Industrial Robotic Arm Programming for Circular Disc Cutting Tasks in Natural Stone Slabs

José Alexandre da Costa Gameiro
josegameiro96@hotmail.com

Instituto Superior Técnico, Universidade de Lisboa, Portugal

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Abstract

The following report discusses the planning and programming of a robotic cell targeted to machine natural stone slabs, namely, by circular disc cutting. This type of task, common to the Natural Stone (NS) manufacturing industry, will serve, in future works, to develop machining strategies based on the performance evaluation of the robot in operation. The machine handled over the project is the KUKA KR 360, a 6-degree industrial robot with arm extension L280-2 and force torque control, installed in demo mode by FrontWave, as part of the INOVSTONE 4.0 project. This system, when fully integrated, will be capable of many different tasks such as object manipulation, automatic tool change and machining. To accomplish the proposed objective, the work flow begins by planning the robot cell considering the equipment characteristics and project requirements. Subsequently, the virtual cell model is built with the purpose of proceeding to the offline programming by defining machining trajectories. That said, the programming proceeds to the path optimization and validation stage. Thus, it is intended to develop a solid program that performs the desired operations in order to draw clear conclusions about the appropriate way of programming machining tasks by robotic arm, for subsequent application of the technology in the NS industry. This way, in this sector, it will be possible to follow the technological developments applied to the industry in order to respond effectively to the new market needs.
Keywords: Industrial Robotics, Natural Stone, Machining, Offline Programming

1. Introduction

The major challenge for the future generations, in particular the ones entering the labor market, is to promote a sustainable economic growth. This, by increasing companies competitiveness with accurate management of human and natural resources, thus aiming life quality improvements, job growth and more attractive wages. Fund mobilization measures, to support Research and Development (R&D) projects, related with technological innovation, can be an important way for the Portuguese economy to thrive. In the Natural Stone industry the development work began in 2002 with R&D projects, such as, Jetstone, Inovstone and StonePT [4][5]. As part of the strategy to promote this technological evolution arises the need for this work, which is contained in the *Inovstone 4.0 – Tecnologias Avançadas e Software para a Pedra Natural* project.

1.1. Natural Stone Industry

Portugal is one of the leading producers of natural stone in the world. The wide range of natural resources makes it an important advantage to compete in the world stage, therefore, contributing to the sector sustainability.

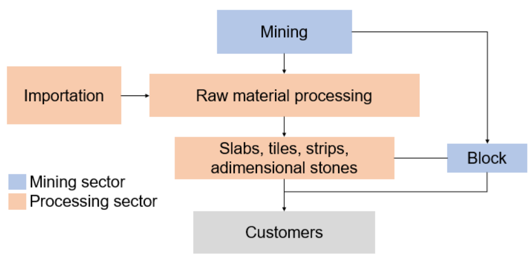

Figure 1: Ornamental Stone, Sub-sector Organization

The Ornamental Stone sub-industry is established by the mining and/or processing companies of limestone, granite, marble, schist and other stones for ornamental purposes. In this sub-sector the blocks extracted from quarries go through the processing companies that convert them into end-customer products, as it is shown in the value chain of Figure 1. In Portugal, the Ornamental Stone sector has seen progressive advances in process industrialization, however, not as much as other industries, such as, automotive and electronics.

1.2. Objective and Contribution

The project aims to evaluate the use of a robotic cell for machining tasks common to the NS industry. In particular, in future tasks, the cell will be used to test and develop disc cutting strategies for later application in the industrial environment. The challenge is to prove the feasibility of robotic arm technology in the NS industry through robotic programming solutions and cell layout planning and optimization. Based on the results, it is intended to acquire the necessary knowledge about possible programming solutions available in order to evaluate the most appropriate method to address the problem. Contributions will be given in several topics, such as, layout planning and Offline programming and simulation.

2. Background

This chapter is intended to address the fundamentals inherent to the project theme.

2.1. Industrial Robotics

Robotics applied to engineering production projects are currently an increasing trend of 21st century. According to ISO 8373:2012 the word robot defines an actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks [12]. The first implementation of an industrial robot dates 1961, in General Motors assembly line. This universal transfer device, as it was called back then, weighed two tons and obeyed point-to-point commands stored in a magnetic drum system. The actuators were hydraulic and were programmed directly in joint coordinates. This means, the angles of the revolute joints were stored during the teaching phase and repeated in operation. Its function was to transfer parts from the foundry to the cooling area, a repetitive but risky task for the workers [9]. Nowadays, developments regarding payload capacity, energy efficiency, process speed, control, programming and economic viability remodeled the industrial robot and contributed to the exponential growth in industrial applications. The numbers provided by IFR are the proof. In 2017, sales of industrial robots increased by 30 % to 381 thousand units, a growth verified for the fifth consecutive year, reaching a market value of 14.4 billion euros [6]. The functions assigned to this type of technology are represented by three major groups of operations: handling, assembly or inspection and processing.

One of the biggest advantages of the industrial robot lies in the increased mobility and workspace. By means of workspace, Mikell P. Groover, Mitchell Weiss, Roger N. Nagel and Nicholas G. Odrey in *Industrial robotics: Technology, programming and applications*, define it as the 3-D space, illustrated in Figure 2, where the robot end, without end effector, can reach [10]. Also, as part of the major characteristics of an industrial robot is the payload capacity. This load capacity can be defined as the maximum weight handled by the robot in the most adverse condition. Taken in this indicator is the weight of the tool, often called as end effector.

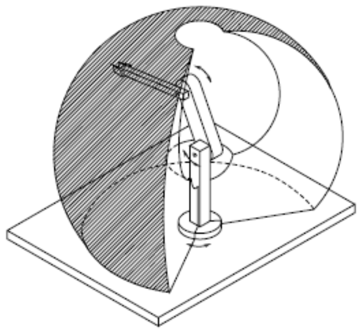

Figure 2: Anthropomorphic robot workspace [2]

2.2. Industrial Robot Programming

Robot programming is an essential task to define the work cycle in which information, such as, positions, movements, speeds, logic signals, decisions, among others are incorporated. This can be done in two distinct ways: online or offline, whereas each has benefits and limitations. Industrial robot programming was initially thought through the online programming method. This type of programming can also be called teach & learn, since positions are first taught and only then reproduced in operation [10]. Disadvantages include the difficulty to program complex tasks and the need to use the robot for programming purposes. Despite its disadvantages, this type of programming is one of the most used in industry. Above all, due to its low cost being sufficient to program simple tasks. However, to address most of the limitations in online programming arises offline programming. This method does not require the robot directly. The programs are created and edited in an external interface, normally a computer. The code can be created in different ways, however, the most significant are direct programming through robot manufacturer's own textual programming language and programming through virtual graphic environments [1]. The advantage of virtual programming environments over direct programming is that it can verify, offline, the robot's behavior regarding singularities, collisions, joint and range boundaries. The major disadvantage of offline programming consists in transposing the tasks into the physical environment. Sometimes correlation between virtual model

and real model does not happen.
The machine handled over the project is a KUKA industrial robot, thus, a deeper study to the functionalities of the compatible programming language, the KUKA Robot Language (KRL), was carried out. A KRL program is made of SRC and DAT files, as it is represented in Table 1. The SRC file, which can be called source, corresponds to the program code. In the other hand, the DAT file, or data, contains the program information [8].

SRC file:	PROG01.**src**
DAT file:	PROG01.**dat**

Table 1: KRL program with two correlated files

There are two distinct ways for defining targets in 3-D space, this means, positions to be reached by the robot. Through joint coordinates, Figure 3, that can be defined as the values of the rotation angles of each axis that serve to describe a position and orientation of the robot in space. Another way is through the X, Y, and Z components, which are the values of the cartesian coordinates in 3-D space, and the components A, B, and C that concern the rotation around the Z axis, Y and X respectively [2].

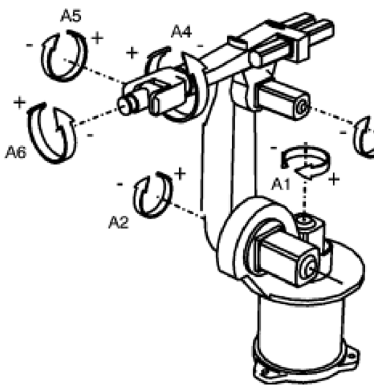

Figure 3: Target in 3-D space through joint coordinates A1 A2 A3 A4 A5 A6 [8]

In industrial robot programming, the frames used are of great importance. For programming purposes the robot controller defines four different types:

- $WORLD: is the origin of the robotic cell and the basis for the robot's origin frame ($ROBROOT) and the rest of the cell equipment. It is fixed in 3-D space and usually located at the base of the robot that is coincident with its own origin.
- $ROBROOT: is the origin of the robot, which is relative to the $WORLD frame, and serves as the basis for the mechanical construction of the robot and its $TOOL frames. It is located at the base of the robot.
- $TOOL: is in the tool tip that is relative to the $ROBROOT frame and serves as a reference point for robot movements. By definition it is located on the robot end, but must be modified depending on the tool being used.
- $BASE: is the origin of the workpiece which is relative to the $WORLD frame and is the reference for the programming coordinates. By definition it is coincident with the origin of the cell which is also coincident with the origin of the robot.

2.3. Natural Stone Processing
As the name implies, the Natural Stone manufacturing industry deals with material of natural origin. Due to a geological process, lasting for thousands of years, physical and mechanical characteristics of the stone are defined [3]. Ornamental stones, or natural stones, are fragile materials that withstand very little deformation before fracturing. In terms of mechanical properties they have good compressive strength, however, approximately zero tensile and shear strength [11]. As far as concerned, the hardness portrays the resistance offered from the ability of one material to "scratch" another. To classify hardness, the Mohs scale from 1 to 10 is used. The higher the hardness, the greater the resistance offered to machining, particularly cutting, so that hard stones require tools with higher hardness. For technical differentiation, the natural stone industry is subdivided into the marble group, soft stone, and granite group, hard stone. A stone considered "hard" is identified by a mineralogical composition rich in minerals with hardness above 6 on the Mohs scale which results in greater tool and equipment wear. On the other hand, "soft" stones, with minerals grade 3 in Mohs scale, are easier to process and thus have a minor effect on tool and equipment wear [13].

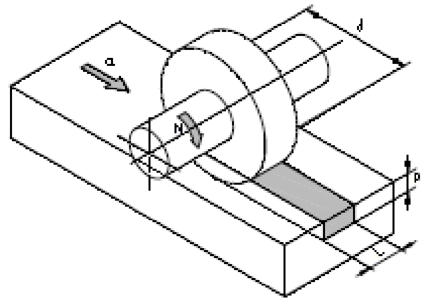

Figure 4: Natural Stone Cutting Process Through Circular Disk

In stone slab disc cutting circular metal discs are used as a tool. Material removal is consolidated through abrasive wear provided by the segments, usually diamond particles, randomly distributed throughout the tool matrix structure. Regarding the performance and results of the natural stone cutting process, it is directly related to the selected operating parameters. For the circular disc cutting process of natural stone slabs several parameters with significant importance are shown in Figure 4:

- Disk rotation speed **N**
- Cutting speed or peripheral disk speed
- Depth of cut **p**
- Feed rate **a**
- Feed type

Regarding the disk rotational speed, usually measured in rpm, it defines the angular rotational speed of the disc which, as a consequence, dictates the cutting speed, depending on the disk diameter, according to the relation given in the Equation 1.

$$\text{cutting speed [m/s]} = \frac{\text{d}}{2}[m] * \frac{2\pi}{60} N[rpm] \tag{1}$$

As a rule, the recommended peripheral speed information is provided by the tool manufacturer. This depends not only on the diameter of the disc, as seen in the equation above, but also on the material to be treated. Quoting S. Carosio and I. Paspaliaris in *Machines and Tools for Stone Quarrying and Processing* cutting speed decreases as the hardness of the treated material increases, due to the increasingly wear action that it has on the tool [13].

2.4. Robot Machining

Today robotic cells are easily found performing, with excellent results, handling, inspection and processing tasks, such as, welding and painting. However, the same does not happen for machining tasks. Due to the inaccuracy problem, that arises from the mechanical construction of the robot, in addition with losses in structural rigidity, caused by larger workspace, it incapacitates the robot to withstand forces from the machining process, namely the cutting force. For reasonable accuracy, in industrial robot machining tasks, the cutting force should be limited [7]. Another problem with robot machining is that it is susceptible to vibration. This is mainly due to the low natural frequency characteristic of its structure. An analysis on the vibration effects of an industrial robot in a machining processes, published in the *Journal of Materials Processing Technology*, made it possible to see sharp increases in cutting force when vibrations occur. All in all, the problems of accuracy, inability to withstand high cutting forces and vibration effects have a direct impact on the quality of manufactured parts. For demanding machining tasks the industrial robot is unlikely to replace the more process oriented industrial machines. However, it is, nonetheless, a valid solution. So much that today there are already solutions for natural stone machining, by robotic arm, capable of producing sculptures, bathtubs, basins, fountains, tombstones, among other applications.

3. Implementation

The procedure implemented to program the robotic arm for natural stone machining tasks is demonstrated in this chapter. Here, the method adopted to generate the final code with the instructions and machining procedures read by the robot controller is explained. To do so, a CAD/CAM software (SprutCam) is used to perform offline programming in a graphical environment.

3.1. Modeling

As a first step in the procedure of creating a natural stone slab machining program by robotic arm, a robotic cell capable of accomplishing the tasks desired was conceived. The robot used was the KUKA KR 360 with arm extension of 250 mm thus, the KR 360 L280 - 2 with 280 kg of payload capacity and KR C2 controller. This 6-axis robot, with $\pm 0.08mm$ repeatability, provides a workspace of 91 cubic meters and a maximum range of 3076 mm. To use the robot model in SprutCam it was necessary to create an .xml file with precise information about its kinematic structure. To conclude the file, information regarding the end effector and the tool frame, namely, position and orientation relative to the robots end, was evaluated and recorded in .xml. The SprutCam robot model, with information about the robots end (TOOL [0]) and tool frame (TOOL [1]), can be seen in the Figure 5 and Table 2.

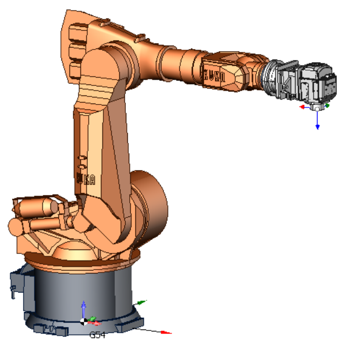

Figure 5: Model KR360 L280-2 in SprutCam

The TOOL frame [1], represented in the previous figure, is located in the area between the spindle and the coupler. For this frame the coordinates and orientations presented are relative to the TOOL [0] which, by definition, is located in the robots end. The coordinates and orientations presented for TOOL [0] are relative to the ROBROOT reference frame located at the base of the robot.

TOOL [0]		TOOL frame [1]	
X	2065	X	223.46
Y	0.00	Y	-1.11
Z	2400	Z	460.18
Rz'	0	Rz'	0
Ry'	90	Ry'	90
Rx'	0	Rx'	0

Table 2: TOOL [0], relative to the ROBROOT, and TOOL [1], relative to TOOL [0]

Following, the final piece CAD model was created. Two slabs, starting from the same raw material with dimensions of 1000 mm x 600 mm x 20 mm. The first with a single central slot, 5 mm deep, and the second with 29 slots 18 mm deep. Both can be seen in Figure 6 and Figure 7.

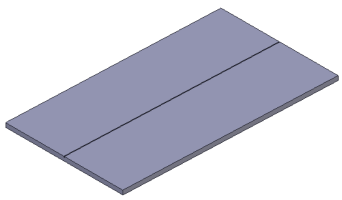

Figure 6: Single cut slab

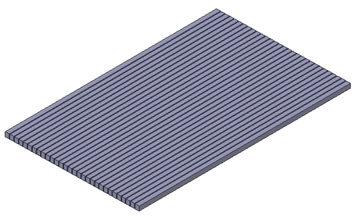

Figure 7: Multi cut slab

3.2. Programming, Simulation and Optimization

In the second stage of the procedure of creating a natural stone slab machining program by robotic arm, the desired cutting paths are defined, tested and optimized according to different operating strategies and parameters.

SprutCam programming logic follows a sequence essentially divided into three steps, each of which, allocated to a different tab in the working window. In Figure 8 an example of the first tab, Model tab, is shown, in which the part to be produced was imported and placed. The Global frame, or WORLD, is located at the base of the robot (which is hidden) while the BASE frame is defined at the top corner of the slab with the following coordinates and orientations:

{X -1000, Y -1767.5, Z 1220, A -90, B 0, C 0}.

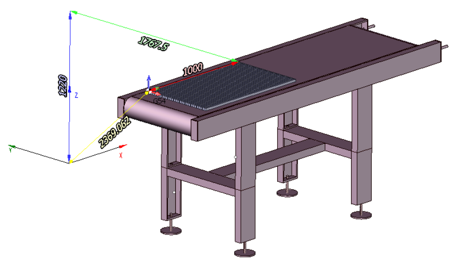

Figure 8: Part Positioning and BASE frame definition

That said, following the previous tab is the Machining tab which allows various functions, such as, choosing and setting the machine, choosing and setting the machining operation and its parameters, choosing and setting the tool, assignment and configuration of machining paths, among others. Table 3 consumes the parameters defined in this step and used in the remaining phases of the work. Speeds were set according to recommended standard values for the process while strategies and Leads were defined due to process optimizations. In the case of Leads, these were used to avoid tool contact with the part in approaching speed.

rotational speed	1000 RPM
cutting speed	26.18 mm/min
feed rate	200 mm/min
rapid speed	10000 mm/min
approach speed	200 mm/min
feed type	down milling
passages	1
stock	0
safe zone	100 mm plane surface
lead in	10 % by tangent line
lead out	10 % by tangent line

Table 3: Operation Parameters

Also, a new tool has been created conceptualizing a real disk with 500 mm in diameter and 3 mm thick.

The coupling between the tool and the spindle was done with a complete and function-oriented solution from HSD. This was followed by the update of the tool frame for the new coupling system. A second tool frame was then defined with a translation of 122.7 mm along the Z axis, relative to TOOL frame [1]. This new frame is located in the center of the disc coupling zone and is coincident with the tool center point, in this case the center of the disc. Coordinates and orientation of this new tool frame, relative to the robots end, TOOL [0], and to the TOOL frame [1] are shown in Table 4.

TOOL frame [2]			
TOOL frame [0]		TOOL frame [1]	
X	344.46	X	0
Y	-1.11	Y	0
Z	460.18	Z	122.7
Rz'	0	Rz'	0
Ry'	90	Ry'	0
Rx'	0	Rx'	0

Table 4: Coordinates and orientation of TOOL [2]

The previous tasks create a fully defined cutting operation that can be simulated in the Simulation tab. Through inverse and direct kinematic models, robot's axes and joints positions are estimated and errors are evaluated. Possible mistakes include collisions, range limits, joint angle limits, singularities, and contact with the part at incorrect speeds, in particular, rapid or approaching speeds. In order to correct the errors mentioned above, but also with potential for trajectory optimization, SprutCam offers a feature that allows alternative options to control the extra degrees of freedom in the robot. Throughout a map, representing the various configurations for the same tool path, where the X axis refers to the position of the tool relative to its starting point and the Y axis to the angular value of the extra axis to be optimized, it is possible to identify fault areas marked by range limits, joint angle limits, singularities and collisions. Figure 9 represents the work done for a single cut. It also, illustrates the functionality described above where it was necessary to correct the the robots configuration to avoid an unreachable area represented by the red color. Also noteworthy are the collision areas, in orange, and the angular joint limit, in pink, which do not interfere with the optimal robot configuration along the path, illustrated by the green line.

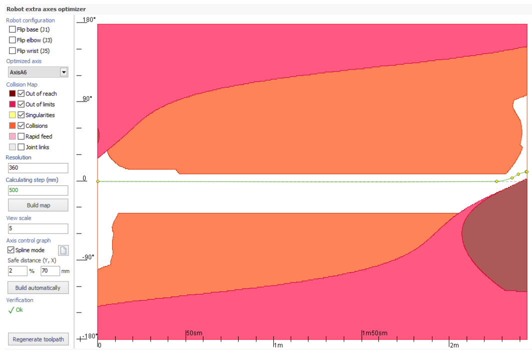

Figure 9: Map designed in a single cut operation

However, for the path trajectory of the circular disc cutting operation it has been planned so that the end-effector maintains a constant orientation with respect to the workpiece. This is intended to improve the tool's performance so that the cut proceeds as homogeneously as possible. For this, in the control of the sixth axis, a fixed direction according to the vector + Z was specified.

Figure 10: Map designed in a multi cut operation

Figure 10 represents the map of a multi cut operation. The sixth axis orientation along the tool path is maintained constant as it is shown by the dashed gray line. In this operation there is no error areas that interfere with the configuration of the robot along the trajectory, so the trajectory is considered valid. After obtaining accurate trajectories, the operation simulated one more time in the Simulation tab. This way the programmer has a graphic perception of the operation performed in which it is possible to evaluate the material removal result.
If the desired outcome is reached, the robot's own code generation phase is followed. To do this, SprutCam comes equipped with a library of post-processors that connect the sequence of operations performed in the software with the text code to be read in the controller. By performing the operation on the post-processor the code is made available and stored in a .txt text file thus completing the programming task in SprutCam.

4. Results

Following the Implementation is the Results chapter which presents the results of the procedure developed and executed previously.

4.1. Offline Simulation and Programming

Offline programming by graphical environment and CAD/CAM software has been considered the best way to approach robot programming due to the advantages it provides. These include the possibility to visualize, offline, the results obtained and the directed functionalities for programming machining tasks. Two case studies were carried out aiming to obtain different types of cutting trajectories in a slab of natural stone. The first has a single central slot while the second has multiple slots in the same type of slab. In the following figures the result of the virtual machining process for the two case studies are presented.

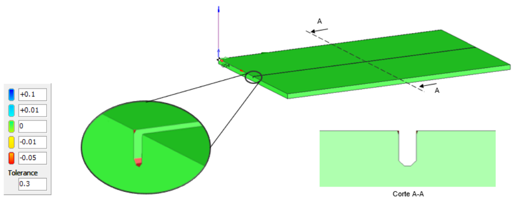

Figure 11: Single cut result

Figure 11 evaluates the cutting performance concerning material removal. The color scale reflects the excess or lack of material removed in the process. Cut A-A represents the profile view of the slot made by the tool. The zoomed image identifies an area of greater imperfection in the lower zone of the slot. Still, the results are quite satisfactory for the overall gross tolerance required.

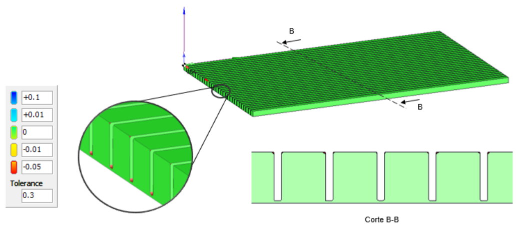

Figure 12: Multi cut result

As in the previous case, the cutting performance of the multi cut process is quite positive and the largest dimensional non-compliance is in the lower part of the groove due to the effect of the tool geometry, as it is shown in Figure 12. Cut B-B represents the profile view of the slots made by the tool. Similarly to the previous one the results are positive due to the type of overall tolerance required.

5. Conclusions

The need for the project research arises in order to contribute with added knowledge to the Natural Stone sector. In particular, discussing how industrial robots can be programmed to perform machining tasks and trying to answer the research question about the advantage of this equipment in the Natural Stone sector. Throughout the project, a programming method was studied and implemented that acquired the necessary knowledge to draw clear conclusions about the best way to approach the problem. Thus, this final chapter presents the conclusions reached during the work.

The problem of programming industrial robots for machining tasks in this project was addressed through offline programming using a CAD/CAM software. Thus it was possible to plan a suitable layout for the task and obtain positive results for the established dimensional and geometric criteria. With the implemented method it was possible to confirm the advantages of offline programming, especially, in terms of layout optimization, simulation, error correction and unforeseen situations. This without having to physically use the robot. Also important to mention are the CAD/CAM software features that make it suitable for programming machining operations. These features include fields that simplify the procedure for setting and changing operating parameters such as rotational speeds, feed rate and machining strategies.

The code generated by SprutCam post-processor proved to be compatible with the robot controller. Thus, it can be concluded that SprutCam programming is a valid solution to generate machining tasks for industrial robots. Without forgetting, however, the importance of compatibility between real environment and virtual environment, especially in regard to the robot's and end-effector kinematic structure which, if does not happen, causes errors in robot position, orientation and configuration.

Nonetheless, the main disadvantage of the implemented method, which makes it unsuitable for customized mass productions, is the inflexibility regarding changes in cutting trajectories and position of the raw material. This is due to the characteristic sequence of CAD/CAM programming, which is dependent on the CAD model of the part being produced, and the need to manually configure the programming base frame (BASE) and/or the tool frame (TOOL). Thus, it was possible to conclude that for a varied mass production the programming method loses its efficiency, since it requires a know-how to perform SprutCam programming and time to reconfigure the BASE and/or TOOL frame.

In final statement, with the work done it was possible to identify and implement a viable approach to program industrial robots for circular disk cutting tasks in natural stone slabs. This contributed to the ultimate goal of making the robot a suitable solution to complement the benefits of manual labor with the production capacity of industrial machines in the Natural Stone manufacturing industry.

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