first method involves techniques such as ultrasounds and are complex to automate in line. In the second case, one of the most relevant techniques is profilometry [27]. There are two basic surface profilometry technologies: contact and non-contact [28]. While contact or stylus-based surface profilometers measure surface texture by dragging a sharp, pointed tool across the surface, which records height variations to form a texture profile, non-contact surface profilometers measure the surface texture by optically scanning a surface with a light or laser, using hence triangulation, or interferometry to measure or capture a surface profile.

4. USE CASES VALIDATION

The methodology described above has been successfully applied in two use cases at an automotive Stellantis plant in Vigo, Spain. These use cases are the smoothing and polishing of a humping weld beam in a part which is composed by two elements which are joined during the manufacturing process. The geometry of this automotive part is quite complex, as shown in Figure 5, in which there are three operating zones and two junction areas.

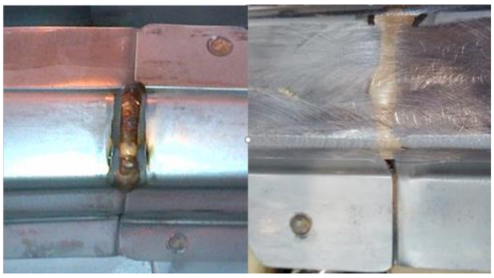

Figure 5. Weld beam. Left: Raw humping weld beam to be deburred and polished. Right Weld beam surface being deburred and polished.

The objective of these use cases is to obtain a surface like the one shown on the right side of Figure 5. To achieve this, the two finishing operations were implemented considering the methodology described in the present document, in order to automatically prepare the surface of this weld beam and, consequently, of this automotive part. The smoothing station has been in use since 2012, whereas the polishing was temporarily used as a proof-of-concept for 4 months.

4.1. Smoothing Use Case

The developed smoothing system follows a “finishing while measuring” strategy [29] [30], which means that part measuring, path creation and machining are performed at the same time. Both sensors and machining tools are mounted on a robot, which develops a predefined trajectory, and depending on the measures from the sensors, this trajectory is slightly changed in position and angle. The sensors are placed so that they measure a zone only some seconds before the machining is performed in such zone. This method was mandatory in order to support the hard real-time requirements of the use case: < 60 seconds of cycle time in total for this operation for each side (there are left and right workplaces).

4.1.1. Part Measuring

Concerning methodology's first step, a laser triangulation smart sensor Gocator from LMI [31] was evaluated. However, due to its high cost, two laser displacement sensors have been used instead. During the smoothing, these two 1D sensors measure the robot's distance from both sides of the beam. This distance may not be the same on both sides, forcing hence a compensation system to be activated to adjust the machining path to adapt it to the geometry of the workpiece. Therefore, at every moment, only one sensor measures the deviation of the workpiece's height with respect to the total, (Step 1 of the methodology), and adjusts the path according to the highest part (Step 2 of the methodology). The sensor used is the one for which the relative error to its set point is smaller. Thus, the error of each sensor is calculated considering the distances shown in Figure 6, which are presented hereafter:

- Sensor Measurement (SM): Sensor measurement at every moment.
- Geometric Delta (GD): Distance between the milling point and the sensor measuring point due to the curvature of the workpiece.
- Offset Sensor (OS): Offset that adjusts the milling path. It is applied to all the points of the path. There is one for each vehicle model and it is identical for both sensors.
- Calibrated value (CV): Distance measured during calibration between sensors and the tip of the mill.

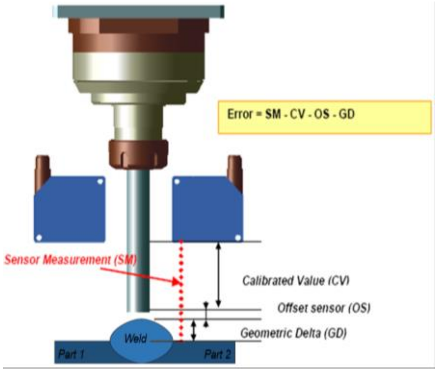

Figure 6. Error position calculations.

4.1.2. Path Creation

As it was previously mentioned, the error of each sensor is calculated at every moment during the path. Both errors are compared with each other, and the sensor with the greatest one is discarded. Therefore, the sensor with the lowest error is used to calculate the path correction. The path is continuously shared with the PLC, so that a robot program adjusts the robot's position to ensure that the path which is being created is as perpendicular as possible to the surface of the piece.

On the other hand, as it was previously mentioned in Section 3.2, a TCP calibration system could be also needed to ensure that the smoothing operation is performed at the right point and does not damage the workpiece. In this case, a high precision optical system has been used, an Advintec TCP from Leoni with a resolution up to 0,01mm [32], for measuring the position of the cutter, whose function is to compensate for deviations or wear by readjusting the robot's TCP position, being the final smoothing cell as shown in Figure 7.

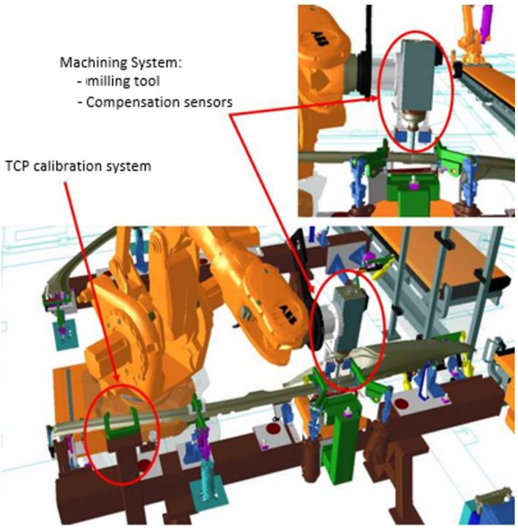

Figure 7. Smoothing Cell.

4.1.3. Finishing Operation

An ABB IRB 6660, 205kg/1.90m six-axes robot was selected in this case to perform the smoothing operation, which consists in performing a milling in which the robot sends the speed and direction of rotation parameters to the adjustable frequency drive through the PLC. The drive is responsible for starting and stopping the engine at the request of the robot. The direction of rotation is determined by the direction of cut of the milling cutter, so climb milling was chosen, and milling with the tool frontal was selected in this case due to the geometry of the part.

Concerning the spindle, it was used a spindle unit VEM EP11, which is equipped with an integral shaft designed for water supply system and air-cooling, and whose motor has a power of 2,2 kW which can reach a speed between 2.800 rpm and 10.000 rpm [33]. Concerning the cutting tool, it was used a SHANK TNFR 200-20S together with a ER32 spring collet.

4.1.4. Part Verification

This smoothing operation is one the two steps designed to fully process the part, from its raw results from the welding to a surface prepared to be shown directly to the customer. Thus, no explicit part verification was implemented at this stage, being the verification performed after the second stage, the polishing.

Considering the methodology and system described above, it was possible to improve the surface quality of the weld beam, as can be shown in Figure 8, letting the zone prepared for the polishing to act. The approximate cost of the components to build such system is around 70.000€.

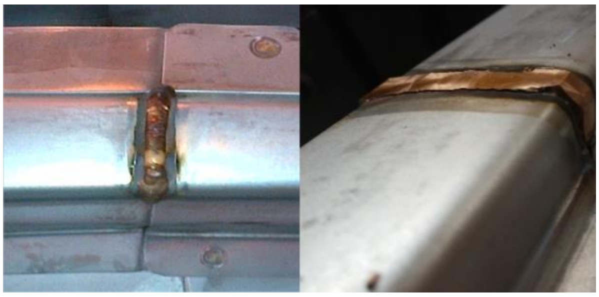

Figure 8. Welding beam. Left: Welding beam before smoothing. Right: Welding beam after smoothing.

4.2. Polishing Use Case

The polishing system also follows the “finishing while measuring” strategy. In this case the force sensors of the robot are providing information to perform an in-the-loop modification of a predefined trajectory, so that depending on these real-time measures from the force sensors, the trajectory is adjusted to the geometry of the part. Again, this was a cycle-time requirement, since only 60 seconds were available to perform this operation.

4.2.1. Part Measuring

This use case involves the polishing of the weld beam after being deburred. A 6-axes force sensor was chosen, in particular an Optoforce force sensor [34] (being these sensors called nowadays OnRobot's HEX 6-axes force/torque sensors). Therefore, as polishing a surface of a workpiece requires following different paths, an algorithm has been developed that allows the robot to process the measurements that the force sensor collects, in real-time.

4.2.2. Path Creation

As the initial and objective final positions of the robot are known, the algorithm interpolates positions reacting to a greater or lesser extent to the force values sent by the sensor, so that the force exerted on the workpiece could remain constant to modify the path depending on the position of the tool. Thus, the operation of the algorithm that controls the application for the polishing process is based on the steps shown in Figure 9.

The main steps of this process are explained as follows:

1) Introduction of fixed parameters: the initial and final points are programmed, and the optimum values of force set point (Fz), interpolation interval (step) and algorithm correction gain (K) are introduced (obtained experimentally).
2) Calculation of the distance: the robot calculates the distance between the current position of its tool and its theoretical final position.
3) When the distance is less than d mm, the algorithm concludes that the tool is in its final theoretical positions and finishes the path. Otherwise, the algorithm proceeds to calculate the next point of the path.
4) To calculate the next point to move, the robot needs to update X and Z coordinates of the current point in which it is placed.
5) With the updated X and Z values, a new point (or pose) is constructed.
6) Inverse kinematics is performed to convert coordinates of the point to the value that robot’s axes must have to reach that pose.

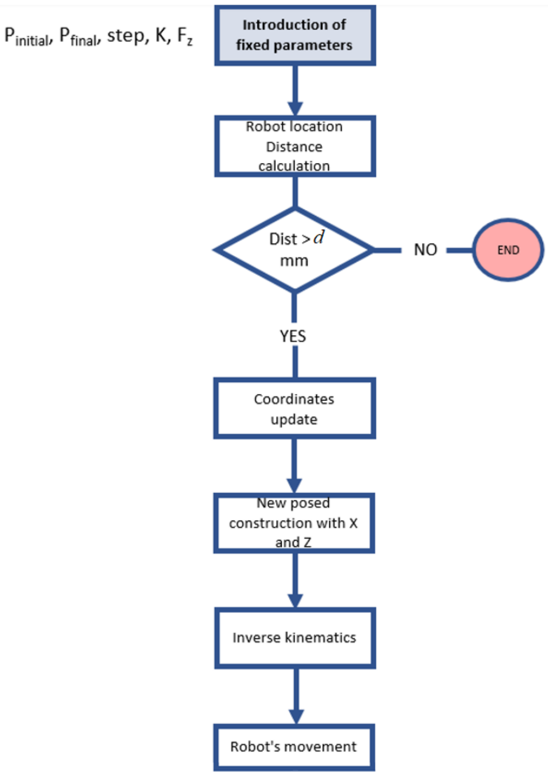

Figure 9. Polishing algorithm Flow chart.

As a qualitative summary, it can be said that the algorithm allows the robot to process the information sent by the sensor and modify its path based on the coordinates of the tool. To adjust the force and keep it constant, a proportional regulator is used. Reaction and interpolation speed depend on the gain and the interval size that is introduced (being the calibration of these parameters purely experimental). In parallel, the robot is continuously checking the current position and comparing it with the final one. When the difference between both positions is minimal, the algorithm resolves the end of the operation.

It is also important to highlight that, during the implementation of the use case, it was observed that tool's rotation introduces new frequencies to the system which distort measurements, which the sensor would collect if only robot's own movement were considered. Thus, to eliminate tool noise, an algorithm was developed to filter frequencies added to the signal received by the sensor when the tool is turned off.

In addition, a correct reset to zero of the sensor must be done. Otherwise, signal values will be displaced. To solve this problem, an arithmetic mean of 10 values of the noise signal were recorded. This average value was subtracted from the Fz value during the execution of the correction algorithm. Hence, it is possible to reset the sensor without affecting the result.

4.2.3. Polishing Operation

The polishing operation follows the path calculated by the algorithm explained above, using a pneumatic and angle grinder with adjustable speed through a solenoid valve. It is a radial operating tool commonly used by operators when performing polishing operations manually. Specifically, it was used a 3M angle grinder with Roloc system abrasive discs, which was fixed to the robot, performing hence the first type of the robotic polishing system mentioned in Section

2.2, the robot hand-hold polishing tool. The zone is polished from 6 to 8 times by the tool to reach the desired result. An architecture can be seen in Figure 10.

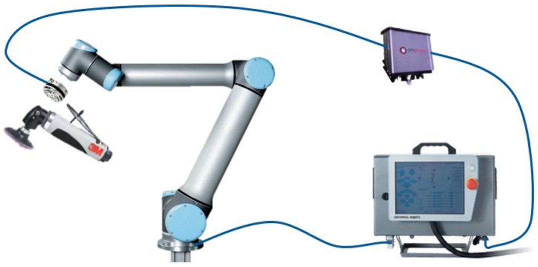

Figure 10. Robotic polishing system.

Concerning polishing control, an active compliance control was performed using through-the-arm technique in which both position and force of the end-effector need to be controlled to complete the task, and in which frequencies were adjusted by an algorithm.

4.2.4. Part Verification

After the polishing process, welding beam's hump has completely been removed, obtaining thus a smooth surface, as can be observed on the right side of Figure 11. The approximate cost of the components to build this system is around 50.000€.

Figure 11. Welding beam. Left: Before being polished. Right: Welding beam after being polished.

This machined surface needs a quality inspection. For this verification, an ABIS II optical sensor system from Zeiss [35] was installed after the polishing stage, as a non-contact automatic surface inspection system. It can accurately detect any surface defect such as cracks, dents, scratches, or bumps, on the part's surface. In case a minimum quality threshold is not reached, the part can be polished again, or discarded.

5. RESULTS

As presented in Section 4, the proposed methodology has been used and deployed in two use cases in a real application scenario. In this Section of results, the specific improvements obtained by these use cases will be commented, as a benchmark of similar applications that may be developed in the future following this same methodology.

Regarding the smoothing use case, the next figures can be obtained:

- The accuracy of the smoothing is 0,2 mm (due to the robot limitations).
- Approximately 500.000 cars have been processed through the in-line smoothing workstation between 2012 and 2022 (at a 50.000 cars every year).
- The volume of material saved for each car is approximately 1.600 mm3, which means 0,080 m3 per year, i.e. 716 Kg in a year.

This solution has been implemented in two factories of Stellantis: one in Vigo, Spain, and one in Wuhan, China, thus providing savings in two locations of the group.

Regarding the polishing use case, its implementation was a proof-of-concept that was temporarily installed in line for 4 months, working on 19.200 cars. It reached an accuracy of 0,2 mm, saving 320 mm3 material per car. This is less material than smoothing for obvious reasons: the smoothing actually removes matter, while the polishing smooths the surface.

Besides these quantifiable results, the main advantages of the systems deployed using this methodology are the human-related improvements. From the ergonomics point of view, automating these operations usually mean improving operators' wellbeing, since the manual execution of these processes if not fully ergonomically suited.

6. DISCUSSION AND CONCLUSIONS

This paper presents a new methodology to organize and guide finishing operations in manufacturing, especially oriented to the removal of burrs and welding outcomes.

The contextualization of this necessity has been presented, as well as the main technologies involved in such framework. Its main stages (part measuring, path creation, finishing operation and part verification) have been described and related. Finally, two real finishing use cases in manufacturing have been shown, as examples of application of the methodology, dealing with smoothing and polishing of a previously welded zone, in automotive manufacturing.

The advantages and KPIs of these use cases can be extrapolated as potential outcomes of similar applications, in terms of quantifiable benefits, but especially in human-related issues such as improvements in workplace ergonomics and quality of life.

The main issue with such systems is usually if it is possible to obtain a good level of aspect quality after the process, equivalent to the obtained by a human operator. We have checked with these use cases that this is indeed the case in metallic materials. The main future challenge is to apply this methodology in other materials, such as plastics (plastic grinding, polishing defects with painted cars …), or composites like carbon fibre or fibreglass, in which this quality level is harder to obtain. We believe that this methodology can orient similar developments in the future, and inspire about how to approach this group of problems related with finishing, machining and aspect results.

ACKNOWLEDGEMENTS

The authors want to acknowledge the contribution of the project "Facendo 4.0", and respectively to the agency GAIN from the Xunta de Galicia regional government of Spain, for its funding.

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