International Journal of Machine Tools & Manufacture 96 (2015) 15–26

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

journal homepage: www.elsevier.com/locate/ijmactool

# Local toolpath smoothing for five-axis machine tools

Sneha Tulsyan, Yusuf Altintas*

*Manufacturing Automation Laboratory, Department of Mechanical Engineering, The University of British Columbia, Vancouver, BC, Canada V6T 1Z4*

ARTICLE INFO

*Article history:*
Received 12 December 2014
Received in revised form
24 April 2015
Accepted 30 April 2015
Available online 27 May 2015

*Keywords:*
Corner smoothing
CNC
Five-axis
Smooth tool path

ABSTRACT

When five axis CNC machine tools follow series linear toolpath segments, the drives experience velocity, acceleration and jerk discontinuities at the block transition points. The discontinuities result in fluctuations on machine tool motions which lead to poor surface quality. This paper proposes to insert quintic and septic micro-splines for the tool tip and tool-orientation, respectively, at the adjacent linear toolpath segments. Optimal control points are calculated for position and orientation splines to achieve $C^3$ continuity at the junctions while respecting user-defined tolerance limits. The geometrically smoothed corners are traveled at a smoothly varying feed with cubic acceleration trajectory profile. The proposed method is experimentally demonstrated to show improvements in motion smoothness and tracking accuracy in five-axis machining of free-form surfaces found in dies, molds and aerospace parts.


## 1. Introduction

Five-axis machine tools are widely used for manufacturing of sculptured surfaces found in aerospace, die and mold industries. The tool paths are splined in CAM environment, but mostly fed into CNC as a series of small linear toolpath segments. The part may also have long linear paths but with sharp corners, see Fig. 1. If the tool motion is ceased at the junctions of linear paths, NC cycle time increases and the surface would have deflection marks caused by the unloading and loading of the tool at very small time windows. As a result, commercial CNCs are programmed to travel around the sharp corners by simply accelerating the drives which will be active in the next linear path segment, while decelerating the currently moving drives before the machine reaches to path junction. Although the machine does not have to stop at the junction, an unknown amount of offset error is left at the corner which may violate the tolerance of the part at high feeds. Some of the advanced, commercial CNC's provide features which pre-process the corners using look-ahead functions, and send corrected trajectory commands to the servo drives [1]. However, the algorithms are propriety and the details of the algorithms are usually not disclosed. The smoothness of the motion profile may also suffer, causing discontinuities in the velocity, acceleration and jerk commands of the drives which lead to poor surface finish and may excite the inertial vibrations of the machine tool.

In order to generate smooth high-speed motion along the toolpath with linear segments, global smoothing approach was employed by Yuen et al. [2] and Lei et al.[3] for five-axis machine tools. However, it is mathematically complex to control and evaluate the exact fitting error in this case [4]. The challenge with the local smoothing approach is to ensure continuity at the junction between the corner rounding curve and the linear segment while respecting pre-defined error tolerance limit. Pateloup et al. [5] and Zhao et al. [6] locally smooth three-axis toolpaths by inserting cubic B-spline between linear toolpath segments. Sencer et al. [4] proposed curvature-continuous smoothing scheme which fits minimum curvature quintic B-splines to blend adjacent lines for three-axis tool motion. While several local smoothing approaches are presented for three-axis toolpaths, there is still very limited work in the field of local toolpath smoothing for five-axis machine tools due to difficulties related to smoothing of orientation. Beudaert et al. [7] utilised dual spline approach, one for the tool tip and another for the tool orientation to smooth five-axis toolpaths. However, due to over-constraining the problem, the proposed solution is highly sensitive to even a tiny variation in orientation. Moreover, dual-spline method does not work well when there is a large orientation change for a very small path segment as shown by Yuen et al. [2].

In this paper, a new decoupled approach is presented to achieve corner smoothing of five-axis toolpaths as shown in Fig. 1. Toolpath position and orientation are smoothed by inserting synchronized quintic and normalised septic micro-splines, respectively between the adjacent linear toolpath segments. Optimal control points are calculated for position splines to achieve $C^3$ geometric continuity at the junctions between the splines and the linear segments while respecting user-defined corner position tolerance ($\varepsilon_{pos}$) limits as presented in Section 2 and orientation tolerance ($\varepsilon_{ori}$) limit in Section 3. After geometrical modification of the toolpath, feedrate planning is performed using cubic

* Corresponding author.

http://dx.doi.org/10.1016/j.ijmachtools.2015.04.014
0890-6955/

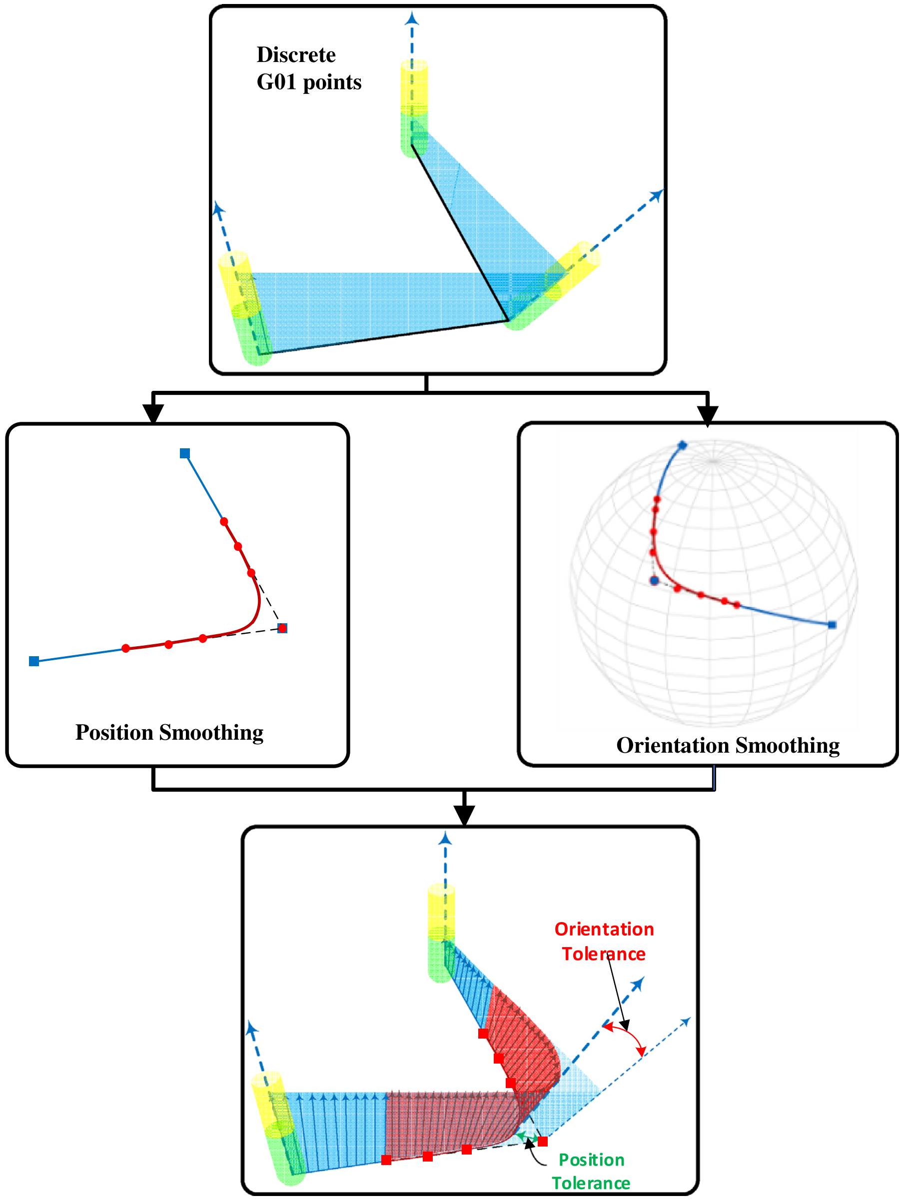


**Fig. 1.** Decoupled approach of five-axis corner smoothing

acceleration profile to preserve $C^3$ continuity in motion. In Section 4, the proposed smoothed toolpath motion is compared against the unsmooth and $C^2$ continuous motion in simulations and experiments to demonstrate the improvements in motion smoothness and tracking accuracy in five-axis machining of free-form surfaces.

## 2. Toolpath smoothing

Five-axis corner is defined by two adjoining linear toolpath segments with tool tip position and orientation vectors represented as $\boldsymbol{p_i} = \left[x_i, y_i, z_i\right]$ and $\boldsymbol{o_i} = \left[o_{ii}, o_{ji}, o_{ki}\right]$ respectively for tool position $i = 1, 2, 3$ such that $\boldsymbol{p}_1 - \boldsymbol{p}_2 = l_1$, $\boldsymbol{p}_2 - \boldsymbol{p}_3 = l_2$, $\boldsymbol{o}_1 \cdot \boldsymbol{o}_2 = \cos\theta_1$ and $\boldsymbol{o}_2 \cdot \boldsymbol{o}_3 = \cos\theta_2$. The sharp position corners are smoothed by fitting quintic micro-splines between linear toolpath segments at each block transition point. Optimal control points for the micro-splines are evaluated based on pre-defined position error tolerance limit $\varepsilon_{pos}$ and conditions for acceleration and jerk continuity at the junction between the linear toolpath segment and the inserted spline segments.

### 2.1. Parametric position micro-spline

A parametric position micro-spline which is inserted between the two linear toolpath segments is defined by the basis functions $N_{i,k}(u)$, $(n+1)$ control points $\boldsymbol{P}_i = \left[P_{xi}, P_{yi}, P_{zi}\right]$ and degree $(k-1)$ with the following form:

$$\boldsymbol{P}(u) = \sum_{i=0}^{n} N_{i,k}(u)\boldsymbol{P_i} \tag{1}$$

The basis functions $N_{i,k}(u)$ are functions of the geometric parameter $u$ and knot vector $U = \left[u_0, u_1, \ldots, u_{n+k}\right]$ and are defined as follows: