Int J Adv Manuf Technol (2013) 66:1489–1497
DOI 10.1007/s00170-012-4433-4

ORIGINAL ARTICLE

Robot machining: recent development and future research issues

Yonghua Chen · Fenghua Dong

Received: 5 March 2012 / Accepted: 29 July 2012 / Published online: 12 August 2012

Abstract Early studies on robot machining were reported in the 1990s. Even though there are continuous worldwide researches on robot machining ever since, the potential of robot applications in machining has yet to be realized. In this paper, the authors will first look into recent development of robot machining. Such development can be roughly categorized into researches on robot machining system development, robot machining path planning, vibration/chatter analysis including path tracking and compensation, dynamic, or stiffness modeling. These researches will obviously improve the accuracy and efficiency of robot machining and provide useful references for developing robot machining systems for tasks once thought to only be capable by CNC machines. In order to advance the technology of robot machining to the next level so that more practical and competitive systems could be developed, the authors suggest that future researches on robot machining should also focus on robot machining efficiency analysis, stiffness map-based path planning, robotic arm link optimization, planning, and scheduling for a line of machining robots.

Keywords Robot machining · NC path planning · Machining efficiency · Industrial robots · Joint stiffness

1 Introduction

Modern industries are heavily dependent on robots that have a wide range of applications such as material transfer, precision assembly, welding, and machining [1–4]. Statistical data from International Federation of Robotics has shown that there is a steady increase in annual robotic sales except 2009 when the financial tsunami had seriously hit the world economy [1]. In 2011, the annual industrial robot sale was estimated to reach 139,300 units, making the worldwide population of operational industrial robots to reach 1,035,000 units. However, this data is dwarfed by the recent reports about ambitious plans in Asian industrial companies to rapidly increase their industrial robots population. For example, there were many media reports in 2011 about an Asian company Foxconn [2] who is going to install one million industrial robots in the next 3 years. Foxconn Technology [2] is a subcontractor for world's leading electronics product companies such as Apple, Microsoft, etc. It employs over one million production workers in China. Due to dozens of suicidal death in a single year in 2010 inside its factories (most were bored due to routine assembly line work), the company announced an ambitious plan to develop and install over one million robotic arms in the next 3 years. Even though most of the robots will be used in operations traditionally performed by robots, some machining-related operations are also expected. This will definitely boost the applications of robots in machining. This instance reflects that the future growth of industrial robots will be even more dramatic when emerging countries start to automate their factories.

According to a white paper published by The Robotic Industries Association in 2009 [3], robotic machining products and services constitute less than 5 % of existing robotic sales, but was seen as a growth application segment over the next 3–5 years. Applications involve the pre-machining of parts made from harder materials, with robots performing various processes at lower tolerances. It was believed that robotic machining could not replace computer numerical control (CNC) machining for three to four axis applications, but is currently viewed as an immediate viable alternative

Y. Chen (✉) · F. Dong
Department of Mechanical Engineering,
The University of Hong Kong,
Pokfulam, Hong Kong, China
e-mail: yhchen@hku.hk

tool for non-metallic materials and for metals depending on the degree of hardness, required surface finish, and part complexity.

The white paper also revealed that the barrier to more widespread adoption of robot machining was a general lack of knowledge by the end-user community regarding the capabilities and advantages of robots in machining applications. A significant effort is therefore required to educate end-users on the capabilities of robot machining before significant increases in robotic machining applications are realized. Realizing the potential of robotic machining, the world's leading industrial robot manufacturers are starting to provide machining robots together with relevant software packages [5–8]. Even traditional computer-aided design (CAD)/computer-aided manufacturing (CAM) software developers such as Delcam [9] have incorporated offline CAD-based robot machining capabilities into their traditional CAD/CAM software packages.

Before being applied to direct machining, robot arms have been used to machining-related jobs. Some studies have shown that robots can perform well in polishing [10–12], grinding [13–16], and deburring [17, 18]. The major purpose of polishing is to generate a glossy or smooth surface, not to modify a part's dimensions. Polishing tools are often soft or flexible, thus positional accuracy requirement is not very high. This has created an excellent opportunity for robots to excel in polishing operations because an articulated robot arm can easily position the polishing tool to any positions that are needed. It was argued that robot grinding and polishing could produce surface quality better than that from three axis CNC milling machines [18, 19]. The better surface roughness from robot grinding/polishing (0.52 μm against 1.30 μm in three-axis milling) is mainly due to the ability of the robot to easily change the orientation of the tool, therefore, it can always keep the tool normal to the polished surface.

As for milling operations, many studies have reported mixed results showing that many improvements must be made before robot milling could be readily applied to milling operations. It is interesting to notice that articulated robots have some problems such as low repeatability, yet the robots were first successfully applied to the finishing operations of machining (polishing and grinding) where part surface quality requirements are high. This may be partly explained by the material removal rate. At the rough cutting (or milling) and finish cutting stages, a large amount of material must be removed. This will subject the robot arm to a large load yet the rigidity of current robot design is not big enough to withstand such a large load in machining. Thus large error in machining may occur.

To overcome the drawbacks of articulated robots in machining, in 2009, European Commission had funded a project called COMET (plug-and-produce components and methods for adaptive control of industrial robots enabling cost-effective, high-precision manufacturing in factory of the future) [19]. This project was aimed at overcoming challenges facing European manufacturing industries by developing innovative machining systems that are flexible, reliable, and predictable with an average cost efficiency savings in comparison to machine tools. Industrial robot technology was chosen as the backbone of the project. The project investigators are aware of the inherent weakness of industrial robots, that is, low positioning accuracy, vibration due to process force, and lack of reliable programming tool. It is widely anticipated that this project will greatly progress the technology in robot machining.

For articulated robots, the repeatability is inherently dependant on its reach distance. The larger the reach distance is, the lower the repeatability will be. This inherent characteristic can be easily explained as when the robot is fully stretched, it is a cantilever beam. The compliance of a cantilever is heavily dependent on the cantilever length. In fact, this characteristic has been manifested by the data provided by commercial robot suppliers (for examples, ABB, Motoman, Fanuc, Kuka). Table 1 shows some data for three selected ABB robot models [7]. It can be seen that as the reach distance increases, the repeatability error is increased too. This table also shows that the repeatability of today's industrial articulated robot can be as high as ±0.01 mm which is sufficient for many low- to medium-accuracy part machining jobs. In fact, most machining jobs do not need a large reach distance. If the reach distance of robot design is further reduced, it will be possible to improve the repeatability even further.

The following will classify recent research on robotic machining into three areas, namely rapid prototyping, vibration/chattering analysis, path planning, and automatic robot programming.

2 Robot machining for rapid prototyping

Articulated industrial robots are flexible, cost-effective, and normally have a large working envelope. However, they have low positional accuracy and rigidity which confine early robotic machining researches be aimed at making large prototypes that are difficult to be made by both CNC machines and layer-based rapid prototyping machines.

Table 1 A robot's reach distance and repeatability

Robot model	Reach distance (mm)	Repeatability (mm)
ABB IRB 120	580	±0.01
ABB IRB 140	810	±0.03
ABB IRB 1410	1,440	±0.05

2.1 Rapid prototyping based on machining

Early robot machining research was aimed at making parts with complicated geometry and limited accuracy (say 1.00 mm). Vergeest and Tangelder had first reported a robotic machining system that was consisted of an articulated industrial robot, a rotatable horizontal platform for stock material fixation and a milling device mounted on the end effector of the robot [20]. The system was capable of making parts within an 80-cm cube. Offline robot programming capability was mentioned yet no detail was reported. Almost at the same time, Chen and Tse also reported a robotic system for rapid prototyping purpose [20]. Apart from the major components as reported in Vergeest and Tangelder's system, the robot arm in Chen and Tse's system was mounted on a 3-m-long linear track which could significantly extend the robot system's machining capability. A detailed robot machining path planning method was reported as well. Further refinement of the robotic machining system was documented in their subsequent publications [21–23]. Figure 1a shows the hardware system setup. Robot machining path simulation and verification are shown in Fig.1b.

In order to further increase the efficiency of robot machining, Huang and Lin reported a dual robot machining system [24]. In their system, the stock is installed on a fixed working table, and two robotic arms are used to collaboratively machine a 3D part. A similar robot machining system with two arms could be seen from the research conducted by Owen et al. [25, 26]. They used two robotic arms with one serving as the stock fixtures and the other as a machining tool. This system has more degrees of freedom allowing parts with more complicated geometry be made. However, the system is more compliant thus needs more careful monitoring of the machining force. Forces acting on the end effectors were monitored to identify the onset of a disturbance so that the system could be slowed down before saturation actually occurred. In response to disturbances, a time-scaling method could reduce the tool speed, thereby reducing the demand on the joint torques and allowing the pre-computed path to be followed more accurately.

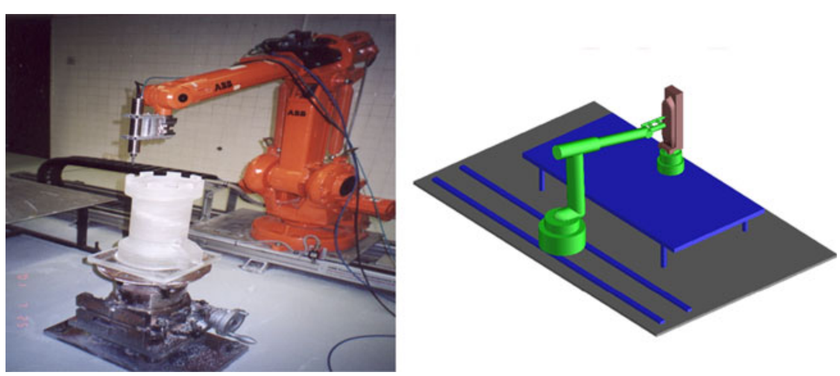
The merits of robot machining were further extended by Lee and Tsai et al. [27] who had tested Internet-based robot machining scheduling and collaboration. This system is good for resource sharing, autonomous repairing, and replacement of damaged parts in hazardous environment or space. To machine a part with better surface quality, Zielinski et al. developed a robotic system that was capable of both milling and polishing [28]. It was believed that large parts machined by a robot machining system could have good surface finish.

Even though articulated robot arms have very good accessibility compared to traditional CNC machines, yet some intricate geometric features such as cavities or internal holes could not be made by articulated robots. Figure 2a shows a sectioned view of a toilet flush model. The internal channels of the model could not be machined by any existing CNC machines. Chen et al. [29, 30] had developed a layer-based method using robot machining that could build parts with complicated internal features such as the ones shown in Fig. 2b and c. The layers do not have uniform thickness. Instead, layer thickness is adaptive to curvature change and accessibility analysis along the build orientation.

2.2 Robot calibration

In order to develop a robot machining system with better accuracy, various calibration methods have been reported. CCD cameras were frequently used to identify the kinematic parameters of the actual machining setup so that positional accuracy of the robot could be improved [23, 24]. Figure 3 shows a vision-based robot calibration method where a gauge cylinder was placed in pre-defined locations on the rotary table [23]. Positional errors Δx, Δy, and Δz were measured using the two cameras installed in orthogonal positions.

Morris et al. reported a robot calibration method using coordinate measuring machine (CMM). Experimental measurements of some robot poses are taken using a CMM. Based on the measurements, a kinematic model is developed



(a) The system set-up (b) Machining path simulation and verification

Fig. 1 A robotic machining system. **a** The system setup; **b** machining path simulation and verification

(a) CAD model (b) A toilet flush model (c) A castle model

Fig. 2 Large parts with internal features made by layer-based robot machining. **a** CAD model; **b** a toilet flush model; **c** a castle model

for the robot arm. Its relationship to the world coordinate frame and the tool is also established [31].

Andres et al. has reported a novel method for the calibration of a complex robotic workcell with eight joints devoted to milling tasks [32]. A planar calibration method is developed to estimate the external joint configuration parameters by means of a laser displacement sensor, thus avoiding direct contact with the calibration pattern. A redundancy resolution scheme on the joint rate level is integrated with a CAM system for the complete control of the robotic workcell during the path tracking of a milling task. In general, a calibration method should serve two purposes. First, it should establish a relationship between the robot coordinate system and the workpiece coordinate system. Second, it should take some measurements so that the kinematic parameters of the robot can be modified to accurately describe the actual position and orientation of the robotic links.

3 Vibration or chattering analysis

Articulated robot arms are very agile and flexible with good accessibility. When used for machining, there is always a tradeoff between low dynamic accuracy and good accessibility. This is why early researches on robot machining were targeted at making prototypes with large size and complicated geometry [20–23, 33]. Accuracy of part making was not a major concern. When used in machining hard or metal materials, the low stiffness of robot machining systems presents a bigger problem. To make things worse, a robot arm's stiffness varies significantly in different directions. For example, the static stiffness of a robot machining system was reported to be 83.65 μm/N in X direction, 20.35 μm/N in Y direction, and 68.76 μm/N in Z direction [34, 35]. Due to the difference of stiffness in different directions, cutting accuracy was also found different in different cutting directions. In order to improve robot cutting accuracy, correlation between vibration/chatter and machining parameters must be established through experiments. For example, Zaghbani et al. had collected vibrations and cutting force signals with analysis in order to find a reliable dynamic stability machining domain with respect to spindle speed [36]. Feedrate is also an important machining parameter. It has a large impact on the machining accuracy as well [35]. Therefore it is desirable to plan an optimal feedrate with a compromise between machining efficiency and machining quality. It was found that a constant feedrate was always preferred if possible throughout the machining process [37].

Given the fact that the low stiffness of a robot arm may cause machining errors, researchers have developed some methods to compensate the errors. Zhang and Pan had reported a method to control the machining error based on deflection compensation and adaptive material removal rate (MRR) [38–40]. The deflection compensation was based on a stiffness matrix in Cartesian space that the researchers had developed based on experiments. The MRR was adaptive to the cutting forces which were measured real-time in the machining process. Based on both deflection compensation and the controlled MRR, it was reported that the machining accuracy of foundry parts could be improved from 0.9 to 0.3 mm.

For automatic offline robot machining programming, Abele et al. developed an offline error compensation model for the machining path [41]. The model can be used for the prediction of the cutting force so that the anticipated cutting deviation could be compensated based on the robot's compliance matrix during actually cutting. Since the cutting tool path could be controlled, the accuracy of an industrial robot for machining could be increased [42].

Because an articulated robot has heterogeneous stiffness within its working envelope, it will be best for a robot to perform a machining job within its possible range of best stiffness. Vosniakos and Matsas had presented a method that the robot milling operation could be performed in regions of the robot's workspace where manipulability, both kinematic and dynamic was the highest, thereby exhausting the robot's potential to cope with the process. By selecting the most suitable initial pose of the robot with respect to the workpiece, a reduction in the range of necessary joint torques

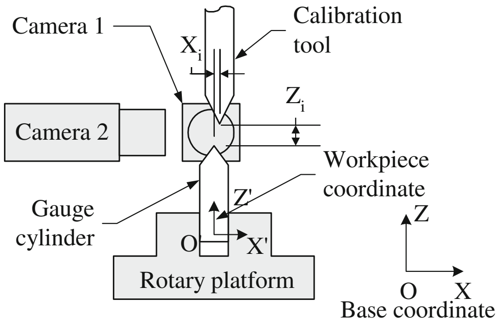


Fig. 3 Calibration of a robot arm

could be reached, to the extent of alleviating the heavy requirements on the robot. Genetic algorithm was used to minimize the joint torque loads given the milling forces. [43]. Similar to Vosniakos and Matsas's work, Lopes and Pires proposed an approach to optimize the workpiece location based on machining trajectory and machining forces. Again, a genetic algorithm was used for the optimization of initial workpiece location [44].

Realizing that the accuracy of robot machining is affected by many factors, Andrisano et al. proposed an integrated approach for robot machining accuracy enhancement based on robotic process simulation, tailored design of mechanical apparatus for the machining system, and software modules for robot control and programming [45]. They also highlighted the importance of machining strategy validation, automatic robot path generation, workcell calibration, and robot code commissioning.

In order to accurately define the dynamic behavior of a machining robot, both experimental method and analytical method have been reported. Bisu et al. have used a frequency method to measure the dynamic response when milling at designated points [46]. Since only very few points could be measured, this method is not directly useful for robot trajectory planning in machining. A more useful method for robot joint stiffness identification is reported by Dumas et al. [47]. They evaluate joint stiffness values with consideration of both translational and rotational displacement of the robot end effector for a given applied wrench (force plus torque). Based on the joint stiffness values, they have also developed the robot's Cartesian stiffness matrix which is more useful for robot machining path planning.

4 Robot machining path planning

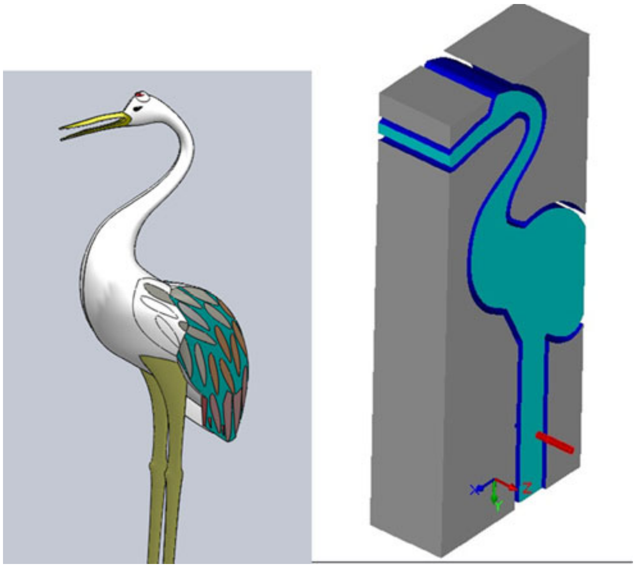
There are many literature reports about automatic CNC machining path planning based on CAD models [48]. In the past 30 years, the authors estimate that at least tens of thousands articles on CNC machining path planning have been published by international journals and conferences. Even by now, articles in this field are still constantly emerging [49]. Compared to the wealth of path planning for CNC machining, very little publications on automatic robot machining path planning could be found. There might be a misconception that robot machining path planning is the same or similar to NC path planning. This misconception may have hindered the development of robot machining. It is true that there are some similarity between NC path planning and robot machining path planning. Yet the difference is substantial. For example, the impact of stiffness on robot machining path planning is significant yet a CNC machine's stiffness has much smaller impact on NC path planning.

Apart from academic research on automatic path planning for robot machining, some commercial companies are also actively engaged in developing software packages capable of generating robot trajectory automatically from a CAD model, or from a tool path. Robotmaster ® has reported a software solution for CAD/CAM-based programming for robot milling and trimming [50]. Robotmaster can create accurate six-axis robot trajectories from tool path data. Singularity, collision, out of reach, and joint extension errors are checked when the robot trajectory is generated. The functionality of Robotmaster has more or less reflected achievement from early research on automatic robot machining path planning [21–23, 51]. However, the dynamic features of a robot are not considered in Robotmaster.

Recent research on robot machining has focused more on the influence of robotic dynamics on machining accuracy and efficiency [46,47,52,53]. Olabi et al. have proposed to optimize the tool-tip feedrate in Cartesian space for a given tool path using a smooth jerk limited pattern with consideration of the joints kinematics constraints [52]. That is, the dynamic characteristics of the robot are considered in determining one of the key machining parameters "feedrate".

Xiao et al. propose a robot trajectory planning method based on cutter location (CL) data generated by conventional CAD/CAM [53]. When doing inverse kinematics, a redundant mechanism is analyzed to avoid the singular configurations and joint limits. A gap bridging strategy is applied to reduce the jerk motion caused by tool retraction and cutting paths connection.

Apart from the above-mentioned articles for path/trajectory planning in robot machining, not much else could be found. Almost all reported robot cutting trajectory planning methods are based on CL data generated by either using an existing method, or by an existing CAD/CAM software package. Based on the authors' experiences, when generating CL data, robot dynamics should be considered. A general principle about CL data generation should be to minimize joint motion when the robot moves from one cutter location to the next cutter location.



(a) the crane bird model (b) machine to near shape

Fig. 4 Machining of a crane bird. **a** The crane bird model; **b** machine to near shape

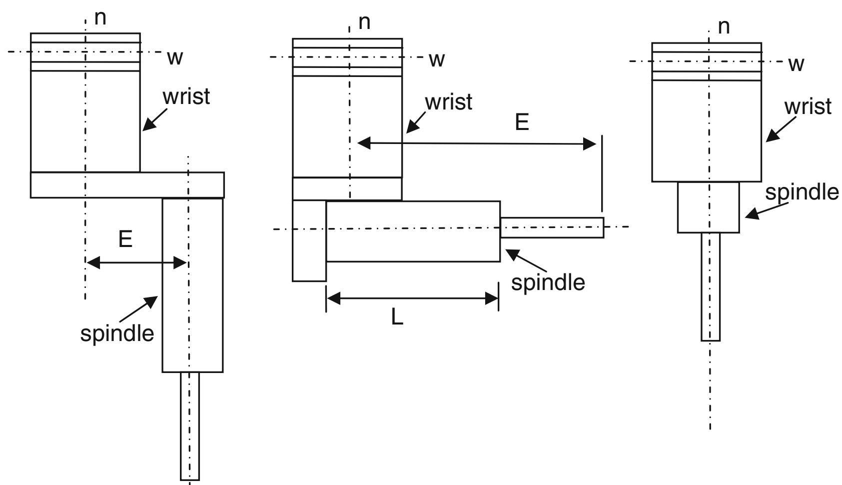
5 Future research issues

Progress in robot machining research is relatively slow in recent years. This may have been the results of a variety of factors. In order to advance the science and technology of robot machining, the following issues are identified and must be studied in the future.

1. Robot machining efficiency has never been investigated: In fact, this is one of the major issues in robot machining that must be addressed in order to extend robot machining to more applications. Normally, robot machining has much bigger advantages when machining large components compared to CNC machining. Yet when machining a large component, in general, more material must be removed. However, due to limited robot rigidity and payload, feed rate, depth of cut, and cutter diameter must be kept to small values. This will limit the material removal rate or machining efficiency. It is desirable to develop some machining strategies such as special cutting path patterns so that machining efficiency could be increased. Figure 4a shows a 3D model of a crane bird. If it is to be made by robot machining based on a rectangular block raw material, a lot of material must be removed. If the excess material is removed bit by bit in a traditional zigzag pattern, it will take a lot of time. Figure 4b shows the rough machining of the part to near shape in the projection plane *X–Y*. It may be followed by make the part to near shape in *Y–Z* plane and *X–Z* plane. After these rough cutting, the excess material is significantly reduced. This will greatly increase the efficiency of robot machining.

   It is also possible to use dual robots machining with one robot for rough machining and the other for finish machining. Robot machining can afford the luxury of multi-robots due to its low cost. This demarcation of machining job may greatly improve robot machining accuracy as well as efficiency because some robot arms are best designed for higher payload and others are designed for greater precision.
2. Develop a rigidity map within a robot's working envelope: For a given point within the working envelope, it can be reached with many possible robot joint configurations, joint configurations many have quite different rigidity which will affect the machining quality. If the rigidity map is known and easily available, optimal joint configurations could be identified for a given machining path. This will help improving the machining quality. In previous robot machining research, almost all reported systems used an existing industrial articulated robot arm

Fig. 5 Spindle attachments to a robot's end link (wrist)



(a) parallel attachement (b) vertical attachment (c) design into wrist with a retrofitted tool spindle. The two popular spindle attachments are shown in Fig. 5a and b. Both attachment methods will weaken the already weak stiffness of a robot arm and complicate the system calculation. A suggestion here is to design the tool spindle into the robot's end link (or wrist) as shown in Fig. 5c so that eccentric force could be avoided and computation simplified.

3. Optimized robot machining system configuration: Robot machining were currently researched based on existing industrial robots that are best suited to material transfer and welding applications. To get the best machining results, research on robot machining should not be restricted to current industrial robot configurations. Investigation on the proportion and design of the links L1, L2, and L3 as shown in Fig. 6 for optimal machining accessibility and rigidity should be conducted.

   We all know that serial robots have accuracy problems mainly due to the error magnifying effect of the arm design and the low arm stiffness. One approach is to scale down the robot arm since this can reduce the effect of error magnification and increase the robot arm's stiffness. The reduced reach range may be compensated by introducing a linear stage for the positioning of the workpiece or mounting of a robot arm to a precision *XYZ* stage as shown in Fig. 6. It is not necessary to control the *XYZ* stage during machining. Instead, positions of the robot arm on the *XYZ* stage can be precomputed so that optimum machining operations in terms of accessibility and rigidity could be performed for a given part. Since *XYZ* stage design and manufacturing is a mature technology which could provide stages with good rigidity and sub-micron accuracy. The addition of the *XYZ* stage will not have visible impairment of the robot system's accuracy and stiffness.

4. Robotic machining lines: The advantages of robotics are best illustrated when a line of robots are used to perform jobs automatically as those frequently seen in a factory's automatic assembly lines. There are researches on isolated robot applications to machining, deburring, grinding, or polishing. Yet no effort has been reported about the development of an automatic machining line that has all of the above functionalities. Figure 7 shows a proposed such robot machining line. The authors do not agree with the concept of concurrent machining with multiple robots since this may create a lot of extra problems such as vibration and torsion. Instead, a dedicated robot for a dedicated operation will make parts with best quality. For example, the robot machining line shown in Fig. 7 has a dedicated rough machining robot and a finish machining robot. The robot for rough machining may be designed for high stiffness, yet the finishing robot might be designed for greater accuracy as the material removal rate in finish machining is normally very small thus the load capacity requirement is low. Other finish machining operations such as grinding or polishing may be added when necessary. If needed, a painting robot may also be added so that a product can be completely made in a single line. Of course, a lot of research work must be done in order to make the automatic robot machining line a reality.

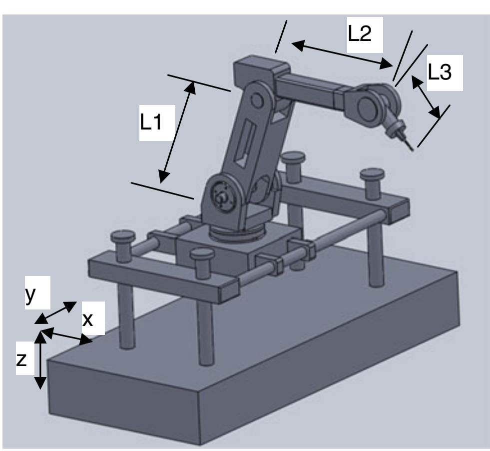


Fig. 6 A proposed robot machining cell

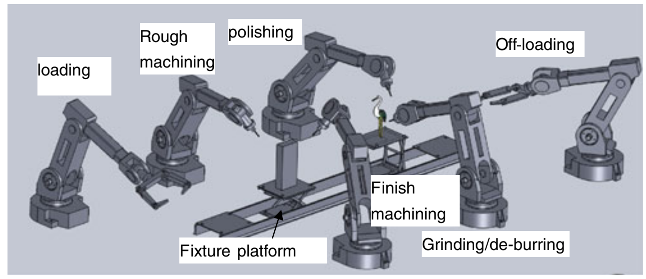


Fig. 7 A proposed robot machining line

6 Discussions and conclusions

This paper has provided a review of recent research and development related to robot machining. It is found that there is still a long way to go before robot machining systems are widely used in practical applications. In current researches, most researchers have chosen to use existing industrial robots that are not designed or optimized for machining operations. The inherent problems of low dynamic accuracy, vibration, and chattering could never be resolved based on current research effort. This has hindered the development of robot machining in recent years.

In this paper, the authors have suggested ways of improving robot machining accuracy and efficiency so that robot machining systems could be widely used in the future. Four future research issues on robot machining are outlined.

It is hoped that research on these issues may eventual advance the technology of robot machining.

References

1. International Federation of Robotics. www.ifr.org. Accessed 18 Feb 2012
2. Foxconn Technology Ltd. www.foxconn.com. Accessed 18 Feb 2012
3. The Robotic Industries Association. www.robotics.org. Accessed 18 Feb 2012
4. He XJ, Chen YH (2009) Haptic-aided robot path planning based on virtual tele-operation. J Robot and Comput Integr Manuf 25(4-5):792–803, Elsevier
5. Kuka Robot Group. www.kuka-robotics.com. Accessed 28 Feb 2012
6. Yaskawa Motoman Robotics. www.motoman.com. Accessed 28 Feb 2012
7. ABB Robotics. www.abb.com/rototics. Accessed 28 Feb 2012
8. Fanuc Robotics. www.fanucrobotics.com. Accessed 28 Feb 2012
9. Delcam. www.delcam.com/. Accessed 28 Feb 2012
10. Kunieda M, Nakagawa T (1985) Robot-polishing of curved surface with magneto-pressed tool and magnetic force sensor. Twenty-Fifth International Machine Tool Design and Research Conference; Birmingham; UK; 22–24 Apr. 1985. pp. 193–200.
11. Takeuchi Y, Ge D, Asakawa N (1993) Automated polishing process with a human-like dexterous robot. Proc. IEEE International conference on robotics and automation, Atlanta USA, May 1993, pp. 950–956,
12. Lin FY, Lu TS (2005) Development of a robot system for complex surfaces polishing based on CL data. Int J Adv Manuf Technol 26:1132–1137
13. Whitney DE (1988) Elements of an intelligent robot grinding system. Proceedings of the Third ERR. Gouvieux, France, pp 381–387
14. Liu L, Ulrich BJ, Elbestawi J (1990) Robotic grinding force regulation: design, implementation and benefits. Proc. IEEE International conference on robotics and automation. Cincinati, USA, pp 258–265
15. Dai H, Yuen KM, Elbestavi J (1993) Parametric modelling and control of the robotic grinding process. Int J Adv Manuf Technol 8 (3):182–192
16. Rena X, Kuhlenkottera B, Muller H (2006) Simulation and verification of belt grinding with industrial robots. Int J Mach Tool Manuf 46:708–716
17. Huang H, Gong ZM, Chen XQ, Zhou L (2002) Robotic grinding and polishing for turbine-vane overhaul. J Mater Process Technol 127:140–145
18. Pires JN, Ramming J, Rauch S, Araujo R (2002) Force/torque sensing applied to industrial robotic debuerring. Sens Rev 22(3):232–241
19. COMET project. http://www.cometproject.eu/. Accessed 28 Feb 2012
20. Chen YH, Tse WC (1997) A robotic system for rapid prototyping. Proc of the IEEE International Conference on Robotics and Automation, USA 3:1815–1820
21. Chen YH, Hu YN (1999) Implementation of a robot system for sculptured surface cutting, Part I, rough machining. Int J Adv Manuf Technol 15:624–629
22. Chen YH, Hu YN (1999) Implementation of a robot system for sculptured surface cutting. Part II. Finish machining. Int J Adv Manuf Technol 15:630–639
23. Chen YH, Song Y (1999) Feature-based robot machining for rapid prototyping. J Eng Manuf, Proc Of Inst Mech Engrs, Part B 213 (B5):451–459
24. Huang HK, Lin GC (2003) Rapid and flexible prototyping through a dual-robot work-cell. Robot Comput Integr Manuf 19(3):263–272
25. Owen WS, Croft EA, Benhabib B (2003) Minimally compliant trajectory resolution for robotic machining. Proc IEEE Int Conf on Advanced Robotics 2:702–707, Coimbra, Portugal
26. Owen WS, Croft EA, Benhabib B (2006) Real-time trajectory resolution for a two-manipulator machining system. J Robot Syst 22(S1):51–63
27. Lee RS, Tsai JP, Lee JN (2000) Collaborative virtual cutting verification and remote robot machining through the Internet. IMechE Proc Instn Mech Engrs, Part B 214:635–644
28. Zielinski C, Mianowski K, Nazarczuk K, Szynkiewicz W (2003) A prototype robot for polishing and milling large objects. Ind Robot 30(1):67–76
29. Chen YH, Song Y (2001) The development of a layer based machining system. Computer-Aided Design 33(4):331–342
30. Chen YH, Yang ZY, Sze WS (2001) Determining build orientation for layer-based machining. Int J Adv Manuf Technol 18:313–322
31. Driels MR, Swayze W, Potter S (1993) Full-pose calibration of a robot manipulator using a coordinate measuring machine. Int J Manuf Technol 8:34–41
32. Andres J, Gracia L, Tornero J (2011) Calibration and control of a redundant robotic workcell for milling tasks. Computer-Integrated Manufacturing 24(6):561–573
33. Vergeest JS, Tangelder JW (1995) Robot machines rapid prototype. Ind Robot 23(5):17–20
34. Oki Y, Kanitani K (1996) Development of robot machining system for aluminum building materials. J JSME 99(937):78–87
35. Matsuoka S, Shimizu K, Yamazaki N, Oki Y (1999) High-speed end milling of an articulated robot and its characteristics. J Mater Process Technol 95:83–89
36. Zaghbani I, Lamraoui M, Songmene V (2011) Robotic high speed machining of aluminium alloy. Adv Mater Res 188:584–589
37. Olabi A, Bearee R, Gibaru O, Damak M (2010) Feedrate planning for machining with industrial six-axis robots. Control Eng Pract 18:471–482
38. Zhang H, Pan, Z (2005) Machining with flexible manipulator: toward improving robotic machining performance, Proc. IEEE/ASME inter Conference on Advanced Intelligent Mechatronics, California, USA, pp.1127–1132
39. Pan Z, Zhang H (2009) Improving robotic machining accuracy by real-time compensation. ICROS-SICE Inter Joint Conference, Fukuoka, Japan, pp. 4289–4294.
40. Abele E, Weigold M, Rothenbucher S (2007) Modeling and Identification of an industrial robot for machining applications. CIRP Ann 56(1):387–390
41. Abele E, Baer J, Pischan M (2010) Prediction of the tool displacement for robot milling applications using coupled modes of an industrial robot and removal simulation, Proc. CIRP 2nd Inter Conf on Process Machine Interactions, Vancouver, Canada.
42. Vosniakos G, Matsas E (2010) Improving feasibility of robotic milling through robot placement optimization. Robot Comput Integr Manuf 26:517–525

43. Lopes A, Pires EJS (2011) Optimization of the workpiece location in a machining robotic cell. Int J Adv Robot Syst 8(6):37–46
44. Andrisano AO, Leali F, Pellicciari M (2011) Integrated design of robotic workcells for high quality machining. Proc of Inter Conf. on Innovative Methods in Product Design, Italy, pp 316–321
45. Bisu C, Cherif M, Gerard A, K'Nevez J (2011) Dynamic behavior analysis for a six axis industrial machining robot, Proc ICASAAM, September, 2011. Bucharest, Romania
46. Duma C, Caro S, Garnier S, Furet B (2011) Joint stiffness identification of six-revolute industrial serial robots. Robot Comput Integr Manuf 27(4):881–888
47. Dragomatz D, Mann S (1997) A classified bibliography of literature on NC milling path generation. Computer-aided design 29 (3):239–247
48. Chen HC, Yau HT, Lin CC (2012) Computer-aided process planning for NC tool path generation of complex shoe molds. Int J Adv Manuf Technol 58:607–619
49. Robomaster. www.robotmaster.com. Accessed 26 Jul 2012
50. Walstra WH, Bronsvoort WF, Vergeest JSM (1994) Interactive simulation of robot milling for rapid shape prototyping. Comput Graph 18(6):861–871
51. Olabi A, Bearee R, Nyiri E, Gibaru O (2010) Enhanced trajectory planning for machining with industrial six-axis robots. 2010 IEEE International conference on Industrial Technology, 14–17 March, France, pp.500–506
52. Xiao WL, StrauB H, LoohB T, Hoffmeister HW (2011) Closed-form inverse kinematics of 6R milling robot with singularity avoidance. Prod Eng 5(1):103–110