A Path Planning Method for Robotic Belt Surface Grinding

WANG Wei, YUN Chao*

Robotics Institute, Beihang University, Beijing 100191, China

Received 24 September 2010; revised 25 November 2010; accepted 20 December 2010

Abstract

The flexible contact and machining with wide strip are two prominent advantages for the robotic belt grinding system, which can be widely used to improve the surface quality and machining efficiency while finishing the workpieces with sculptured surfaces. There lacks research on grinding path planning with the constraint of curvature. With complicated contact between the contact wheel and the workpiece, the grinding paths for robot can be obtained by the theory of contact kinematics. The grinding process must satisfy the universal demands of the belt grinding technologies, and the most important thing is to make the contact wheel conform to the local geometrical features on the contact area. For the local surfaces with small curvature, the curve length between the neighboring cutting locations becomes longer to ensure processing efficiency. Otherwise, for the local areas with large curvature, the curve length becomes shorter to ensure machining accuracy. A series of planes are created to intersect with the target surface to be ground, and the corresponding sectional profile curves are obtained. For each curve, the curve length between the neighboring cutting points is optimized by inserting a cutter location at the local area with large curvatures. A method of generating the grinding paths including curve length spacing optimization is set up. The validity is completely approved by the off-line simulation, and during the grinding experiments with the method, the quality of surface is improved. The path planning method provides a theoretical support for the smooth and accuracy path of robotic surface grinding.

Keywords: robot programming; path planning; belt abrasive; curve length optimization; curvature

1. Introduction

The automatic milling for workpiece with free surfaces has been generally achieved by the computer numerical control (CNC) and other new manufacturing technologies, but the finishing process still depends on experienced manual work. With the rapid development of industry, the complex surface of turbine blades, artificial joints with titanium alloy, sanitary ware, digital appliances and sport equipment turn to be more complex and requiring increasingly high precision, which make the traditional manual machining boring and inefficient. Manual process requires more time and cost, and it is inefficient and difficult to obtain consistent processing quality, which prevents the process of technological progress. The robotic belt grinding system achieves a high degree of accuracy and material removal rate in the parts with complex geometries, and presents a significant advance in the state of the arts in surface grinding. Robotic grinding path generation becomes one of the most important issues to finish the workpiece with complex surfaces.

1.1. Related work

An experienced worker takes several hours to complete the polishing task of a single turbine blade, and the rejection rate is as high as 15%. Manual grinding operation is always completed under poor working conditions and high laboring intensity, which seriously threaten the health of the operator. Robotic grinding system consisting of robot system, belt grinder, measurement, calibration system and other major subsystems, can achieve the automation of finishing process of workpiece with complex geometries, greatly shorten...
the processing cycle, improve processing efficiency, and ensure the consistency of processing quality\textsuperscript{[1-3]}. Robotic belt grinding can be used to improve the surface quality, part remanufacturing and part shaping\textsuperscript{[3-4]}. Robotic belt grinding system with potential widespread applications will replace manual grinding experience.

The finite element model (FEM) between wheel and the local elastic contact wheel using the local surface curvature as the geometric boundary conditions was established, and the depth of cut on the workpiece was further studied and predicted\textsuperscript{[5-6]}. Ma, et al. pointed out that the axis of the contact wheel must coincide with the principal axis of the normal curvature to achieve the maximum cutting strip\textsuperscript{[7]}. While the movement of the principal axis of the normal curvature to achieve that the axis of the contact wheel must coincide with the principal axis of the normal curvature to achieve the maximum cutting strip\textsuperscript{[7]}. The results are finally applied to practical processing. Shi, et al. considered the curvature features of three different shapes of the contact wheel, and proposed the control method of the sixth axis by the principles of non-interference, effective space and maximum cutting strip\textsuperscript{[8]}. Huang, et al. presented a high precision processing methods of free form surface, established the six-axis grinding and polishing system, which provided a basis for a reasonable turbine blade polishing process parameters\textsuperscript{[9]}. To understand the way of the abrasive grains removing the material in the belt and workpiece interface, a method was set up based on the provided important and essential information including the normal load distribution, the local coefficient of friction\textsuperscript{[10]}

A new model based on a neural network technique was developed to replace the FEM to calculate the force distribution, which approximated the FEM model with an acceptable tolerance but can be executed much faster than FEM\textsuperscript{[11]}. A dual drive curve tool path planning method was proposed as the tool was positioned along the dual drive curve under the conditions of tool path smoothness\textsuperscript{[12]}. The concept of time-minimal tool paths was introduced, and a solution to the problem of optimal tool path generation was given in the form of an integral equation\textsuperscript{[13]}. A machining potential field method which was constructed by considering both the part geometry and the cutter geometry to represent the machining-oriented information on the part surface, was presented to generate tool paths for multi-axis sculptured surface machining\textsuperscript{[14]}. New algorithms for automatic tool path generation for five-axis filleted end mill finish-surface machining were presented for determining tool forward step and tool path step-over that produce a grind-free surface\textsuperscript{[15]}. A special software was developed to plan cutting path for ruled surface impellers, and an approximation algorithm to generate cutting path for machining integral ruled surface impellers was proposed\textsuperscript{[16]}

1.2. Motivation

The previous studies regard the normal vector as a contact geometric constraint and calculate the distribution of contact force. Two principal curvature axes should be coincided with the feed direction and the direction of contact wheel axis, and the wide-strip processing can be achieved. However, the technical requirements of normal curvature for the grinding path have not yet been deeply researched. On a grinding path composed of a series of discrete cutter locations, the curve between two neighboring cutter locations is always interpolated by the line or circular arc. During the grinding process, the density of cutter locations is improved dramatically by manual experience to narrow the curve length. It avoids the over-cut processing, but it also leads to inefficient processing. Curvature is the bending quantitative indicators measuring the path curve in the normally intersecting plane, so the curve length between adjacent cutter locations should be narrowed for the contact area with a large curvature. On the contrary, it should be increased.

The layout of a robotic belt grinding system is described in Section 2. The curve length optimization algorithm for free surface grinding can be found in Section 3. In Section 4, the effectiveness of the algorithm is verified by the simulation and grinding experiments. The last section presents the conclusion.

2. A Robotic Belt Grinding Workcell

A typical robotic belt grinding system can be shown in Fig. 1. With the PPPRRR serial spatial kinematical chain, the grinding robot has a wide space of dexterity and high contact stiffness. The workpiece is picked by the end, while the belt grinder stays at a given pose with respect to the base of the robot. As the first three joints are translational, the closed solution of the inverse kinematics exists.

![Fig. 1 Robotic belt grinding system.](image)

The kinematical schematics can be shown in Fig. 2. The technical parameters of grinding robot and belt grinder are given in Table 1 and Table 2. The robotic belt grinding system is widely used to grind the sculptured surfaces and the grinding paths are generated by the off-line planning method.
Fig. 2 Schematics of robotic belt grinding chain.

Table 1 Parameters of grinding robot

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint workspace</td>
<td>X: 400 mm, Y: 400 mm,</td>
</tr>
<tr>
<td></td>
<td>Z: 500 mm, α: 360°,</td>
</tr>
<tr>
<td></td>
<td>β: 360°, γ: 360°</td>
</tr>
<tr>
<td>Load/N</td>
<td>400</td>
</tr>
<tr>
<td>Maximum speed/(mm·s⁻¹)</td>
<td>500</td>
</tr>
<tr>
<td>Repeatability/mm</td>
<td>±0.02</td>
</tr>
<tr>
<td>Capacity/kW</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 2 Parameters of belt grinder

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range of contact force/N</td>
<td>50-300</td>
</tr>
<tr>
<td>Accuracy of force control/N</td>
<td>±10</td>
</tr>
<tr>
<td>Adjusting time/ms</td>
<td>25</td>
</tr>
<tr>
<td>Belt speed/(m·s⁻¹)</td>
<td>0.28</td>
</tr>
<tr>
<td>Type of contact wheel</td>
<td>Cylinder</td>
</tr>
<tr>
<td>Diameter of contact wheel/mm</td>
<td>50-150</td>
</tr>
<tr>
<td>Width of contact wheel/mm</td>
<td>20-50</td>
</tr>
<tr>
<td>Belt length/mm</td>
<td>3350</td>
</tr>
<tr>
<td>Capacity of spindle/kW</td>
<td>3.7</td>
</tr>
</tbody>
</table>

3. Optimization Algorithm to Generate Grinding Paths

3.1. Problem description

The complex geometries are mathematically defined by parametric forms such as the well-known Bézier, B-spline and non-uniform rational B-spline (NURBS) types [17]. The cutter-contact points generated by the method of constant parametric line, will not be uniformed. A series of planes are used to insert with the target surface, and the corresponding sectional profile will be obtained. The contact wheel will move along the curves smoothly to cut the metal materials. Without the consideration of the normal curvature, neither of the method will be possible to create enough smooth paths.

As the dexterity of the grinding robot and flexible contact between the contact and workpiece, robotic belt grinding can generally be used to perform the grinding task as the human labor does. Human experience and analysis of the geometrical construction are combined to direct the path generation procedures. Before the robot is employed to grind the complex surfaces, the manual grinding procedures must be observed and recorded. Then the feed directions and style of the arrangement of tool path will be obtained to get the cutter location files. If the dexterity of robotic system has not passed the evaluation, some degrees of freedom will be added to the grinding kinematic chain for the current grinding task. For the grinding task of sculptured surface, the tool paths generated by the methods of constant parametric lines and sectional profiles will not be applicable.

In the robotic belt grinding systems, flexible contact between the contact wheel and the workpiece exists, and a certain amount of materials will be cut by the floating supporting force and high belt speed. The contact stiffness of the robotic belt grinding system turns to be very low, so the cut depth in fact is always less than the feeding depth. It is obvious that the effective method for decreasing the linear approximation error is to reduce the step-forward distance and increase the number of cutter locations [18].

The curve length of the neighboring cutter contact must be optimized with the constraint of the local normal curvatures to guarantee that the continuous cutting depth. Firstly, the cutter location files will be obtained by the differential formulations, then the inverse kinematics will be applied to calculating the robotic joint configurations, which can be connected by movement instructions to form a complete robotic grinding path. The procedures of path generation can be explained as follows:

(1) Take the manual procedure as the references to obtain the sectional profile of the grinding paths.

(2) Estimate the curve length of the profile to figure out the corresponding intervals of the grinding cutter contact point, and divide the parametric domain.

(3) Calculate the coordinates and curvature of the cutter location on the grinding curve. If the curvature turns to be large enough, the interval of neighboring cutter locations on the parametric domain must be narrowed in half by inserting a middle cutter location.

(4) Calculate the parametric coordinates and local contact frames of the grinding cutter contact point by the algorithms of surface approaching to obtain the sequences of the cutter locations. To obtain the maximum grinding strip width, the X-axis of the local frame is superposed with the minimum principal axis of local curvature.

3.2. Path optimization

3.2.1. Geometrical deduction

The definition of NURBS curve is
where \( u \) and \( v \) are the independent variables, \( W_{i,j} \) is the weight vector of control points \( P_{i,j} \), \( n \) the number of control points in \( u \) direction, \( p \) the B-spline order in \( u \) direction, \( m \) the number of control point in \( v \) direction, and \( q \) the B-spline order in \( v \) direction.

Assume that both \( S_u(u,v) \) and \( S_v(u,v) \) are tangential vectors of the surface \( S \) at \((u,v)\). The normal vector at \((u,v)\) is

\[ N(u,v) = S_u(u,v) \times S_v(u,v) \]  

Let us define the equation as

\[ r(u,v) = S(u,v) - P \]  

which refers to the vector from \( S(u,v) \) to a certain position \( P \).

To obtain the coordinates \((u,v)\) satisfying that

\[
\begin{align*}
&f(u,v) = r(u,v) \cdot S_u(u,v) = 0 \\
g(u,v) = r(u,v) \cdot S_v(u,v) = 0 
\end{align*}
\]

Newton-Rupson method will be used to calculate the \((u,v)\), which is the parametric coordinates of the cutter location. The convergent conditions of Eq. (12) and Eq. (13) are

\[
\begin{align*}
&|f(u,v)| = |S_u(u,v) - P| \leq \varepsilon_1 \\
&|g(u,v)| = |S_v(u,v)| \leq \varepsilon_2 \\
&|S_u(u,v) \cdot (S_v(u,v) - P)| \leq \varepsilon_3 \\
&|S_v(u,v) \cdot (S_u(u,v) - P)| \leq \varepsilon_4 \\
&|S_u(u,v) \cdot S_v(u,v)| \leq \varepsilon_5 \\
\end{align*}
\]

where both \( \varepsilon_1 \) and \( \varepsilon_2 \) are minimums.

3.2.2. Algorithm of curve optimization

Generally, the curve length between the neighboring cutter locations on the target surface must be 1-2 mm by the robotic belt grinding system. The control polygon of the sectional profile curve can be set up, and the accurate calculation of curve length is time-consuming and unnecessary. Depending on the concave hull property of the NURBS curve, the sectional profile curve will lie inside its control polygon, so the circumference length of the control polygon can be considered as the curve length. The algorithm can be further explained as follows:

1. The target surface \( S \), the width \( b \), the diameter \( d \) of the contact wheel and the allowed curve length \( s_{\text{max}} \) of the neighboring cutter locations are given.

2. The intersecting plane \( PL_i \) will be created to insert with the target surface \( S \), where the distance of the
neighboring plane is less than \( b \).

(3) The sectional profile curve \( C_i \) between the \( PL_i \) and \( S \) will be converted into a NURBS curve.

(4) When the NURBS curve is parsed, the control polygon will be obtained and the curve length \( l \) can be estimated by Eq. (10). Assuming that \( h = l / s_{\text{max}} \), a chain of equal-spaced parameters will be set up, \( \{ u_j | u_j = u_i + (u_{i+1} - u_i) / h \} \), \( u_i \) is the low limitation, \( u_a \) is the upper limitation of the parametric domain, and \( j \leq h \). Let \( j = 0 \).

(5) Using Eq.(9), the curvature \( k_j \) of \( C_i \) on parameter coordinates \( u_j \) can be obtained.

(6) If \( 1/k_j < d/4 \), go to (9); else go to (7).

(7) If \( 1/k_j < d/2 \), go to (8); else a new contact wheel with smaller diameter will be substituted and return.

(8) If \( j \) points to the head of the chain, a new node \( (u_j + u_{j+1}) / 2 \) will be inserted into the chain between nodes 0 and 1, \( j++ \); else, a new node \( (u_j + u_{j-1}) / 2 \) will be inserted into the chain between nodes \( j \) and \( j-1 \).

(9) If the traversal is not completed, \( j++ \) and go to (5); else, using Eq. (1), the chain of cutter contact point \( T_j \) will be obtained, then go to (10).

(10) As all the cutter contact point of \( T_j \) are on the surface \( S \), by Eq. (13), the parametric coordinates \( (s_j, t_j) \) of cutter location \( T_j \) can be calculated.

(11) By Eq. (12), the normal vector \( N \) at \( (s_i, t_i) \) can be obtained.

(12) Set \( T_i \) as the origin, \( N \) the Z-axis, and the feeding direction as the X-axis, then the local contact frames of cutter locations will be obtained. Then return.

The algorithm can also be explained in Fig. 3. By inverse kinematics of grinding robots, the grinding paths can be obtained. By the Newton’s iterative procedure above, a list of discrete robot configurations in correspondence with the list of targets can be calculated. As the interval between the neighboring cutter contact points in the same grinding path is small enough, and the corresponding neighboring configurations of the grinding robot are interpolated by the cubic spline method, the end can pass the cutter contact points smoothly to achieve the robot control programs in the joint space.

Fig. 3 Flow chart of path generation.

4. Simulation and Experiments

4.1. Simulation by off-line programming system

The off-line programming system of robotic belt grinding system is used to help the programmer generate the programs of grinding paths, whose core is the graphic simulation platform. The three modules of kinematics modeling, grinding features and path generation are the base of the graphic simulation. The off-line programming system established can be shown in Fig. 4. The kinematic simulation of grinding process can be seen in Fig. 5. For a typical grinding task, a curve with uniformed curvatures is shown in Fig. 6. The path by the optimizing method in Fig. 7(a) includes more middle cutter locations at the local contact area with large curvatures than the contrast path without optimization in Fig. 7(b).

Fig. 4 Off-line programming platform.
4.2. Grinding systems

Under the same grinding parameters, a group of contrastive belt grinding is done.

If the constant parametric line method is used to generate the grinding paths, the surface ground can be seen in Fig. 8(a). The surface grinding quality can be seen in Fig. 8(b) if the algorithm based on the curve interval optimization is used. The smoothness and accuracy with optimization turn to be much better than those without optimization.

5. Conclusions

(1) A belt grinding robot workcell and off-line simulation platform are forwarded.

(2) Based on the classical sectional profile method, a new algorithm by the optimization curve interval is advanced to generate more cutter locations at the local surface with large curvature and less cutter locations at the local surface with small curvature. With the optimization algorithm, the accuracy and efficiency of the robotic belt grinding are integrated. Firstly, by the concave hull property, the curve length of the sectional profile can be estimated and the number of the curve intervals can be obtained. Secondly, the parametric domain of the sectional profile is divided into equal intervals, and parametric coordinates and position of the target points can be achieved. Thirdly, the curvature is computed point by point. If the magnitude of the curvature exceeds the given value, a middle cutter location will be inserted before the current cutter location. Finally, with the surface inversion, the cutter locations of the new grinding paths can be obtained.

(3) The algorithm is verified not only in the off-line simulation but also in the robotic belt grinding systems.

References


WANG Wei et al. / Chinese Journal of Aeronautics 24(2011) 520-526


Biographies:

WANG Wei  Born in 1982, he is currently doing his post doctoral research in Robotics Institute, Beihang University. He received his Ph.D. degree from Beihang University in 2009. His main research interests include automation in logistics and robotic manufacturing.
E-mail: jwwx@me.buaa.edu.cn

YUN Chao  Born in 1952, he is currently a professor in Robotics Institute, Beihang University. He received his Ph.D. degree from Tianjin University in 1994. His main research interests include robotics and advanced dynamics.
E-mail: cyun18@vip.sina.com