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5-axis local corner rounding of linear tool path discontinuities

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ABSTRACT

5-axis high speed machine tools are widely used in industry. Most of the time, the tool path is described with linear segments (G1) which leads to tangency discontinuities between blocks. The aim of this paper is to smooth the tool path geometry using a 5-axis corner rounding method suitable for acceleration and jerk limited feedrate interpolation.

Several methods have been developed in 3-axis but 5-axis corner rounding is still a challenge due to the difficulties linked to the smoothing of the orientation. The proposed corner rounding model allows to control precisely the contour and orientation tolerances in the Workpiece Coordinate System for 3 and 5-axis tool path. To smooth the tool tip position and the tool orientation in the corner, 5-axis tool paths are represented by two B-Spline curves.

The main difficulty is the connection between the initial tool path and the newly inserted smoothing portion. To obtain a smooth connection of the orientation a parametrization spline is required to link the bottom and top B-Spline parameters. This algorithm is integrated to a feedrate interpolator which controls a 5-axis milling machine equipped with an Open CNC.

1. Introduction

Whilst major improvements in computer aided manufacturing (CAM) and machine tools design have been observed, advances in the design of computer numerical control (CNC) have been limited. Even if polynomial and B-Spline representations of the tool paths have been introduced in the industrial CNCs, most of the milling tool paths are still defined by G1 blocks (linear interpolation). However, this description generates tangential discontinuities at each transition between the linear segments. Considering that the machine tool axes have acceleration and jerk limitations, the only solution to avoid a full stop at each transition is to smooth the geometry to obtain a continuous tool path. That means that the CNC has to modify the geometry given in the part program using user tolerance parameters.

The feedrate interpolation is closely linked to the geometry of the tool path. It is possible to use a decoupled approach [1] which will first design a continuous tool path geometry and then find an admissible motion law along this fixed geometry. The other solution is to treat the problem globally with a combined approach which will compute both the geometry and the motion law at once. This approach used for example in [2] requires some hypotheses about the feedrate and acceleration which are not always verified. The rest of the paper will focus on the decoupled approach. Once the geometry is smoothed, the feedrate planning can be performed using, for example, the previously developed velocity profile optimization [3].

Depending on the context, two main methods are available to smooth the tool path geometry, respectively the global smoothing and the local smoothing. If a portion of the tool path is composed of a high density of short segments, it is possible to approximate all the segments by a curve. On the other hand, if the tool path is composed of long segments, it is important to follow precisely these segments and thus each transition has to be locally smoothed. This paper focuses on the latter problem which has been studied by several authors for 3-axis tool paths but which is still a challenge in 5-axis milling.

Global smoothing has been studied in 3-axis where the main difficulty is to respect a given contour tolerance around the programmed segments, see Siemens compressor [4] and other publications like [5,7,6].

In 5-axis, global smoothing techniques are also widely studied. Different solutions can be used to smooth the orientation: quaternions [8,9], spherical B-Splines [10,11], position and orientation curves [12,13], drive movement smoothing [14–16].

Global smoothing techniques cannot be applied for local corner rounding because several requirements cannot be fulfilled. First the contour and orientation modifications have to be controlled locally and precisely avoiding oscillations. Second, the corner rounding curve has to be connected to the initial tool path. Thus our research not only brings new contribution for 5-axis local

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tolerance management but also for the orientation connection of two portions of 5-axis tool path defined by B-Spline curves.

Local smoothing has been widely studied in 3-axis. Indeed, different methods which give similar results are detailed in the literature. They all give a satisfying corner rounding curve in terms of contour error and continuity management. Indeed G^2 continuity is assured to allow jerk limited feedrate interpolation. Yutkowitz and Chester [17] registered a Siemens patent describing a 3-axis corner rounding method based on two 4th order polynomial curves. Erkorkmaz et al. [18] use a 5th order polynomial curve to round the corner. A cubic B-Spline with eight control points is used by Pateloup et al. [19] whereas a cubic B-Spline with five control points is used by Zhao et al. [20]. Ernesto and Farouki [21] employed a Bezier conic and optimized the feedrate along the curve under acceleration bounds. Bi et al. [22] used two cubic Bezier curves to round the corner. None of these papers tried to extend their solution to 5-axis tool path which brings new challenges. To the best of our knowledge, no previously published work has tackled the problem of 5-axis corner rounding.

It is possible to broaden the context of corner rounding. Indeed, most of the publications are focused on the need for the CNC to round corner using generally a small tolerance of the order of a few hundredths of a millimetre. However, as in Pateloup et al. [19], it can also be applied in a CAM context with a fairly large geometrical deviation. Within the framework of the Step-NC standard development which is a high level intelligent programming environment, it could be useful to be able to locally round a CAM tool path. The solution presented in this paper is multi-scale and can be applied to both contexts.

The aim of this paper is to propose a new 5-axis corner rounding method. 5-axis corners are rounded using two B-Spline curves which define the tool tip and tool orientation. This solution is especially suited for flank milling as the contour and orientation tolerances are precisely controlled. The main difficulty is coming from the orientation smoothing and more specifically from the connection between the initial tool path and the newly inserted smoothing portion. The orientation connection problem between two 5-axis portions is addressed in details and solved using a third B-Spline curve for the parametrization of the tool orientation.

The rest of the paper is organized as follows. First, the 5-axis corner rounding geometry is presented in Section 2. Then, the problem of the continuous variation of the orientation is addressed in Section 3. Experiments and simulations are carried out in Section 4 to demonstrate the efficiency of the proposed method. Finally, the paper is concluded in Section 5.

2. 5-axis corner rounding method

After an analysis of the different orientation smoothing solutions, a representation of the 5-axis tool path based on two curves is chosen. The typical 3-axis corner rounding problem has to be solved using a model which is then extended for the 5-axis corner rounding problem. Finally, it is shown that the main difficulty comes from the orientation connection which is an original problem.

2.1. Analysis of the different orientation smoothing solutions

Several solutions are available to smooth the tool orientation. The solutions based on a modification of the tool path in the Machine Coordinate System [16,15,14] have two main drawbacks. First, it is difficult to control the geometrical deviation on the workpiece resulting from a modification of an axis movement. Then, those solutions require the machine kinematical transformation, so they are dedicated to a specific machine tool. That is why solutions based on a modification of the tool path in the Workpiece Coordinate System are preferred here.

Rotation smoothing can be carried out using spherical B-Splines on the unit sphere [10,11] or smoothing the orientation components $i\ j\ k$. Other solutions using quaternion have also been developed [8]. But here again, the use of these techniques does not allow a precise control of the resulting workpiece geometry. Another important need for corner rounding is to avoid the oscillations which could be generated by these methods.

To avoid the oscillations and to control precisely the geometrical deviations, a representation of the 5-axis tool path by two curves is chosen. The bottom curve defines the locus of the tool tip locations and the top curve defines the locus of a second point belonging to the tool axis [12]. Thus the corner rounding is performed on both 3D curves which leads to apply a 3-axis corner smoothing method twice.

2.2. 3-axis corner rounding method

As we have just seen, 5-axis corners are defined by two curves which have to be rounded as for 3-axis corner rounding problems. The aim of the 3-axis corner rounding algorithm is to obtain a G^2 continuous geometry along which the jerk limited feedrate profile will further be computed, Fig. 1.

The modified geometry has to satisfy the specified contour tolerance ε. Many 3-axis methods have been proposed in the literature, the model presented here is simple and suitable for the extension to 5-axis.

By construction with three control points aligned, the connection between the rounding curve and the previous and following segments is G^2. The definition of the cubic B-Spline used to round the corner is given in Eq. (1) with $\mathbf{P}_i$ the control points, B_{i3} the basis functions and $\mathbf{u} = [0\ 0\ 0\ 0\ 0.5\ 1\ 1\ 1\ 1]$ the knot sequence, see Fig. 1.

$$\mathbf{C}(u) = \sum_{i=0}^{4} B_{i3}(u)\mathbf{P}_i \quad (1)$$

Taking Eq. (1) and the definition of the basis functions B_{i3}, Eq. (2) can be obtained (further details are given in Appendix A). With this construction of a cubic B-Spline with five control points, the point $\mathbf{C}(u=0.5)$ does not depend on the control points $\mathbf{P}_0$ and $\mathbf{P}_4$. The points $\mathbf{P}_1$ and $\mathbf{P}_3$ are positioned symmetrically so the distance $L_1 = \mathbf{P}_1\mathbf{P}_2 = \mathbf{P}_2\mathbf{P}_3$ (Fig. 1). This curve definition allows to have the maximum contour error exactly in the middle of the rounding

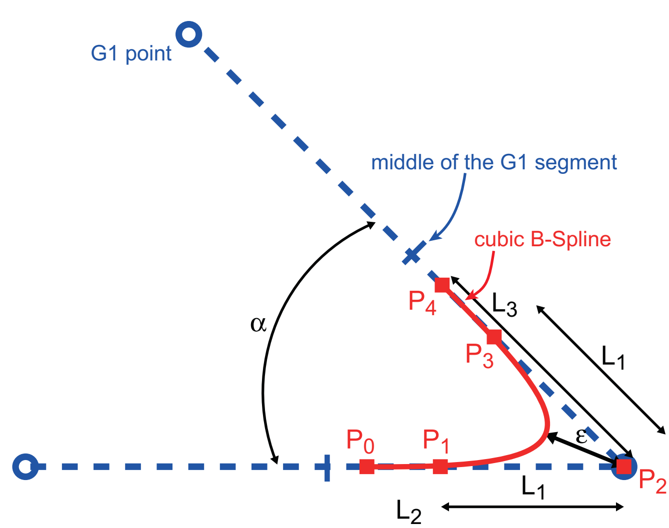

Fig. 1. 3-axis corner rounding method.