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Study of the application of a collaborative robot for machining tasks

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Abstract

The importance of collaborative robots is increasing very fast in the industry. They have several advantages over the 'classical' robot arms: they may work side-by-side with humans, their environment needs less adaptation, they may be easily transported, etc. Their joints are more elastic than those in classical robots. For this reason, they are less suited for machining. In this work, a collaborative robot, a sensor of 6 Degree of Freedom (DOF) and a spindle with flex-shaft attachment are used to perform milling operations on soft materials. An inner/outer loop control is being developed to control the movements and the cutting forces. The experiments have been designed to evaluate the capability of the robot with milling operations with different parameters. An analysis of the dimensions and the finished surface will be carried out. The contribution of this article is to determine the possibilities and limitations of the collaborative robots in machining applications, with external control of forces.

Keywords: Robotic machining; elastic robots; co-bots; force control.

1. Introduction

It is known that in the last years, industrial robots have been used in many manufacturing applications, such as welding, painting, metrology, assembly, and machining. The prediction of the International Federation of Robotics, IFR [1], is that by 2020 more than 1.4 million new industrial robots will be installed in factories around the world. The last trend in this area is the use of collaborative robots in industry [2]. Car companies will replace old-style industrial robots with a combination of humans and collaboratives robots (co-bots) assisting humans to gain needed flexibility.

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The field of co-bots has been expanded significantly over the past ten years. A collaborative robot is a robot, which can safely work directly alongside human workers to complete a task. The significant benefits of these new co-bots are their flexibility, safety, ability to be rapidly deployed, and ease of training. These robots along with the benefits of Industry 4.0 will allow a deep change in future manufacturing and production processes. In the academic world, smart robotics applications are being developed and tested every day where collaborative robots can directly cooperate with the human operators connected through an efficient communication network [3].

In the field of machining applications, robotic arms can be applied for tasks such as milling, drilling, cutting, grinding, brushing, polishing, and deburring. Depending on the field of application, the robots tend to replace manual tasks especially in operations that are noisy, pollutant and unhealthy for operators [4]. Also, they appear as an alternative for CNC machine tasks where a large volume of work and the development of complex geometries are required. In addition to these advantages, robots have good programmability, adaptability, and flexibility with a lower investment cost in contrast to a CNC machine tool with the same workload [5]. The disadvantage of the use of robotic arms lies mainly in that they present a lower stiffness compared to CNC machines. The stiffness for an articulated robot is 1 N/μm, which is lower than the stiffness of a standard CNC machine, 50 N/μm. This factor combined with the forces produced in the cutting process generates deflections in the end-effector causing position errors, vibrations, bad quality and low accuracy of the manufactured part. In some cases, the end-effector deflections produced by the cutting forces have reached 10 mm [6].

The high productivity, flexibility, and quality of co-bots together with low cost and high levels of safety make them a very good alternative in machining tasks [7]. However, the disadvantages of these robots, from the point of view of manufacturing, is that their stiffness is even lower than that of a traditional robot. Therefore these have been used more in tasks of pick and place, machine tending and quality inspection. Their stiffness is lower due to their joints usually contain harmonic drives, which have a great reduction and low weight, but add more elasticity to the articulation of the robot. This elasticity produces that dynamic and control models of the robot arm which are more complex [8].

To reduce the effects on classical robots, many investigations have been carried out using various methodologies and procedures. One of the most used process control methodologies, which consists of using loops of motion control or force, to compensate deviations due to low joint stiffness [9]. Various models have already been developed and evaluated for milling and drilling processes; however, due to the non-linear relationship and other uncertainties of the robotic machining system, there are differences between the ideal model and the current model. To introduce such a deviation, it is necessary to introduce advanced control schemes to adjust the parameters in accordance with the machining status. Due to this, advanced control approaches have been made, including adaptive control, fuzzy logic control and neural network control. Approaches to force/position control have also been proposed [10]. The latter can be used to see its effect on machining with a collaborative robot. Control of interaction between a robot manipulator and the environment is crucial for successful execution of tasks, like the machining where the robot's end-effector has to manipulate a cutting tool to perform some operation on a surface.

During the interaction, the environment sets constraints on the geometric paths can be followed by the end-effector. (constrained motion). The use of a pure motion control strategy for controlling is a candidate to fail. This control can be used only if the tasks were accurately planned; therefore, it requires an accurate model of the kinematics and dynamics of the robots and the environment (geometry and mechanical features); the last is difficult to obtain.

In practice, the contact force is the variable that describes the state of interaction in the most complete way. Interaction control strategies can be grouped into two categories; those performing indirect force control and those performing direct force control. The first achieve force control via motion control without explicit closure of a force feedback loop. The last, offer the possibility of controlling the contact force to the desired value, thanks to the closure of a force feedback loop [11].

Within the direct force control loops we can find the inner/outer loop, either by using the movement control loop by position or by speed, as can be seen in figure 1(a) and 1(b), respectively.

In the figure, f_d denote the desired force reference, C_F and K_F are control force matrix whose elements give the control actions to perform along with the operational space directions of interest, M_d is a mass matrix, K_P and K_D are the matrices of the inner loop PD (proportional-derivative) control, K is the passive stiffness, x_e and f_e are the 'pose' (position and orientation) and force of the end-effector, and x_F is a suitable reference to be related to a force error, whose relation with the force error can be expressed as,

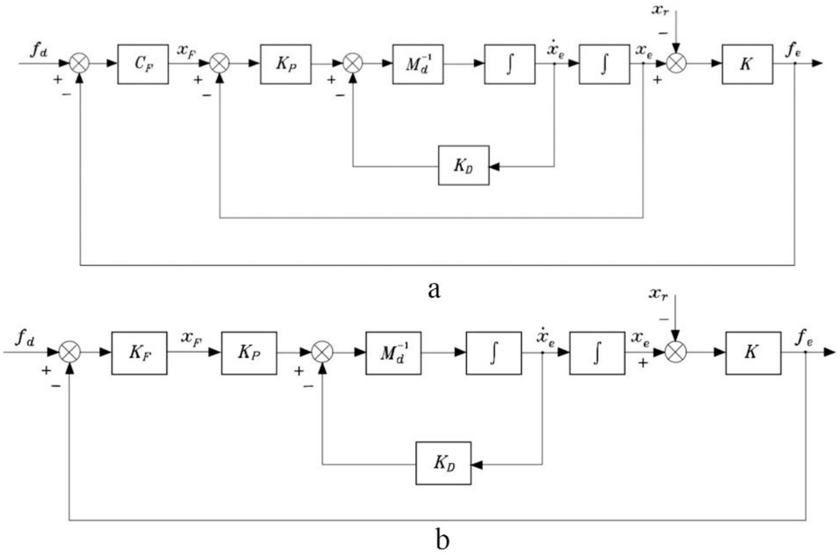


Fig. 1. (a) Block scheme of force control with inner position loop; (b) Block scheme of force control with inner velocity loop.

$$x_F = C_F(f_d - f_e) \tag{1}$$

The equation (1), C_F matrix performs the external control loop with PID (proportional-integrative-derivative)-type controls. However, given the high propensity to noise of the force sensor, the classical derivative control action is not applicable in the outer loop. Two alternatives are usually used [12]. The first is to pass the force error through a low pass filter, where 'a' is the cutoff frequency of the filter itself. In this case, the expression of the control action in the Laplace domain would be:

$$x_F = f_d + (K_P + K_D s)\left(f_d - \frac{a}{s+a} f_e\right) \tag{2}$$

The second possibility is to use the speed instead of the derivative of the force to dampen the system,

$$x_F = f_d + f_P(f_d - f_e) - K_d\dot{x} \tag{3}$$

The previous examples show how the control force is possible to be implemented in a robotic system. This article proposes an analysis of the effects on the dimensions and the finishing surface of the parts machined with collaborative robots. Also, it is a preliminary study of the cutting forces to determine the possibilities and limitations of implementing a force control as shown above.

The article is structured as follows: Section 2 presents the methodology, materials, and experiments; Section 3 shows the results and discussion of the robotic machining, and finally, the conclusions are presented in Section 4.

2. Methodology

The design of the experiment consists in perform slot and step operations to study the effects of the parameters of cut, such as; depth of cut, cut speed, feed speed and the position of the robot. To study the effect of less stiffness present in collaborative robots, milling operations are carried out on two robots with different characteristics. Table 1 shows the main characteristics of these.

The machining cell with a robotic arm is made up of robot plus force sensors, specifically for the case of the Mitsubishi robot, an ATI Delta force sensor is used for the UR3 robot, OnRobot HEX-EB165, both sensors have 6 degrees of freedom.

Table 1. Robots specifications.

Robot	Axis	Max load (N)	Reach (mm)	Speed End-effector (m/s)
Mitsubishi RV-2AJ	5	20	480	2.1
Universal Robot UR3	6	30	500	1

The same spindle was used, composed by a Dremel model FortiFlex which has a flexible head which was installed in the end-effector of each robot through a coupling of writer's manufacture. In Figure 2, both workbenches can be seen. The 6-DOF sensor ATI has been mounted on the worktable, and the OnRobot sensor has been mounted on the end-effector. The sensors relate to the robots trough of an interface with LABVIEW, and the sensor measures the contact force between the end-effector and the workpiece. This sensor allows measurement of the machining force in the plane of work. Therefore, the goal of control is to achieve the desired force.

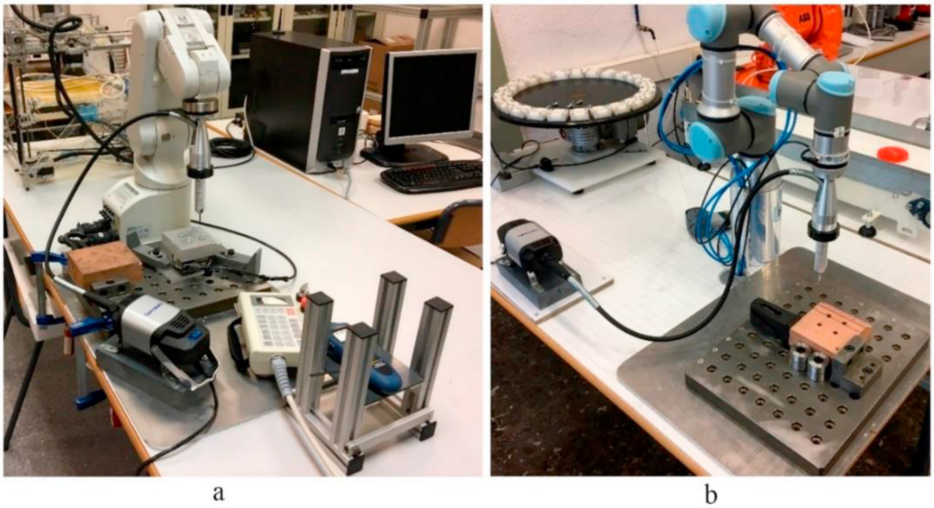


Fig. 2. (a) Machining cell with Mitsubishi robot; (b) Machining cell with UR3 robot.

The milling operations consisted of slots and steps on rough material 100 mm in length. The cutting tool used was a flat mill with 4 mm diameter, and two-edged, the conditions of cut are 19600 rpm and a feed speed of 4080 mm/min. The other conditions of cut are shown in table 2.

Table 2. Experiments parameters.

N°	Robot	Material	Operation	Depth of cut (mm)	Width of cut (mm)
1	Mitsubishi RV-A2J	Aluminum	Step	1	4
2	Mitsubishi RV-A2J	Resin	Slot	1	4
3	Universal Robot UR3	Resin	Step	0.5	2
4	Universal Robot UR3	Resin	Step	1	2
5	Universal Robot UR3	Resin	Step	2	2
6	Universal Robot UR3	Resin	Step	1	4
7	Universal Robot UR3	Resin	Step	2	4
8	Universal Robot UR3	Resin	Slot	0.5	4
9	Universal Robot UR3	Resin	Slot	1	4
10	Universal Robot UR3	Resin	Slot	2	4

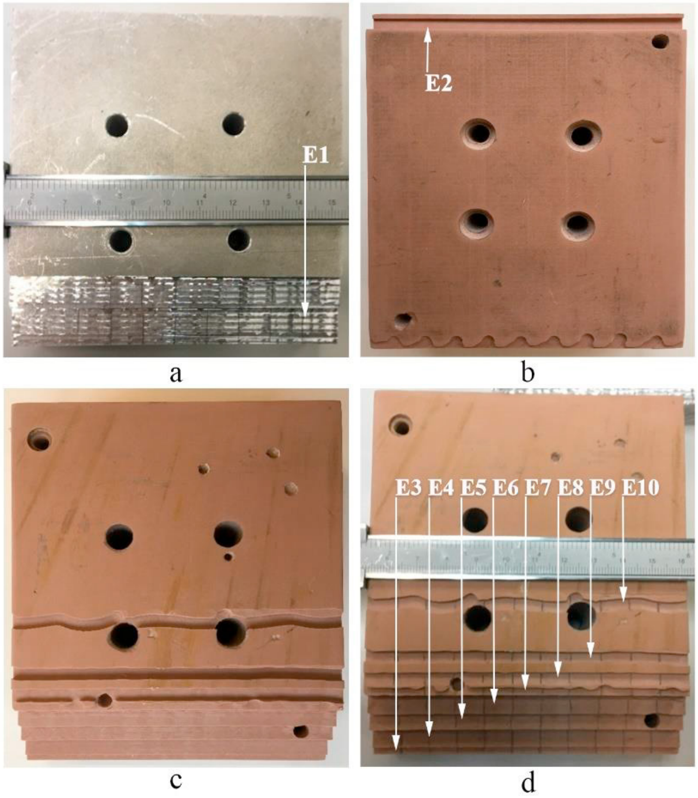
It should be noted that to obtain the real spinning revolution of the spindle; a digital tachometer PCE-DT-65 was used. This measure is necessary to verify the revolutions executed by the Dremel since it does not have direct control to designate it.

For correct programming of the robots and to ensure the dimensions in the final piece, a 'Digigraph 3D-taster' probe and a 'Tschorn Standard Zero Presetter' comparator were used to accurately locate the zero origin of the piece and the lengths of the tools. After machining, the dimensional tolerances were analyzed with a comparator clock 'Standard G' and Surface Roughness Tester 'Mitutoyo SJ-201'. To take advantage of the material, the sequence of operations was carried out in the form of a staircase with each step representing different cutting conditions. This also allows having the same reference (side face of the piece) to make subsequent measurements.

3. Results and Discussion

3.1. Machining with robots

The results of the experimental machining without force control can be seen in Figure 3, in part (a), the results for milling in aluminum by the Mitsubishi robot are shown. It can be observed with the naked eye that there is a poor finish, mainly due to a small advance and the effect of the cutting forces on the robot arm, which could be seen visually as a resistance of the arm to follow its movement, which generates a shallow grid In the case of the performance of the Mitsubishi robot with the resin, slot Figure 3(b), a good finish can be observed for the same cutting conditions. In Figure 3(b), in the lower part you can see the effect of milling with the elastic robot UR3. As it can be observed for the same conditions of cut, 2 mm of depth of pass and a width of the diameter. The machining is completely affected by the low stiffness of its joints, generating these waves because the movement control will proceed to recover the indicated displacement. Here it is demonstrated how soft materials such as resins already affect the performance of the process.



a b

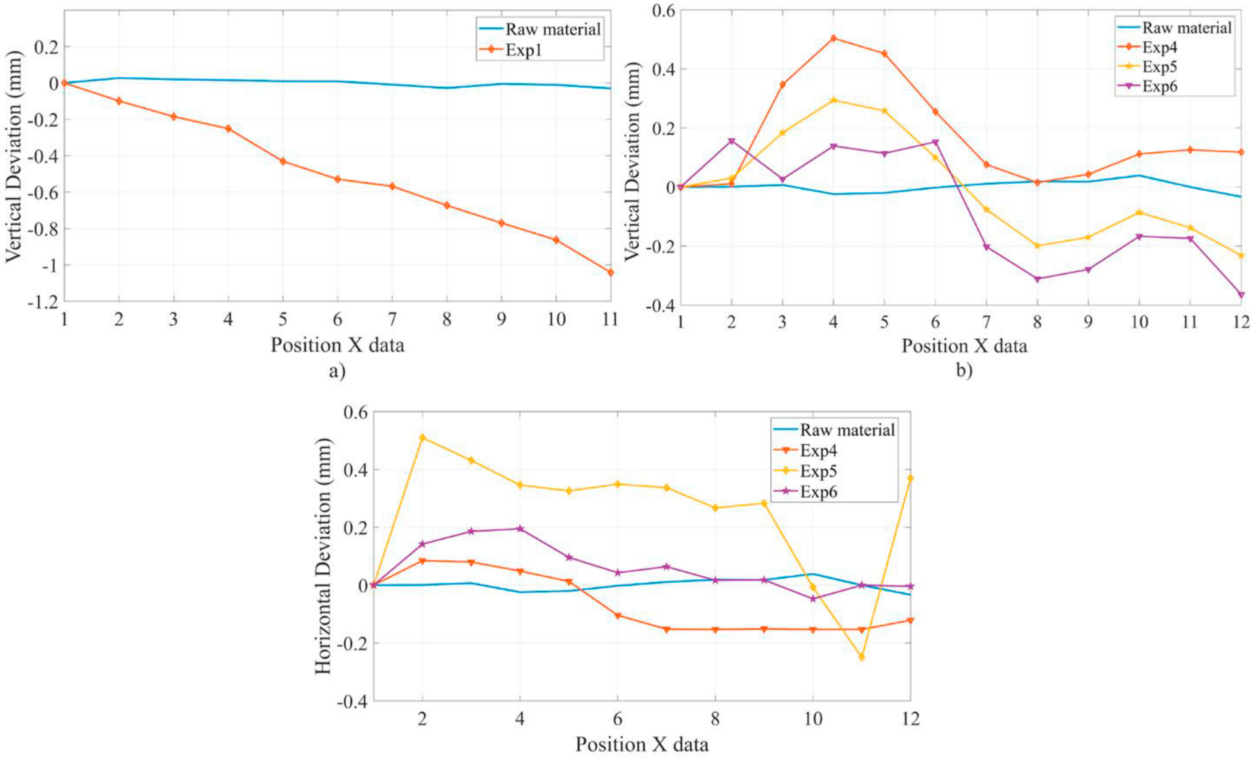
c d

Fig. 3. (a) Machined aluminum part; (b) Machined resin part face a; (c) Machined resin part face b; (d) Machined resin part with experiments.

In Figure 3 (c) and (d), one can see the rest of the experiments made with the collaborative robot in resin. As can be seen, as the cutting conditions increase, the instability of the process increases to such an extreme, as in experience E10, where the tool deviates completely.

In Figure 4, a graph with a dimensional analysis of the milled pieces is shown. The vertical deviation indicates the deviation generated in the depth of cut concerning the plane of cut, on the other hand, the horizontal deviation is the deviation of the path contained in that plane of cut concerning the programmed one.

In the case of the Mitsubishi robot, Figure 4(a), an increase of the vertical deviation is observed as the position in the direction of the cutting feed increased. This increase is constant, and its variations with respect to the trend line are small, this is explained by the fact that the robot is more rigid than the collaborative one, but its maximum deviation is due to the fact that the 5-axis design does not allow adjustment to the orientation of the tool center point, with which a work plane different from that of the piece is obtained.



a)

b)

c)

Fig. 4. (a) Vertical deviation in aluminum; (b) Vertical deviation in resin; (c) Horizontal deviation in resin.

Table 3. Roughness results.

Surface	R_a (μm)	R_y (μm)	R_z (μm)	R_q (μm)
Resin raw	2,85	24,76	17,72	3,65
Exp 3	3,81	30,82	23,56	4,93
Exp 4	3,81	26,52	22,31	4,74
Exp 7	6,51	76,53	42,38	8,33
Aluminum raw	2,47	15,94	13,65	3,09
Exp 1	1,49	10,49	8,20	1,86

In Table 3, the results obtained with the roughness tester are attached. The samples are not filtered, the cut-off length is 0.8 mm, and the evaluation length is five times cut-off length.

Despite the reduced appearance of machining in aluminum, the result of milling is better than workpiece raw. In the case of the collaborative robot, the increase in roughness is not as pronounced as the dimensional tolerances.

3.2. Cutting Forces

In order to be able to carry out an inner/outer loop control, it is necessary to know the force profiles of the machining operations carried out. As can be seen in Figure 5, the machining presents much instability. This is mainly due to the low stiffness of the wrist joints, which, if they are not included in the control loop, would generate perturbations in the force measured by the sensor.

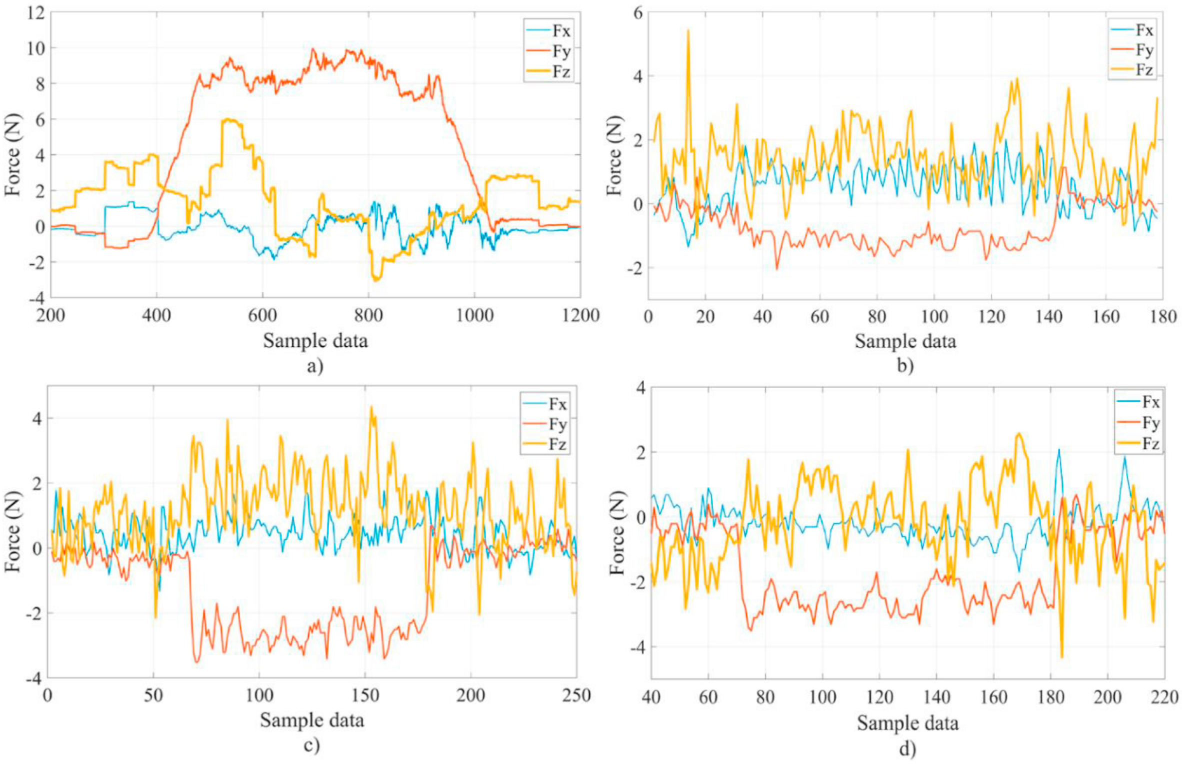


Fig. 5. Machining forces (a) Experiment 1; (b) Experiment 4; (c) Experiment 6; (d) Experiment 9.

The collaborative robot UR3 has many advantages to implement a force control because its inner control allows read easily the position and velocity variables in joints and end-effector reference frame. We implemented a control inner/outer loop, as in the equation (3), trough the command script 'speedL.' When performing tests with force control, the instability in the measurements significantly affected the control loop, generating errors that were not compensated. So, it is necessary to go deeper into the robot machining model to make the control more precise. A first alternative is to include the elasticity of the joints in the control loop through a correct definition of the matrices of stiffness in joint and task space. This implies modifying the dynamic model of the robot to consider it as an elastic no lineal model, with which the effects due to flexibility could be diminished.

4. Conclusions

Given the results obtained, the lack of stiffness of the collaborative robot arms makes it difficult to achieve machining operations with controlled dimensional and finishing requirements. However, the reduction system that collaborative robots incorporate in their joints allows a greater adjustment to reach them, compared with rigid robot arms.

In the collaborative, the stiffness can be determined individually, in each joint, depending on the configuration adopted by the arm and the cutting conditions used (cut feed, spindle speed, step depth, and overlap).

As has been verified in the preliminary tests carried out to evaluate the use of a collaborative robot in the performance of machining operations, its control must be completed with an external loop. It will capture instantaneous efforts in real-time, which will serve to modify the Cartesian deflection using the matrix of stiffness of the arm. In this way, it will be possible to act dynamically on the trajectory carried out in order to meet objectives.

To achieve this, a precise mathematical model is needed according to the actual behavior of the arm's hardware (depending on the type of installed gearboxes, machining operation, tools, etc.), which allows expansion of the stiffness matrix tested it against variations, in part from its variables, measured externally.

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