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Overview of the state of robotic machining: Current situation and future potential

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Abstract

Nowadays industrial robots are an appropriate technology for developing flexible and reconfigurable manufacturing systems which contribute to perform automatically operation such as milling, cutting, drilling, grinding, deburring and polishing. Machining robots symbolize a cost-saving and flexible alternative compared to conventional CNC machines which are the restricted working area and produced shape limitations. The improvement of individual elements and development of new devices has caused a perception change about the use of industrial robots to perform machining operations. The approach to this research was to analyze technical barriers of individual components that it was broken-down as well as full improving the system. This document is intended to provide technical constraints, current technology and future potential researches about robotic machining.

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1. Introduction

Automation of manufacturing processes, using robotic systems, is changing the way the production systems are conceived in general. In this sense, industrial robots represent a reliable alternative technology for the development

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of flexible and reconfigurable manufacturing systems solved different manufacturing tasks as handling, welding, assembly, spray painting, machine tending and machining. The incorporation of robotic cells to manufacturing process is constantly increasing worldwide and forecasts indicate that It will continue to increase in the future. Although the sale of robots suffered a major setback as a result of the economic crisis of 2009, luckily this situation has reversed since 2010. Many of this robots sales again increased by almost 40% in 2011, driven mainly by the automotive industry and the metal industry [1]. The 78% of the robots sale is destined to solve handling and welding activities [2], while the percentage of industrial robots aimed at resolving material removal operations are certainly less than 5% of total sales, including in this classification handlers to carry out polishing, deburring, milling, cutting, drilling, etc.

Yet machining robotic cell is applied in different industrial sectors and can solve many key manufacture processes in large variety of products. The successful implementation of industrial robots include a large number of industrial sectors, as shown in the Table 1.

Table 1. Products and process used in different industries [3].

End-User Segment	Process	Product
All segments	Milling	Rapid prototyping
Aerospace	Grinding, polishing, drilling, cutting	Turbine blades, bulkheads, insulation, wing segments
Automotive	De-flashing, grinding, drilling, milling, cutting	Engines, truck frames, body panels, door knobs, bumpers, stamping dies, sand cores
Fashion	Milling, sanding	Mannequin molds, mannequins
Foundries	De-burring, milling, drilling, routing, finishing	Molds, castings
Marine	Milling	Boat hauls
Medical	Grinding, polishing	Prosthesis
Entertainment Ind.	Milling	Move set props, amusement park scenery
Plastics	Milling, routing	Molds, helmets
Woodworking	Milling, routing	Hot-tub molds, furniture, trim, banisters, modeling board

On one hand robots have been applied to the machining tasks, which consists in controlling the robot path using the tool center point (TCP), more like the traditional applications of CNC machining such as milling, turning, drilling, routing and cutting. On the other hand they have been applied to solve surface finish tasks, which is based on controlling the force of working tool on the workpiece surface, more focused on applications such as grinding, brushing, polishing, de-burring, and de-flashing. Thus, the robotic applied to solve surface finish tasks has as the main purpose to solve manufacturing processes that traditionally have been carried out by manual operations, while robotics applied to machining tasks represent a new alternative option to CNC machining centers or rapid prototyping machines.

This paper is intended to address the study of the art state about robotic machining applications, firstly establishing a technical and economic comparison among different technology competency. In terms of accuracy, the industrial robot is worse than any conventional machine tool but better or comparable to a rapid prototyping machine type STL or SLS. Taking into consideration the industrial segments and materials, the robots represent a more versatile alternative in comparison to rapid prototyping machines, well it is possible to shape pieces in different materials (wood, wax, foam, resin, etc.) without compromising accuracy levels, reason why this systems might be a good substitute for RP machines.

The design of any piece, which is obtained by machining, is conditioned by type of manufacturing operations required and area or volume of the working zone associated to the production systems, among others. The piece size and complexity determine the machines which be manufactured as well as the types of operations to perform. It is precisely here where conventional machining machines find their main disadvantage to robot cells by having a more limited work area in general.

A medium-sized industrial robot can easily cover a 7 or 8 m3 working volume, and if It is considered the possibility of including external linear or rotary axes the working zone is remarkably increased [4]. Furthermore, these manipulators feature a flexible kinematics, allowing to work large pieces by individual operations, as well as achieve path work in multiple configurations of the robot axes. This point represents a great advantage when it comes to manufacture pieces with complex shapes and difficult access, dispensing with devices and special production techniques necessary to carry out manufacturing process in conventional machine. In contrast, robotic machining has a clear disadvantage when it increases the hardness of the materials, obtaining values of tolerances and surface quality significantly lower compared to the CNC machines.

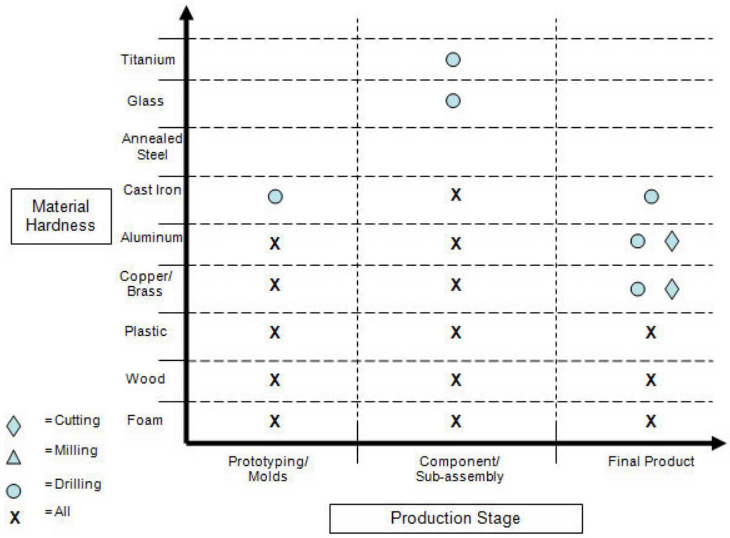

Fig. 1. Production Stage and Material Hardness [5]

Today It rarely arise problems in performing robotic machining operations when the material has low hardness (foam, wood, plastic, etc.) independently of the stage of manufacture; prototyping, intermediate or final product. The limitations arise when they are machined materials as bronze, copper, aluminum alloys, titanium, ceramics or cast iron, see Figure 1.

There is some consensus among manufacturers, integrators and end-users, who believe that it would not be feasible to replace CNC machines for robots in machining applications that It is required 3 or 4 axes of motion, but if it would be appropriate in those cases where the machining requirements are less than that provided by the CNC equipment, when capacities of systems far exceed the accuracy requests of the work pieces.

The robots ability to carry out machining operations in 3, 4 or 5 axes, the high flexibility of the tool positioning, the size of the area or volume of work available and the purchase price (cost reduction between 30% and 50%) of a robotic machining cell have turned this production system into a competitive alternative for the CNC machine. If this minimum configuration of robotic machining cell is integrated supplementary devices as external axes, artificial vision system or force control systems, the functionality and flexibility of the robotic cell is increased but the cost also.

2. Technical barriers of robotic machining cell

One typical robotic machining cell is a complete manufacturing integrated system that is composed of industrial robot, controller to command five or more axis of motion, spindle to active tool rotation that remove material from a part and robot compatible CAD/CAM software to programming multiple paths. Sometimes, application specific ancillary equipment, such as seventh axis slide, indexing table, force sensor, and vision system can increase the functionality and flexibility of the work cell.

Industrial robot limitations have been largely investigated by different authors and this has allowed to identify the problems associated with robotic machining. The main barriers to be overcome in machining operations using industrial robot are related to the motion poor accuracy in presence of changing cutting forces and vibration system.

On the one hand, robot stiffness is probably the limiting factor main to robotic machining when the material hardness increases. In general, industrial robots stiffness is less than 1N/μm while conventional CNC machine tool centers often have more than 50N/μm. Then, robots overall stiffness is much lower respect to the CNC machine and furthermore is strictly dependent from its configuration [6]. Similarly, robot natural frequency used to take values from 20 Hz to 10 Hz with large payloads on the TCP [7]. It is much lower than the conventional CNC machine tool, which are several hundred or thousand Hz. If we take into consideration that the real forces of the machining process are periodic, and sometimes unpredictable variation, it is not surprising that the low rigidity of the robot lead to overall system vibrations or even the phenomenon of chatter.

On the one hand, It is noted industrial robots incorporate high ratio gear reducers which cause frictions losses and backlash. For some writers, the joints backlash is the major source of machining accuracy errors [8], with a primary influence from axis 1. Considering that the axes 1, 2 and 3 of the robot are intended to achieve the trajectory points (the axes 4, 5 and 6 determine the tool orientation to a greater extent), It is possible to deduce that a small value of radial play in reduction gears can induce a significant error in the accuracy of the tool center point. Furthermore, this type of error is less predictable in comparison with the robot stiffness because the effect induced on the tool central point cannot be oriented in the same direction as the cutting forces of the machining process.

Finally, It should mention other limitations of machining robots such as the resolution of the control elements or control memory responsible for managing the processing data and work paths, which usually are much less accurate than in the CNC machine .

3. Robotic machining cell main technical improvents

The technological advances and innovations that have experienced the robotic machining field in recent years, has overcome certain barriers and constraints which delayed the inclusion of articulated robots the assumption for shaping operations by material removal.

First, the lack of a specific normative with respect to the programming language, equivalent to standards used in CNC machine tool, and the slow evolution the path simulation programs for robot have been a serious limitation in the development of robotic machining solutions. Fortunately, today there are a wide range of IT tools intended to scheduled and carried virtual simulations of robot trajectories. Users of robotic cells can use the workpiece CAD information and generate the path of the tool the same way which is programmed a CNC machine, Figure 2. Using the work paths is possible to study the machining process through a virtual simulator that allows to play robot moves and identify mistakes as reach point out, overcome axis travel limit, over travel, wrist flip, singularity or collision. Below some robot machining simulation software currently available on the market are appointed: ABB RobotWare Machining FC, FANUC Roboguide, KUKA CAMRob, Motoman MotoSim EG, Robotmaster KMT CamPro or DELCAM PowerMILL Robot Interface.

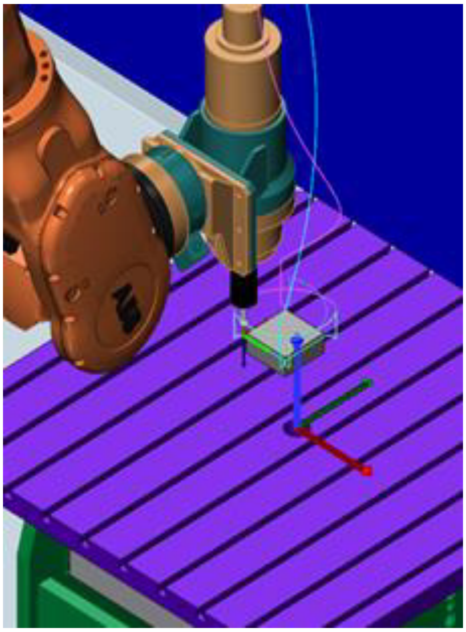

Fig. 2. Robotic simulator.

Second, accuracy and rigidity of industrial robot does not have facilitated its inclusion in machining applications. The development of robotic machining cells is a very risky bet for engineers, and unreceptive production option for end users who are used to using conventional machines. As a result, Robot OEMs have developed robotic arms specifically designed for use in robotic machining applications as Stäubli RX170 hsm, ABB IRB 6660, KUKA KR 500-3 MT, Motoman DX1350N and FANUC F200iB. These robot models have mainly improved stiffness values and accuracy values in path. Still, the intrinsic limitations of own industrial robot have not been overcome in full and there is still a long way to go.

Third, the determination of the real geometry of robot, or what is the same thing knowing the true kinematic manipulator taking in account geometric errors [9],is one of the most studied limitations that is resolved by different calibration methods. There are different possibilities for pose measurement with industrial robots as touching reference parts, distance sensors, laser interferometry, theodolites, calipers or laser triangulation. Other systems of the robot TCP calibration have based on vision cameras [10].

Finally, although spindles have not been a significant limitation in the development of robotic machining applications because the models used in CNC machine can be integrated directly these systems, spindles manufacturers have designed specific solutions characterized by a lightweight construction to minimize loading on the robot wrist.

4. Robotic machining model: accuracy and vibration

In industry has existed, and exists, tendency to apply in a direct way the machining conventional philosophy to the robotic systems, Figure 3. Using this approach many people have failed in the attempt because the difference between both manufacturing systems advise a previous study that orients the resolution of each individual application. The knowledge about robotics and machining technology must be adequately connected to get acceptable success rates.

In this sense, it is necessary to emphasize the great learning work which robotic end-users are subjected, previously accustomed to using machining centers, due to lack of methods and procedures that recommend a preferential work guidelines, opposed to other less recommended, allowing to production pieces within a manufacturing tolerance range and acceptable quality surfaces.

Fig. 3. Robotic machining cell.

The low stiffness of robots, one of its main limitations, has not been technical barrier especially determinant in the development of industrial solutions for resolving handling, welding, assembling, or other operations where system external forces are caused mainly to acceleration of the robot itself and gravitational effects. However, industrial applications where the robot is subjected to periodic forces of the manufacturing process, as in the case of machining forces, this problematic has not been addressed sufficiently until now.

The study of robot structural rigidity for machining processes has been discussed timidly by some authors, and among most remarkable advances must be cited the dynamic and kinematic robot model proposed by Bauer, J [11],which has allowed to characterize the elasticity and equivalent damping of the articulated structure by virtual axes referred to Robot Cartesian Coordinate System. In order to determine structural rigidity of the manipulator is necessary, therefore, to identify the parameters of the robot model and perform several experiments among which it must mention modal analysis or robot stiffness measurement in different points of the workspace. Model implementation allows to predict deviation of the robot trajectory under external forces, representing an extremely useful tool to simulate [12] the robot's behavior in different conditions machining and estimate accuracy errors during the trajectory.

Overall vibration of the system represents another problematic that does more difficult to incorporate industrial robot to machining process. In spite of being an issue extensively investigated, particularly focusing on the analysis of machining conventional centers and CNC machines [13], [14] y [15], vibrating mechanism applied to the robotic machining should also be checked. It is possible to recognize advances in this direction, such as Pan contributions [16] about stability criteria and guidelines to avoid vibration during the process. Still it is necessary to explore this field in order to understand in a broader way the influence of vibration effects on work piece surface quality.

5. Conclusion and future work

Nowadays robotic machining is considered an immediate feasible alternative for processing nonmetal materials, or even metal materials depending on the degree of hardness, workpiece geometric complexity, manufacturing tolerances and surface finish required. Recent technological advances have contributed to improve mechanical behavior of industrial robot and reduce the generation time of reliable working paths, increased the use of robotic cells for resolving machining applications.

However, the absence of rules that guide users of robotic cells continues to add high level of uncertainty about the possible results of the process. End users can not permit that the success of robotic machining depends on the operator intuition, either proper selection of strategies and cutting conditions or awful process of trial and error, and therefore this is a extra barrier that should be overcome.

As deflection and vibration of the tool center point during the work path depend heavily on robot stiffness and system natural frequencies, this document proposes to address the problems relating to the accuracy and surface finish of robotic machining through the study of relative orientation the cutting force vector respect to the stiffness of robot.

In this way, it is expected that simultaneous evaluation of the magnitude and direction of cutting forces, stiffness of robotic system and frequencies or vibration modes during machining process, help to identify stable work ranges in which is obtained an advantageous equilibrium between robot stiffness and cutting forces, deducing rules to guide workers about correct use of the robots considering its peculiar limitations.

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