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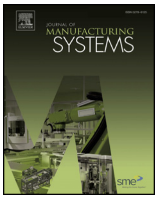

A multi-objective tool-axis optimization algorithm based on covariant field functional

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ABSTRACT

In multi-axis machining, sudden change of tool-axis orientation has adverse effects on the machining quality and efficiency. In this paper, we proposed a mathematical framework to generate smooth tool-axis variation even on part surfaces lacking G2 and/or G1 continuities. An integral functional is formulated as the object function to represent the measurement of the rate of tool-axis change. The functional is covariant so that the result is independent of surface parameterization and applicable to non-Euclidean geometry. The minimization of the integral functional ensures minimal fluctuation of tool-axis. Other machining requirements, such as gouging-free, preferred (or greedy) direction, are incorporated into this optimization problem as constraints. The unified optimization problem is solved by a Finite Element Method (FEM) numerical method. The proposed algorithm is implemented in the planar sections of blade rough machining to produce tool path with smooth tool-axis variation. Machining results indicate that the presented algorithm can improve machining quality/efficiency and avoid gouging.

1. Introduction

With the introduction of lower cost multi-axis machine tools and robust multi-axis Computer-Aided Manufacturing (CAM) systems, multi-axis machining is gaining more attention in both academic research and industrial applications [1–5]. The main reason is that multi-axis machining offers additional benefits than traditional three-axis machining, such as less number of setups, better tool accessibility, reduced machining time and improved surface finish, especially in machining complex sculpture surfaces. The advantages come from the rotary axes that are added to the linear X, Y and Z axes of three-axis machines. The additional freedom from the rotary axes allows the flexibility to avoid collision/gouging and control the cutting condition during machining.

Tool-axis computation for multi-axis machining is a challenging topic and lacks a systematic and comprehensive solution covering a wide range of machining requirements [6]. Multi-axis tool path computation involves the computational complexity of the tool-axis values that belong to a non-Euclidean space. Furthermore, multi-axis tool path generation must deal with the problem of the jaggedness of the tool path caused by the change rate of tool-axis orientation. Sudden changes of tool-axis must be suppressed to respect the machine tool load limits and minimize cut marks on the workpiece. At the same time, we have to consider the avoidance of local and global interference [7,8].

There are many previous works dedicated to tool-axis computation in multi-axis tool path generation. As a summary, these works focus on the following three main requirements in tool-axis computation:

R1 preferred direction

The preferred direction requirement means a greedy tool-axis orientation at certain or all locations to optimize cutting conditions, such as matching the cutter profile with the part surface, to achieve optimal cutting condition or realize maximum cut width or minimum cusp height.

R2 gouge avoidance

Gouge avoidance requirement forbids the cutting portion of cutter from interference with the part surface except on the CC point. Gouging occurs when the penetration depth between the cutter and the part exceeds the tolerance value.

R3 smoothness

The smoothness requirement has two meanings, one is the smooth tool path and tool orientation in Workpiece Coordinate System (WCS), and the other is the smooth axes motion in the abstract axes space. Usually the smoothness of tool path/orientation in WCS is a prerequisite of smooth axes motion.

Most of previous works only addressed one or two of these requirements, while this paper aims to provide a systematic optimization

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framework covering all three machining requirements. Not limited to these requirements, the proposed framework is open and extensible so that new requirements can be incorporated as additional constraints or weighted objective expressions.

For preferred direction requirement (R1), literatures [9,10] devoted their work in finding the optimal tool orientations. The objective in [9] is to obtain the largest feasible machining strip width, and [10] states that the optimal tool orientation occurs when the curvature of the cutter's swept profile matches with the curvature of the local part surface. [10] further corrects the tool orientation to avoid local gouging and global collisions.

Regarding gouge avoidance requirement (R2), the methods reported in [10–12] compared the effective cutting curvature of the tool's swept surface with the normal curvature of the part surface at the contact point to identify local gouging, then took measures to avoid it. Other works [8,13–15] also provided methods to generate five-axis local interference-free tool path.

The aforementioned works treated the influence of part surface geometry or gouging and interference-free requirements as strong constraints, but did not build a unified optimization framework to obtain trade-off between tool orientation smoothness and other necessary requirements. The tool path computed by these algorithms often requires a drastic change of tool-axis between neighbouring contact points.

Drastic/sudden change of tool-axis needs to be smoothed. Generally, there are two approaches to smooth the tool-axis during machining: one is to reduce the sharp geometrical variations of the tool-path (tool location and tool-axis), which is called geometrical smoothing in WCS; another is to use the numerical controller to find a smooth velocity profile that respects all the kinematical constraints of the drives during NC machining, which is regarded as axes motion smoothing in MCS.

To obtain a better performance in smoothness requirement (R3), many researchers reported works related to geometrical smoothing methods. [16] used forward and backward smoothing to find the better path with smaller tool-axis change. [17] proved higher order discontinuity of the part geometry (and hence tool-axis orientation) causes the lower order discontinuity in the tool path. It provided a gouging/collision free and interpolation based tool path computation algorithm to obtain smooth five-axis tool path. [18] proposed a configure-space search method to generate globally optimal tool orientation for five-axis machine. The method found at each CC point the orientation of the tool that minimized cusp height while free of gouging/collision. The tool motion is further smoothed by searching the alternative tool orientations in the C-Space with the smallest change of tool orientations (shortest C-distance). [5] used a tool orientation smoothing method based on quaternion interpolation algorithm to generate smooth and interference-free Cutter Location (CL) data. [19] first used a heuristic method to generate interference-free tool path with better machining efficiency, then developed a hybrid Particle Swarm Optimization (PSO) algorithm to reduce the drastic change of tool-axis. Cutter accessibility and surface finish requirements were taken as constraints. [20] proposed a tool orientation optimization method based on C-space computation. The smoothness of the tool orientation is obtained by finding the shortest path on a constructed difference graph. The method is only applied on triangular mesh models. [21] reported a reference plane based algorithm to generate a set of smoothly aligned tool orientations along a tool path on machining Bladed disk (BLISK). The proposed method considered collision-free and overall smoothness. [22] provided an approach to control the tool orientation for 5-axis CNC milling of gently curved surfaces with ball-end cutters. The aim is to minimizing "unnecessary" variations of tool orientation while maintaining constant cutting speed. [23] reported a graph-based optimization method that found a sequence of tool orientations that can minimize various cost functions including displacement of machine rotary axes. [24] presented a cutter-partition based tool orientation optimization method in order to eliminate gouging and preserve optimal cutting condition, but didn't guarantee smooth tool orientation.

Motion smoothing method also provides an effective way to optimize tool-axis [25–27]. [25] utilized the concept of C-space for generating tool-path using a bi-directional search algorithm; the generated tool path satisfies both local and global interference-free conditions, and also respects a user-specified tool's angular velocity limit. [26] presented a path smoothing algorithm by iteratively doing a local joint movement smoothing to raise the real feed-rate. The optimization started from a given tool path, and used velocity, acceleration and jerk limits of each drive to identify the areas where the tool path has to be smoothed.

The aforementioned tool-path smoothing methods try to overcome the drastic tool-axis changes caused by satisfying requirements R1 and R2. Since the smoothing remedies occurred after the tool-axis has been generated according to certain requirements, the remedies may cause there solutions to other requirements to deteriorate.

Most leading CAM software products lack flexibility when computing tool orientation for complex surface machining. The tool-axis is defined and computed based on user-defined mathematical methods that usually have no correlation with machining requirements. As a consequence, intensive user interaction is still needed when generating tool path. Furthermore, the resulting tool paths usually don't guarantee the mentioned three requirements. What the burden is for the users is to verify the tool path against the requirements and change the parameters and re-generate when necessary.

Summarizing the survey of past research and current commercial solution, none of them addressed the requirements of smoothness, preferred direction, and interference avoidance together and built a systematic/comprehensive framework to carry out tool-axis computation. As a result, the computed tool paths are not completely satisfactory.

In this paper, we present a unified mathematical framework to fully address the requirement of smoothness and a wide range of machining conditions. Based on the analysis of the mathematical implications of tool-axis requirements collected from practical use examples, we build the mathematical models equivalent to these requirements and then integrate them into the unified framework. An integral functional is formulated as the object function to represent the collective measurement of the rate of tool-axis change. The minimization of the integral functional ensures minimal fluctuation of tool-axis. Other tool-axis requirements, such as gouging-free and preferred direction, can be incorporated into this optimization problem as constraints. A FEM numerical recipe is provided to solve the unified optimization problem.

This paper is arranged as follows: Section 2 presents the blade roughing as the case study of tool-axis optimization. In Section 3, the unified mathematical framework is built considering the smoothness of tool-axis and a wide range of machining requirements. Section 4 gives the FEM recipe to solve the optimization problem. In Section 5, we implement the unified framework in four-axis blade milling and present the numerical results of tool axis computation to show its effectiveness. In Section 6, experiments and validation on four-axis turbine blade roughing are described. And Section 7 gives conclusions and the plan for future work.

2. Case study – blade roughing

As stated in the previous section, the proposed algorithm framework is general and inclusive. In this paper we use blade milling as an introductory use case to exemplify its usefulness. Other test cases will be presented in subsequent research.

A typical tool-axis computation strategy in blade milling is shown in Fig. 1. $C_i (i = 0, \dots, n)$ denotes a series of Cutter Contact (CC) points on a tool trajectory. $\mathbf{A}_i$ is the corresponding tool-axis computed by using a "Relative to Normal" method on CC point C_i. The "Relative to Normal" method makes the tool-axis keep a constant lead angle (also called