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A BRIEF REVIEW OF ROBOTIC MACHINING

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Abstract: *The approach of this paper was to analyze the technical borders of industrial robots and to provide an overview of current technology, technical constraints and the potential types of future research suggestion concerning robotic machining. These complex automation machines used in manufacturing processes are an emerging chapter of industrial engineering that contribute to automatically performing operation in subtractive manufacturing and sheet metal forming processes. Compared with CNC machines which have shape limitations and have the restricted working area, the industrial robot is a flexible, cost-saving alternative.*

Key words: Subtractive Manufacturing, Sheet Metal Forming, Industrial Robot, Robotic Manufacturing

1. Introduction

Subtractive manufacturing, together with the sheet metal forming, represent the most widespread and used methods of generating the finished parts shape with applicability in the most well-known industries: automotive, aeronautical, electrical/electronics, rubber and plastics, food and beverage, metal and machinery industry. If until recently there was a well-defined difference between the two large groups of manufacturing processes, more recently due to technological developments, as well as economic conditions, researches in the field of subtractive manufacturing or sheet metal forming have greatly expanded the area of applicability. Through the industrial robot these two groups have managed to fulfill more and more the current requirements to produce parts in conditions of dimensions, shapes, precision and costs that were a short time ago accessible only to the processing through CNC machine.

2. Comparison between CNC machine and Industrial robot

The CNC machine is a metalworking tool that can manufacture complicated parts through different processes (e.g. boring, drilling or milling) which can deliver higher machining accuracy with high stability [1]. Besides the fact that their functions are single, the acquisition cost of such CNC machines will be beyond the reach of many companies. Moreover, the major drawback is the restricted working area and their produced shape limitation. Large multi-axis CNC machines, which requires a large factory size, are used to mill large parts in aerospace and energy industries with a high operational cost [2]. Even though the CNC machine market is evolving continuously, adding axes, bringing in new models and developing new ways to do the job more easily, from a conceptual point of view, industrial robots are a viable alternative to CNC machine mainly where complex geometries and a large volume of work are required.

The variety of industrial robot applications is constantly increasing, and the use of robots in industrial manufacturing processes is increasing year by year [3]. In addition, the modernization and refurbishment continue to warrant further investigation into the field of robots in countries that are already automated. The constant increase of the use of the robot is justified by its functionality. There are many reasons for this, such as operator protection in difficult working conditions and environments, time savings, superior quality, higher productivity, lower costs, etc.

As shown in figure 1, as opposed to a CNC machine tool, an industrial robot, with the same workload, can achieve complex 3D shapes, since it owns a higher workspace, good programmability, flexibility and adaptability [4]. When robots are used a 20-30% reduction in the total cost has been shown in different researches [5, 6].

Low:
- Workspace

High:
- Cost
- Precision
- Feed throughput

Low:
- Costs
- Precision
- Feed throughput

High:
- Workspace
- Flexibility
- Re-programmability

Figure 1: CNC Machining and robot characteristics

3. Industrial robots used in manufacturing

Industrial robots were initially used for tasks requiring millimeter level accuracy and repeatability, mainly the "pick and place" operations. In these days, applications of robots include painting, pick and place, assembly, welding, palletizing, packaging and labeling, product inspection and testing; all accomplished with high endurance, precision and speed. Over the last two decades, the applications of industrial robots are dramatically increased, being used for machining applications: e.g. sanding and sawing, trimming, de-flashing, de-gating, drilling, grinding and milling.

A new sheet metal forming process – the incremental sheet-forming, is mainly used in aeronautical, automotive or medical applications due to advantages of this process: the high flexibility and formability, the short lead time, the lower cost in small batches [7, 8]. Even thorough the mainly advantage of using industrial robot in incremental sheet-forming is defined by the act that the strain and relative thickness of the sheet metal could be measure online [9, 10].

Statistical data from International Federation of Robotics has shown that the industrial robotics market experienced record unit sales of 422,271 in 2018 [3]. This number represent a new peak for the six year in a row and a clear signal of the accelerating rise in demand for industrial robots worldwide. Even if, the metal and machinery industry is the third major sector after automotive and electrical/electronics industries, with sales increased by 55% in 2017, to a new peak value of 44,536 units.

In Table 1 is shown the remarkable implementation of industrial robots on many industrial sectors.

Table 1. Products and process used in different industries

End-User Segment	Process	Product
All segments	Milling	Rapid prototyping
Automotive	De-flashing, grinding, drilling, milling, cutting	Engines, truck frames, body panels, doorknobs, bumpers, stamping dies, sand cores
Aerospace	Drilling, Cutting, grinding, polishing	Turbine blades, bulkheads, insulation, wing segments
Foundries	De-burring, milling, drilling,	Molds, castings

	routing, finishing	
Fashion	Milling, sanding	Mannequin molds, mannequins
Marine	Milling	Boat hauls
Medical	Grinding, polishing	Prosthesis
Plastics	Milling, routing	Molds, helmets
Woodworking	Milling, routing	Hot-tub molds, furniture, trim, banisters, modeling board
Entertainment Ind.	Milling	Move set props, amusement park scenery

Source: Robotic machining white paper project [11]

3.1 Industrial robot accuracy issues

Large manufacturing errors that occur limit application of the robot for high precision machining are given by their limited accuracy and lack of stiffness [12, 13]. In these days, a high-end CNC machines can achieve accuracies between 20-50 microns, while a KUKA KR-270 robot with the repeatability of 60 microns can be calibrated to reduce the pose error of the robot up to 170 microns positioning accuracy [14].

(a) **(b)**

Figure 2: Industrial robots used in subtractive manufacturing and sheet metal forming – (a) Kuka Quantec KR270 2700 used for milling [15]; (b) The KUKA KR6-2 robot used for SPIF processes at Lucian Blaga University of Sibiu [16]

During the last few years, many researches were conducted in order to rationalize robotic machining. It was concluded that from different performances parameters associated to the industrial robot, precision is frequently used to describe its capabilities, being divided into resolution, accuracy and repeatability.

The resolution of a robot is a parameter that depend of the design of the control unit and mainly on the position sensor. The resolution of the control system is the first to influence the reproducibility of the manipulator. A clear distinction must be made between the programming resolution and the control resolution.

The accuracy of the manipulator is called his ability to reach a given point in the workspace. The payload together with velocity of movement will greatly influences the accuracy and repeatability of an industrial robot. The main sources of inaccuracy are represented by backlash, zero position error and joint elasticities. The entire chain of components between the final effector and the base of the robot that influence the accuracy of a robot, is represent by:

1. External errors
    - environment (represented by the building structure and the floor structure);
    - robot fixture to the floor;
    - ambient temperature;
    - tool holder compliance;
    - spindle support compliance.
2. Internal errors
    a. Geometrical errors - emerge from manufacturing tolerances of the robot components:
        - links tolerances - determine inaccuracy in the pose of the tool center point;
        - joint errors in the axes - fetch a significant contribution to robot pose accuracy [17, 18].
    b. Non-geometrical errors - emerge in a local environment and cannot be compensated through calibration:

    - wear and nonlinear effects (represented by stick-slip motion, nonlinear stiffness and hysteresis in servo drives [19, 20]);
    - structural distortions (represented by links, energy-transforming devices and load-transmitting components);
    - compliance errors (displacement of the wrist end in response to a force or a torque exerted against it);
    - wear of the component parts;
    - internal heat sources, e.g. motors.
  c. System errors
    - inadequate calibration;
    - rounding error in the robot computer control unit;
    - control implementation errors;
    - sensor measurement errors.
3. Process Dependent Errors
  a. Machining force
    - represent the most dominant source of error in subtractive manufacturing, inducing deflection of the robot structure [21];
    - machining force values depend on the process parameters and outcome in a distinctive value for the material removal rate.
  b. Lubrication system
    - a relevant factor, especially for the final workpiece quality;
    - decrease the contact friction coefficient between the workpiece and the cutter tool;
    - redound to avoid the first type of chatter.
  c. Chatter
    - significant topic in robotic machining due to low stiffness which causes low productivity.

Repeatability is a statistical term associated with accuracy, describing the ability measure of the robot to constantly reach a specified point. It's well known that larger weight causes larger deformations to the robot's links and greater joint loading, which affect accuracy. Since accuracy depends on the special task of the final effector and repeatability is almost independent of the final effector's load, it was observed that majority robot manufacturers offer a numerical value for repeatability of their robots. Robot repeatability will usually be better than accuracy, normally measured in hundreds of millimeters. Depending on the manufacturer, the repeatability of articulated robots as per ISO 9283 is ±0.1 mm or better [22]. Therefore, as long as a robot has good repeatability, the robot's accuracy can be improved through a calibration process.

4. Conclusions

This paper provided an analysis of recent research related to robot processing in subtractive manufacturing and sheet metal forming. It is shows that the potential for machining with industrial robots is huge, specifically in the auto industry among emerging parts and some traditional parts as well. Even though it has been shown in this paper that industrial robots advantages are a high level of flexibility and bigger workspace that can exceed the CNC machines, we must admit that there is still much to be done until robot processing systems will widely be used in more applications.

As shown by the different available researches, the main source of the inaccuracies the robot makes can't be linked to a single part or factor but are instead the result of the linked smaller causes that we have enumerated above. Taking in account that most researches used an industrial robot that is not directly designated for manufacturing operations, the inevitable issues of low dynamic accuracy, vibration and sliding was not under discussion based on current research efforts. Future research will evaluate and propose ways to improve the robot accuracy and efficiency in subtractive manufacturing and sheet metal forming processes, so that robot processing systems can be widely used in the future.

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