

Industrial Robotic Arm in Machining Process Aimed to 3D Objects Reconstruction

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Abstract—Industrial robots are a technology which is highly present in industry and can perform several tasks, namely machining activities. Different than CNC machines, which work with G-code and have available several software applications to generate the machine code, there is a lack of software for robotic arms, in addition to each application depending on its own language and software. This work studied a way to use different robotic arms for 3D part machining processes, to perform 3D objects reconstruction obtained through a low-cost 3D scanner. Dealing with the 3D reconstruction by integrating 3D acquisition and robotic milling with software available on the market, this paper presents a system that acquires and reconstructs a 3D object, in order to seek greater flexibility with lower initial investments and checking the applicability of robot arm in these tasks. For this, a 3D object is scanned and imported to a CAD/CAM software, to generate the machining toolpath, and a software application is used to convert the G-code into robot code. Several experiments were performed, using an ABB IRB 2600 robot arm, and the results of the machining process allowed to validate the G-code conversion and milling process using robotic arms, according to the proposed methodology.

Keywords—Flexible manufacturing systems, Reconstruction of 3D objects, 3D scanning, Skanect, CAM software, Fusion 360, RoboDK, Industrial robots in machining tasks

I. INTRODUCTION

The process of reconstructing an existing scene or an object of the real world is in constant development, seeking to make this process more efficient and viable. There are various applications for 3D reconstruction, being used in engineering areas, conservation of historical monuments, medicine, among others. The 3D reconstruction of an object can occur, e.g., to recreate a product no longer being manufactured or for which was lost the original design plans, improve an existing product, analyse competitor products, conserving a model or sculpture, and resizing a model.

To facilitate this virtual recreation process, 3D scanners emerged, which assist in acquiring 3D scenes with high complexity, thus facilitating the 3D modelling process. The use of 3D scanners to acquire objects and scenes can be

carried out by different methods, which imply the accuracy of the acquisition, acquisition and processing time, price of the equipment, and the software available for that method or device. Since 3D scanners are used in several areas, they have evolved considerably to cover other applications and be used with a new purpose, such as the emergence of low-cost versions that can be used by hobbyists and researchers [1], [2].

After obtaining a virtual 3D model by a 3D scanner, it is necessary to use a machining process, such as CNC, or additive manufacturing (through 3D printing), to recreate the model. The manufacturing process to manually generate machining projects with a higher level of complexity becomes challenging. However, with CAM software, the complexity can be significantly reduced, and all the necessary paths for machining of a CAD model file can be generated [3]. Most of these CAM programs are aimed to CNC machines, due to its machining services with a high level of rigidity, that allow perform to machining in several types of materials. However, CNC machines are only intended for machining operations, have a high initial cost and limited working area.

Industrial robots have low rigidity compared to a CNC machine, which generates vibrations and, consequently, deformations, in addition to the fact that most commercial software for toolpath is aimed at CNC machining (for the creation of toolpath and configuration of the machine characteristics). However, industrial robots also have their advantages, such as their large work volume, lowest initial cost, and multitasking ability, which allows high adaptability of great value for manufacturing, since the market is continually changing and needs to produce customised parts [4], [5]. Thus, due to the possibility of using materials different from the ones used in 3D printing, having a working area more extensive than CNC machines, and perform more several multi-axis operations, using an industrial robot in the machining process arises.

Industrial robots are integrated into various sectors of the industry. They can be used to machine parts, just requiring

a machining tool and the robot toolpath (which is different for each robot arm brand). Currently, CAD/CAM programs are implementing the functionality for converting G-code to robot codes and companies such as ABB, FANUC, KUKA, and Stäubli are investing in industrial robots for machining operations. Each one of these companies has already a robot model focused on this task, with higher rigidity and better repeatability [6].

Bearing these ideas in mind, the remainder of this paper is organised as follows. After this introduction, related work about 3D scanning and 3D reconstruction is presented in Section II, followed by the system methodology in Section III. The obtained results are presented in Section IV and Section V presents the main conclusions of this work and some ideas for possible future work.

II. RELATED WORKS

With the evolution of the processing capacity of computers from the end of the '50s, the 3D acquisition has been evolving and, since then, new methods have emerged, allowing greater accuracy and increased acquisition volume, with lower-cost and acquisition time [7]. With the advent of low-cost 3D scanners, these have become affordable for hobbyists and researchers. Current publications have shown low-cost 3D scanner applications with different techniques. As an example, in 2016, Moreira used a free software for a 3D scanner with triangulation method [8]. In 2018, Oliveira used an embedded system to automate the acquisition of images for 3D acquisition using photogrammetry [9]. On the other hand, Liu and Lin tested a high-order of sinusoidal patterns in addition to conventional sequential binary patterns to improve scanning and reduce errors in the 3D acquisition by Structured-light [10]. In addition to these projects, there were projects in 2017 dealing with the integration of 3D acquisition with a 3D printer [11] and CNC machining, when Santos used a CAD model properly acquired and treated, in a CAM software to obtain the G-code, to milling the part on a CNC machine [12]. Trying to improve the CNC machines and 3D printers range limitation, some proposals appear to find different ways to perform these jobs. A method that has been researched to increase flexibility and widen the work area is the inclusion of industrial robots in executing these tasks. The CAM software has been used to generate the toolpath for industrial robots in finishing operations, such as in 2012, by Angelino, which used an industrial robot for guitar finishing [13], or in 2014, when a force control system seeking to optimise the finishing process with robots was used [14].

Also, in 2013, an ABB IRB 2400/16 robotic arm was used to do 3- and 5-axis machining of complex surfaces, obtained in CAD formats [6], and in 2018, Pollák et al. used an ABB IRB 140 robotic arm to perform 3D printing on larger scales than a conventional 3D printer [15]. In 2020, a Nachi SRA166 robot arm was used to perform 3D parts machining from a CAD model [16], and Miranda used contours of objects obtained through photographic recording, to machine custom items with an industrial robot [17].

Regarding all the previous related works just mentioned, this work aims to develop a reconstructing system, integrating a low-cost 3D acquisition system with a milling process, using an industrial robotic arm.

III. SYSTEM DESCRIPTION

Thus, the objective is the reconstruction of 3D objects by acquiring its shapes or objects in a virtual model through a 3D scanner and use this model to carry out machining of materials (such as polystyrene, polyurethane, or other low rigidity material) using industrial robot arms, with the toolpath generated through CAD/CAM software programs and converted to robot code, as depicted in Figure 1.

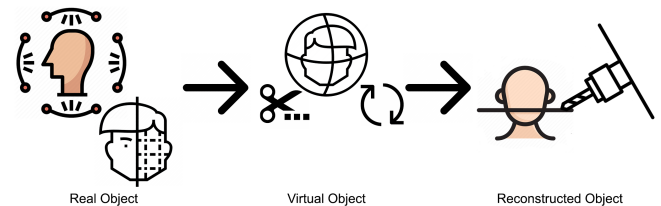


Fig. 1. Illustration of the process for identifying an object and milling it using an industrial robot.

To accomplish the objectives of this work (the machining of parts acquired by a 3D scanner), will be used the methodology shown in Figure 2. This methodology uses the Skanect software to acquire the 3D image with the Kinect sensor, adopts the Fusion 360 to generate the G-code, and RoboDK to convert this code to the ABB IRB 2600 robot with the IRC5 controller, available in the Industry and Innovation Lab (iiLab) of INESC TEC. Each of these tools and steps will be explained further below.

In the 3D acquisition stage four possible tools were considered: (i) Meshroom, (ii) Kinect, (iii) RealSense, and (iv) Ciclop. As the aim of this work was to apply the robotic arm in the machining process, the quality of 3D image acquisition was not the decisive factor, but most important was to have the hardware available, the acquisition time and a software with free export capability. Thus, the chosen alternative was the Kinect sensor combined with the Skanect software.

With Skanect, the object that will be acquired in 3D must be positioned in a place that allows performing the acquisition movement around it or on a platform/chair swivel. With the object adequately positioned, the Skanect software makes the acquisition and exports the acquired model in the STL format. Then, this STL must be treated in the MeshLab software to become a solid object and in Meshmixer is cut only the part of interest. The edited STL is imported into Fusion 360, which uses several tools to create a toolpath for machining a workpiece, in the G-Code format. An add-on in Fusion 360 exports that G-code to RoboDK, which subsequently converts it into a RAPID code to work with ABB robots, using the IRC5 controller.

Finally, with the generated RAPID code, simulations are performed using the RoboDK to validate the toolpath and

machining position and then tested on the ABB 2600 industrial robot. First is checked whether the toolpath's initial steps go as expected and, if so, the workpiece is placed to be machined automatically, following all the lines programmed by the software.

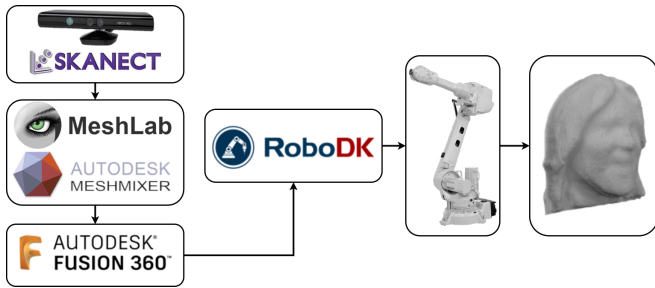


Fig. 2. System architecture.

For this work, it was decided to carry out the acquisition of people's faces. During this process, it is needed to accomplish an acquisition without sudden movements and maintaining a certain distance (the software itself indicates if the distance is correct), not losing the reference points or making wrong acquisitions. If errors occur in the final model, it is necessary to make another acquisition. The result of the acquisition is processed by the software and can then be post-processed using its tools, such as to reduce the number of faces of the scan, look for places with holes and attempt to fill them, and move, crop and remove random or floating smaller parts. Finally, Skanect allows exporting the generated file, in formats such as: .PLY, .OBJ, .STL or .VRML, with a maximum limit of 5000 meshes for the free version of the program.

With the generated STL file of the face, it is necessary to make some adjustments to work on it, using the software MeshLab and Meshmixer. First, the MeshLab functions are used to clean up unwanted points and parts of the acquisition and build an entire object from the STL file. After this step, the new file is treated in Meshmixer to make a solid object, perform cuts, rotate, translate, adjust, and resizing of the mesh.

To reach the model used in the machining process, the characteristics that would limit the milling process in practice were considered, avoiding the collision between the spindle support and the workpiece, requiring to limit the maximum height of the part to be machined. This limitation ensures that the spindle support does not pass in parts of the workpiece that should not be roughed out.

When the file of the machining part is ready, its is imported to the CAD/CAM Fusion 360 software, and created the tool that will be used. To be possible to work with the STL file in the Manufacture part of the software, it is necessary to perform a conversion of mesh to a Boundary representation. After these steps, it is possible to generate the machining toolpath for the roughing process.

In the tools section of Fusion 360, it is possible to send the G-code (toolpath) created directly to the RoboDK software. Before sending the code, a virtual workspace must be

configured, according to the robot and tools used. The Tool Center Point (TCP) of the robot must be obtained (by the robot controller), as this is considered when converting the toolpath in RoboDK. The TCP and the reference coordinate work point must be updated in the RoboDK, to validate and make the junction between the virtual world and the real world, considering the actual tool and the machining start coordinate point to convert the code.

The export file will be generated in the ".mod" format, and the controller identifies only ".pfg" files. To load the programs into the robot, it is necessary to create a standard .pfg file, calling the first .mod file generated by RoboDK. The RAPID code is transferred to the robot controller (through an Ethernet connection between the controller and the computer, using the FileZilla software) to start machining the part, as shown in Figure 3.

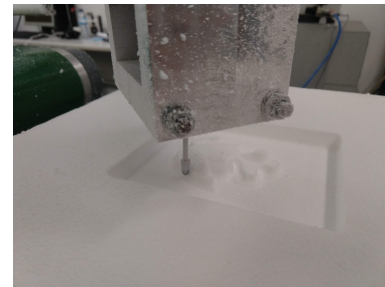


Fig. 3. Roughing process illustration.

IV. RESULTS

The 3D image acquisition made in this work was limited by the accuracy of the 3D scanner used. Thus, the faces' acquisition was carried out, as it presented details on a size that can be acquired by the 3D scanner used. After the acquisition, the 3D image is adjusted using MeshLab and Meshmixer software, as depicted in Figure 4.



Fig. 4. First adjustments of the acquired image.

The 3D model was cut to obtain the model used in the machining process. To avoid the collision between the spindle support and the workpiece, the maximum height of the part to be machined was limited, as depicted in Figure 5.

This process was repeated for a second face. Thus two faces acquired were readjusted to the interest machining part, as depicted in Figure 6.

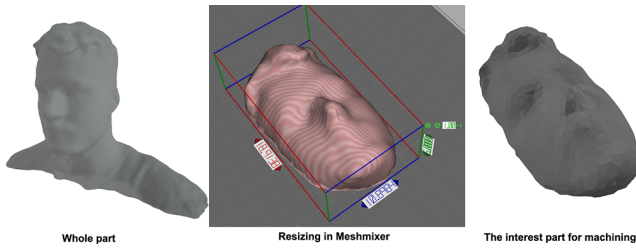


Fig. 5. Cutting and resizing the 3D image.



Fig. 6. 3D image reajusted used in the machining processes.

To simulate and convert the G-code in the RoboDK, a virtual workspace was created. In this workspace was included the IRB 2600-20/1.65 robot, the tool model, a part to represent the workpiece, the respective tooltip frame (which is calibrated with the real TCP values), and a reference frame of the initial machining point, as represented in Figure 7.

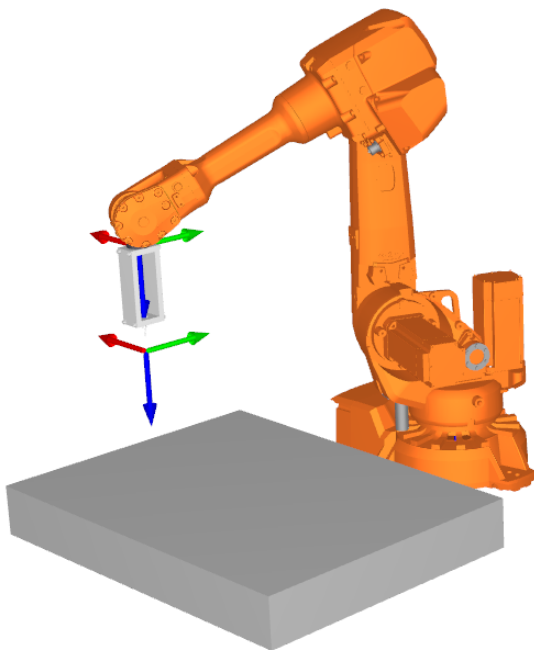


Fig. 7. Virtual workspace in RoboDK.

The first milling process carried out was of a face with 30 mm high, shown in Figure 8. This test was limited to 30 mm of height due to the milling cutter used.

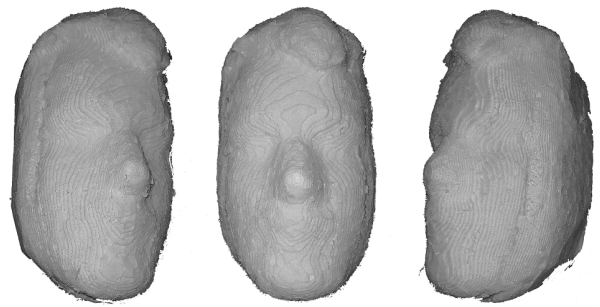


Fig. 8. Roughing process of a 30 mm height face.

To better visualise the milling process with a robot arm (machining of a larger part) a different method was adopted. In the second milling test, the roughing process was divided in two stages, first machining the top and then the bottom of the part, as shown in Figure 9, depicting the CAM simulation.

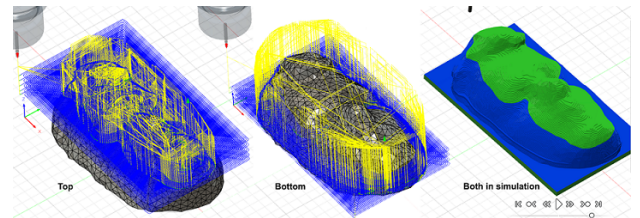


Fig. 9. Roughing process of a face in two stages.

When machining the top part, it was observed that due to the fact that both the robot and the part were not fixed to the ground, in addition to the level of stiffness of the robot arm used, the machining process was having failures, as shown in the Figure 10.

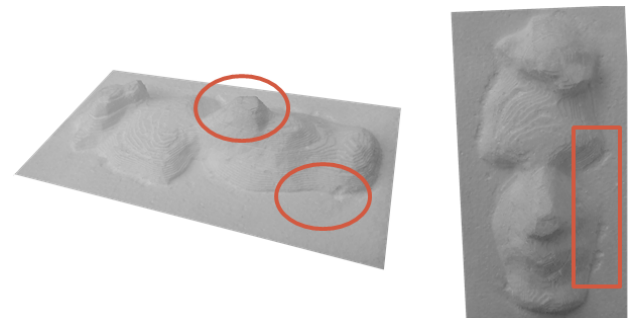


Fig. 10. Failures in roughing process of the top face.

In order to avoid these flaws, an acceleration limitation was used for subsequent machining operations, implemented directly in the generated code. So the top and the bottom of the part were machined with the limitation, resulting the parts shown in Figure 11.

After the two machining steps, the top part was cut and placed under the bottom part, and compared with the simulation of the roughing process, as shown in Figure 12.

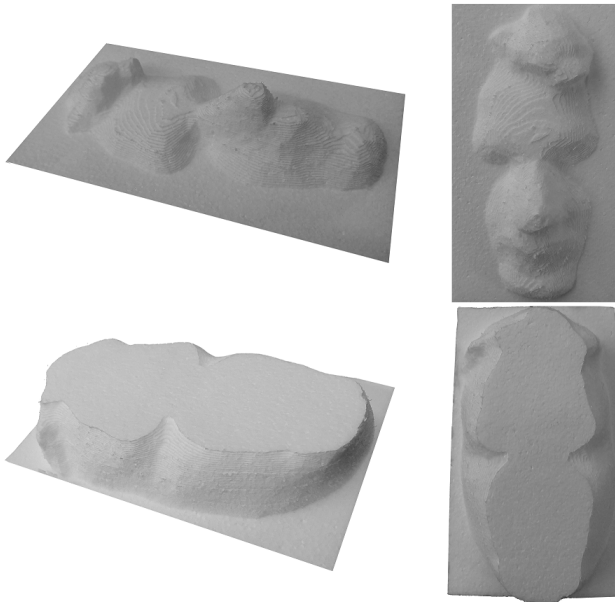


Fig. 11. Roughing process of a 60 mm height face in two stages.

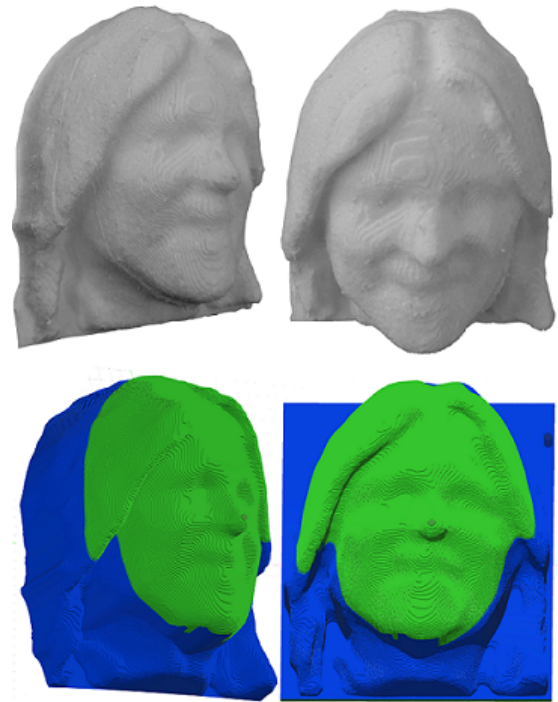


Fig. 13. Comparison of the real and simulated of a different face.

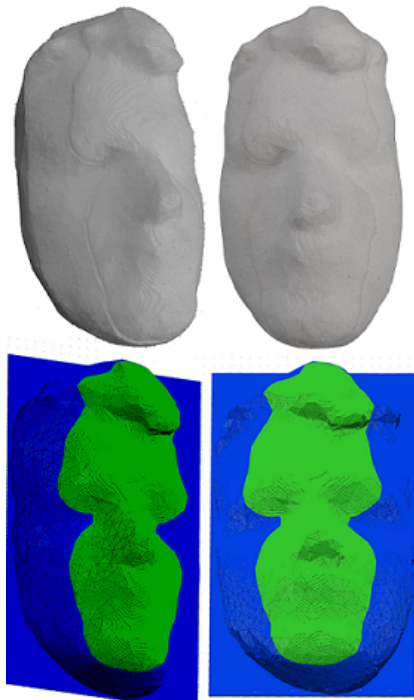


Fig. 12. Comparison of the real and simulated face.

Also, to perform more machining tests with the robotic arm, a different face was machined. The comparison of the real and simulation roughing process of this face is shown in Figure 13.

Because the milling processes took place with interruptions, and there was some switching from manual to automatic mode, the machining times were not recorded accurately. However, these times were estimated through the simulation in RoboDK, as depicted in Table I, for the machining of the 30 mm part

(Figure 8), the 60 mm face (Figure 11) and the new face (Figure 13).

TABLE I
ESTIMATED MACHINING TIMES ON ROBODK.

Parts	Machining time
30 mm height	42 min
Top 60 mm height	178 min
Bottom 60 mm height	104 min
Top new face	91 min
Bottom new face	127 min

V. CONCLUSION

The RoboDK software was used to convert G-code into robot code, which proved successful and provided a large number of robot models. In addition, the possibility of creating a custom tool from a CAD model with the respective TCP acquired in the real world was obtained. With the tests performed, it was possible to verify that with the acquisition of real points updated in the software, it was generated a correct code respective to the robot model used.

The acquisition using the Kinect sensor, with the Skanect software, generated faces with enough characteristics to differentiate each one, even without the small details, thus being suitable for the project objective and being a low-cost choice for 3D image acquisitions. However, this was the stage where most of the characteristics concerning the real model were lost, followed by the technique used for machining, due to only the roughing process that has been applied without a finishing process.

The robot performed the machining process with great accuracy (compared with the CAM simulation model), although it depends on limiting its acceleration, to reduce the vibration caused and achieve better results in the machined part. Therefore, for a better 3D reconstruction, another 3D acquisition method and a multi-axis finishing technique should be the main changes.

The 3D acquisition part's adjustment process made in this work was only to remove the holes, resize, cut the parts of interest, and rotation. However, the acquired 3D image could be used in other applications, such as to remodel a given existing part or create custom items, e.g., create a custom mask with the person's face, or in medicine to create an artificial limb.

The work performed proved the use of industrial robots in machining services and showed software programs available on the market to assist this process. These equipments have a large work volume, greater flexibility and a lower initial cost than a CNC. In addition, a robotic arm is capable of carrying out other tasks, for instance allowing to position the part to be machined and remove it after machining, which allows high adaptability as a great value for a manufacturing system, since it is constantly changing and needs to produce customised parts.

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