A STUDY ON ROBOT ARM MACHINING: ADVANCE AND FUTURE CHALLENGES

Rodrigo Pérez*, Santiago C. Gutiérrez y Ranko Zotovic

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Abstract

Nowadays, it is not uncommon to find news and research about robotic machining applications, as milling and drilling. The flexibility, programmability and low price of robots, conversely to CNC machines, makes robotic machining an interesting opportunity for manufacturing of large parts. In this paper, the authors show the current advances on developments of robotic machining and a theoretical framework of the process, evidencing its weaknesses and strengths. Since the low stiffness of robots is their main disadvantage, the target of researchers is to improve this characteristic, and therefore avoid adverse effects like vibration, which influences the machining accuracy. The last developments can be categorized according to their research field: modelling and control of the process, robot workspace optimization, redundancy analysis, vibrating/chatter analysis and new designs and methodologies for the improvement of machining. These researches increase the efficiency and accuracy of the process with the goal to convert robots in a real alternative to CNC machines. In fact, the authors are working on the aim of proposing a characterization of several machining operations with robots, considering a force/torque control that provide the system a feedback with the improved stiffness matrix to correct errors and improve the accuracy during machining.

Keywords: machining robot arm; industrial robots; stiffness matrix; robotic accuracy

1. Introduction

Machining with robotic arms is the combination of two areas or fields in engineering: machining processes and robotics. As is known, the first field uses numerical control machine tools to perform machining operations with great reliability and accuracy to make parts for various types of industries. On the other hand, industrial robots are studied to be commonly used in applications of low contact forces, such as material handling, welding, assembly, painting, etc.

The use of robotic arms in the industry is in continuous increase with an average growth of 12% per year, estimating that, in the year 2020, a total of 3,000,000 robots will be in operation [1]. In addition to its typical applications, in the last two decades, the interest in using robotic arms in machining tasks has grown, although their use in this area is still less than 5% of total sales [2]. The incorporation of robot arms for machining tasks includes many industrial sectors, from the automation and aerospace sector to medical industries. The robots have been applied for machining tasks such as milling, drilling, roughing and cutting. Also, they have been applied to solve surface finish tasks in applications as grinding, brushing, polishing and deburring [2], [3], [4].

Depending on the field of application, the robots tend to replace manual tasks, a category in which we can include collaborative robot arms. The fact that product life cycles are becoming shorter and the demand for high quality standards increases, industries look for an alternative to manual processes or inflexible automated solutions [5], especially in operations that are noisy, pollutant and unhealthy for operators as the environments of the automotive industry [6].

Robots also appear as an alternative for CNC machine tasks where a large volume of work and the development of complex geometries are required. In the aerospace and energy industry, large multi-axis CNC machines are used to mill large parts, which requires a large factory size, as well as incurring high operational costs [7]. Industrial robots are enabled to process complex 3D shapes, in addition to having a large volume of work, which can be increased with extra axes. 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 [4], [6]. Some studies indicated a 30% of reduction in the total cost when robots are used [8].

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/ μ m, which is lower than the stiffness of a standard CNC machine, 50 N/ μ m [6]. This main 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 [3]. In some cases, the end effector deflections produced by the cutting forces have reached 10 mm. Table 1 shows a detailed comparison of CNC machines and robotic arms for machining tasks.

Indicator	CNC machine	Industrial Robot
Accuracy	-0.005 mm	-0.1 – 1.0 mm
Repeatability	-0.002 mm	-0.03 – 0.3 mm
Workspace	Limited	Large
Workspace extending	Impossible	Possible by adding extra actuated axis.
Kinematic architecture	Cartesian	Serial
Number of actuated axes	3 or 5	6+
Kinematic redundancy	Non	Yes, 1 degree of freedom at least
Complexity of trajectory	Suitable for de 3/5 axes machine	Any complex trajectory
Relation between actuated and operational space	Linear	Non-linear
Actuator feedback	Single encoder	Single or double encoders
Mechanical compliance	Relatively low	Relatively high
Compliance error compensation	Non-required	Mechanical (Gravity compensators) Algorithmic (off-line and/or on-line)
Dynamic properties	Moderate, homogeneous with the workspace.	High, heterogeneous with the workspace.
Programming language	Standardized G-code language	Manufacture specified languages (KRL, V+, Karel, RAPID, Inform, etc.)
Manufacturing flexibility	Single or several similar operations	Any type or operation
Price	Competitive for 3 axis tools. Expensive for 5 axis tools	Competitive for 6 axis robots.

Table 1. Comparison of CNC machines and robots for machining. Adapted of [4].

The high reduction ratio in the robot joints causes loss of friction and backlash. A small variation in the reduction ratio of the joint can induce a significant error in the accuracy of the tool center point (TCP). The difference with the errors due to 'low stiffness' lies in that these last effects are less predictable [3].

This work focuses on the correct understanding of the phenomenon of robotic machining, to develop the guidelines of a new proposal to facing future challenges, specifically we focus in the exploration and evaluation of the latest advances in this area. This paper is organized as follows; Section 2 describes the robotic machining model, Section 3 show the last advances in the area, Section 4 describes the future challenges and the authors' proposal. It ends with the conclusion in section 5.

2. Main challenge: Robotic machining model

To understand the disadvantages and analyze the behavior of the robots during a machining process, it is necessary to use an adequate and accurate mathematical model to predict the displacement of the robot structure under an applied load.

Robotic systems are designed to achieve high position accuracy. The elastic properties of its links are considered insignificant, thus the dominant factor that contributes to the deflection of the manipulator is the joint compliance. This is a product of the flexibility produced by: the geometry and the properties of the joint material, the actuators and others transmission elements and the robot posture [9], [10].

Joint compliance is the biggest problem for the deviation of the TCP. This variable is the inverse of the stiffness. Hence, to analyze the structure of the robot it is necessary to determine the value of the stiffness of each joint [11]. The factor of stiffness in machining is so important that many topics of research in robotics have been developed in this area. In general for robots many aspects have been discussed, such as, modeling the stiffness of serial and parallel robots, identification of stiffness parameters and analysis of stiffness characteristics [10].

Pashkevich A. et al, [12] in their studies performed an analysis of existing stiffness models, which can be seen in Table 2. As can be analyzed, if there are more assumptions, there will be an increase in the complexity of the joint model. According to the analyzed literature, the commonly used models correspond to the cartesian stiffness matrices proposed by Salisbury and Chen & Kao [13].

Publications	Model & assumptions	Stiffness matrix
Salisbury (1980)	Serial manipulator, elasticity in actuators.	$K_c = J_\theta^{-T} \cdot K_\theta \cdot J_\theta^{-1}$
Zhang et al. (2004)	Serial kinematic chain without passive joint, elasticity in virtual joints.	$K_c = \left(\sum_i J_{\theta i} \cdot K_{\theta i}^{-1} \cdot J_{\theta i}^T \right)^{-1}$
Pashkevich et al. (2009)	Serial kinematic chain with passive joint, elasticity in virtual joints.	$\begin{bmatrix} K_c & * \\ * & * \end{bmatrix} = \begin{bmatrix} J_\theta \cdot K_\theta^{-1} \cdot J_\theta^T & J_q \\ J_q^T & 0 \end{bmatrix}^{-1}$
Chen & Kao (2000)	Serial or parallel manipulator with external loading (non-over constrained).	$K_c = J_\theta^{-T} \cdot (K_\theta - K_F) \cdot J_\theta^{-1}$
K_c – Cartesian stiffness at the end effector (6×6) K_θ – Joint stiffness of the virtual springs ($n_\theta \times n_\theta$) J_θ – Jacobian of the virtual springs ($6 \times n_\theta$)		J_q – Jacobian of the passive joints ($6 \times n_\theta$) K_F – Stiffness matrix induced by external loading ($n_\theta \times n_\theta$) θ_i – Position of robot joint i.

Table 2. Summary of related works for the Cartesian stiffness matrix. Adapted of [12]

To determine the Cartesian stiffness matrix, the models used the principle of virtual work, which allows making certain assumptions about the static case. Under this principle, the work must be the same in any set of coordinates, that is, the work in Cartesian coordinates must be the same as the work in the joint coordinates. Therefore, by mathematically developing the equality of virtual work, the expression for the Cartesian stiffness matrix is given by,

$$K_x = J(Q)^{-T} \cdot K_q \cdot J(Q)^{-1} \quad (1)$$

Where K_q corresponds to the joint stiffness matrix and $J(Q)$ the Jacobian matrix of the robot. As it can be seen, this expression corresponds to the model exposed by Salisbury, but this formulation is valid only when the robot is in a quasi-static configuration, without external loads or when the Jacobian matrix is constant through the robot's workspace, (e.g. cartesian robot) [7]. Through the Conservative Congruence Transformation (CCT), Chen, et al. [13], added an extra term known as K_g or K_f , which considers changes in geometry under the presence of external charges F . Therefore, we have,

$$K_x = J(Q)^{-T} \cdot (K_q - K_g) \cdot J(Q)^{-1} \quad (2)$$

Where K_g is defined by,

$$K_g = \underbrace{\left[\frac{\partial [J(Q)]^{-T}}{\partial \theta_1} F \quad \frac{\partial [J(Q)]^{-T}}{\partial \theta_2} F \cdots \frac{\partial [J(Q)]^{-T}}{\partial \theta_{n-1}} F \quad \frac{\partial [J(Q)]^{-T}}{\partial \theta_n} F \right]}_{n \times n} \quad (3)$$

This extended definition of stiffness considers the loads of external forces on the end effector. It is not commonly used, since many studies consider their negligible value when the robot is in work zone with optimized stiffness.

For an articulated arm, the Cartesian stiffness matrix is not a diagonal matrix and depends on the configuration of the robot. This indicates that, firstly, the force and the deformation in the Cartesian space are coupled. Force applied in one direction generates a deformation in all possible directions. Secondly, the stiffness is a function of the robot's kinematics through the Jacobian, $J(Q)$, which changes significantly in the robot workspace and according to the position the robot has.

With the assumption that the joint stiffness is constant and that the changes of position can be modeled, the Cartesian stiffness could be calculated. Therefore, the deformation of the TCP under the action of an external force could be estimated as,

$$\Delta X = J(Q)^{-T} \cdot (K_q - K_g) \cdot J(Q)^{-1} \cdot F \quad (4)$$

Some authors use the Compliance matrix for the definition of the previous equation, avoided calculation errors in the determination of the inverse Jacobian. In general, the main difficulty of the implementation of this model is that the determination of joint stiffness is considered constant and must be achieved experimentally. Therefore, there are several methodologies that can be observed in the works of Zhang H. et al. [6], Abele E. et al. [11], Dumas C. et al. [14] y Olofsson B. et al. [15].

3. Advances in robotic machining

Robotic machining has been limited to soft materials such as plastics and/or aluminum and the use of conservative feed speeds to avoid excessive cutting forces in the process. To deal with these problems, various researches have been made with the aim of overcoming them. Chen Y. et al, [2] studied the researches carried out until 2013, and classified them into categories according to the line of work, such as development of robotic machining systems, machining path planning, vibration/chatter analysis and dynamics.

Almost contemporarily, two projects under the European Union financing have been developed to enhance the machining with industrial robots, the first project called, "COMET" ("Plug-and-produce **C**omponents and **M**ethods for adaptive control of industrial robots enabling cost effective, high precision manufacturing in factories of the future") wanted to reinforce the knowledge and methodologies for the implementation of robotic machining. They developed aspects such as kinematic and dynamic robot modeling, auto programming software, trajectory tracking and high dynamic composition mechanisms. Its objective was to reduce the errors produced in machining through an adaptive control of the process. The second project called "HEPHESTOS": "Hard Material Small-Batch Industrial Machining Robot", had as main objective the development of new technologies for the robotic machining of hard materials to provide a standard for planning machining, programming and control in real time. Both projects introduced important advances in the area.

More current studies, as the one conducted by Klimchik A. et al. [4], have defined the last advances in the following aspects; (1) Improve stiffness of the manipulator, either by increasing the section or using advanced materials. (2) Use gravity mechanical compensators to reduce compliance errors. (3) The use of second encoders placed on the motor shaft to compensate errors. (4) The application of off-line error compensation techniques to modify the input path in the controller.

In general, a robotic machining cell is an integrated manufacturing system that consists of an industrial robot of 5 or more axes, a spindle for cutting tools and a compatible software for programming multiple trajectories. In addition, depending on the application, auxiliary elements can be added, such as a seventh sliding axis, rotating tables, force/torque sensors and vision systems that will increase the functionality and flexibility of the cell. Next, a review of the state of art about last advances and studies regarding robotic machining are shown to obtain a better conception of the models and architectures used.

3.1. Control of the machining process

The control models for robotic machining can usually be differentiated into two types; (1) generation of off-line compensation, where a precise model of stiffness and cutting forces is necessary to estimate the deflections occurred during the process and (2) compensation on-line, where the use of force/torque sensors are the key tool for programming and control in real time [16], [17]. Specifically, we will find force controls, force/position controls and impedance controls. These control types are used with adaptive, robust, intelligent or classical control methods or techniques [18].

Pan Z. y Zhang H. [6], [9], in their research focused on improving the quality and efficiency of robotic machining through two methods; compensate the deformation of the robot and maximize the material removal rate. To achieve this, firstly, they used the conventional stiffness model and a force sensor to perform a real-time compensation of the programmed trajectory. In Figure 1, the compensation principle can be appreciated.

Fig. 1. (a) Principle of real time deformation compensation. (F_m^s : sensing force, q_r , joint position). [6], [9].

Secondly, its purpose was to maximize the material removal rate (MRR), which is given by the following relationship,

$$MRR = w \cdot d \cdot f \quad (5)$$

Where w is the width of cut (mm), d the depth of cut (mm) and f the cut feed in (mm/min). The width and depth of cut are kept constant therefore a conservative value is usually given for the cut feed to avoid damage to the spindle. To maximize this rate, they used an adaptive type control. But, as it is complicated to measure the material removal rate directly, they regulated this value through force measurement of the sensor at the end effector. Adjusting adaptively the cut feed to regulate the force allowed to extend the life of the tool and increase the productivity of the process. The experimental results of the controls in real time allowed them to reduce the work cycle from between 30% and 50% and improved the surface quality with a superficial accuracy from 0.9 mm to 0.3 mm. In a subsequent research [19] the authors applied different types of control for the material removal rate, including a PI (Proportional and Integral), adaptive and fuzzy control. The adaptive control being the one that delivered better results from the point of view of the stability of the system.

In Tyapin I. et al. [16] we found a comparison of two models for calculation of offline force, the first only considers the influence of the depth of cut and the second considers the influence of the depth and width of cut as parameters. Their results indicated that the second model is more accurate to identify deviations from the process.

Other more current methodologies have been found in the work of Sörmo O. et al [20] and Chen S. & Zhang T. [21], who developed an adaptive force control model. Also, in the work of Cano P. et al [22], who developed an iterative learning control, and in the work of Ilyukhin Y. et al. [23], who developed an adaptive control, but they used signals of the currents in the windings of motors to provide information about the loads acting on the drives.

Cen. L et al. [7], have proposed a model that allows a better understanding of the dynamic effects produced in the milling forces. Their model differs from the others, because they do not use static cut models that are only valid for the features of CNC machines. Based on the Sutherland and DeVor studies, the instantaneous milling force is a function of the instantaneous thickness of the chip, which in turn is affected by the flexibility of the machining system. Therefore, an iterative calculation of the balance of the dynamics of the chip load without cutting at each instant of time is required. This theory plus the use of the improved stiffness model allowed the creation of an algorithm to calculate the instantaneous dynamic force.

The comparison of the dynamic model with the experiments showed a reduction from 50% to 75% in the calculation errors of forces. Similar research can be found in the work of Klimchik A. et al. [24], but they used the stiffness model proposed by Pashkevich A. et al, [12]. In the case of drilling process control, we found the works of Garnier S. et al. [25] and Gomes D. et al. [18], both emphasized that the control of the process should be carried out in three phases; the first contact or indent phase, the material removal phase and the final contact phase. The first work realized a theoretical model estimating the force of each phase and thus compensating the trajectory. The second work realized a force control in real time that diminished the sliding produced in the first contact, but even so, it cannot avoid deflections in other directions.

The results showed are very interesting, since demonstrate the reliability of using the improved stiffness model that consider the dynamics parameters. The application of this model could allow a more accurate online force control to compensation in real time.

3.2. *Planning and programming trajectories in machining.*

To handle the lack of standardization in robot programming, producers have offered solutions in software such as, Kuka CAMRob, Motoman Standard CNC G-Code Converter, FANUC Roboguide, etc., to transfer trajectories into the robot program. Other external companies have also offered some specific programs such as Robotmaster, PowerMill, etc. [26]. However, the use of external software implies an extra cost. In the literature we can find with certain methods to program and plan the trajectory of the robot. Pan & Zhang [9], proposed a simple and quick method to program the trajectory of machining. They only used the flex pendant of the robot and marked several guide points through trajectory of the TCP. Then a robot self-learning process linked such points and finally a post processor filtered and reduced the data to generate a program. Some efforts have also focused on generating an approach to standardize robotic machining, as in Huynh H. et al. [27] who simulated the machining process using a simplified multibody model, or Zivanovic S. et al. [28] who proposed an approach for the application of new standards in machining operations through the use of industrial robots. The methodology developed in accordance with the ISO 10303-238 standard was proposed for the execution of programming, simulation and robot machining process.

3.3. *Redundancy*

As mentioned above, the behavior of the robot varies in the workspace, since both its kinematics and dynamics depend on the position. Each posture has its own state of stable conditions and along the trajectory the robot arm can have infinite number of configurations, therefore the researchers take advantage of this redundancy to improve the machining.

A robot is redundant when the degrees of freedom (DOF) of the end effector are less than the degrees of freedom of the joint space. This redundancy increases the accessible volume and the ability of the robot to avoid obstacles. In the literature, three types of redundancy were defined:

- Structural redundancy: Joint space dimension m is larger than the operational space dimension n .
- Kinematic redundancy: Joint space dimension m is larger than the task realized degree t .
- Functional redundancy: Operational space dimension n is larger than the task realized degree t .

Mousavi, S. et al. [29], experimentally evaluated the use of functional redundancy for one and two degrees of freedom. Their experiments showed that using a degree of freedom allowed them to obtain more stable areas where productivity can be doubled. On the other hand, adding a second degree of freedom in redundancy could increase productivity by 40% or conversely it could be diminished. In Figure 2, stability can be observed for 1-DOF (rotation angle of six axis).

Fig. 2. Stability as function of the redundancy of 1-dof [29].

In subsequent research [30], the use of a degree of redundancy was optimized by using a model to adaptively control posture throughout machining. The experiments demonstrated the benefit of using a functional redundancy control to improve stability, achieving improved accuracy from 11 to 2.5 μm for the same cutting conditions. The importance of these studies is that the use of redundancy allows movement from unstable to stable areas without changing the cutting conditions and thus ensure the machining result. The disadvantage is that they do not consider the dynamic effects of machining.

3.4. Posture optimization in robots.

The redundancy of robots allows the improvement of dexterity and thus raises their performance. In this sense, many researchers created and analyzed indices to evaluate the effectiveness of the robot's posture during machining operations.

Some known performance indices are:

- 'Number condition' of the Jacobian matrix is the upper limit of the relative amplification of rounding error when solving a system of linear equations to measure the distance to singularities.
- 'Manipulability' is the absolute value of the determinant of the Jacobian matrix. It was stated that a good manipulability index indicated a point in the workspace "far away" from the singularities.
- 'Velocity ratio' measures the robot's ability to move in a given direction.
- 'Force transmission ratio' represents the robot's ability to balance a given load.
- 'Joint-force index' is defined as the ratio between the maximum static force in any joint and the external load.

However, other authors have created other indices to optimize the position of the robot, as is the case of Zargarbashi et al. [31] who defined the new index known as 'Robot Transmission Ratio' (RTR), which is the absolute value of the cosine of the angle between the vector of torque and the joint-rate vectors. Its objective is trying to quantify the effectiveness of the actuator force in producing a prescribed robot posture. Maximizing this index allows minimizing the magnitudes of the torque and position vectors, which lets the engines to work in accordance with their capacities.

Caro S. et al. [8] made a methodology to determine the best place in the workspace to perform the machining operation. They define a criterion of quality of the machining which is expressed in terms of the displacement of the tool, the objective of optimization is to minimize this index. The theoretical results showed that the optimal workspace is associated with the best redundancy scheme.

Guo Y. et al. [10], defined another index which is based on measuring the stiffness of the robot in certain positions. They studied the "translational compliance sub-matrix", which expresses the relationship between the translational displacements of the end effector and the applied force. The experiments carried out maximizing the index in drilling tasks demonstrated a uniform finish and lower deflections of the tool, which indicated a greater resistance of the robot to the machining forces.

The previous works have been focused on obtaining methods to select the orientation for a specific position of machining, but to obtain the optimal machining position it is necessary to optimize the global workspace of the robot. Lin Y. et al. [32] proposed a posture optimization methodology, which is based on evaluating three indexes in maps of the robot's workspace: kinematics, stiffness and deformation. With this, the best machining performance can be determined. In Figure 3, the optimized posture can be appreciated following the previous methodology, this allows the decrease of the deviations from 0.61 to 0.25 mm.

Fig. 3. The placement of workspace with respect to robot [32].

Despite the good results in the optimization indexes, it can be observed that none consider the dynamics effects of the process, they are only based on kinematic and static criteria, so the consideration of dynamic models such as the one presented in Cen et al. [7] could improve the results in the optimization of the workspace of the robot.

3.5. Vibration/chatter analysis.

One of the biggest obstacles to defend the use of robots in machining processes are the vibrations that are generated during the process. The natural frequency usually takes values from 10 to 20 Hz, lower value than CNC machines, so taking into consideration that the cutting forces in the machining are periodic and sometimes have unpredictable variations, the occurrence of phenomena of vibration or chatter it is not surprising [3].

As main sources of these vibrations, two phenomenon have been identified; regenerative chatter and mode coupling chatter, the first is due to the variation in the forces and depth of cut and the second is due to the vibration of the mass system in all its degrees of freedom with different amplitude and phase [5]. These adverse effects damage the surface, which is compounded by poor dimensional accuracy, the tool life is reduced and can even cause damage in the machine. Several investigations have been developed to reduce or eliminate this problem.

Pan Z. et al [5], in their studies, discovered that when the chatter occurs, the amplitude of the cutting force increases drastically and the chatter frequency can be observed through the Fast Fourier Transform from the sensor data. While they studied the process with different directions of advances and depths of cut, they observed the presence of a low frequency vibration (10 Hz) when the depth of cut was only 2 mm moving in minus Z direction. This frequency corresponds to the natural frequency of the base of the robot, so when the vibration occurs it occurs throughout the structure. This vibration does not change with the variation of cutting parameters or the location of the work surface, but it varies according to the location in the robot workspace and the direction of movement.

It is known that using high spindle speeds theoretically reduces vibrations for any depth of cut. But experiments showed the opposite, so the authors, exposed the mode coupling chatter as the biggest factor of this vibration. Pan et al [5] proposed a model of two degrees of freedom, which allowed the analyzes of the behavior of the robot. Their model corresponded to the experimental results and the main factors were the configuration of the robot and the depth of cut. As recommendations, they proposed to use specific tools to control the direction of the cutting forces, in addition to using robot positions and trajectories that minimize the angle between the resultant cutting force and the maximum direction of the robot's main stiffness.

The drawback of this model is that it cannot be applied to different types of cutting operations continuously, since the range of motion and flexibility of the robot is affected. Cen L. et al, [33] presented a model to avoid mode coupling chatter, but based it on the improved stiffness model. This model avoided having to change cut feed direction or the orientation of the piece. This new model allowed definition of the cutting parameters to obtain a greater stiffness when altering the direction of maximum stiffness, as shown in Figure 4. The experimental results of the model showed a reduction greater than 45% in the resultant force and a reduction of the mode coupling vibrations occurred when increasing the advance speed.

Fig. 4. Comparison between Pan et al. and Cen et al. chatter avoidance methods: (a) Old method, (b) New method. F: force, K: stiffness, β : angle between X-axis and force, γ : angle between force and maximum stiffness [33].

Other authors such as Vieler H. et al. [34], proposed a vibration reduction methodology through the use of secondary encoders. These encoders measure the output position of the engine, which allows to generate an offset and, this way, an error compensation is achieved. The amplitude of the deviation was reduced from 0.75 mm to 0.25 mm. Although this model reduces certain effects, it has the problem of not considering the dynamic effects in the definition of the stiffness.

3.6. Devices and methodologies.

Sörnmo O. et al. [35] and Mohammad A. et al. [36], developed a system known as a macro-mini manipulator, which consists of a robot arm as macro manipulator that allows the exercise of the main movements of the process and the mini manipulator which consists of a device specifically designed to perform the respective improvement. In the case of the work carried out for Sörnmo O. et al., the micro manipulator, in which the spindle is mounted, had a mechanism operated by piezo-actuator that allowed the compensation of the deflections in three directions, through strain gauges and capacitive sensors that measured the Spindle position. The experimental results of this system achieved precisions in milling of $\pm 12 \mu\text{m}$. On the other hand, the work presented in Mohammad A. et al., the mini manipulator controlled the force applied in the polishing processes with which it reduced the inertial effects that caused unwanted vibrations.

Möller C. et al. [37], used secondary encoders to improve the quality of machining in the aerospace industry. The use of secondary encoders and an adaptive control allowed improvements of the effective stiffness and repeatability of machining operations. They tested this model experimentally through the evaluation of repeatability with circular movements increasing accuracy twofold over the case without encoders.

Tian F. et al. [38], presented a specific solution to solve the problems of polishing on curved surfaces, their objective was to control the polishing forces through a platform with flexible abrasive tool, which in conjunction with the control of the robot allows polished mirror quality. On the other hand, Barnfather J.D. et al. [39], investigated the compensation of dimensional errors through data from a cloud of points using optical scanners. They showed an efficient method that can perform an inspection of the cloud of points, which were aligned with the cutting coordinates and was used to compensate the trajectory. Their results improved dimensional errors by 96%.

Finally, the work of Denkena B. et al. [40] focused on a new robot design that had enough stiffness to withstand the forces of machining. After evaluating several designs, they concluded that a mixture of robot arm with conventional machine is the best combination to face the machining tasks. All these proposals are good for a specific case, but they do not solve the general problem of robotic machining.

4. Future Works

Analyzing the advances obtained in robotic machining, it has not yet been possible to unify a procedure or methodology that can be used for more than one machining operations. We believe that the cutting force and robot stiffness modeling can be improved by using as a basis the proposal of Cen L. et al.

The problem of programming robot arms for machining processes continues, even though, certain attempts have been made to normalize the language. Also, there is no complete development of special equipment for robotic machining, as there could be the creation of specific spindles or sensors with low weight.

The study of the advances in the area is the first step to direct the future work. The authors want to evaluate the capacity and feasibility of industrial robot arms and collaborative robot arms for their use in machining operations with soft materials by proposing modifications in their control to convert it into an adaptive control and improve its behavior in machining operations. The objective of our work will be (1) Characterize the machining processes with industrial and collaborative robot arm, (2) Study the dynamics and control of robot arms and propose the appropriate modifications to convert them into an adaptive control and (3) Evaluate technically and economically the application of sensor elements and control methods to be integrated into machining processes with robotic arms.

5. Conclusion

Robotic machining has several specific problems and multiple heterogeneous contributions by different authors. The aim of this article has been to clarify the concepts and understand better the problems. We have proposed a review of the theoretical background, as well as the state of art about recent research and developments related to robotic machining. Despite the great advances of the last decade, there is still a long way to go until robotic machining is widely used in industry.

The advances reviewed show us that robots have the full capacity to be improved to deal with these new operations. Not only can the new robot designs be improved by having a better understanding of the process, these advances could give a second life to the robots that are in multiple companies performing their typical tasks. If the industrial robots were able to provide accurate positions under contact situations in the same way as their well-known good repeatability, robotic machining could be a very significant improvement for many applications.

The best way to control the accuracy of the machining operations performed by robot arms seems to use a method that considers the torque generated. The control system for the robot arm needs to have feedback of the dynamic to prevent damages in their joints and engines and to achieve the required accuracy.

The authors suggest studying certain areas of robot machining that have not been developed completely (modelling and programming of robotic machining), as well as the proposal to evaluate and demonstrate the feasibility of the process with the aim of this being applied to multiple machining operations. Possibly, the main contribution of this article is to restructure a field which has so many different problems and varies approaches to the solutions.

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