Proceeding of the IEEE
International Conference on Robotics and Biomimetics
Dali, China, December 2019

Path planning of grinding robot with force control based on B-spline curve

Yinhui Xie, Jinxing Yang, Mingqi Feng, Weilong Huang, Jun Li*
Quanzhou Institute of Equipment Manufacturing, Chinese Academy of Science
Quanzhou, China

***Abstract*—In order to realize the stable control of grinding force during the robot grinding process, a robotic path optimization method based on B-spline curve is proposed. According to the given control points, the function model of B-spline curve was established to interpolate, and the path based on B-spline curve was fitted to achieve the goal of path smoothing. The test experiment of grinding force was carried out and the experiment results showed that the force change of the path based on B-spline curve was less fluctuation than that of the general path. Therefore, the path based on B-spline curve can effectively reduce the fluctuation and deviation of grinding force in machining process and provide a stable machining environment for realizing the constant control of grinding force.**

***Index Terms*—Grinding Robot, force control, path plan, B-spline curve**

I. Introduction

With the development of industrialization, the processing and manufacturing industry is in rapid development. In industry, both quality and quantity requirements of the grinding which is essential to the machining process is constantly increasing. At present the domestic manufacturing enterprises mainly rely on handwork to complete precision machining of complex surface, such as engine blades, precision molds and aspheric optical elements. The handwork is low efficiency with poor working conditions, and it is difficult to obtain high surface quality. Industrial robot with multiple degrees of freedom has the advantage of high flexibility [1, 2]. In the process of surface grinding, robot can be closely attached to the surface to improve the machining accuracy of workpiece. Therefore robot can replace manual automatic grinding of the complex surface. The grinding robot is equipped with a grinding tool at the end of robot. The grinding tool is controlled by robot to move according to the set path and speed, and the material removal of workpiece is generated by the high speed rotation of grinding tool.

In the process of robot grinding, the deviation between the robot grinding tool and workpiece will produce contact force. The larger contact force is more easily to cause damage to the robot and workpiece [3, 4]. The value of contact force affects the machining accuracy of workpiece, and the task requirements cannot be met only through the robot position control system. Therefore, the robot must control the value of contact force in the grinding process, and adjust the contact force feedback to adapt to the changes in environment actively and meet the requirements of processing and production. In the grinding robot system with force control, the tool path is one of main factors affecting change of grinding force. Because the feedback control of grinding force has a certain delay, the existing path of robot is likely to cause excessive deviation of grinding force [5-7]. Thus, we present an optimization of path plan method based on B-spline curve, so as to realize the stable control of grinding force during the robot grinding process.

II. The Grinding Robot System with Force Control

In order to control the value and direction of grinding force in grinding process, a set of grinding robot system with force control is built as in Fig. 1. The grinding robot system with force control comprises main parts including KUKA six-axis robot, six-dimensional force sensor, motorized spindle, grinding tool and workbench [8]. The model of KUKA six-axis robot is KR60 with a load of $60kg$. The force sensor is connected to the robot flange. And the clamping device of motorized spindle is mounted on the side of sensor flange, so that the barycenter of end tool is close to the flange of mechanical arm. It can reduce overall length of the end tool and improved the rigidity of mechanical arm during processing. The six-dimensional force sensor is used to measure the force information of three-dimensional space in the cartesian coordinate system. In the sensor coordinate system, the pressure range of the x and y direction is 330N and the pressure range in the z direction is $990N$. Moreover the torque range of x, y, and z direction is $30N \cdot m$. And high speed motorized spindle was selected to provide the rotary power of grinding tool. The motorized spindle can be adjusted the speed of main spindle according to the specific machining requirement. The output power of motorized spindle is $2.4KW$ and the maximum speed is $24000rpm$.

The workflow of grinding robot with force control is illustrated in Fig. 2. The force between grinding tool and workpiece is measured and by the force sensor while grinding. The data of grinding force is transmitted to controller, and the grinding force is keeping constant through the force-position control

This work was supported by Laboratory of Robotics and Intelligent Systems (CASQuanzhou) and Scientific and Technological Project of Quanzhou (No.2018C015).

Yinhui Xie, Jinxing Yang, Mingqi Feng, Weilong Huang and Jun Li* (corresponding author)* are with Quanzhou Institute of Equipment Manufacturing, Chinese Academy of Sciences, Quanzhou, China ($xyh1932@fjirsm.ac.cn$, $jxyang@fjirsm.ac.cn$, $mqfeng111@163.com$, $809388932@qq.com$, $junli@fjirsm.ac.cn$).

978-1-7281-6321-5/19//$31.00 ©2019 IEEE

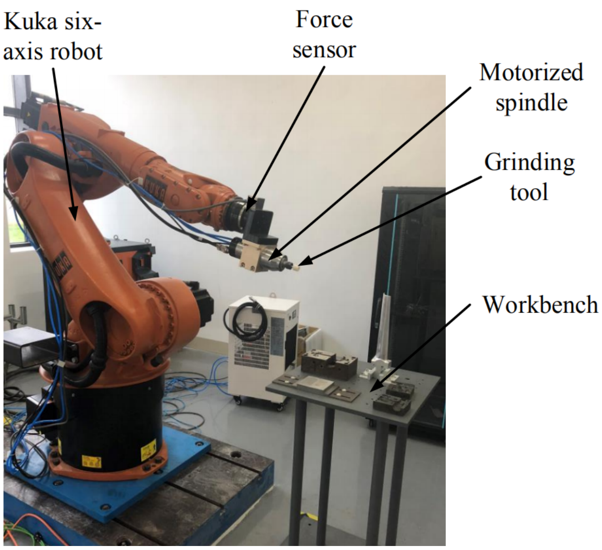


Fig. 1. The grinding robot system with force control

algorithm. Then the grinding tool is positioned accurately to grinding by six-axis robot.

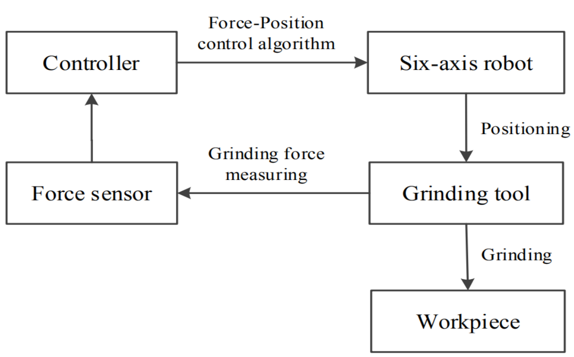


Fig. 2. The workflow of grinding robot with force control

III. The Path Planning Based on B-spline Curve

In the process of robot grinding, the main influencing factors of grinding force include speed of grinding tool, size of grinding particle and motion path of robot. Because the positioning of grinding tool is controlled by grinding robot directly, the size of the grinding force is influenced by the feed of grinding tool relative to workpiece. And there are many angular points in the motion path that will cause great fluctuations for the grinding force. Therefore, to keep the rationality of tool path is a prerequisite for the force-controlled grinding. In order to solve this problem, the tool path is interpolated to smooth by B-spline curve.

The B-spline curve is a series of curves which developed on the basis of Bezier curve. And the B-spline curve can overcome the inconvenience produced by the overall control of Bezier curve and make local adjustment without changing the shape of the whole path when dealing with the path smoothness [9, 10]. The B-spline curve can be classified into various types according to different classification criteria. According to t distribution of nodes, the B-spline curve can be divided into four types: uniform B-spline curve, quasi-uniform B-spline curve, general non-uniform curve and piecewise Bezier curve. It can also be divided into open curve and closed curve according to whether the first and last points are separated.

The B-spline curve is obtained by approximating polygon. The $n+1$ control points are given, and n times B-spline curve is expressed as

$$C(u) = \sum_{n}^{i=0} N_{i,p}(u) P_i, u \in [0,1] \tag{1}$$

where $N_{i,p}(u)$ is B-spline basis function.

$$N_{i,0}(u) = \begin{cases} 1, u = [u_i, u_{i+1}] \\ 0, otherwise \end{cases} \tag{2}$$

$$N_{i,p}(u) = \frac{u-u_i}{u_{i+p}-u_i} N_{i,p-1}(u) + \frac{u_{i+p+1}-u}{u_{i+p+1}-u_{i+1}} N_{i+1,p-1}(u) \tag{3}$$

where u is node, $U = [u_0, u_1, ..., u_{i+p+1}]$ is node vector. From the recurrence formula, the i-th B-spline $N_{i,p}(u)$ is determined by $p+2$ nodes. And the shape of B-spline curve is determined by control points and node vector. It can be seen that the definition of B-spline curve was still adopted the control vertices and independent of other vertices from Eq. 1. It overcomes the Bezier curve lacking local property and retains the characteristics of excellent control. Many properties of B-spline curve make B-Spline curves be widely used. It can be summarized as follows:

(1) Recursiveness, which can be indicated by the recursion formula.

(2) Normative,$\sum_{n}^{i=0} N_{i,p}(u) = 1$

(3) Property of local support,$N_{i,p}(u) \begin{Bmatrix} \geqslant 0 & u \in [u_i, u_{i+p+1}] \\ = 0 & else \end{Bmatrix}$, it can be seen from the formula that B-spline curve involves nonnegativity.

(4) Convex hull property. The convexity of B-spline curve is a union set of convex hull of several curve segment whose convex hull region is less than or equal to the convex hull region of Bessel curve defined by the same set of control vertices. And the b-spline curve is always within its convex hull. Convex hull property results that the p-th B-splines defined by these vertices degenerate to this point of coincidence when $p+1$ vertices overlap in order. And when $p+1$ vertices are collinear in order, the p-th B-spline curve defined by these vertices degenerates to a line segment.

(5) Geometric invariance and affine invariance. Because the actual track nodes are usually unevenly spaced, an inhomogeneous B-spline curve is used to calculate. The node vector definition of nonuniform B-spline basis is an arbitrarily distributed node vector $U = [u_0, u_1, ..., u_{i+p+1}]$ (where the sequence of nodes is non-recursive minus, both ends of the node repeatability $\leqslant p+1$, the inner node repeatability $\leqslant p$) [11,12] .

The properties above-mentioned make B-spline curve more applicable and flexible in curve fitting. Fig. 3 depicts the three-point fitting of B-spline curve. P_0, P_1 and P_2 are the control points. And the smoothing process of folding points can be achieved by B-spline curve fitting.

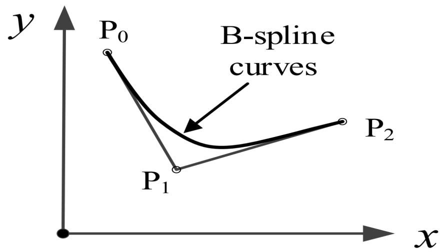


Fig. 3. The B-spline curve fitting

The B-spline curve is used to fit the motion path of end tool so as to achieve the purpose of folding point smoothing. The folding point smoothing can decrease the curvature of motion path at folding point effectively, and reduce the fluctuation of grinding force that caused by excessive change of path curvature.

IV. The Test Experiment of Grinding Force

To verify that the path based on B-spline curve can reduce the fluctuation of grinding force, two kinds of machining paths namely the general path and the path based on B-spline curve were set up. The same pressure was applied at workpiece surface with two kinds of machining paths in grinding process respectively, and the data of grinding force was collected through the force sensor. TABLE I shows the conditions of each grinding experiment. Where G represents the general path and B represents the path based on B-spline curve. Three control points were set for the path based on B-spline curve that are corresponding to the points of starting, contacting and finishing.

The grinding tool is a cylindrical nylon grinding head with a diameter of $35mm$, as shown in Fig. 4. The workpiece is a plane steel plate of $100mm{*}100mm{*}20mm$, and the material of workpiece is $45\#$ steel, as shown in Fig. 5. According to the conditions of each grinding experiment in TABLE I, six sets of experiments were carried out respectively, and the data of grinding force was collected by force sensor.

TABLE I
THE CONDITIONS OF EACH GRINDING EXPERIMENT

No.	Pressure (N)	Rotate speed (r/min)	Path
1	10	500	G
2		500	B
3		750	G
4		750	B
5		1250	G
6		1250	B

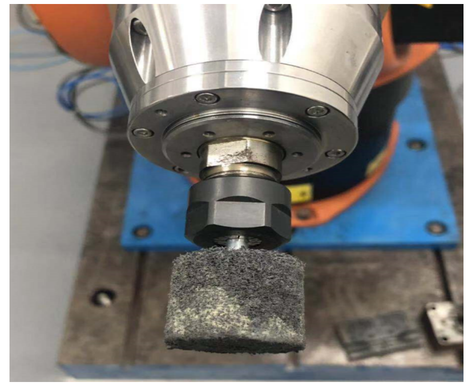


Fig. 4. The grinding tool (a cylindrical nylon grinding head)

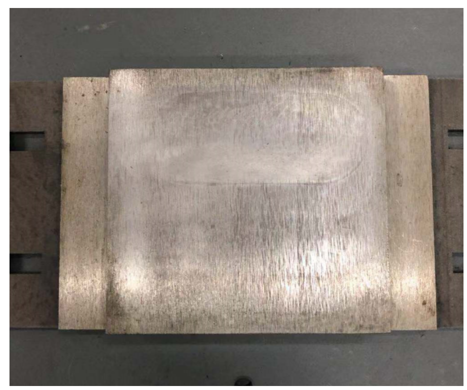
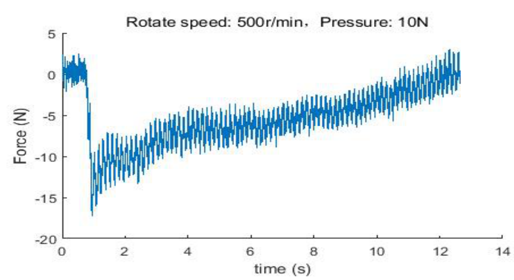
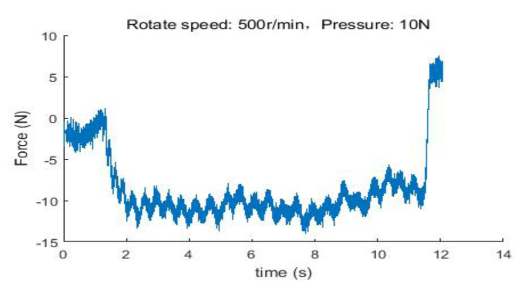


Fig. 5. The workpiece (a plane steel plate)

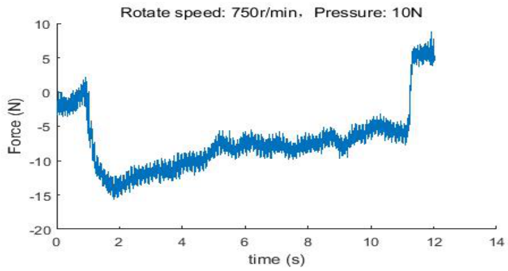


(a) the general path

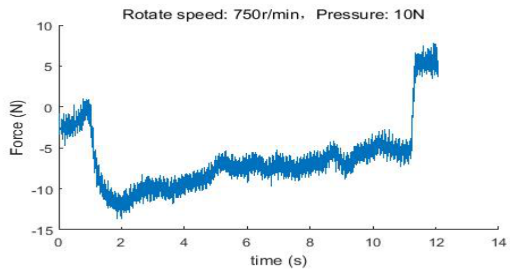


(b) the path based on B-spline curve

Fig. 6. The changes of grinding forces when rotate speed is 500 r/min

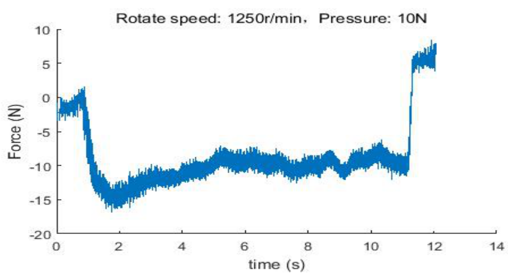


(a) the general path

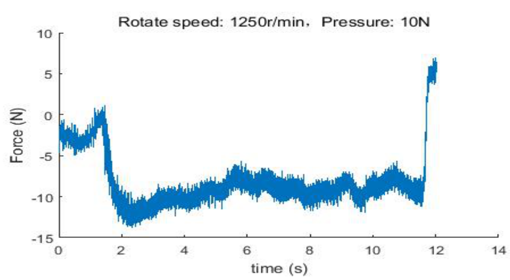


(b) the path based on B-spline curve

Fig. 7. The changes of grinding forces when rotate speed is 750 r/min



(a) the general path



(b) the path based on B-spline curve

Fig. 8. The changes of grinding forces when rotate speed is 1250 r/min

Fig. 6, Fig. 7 and Fig. 8 show the changes of grinding forces with the two paths in grinding process when rotate speeds are 500 r/min, 750 r/min and 1250 r/min respectively. When the grinding tool contacts the workpiece, the grinding force will suddenly increase. The path based on B-spline curve is made a change at contacting point relative to the general path. And the maximum pressure of the path based on B-spline curve in process of machining is smaller than that of the general path, as shown in TABLE . By comparing the changes of grinding forces with the two paths at same rotate speed, it can be clearly seen from the figures that the force change of the path based on B-spline curve is less fluctuation than that of the general path. In order to compare the dispersion degree of grinding forces with the two paths, the standard deviations of grinding forces were obtained by numerical calculation. As shown in Fig. 9, the standard deviation of the path based on B-spline curve was smaller than that of the general path when rotate speed is same. The experimental results verify that the path based on B-spline curve can effectively reduce the fluctuation and deviation of grinding force in machining process and provide a stable machining environment for the constant control of grinding force.

TABLE II
THE MAXIMUM PRESSURE OF EACH GRINDING EXPERIMENT

No.	Rotate speed (r/min)	Path	Maximum pressure (N)
1	500	G	-17.21
2	500	B	-13.98
3	750	G	-15.70
4	750	B	-13.69
5	1250	G	-16.88
6	1250	B	-13.82

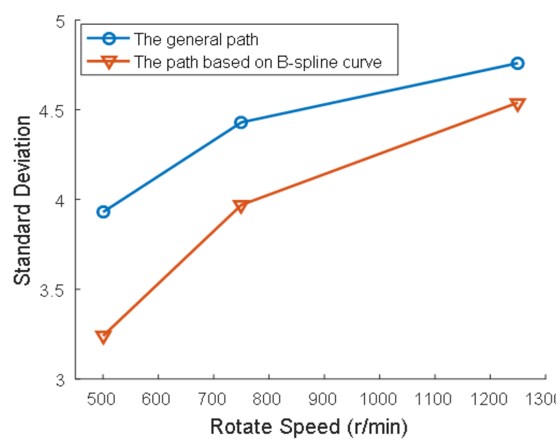


Fig. 9. The standard deviation of grinding forces

V. CONCLUSION

In this paper, a robotic path optimization method based on B-spline curve was proposed, which was applied to the grinding robot with force control to realize the stable control of grinding force. According to the given control points, the function model of B-spline curve was established to interpolate, and the path based on B-spline curve was fitted to achieve the goal of path smoothing. Then the experiments of grinding were carried out with three rotate speeds. The same workpiece was processed with the path based on B-spline curve and general path respectively, and the variation of grinding force was collected. The experimental results showed that the force change of the path based on B-spline curve was less fluctuation than that of the general path. Therefore, the path based on B-spline curve can effectively reduce the fluctuation and deviation of grinding force in machining process and provide a stable machining environment for realizing the constant control of grinding force. In the following studies, the force control algorithm will be added in the experiment to explore the influence of path on the stable control of grinding force.

ACKNOWLEDGMENT

This work was supported by Laboratory of Robotics and Intelligent Systems (CASQuanzhou) and Scientific and Technological Project of Quanzhou (No.2018C015).

REFERENCES

[1] Matthias Pischan. Deburring of Cross Holes in Titanium Using Industrial Robots[J]. Advanced Materials Research, 2013, 2570(769).

[2] Rui Feng Li, Development Strategy for China Industrial Robot[J], Aeronautical Manufacturing Technology, 2010, 9: 32-37.

[3] Fusheng Tan, Jingguo Ge. Research on Force-control-based Robotic Machining and its Package Implemenation[J], Journal of Shanghai Electric Technology, 2008(2):35-40, 48.

[4] Huapeng Du. Automatic Polishing on Titanium Alloy Parts Based on the Force/Position Control Method[D], Dalian University of Technology, 2014.

[5] Abd El Khalick Mohammad, Jie Hong, Danwei Wang. Design of a force-controlled end-effector with low-inertia effect for robotic polishing using macro-mini robot approach[J]. Robotics and Computer-Integrated Manufacturing, 2018(49), 54-65.

[6] Zhimin Rao, Bing Guo, Qingliang Zhao. Investigation of contact pressure and influence function model for soft wheel polishing[J]. Applied Optics, 2015, 54(27):8091-8099.

[7] Antonio Lopes, Fernando Almeida. A Force-impedance Controlled Industrial Robot Using an Active Robotic Auxiliary Device[J]. Robotics and Computer-Integrated Manufacturing, 2008(24)300-308.

[8] Yinhui Xie, Wenbin Zou, Yongtai Yang and Jun Li. Design of robotic end-effector for milling force control, IOP Conference Series: Materials Science and Engineering, 423(2018), 01203.

[9] Caiping Duan, Chao Liu, Qi Wang. Application of B-spline Theory to UAV Flight Track Smoothing[J]. Wireless Internet Technology, 2018(3):141-144.

[10] Taizhi Lu, Wu Zhou, Chunxia Zhao. Improved Visibility Graph Method Using Particle Swarm Optimization and B-Spline Curve for Path Planning[J]. Journal of Huaqiao University(Natural Science), 2018,38(1):103-108.

[11] Linfeng Li, Lei Ma. A Research on the Cubic Uniform B-spline Curve and Its Application on Trajectory Planning Algorithm of Industry Robot[J]. Science Technology and Engineering, 2013, 13(13):3621-3625+3646.

[12] Chengzhi Liu, Xuli Han, and Juncheng Li . Progressive-Iterative Approximation by Extension of Cubic Uniform B-spline Curves. Journal of Computer-Aided Design & Computer Graphics, 2019, 31(6):899-910.