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MACHINING WITH ROBOTS: A CRITICAL REVIEW

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ABSTRACT

Conventional material removal techniques, namely those of CNC milling, have proven to be able to deal with nearly any machining challenge. On the other hand, the major drawback of using conventional CNC machines is their restricted working area and their produced shape limitations From a conceptual point of view, the industrial robot technology could provide an excellent base for machining that would be both flexible and cost efficient. However, industrial machining robots lack in absolute positioning accuracy, are unable to reject/absorb disturbances, in terms of process forces, and lack in reliable programming and simulation tools so as to ensure right first time machining, at production start-ups. This paper reviews the penetration of industrial robots into the challenging field of machining.

KEYWORDS

Robot, Machining, Accuracy, Programming

1. INTRODUCTION

Recent developments in machining and tool design technology, especially in milling operations, reflect the requirements for flexibility in order to adapt to the changes taking place in the market, in the society and in the global economic environment (Chryssolouris, 2006), for the reduction in weight and dimensions, high surface quality and accuracy of the produced parts (Fig. 1). These improvements result in machine tools of high precision and accuracy.

Major objectives of manufacturing engineering today are being evolved. The market requirements indicate that emphasis should be given to a low-volume and a large-variety, even in a high volume production industry, in order for global competition to be dealt with. Flexibility is also required to use the same facilities of the minor or major model changes that come in equipment's effective life span.. The basic work-piece can be modified as shown in Fig. 2, demanding flexibility in its manufacturing (Sharma, 2001).

An industrial robot can fulfill the need for todays and tomorrow's industry for a cost and time efficient, yet flexible means of material processing. There are various robotic cells already introduced to the process of welding and material handling and excellent results have been achieved. Moreover, many studies have been conducted on articulated robot applications in machining processes, such as polishing (Yamane et al, 1988), (Takeuchi et al., 1993), grinding and de-burring (Kunieda et al, 1988).

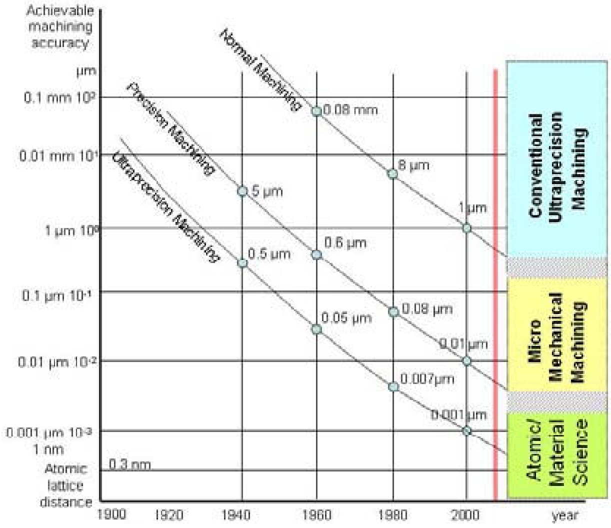

Figure 1 - Dimensional size for the micro-mechanical machining. Modified Tanigushi curve (Stavropoulos, et al, 2007)

Moreover, statistical data have shown (Fig.3) that the number of operational robotic cells is constantly increasing worldwide and future predictions suggest that the robot market should continue to increase in the future. (Industrial Robot Statistics, 2010)

On the other hand, machining tasks are not carried out by robots, despite being established in most of the shops, since it is conventional CNC milling machines that are being used. The major drawback of using conventional milling machines is their limited working area that usually forces one part to be machined in multiple operations, or even the part to be split in pieces and be reassembled after completion. In some extreme cases modifications of the machine itself takes place in order to accommodate a bigger part. On the other hand, robotic machining cells can machine large parts in single operation setups, due to wider working envelopes reaching up to 7.5 m^3 (cubic if we talk about volume) In conjunction with the extensive robot’s turning range, the working envelope usually covers more than 20m3 (Chen & Song, 2001), enabling the machining of very large work-pieces. Finally, robot machining, as a tool positioning system, due to the flexible kinematics of robot arms, is often capable of machining parts with intricate details and complex shapes, whilst a conventional CNC machine needs special fixtures and techniques to produce them.

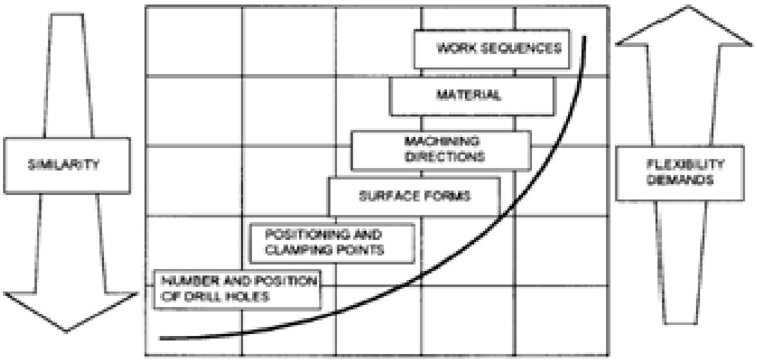

Figure 2 – Deviations in basic work-pieces with design change (Sharma, 2001).

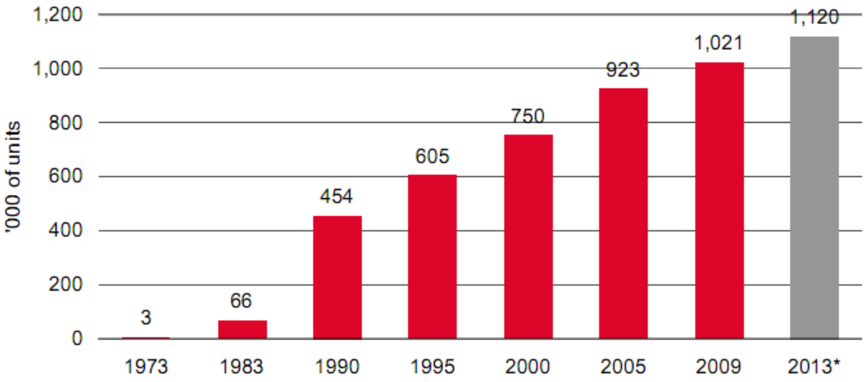

Figure 3 – Estimated worldwide operational stock of Industrial Robots (Industrial Robot Statistics, 2010)

2. ROBOTS IN AUXILIARY ROLE

2.1. WELDING AND FINISHING

In order for industrial robots to accomplish non-structured and more sophisticated tasks, sensorial capabilities are required. The automotive industry is one of the major users of machine vision. One of the first applications of vision systems in automotive, was for seam tracking during welding operation (Michalos et al, 2010). On the other hand, industrial robots fulfill the automotive industry's need for flexibility in tooling and fixturing (Papakostas et al, 2006). In other metal processing tasks, Asakawa proposed a polishing system, using a purpose developed CAD/CAM system, an ultrasonic vibrational tool with a ceramic tip and a 6- degree of freedom robot, achieving only limited results (Asakawa et al, 1995). Sanders et Al. (Sanders, Lambert, Jones, & Giles, 2010) proposed the combination of a robot welding system with an image processing system in order to gather data about the weld characteristics/geometry generate robot programs and calibrate the robot path.

2.2. RAPID PRODUCTION

Although machining with robots possesses some unique advantages over conventional machining processes, it also has some of their common problems. The most common is the machining of hollow features or deep cavities, when collisions may occur between the tool holder and the part surface. One way to overcome this issue is layer based machining, making industrial robot excellent candidates for Rapid Tooling (RT) machining operations. The accuracy of robots, although it is lower than that of a conventional machine tool, is better or comparable with that of rapid prototyping machines, such as SLA and SLS. At the same time, robots can successfully machine in wood, wax, foam and similar materials, without sacrificing the accuracy levels. In comparison with the conventional rapid prototyping machines (RT), the material choice is far wider, indicating that a standard robot, although limited to conventional machining cases, could be a good substitute to the RP machines (Song & Chen, 1999). Y Song et al. proposed the usage of a conventional industrial robot (IR) and CAD package with the purpose of developing a module to check the programmed toolpath for collision and create the actual robot program. Based on the Denavit - Hartenberg (Denavit-Hartenberg Parameters) rules, the model calculates the geometry of the robotic arm while machining. In order to detect gouging, Song et al. used a virtual tool 0.1 mm shorter than the actual one and calculated the intersection between the tool and the workpiece. In order for gouging to be avoided, when there was an intersection, the tool path was redefined by moving the tool within a cone, whose apex point was the tool contact point as shown in Fig.4.

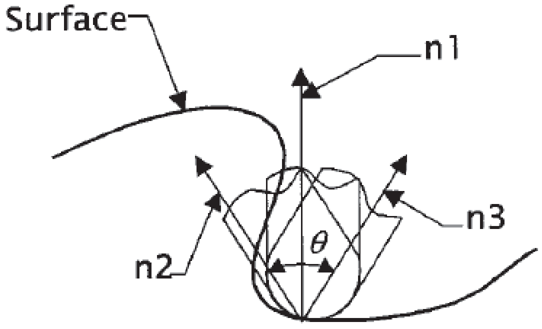

Figure 4 - Finding a collision-free tool position by moving the tool along a cone

Huang and Oliver (Huang & Oliver, 1994) presented a method which was capable of initial chordal approximation, true machining-error calculation, direct gouge elimination, and non-constant parameter tool pass- interval adjustment; Lin and Koren (Lin & Koren, 1996) proposed a non-constant offset method, based on the previous tool path in order to avoid redundant machining; Oliver (Oliver et al, 1993) proposed an approach which exploited surface normals and the geometry of the tool to characterize accurately the chordal deviation, having resulted from the actual tool motion and could detect gouging in areas of large curvature variation. As a specific implementation, (Suh & Lee, 1990) experimented with nonmetal materials and proposed a method to machine a pocket with a convex or concave free-form surface bounded by lines, circular arcs and free-form curves. In order for the machining process to be improved, in terms of speed and quality, first there was used a rough cutting process to remove the main volume of the material and then a second finishing operation, with smaller tool and cutting depth, to finalize the cutting process. As a result, without sacrificing the machining time, the cutting accuracy was slightly larger than the actual accuracy of the robot.

3. ROBOTS IN MACHINING

3.1. ACCURACY ISSUES

Most industrial robots are constructed on a cantilever concept. Their arms include motors, brakes and reduction gears, struggling to achieve a high positioning accuracy of 0.5-2mm (Vergeest & Tangelder, 1996). In addition they are prone to disturbances from the process forces. K. Young et al. conducted a trial on modern serial linkage robots to assess and compare robot accuracy. Each robot has been measured, in a similar area of its working envelope, by the laser interferometer system (Young & Pickin, 2000). The results and conclusions from this trial have shown that the accuracy is average, though it is dependent on a calibration process which is far from robust.

In figure 5, the straightness measurement of a typical IR is presented. Deviation in the X-axis when travelling in the Y direction is within an error band of approximately 0.7mm across the measured envelope, presented a significant deterioration of accuracy, in 50% of the working envelope.

The main issue that prevents the usage of industrial robots, in a heavy machining application (metal milling, etc.), is their proneness to machining forces, inducing disturbances and their inability to reduce or eliminate them. In the course of the EU funded research program COMET (COMET Project - Plug and Produce COMponents and METhods for adaptive control of industrial robots enabling cost effective, high precision manufacturing in factories of the future) the tool acceleration, while machining with a robot, was measured indirectly, using 500 kHz acceleration sensors. The results showed that there was a constant deviation in the Z-axis while machining (Fig.6) (Euhus & Krain, 2010). This is the result of the tool's cutting edges going into the material and producing cutting forces that affect the cutting quality.

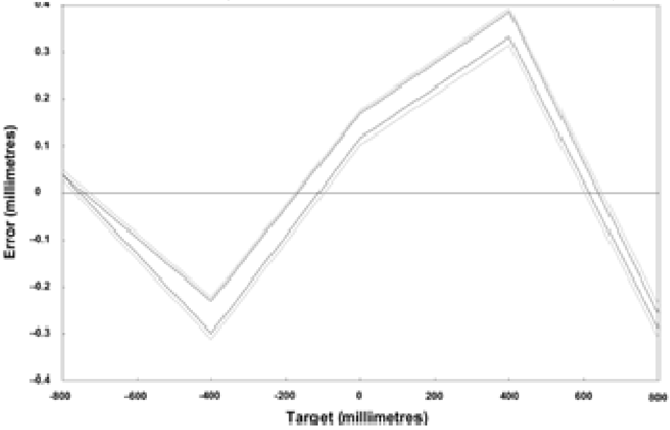

Figure 5 - Deviation in the X-axis when travelling in the Y direction

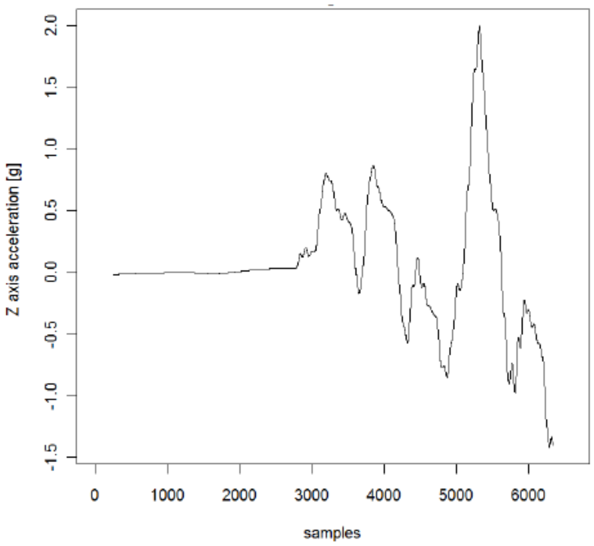

Figure 6 - First micro seconds of milling, tool contact (sampling freq.: 500 kHz, sensor: Artis VA-2-S)

Matsuoka proposed the usage of an articulated robot featuring a small diameter end mill to reduce the cutting force in order to compensate for the low stiffness of the articulated robot and high-speed cutting (Matsuoka et al, 1999). Veryha proposed and verified both theoretically and practically, a method for joint error mutual compensation, allowing localization of special robot poses in increased accuracy. In order to use a non-uniformity of the robot pose accuracy characteristics of the different robot configurations, the method of the joint error maximum compensation for redundant robotic manipulators was developed (Veryha & Kurek, 2003).

3.2. VIBRATIONS – CHATTERING

Another main issue of robot machining is the effect of vibrations on the surface quality produced. Due to the low natural frequency of articulated robot body, resonance can occur due to machining process vibrations. Oki et al., focusing on the cutting of workpieces from an extruded aluminum alloy, assessed the effect of vibrations on the characteristics of end milling operation. Their experiments proved that during high-speed cutting, the generated process frequency is high enough without resonance issues, thus ensuring stable and normal end milling with restrained chatter and vibration of the articulated robot (Oki & Kanitani, 1996).

Oki et Al. also proved that the cutting direction affected the process accuracy by experimenting on machining right-handedly and left-handedly a cylindrical shape. Due to the change in the cutting surface's side, the cutting forces differ and the articulated robot is deformed differently in each cutting direction and as a result, the accuracy of the machining process is different in the right (digger diameter) and left (smaller diameter) hand cutting.

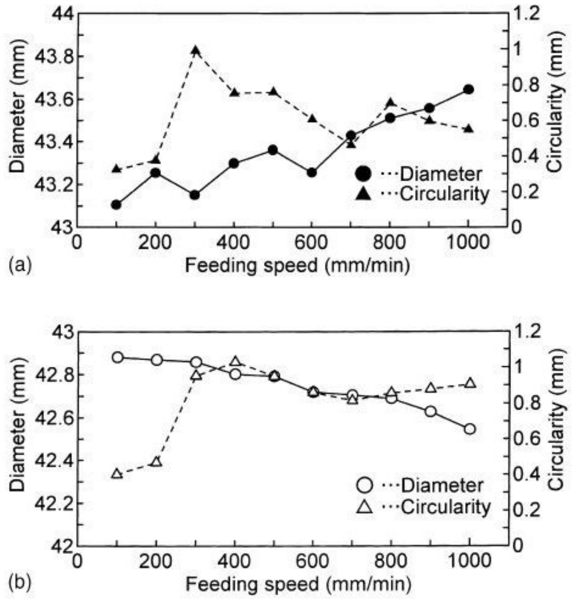

Figure 7 - Relationship between circularity and circularity: (a) right-turn; (b) left-turn

Zengxi Pan investigated chattering due to machining vibrations, using a Force/Torque sensor between the robot wrists and the spindle. Zengxi Pan observed that every time that chatter occurred, the force amplitude increased dramatically, even while machining was taking place in low cutting depths (2mm) (Zengxi et al, 2006). Moreover, the chatter characteristics were changing depending on the robot pose, joint orientation and loading This was mainly due to the dramatic difference in stiffness characteristics from that of industrial robots being less than 1N/um, while the standard CNC machines have stiffness greater than 50 N/um, thus the maximum cutting force for robot applications is limited to around 150N parallel and 50N axially to the cutting direction, in order to maintain reasonable accuracy. Based on the experimental results and modeling of the process, the margin while chatter was not introduced to the process, was calculated to be in the range of 10Hz (around 3600rpm). Tool breakage and premature failure was a major issue in machining applications. Jay Lee proposed the application of a force/torque sensor to monitor the thrust force as an indication of Tool condition (Lee).

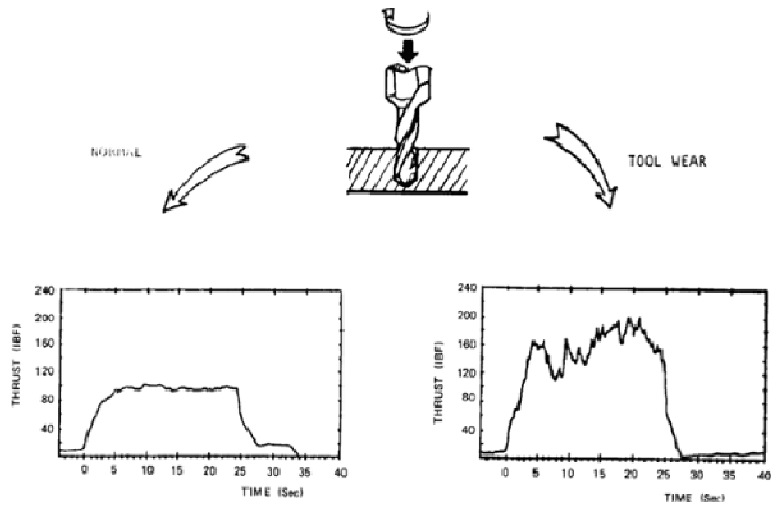

Figure 8 - Thrust force sensing for drilling process

This proposal has also had an application in overload cases, such as in collisions and robot overloading.

3.4. CALIBRATIONS METHODS

In order to calibrate an industrial robot to reach higher accuracy levels, various types of coordinate measuring systems (CMM) and other ones have been utilized. Chunhe Gong presented a methodology to identify geometric errors of industrial robots using a laser tracker and inverse calibration process. Both geometric and thermal errors were calibrated. The produced models were built into the controller and were used to be compensating for quasi-static thermal errors due to internal and external heat sources. Experimental results showed that the robot accuracy was improved by an order of magnitude after calibration (Gong & Yuan, 2000). Sabri Cetinkunt et Al. developed a strategy for cutting force compensation using wrist force sensors (Cetinkunt & Tsai, 1990). Using wrist-force sensors, the reaction torques at the joints due to the cutting force is compensated to eliminate the cutting force reaction effects. The movement of the robot hand with the tool is a position control only with cutting. While it is cutting, then the cutting force will react to the joints as known disturbance torque inputs and should be compensated based on force sensor measurements. In other applications, CCD cameras were also used (Huang & Lin, 2003) for identifying the parameters that were to be corrected in conjunction with software aspiring to calculate the corrected tool path.

3.5. PROGRAMMING

As far as the programming side of machining with industrial robots is concerned, it still has a major disadvantage against that of the conventional CNC machines. Robots are mainly programmed with the use of the traditional "teach and repeat" method of programming. The user manually moves the robot in predefined positions and the latter saves the coordinates. As a result, the accuracy is not of great importance to this method and is generally considered low. The CNC machines are programmed offline; usually using dedicated software, based on known reference coordinates. Y. H. Chen et Al. proposed a programming method for industrial robot rough machining. Using a grid array, in XYZ directions, both the actual tool and the model of the part to be cut is represented (Chen & Hu, 1995). By changing the grid resolution, the accuracy of the generated toolpath is also altered (Hu & Chen, 1999).

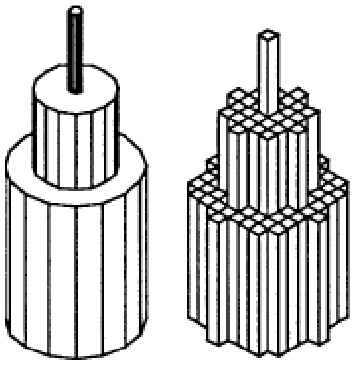

Figure 9 - Rectangular grid approximation

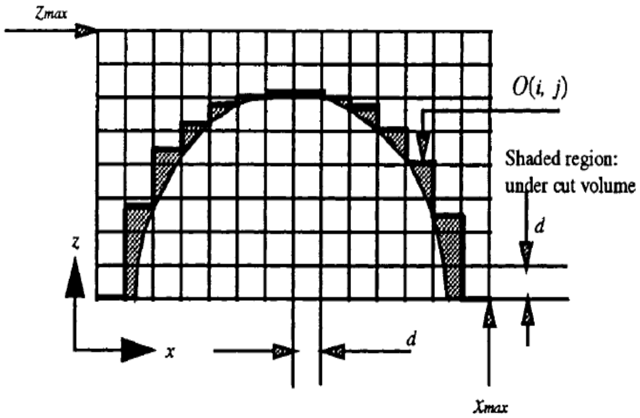

Figure 10 - Error analysis

By the same approach, secondary operations such as gauging, can be detected and avoided. On the other hand, as the grid size affects the surface quality besides the roughing process, it also affects the actual size of the program, making it difficult to be handled by some controllers. Y. N. Hu et Al. proposed the method of finishing machining, by implementing in conventional 5-axis strategies the advantage of industrial robots 6th axis motion, called swivel (Hu & Chen, 1999).

A dual robot setup that is widely used in assembly and handling applications can also be used in applications where a single robot setup cannot reach all points. W. S. Owen et Al. proposed a dual robot setup, with one robot, handling the material and the second one, bearing the tool (Owen, Croft, & Benhabib, 2004).

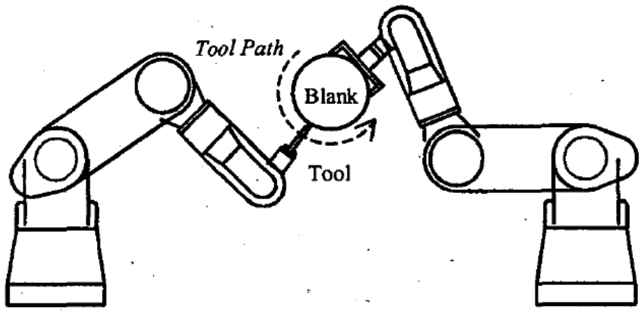

Figure 11 - Two manipulator machining system

Due to the redundant DoF, the authors designed an off-line programming system with an integrated algorithm to optimize the tool's trajectories, using the pseudo-inverse method. The approach monitors the torque in the robot axes while it also finds the optimum configuration/poses to improve the accuracy of the final part by decreasing tool deflection and the optimum absorption of machining forces. Hsuan-kuan Huang et Al. developed a dual independent robot machining cell, where the programming development was carried out through the CAM software for the generation of cutter location data of 5-axis milling, together with a post processor for the translation of CL data into linear and rotational motions of the robot cell controller. The implementation of the dual robot setup was achieved by dividing the original CL data into two parts taking into account the collision detection between the two robots and the minimization of force generated inaccuracy of the final geometry. The author also developed an offline programming module, enabling an off-line programming and simulation of the dual robot machining cell (Huang & Lin, 2003).

4. CONCLUSION

Industrial Robots can considerably contribute to improving the efficiency of machining operations. Their high level of flexibility and extended working space can outperform the conventional machine tools. Due to their extra degree of freedom, an IR can machine complicate geometries that otherwise would need special fixturing elements and multiple machining operations. In addition, an IR offers the possibility of a dual machining setup, either with spindle on the robot, or the workpiece on the robot and in conjunction with the extended payload range (from 5kg to more than 400kg); even the heavier and larger parts can be machined. Finally, industrial robots, mainly used in handling and welding applications, are already well established in most machine shops.

On the other hand, it is clear that robots have some serious disadvantages in terms of accuracy, repeatability and handling machining processes, when they are being compared with the conventional CNC machine tools. Although there are cases of machining with robots, they are extremely limited. This is due to their low absolute positioning accuracy and their lacking in a programming and simulation system sufficient enough for the generation of 100% correct robot path programs.

The major drawbacks of an IR are currently being addressed, by having developed advanced simulation technics, intelligent programming software and improved calibration processes. The novel IR models feature improved controllers with reference to their computing power and precision, enabling the usage of more complex calibration algorithms and more detailed NC programs. At the same time, advanced external compensation mechanisms and tracking systems, are under development, in order to improve even further the IRs' machining accuracy, at the same or higher levels than those of the conventional NC machine tools.

The EU funded research program COMET develops a CAM based industrial robot programming system, which incorporates analytical dynamic and kinematic models of IR and in co-operation with a robot tracking system as well as a high dynamic compensation mechanism, developed to this effect, the COMET platform aims at achieving an accuracy level of less than 50um in milling applications. The final result will be a "plug and produce" platform that will be replacing the ordinary machine tools without sacrificing accuracy and machining speed (COMET project results).

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