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A High-speed and Smooth Feedrate Planning Algorithm for Small Line Segments Based on B-spline Curve

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Abstract. The machining feedrate, especially for the tool path presented by the small line segments, is low and fluctuates frequently when the tool path is too short, and this phenomenon increases the machining time and reduces the machining quality. To resolve these problems, a feedrate planning algorithm for small line segments based on B-spline curve is proposed. Firstly, the tool path is smoothed by B-spline curve at the junction of adjacent small line segments to increase the machining velocity and improve the machining quality. Secondly, the tool path is divided into different velocity planning intervals according to the curvature, and the velocity planning intervals are merged into velocity planning units to reduce velocity fluctuation and improve the machining quality. Thirdly, a high-speed and smooth feedrate planning algorithm is proposed to further improve the machining efficiency. Through keeping the acceleration of the velocity profile non-zero at the corners of the tool path, the algorithm can efficiently reduce the machining time. The experiments demonstrate that the proposed algorithm is able to achieve high machining speed and generate fine surface quality.

Keywords: B-spline transition, look-ahead, surface quality, velocity planning

1 Introduction

To machine complex surface of special parts such as dies and automobile components, CAD/CAM systems generate numerical control programs made up of small line segments [1-2]. Since small line segments are not continuous, the motion of the machine tools has to stop at the junction of adjacent segments, leading elongated machining time and rough surface finishes [3]. To realize a continuous transition between consecutive linear segments, circle transition method [4-5] is adopted by most conventional computer numerical control (CNC) system, but this method only delivers velocity continuous (C1) motion transition, while B-spline, having acceleration continuous [6-7] (C2), is adopted by step-NC [8] as the standard data format for CAD/CAM systems and CNC system and used in high-end CNC system.

The smoothed tool path is divided into independent velocity planning units based on the small line segments during the process of machining. As the machining velocity plays an important role in the smoothness, accuracy and stability of the machining process, it is critical to develop an efficient and applicable velocity planning method. A lot of velocity planning methods have been proposed by researchers of industry and academia. The linear acceleration/deceleration (ACC/DEC) algorithm [9-10] and the exponential ACC/DEC algorithm [11] are commonly used in conventional CNC system, but the feedrate profile is not smooth and the sudden change of ACC/DEC induces the vibration of machine tools,

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reducing the machining quality and machining efficiency. To reduce the machining time, adaptive velocity planning method was proposed [12-13], but the acceleration is not continuous and the chord error cannot be kept under the maximum value allowed by the system. To get continuous ACC/DEC profiles, the velocity planning method with limited jerk have been employed by industry [4, 14], but the detailed technology was not given, while lots of research work have been done by many researchers. Du et al [15] introduced a velocity planning method with limited jerk and compensated round-off error for NURBS curves, Dong et al and Tajima et al gave an adaptive and jerk-limited velocity planning method [16-17]. However, the machining capacity of the machining tools was not fully used as these methods were not based on the maximum jerk values of different axis and the algorithm to avoid the phenomenon of low-speed region in the adaptive interpolation process was not given. To overcome these shortages, an axial-velocity planning method was employed [18], while the algorithm to determine the starting point of adaptive interpolation areas was proposed [19] to avoid the phenomenon of low-speed region. To get more smooth velocity profiles, Fan et al. [20] proposed a velocity planning method which has continuous jerk profiles and consists of 15 sections. However, the computation load of this method is too heavy making the method cannot be used in the real-time interpolation process, and none of these methods mentioned above considered the velocity fluctuation caused by the tool path when the small line segments are very short. When the segments are very short, the time taken by the ACC/DEC process of planned velocity profiles for each segments is short, making the machining velocity generates frequent fluctuations, while machining time becomes longer and the machining quality becomes worse. In order to resolve these problems, Dong et al. [21] adopted TFF method to produce smooth velocity, but the tool path is not smoothed and the output of velocity would be larger than the maximum allowable velocity of some small line segments, which would affect the machining quality and machining accuracy. Furthermore, all the velocity planning methods [9-21] schedule the velocity planning profiles only base on the independent velocity planning units, so the ACC/DEC values at the junction of adjoin units are all zero, elongating the machining time.

To generate smooth velocity profiles with limited-jerk for small line segments, this paper proposes a high-speed and smooth feedrate planning algorithm based on B-spline curve. The B-spline curve is used to smooth the corners of the small line segments, which ensures that the tool path has continuous curvature and the jerk-limited velocity planning method can be used based on the geometric features of the generated tool path. To reduce the velocity fluctuation caused by the short velocity planning units, a velocity planning unit consolidation method is given to reduce the number of the units and generate longer units. Meanwhile, in order to reduce the machining time, a new velocity planning method with no-zero ACC/DEC value at the connection of adjoin velocity planning units is given. The proposed method can reduce the fluctuation of ACC/DEC profiles and the machining time. Furthermore, combined with the velocity planning unit consolidation method, the new velocity planning method can improve the machining efficiency and generate better machining quality.

The paper is structured as follows: section 2 uses B-spline curve to smooth the tool path and divides the tool path into different velocity planning units, while the new velocity planning units are generated based on the unit consolidation method. Section 3 proposes a new velocity planning method, and the ACC/DEC is set to be non-zero at the junction of adjoin units to improve the machining efficiency. In section 4, experiments are carried out to test the performance of the algorithm. Section 5 concludes the paper.

2 Corner Transition and Velocity Planning Intervals Division

2.1 The Transition Model

The tool path described by the small-line segments needs to be smoothed by B-spline curve, and the formula of the B-spline curve is shown as follows [7]:

$$C(u) = \sum_{i=0}^{4} N_{i3}(u) Pt_i \quad \textbf{(1)}$$

Where Pt_i and $N_{i,3}(u)$ stand for the control points and B-spline basis functions respectively, and the knot vector is $U = \begin{bmatrix} 0 & 0 & 0 & 0 & 0.5 & 1 & 1 & 1 & 1 \end{bmatrix}$.

The *pth* degree B-spline basis functions are recursively defined as follows [20]:

$$N_{i,\mathrm{p}}(u)=\begin{cases}1 & if\ u_i \le u < u_{i+1}\\ 0 & otherwise\end{cases}$$

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

As shown in Fig. 1, control points of the B-spline can be calculated by:

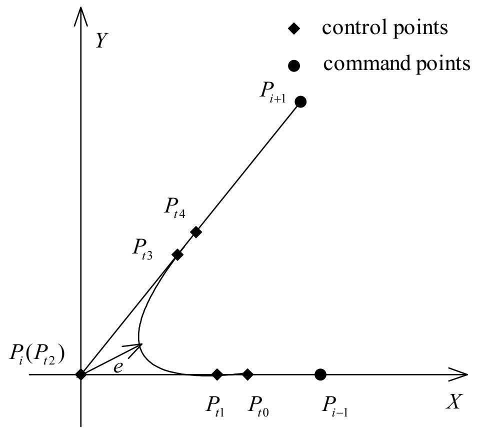


Fig. 1. The B-spline transition curve

$$Pt_1=\frac{2e(\mathrm{P}_{i-1}-\mathrm{P}_i)}{\cos(\alpha/2)\left|\mathrm{P}_{i-1}-\mathrm{P}_i\right|}+Pt_2 \tag{2}$$

$$Pt_0=\frac{2.8e(\mathrm{P}_{i-1}-\mathrm{P}_i)}{\cos(\alpha/2)\left|\mathrm{P}_{i-1}-\mathrm{P}_i\right|}+Pt_2 \tag{3}$$

Where e and α are the maximum contour error and the corner angle of the tool path respectively, while the ratio between the lengths of $\left|P_{t2}P_{t4}\right|$ and $\left|P_{t2}P_{t3}\right|$ is set to be 1.4 by Pateloup et al [22] and adopted in commercial CNC system [23].

2.2 Threshold Velocity

The threshold velocity is defined as the maximum velocity allowed by the transition B-spline curve. According to Eq. (1), the function value and derivative values of the transition curve where u=0.5 can be expressed as:

$$\begin{cases}C(0.5)=\frac{1}{4}P_1+\frac{1}{2}P_2+\frac{1}{4}P_3\\ C'(0.5)=-\frac{3}{2}P_1+\frac{3}{2}P_3\\ C^2(0.5)=6P_1-12P_2+6P_3\end{cases} \tag{4}$$

Then, the curvature of B-spline where u=0.5 can be calculated, and the threshold velocity can be gotten by Eq. (5), where e stands for the maximum contour error tolerance allowed by the system.

$$v=\frac{2}{T}\sqrt{\frac{2el_1}{c_1}-e^2} \tag{5}$$

Where $c_1 = \dfrac{4\cos\frac{\alpha}{2}}{3\sin^2\frac{\alpha}{2}}$, and l_1 is the length of vector $\overrightarrow{P_{t2}P_{t4}}$.

In Fig. 1, the line between P_{t2} and P_{t4} is called transition line, the length of vector $\overrightarrow{P_{t2}P_{t4}}$ is called transition length of the corner. In order to avoid intersection of adjacent transition curves, the length of transition line is set as follows:

$$l_i = \min(L_{P_iP_{i-1}}/2, L_{P_iP_{i+1}}/2) \tag{6}$$

Before actual machining, the tool path needs to be divided into different velocity planning units according to the maximum allowable velocity. If the unit is too short, the machining velocity would fluctuate frequently which would cause bad machining quality. In order to avoid this phenomenon, the short velocity planning units is merged and regarded as a single velocity planning unit, the formula used to generate new planning units is shown as follows:

$$\frac{\left|v_{threshold\_i} - v_{threshold\_i-1}\right|}{\frac{1}{n}\sum_{j=i+1-n}^{i}\left|v_{threshold\_j} - v_{threshold\_j-1}\right|} \le rate_v \tag{7}$$

Where $v_{threshold\_i}$ is the threshold velocity, and $rate_v$ is the system parameter which stands for the maximum velocity fluctuation rate allowed by the system. In the merged velocity planning unit, the new threshold velocity is set as $\min(v_{threshold\_j}, v_{threshold\_j+1}, \cdots, v_{threshold\_j+N})$, while the new length is set as $\sum_{i=j}^{j+n} s_i$.

3 Smooth Feedrate Planning

3.1 Look-ahead Algorithm

The machining velocity of the machine tools has an important pact on the machining quality and machining efficiency. To reduce machining time and the shock of the cutter during the machining process, the algorithm proposed in this paper uses the look-ahead method to plan the velocity profiles. The look-ahead method can generate smooth velocity profiles through the forward planning process and the backward planning process, and the parameters of the look-ahead window, such as the size of the window, are set by the CNC system.

In the velocity planning process based on the look-ahead method, the backward planning process is adopted to calculate the maximum velocity allowed by the system for the current velocity planning unit. As shown in Fig. 2, the size of look-ahead window is set as N.

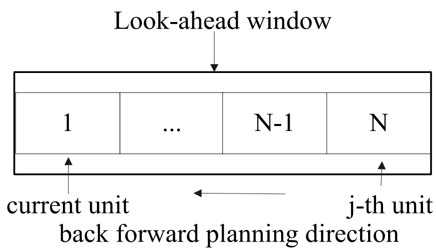


Fig. 2. The look-ahead window

The parameters $P(j) \rightarrow s$ and $P(j) \rightarrow V_{\max}$ are the length and the maximum end velocity of the jth velocity planning unit respectively. The steps of the backward velocity planning process are shown as follows:

(1) Calculate the value of V_{end}, which stands for the maximum velocity that can be reached during the machining process of the jth velocity planning unit.

(2) Let $vs = \min(P(j) \to V_{\max}, V_{end})$.

(3) Let $j = j-1$, if $j > 1$, return to step (1), else

(4) The maximum allowable end velocity of current planning unit is vs.

After the backward planning process, the forward planning process based on the bell-shaped ACC/DEC method is executed to generate the kinematic profiles for the current planning unit, including velocity profile, acceleration profile and jerk velocity profile.

3.2 Smooth Feedrate Planning Algorithm

In order to generate smooth machining velocity, the bell-shaped ACC/DEC method illustrated in Fig. 3 is adopted. The acceleration profile can be gotten by Eq. (8), while the corresponding machining distance profile can be described by Eq. (9).

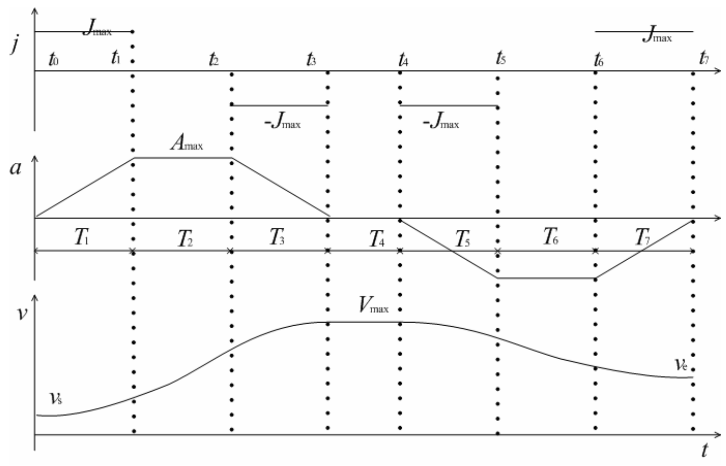


Fig. 3. The kinematic profiles

$$a(t) = \begin{cases} J_{\max} t, 0 \le t < t_1 \\ J_{\max} t_1, t_1 \le t < t_2 \\ J_{\max} t_1 - J_{\max}(t - t_2), t_2 \le t < t_3 \\ 0, t_3 \le t < t_4 \\ -J_{\max}(t - t_4), t_4 \le t < t_5 \\ -J_{\max}(t_5 - t_4), t_5 \le t < t_6 \\ -J_{\max}(t_5 - t_4) + J_{\max}(t - t_6), t_6 \le t < t_7 \end{cases} \tag{8}$$

$$s(t) = \begin{cases} v_s t + \frac{1}{6} J_{\max} t^3, 0 \le t < t_1, s_1 = v_s t_1 + \frac{1}{6} J_{\max} t_1^3 \\ s_1 + v_1(t - t_1) + \frac{1}{2} A'_{\max\_1}(t - t_1)^2, t_1 \le t < t_2, s_2 = s_1 + v_1(t_2 - t_1) + \frac{1}{2} A'_{\max\_1}(t_2 - t_1)^2 \\ s_2 + v_2(t - t_2) + \frac{1}{2} A'_{\max\_1}(t - t_2)^2 - \frac{1}{6} J_{\max}(t - t_2)^3, t_2 \le t < t_3 \\ s_3 + v_3(t - t_3), t_3 \le t < t_4, s_3 = s_2 + v_2(t_3 - t_2) + \frac{1}{2} A'_{\max\_1}(t_3 - t_2)^2 - \frac{1}{6} J_{\max}(t_3 - t_2)^3 \\ s_4 + v_4(t - t_4) - \frac{1}{6} J_{\max}(t - t_4)^3 \quad, t_4 \le t < t_5, s_4 = s_3 + v_3(t_4 - t_3) \\ s_5 + v_5(t - t_5) - \frac{1}{2} A'_{\max\_2}(t - t_5)^2, t_5 \le t < t_6, s_5 = s_4 + v_4(t_5 - t_4) - \frac{1}{6} J_{\max}(t_5 - t_4)^3 \\ s_6 + v_6(t - t_6) - \frac{1}{2} A'_{\max\_2}(t - t_6)^2 + \frac{1}{6} J_{\max}(t - t_6)^3, t_6 \le t < t_7, s_6 = s_5 + v_5(t_6 - t_5) - \frac{1}{2} A'_{\max\_2}(t_6 - t_5)^2 \end{cases} \tag{9}$$

The bell-shaped ACC/DEC method called traditional method in this paper can generate smooth velocity, but not make full use of the capacity of the machining tools, so a new modified method is proposed.

As shown in Fig. 4, the tool path presented by the command points $p_x(x = i-1, i, \cdots j)$ is smoothed by B-spline curve, and two velocity planning units are given by threshold points $P_{threshold\_x}(x = i, i+1, i+2)$, then the modified velocity planning method is shown as Fig. 5, and the steps of the algorithm are given as follows:

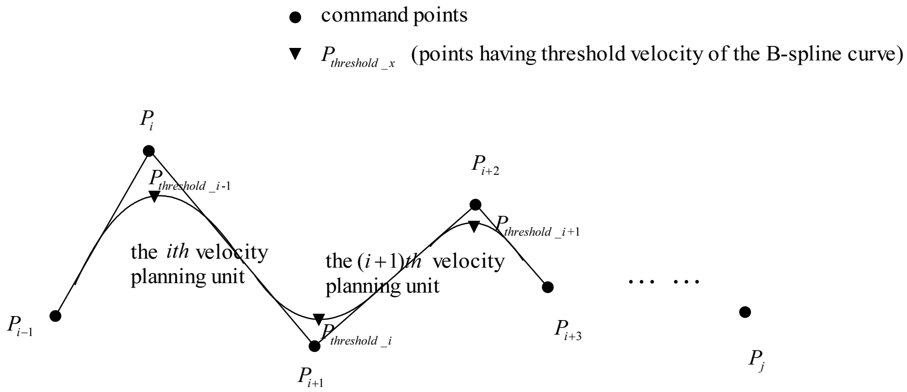


Fig. 4. Partial tool path

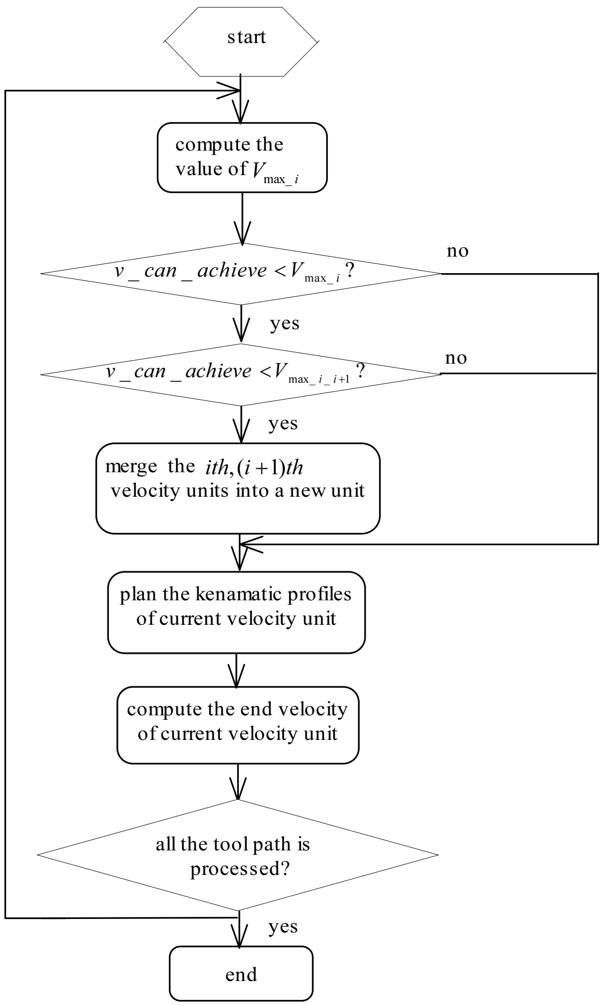


Fig. 5. The flowchart of the algorithm

(1) For every velocity planning unit, the first step before velocity planning is to determine the maximum velocity that is allowed which can be expressed as follows:

$$V_{\max\_i} = \min(V_{threshold\_i}, V_{look\_ahead\_i}, V_{command}) \quad \textbf{(10)}$$

The parameters in the Eq. (10) are described as follows:

$V_{threshold\_i}$: the maximum velocity on the point $P_{threshold\_i}$.

$P_{threshold\_i}$: the maximum velocity determined by the look-ahead method on the point $P_{threshold\_i}$ in the current period.

$V_{command}$: the maximum velocity allowed by the CNC codes.

$$V_{\max\_i\_i+1} = \min(V_{threshold\_i+1}, V_{look\_ahead\_i\_i+1}, V_{command}) \quad \textbf{(11)}$$

(2) Suppose the start machining velocity of the ith velocity planning unit is vs_i , the start acceleration is as_i , and the velocity that can be achieved on the point $P_{threshold\_i}$ could be calculated by the bell-shaped ACC/DEC method is named $v\_can\_achieve$. If $v\_can\_achieve$ < $V_{\max\_i}$, it means the machining capacity on the current tool path is not fully used. The value $V_{\max\_i+1}$ can be calculated as follows:

Where $V_{look\_ahead\_i\_i+1}$ is the maximum velocity generated by the look-ahead method during the process to calculate the value of $V_{look\_ahead\_i}$.

(3) If $v\_can\_achieve$ < $V_{\max\_i\_i+1}$, the kinematic profiles can be modified to achieve a higher machining speed, and the process can be described as follows:

(a) Calculate the value of pre-distance, and the formulas are shown as follows:

$$t = as\_i / J \quad \textbf{(12)}$$

$$vs\_i' = vs\_i - as\_it / 2 \quad \textbf{(13)}$$

$$pre\_dis\tan ce = vs\_i't + 1/6Jt^3 \quad \textbf{(14)}$$

(b) Plan the kinematic profiles for the virtual velocity planning unit. The length of virtual velocity planning unit is defined by the $pre\_dis\tan ce$, the tool path length of current velocity planning unit S_i and the next velocity planning unit S_{i+1} , and shown as follows:

$$S_{virtual} = pre\_dis\tan ce + S_i + S_{i+1} \quad \textbf{(15)}$$

Then, the kinematic profiles is generated by the bell-shaped ACC/DEC method according to the value of $S_{virtual}$, while the maximum allowed velocity is set as $\min(V_{\max\_i}, V_{\max\_i\_i+1})$.

(c) Calculate the velocity value and acceleration value at the end point of current velocity planning unit as follows:

Firstly, calculate the time internal that the distance $pre\_dis\tan ce + S_i$ located in according to Eq. (9).

Secondly, calculate the time t_i that the distance $pre\_dis\tan ce + S_i$ takes according to $s(t)$ and the time internal.

Thirdly, the velocity and acceleration at the time t_i can be calculated by the Eq. (8) and are named $vs\_i{+}1$ and $as\_i{+}1$ respectively.

(4) If all the tool path is processed, the machining process is over, else go to step (1).

4 Experimental Validations

The starfish shape, containing 100 command points, is used to verify the performance of the algorithm proposed in this paper and shown in Fig. 6.

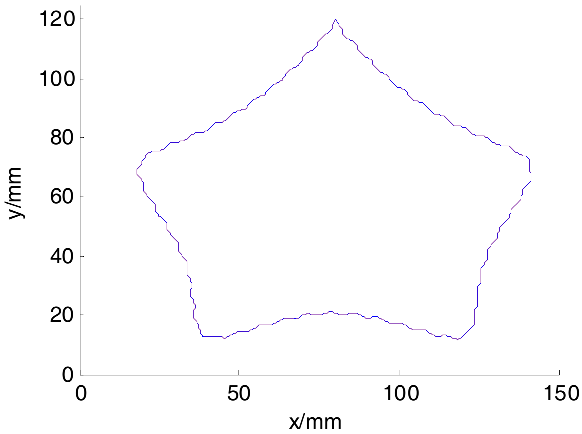
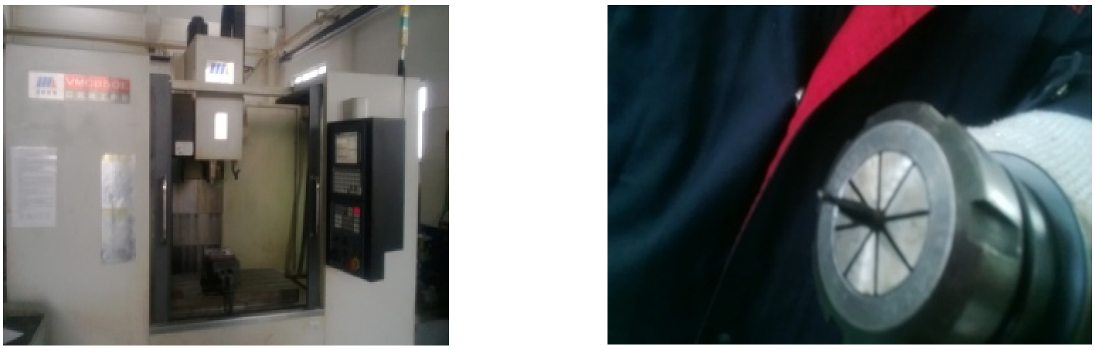


Fig. 6. Starfish shape profile

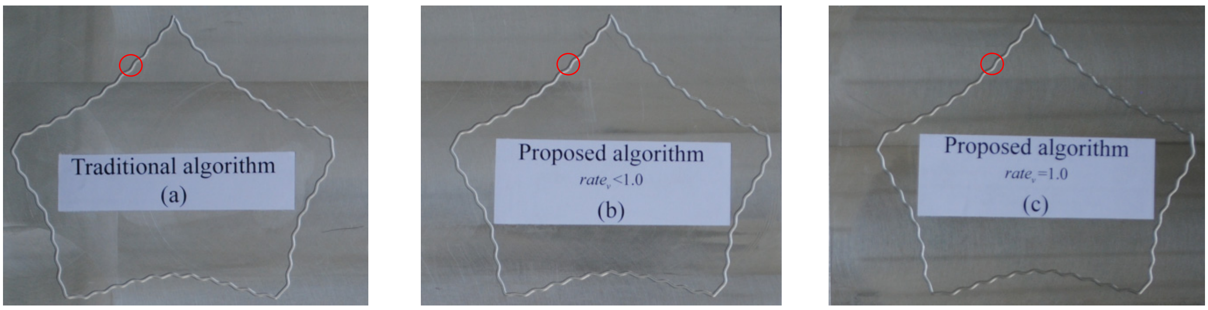
As shown in Fig. 7, the machining center, which is equipped with a ball-end cutter with radius equals to 1mm and an open CNC system developed by the authors [23], is used to verify the algorithm proposed in this paper. The carving material used in the experiments is 7075-T7451 aviation aluminum [24].



(a) SMTCL VMC850E machining center (b) ball-end cutter

Fig. 7. The machining center and the ball-end cutter

There are three principles in the CNC machining field: accuracy, velocity, and surface quality [25]. So experiments are taken to validate the performance of the algorithm in three aspects: machining speed, machining precision and surface quality, and the machining result are shown in Fig. 8.



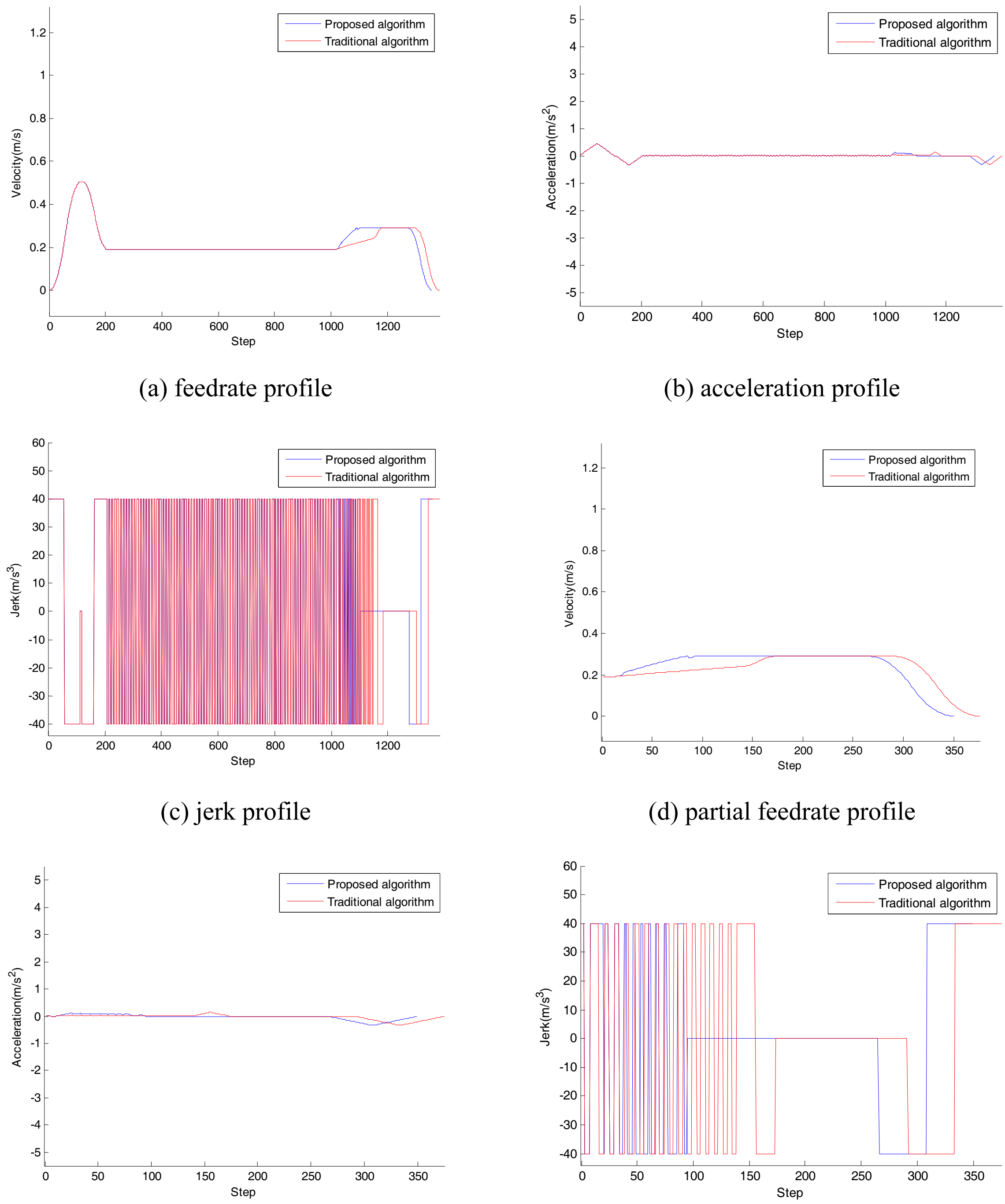
(a) traditional algorithm (b) proposed algorithm, $rate_v$<1.0 (c) proposed algorithm, $rate_v$=1.0

Fig. 8. The machining results

4.1 Machining Speed

The feedrate F is 1.2m/s, the maximum acceleration is $5m/s^2$, the maximum jerk is $40m/s^3$, the sample time T of the CNC system is 0.002s and the maximum contour error tolerance is 1mm.

When $rate_v < 1$, the kinematic profiles generated by the traditional velocity planning algorithm and the proposed velocity planning algorithm are illustrated in Fig. 9.



(a) feedrate profile (b) acceleration profile

(c) jerk profile (d) partial feedrate profile

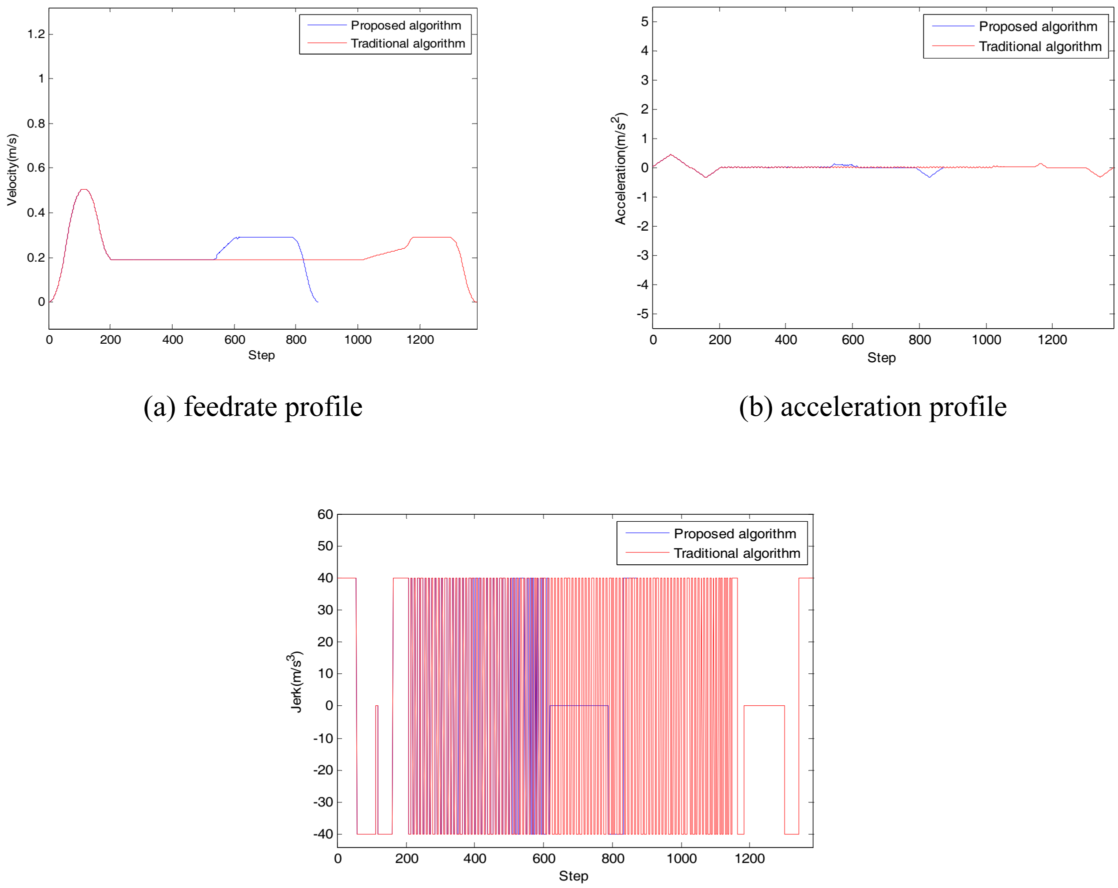
(e) partial acceleration profile (f) partial jerk profile

Fig. 9. The kinematic profiles contrast and partial profiles of tool path (84th-96th segments)

As shown in the Fig. 9(a), Fig. 9(b) and Fig. 9(c), the machining time taken by the traditional velocity planning algorithm and the proposed velocity planning algorithm are 2.770s and 2.718s respectively. This is because the traditional machining process can't make full use of machining capacity allowed by the tool path (84th-96th segments), and the corresponding kinematic profiles are shown in Fig. 9(d), Fig. 9(e) and Fig. 9(f).

As shown in the Fig. 9(d), Fig. 9(e) and Fig. 9(f), the machining time taken by the traditional velocity planning algorithm and proposed velocity planning algorithm are 0.752s and 0.700s respectively, and the proposed algorithm has a significantly improvement in machining efficiency. It is because the acceleration at the junction point of adjacent tool path is not zero in the proposed algorithm, and this contributes to the improvement of the machining speed.

when $rate_v$=1, the kinematic profiles generated by the traditional velocity planning algorithm and the proposed velocity planning algorithm are illustrated in Fig. 10, and the machining time is 2.770s and 1.746s respectively. The propose algorithm has a great improvement in machining efficiency which is caused by the decrease of acceleration fluctuation and full use of acceleration capacity.



(a) feedrate profile

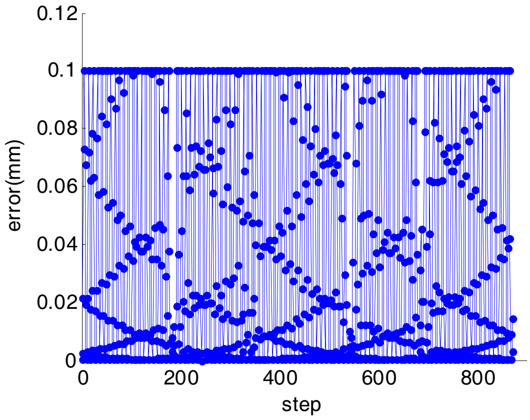
(b) acceleration profile

(c) jerk profile

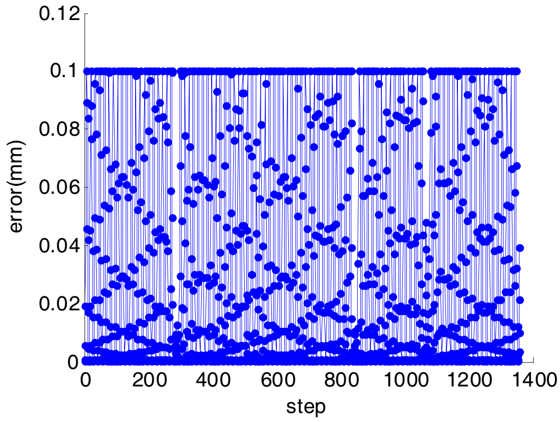
Fig. 10. The kinematic profiles contrast

4.2 Machining Precision and Surface Quality

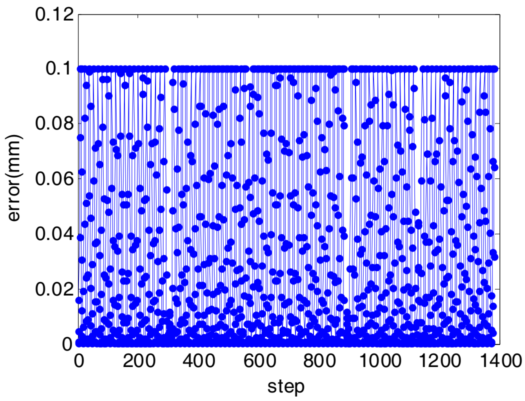
The machining errors generated by the traditional algorithm and proposed algorithm are shown in Fig. 11, and they all meet the system requirements.



(a) proposed algorithm, $rate_v$=1.0



(b) proposed algorithm, $rate_v$<1.0

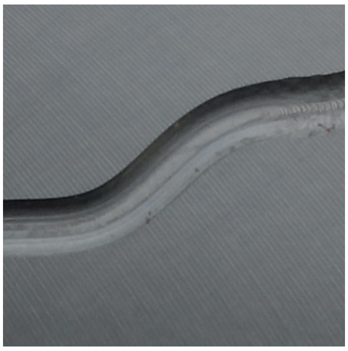


(c) traditional algorithm

Fig. 11. Contour error

The partial profiles of Fig. 8 marked by the red circles are shown in Fig. 12, it can be found that the proposed algorithm has better machining quality than the traditional algorithm.

(a) traditional algorithm



(b) proposed algorithm, $rate_v$<1.0

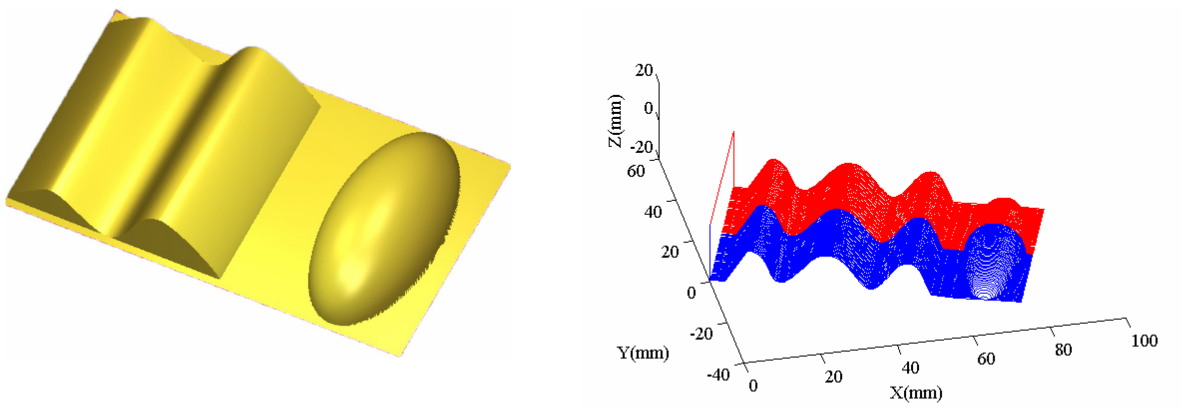
(c) proposed algorithm, $rate_v$=1.0

Fig. 12. The partial profiles of machining results

4.3 Experiments in Three-dimensional Space

LT series CNC systems [23] are designed with the functions of five-axis transformation, RTCT (rotation tool center point control) and 3D radius compensation, so the authors only need to focus on the control of cutter location, and a more complex experiment conducted in three-dimensional space is used to verify the performance of the algorithm proposed by this paper. As shown in section 4.2, the proposed algorithm generates better machining quality and higher machining efficiency when the $rate_v = 1$, therefore this parameter is used in this part to make the comparison of traditional algorithm and the proposed algorithm.

A workpiece containing 16660 command points is shown in Fig. 13(a), and the tool path is shown in Fig. 13(b). In Fig. 13(b), the tool path shown in blue lines and red lines are machined by the traditional algorithm and proposed algorithm respectively. The feedrate is 2m/s, the maximum acceleration is 5×10^{-2}m/s^2, and the maximum jerk is 4m/s^3, and the other parameters are set as same as section 4.1. Since the tool path is too long, two symmetrical tool path marked by star lines are selected and shown in Fig. 14, and the corresponding kinematical profiles of the first seven line segments of the two tool path, which are marked by star lines, from the left of the picture are given in Fig. 15.



(a) workpiece (b) tool path

Fig. 13. The partial profiles of machining results

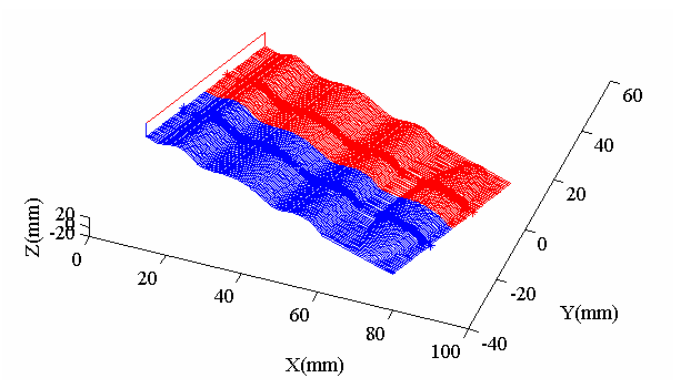
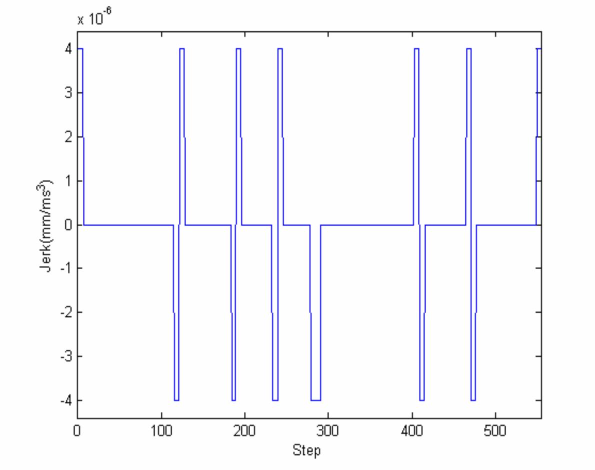
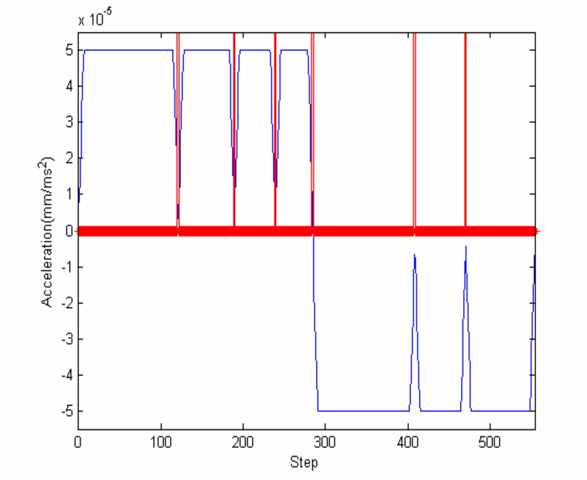


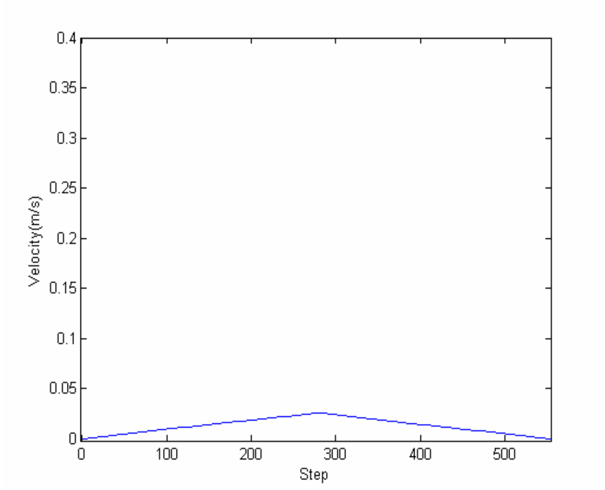
Fig. 14. Selected tool path



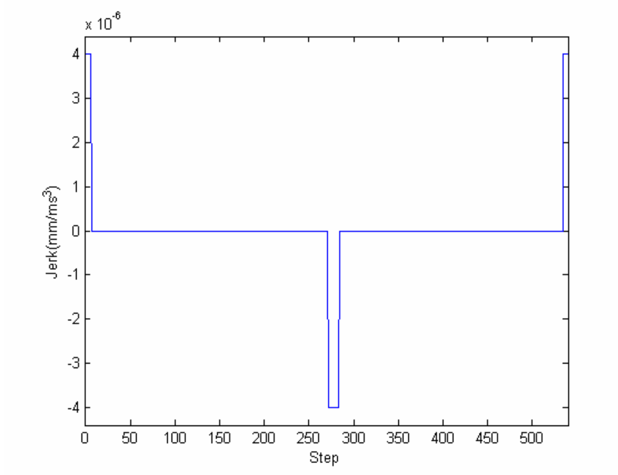
(a) jerk profile, traditional algorithm



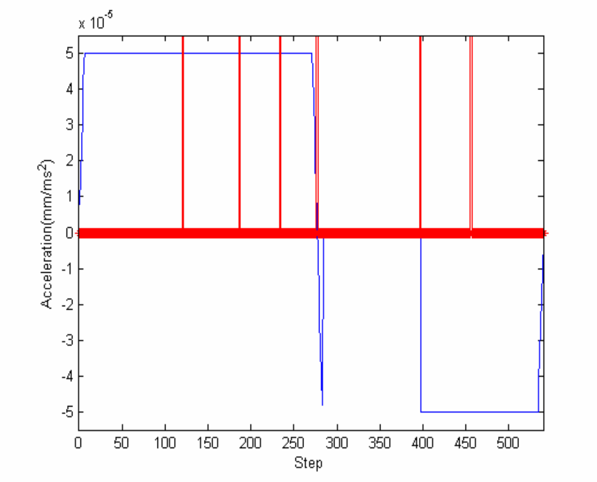
(b) acceleration profile, traditional algorithm



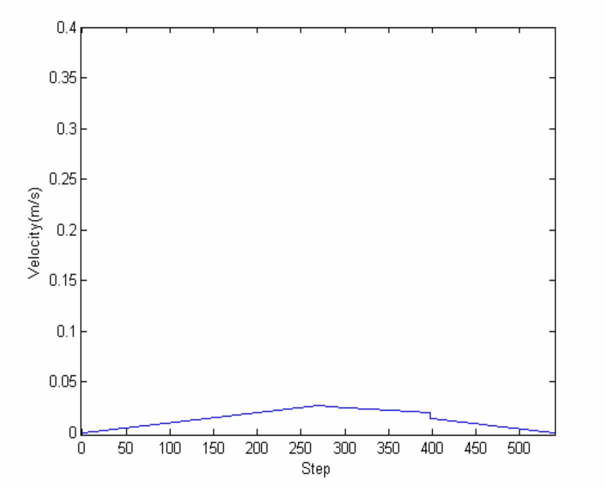
(c) velocity profile, traditional algorithm



(d) jerk profile, proposed algorithm



(e) acceleration profile, proposed algorithm



(f) velocity profile, proposed algorithm

Fig. 15. Kinematic profiles of machining results

The kinematic profiles of the machining process are given in Fig. 15. As shown in Fig. 15(a), the jerk profile of the traditional algorithm changes thirteen times, while the proposed algorithm changed only three times. The difference in the number of changes results in the different fluctuation of the acceleration profiles. As can be seen from the figures of Fig. 15(b), the acceleration of the traditional algorithm reaches the maximum value for four times and the minimum values for three times, and the maximum velocity is 26.08 mm/s at 0.568s as shown in Fig. 15(c), while the acceleration of the proposed algorithm reaches the maximum value for only one times and the minimum values for two times, and the maximum velocity is 27.27 mm/s at 0.554s as shown in Fig. 15(f).

From the contrast of the traditional algorithm and the proposed algorithm, it can be found that the traditional algorithm has seven velocity planning units which is same as the number of small line segments of the tool path, this is because that the ACC/DEC value is set to be zero at the junction of adjoin velocity planning units, so the ACC/DEC has to be zero at the starting point and the ending point of every velocity planning units, limiting ACC/DEC ability of machine tools, so the maximum velocity value generated by the traditional algorithm is smaller than the proposed algorithm. As shown in Fig. 15, the machining time taken by the traditional algorithm and the proposed algorithm are 1.108s and 1.080s respectively, which means that the machining time used by the traditional algorithm is longer. Through the velocity planning unit consolation method and the non-zero acceleration planning method the proposed algorithm has only three velocity planning units, making higher maximum velocity value and machining efficiency.

The machining results is shown in Fig. 16, and the partial views of this workpiece marked by red rectangles are shown in Fig. 17(a) and Fig. 17(b). Part A and Part B are the machining results of the traditional algorithm and the proposed algorithm respectively.

The frequent fluctuation of the acceleration of the traditional algorithm, shown in Fig. 15, generates the constant vibration of the machine tools during the machining process, leaving unnecessary marks on the surface of the workpiece, so the surface quality of the workpiece machined by the traditional algorithm, shown in Fig. 17(a) is worse than that of the proposed algorithm shown in Fig. 17(b).

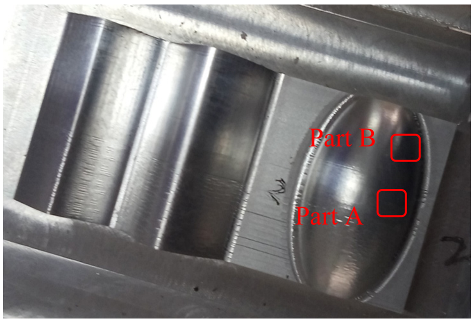
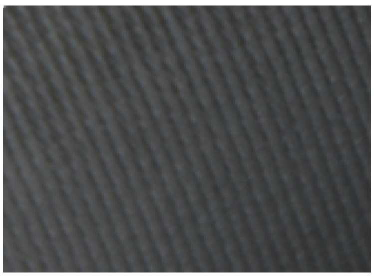


Fig. 16. The machining results

(a) Part A of Fig. 16, traditional algorithm



(b) Part B of Fig. 16, proposed algorithm

Fig. 17. The partial views of machining results

5 Conclusions

In this paper, a high-speed and smooth feedrate planning algorithm for small line segments based on B-spline curve is proposed. The algorithm smoothes the tool path, merges short velocity planning units and adopts modified velocity planning method with non-zero ACC/DEC values at the junction of adjoin velocity planning units to reduce the fluctuation of the machining velocity and improve the surface quality.

Compared with previous works, the proposed algorithm has the following advantages: (1) the consolidation of short velocity planning units reduces the velocity fluctuation. (2) the modified velocity planning method not only generates smooth machining velocity, but also takes less machining time.

One 2-D starfish shape and a workpiece in three-dimensional space are machined by the machining center. Experimental results demonstrate the proposed algorithm can achieve satisfied machining speed and surface quality.

Because of the functions of five-axis transformation, RTCT (rotation tool center point control) and 3D radius compensation, the method proposed in this paper is not only suitable for three-axis machine tools but also for five-axis machine tools. Five-axis NC machine tools include two kinds: the end-milling machine tools and the side-milling machine tools. Different from the end-milling machine tools, the coordinated movement of the tool tip and tool shaft [26-27] of the side-milling machine tools have important influence on machining efficiency and processing quality. Therefore, study the velocity planning method that is suitable for the coordination of the movement of the tool tip and tool shaft is the next research object of the authors.

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