Proceedings of DET2011
7th International Conference on Digital Enterprise Technology
Athens, Greece
28-30 September 2011

MACHINING WITH ROBOTS: A CRITICAL REVIEW

John Pandremenos
Laboratory for Manufacturing Systems &
Automation, Univeristy of Patras, Rio, Patras
26500, Greece
jpandrem@lms.mech.upatras.gr

Christos Doukas
Laboratory for Manufacturing Systems &
Automation, Univeristy of Patras, Rio, Patras
26500, Greece
cdoukas@lms.mech.upatras.gr

Panagiotis Stavropoulos
Laboratory for Manufacturing
Systems & Automation,
Univeristy of Patras, Rio,
Patras 26500, Greece
pstavr@lms.mech.upatras.gr

George Chryssolouris
Laboratory for Manufacturing
Systems & Automation,
Univeristy of Patras, Rio,
Patras 26500, Greece
xrisol@lms.mech.upatras.gr

ABSTRACT

Conventional material removal techniques, like CNC milling, have been proven to be able to tackle nearly any machining challenge. On the other hand, the major drawback of using conventional CNC machines is the restricted working area and their produced shape limitation limitations. From a conceptual point of view, industrial robot technology could provide an excellent base for machining being both flexible and cost efficient. However, industrial machining robots lack absolute positioning accuracy, are unable to reject/absorb disturbances in terms of process forces and lack reliable programming and simulation tools to ensure right first time machining, at production start-ups. This paper reviews the penetration of industrial robots in 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 to adapt to the changes taking place in the market, in the society and in the global economic environment (Chryssolouris, 2006),reduction in weight and dimensions, high surface quality and accuracy of the produced parts (Fig. 1). These developments result to the development of machine tools of high precision and accuracy.

Major objectives for manufacturing engineering today are evolving. Market requirements indicate that emphasis should be given to low-volume and large-variety, even in high volume production industry, to face global competition. Flexibility is also required to use the same facility for the minor or major model changes that come in effective life span of the equipment. Basic work-piece may change in different manners as shown in Fig. 2, demanding flexibility in its manufacture (Sharma, 2001).

An industrial robot can fulfill the need of todays and tomorrows industry for a cost and time efficient, yet flexible mean 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).

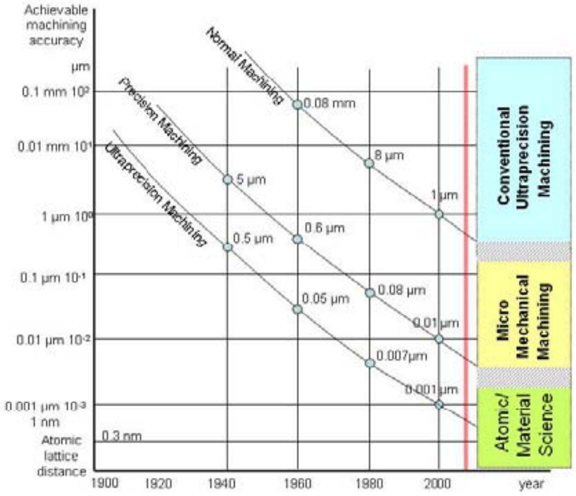

Figure 1 - Dimensional size for the micro-mechanical machining. Modified Tanigushi curve (Stavropoulos, et al, 2007)

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 will continue to increase in the future. (Industrial Robot Statistics, 2010)

On the other hand, robots are not used for machining tasks, although being established in most shops. Instead, conventional CNC milling machines are used. The major drawback of using conventional milling machines is the limited working area available that usually forces to machine one part in multiple operations, or even split the part in pieces and reassembled after completion. In more 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), allowing the machining of very large work-pieces. Finally, robot machining, as a tool positioning system, due to the flexible kinematics of robot arms, are often capable of machining parts with intricate details and complex shapes, that conventional CNC machine need special fixtures and techniques to produce them.

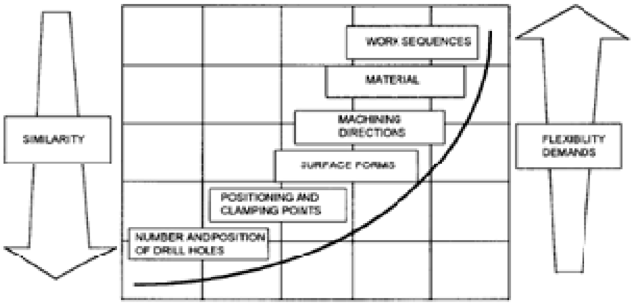

Figure 2 – Deviations in basic work-pieces with design change (Drishtikona).

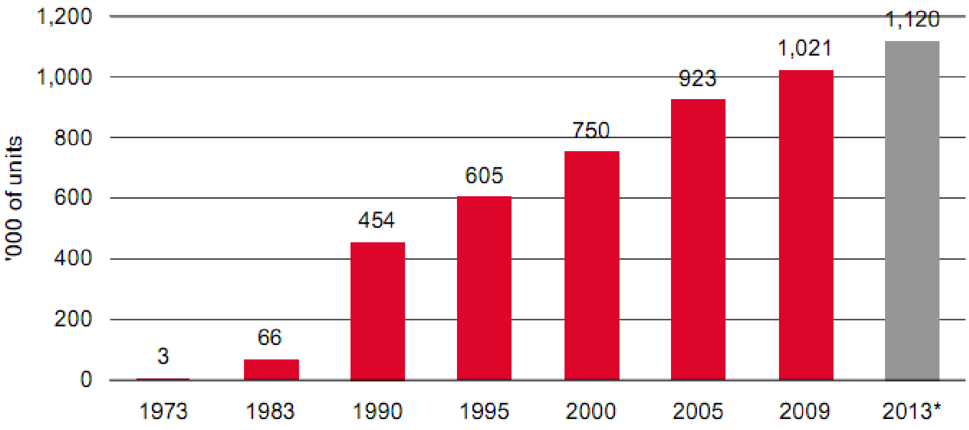

Figure 3 – Estimated worldwide operational stock of Industrial Robots (Industrial Robot Statistics, 2010)

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 need of the automotive industry 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 degrees 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 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 lower than that of a conventional machine tool, is better or comparable to 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 accuracy levels. In comparison with conventional rapid prototyping machines (RT) the material choice is far wider, indicating that a standard robot, although limited in conventional machining cases, could be a good substitute to RP machines (Song & Chen, 1999). Y Song et al. proposed the usage of a conventional industrial robot (IR) and CAD package with a purpose developed a module to check the programmed toolpath for collision and create the actual robot program. Based in 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 tool and calculated the intersection between tool and workpiece. To avoid gouging, when there is 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.

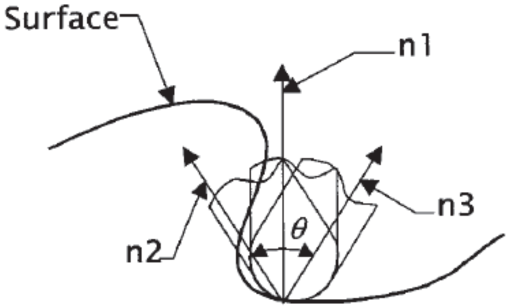

Figure 4 - Finding a collision-free tool position by moving the tool along a cone

Huang and Oliver (Huang & Oliver, 1994) presented a method which is 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) propose an approach which exploits surface normals and the geometry of the tool to characterize accurately the chordal deviation resulting from actual tool motion and can 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. To improve the machining process in terms of speed and quality, first a rough cutting process was used 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 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 as a cantilever, in which each of the arms is supported by motors, brakes and reduction gears, they struggle to achieve high positioning accuracy level, being limited to 0.5-2mm (Vergeest & Tangelder, 1996) and at the same time are more 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. Using a laser interferometer measurement system each robot has been measured in a similar area of its working envelope (Young & Pickin, 2000). The results and conclusions from this trial show that the accuracy is average, though it is dependent on a calibration process which is far from robust.

In figure 5, the straightness measurement for 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 heavy machining application (metal milling, etc.) is their proneness to machining forces induced disturbances and their inability to reject 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 robot, was measured, using 500 kHz acceleration sensors. The results showed that there is a constant deviation in the Z-axis while machining (Fig.6) (First metal cut at TEKS).

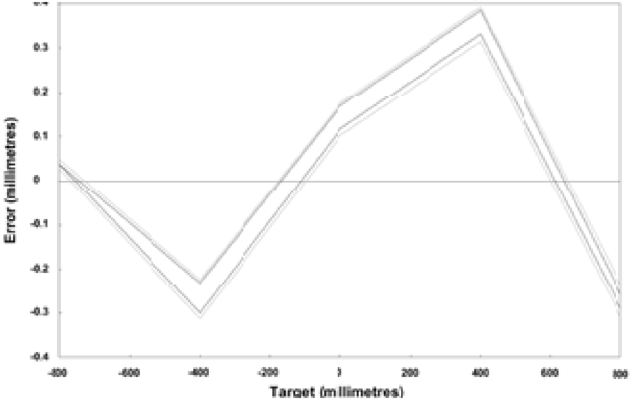

Figure 5 - Deviation in the X-axis when travelling in the Y direction

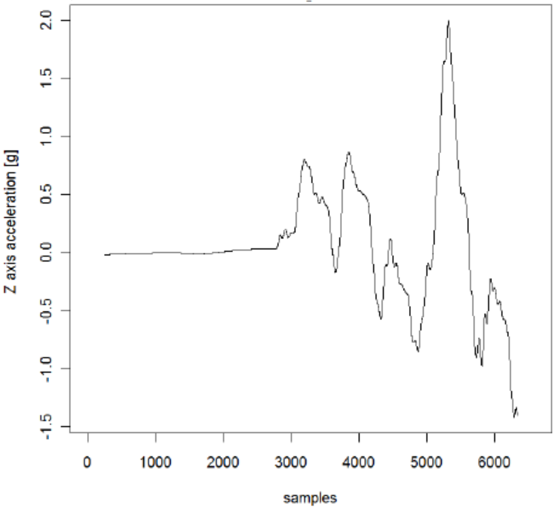

Figure 6 - First micro seconds of milling, tool contact (sampling freq.: 500 kHz, sensor: Artis VA-2-S)

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 for increased accuracy. In order to use a non-uniformity of the robot pose accuracy characteristics for 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 to the produced surface quality. Due to the low natural frequency of articulated robot body, resonance can occur due to machining process vibrations. Oki et Al., focusing in 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, 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 affects the process accuracy by experimenting on machining right-hand and left-hand a cylindrical shape. Due to the change of the cutting surface side, the cutting forces differ and the articulated robot deforms differently to each cutting direction and as a result the accuracy of the machining process is different in right (digger diameter) and left (smaller diameter) hand cutting.

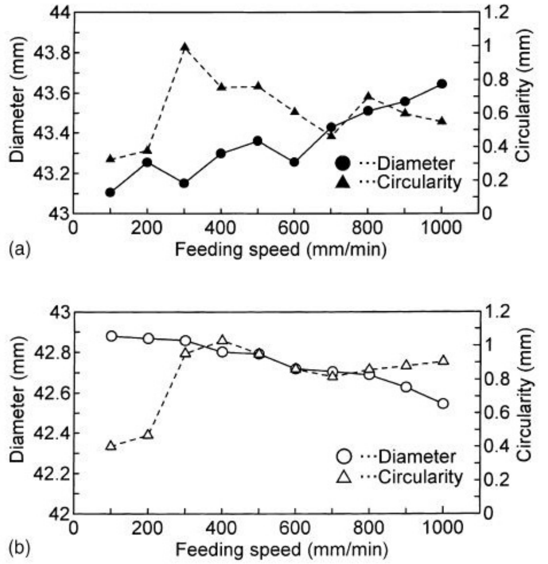

Figure 7 - Relationship between circularity and circularity: (a) right-turn; (b) left-turn

Zengxi Pan investigated chattering due to machining vibrations, using a Force/Torque sensor between the robot wrists and the spindle. Zengxi Pan observed that when chatter occurred the force amplitude increased dramatically, even while machining in low cutting depths (2mm) (Zengxi et al, 2006). Moreover chatter characteristics are changing depending on the robot pose, joint orientation and loading This is mainly due to the dramatic difference in stiffness characteristics with that of industrial robots being less than 1N/um, while 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 experimental results and modeling of the process, the margin while chatter will not be introduced to the process was calculated to be in 10Hz range (around 3600rpm). Tool breakage and premature failure is 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).

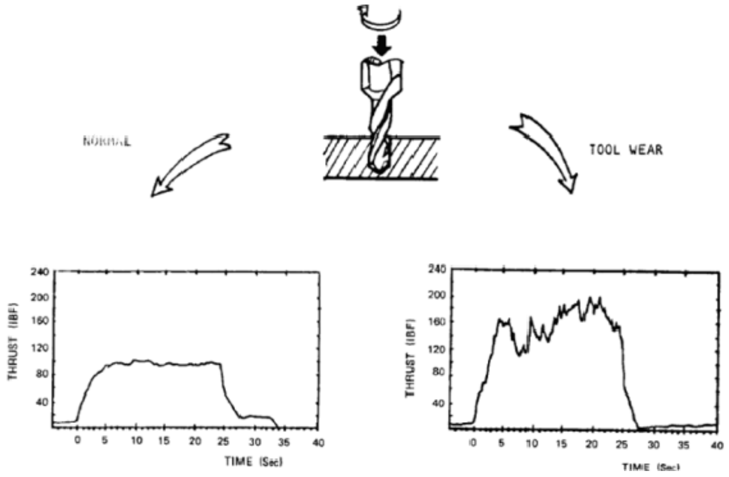

Figure 8 - Thrust force sensing for drilling process

The proposal has also application in overload cases, such as 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 measuring systems 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 used to compensate for quasi-static thermal errors due to internal and external heat sources. Experimental results showed that the robot accuracy is 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 sensor, the reaction torques at the joints due to the cutting force is compensated to eliminate the cutting force reaction effects. The movement of robot hand with 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) to identify the parameters to be corrected in conjunction with a purposed developed software to calculate the corrected toolpath.

3.5. PROGRAMMING

As far as the programming side of machining with industrial robots is concerned, it is still a major disadvantage against the conventional CNC machines. Robots are mainly programmed using the traditional “teach and repeat” method of programming. The user manually moves the robot in predefined positions and the robot save the coordinates. As a result, the accuracy is not of great importance for this method and is generally regarded as being poor. CNC machines are programmed offline; usually using dedicated software, based on a 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).

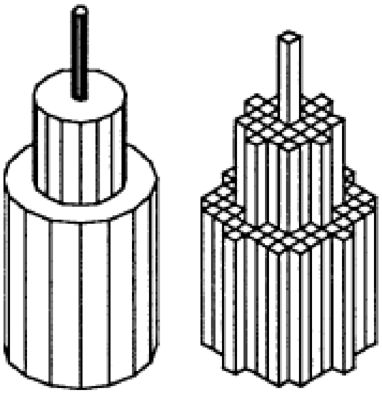

Figure 9 - Rectangular grid approximation

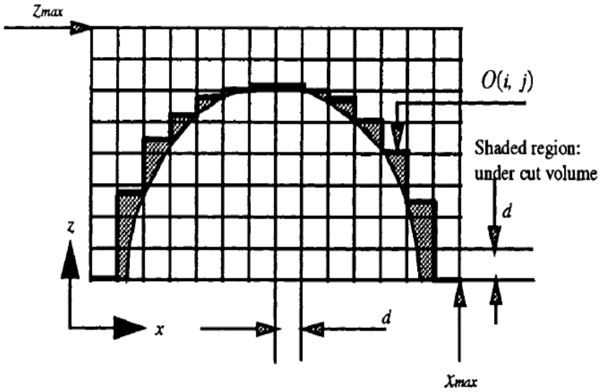

Figure 10 - Error analysis

Using the same approach, secondary operations as gauging can be detected and avoided. On the other hand, as the grid size affects the surface quality after roughing process, but also affect the actual size of the program, making difficult to handle by some controllers. Y. N. Hu et Al. proposed a method for 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).

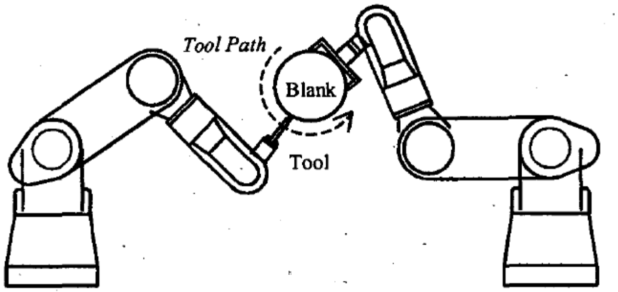

Figure 11 - Two manipulator machining system

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

4. CONCLUSION

Machining with Industrial Robots has a lot to contribute to the improvement of efficiency in machining operations. Their high level of flexibility and extended working space can outperform conventional machine tools. Due to the extra degree of freedom, IR can machine complicate geometries that otherwise would need special fixturing elements and multiple machining operations. Also, IR offers the possibility for 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 are already well established in most machine shops, being used mainly for handling and welding applications.

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

The major drawbacks of IR are currently being addressed, by developing advanced simulation technics, intelligent programming software and improved calibration processes. Newer IR models feature improved controllers in aspects of computing power and precision, enabling 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, further improving the machining accuracy to same or higher levels that conventions NC machine tools..

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

REFERENCES

Industrial Robot Statistics. (2010, Sept 30). Retrieved July 20, 2011, from The International Federation of Robotics: http://www.ifr.org/uploads/media/Charts_industrial_robots_2010.pdf

Asakawa, N., Daisuke, O., & Takeuchi, Y. (1995). Automation of polishing work by an industrial robot (5th report, 6-axis control polishing with ultrasonic vibrational tool). Transactions of the Japan Society of Mechanical Engineers, pp 4049-4054.

Cetinkunt, S., & Tsai, R.-L. (1990). Position error compensation of robotic contour End-Milling. International Journal of Machine Tools and Manufacturing, Vol.30, pp 613-627.

Chen, H., & Hu, Y. (1995). Implementation of a Robot System for Sculptured Surface Cutting. Part 1. Rough Machining. International Journal of Advanced Manufacturing Technology, pp 624-629.

Chen, Y., & Song, Y. (2001). The development of a layer based machining system. Computer-Aided Design , Vol. 33, pp 331–342.

Chryssolouris, G. (2006). Manufacturing systems – theory and practice 2nd ed. New York: Springer-Verlag.

Chryssolouris, G., Stavropoulos, P., Tsoukantas, G., Salonitis, K., & Stournaras, A. (2004). Nanomanufacturing processes: a critical review. Int. J. Materials and Product Technology, pp 331-348.

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. (n.d.). Retrieved June 20, 2011, from http://www.cometproject.eu/: http://www.cometproject.eu/

COMET project results. (2011). Retrieved May 20, 2011, from Plug-and-produce COmponents and METhods for adaptive control of industrial robots enabling cost effective, high precision manufacturing in factories of the future: http://www.cometproject.eu/publications/Delcam-PSIR.pdf

First metal cut at TEKS. (2010). Retrieved May 20, 2011, from Plug-and-produce COmponents and METhods for adaptive control of industrial robots enabling cost effective, high precision manufacturing in factories of the future: http://www.cometproject.eu/publications/ARTIS-first-metal-cut-at-TEKS.pdf

Gong, C., & Yuan, J. N. (2000). Robot thermal error calibration and modeling with orthogonal modeling. Japan– USA Symposium on Flexible Automation.

Hu, Y. N., & Chen, Y. H. (1999). Implementation of a Robot System for Sculptured Surface Cutting. Part 2. Finish Machining. International Journal of Advanced Manufacturing Technology, pp 630-639.

Huang, H.-k., & Lin, G. C. (2003). Rapid and flexible prototyping through a dual-robot workcell. Robotics and Computer Integrated Manufacturing, Vol. 19, pp 263-272.

Huang, Y., & Oliver, J. H. (1994). Non-constant parameter NC tool path generation on sculptured surfaces. International Journal of Advanced Manufacturing Technology, pp 281-290.

Jinno, M., Ozaki, F., Tatsuno, K., Takahashi, M., Kanda, M., Tanada, Y., et al. (1995). Development of a force *controlled robot for grinding, Chamfering and polishing. IEEE International Conference on Robotics and Automation, pp 1455-1460.*

Kunieda, M., Nakagawa, T., & Higuch, T. (1988). Robot-polishing of curved surface with magnetically pressed polishing tool. J. JSPE 54(1), pp 125-131.

Lee, J. (n.d.). Apply Force/Torque Sensors to Robotic Applications.

Lin, R. S., & Koren, Y. (1996). Efficient tool-path planning for machining free-form surfaces. ASME Journal of Engineering for Industry, Vol. 118, pp 20-28.

Matsuokaa, S.-i., Shimizua, K., Yamazakib, N., & Okib, Y. (1999). High-speed end milling of an articulated robot and its characteristics. Journal of Materials Processing Technology, Vol. 95, pp 83-89.

Michalos, G., Makris, S., Papakostas, N., Mourtzis, D., & Chryssolouris, G. (2010). Automotive assembly technologies review: Challenges and outlook for a flexible and adaptive approach. CIRP Journal of Manufacturing Science and Technology, pp 81-91.

Oki, Y., & Kanitani, K. (1996). Development of robot machining system for aluminum building materials. J. JSME 99, pp 78.

Oliver, J. H., Wysocki, D. A., & Goodman, E. D. (1993). Gouge detection algorithms for sculptured surface NC generation. ASME Journal of Engineering for Industry, Vol. 115, pp 139-144.

Owen, W. S., Croft, E. A., & Benhabib, B. (2004, April). Real-Time Trajectory Resolution for Dual Robot. Proceedings of the 2004 IEEE International Conference on Robotics & Automation.

Papakostas, N., Makris, S., Alexopoulos, K., Mavrikios, D., Stournaras, A., & Chryssolouris, G. (2006). Modern Automotive Assembly Technologies: Status and Outlook. The 1st CIRP-International Seminar on Assembly Systems.

Sanders, D. A., Lambert, G., Jones, J. G., & Giles, E. (2010). A robotic welding system using image processing techniques and a CAD model to provide information to a multi-intelligent decision module. Assembly Automation, pp 323–332.

Sharma, I. R. (2001). Latest Trends in Machining. Retrieved July 19, 2011, from Indra Drishtikona: http://www.drishtikona.com/books/latest-trends-in-machining/ch-all.pdf

Song, Y., & Chen, Y. H. (1999). Feature-based robot machining for rapid prototyping. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 1999, pp 451.

Stavropoulos, P., Salonitis, K., Stournaras, A., Pandremenos, J., Paralikas, J., & Chryssolouris, G. (2007). Advances and challenges for tool condition monitoring in micromilling. IFAC Workshop on Manufacturing Modelling, Management and Control, (pp. pp 211-216). Budapest, Hungary.

Suh, Y. S., & Lee, K. (1990). NC milling tool path generation for arbitrary pockets defined by sculpture surfaces. Computer-Aided Design, Vol. 22, pp 273-284.

Takeuchi, Y., Asakawa, N., & Dongfang, G. (1993). Automation of polishing work by an industrial robot. SME International Journal, Series C 36, pp 556-561.

Vergeest, J. S., & Tangelder, J. W. (1996). Robot machines rapid prototype. Industrial Robot, pp 17-20.

Veryha, Y., & Kurek, J. (2003). Application of Joint Error Mutual Compensation for Robot End-effector Pose Accuracy Improvement. Journal of Intelligent and Robotic Systems, Vol. 36, pp 315–329.

Wilson, M. (1999). Vision system in the automotive industry. Industrial robot: An international journal, pp 354-357.

Yamane, Y., Yin, R., Okamoto, H., Yamada, M., Yonezawa, Y., & Narutaki, N. (1988). Application of multi-joint type industrial robot to scraping of surface plate. J. JSPE 55, pp 1787-1792.

Young, K., & Pickin, C. G. (2000). Accuracy assessment of the modern industrial robot. Journal of Industrial Robot, Vol. 27, pp. 427-436.

Zengxi, P. b., Zhang, H. a., Zhub, Z., & Wang, J. a. (2006). Chatter analysis of robotic machining process. Journal of Materials Processing Technology, Vol. 173, pp 301–309.